Design and Analysis of Special Purpose Cutter for Machining Solid Propellant Grain

A Dissertation work

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for the award of the degree of

DOCTOR OF PHILOSOPHY

in

MECHANICAL ENGINEERING

by

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Under the guidance of

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July, 2018

Dedicated with Love and Devotion

to

My mother

(Late) Smt.K.Koteswari

Thesis approval for Ph.D

This thesis entitled "**Design and analysis of special purpose cutter for Machining Solid Propellant Grain**" by **Mr. Kishore Kumar Katikani (Roll No. 701211)** is approved for the degree of Doctor of Philosophy

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CERTIFICATE

This is to certify that the work presented in the thesis, entitle "**Design and analysis of special purpose cutter for Machining Solid Propellant Grain**" which is being submitted by **Mr. Kishore Kumar Katikani (Roll No. 701211)**, is a bonafide work submitted to National Institute of Technology, Warangal in partial fulfillment of the requirement for the award of the degree of **Doctor of Philosophy in Mechanical Engineering**. To the best of our knowledge, the work incorporated in the thesis has not been submitted to any other university or institute for the award of any other degree or diploma.

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Kishore Kumar Katikani

DECLARATION

This is to certify that the work presented in the thesis entitle "**Design and analysis of special purpose cutter for machining of Solid propellant Grain**" is a bonafide work done by me under the supervision of **Prof. A. Venu Gopal & Dr. V. Venkateswara Rao** and was not submitted elsewhere for the award of any degree.

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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ABSTRACT

The main workhorse of satellite launch vehicles and long-range missiles are powered by large Solid propellant Rocket Motors (SRM) because of their simplicity, minimum manufacturing time and they are credited with reliability and consistent performance. These SRM are produced with case bonded Composite Solid Propellant (CSP) grains with suitable binder and oxidizer formulation as main propulsion system. In comparison to liquid engine rockets, solid rockets are relatively simple, easy to apply, require little servicing and have minimum or no moving parts. Thrust characteristics of the solid rocket motor are largely determined by the initial ignition surface of the propellant grain to meet specific requirements. Due to economic and technical reasons, surface area of the propellant exposed to initial ignition, called grain configuration, is to be accurately achieved by machining.

Machining is required to trim off the uneven and porous top surface of the propellant grain and also to generate the desired configuration for the grain. However, the CSP is sensitive to friction, heat, static charge and impact load which are generally associated with machining. In view of this, the chips and powder produced during machining of grain are to be disposed immediately from cutting zone because they become further sensitive to ignition in tiny form. Since these composite propellants are also hygroscopic in nature, the application of cutting fluid leads to disqualification of grain.

Hence, the motivation for the present work is to design and analyse custom-built cutting tool for safe machining of composite solid propellant grain of SRM as regular cutters are not able to meet the above requirements. A special purpose cutter has been designed in the present work to cater versatile machining operations required for different contours of grain configuration with a provision made for an instant and safe disposal of chips.

The experimental studies on microstructure of CSP are carried out for the assessment of 'Hazard to machine' material on safety aspects due to non-availability of data in machining aspects. Experimental investigation of microstructure of CSP by SEM analysis and their mechanical properties by INSTRON UTM are performed to decide the tool material and its geometry such

as nose radius, rake and relief angles. This study enabled proper design of cutting element and to conceive safe experimental set up for an effective conduct of machining trials.

A prototype cutter is developed for the evaluation of tool signature for low cutting force. This work resulted in the development of a disk shaped cutter with HSS as the tool material. Based on the existing designs, 4 conical inserts were employed on the periphery of the cutter. The micrographical studies revealed that large rake and relief angles are required for the tool in order to minimize the cutting forces. Exat values of tool signature is experimentally evaluated for minimum cutting force and these values are considered for the final cutter assembly.

To meet the machining requirement of propellant grain, a final cutter assembly called 'Turbine cutter' was developed and its performance is evaluated through machining trials under stringent safety machining conditions as prescribed in the Department of Defence safety manual for ammunition and explosives, US Government. A new concept of chip slicer is introduced for safe disposal of propellant chips. Staggered chip slicer is incorporated in order to yield good surface finish and for instant disposal of chips. The cutter developed is simple in construction with minimum components and no moving or sliding parts to avoid source of friction in the cutting zone and yet versatile in application to meet the different profiles of given grain configuration.

The cutter is also economical as a provision for indexing the insert is incorporated in the present design. Cutter is also provided with self and instant chip evacuation provision when integrated with Chip and Dust Collection System (CDCS) to meet the safety requirement of machining.

The effect of process parameters on cutting power and material removal rate was evaluated based on full factorial (27) experiments on live propellant material using the developed turbine cutter. Two factor interaction (2FI) models for low cutting power and maximum material removal rate were developed to investigate the influence of process parameters in machining CSP materials. ANOVA is performed to evaluate the significant process parameters for safe and effective machining. Response surface methodology (RSM) is used to find the optimum machining parameters for safe and effective machining of CSP materials and mathematical modelling. Adopted approach and models for optimising the

cutting parameters are also validated. This analysis establishes the safe and effective machining parameters for 'hazard to machine' CSP material using Turbine cutter.

Tool wear studies are also carried out to understand the predominant tool wear mechanism in machining of CSP material with the developed HSS Turbine cutter. The micrographs of cutting insert obtained from Scanning Electron Microscope and Vision Inspection System after machining are analysed. It was observed from the analysis that the predominant tool wear in machining the CSP grain is the progressive chemical wear. It is also found that the developed turbine cutter at uncontrolled ambient condition has a tool life of 60 hrs. Thorough cleaning of cutting element with Dioctyl adipate (DOA), subsequent cleaning with water and drying of the insert at the end of every cutting day ensures to extend the tool life significantly.

The present research focuses on the development of a special purpose cutter for machining hazard to machine materials by meeting the safety requirements. This cutter further helps in machining of required grain configuration with a single tool and set-up. It also provides a methodology for machining composite propellants that contain energetic ingerdients.

Keywords: Propellant grain machining, composite solid propellant, Turbine cutter, chip slicer, Design of experiments, chip evacuation and chemical tool wear.

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1. 1 Background of Solid propellant Rocket Motors (SRM)

Rocket launches have become a familiar and interesting activity in space and defence application in India. The main workhorse of long-range missiles and satellite launch vehicles are powered by large Solid propellant Rocket Motors (SRM), to boost the vehicle during lift off. As the word "engine" is as to liquid rockets, the word "motor" is common to solid rockets, because the propellant is contained and stored as chemical energy in the combustion chamber of SRM, can be directly converted to kinetic energy and sometimes for long-time storage up to20 years [1-2].

Historically, SRM have been credited with having no moving parts. In comparison to liquid rockets, solid rockets are relatively simple in construction, easy to apply, and require little servicing and reliable in operation. SRM have become most preferred option among scientists and engineers on account of their inherent simplicity, lower development time and cost in addition to their capability to pack and deliver brute power.

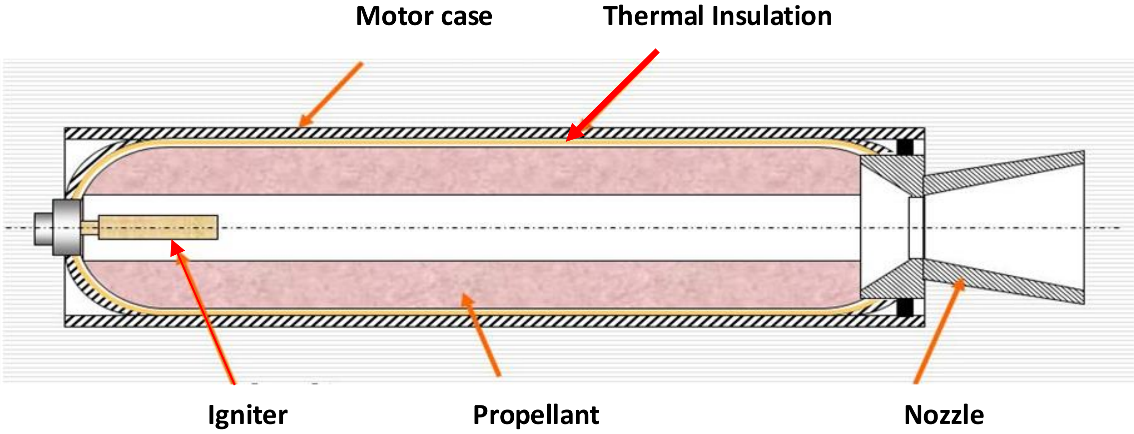


Fig.1.1: Fundamental components of solid propellant rocket motor (SRM)

The important components of rockets motor such as casing, thermal insulation, propellant, igniter and nozzle and their constructional arrangement is illustrated in the Fig.1.1. Case of motor is either made by metals like ASM 6487, ASM 6520 and maraging steels whose mechanical strength is more than 1000MPa or composite materials (glass, carbon, kevlar) produced by filament winding and should capable to withstand an internal pressure resulting from combustion [2]. Thermal insulation next to case material is to provide thermal shield to case from the combustion heat generated by grain burning and to withstand the temperature up to 3500 K. Synthetic nitrile rubber and Ethylene propylene diene monomer (EPDM) rubber are most favourable options for thermal insulation materials. The ‘grain’ is the solid body of the hardened propellant material alone and accounts for 82 to 94% of the total motor mass. Typically propellant grain has either free strand or case bonded architecture. Free strand architecture is contained inside the casing cartridge after polymerisation and supported by elements such as wedges, springs and grids whereas case bonded propellant grains are obtained by casing the propellant directly in to thermal insulated case before polymerisation [2-3]. A convergent-divergent nozzle made of carbon-epoxy/glass epoxy outer body and high ablating, refractive inner material made of carbon, silica, graphite, phenolic resin and carbon-carbon composites are used to convert the pressure energy in the chamber into kinetic energy. The igniter system brings the necessary energy to the surface of propellant grain to burn it by means of pyrotechnic substance.

1.1.1 Propellant and propulsion

A propellant is a mixture of oxidizer and fuel used to produce large amounts of combustion gases on initiation of chemical reaction by suitable ignition. Propellant provides thrust to the rocket motor for the given time which places it on the desired trajectory.

The grain is the shaped mass of processed solid propellant inside the rocket motor [4]. The propellant material and geometrical configuration of the grain determine the motor performance characteristics [5].

Propulsion mechanisms provide a force that moves bodies that are initially at rest, changes a velocity, or overcomes retarding forces when a body is propelled through a medium. Jet propulsion is a means of locomotion whereby a reaction force is imparted to a device by the momentum of ejected matter. Rocket propulsion is a class of jet propulsion that produces thrust by ejecting stored matter, called propellant. The source of energy for rocket propulsion is from chemical combustion of propellants/fuels.

1.1.2 History of development of missile propulsion

Solid propellant rockets were first reported to be used by the Chinese in 1231A.D for military purpose [6]. Development of explosives and propellants began with the use of gun powder. Military rockets were envisaged in China and India nearly 2000 years ago [7]. The chronology of development of propulsion is as follows.

- Liquid oxygen and alcohol rockets were fired in America between 1918 and 1936 revived interest in rocket propulsion.
- In Germany similar experiments were carried out in thirties. Later research expanded to begin development work on military rockets. German Rockets were fitted with guidance and control thus giving birth to guided missiles.

- On Aug 23, 1944 German aircraft launched the MS-293 against allied ships in the Bay Biscay. This weapon was rocket propelled glide bomb and was controlled in flight by radio command. The other well-known German V1 and V2 missiles were auto piloted.
- The first American missile BAT was used against Japan in 1945.
- Work in the field of solid propellants started in India by mid-sixties with the launching of sounding rockets with international participation and in1978, an indigenous multi stage solid propellant based launch vehicle was tested.

1.2 SRM and its classification

The components propellant grain, igniter, nozzle and motor case together constitutes SRM. Various components of SRM and their classification are summarized in this section.

1.2.1 Solid propellant Rocket Motor

SRM is proved to be highly reliable propulsion systems providing high thrust, necessary for initial lift off to any vehicle. The solid propellant rocket motor is made of primarily three individual sub systems Igniter, Solid Propellant and Nozzle. Integrating these three subsystems constitute the Solid propellant Rocket Motor [8].

1.2.1.1 Solid Propellant Grain

In solid propellant rocket motor, the aggregate of propellant mass is known as 'propellant grain' Solid propellant can remain in the state of readiness for a long time. The constituents of a typical solid propellant grain are propellant, insulation and inhibition. Solid propellant is the largest sub-system by weight and size in any solid rocket motor [9]. Solid propellant contains all materials which are necessary for sustaining combustion.

1.2.1.2 Motor Case

Motor case acts as container for propellant and house the insulation, liner and inhibition systems. Hardware withstands the pressure and temperature of the burning propellant. The SRM is made up of metallic or composite case.

1.2.1.3 Insulation and Liner systems

Insulation system has the primary function of protecting the motor case from high temperature combustion gases that generates during functioning of rocket motor. Liner system acts as adhesive aid in the integration of propellant with insulation. Liner material like Chemlok or Pedcoat are being used to give good tensile bond strength, shear and peel strength between motor case to insulation and insulation to propellant interfaces.

1.2.1.4 Inhibition System

Surface area of propellant available at any time for burning determines the pattern of burning and the pressure and thrust developed by the motor. Solid propellant grain configuration is pre-designed to meet the exact requirement of pressure-time or thrust-time components. Selective blocking of burning surface area by suitable polymeric material is termed as inhibition. Requirements of inhibition are low density, compatibility with propellant, good mechanical and interface properties, low erosion rate, high decomposition temperature and good char retention characteristics [10].

1.2.1.5 Propellant System

Desirable Characteristics [11] of propellant are

a) High specific impulse and high density.
b) Predictable and reproducible burning rate.
c) Adequate physical properties over the intended operating temperature range.
d) Good aging characteristics and long life.
e) Availability of raw materials and easy handling.
f) Low hydroscopic and non-toxic exhaust gases.

The shape and quality of initial ignition surface influence the thrust characteristic of the motor. Achieving the predictable and reproducible burning rate for evaluation of characteristics of the grain is possible by precise machining of propellant grain configuration.

1.2.2 Classification of SRM

Modern SRM used for present day application are classified based on many factors as shown in Table 1.1.

Table 1.1: Classification of solid rocket motors [4]

Basis of classification	**Example of classification**
Application	Large boosters, Gas generators, Tactical missiles, Ballistic missiles, high altitude motors etc.
Propellant	Composite: Heterogeneous (physical) mixture of powdered metal (fuel), crystalline oxidizer and polymer binder Double-base: Homogeneous mixture (colloidal) of two explosive (usually nitro-glycerine in nitrocellulose) Composite-modified double-base: Combines composite and double-base ingredient. Steel monolithic: one-piece steel case

Diameter /Length	0.005-6m / 0.025 - 45m
Case design	Fibre monolithic : Filament wound (high-strength fibbers) With a plastic matrix Segmented: Case (usually steel) and grain are in segments which are transported separately and fastened together at launch site
Grain configuration	Cylindrical: cylindrically shaped, usually hollow End-burning : Solid cylinder propellant grain Other configuration: wagon wheel, star, dog bone, multi perforated monocycle, fin cycle etc.
Grain installation	Case-bounded: Adhesion exists between grain and insulation as well between insulation and case; propellant is usually cast into the case Cartridge-loaded: Grain is formed separately motor case and then assembled into case
Explosive hazard	Class 1.3: Catastrophic failure shows evidence of burning and explosion not detonation Class1.1: Catastrophic failure shows evidence of detonation
Thrust action	Pulse rocket : Two or more independent thrust pulses or burning periods, Step-thrust rocket: Usually, two distinct levels of thrust Neutral grain: Thrust remains essentially constant during the burn period Progressive grain : Thrust increase with time Regressive grain: Thrust decreases with time
Toxicity	Toxic and non-toxic exhaust gases

1.3 Development of composite propellants and its application

The composite propellant was invented in 1942 at Guggenheim aeronautical laboratory, California Institute of Technology. Propellants with potassium per chlorate (Kilo) as oxidizer initially, subsequently ammonium per chlorate replaced as oxidizer used to improve performance. Polysulfide binder system was used in 1950, which improved the reproducibility and mechanical characteristics. Introduction of aluminum as the metallic fuel was another major breakthrough in the field of composite propellants for improvement in specific impulse and to suppress acoustic oscillation related combustion instability problems as presented by Herder.et.al[12]. Established Process ability aspects and contemporary developments in the field of polymer theology of HTPB / AP/Al based composite propellants were enabled large scale processing requirement for heavier solid propellant booster stages. The relationship between particle size, shape, viscosity of slurry and mechanical properties of composite propellants had modeled to predict optimum process parameters. The models for kinetics of polymer network build up developed by Paul. Flory et al [13] was of great help in the study of HTTP based composite propellant processing [13, 14]. Most suitable and opted propulsion systems for long - range missile and space vehicle booster are presented in Table 1.2.

Table 1.2: World largest solid rocket motors using composite propellant system [2]

Parameter	**S 139 India**	**S 200 India**	**M 14 Japan**	**P230 Europe**	**ARM USA**	**SCRUM USA**
Diameter(m)	2.8	3.2	2.5	3.0	3.8	3.1
Length(m)	20	22	14	27	46	34
Propellant weight (T)	139	200	70	237	547	313
Propellant system	HTPB/AP	HTPB/AP	HTPB/AP	HTPB/AP	HTPB/AP	HTPB/AP
Isp – vaccum(s)	270	270	276	271	270	286
Number of segments	5	5	5	3	4	4

The comprehensive application of composite propellants in the recent days include to build the propulsion systems of Space launch vehicles, Military missiles, Research airplanes, Assist-takeoff rockets for airplanes ejection of crew escape capsules, Personnel Propulsion belts, Propulsion for target drones, weather sounding rockets, Signal rockets, decoy rockets, spin rockets, Vernier rockets and underwater rockets for torpedoes and missiles [9].

Application of HTPB / AP based composite propellants for defence requirement in India has caught momentum during Integrated Guided Missile Development programme (IGMDP) for ballistic missiles Agni-I, Agni-II, Agni-III, Agni-IV and recently test fired Agni-V in addition to ISRO's most trusted launch vehicles PSLV.

1.3.1 Propellant for long range missile and CSP of present interest

Most of the rocket motors for defence application and booster motors for space launching applications use Hydroxyl Terminated Poly Butadiene (HTPB) propellant as 'work horse propellant'. Composite propellants form a heterogeneous propellant grain with different ingredients depending on its application. Composite propellant accounting for more than 85% by weight of the rocket consists of Ammonium Perchlorate (AP) as oxidizer and Aluminium powder as solid fuel. Conventionally, HTPB is used as, a bonding resin to improve binder oxidizer adhesion in processing composite propellants for large size solid rocket motors. This binder contains the carbon and hydrogen. During combustion it decomposes releasing the carbon monoxide, carbondioxide, and water vapor. HTPB was used in processing the SRM of present study. The curing agent Toluene Di Isocyanate (TDI) helps to crosslink the binder. Metallic powders are generally used to enhance the ballistic performance of propellant formulations. The Aluminium that constitutes around 18% is the fuel that is in the form of fine metallic powder. The fuel increases the chemical energy of solid propellant. The energy increase is due to exothermic reaction with oxidizer. Plasticizer used in the present case of SRM is Di Octyl Adipate (DOA). Plasticizer improves the processing by reducing viscosity of slurry and enhances the mechanical properties. The requirement of plasticizer is low molecular weight, high boiling point, and non-volatile liquid, compatible with propellant ingredients. The quantity added in the composite propellant is around 3% of the total quantity. Phenyl Beta Naphthyl Amine (PBNA), Aluminium oxide (Al_2O_3) and cross linker are also used in small quantities to improve the mechanical and ballistic properties. Antioxidant will help in good aging characteristic. The Activated Copper Chromate (ACR) is added suitably in small quantity to modify the burning rate of propellant grain. Ingredients of HTPB/AP base case bonded composite propellants grain processed in vacuum casting are presented in Table 1.3. Tolin Di Isocynate (TDI) is common Curator for HTPB binder cum fuel and Active iron oxide/Copper chromite as Modifier yields heterogeneous mixture of propellant grain. Specific impulse of 245 sea level / 270 vacuum can be obtained with this composition. Various ingredients that goes into the formulation of HTPB/AP/Al based composite propellants are summarized in the Table 1.3.

Table 1.3: General composition of HTPB/AP composite propellant

Sl. No.	Ingredients	Function
1	HTPB	Binder
2	TDI	Curator
3	DOA	Plasticizer
4	Ambilink	Binder additive
5	Phenyl Beta Naphthyl Amine (PBNA)	Antioxidant
6	Al	Metallic fuel
7	AP (fine/coarse)	Oxidizer
8	$Al_2 O_3$	Anticaking agent for AP fine
9	ACR	Burn rate catalyst

1.3.2 Manufacturing of solid propellant rocket motors and hazard classification

Processing of the solid propellant especially highly filled system with 85-90% solids and 10-15% liquids, poses a complex technological problems. Key factors in formulating the requirements are high specific impulse, good mechanical properties, required burn rate, easy process ability, longer pot life, long and reliable storage life etc.[15]. A schematic diagram of processing the rocket motor in vacuum chemical casting method is shown in Fig.1.2 on process type layout.

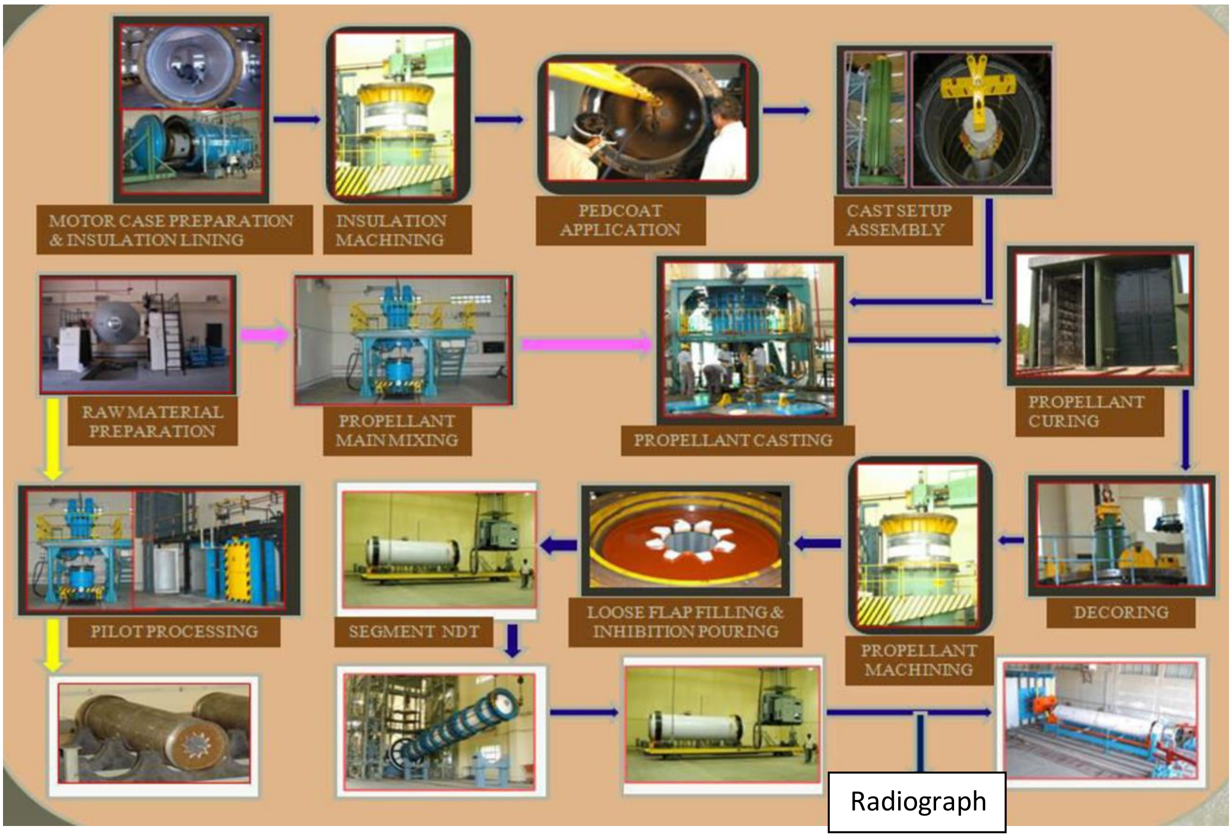


Fig.1.2: Process chart of Solid propellant Rocket Motor

a) Grain Machining

After retrieval of cores/mandrels positioned in the motor case during casting for producing internal bore, propellant grain is then taken up for grain trimming/machining. Generally the two ends of grains are to be machined to get required grain length and interface dimensions. Machining is also required producing desired configuration on propellant grain.

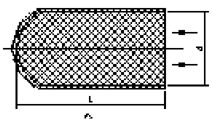
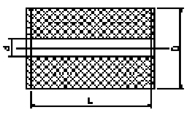
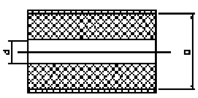
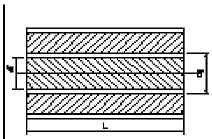
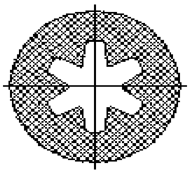
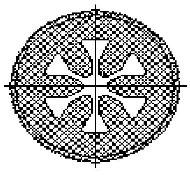
b) Hazard classification

With proper precautions and equipment, all common propellants can be manufactured, handled, and used safely. It is necessary to fully understand the hazards and the methods for preventing hazardous situations arising. Each material has its own set of hazards and machining of HTPB/AP/AL composite propellant fall under 1.3 hazard division classifications while the certain critical processing stages like blending, mixing, casting etc.as shown in Fig.1.2 come under 1.1 hazard division classifications and the rest fall under 1.3hazard divisions. Hazard division 1.1 and 1.3 refers to detonation and mass fire & heat radiation hazard respectively as per American department of defence safety manual on hazard classification of explosives [1, 3].

1.4 Overview on various configurations of SRM Grain and method of their production

Different types of grain configuration in SRM for specific requirements are shown in Table 1.4.

Table 1.4: Different grain configurations of solid propellant rocket motor

S.No.	NAME	FIGURE	APPLICABLE WEB FRACTION	TYPICAL VL	ADVANTAGES	DIS-ADVANTAGES
1	END BURNING	 $Ab = \pi d^2/4$ web = L	>1.0	100%	I) HIGH VOLUMETRIC LOADING FRACTION II) USEFUL FOR LONG DURATION MISSIONS III) NEUTRAL PRESSURE TIME TRACE	I) REQUIREMENT OF HIGH BURN RATE II) HIGHER LINER THICKNESS
2	RADIAL BURNING GRAINS / INTERNAL EXTERNAL BURNING TUBE	 $Ab = \pi(D+d)L$ web = (D−d)/4	0.3 – 0.6	70% – 80%	I) NEUTRAL BURNING II) LACK OF SLIVER III) GRAIN PREVENTED FROM AERODYNAMIC HEATING	HIGHER LINER THICKNESS
3	INTERNAL BURNING TUBE OR SHELL	 WEB = (D−d)/2.0 $Ab = \pi(D+2y)(L-2y) + \pi/2(D-(d+2y)$ y = Web burnt	0.5 – 0.9 (L/D<2)	75% – 85%	I) LACK OF SLIVER II) LEAST SUSCEPTBLE TO EROSIVE BURNING AS A RESULT OF CONFIGURATION COMPLEXITY	I) BURNS PROGRESSIVELY IF L/D IS MORE II) L/D IS LIMITED
4	ROD AND SHELL		0.3 – 0.5	60% – 80%	I) NETURAL BURNING II) SLIVERLESS	SUPPORT ROD IS DIFFICULT
5	STAR		0.3 – 0.6	80% – 80%	I) DESIGN FLEXIBILITY IS ROD II) CASE BONDED • CONFIGURATION III) HIGH INSULATION THICKNESS NOT REQUIRED	I) SLIVER IS PRESENT AMOUNT OF SLIVER DEPENDS ON THE OF SPECIFIC DESIGN
6	WAGON WHEEL		0.1 – 0.3	60% – 80%	I) FLEXIBILITY OF DESIGN	I) VIBRATION AND SHOCK CONSIDERATIONS ARE SIGNIFICANT II) VI IS RELATIVELY LOW

Generation of grain configuration using process aiding tools like mandrels or cores or inflatable bellows or dissolvable mandrels during the casting itself and subsequent removal of the same being practiced in past [4].Various methods of producing the required configurations on propellant grain are as follows

1.4.1 Coated metal mandrels

Mandrels are used during casting and curing to assure a good internal cavity or perforation instead of machining process. They are made of metal in the shape of the internal bore (e.g., Cylinder, star or dog-bone) and are often slightly tapered and coated with a nonbonding material, such as Teflon, to facilitate the withdrawal of the mandrel after curing without tearing the grain. These mandrels/moulds are usually expensive and time-consuming to manufacture and also is subjected to a controlled temperature-pressure-time cycle while curing the grain.

1.4.2 Collapsible mandrels:

For complicated internal passages, such as a conocyl, a complex built-up mandrel is necessary, which can be withdrawn through the nozzle flange opening in smaller pieces or which can be collapsed and retracted after curing of propellants. Some manufacturers have successful in making permanent mandrels (which are not withdrawn but stay with the motor) out of lightweight foamed propellant, which burns very quickly once it is ignited and form the grain shape before actual grain initiated for ignition.

1.4.3 Fix and fire type mandrels:

Some manufacturers have successful in making permanent mandrels (which are not withdrawn but stay with the motor) out of lightweight foamed propellant, which burns very quickly once it is ignited and form the grain shape before actual grain initiated for ignition.

1.4.4 Inflatable Bellow Mandrels:

These mandrels sometimes used to form secondary slots and the bellow will be deflated after the propellant is cured allowing the deflated rubber tube to be removed along the central bore. However because of limited dimensional stability inherent in such rubber tubes, reproducing the intricate shapes or exact slot dimensions is often difficult

But these practice leads to undesirable separation of propellant from the case walls and undue aggravation of already existing bond imperfection between the propellant and the case but may be favorable only when the grain configuration is simple without complex or protruded contours. However, for the size, strength and precision required on grain configuration, these methods are still technologically or economically not viable for batch / piece production of SRM during its development phase where consistency of size and shape grain configuration is important for performance evaluation. Retrieval of mandrels from gain will leads to sudden accumulation of static charges due to friction between large contact surface area of mandrel and grain. The accumulated static charge becomes a stimuli to initiate ignition causing mass fire hazard of propellant grain.

Hence this method is restricted to small grains for producing the grain configuration. For these reasons, machining offers an attractive alternative for manufacturing grains of SRM with suitable configuration in both batch and mass production application.

But the problems associated with machining transverse slots about the axis of central bore in the dendrite grain configuration as shown in Fig.1.3 are that, such operation produces large quantities of propellant waste, which needs to be disposed safely. This operation also carries a danger of accidental ignition, because of the heat associated with machining friction and other mechanical stimuli [16]. Accidental contact of tool with the metal case is another possible chance for accidental ignition. Fundamental experiments on milling of similar rubber materials found in literature [17] that emphases the different considerations for work accuracy and to avoid burning of work material in high speed machining.

1.5 Motivation for the present work

In general the ballistic requirement of SRM cannot meet by simple casting but require machining operation on the propellant grain to generate the desired configuration for initial ignition surface. The cast end faces of grain often trimmed to flat surface by non-sparking hand tools manually if the size of grain is small, minimum material is to be removed and surface irregularities are minimum[1]. However if the large quantity of material to be removed or the profiles to be made on the grain are complex or inaccessible to trimming operator or when the configuration is to be precise for consistent evaluation of ballistic performance of grain, the competent and viable solution for accurate production of required configuration on propellant grain is machining. In addition to this, uneven and porous surface of propellant grain, caused by non-uniform deposition of propellant slurry during final stages of casting, extra propellant being cast for shrinkage allowance as the casting being single shot operation needs to be machined to bring the size of grain to exact dimensions. Sometimes grain at nozzle end segment requires counter bore machining with corner fillet to accommodate the submerged portion of nozzle hardware [3-6]. To cater all these requirements there is no simple and versatile cutting tool available commercially, hence design, development and analysis of a custom-build cutting tool is essential.

The three different grain configurations of one of SRM of the ballistic missiles for its three different stages of its flight are shown in Fig.1.3. This requirement is emerged for development of new grains in the recent past in India is the study of author's interest which is illustrated in the Fig.1.3. Propellant grain having axisymmetric dendrite shape configurations [18] in addition to combination of profiles/contours in second and third stages of motor are shown clearly in Fig.1.3.

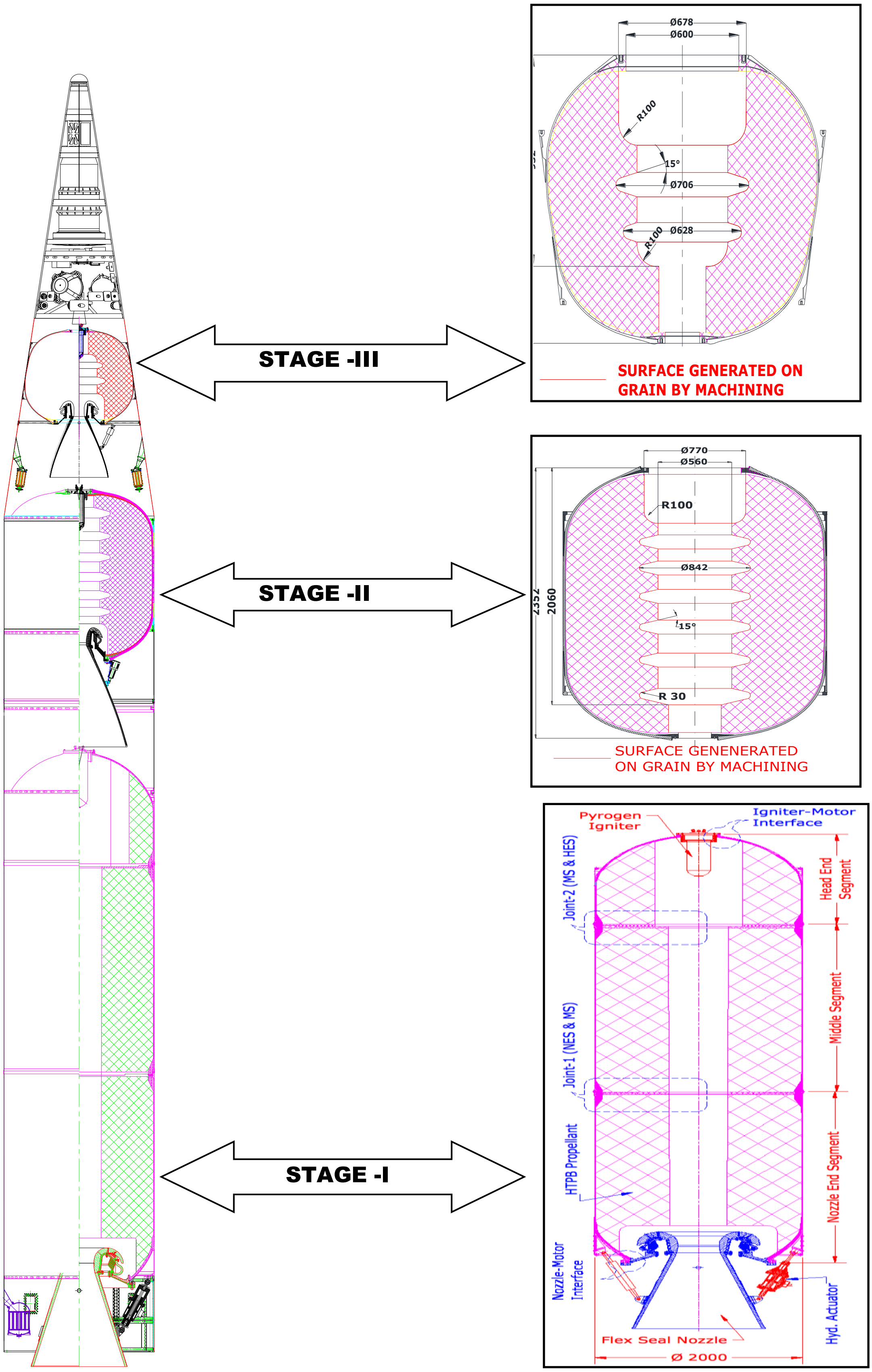


Fig.1.3: SRM with axisymmetric dendrite shape propellant grain configurations

But Propellant grain machining is critical because the HTPB based composite solid propellants (CSP) are sensitive to friction, heat, static charge and impact load which are inevitable in conventional machining operations. The viscoelastic CSP exhibits low hardness (Shore 'A' hardness of order 65-90) offering poor rigidity to cutting forces with exposed fire hazard. The chips and powder generated during machining of grain to be disposed off immediately from cutting zone because they become further sensitive to ignition in fine and tiny form. Since, these composite propellants are hygroscopic in nature and exhibit poor mechanical and ballistic properties in wet environment, external application of cutting medium in the cutting zone leads to disqualification of grain.

Therefore a special purpose contouring cutter is to be developed to meet the said functional demands and also to comply with safety requirements for safe and effective machining of propellant grain. Yet the tool shall have versatile application to machine different profiles and configurations on propellant grain and have the feature to dispose the propellant chips and powder during machining. The cutter needs to be simple to use and easy to assemble & maintain with minimum components.

1.6 Organization of thesis

The thesis is organized in **7** chapters. The description of each chapter in brief is discussed below.

Chapter 1 - 'Introduction' narrates an introduction to the solid propellant rocket motors, classification of SRM, methods of processing, application of SRM, various grain configurations, grain configuration of present interest, motivation for present research work and organization of thesis.

Chapter 2- 'Literature Review' presents the various works that are reported earlier with discussion and scope for the present work. The technical gaps in the literature for similar application are identified and discussed the suitable methods to address the gaps to bring out a simple, safe, and yet a versatile cutter .The overall objectives of the research work is presented with action palan.

Chapter 3 - 'Investigation on microstructure of CSP material for cutting tool design' provides an understanding on microstructure of CSP, various ingredients and their dispersion in composite matrix, porosity analysis, typical mechanical failure analysis and hazard associated in machining of propellants. Determination of mechanical properties of propellant on machining aspects is inclusive of the study. These studies enabled to identify the range of rake angle & relief angel, nose radius of tool and auxiliary systems required for safe machining of propellant grains. The conclusion drawn in these studies will be used for deriving the design concept of custom-build cutter for machining of CSP.

Chapter 4 -'Design and development of prototype contouring cutter for machining of CSP material' presents challenges in machining of CSP, machining requirement of grain, methodology for selection of cutter body , cutting element and tool material for design of prototype cutter. Experimental results based on fraction factorial of DOE for identification of machining parameters for stable cutting force are presented. The experimentation with selected parameters for concluding the tool signature through experiments on prototype cutter is also part of the chapter.

Chapter 5 -'Development of Turbine cutter and analysis of cutting parameters for safe and effective machining of CSP materials of SRM' presents the development of custom-build hollow contouring cutter (Turbine cutter) for machining CSP material. The experimental plan for evolution of safe cutting parameters is presented based on general full factorial design. Two factor interaction (2FI) models for low cutting power and Max MRR are developed to investigate the influence of machining parameters in milling of CSP material. The effect of speed, feed and depth of cut has been evaluated using Response surface methodology (RSM). Presented the approach and models for optimizing the cutting parameters in machining 'Hazard to machine' materials. Analysis of safe and effective machining parameter for machining CSP material using developed Turbine cutter is presented.

Chapter 6 – 'Analysis of HSS tool wear mechanism in machining of HTPB based Composite propellant grain' presents the tool wear studies while machining CSP grain at concluded optimum machining parameters to understand predominant tool wear mechanisms, chip morphology for this new tool and work material combination. Established limiting values of HSS tool wear in machining of CSP material.

Chapter 7 – 'Summary, Conclusion and Scope of Future work' presents the summary of results from the above studies, conclusions drawn from investigations and experiments and scope of future work pertaining to the present research.

2. 1 Introduction

The main workhorse of satellite launch vehicles and long-range missiles are powered by large solid rocket motors (SRM) because of their simplicity and minimum manufacturing time. Generally vacuum casting techniques are used to produce the Composite solid propellant (CSP) grains, where the heterogeneous mixture of propellant is cast into the motor case and cured. Thrust characteristics of that SRM are established by the grain configuration and the rate at which the solid propellant burns. Precise controlling the surface area of the propellant exposed to initial ignition may be required to tailor these thrust characteristics of the solid rocket motor to meet specific requirements. To produce such grain configuration, the central bore is usually formed in the grain by positioning a mandrel in an empty case of rocket motor along the central longitudinal axis or by leaving a vacant core in the propellant. The secondary slots will be produced by different methods. In the present study multiple secondary transverse slots axisymmetric with central bore in the grain, and the entire internal surface together with central bore and slots formed the grain configuration. Proper understanding of machining of HTPB /AP/Al based propellants and the difficulties associated to produce such grain configuration by machining techniques needs thorough study of

- Need of HTPB/AP propellant grain Machining
- Machining of solid propellants
- Previous work on propellant cutting tools/apparatus
- Morphological studies on composite solid propellants materials
- Development of special purpose cutting tool for CSP work materials
- Evolution of tool geometry
- Optimization of cutting parameters
- Tool wear

Machining of propellants is a risky task because the HTPB/AP/Al based composite propellants are sensitive to mechanical stimuli such as friction, heat, static charge and impact load which are inevitable during machining operation. But literature on machining, cutters for machining of HTPB /AP/Al based propellants is seldom found in open source due to their application for strategic use probably. Therefore materials with nearly equivalent mechanical properties and physical characteristics are considered for literature review in this discretion.

2.1.1 Some fundamental meanings and definitions of the terms used in literature:

The various terms that are used by the researchers in the literature are defined in the present section.

i. **Visco elasticity:** It is the property of the certain materials like polymer composites that poses both viscous and elastic characteristics when they undergo deformation. These materials exhibit time dependent strain along with the instantaneous strain on loading. The instantaneous strain represents the elastic characteristics of the material while the time dependent strain represents the viscous characteristics. There is always a phase difference between the applied stress and the strain response.

ii. **Solid propellant**: It has several connotations and the most pertinent one in this work is the rubbery mixture of fuel, oxidizer and other ingredients that have been processed and constitute the finished grain.

iii. **Propellant grain:** The grain is the shaped mass of processed solid propellant inside the rocket motor. It can be produced by casting, molding or extrusion. Its appearance and feel is similar to that of hard rubber.

iv. **Grain configuration**: The geometry of the initial burning surface of a grain when ignited in a motor. The material composition and geometrical configuration of propellant grain determines the motor performance characteristics.

v. **Rocket motor**: A rocket motor is a projectile with certain payload propelled by ignition of propellant for a definite range. Since rocket motor converts chemical energy stored as propellant to kinetic energy, it is called as motor.

vi. **Web thickness**: The minimum thickness between initial burning surface and the insulated case wall of grain.

vii. **Web fraction**: The ratio of the web thickness to the outer radius of propellant grain.

2.2 Need for Machining of CSP grain in SRM

Various machining requirements of propellant grain in manufacturing of SRM are discussed in the following sections.

2.2.1 Functional need

In manufacturing of solid propellant rocket motors it is sometimes necessary to machine the propellant grain with intricate contours to generate the specific surface area on the grain in order to obtain required thrust characteristics. Thrust characteristics of SRM are largely determined by the internal configuration i.e., initial ignition surface of the propellant grain to meet specific requirements [2]. The required grain configuration, to be accurately achieved by machining. Sometimes segment of grains are also to be machined at both faces before they are assembled into full motor to bring grain size and weight to exact specifications.

2.2.2 Integration need

Large size solid propellant rocket motor are processed in segments by vacuum casting technique are not generally produced to exact dimensions. This is due to uneven and porous surface of grain caused by non-uniform deposition of propellant slurry during final stages of casting. The grain also subjected to minor dimensional changes during curing of propellant. Therefore casting is done with extra propellant to provide some allowance to the grain which may be further trimmed off after curing. Now to bring the grain size to exact dimensions, extra propellant in each segment is to be trimmed off. Some cases, exact level of propellant at one side of each segment is obtained by casting fixtures and other side needs to be machined to required level. Further to house the submerged nozzle assembly of rocket motor, propellant grain at nozzle end side requires counter bore with corner fillet for nozzle integration, is another requirement of machining propellant grain. To achieve the desired compression gradient along the radial direction in 'dry joint' configuration of motor at segments joint for a leak proof assembly, in-situ trimming of grain by machining is essential in such cases.

2. 2. 3 Economical need

However, for the size, strength and precision required on grain configuration, few non machining methods that seems possible for producing desired grain configurations on SRM are still not technologically or economically viable for batch / piece production of large SRM during their development phase, where the developers come across variety of grain configurations. Precise production of dimensions, generation of complex profiles, large size of job, accumulation of static charges while withdrawal of mandrels from grain restrict these methods to apply. By virtue aforesaid economic and technical reasons, machining offers an attractive alternative for producing the grain with suitable configuration in both batch and mass production.

2. 2. 4 To reclaim hardware for reuse

During the development phase of solid propulsion system, sometimes it may necessary to remove solid propellant from a rocket motor case due to formulation errors or noncompliance of quality requirements and replace the propellant. CSP materials for rocket motors are typically composed of solid particles of oxidizer and aluminium powder bound together with a synthetic rubber-like material generally a polymer. The resulting material that may be torn apart and shredded by impingement of jets of water at ambient temperature and a pressure in the range of 4000 to 6000 pounds per square inch (psi) were disclosed in literature [19].The method and apparatus so disclosed is satisfactory for metal cases since metal cases can withstand to the high pressures of 4,000 to 6,000 psi, but the use of such process with a rocket case made of composites (fiber glass, graphite, aramid etc. Filled with suitable resin) invariably results in damage to the case. However to overcome the said difficulty machine controlled removal of material from case using suitable cutting assembly is thought of. In order to reclaim the loaded non-metallic case of SRM, it is inevitable to remove the bulk rejected propellant material from the casing without harming the case. More particularly, the use of cutter assembly to remove the propellant in the form of chips by machining operation is found, more reasonable.

2.3 Machining of filled composite elastomer materials

Literature on machining of HTPB /AP/Al based propellant seldom found in open source, therefore machining of elastomers which exhibit equivalent mechanical and similar physical properties were studied for near comparison. Strenkowski et al [20] conducted orthogonal rubber cutting experiments and observed the effects of various process parameters on machined surface roughness and chip morphology. It was found in that studies, feed rate and rake angle have a significant effect on the types of chips generated in orthogonal cutting. Long and continuous ribbon-like chips and corresponding smooth machined surfaces were observed while high feed and speed conditions employed at large rake angle of tools. Use of ANSYS to study stiffness of rubber work material was carried out by researchers. It is found form their studies that because of the low elastic modulus of work material, design of the work piece holding/clamping fixture was a critical factor in achieving good surface finish of elastomers in end milling [21-22].

The machinability of thermoplastic, thermo setting polymers and effect of their viscous properties on surface integrity & chip formation and machining process were studied by Xiao.et.al [23]. It was noted in these studies that viscous deformation of polymer plays a deceive role in determining the quality of machined surface & appropriate machining conditions must be selected to ensure the material removal deformation falls in the regime without viscoplastic scaling or tear & brittle cracking. The optimum machining conditions must be based on properties of polymer such as fracture toughness, glass transition temperature and molecular mobility. The shear stress in the shear plane of the chipping is a good measure of the coupled effect of strain rate and temperature rise. In the study it was also identified two new types of chips whose deformation and curling were in close relation to the surface integrity of the machined components.

Murakawa et al [17] investigated, cutting speed is a key factor in elastomer machining and high cutting speed generates good surface finish. However, at high cutting speed, smoke is generated due to the burning of elastomer chips. It becomes an environmental and health hazard and limits the cutting speed in elastomer machining. Hence effective cutting speed is desirable for elastomer machining. The research conducted in [22] shows solid carbon dioxide cooled elastomers, compared to the room temperature work piece, and generated larger cutting forces in end milling. With observed cutting forces in this study, effects of cutting speed, tool heating, and work piece cooling are investigated. The groove width after end milling of elastomer is significantly smaller than the tool diameter. This was analysed due to the low elastic modulus and large deformation of the elastomeric work piece exhibited during machining

2.4 Previous work on propellant cutting tools/ apparatus

Extensive literature search conducted regarding use of special purpose versatile cutter assembly suitable for machining composite propellants, having energetic ingredients. Specific search on machining of complex grain configuration that combines various profiles in its configuration in case bonded SRM was carried out.

Cutters for milling of solid propellant grains are known in the prior art by, Keith et al [24]for their invention “Propellant Milling tool, Butterfly cutter” only addressed the machining of plane surfaces without safe chip disposal provision. A major drawback in such cutters is that they can be used only for one particular type of machining operation such as facing or trimming end faces of grain and not suitable to machine required contouring operations such as filleting, grooving , slot machining etc.

Yet another assembly devised to machine the grooves about the axis of bore in the grain by Paul Hoekstra et.al [25], in their patent titled “Propellant grain machining device and method”, and their previous invention “Propellant grain machining device”, claimed an assembly which is devised to machine the grooves about the axis of bore in the grain [26]. The apparatus consists of a telescoping arm connected to a spindle. A cutting tool with two cutting edges called primary and secondary cutter is connected to the distal end of the telescoping arm. The secondary cutter is positioned adjacent the primary cutter and configured to make cuts through the portions of propellant grain along its path such that the grain is cut away from rocket motor in to multiple tiny pieces. The telescope arm carries a number of interconnected concentric sliding cylinders configured with a multiple ball/spring dents. It carries bearings and each bearing exert a resistant load for restringing one of the concentric cylinders. It is such that the innermost unextended part of said concentric cylinders extends prior to the extension of any other of said unextended concentric cylinder. But the device is complex in construction with number of elements / parts and various moving parts demanding tedious prior setting operations to use and maintain. This assembly also carries single point cutting tool as main cutting element not fit for the purpose of maximum material removal rate [25-26]. The transfer of energies associated with moving parts to propellant grain is not eliminated completely in the invention. Another method and tool for machining a transverse slot about a bore is found. But it is not capable for trimming end faces of propellant grains / facing at reasonable material removal rate in absence of multipoint cutting elements in the assembly [27]. A comprehensive machining setup specially designed as 'milling machine' is complex in construction for assembling and use, which cannot be adopted to general purpose machine tools and needs excess lead time to start the machining operation [28].

Still another invented devices and assemblies were found which did not address the effective disposal of propellant chips and powder being produced from machining, which are more sensitive to said mechanical phenomenon. Few methods were suggested for generation of desired configuration in the propellant grain using special processing aid tools like mandrels or cores or inflatable bellows during the casting itself and subsequent removal of the same. But these methods practically leads to undesirable separation of propellant from the case walls and undue aggravation of already existing bond imperfection between the propellant and the casing, but may be favourable only when the grain configuration is small, simple without complex or protruded contours [29]. Precise control of dimension of grain configuration by such aiding tools is again a technical challenge when working with such large sized solid rocket motor castings. Another portable slotting device [30] invented for machining conical slots using hydraulic telescopic arm and control systems can only be used for slotting operation but not suitable for facing and profiling operations. Low material removal rates of single point cutting tool for a given volume of material limit its application for machining the grain configuration considered in the present study.

A book on rocket propulsion elements for practicing professional in the field of rocketry [4] has strictly cautioned about the hazard nature of HTPB propellants and suggested thorough study of the hazard behaviour and properties of each propellant before they are handled. The book did not provide the insight on the process equipment and tools to manufacture solid propellant rocket motor grain.

Process document titled "Solid propellant processing factors in rocket motor design" [1] present the difficulties associated in machining propellant, which depends on the physical properties of the formulation, shape and sensitivity of the propellant. The various steps to be taken for machining the propellant grain includes the selection of special cutting tool, maintenance of sharp cutting edges to avoid friction and special precautions or interlocks to prevent the accidental contact of cutting tool with metal parts of rocket motor to reduce the hazard of accidental deflagration of propellant grain. However the focus on primary cutting angles of tool signature and safe cutting parameters to machine propellant grain was not mentioned.

An invention named “milling machine” provides a unique solution for forming any internal geometric configuration on propellant grain of any motor which has a nozzle opening. The generation of configuration is accomplished by means of a remotely operated milling machine which has a cutter or end mill controllable with regard to cutting speed, feed rate, angular orientation and radial indexing with the work piece. The machine is able to provide automatically a predetermined cross sectional propellant charge cavity in a rocket motor using an extendable end mill insertable into previously formed bore/cavity. The end mill cutter is pivotable and adapted to be extended within the core work piece /central hole of grain by remotely controlled power means [28].

Various grain configurations to meet the different Thrust –time plots of vehicles to be considered while designing the solid propellant grain was disclosed [31-32] in design monogram of space vehicles, but various tooling and process aids requirements to generate that grain configuration were not clear. In other invention Robert gerber et al [33] presented a machine for cutting a cylindrical specimen of rocket propellant. This is used to extract small samples from main propellant grain for evaluation of mechanical properties.

To produce asymmetrical constant cross section bore in propellant grain of SRM, sometimes a non-machining method was adopted [34]. A flexible bag in elongated position is fitted inside templates that had aligned openings corresponds to the shape that is desired in the bore of grain of SRM. The bag is filled with a multiple of solid pieces each having a cross section substantially less than that of the bag, with the bottom sealed. When the bag filled with the solids, then to exhaust, air suction is applied to the bag by vacuum needle until the bag is very tight on the solid pieces contained therein. The hole made for vacuum needle thereby is sealed, after the vacuum needle is withdrawn, and the templates are removed from the bag. After use in loading a solid rocket motor with propellant, the bag is cut open, the solid pieces are removed, and the bag is out of the bore to form the shape in propellant. But the invention is not appropriate for the forming radial groves, at great depth in propellant.

Another non machining methods to generate grain configuration in rocket motor using fix and fire type and chemically collapsible type mandrels is found in the literature [35-36]. The objects of one the invention to generate grain configuration in spherical rocket motor case is found [35] to provide a novel method and tool/apparatus for casting of solid propellants which adapts the propellant to be cast in a monolithic spherical casing with a central chamber having greater width than the opening in the casing. To produce the central chamber in the propellant grain in the spherical shape rocket engine casing having a single opening the following method was adopted by inventor. When the leaves/petals of a material forming the desired shape which when melts at a temperature below the ignition temperature of the propellant. The curved edges concentric to the curvature of the spherical casing were inserted into the spherical casing through the opening therein, assembling the leaves to form a core having a greater width than the width of the single opening. With curved peripheral edges in position, propellant was cast around the core and allowed to cure to form a solid mass and then supplying a heating medium at the interior of the casting to melt the leaves and provide a central opening with flutes projecting radially there from.

Yet another cutting assembly that includes a multiple primary cutting wheels, secondary cutting wheels and secondary cutters which are mounted to a mounting head was available in the US patent by Kierstead et al [29], which is relevant to partially meet the present requirement of machining. The mounting head is attached to an arm for swivel about an axis of rotation. Means are provided for rotating the mounting head. The cutting wheels are mounted to the mounting head for rotation about an axis of mounting head. Provision for transverse tilt of mounting head also incorporated. Each secondary cutting wheel includes multiple cutting blades extending outwardly from the rim. The cutting blades are each configured with radially extending cutting edges for cutting in a direction normal to the axis to the axis of rotation of mounting head. The cutting blades are oriented at approximately 30 degree angle to the axis of rotation of first cutting wheel, with the angle of orientation of cutting blade of the second cutting wheels being opposite in direction to the angle of orientation of cutting blade of the first cutting wheel. The secondary cutter includes a substantially circular cutting blade for making in the propellant which is substantially transverse to the cuts made by the first and second cutting wheels [29].

This assembly did not address the effective chip evacuation form the cutting zone and contain large number of parts in the assembly. The cutting blades extended outward from the secondary wheel are weak due to thin cantilevered spikes, posing the danger of breakage in moderate depth of cuts and its complex turbine blade line geometry make its manufacturing a time consuming and expensive affair. The tool holder is also not designed for contouring operations restricting it for versatile machining application.

Howe ever, none of these references discussed above individually or separately suggested a simple, safe, comprehensive and versatile cutter assembly to cater the machining requirement of solid propellant grain.

2.5 Morphological studies on composite solid propellants materials

Since limited literature found on open source about the morphological studies on HTPB/AP composite propellant, publications on elastomers whose mechanical and physical properties are nearly similar to composite propellants are considered in the study.

Rajesh Nayak et al [37] explained that the form of chip produced is one of the major parameters influencing productivity in elastomer machining. Here chip formation mechanism is classified through experimentation based on chip size, shape and chip type provides useful information for understanding the process of chip formation. It is revealed in their study, that chip types are closely related to the machined surface finish. It has also been shown that the morphology of elastomer chips can be categorized into three basic types: (i) continuous ribbon-like chips with a smooth machined surface (ii) segmented chips with a rough machined surface and (iii) discontinuous chips with an even worse surface finish.

In case of elastomeric work material, continuous ribbon-like chips were associated with a smooth surface finish, which occurred with tools of large rake angle and under cryogenic cooled work piece conditions. In contrast, discontinuous chips are associated with a rough machined surface that results from cutting with small rake angle tools at ambient temperatures. The FEA simulations by Rajesh Nayak et al [37] showed good agreement with the experimental results that the unique mechanical properties of elastomers, particularly the large elongation to fracture and low thermal conductivity, can greatly affect the chip formation during machining. Most elastomer parts are manufactured in moulding process. The machining process was studied for prototype or low-volume manufacturing of elastomer parts to avoid making the mould with complicated shape. The accurate measurement to quantify the roughness of machined surface of elastomer using the contact stylus method is a technical challenge because the fine features and asperities on the elastomer surface are deformed by the contact force. This has been discussed by Stupak et al. [38] and tried the profilometer to characterize the worn surface of rubber where in with the use of non-contact optical method, the low reflectivity of the surface was also a problem. A classification system that identifies elastomer chips based on their size and morphology using optical pictures and Scanning Electron Microscopy (SEM) micrographs to examine and classify chips were adopted [39].

Vulcanized natural rubber compound degrades and form gases into smoke at temperature, around 150 to 200°C [40].This is lower than the 300°C tip temperature of the induction-heated tool. The high specific energy in the chip generates localized high temperature during cutting, which burns a portion of the elastomer material, generates smoke and creates the particular type of chip morphology with the melting surface texture. Higher chip temperature is expected at high spindle speed, induction-heated tool, and room temperature work piece [41].

Studies on microstructure of composite rubber like work materials is essential in addition to evaluation of mechanical properties for design, development of cutter and also for better understanding of machining process.

2.6 Development of special purpose cutting tools

The defence and space industry have increasing interest in HTPB/AP/Al composite propellant material for its missile and rocket boosters respectively. However this material is classified as Hazard division 1.3 as per the defence explosive handling safety manual of US, posing fire accident when attempted to machine using existing cutting tools. Thus there is a need for a special purpose multipoint cutter assembly which is provided with suitable geometry & cutting angles to meet the functional and safety requirement.

Very few articles/patents [24-30] can be found on the apparatus/ systems for machining of solid propellants in the literature. None of the papers/patents have more theoretical approach in dealing with the method and arrangement of various components to perform the cutting operation for specific application of complex contours on propellant grain. None of the apparatus/system is versatile to meet the variety of machining operations to complete the required grain configuration considered under this study. Due to heterogeneity and viscoelasticity of HTPB/AP/Al composite propellant material where powder ingredients are embedded in HTPB binder matrix neither the models of metal cutting nor the models of elastomer can be implied directly for study and analysis.

In the preliminary design phase of new milling tool, a closest design concept with holistic model was applied focusing four major areas namely the customer domain, the functional domain, the physical domain and the process domain that steers the design concepts. The iterative route between these four domains, will ultimately lead to implementing the identified functions by appropriate technical solutions. Technical solution that is cost-efficient and easy to implement and yet safe to apply for hazardous to cut material will be opted. Application of the PLM concept in the conception and production phase, and applying creative design methods such as TRIZ [42], Optimum construction variant for quick locking and unlocking the inserts was identified by Michael et al [42] in designing of a new construction variant for the milling cutter that consists in a quick change of the worn inserts. Paul et al [43] presented an innovative round insert face milling cutter and method for its design and verification using commercially available numerical tools.

A method for reducing the tool temperatures &tool wear in metal cutting and to enhance the tool life by continuously changing the active cutting portion of the tool was proposed by Raju et al [44].This was achieved by using a circular profiled tool which rotates about its axis as the tool is fed into the moving work piece and such tools have been referred to as 'Rotary Tools'. In face milling with rotary tools, the cutting forces developed are less compared to conventional face milling cutting due to lower friction at the rake face there by reduced amount of work done in chip formation. Hence, rotary tool face milling can be effectively used in machining of 'difficult to machine' aerospace materials with high feed and depth of cut. The cutter body considering the maximum load conditions has been modelled using Solid works CAD package &analysed using ANSYS package for stress distribution. The rotary face milling cutter has been validated for with different inclination angles such as 20°, 30°, 40° and 50°. The cutter developed was successfully employed for machining of hardened steel, Titanium alloys for aerospace applications [44].

Another invention related to a cutting insert for chip removal during machining was found, where cutting insert has a substantially circular cutting edge formed at a transition between an upper side and an edge surface of the cutting insert with indexing provision. The arrangement is provided in a position relative to a reference line or axis of the tool in order to orient the chip breaker portion in the chip surface to a desired position [45].

Machining of elastomers/ Difficult to cut materials uses unique cutting tools which are designed according to 3 systems

i. Single point cutting tool system
ii. Rotary cutting system
iii. Combination of these two system

CAD package were found useful for design iteration, development and analysis of cutting tools. Its application for structural and dynamic assessment of special purpose cutting tools was also found.

2.7 Literature on tool wear in machining composite material

Researchers concentrated mostly on the study of wear mechanism and also investigated the mathematical relationship between wear due to various wear mechanisms and cutting process variables such as cutting speed, cutting temperature of tool face and normal pressure on tool face. Some tool wear equations taking into account of one or several wear mechanisms are also developed, such as Usui's tool wear equation [46].

2.7.1 Tool Wear Phenomena

Under high pressure, high temperature, high sliding velocity and due to mechanical or thermal shock in cutting area, cutting tool is subjected to complex wear mechanism, which consists of some basic wear types such as crater wear, flank wear, chemical wear, thermal crack, brittle crack, fatigue crack, insert breakage, plastic deformation and build-up edge. The dominating basic wear types vary with the change of cutting condition and degree of affinity between work and tool materials.

2.7.2 Tool Wear Definition

Tool wear describes the gradual decay or failure of cutting tools due to regular and continuous operation. It is characterized by the change of shape of the tool, during cutting, due to the gradual loss of the cutting material [47]. During operation, cutting tools are subjected to an extremely severe rubbing process. They are in contact with both formed chips and the work piece, under conditions of high temperature and high stress. The situation further aggravates due to the existence of extreme stress and temperature gradients near the surface of the tool [47]. The cutting tool can fail in three different modes viz. Fracture failure, Temperature failure and Gradual wear. Wear mechanisms can be divided into abrasion, adhesion, diffusion, and oxidation.

2.7.3 Wear Mechanism

In order to identify the appropriate way to slow down the wear process and to analyse the wear mechanism in metal cutting many research works are carried out. It is found that tool wear was combination of several tool wear mechanisms. Tool wear mechanisms in metal cutting include abrasive wear, adhesive wear, diffusion wear, oxidation wear, solution wear, electrochemical wear, etc. Among them predominant are abrasive wear, adhesive wear and diffusion wear.

Predominant wear mechanisms are different under different cutting conditions. For a particular combination of cutting tool and work piece, the dominating wear mechanisms vary with cutting temperature. According to the temperature distribution on the tool face, it is assumed that crater wear is mainly caused by abrasive wear, diffusion wear and oxidation wear, but flank wear mainly dominated by abrasive wear due to hard second phase in the work piece material as shown in Fig.2.1.

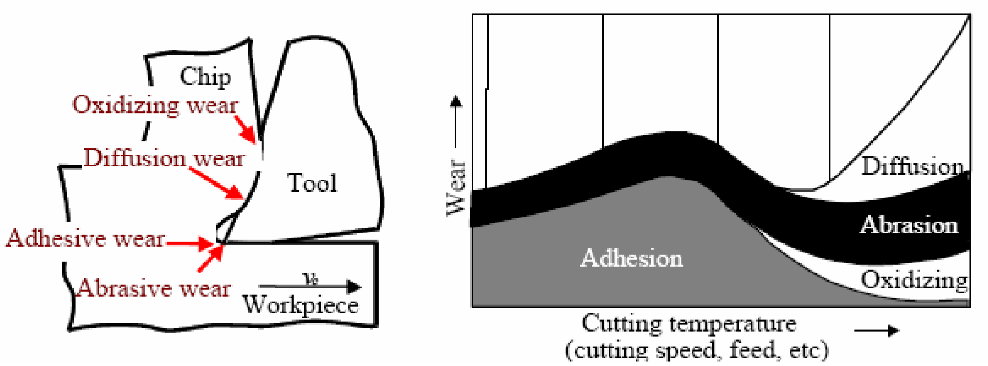


Fig.2.1: Different tool wear mechanisms in metal cutting [47]

The microstructure and behaviour of two high speed steel grades M2 and ASP30 using SEM micrographs while hobbing a gear are presented [48] and concluded the grade of tool material cannot change the wear mechanism but wear resistance can be improved by correct selection of tool material considering the cutting conditions used and machining economy. Hence, generalized wear theory cannot be directly used for accurate study of the tool wear in propellant cutting. The abrasive wear in M2 hob (see Fig 2.2) is more severe compare to ASP 30 hob as shown in Fig 2.2 & 2.3 respect because the later one high hardness and wear resistance

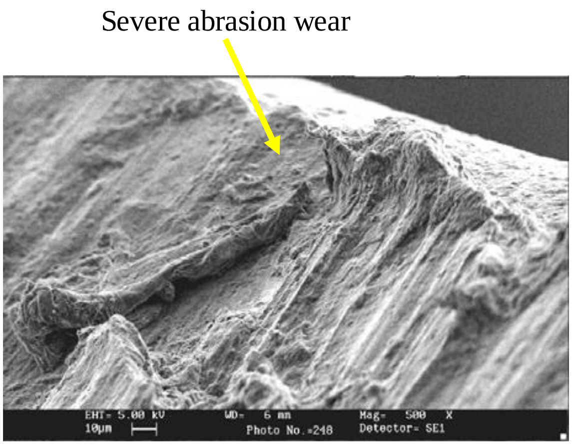


Fig.2.2: SEM topography of M2 hob [48]

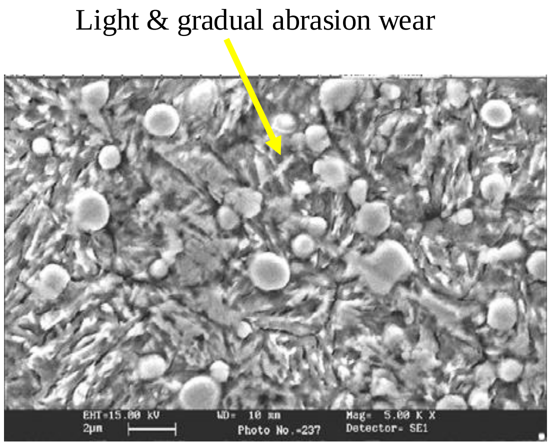


Fig.2.3: SEM micrograph of ASP 30 [48]

2.8 Evaluation of tool geometry

Generally, whenever possible for semi-finishing and finishing operations a positive rake cutting edge is recommended. Positive rake geometry ensures minimization of work hardening of the machined surface by shearing the chip away from the work piece in an efficient way in addition to minimizing built-up-edge. Dull or improperly ground edges increases cutting forces during machining, causing metal build-up, tearing and deflection of the work material whereas light hones and sharp cutting insert are useful in preventing material build-up and improving surface finish. However sharp insert edges are more fragile and susceptible to chipping during machining.

Therefore honed edges are recommended for most roughing operations where there are minimum concerns about surface roughness. Usage of large nose radius wherever part geometry does not demand otherwise can reinforce the cutting edge. This has the effect of decreasing the force at any one point preventing localized damage. To prevent vibration and subsequent chatter that can cause surface roughness and tool fracture, machining with a rigid set-up is essential. Tighter tolerance can be ensured with rigid machine and tool set-ups.

The rotary face milling cutter was used with different inclination angles such as 20°, 30°, 40° and 50° and the cutter developed was successfully employed for machining ‘difficult to machine’ materials like hardened steel, Titanium alloys for aerospace applications by Raju et al [44]

A paper by Nayak et al [49] focused on understanding the influence of working condition on the machinability of elastomer. Turning experiments under different Rake angle, Cutting speed, Feed and constant Depth of cut were conducted under ambient and cryogenic conditions and it was concluded that rake angle of 30^0 at least must be maintained to reduce cutting force for any feed rate.

2.9 Optimization of cutting parameters

Optimization is the selection of best possible input parameters for a given criteria on the outputs. In case of machining, the criteria can be minimum tool wear, minimum cutting time, best surface quality, least cutting force/power, maximum material removal rate or a combination of these criteria. For a machining process, the cutting conditions play an important role in the efficient use of a machine tool. Since the cost of machining is influenced by the cutting conditions, optimum values have to be determined before a part is put into production. This need is even greater in the case of rough machining since a greater amount of material is removed thus increasing possible savings in both machining time & time of exposure to risk. The optimum cutting conditions in this context are those which do not violate any of the constraints that may apply on the process and satisfy the economic criterion.

Literature survey revealed that a series of experiment have been carried out using Design of Experiments to investigate the influence of cutting conditions such as cutting speed, feed rate per tooth, feed velocity on tool life, tool wear and surface finish in metal cutting. Some procedures for maximization of production rate using the machining economics techniques were found [50-52], Other procedures for optimum cutting parameters noted in the literature were performance envelope and linear programming [53].Kahraman [54] used RSM for prediction and analysis of surface roughness of alloy steel and the estimate the contribution percentage of each cutting parameter in optimisation of performance characteristic. Yung-Kuang et al, [55] had carried the research work in optimization of turning operation parameters using the Grey relational analysis method. Nine experimental runs based on an orthogonal array of Taguchi method were performed. The quality targets selected were surface properties of roughness, well as the roundness of job. An optimal parameter combination of the turning operation was obtained via Grey relational analysis. By analysing the Grey relational grade matrix, the degree of influence on each controllable process factor on to individual quality targets can be found. The depth of cut was identified to be the most influential on the roughness average and the cutting speed is the most influential factor to the roughness maximum and the roundness. Additionally, the analysis of variance (ANOVA) is also applied to identify the most significant factor; the depth of cut is the most significant controlled factors for the turning operations according to the weighed sum grade of the roughness average, roughness maximum and roundness. Although many of these works consider the machine power as the only process constraint, some of the recent researchers considered constraints such as chip control [56], maximum allowable force [56-58], etc.

In a thesis by Oxley et al [59] presented an analytical approach, from which cutting forces, tool life, etc. and subsequently optimum cutting conditions can be predicted in turning with oblique nose radius tool on the basis of developed orthogonal machining theory.

Some of the researchers followed the below optimized methods

a) Analysis of effect of parameters at various cutting parameter ranges
b) Conducting experiments based on Design of Experiments (DOE) methodology
c) Taguchi method for optimization involving orthogonal array, S/N ratio and Pareto analysis of ANOVA (Analysis of Variance). It is also useful for finding the effect of interaction of various parameters
d) Use of ANN (Artificial Neural Networks) for model development.
e) Genetic algorithm coupled with ANN was used for model development.
f) Grey relational & RSM analysis was used for multi-objective optimization.

2.10 Summary of literature review and objectives

Various needs for machining of solid propellant rocket motor can be summarized into functional need, integration need, economical needs and to reclaim hardware for reuse and these needs are dependent on many factors such as size and profiles of grain configuration and SRM, quantity of material to removed and developmental stage of SRM, economics etc.,. Machining of propellant grain is most viable, precise and economical method for generating the configurations on propellant grain.

Morphology studies on CSP material were carried out in earlier research work with an emphasis to improve ballistic performance, but not on cutting tool design perspective. Therefore analysis of heterogeneous composite solid propellant works material for cutting tool design is essential.

Very few patents on cutting apparatus/ mechanisms found in the literature for machining propellant materials each for specific application and with different emphasis. None of the references individually or separately suggested simple, safe, versatile and comprehensive cutter assembly to cater the machining requirement. A custom-build cutting tool to use on CSP materials to meet both the safe and versatile machining requirement of grain configuration is essential. Design and development of such cutter assembly with suitable inserts provides a great cost and time advantage in addition to offering safe machining practices.

No literature in open source on the method to derive the tool signature for cutting 'Hazard to machine' material in particular the CSP material, probably because of the work material application in strategic use. Evaluation of tool signature through experimentation for low cutting force is essential for safe machining of propellant grain.

Non availability of standard method for design and development of special purpose cutting tools and evaluate process parameters for 'Hazard to machine' material. However limited data on cutter design methodology using CAD packages for 'difficult to machine' aerospace materials were found.

Use of fractional factorial experiments strategy from Design of Experiments (DOE) allows us to reduce the number of experiments to be conducted for concluding the cutting parameters for low cutting power and Maximum MRR. Cutting parameters in some cases can produce interaction effects that are important to understand the productive region of the machining zone. Conducting full factorial experiments gives us an idea of all the interactions present and further the results are used in developing suitable model. Grey relation analysis are useful for multi objective optimisation problems.

Generalized wear theory cannot be directly used for accurate study of the tool wear in propellant cutting [48, 60]. Study and analysis of tool wear in machining of propellant material using developed tool is essential for validation of cutting tool and to establish limiting values of tool wear. The results of the studies will be used to decide the tool life in the new combination of tool and work materials.

From the above discussion, gaps in the literature determined and objectives of present work can be summarized as follows:

- To analyze heterogeneous composite work material having energetic ingredients, for design of cutting tool.
- To design suitable cutter geometry for machining CSP grain having complex grain configuration.
- To design & develop a prototype cutter and experimental setup for evaluation of tool signature.
- To design and analyse custom-build contouring cutter and experimental set up to perform machining on actual propellant materials.
- To conduct full factorial experiments for evaluation of machining parameters with the developed cutter
- To analyse the tool wear mechanism in machining of CSP with developed cutting tool and determination of predominant tool wear mechanism. Establishing criteria of tool life for developed cutting tool.

The Research work plan for design and development of final contouring cutter and the distribution of work in each chapter is illustrated in the Fig 2.4

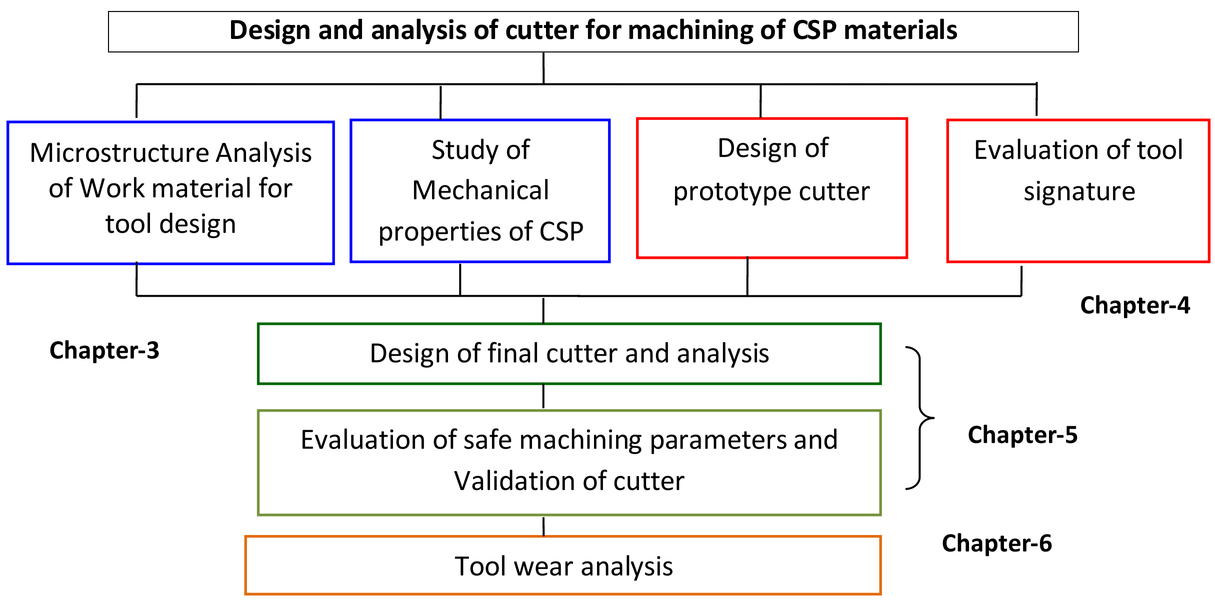


Fig.2.4: Research work plan for design and development of final contouring cutter

3.1 Introduction

Composite Solid Propellants (CSP) form an important class of solid rocket propellants, widely used in defence and space applications due to its ease of processing and superior performance in term of burning rate, characteristic velocity, specific impulse, low pressure exponent [3, 4, 61].CSP are ideally suitable for the large booster stages of satellite launch vehicles and long range missiles, which demands high thrust output during take-off. CSP are not only classified by their principal ingredients such as principal oxidizer, binder or fuel ingredient but also based on the condition in which its constituent ingredients are interconnected. Based on ingredients interconnection they are classified as 'homogeneous' where ingredients are linked chemically such that the resulting physical structure is homogeneous throughout or heterogeneous where the ingredients are physically mixed, resulting in a heterogeneous physical structure. Common examples of homogeneous propellants are single-base (NC-Nitrocellulose) or double-base (NC and NG-Nitroglycerine) propellants. Hydroxyl terminated polybutadiene (HTPB) based composite solid propellants (CSP) are heterogeneous. The energetic materials in CSP such as ammonium perchlorate (AP) particles and Aluminium (Al) powder are embedding by polymer matrix [62].HTPB based CSPs are processed by chemical casting, cured, vulcanized and cooled to produce the desired mechanical and ballistic properties with specified burning surface geometry. To manufacture grain with complex configuration such as dendrite grain configuration, set of moulds or inflatable and deflectable cores must first be produced if the size of grain and its configuration is reasonable. Manufacturing these moulds is expensive, time-consuming and not safe to use if surface of geometry and/or size of grain is large. However, for the given size, grain configuration and precision required on the propellant grain, these methods are still not technologically or economically viable. Hence machining offers an attractive alternate for manufacturing propellant grains having complex contours in configuration.

Study of mechanical properties of work material and selection of tool material compatible for machining the given work material is a general practice for design of general-purpose cutter. Likewise mechanical properties, material structure and hazard response of CSP when subjected to mechanical stimuli under machining condition needs to be assessed prior to the design of cutter assembly. To address these issues, an attempt was made in the present chapter, for identification of energetic ingredient that contributes for hazardous situations while machining the CSP material and assessment of various mechanical stimuli that present during the machining of propellant grain. As HTPB/AP/AL based CSP are processed with high energetic materials and when these materials subjected to mechanical insult and thermal insult initiated by high pressure or temperature, which may create high localized temperatures leading again to thermal ignition via several mechanisms such as friction between the energetic material and metallic tool, shear within the energetic material, fracture and intergranular friction in the energetic material, or compaction with void collapse and heating. Therefore it is necessary to fully understand the microstructure of propellant material, various ingredients and their dispersion in composite matrix, hazard nature of work material at given working ambience to prevent hazardous situations arising while machining CSP material. The conclusions drawn in the experimental studies will be used for deriving the design concept of special purpose cutter for machining of CSP. Chemical composition of work material, its microstructure is important for the assessment of machining process of CSP material as polymeric materials, because the effect of composition though, are not always clear, the constituent element of work material, tool material both separately and collectively influence the machining process.

Composite Solid Propellant being used as work material in the present study consists of a matrix of HTPB, loaded with 80% to 85% of solid particulate of AP and Al by weight. Its mechanical properties are non-linear and the failure process is complex. The mechanical properties relevant to machining of CSP material are studied as part of work material studies for design and develop a special purpose cutter required for machining this energetic and ‘hazard to machine’ material.

Composition of propellant grain is studied for volumetric dispersion of ingredients in composite structure by micrographic method. SEM and metallographic microscope images are studied to understand the composite matrix, embedment of ingredients along the cutting plane and the ingredients that a cutting tool wedge can interact during cutting operation. The surface produced by cutting a propellant sample with sharp edged blade and the one produced by typical breakage were compared and analyzed in cutting perspective.

3.2. Ingredients of HTPB/AP/AL based CSP grain

HTPB/AP/AL based composite propellants are heterogeneous system containing functional polymer binder and high concentration of oxidizer crystals and a metallic fuel powdered (Aluminium) held together in a matrix of synthetic rubber binder, such as Hydroxyl terminated polybutadiene (HTPB). It includes the propellant having two distinguished phases, solid particle phase (fuel and oxidizer) and continuous polymer matrix phase. CSP is cast chemically from a mix of solid ammonium perchlorate (AP) crystals, AL powder and liquid HTPB ingredients. Tolin Di Isocyanate (TDI) is common curator for HTPB binder cum fuel and active iron oxide/Copper chromite as modifier yields heterogeneous mixture of propellant grain [64-65].The formulation is as shown in Table 3.1. X, Y and Z values are formulation specific for different application.

Table 3.1: Typical Composition of HTPB/AP composite propellant

S. No	Ingredients	Function	Weight %
1	Hydroxyl Terminated Polybutadiene (HTPB)	Binder	X
2	Toluene Di – Isocyanate(TDI)	Curator	10. 78 - X
3	Ammonium Perchlorate- NH_4Clo_4 (AP) (Coarse)	Oxidiser	(68-Y-Z) a/(a+b)
4	Ammonium Perchlorate (Fine)	Oxidiser	(68-Y-Z) b/(a+b)
5	Active Copper Chromite(ACR)	Ballistic Modifier	Z
6	Aluminium Powder (Al)	Fuel	18. 00
7	Ambilink	Cross Linker	0. 12
8	Di Octyl Adipate (DOA)	Plasticiser	3. 00
9	Phenyl Beta Naphthyl Amine (PBNA)	Anti-Oxidant	0. 10
10	Aluminium Oxide-$Al_2 O_3$	Flow Aid	Y
Coarse AP= a ; Fine AP= b ;		**X= 10. 04 - 10. 10 %**	**Y= 0. 1 % Z<0. 2%**

3.2.1 Hydroxyl Terminated Polybutadiene (HTPB)

The HTPB is a yellowish liquid, polymeric binder and is normally produced by free radical polymerization has become the best binder available because of its processability and higher energy content compared to other binders [63-64].Most common polymers become soft at high temperatures and brittle at low temperatures. However, HTPB is able to demonstrate good mechanical properties at low temperatures and good aging characteristics. Although HTPB is an inert binder [65, 66], curing it with isocyanate will form a polymeric binder, which has superior mechanical properties. Generally, HTPB can be cured using a different isocyanate, such as Toluene Di isocyanate (TDI), Isophorone di isocyanate (IPDI), or Diphenyl di isocyanate (DDI) [63].TDI and IPDI are the most commonly applied for cast-cured propellants. The current propellant grain under study is produced using TDI as curing agent.

3.2.2 Aluminium (Al)

The second ingredient in composite propellants is metal fuel, added in composite propellants to enhance performance by increasing the combustion temperature which include beryllium, zirconium, boron, magnesium and aluminium (Al). Compared to others, Al is the best metal fuel because of the high heat of combustion, low cost, ready commercial availability, low degree of toxicity and relatively high combustion efficiency. In the usual form, Al is powder or dust and can damage the lungs if inhaled [66].But in coarser forms like the powder, it is less dangerous [62].For a composite propellant, Al usually constitutes around 5% to 25% of the propellant weight [65] and acts as a metallic fuel and additive to enhance the performance of a rocket motor. The decomposition of Al produces a high combustion temperature. The combustion temperature increases approximately 15% by the addition of 10% of aluminium [66].Al has a high heat capacity, which releases a large amount of energy that significantly expands the gases in the combustion chamber.

3.2.3 Ammonium Perchlorate (AP)

Major ingredient in composite propellant is the oxidizer, whose function is the supply of oxygen or oxidizing materials for deflagration of a solid propellant [70].Some of the most common oxidizers include ammonium nitrate (AN), potassium nitrate (KNO_3), potassium perchlorate ($KClO_4$), sodium nitrate ($NaNO_3$), and lithium perchlorate ($LiClO_4$). Nevertheless, these oxidizers produce a much lower specific impulse compared to AP, except for $LiClO_4$, which is slightly lower than AP [66].The problems with $LiClO_4$ are hygroscopic and expensive. The proven and widely used oxidizer is ammonium perchlorate (AP), which replaced potassium perchlorate as an oxidizer. At room conditions, AP is a powder of white crystalline material with a density of approximately 1949 kg/m^3. AP is a powerful oxidizer and was used as an oxidizer in various types of propellants and pyrolants (energetic materials that generate hot flames upon combustion) [65].Two major reasons for AP’s widespread use are its stability, resulting in safe munitions, and its ability to control a propellant’s burning rate. The particle sizes of AP can affect the manufacturing process and burning rate of a propellant. It is also reported that the burning rate increases with decreasing particle size of AP [1].Sizes below 40 µm are considered hazardous because of easy ignitability and sometimes detonation [66].For the application of composite propellants, AP usually constitutes around 59% to 90% of the propellant weight [62, 66].Theoretically, the performance of AP/HTPB propellant will decrease significantly when using a mass fraction of AP higher than 90% [66].AP is slightly soluble in water, a favourable trait for propellant use. All the perchlorate oxidizers produce hydrogen chloride (HC1) and other toxic and corrosive chlorine compounds in their reaction with fuels. Ammonium perchlorate (AP) is available in the form of small white crystals. Particle size and shape influences the manufacturing process and the propellant burning rate. Therefore, close control of the crystal sizes and the size distribution in a given quantity or batch is required. AP crystals are rounded to allow easier mixing than sharp, fractured crystals.

3.2.4 Additives

Another ingredient that is added in the composite propellants is additives generally added for altering the curing time, improving rheological properties for easier casting (plasticizers), altering burning rate (burn rate modifiers), improving bonding (bonding agents), improving the physical properties, or improving aging characteristics. The most suitable plasticizers used with HTPB are DOA due to the ability to improve the process ability and pot life of HTPB propellants and it accounts for around 1% to 5 % of the propellant weight. Previous studies have reported that a composite solid propellant burn rate can be modified by addition of small quantities (< 3%) of burn rate modifiers such as Nitramine [80, 81] to its composition [67].

3.3 Micrographical investigation of CSP material

The propellant is hardened by cross linking or curing the liquid binder polymer with a small amount of curing agent, and curing it in an oven, where it becomes hard and solid. Conventional composite propellants usually contain between 60 and 72% Ammonium perchlorate (AP) as crystalline oxidizer, up to 22% aluminium powder (A1) as a metal fuel, and 8 to 16% of elastomeric binder including its plasticizer.

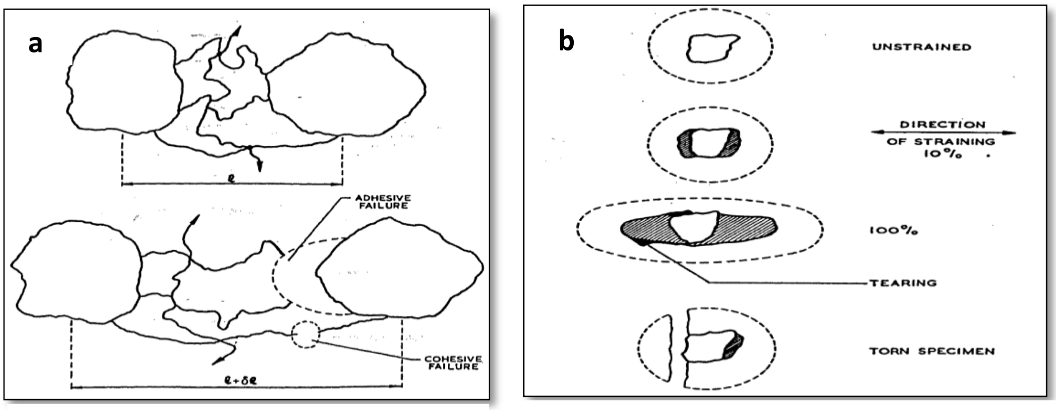
Every ingredient in the composition of CSP plays a vital role for different aspects of the formulation but its role on machining aspect was not addressed. Therefore, before the propellant is machined, a thorough study should be conducted to ensure safe and predicted behaviour of machining process. In comparison with metals, CSP are complex because both their material and geometric behaviour are non-linear. CSP are isotropic, highly deformable, viscoelastic, and nearly incompressible [67-71]. Size and shape of the ingredients, adhesive binding of polymer binder with other ingredient of CSP and Chemical affinity of ingredients with tool material, bonding and dispersion of ingredient in the composite matrix, strength of cross link, porosity of material etc., will have influence in determining the signature of cutting tool and resulting cutting forces.

The micrographical study of this CSP work material is essential to understand the machining of these materials using wedge shaped cutting tool to conceive the required tool signature. Understanding of ‘Hazard to machine’ propellant grain material on safety aspects is essential for proper design of cutting element and to conceive safe experimental set up for conduct of machining trials to understand machining process. This will enable the tool designer to incorporate suitable features in the cutting tools for mitigating/preventing hazardous situations arising out of the machining operation. Hence the analysis of propellant samples of particular formulation is more relevant. With proper precautions and suitable equipment, HTPB/AP/Al based CSP can be manufactured and handled safely. The conclusions derived from these studies will form the inputs for design of safe and versatile cutter assembly for effective machining of CSP.

3.4 Study on microstructure of CSP material for design of cutting tool.

Theoretical failure criteria of CSP can be classified as either microscopic or macroscopic. The macroscopic criteria treat the composite propellant as a continuum and general theories such as thermodynamic elasticity, viscoelasticity etc. are used to describe the behaviour. Whereas microscopic criteria treat propellant as a conglomeration of particles and microscopic theories involving such phenomena as binder filler interaction, effect of particle size and shape, and inter-particle frictions etc. must be, combined to give overall criteria [73-74].

For high concentrations of strongly bonded filler particles no satisfactory empirical or theoretical relationship has been established. The response of such highly filled materials not only exhibit a strong time and temperature dependence but also indicate significant nonlinear stress-strain behaviour from linear viscoelastic behaviour at relatively low strain levels [82].This behaviour is attributed to the separation of the soft matrix from the hard filler particles and the formation of voids as shown in Fig.3.1. This phenomenon is called dewetting and was first observed in experiments on filled vulcanized rubbers [67-69].Analysis of biaxial strip test to study the mechanical behaviour of the polymers and intern structural integrity of SRM while designing a solid propellant rocket motor for particular application is in practice.



a) Polymer reaction between filler particles on stretching

b) Dewetting and tearing around a particle

Fig.3.1: Theoretical model of CSP structure [70]

Influence of microstructural factors of propellant material on cutting tool design

The microstructure of propellant grain such as the bonding strength between binder and other ingredients in the matrix, dispersion of constituents along the cutting planes, the major constituents that comes in interaction with the cutting edge during machining, the sensitivity of the dispersed constituents in the cutting planes their size and shape will help to decide the tool material and tool signature of the cutting elements and qualitative estimation of cutting forces in addition to understand the affinity of work material with tool material. Macroscopic studies are also essential to understand the deformation of work material in bulk form when subjected to cutting forces, the rigidity that the work material to cutting tool and mechanism of formation of chip. The present study is restricted to microscopic studies on CSP material for cutting tool design perspective only and dealt in great detail in the subsequent sections.

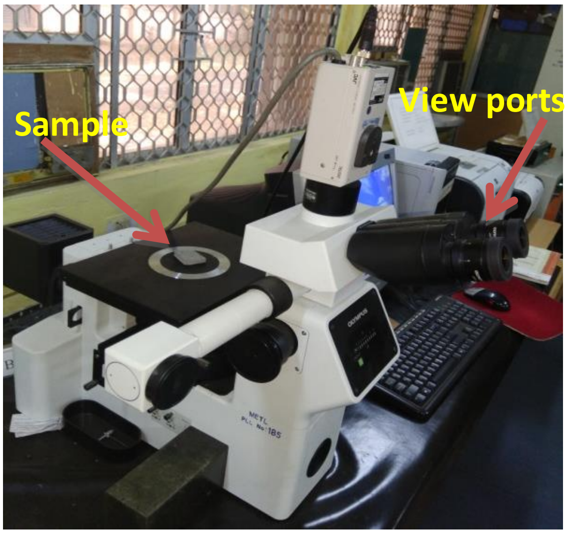
3. 5 Phase volume fraction analysis of CSP material

The inorganic filler AP and Al are by far the largest part of the composite by formulation in the present HTPB propellant. Particle shape, size and distribution is therefore of predominate importance. Since the propellant material is heterogeneous composite, study of volume fraction of the ingredients on any cutting plane that a cutting edge to be subjected will help to understand the interaction between cutting tool and work material, in particular the ingredient of CSP. In the present study percentage volume of ingredients in material matrix were measured by Image Analyser.

The image analysis for the study of interfacial bonding in solid composite propellant in the earlier research was used by Serb et al [75] for determining the quantity, area and radius of non-bonded oxidizer crystals by means of stereoscopic and metallographic microscope with digital camera. Similar approached adopted for this studdy.

3.5.1 Method

Three samples (50x50x15mm size) drawn from the Solid Rocket Motor (SRM) grain were photographed using metallographic microscope (Microscope GX71, Olympus, Magnification: 2000x) with digital camera and images obtained were analysed using the Met Image Lx Plux VM software. Met Image is an Image analysis software which enables to analyze images captured from microscopes as shown in Fig.3.2(a) to obtain specific measurements that include caliper measurements such as length, areas and distances and counting and classifying objects, particle sizing, particle spacing, etc.

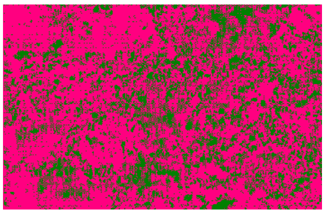
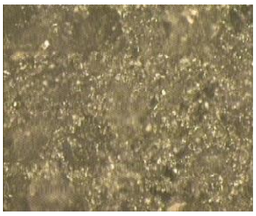
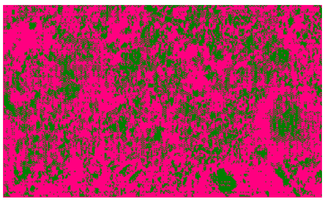
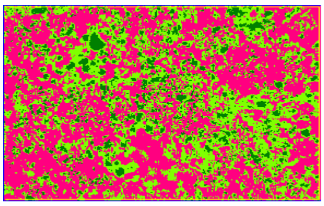
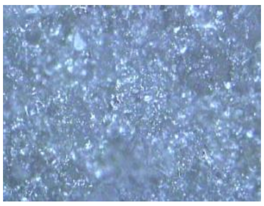


a) Metallographic microscope(GX71, Olympus) b) Scanning Electron Microscope(JOEL JSM - 6610LV)

Fig.3.2: Equipment for Micrographical studies of CSP

3.5.2 Results

Table 3.2: Phase volume fraction analysis report of CSP sample

Sample No.	Sample volume fraction in colour micrograph (x100)	Sample volume fraction in monochrome micrograph (x100)	Phase volume fraction analysis
1			<u>Phase/Volume Fraction Analysis: Results</u> <u>Summary</u> Fields Measured 1 Analysed Area 0. 5165 sq. mm. Standard Used ASTM E 562
2			<u>Phase/Volume Fraction Analysis: Results</u> <u>Summary</u> Fields Measured 1 Analysed Area 0. 5165 sq. mm. Standard Used ASTM E 562
3			<u>Phase/Volume Fraction Analysis: Results</u> <u>Summary</u> Fields Measured 1 Analysed Area 1. 162 sq. mm. Standard Used ASTM E 562
	Magnification : X 200		

Sample no	AP (ρ=1. 95)	Binder+ metallic fuel (ρ=2. 4)
01	71. 51	28. 49
02	67. 21	32. 79
03	64. 86	35. 14
Average	67. 86	32. 14

3.5.3 Discussion

The observed difference in colour was utilized by MetImage Lx Plux software to determine volume percentage of AP particle and their distribution. The results shows, Table 3.2, that the AP particles were distributed approximately uniform throughout but with very little agglomeration in the analysed plane. Average volume of major ingredient (AP) in three specimens is 67. 86%. Major portion of propellant surface matrix is filled with NH_4ClO_4 (68% by volume) and rest of the portion (32%) with metallic fuel (AL) and binder. The Al powder together with binder is distinguished with single colour counting the combined volume of Al and HTPB binder to 32%as Al is tightly filled binder matrix. From this analysis it can be inferred that the cutting edge of the tool, by and large interacts with Ammonium perchlorate and metallic fuel during cutting.

3.6 Porosity analysis

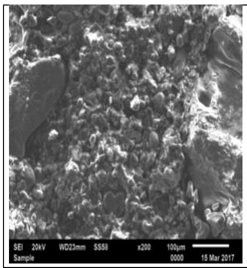
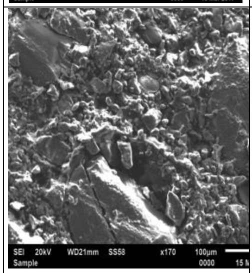
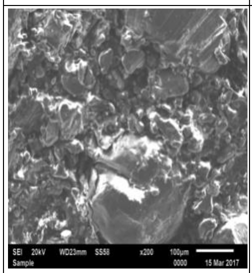
Composite material is sensitive to history of loading, and the damage is not only cumulative but the rate of accumulation also depends on the amount of previous damage like excessive agglomeration, dewetting and porosity etc. , and such cases cannot be treated by the failure surface method. The position of major porosity and their area in specimen has great influence on the mechanical properties. Poor interaction between binder and fillers found mostly with oxidizer (AP) and not with metal fuel. The formation of micro porosity in the composite is due to entrapped air into the mixture during mixing and casting stage, which tries to emerge during vacuum casting. Study of propellant on porosity aspect provides the idea that how the subsequent propagation of crack/ tear of polymer chain takes place while the cutting edge interacts with work material during machining using wedge shaper cutting tool.

3.6.1 Method

Three samples (50x50x15mm size) were imaged in SEM (JOEL JSM -6610LV SEM Accelerating voltage: 0.3-30 kV Magnification: X 5 to X 300,000, and Resolution: 3nm) and images are fed into the Met Image Lx Plux VM Image analysis software to measure the size of pores and count the number of pores and the results are shown in Table 3.3. The analysis is carried out as per the standards ASTM B 276.

3.6.2 Results

Table 3.3: Porosity analysis report of CSP samples

	Classes	Area%	Pores/sqmm	Type	Porosity Analysis	Results summary
	**Classes**	**Area%**	**Pores/sqmm**	**Type**	**Porosity Analysis**	**Results summary**
	A: 0 – 10 µm	0.0222	6.0562	A02	Fields measured	1
	B: 10– 25µm	0.0472	5.6076	B02	Total Area	4.458 sq mm
	25 – 75 µm	0.222	1.3458		Porosity	0.5283%
	75 – 125 µm	0	0		Pores/sqmm	13.234
	>125 µm	0.4367	0.2243			
	**Classes**	**Area%**	**Pores/sqmm**	**Type**	**Porosity Analysis**	**Results summary**
	A: 0 – 10 µm	0.0051	1.3458		Fields measured	1
	B: 10– 25µm	0.0240	3.3646	B02	Total Area	4.458 sq mm
	25 – 75 µm	0.0033	0.2243		Porosity	0.542%
	75 – 125 µm	0	0		Pores/sqmm	5.159
	>125 µm	0.5102	0.2243			
	**Classes**	**Area%**	**Pores/sqmm**	**Type**	**Porosity Analysis**	**Results summary**
	A: 0 – 10 µm	0.0357	9.6451	A02	Fields measured	1
	B: 10– 25µm	0.0748	10.313	B02	Total Area	4.458 sq mm
	25 – 75 µm	0.0244	1.1215		Porosity	0.664%
	75 – 125 µm	0	0		Pores/sqmm	21.308
	>125 µm	0.5299	0.2243			
Magnification: X200	Size of Pores with Max % pores/mm^2: < 25µm				Average Porosity: 0. 578% Avg No of pores/ Sq.mm:13	

3.6.3 Discussion

It is observed from the formulation records that in bimodal distribution of AP particles, coarse to fine ratio of 2:1 being used for present propellant understudy. The average AP particle size is 300 µm for Corse and 45 µm for fine distribution. It is found from the porosity analysis of specimens through the micrograph analysis that the average area percentage of porosity is 0.57 and average number of pores/sq.mm is 13. It is also observed in the results as shown in Table 3.3 that the maximum number of pores appears in the size range less than 25 µm. This count may also include the voids formed by dewetting and de-bonding of propellant ingredient whose size is less than 25 microns, during the fracture of specimen while preparing the specimen. However in the bimodal distribution of AP, contribution of AP particles whose size is less than 25 micron is negligible, hence the major reason for porosity is attributed to pocket of air that was entrapped into the mixture during blending and mixing stage, which tries to emerge during vacuum casting forming discontinuities of binder structure in matrix. The micro porosity contributes favourably for low cutting force of CSP material. It is also observed from this study that the cutting force fluctuation during machining also envisaged due to presence of large number of AP coarse particles, agglomeration of particles and non-uniform spread of porosity.

3.7 Analysis of fractured and cut section of propellant materials using SEM

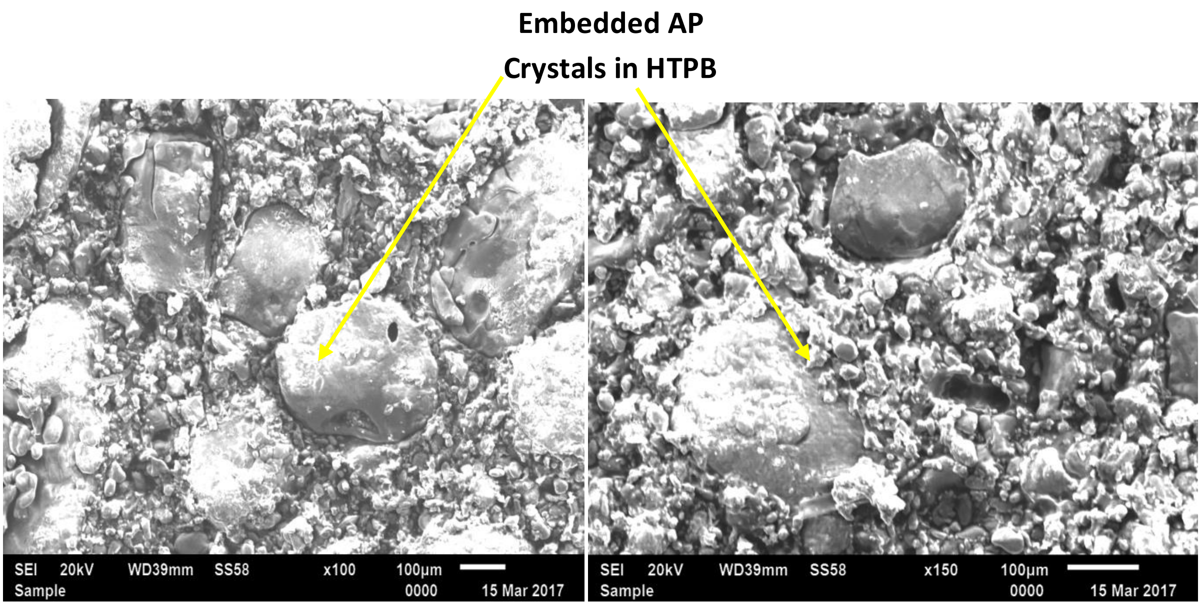
While machining the grain, the main failure mechanism in these materials is the deboning process occurring between the binder and the ingredient particles and the adhesion quality is of a crucial importance. When propellant specimen is stretched, propellant specimen behave as rigid solid fillers adhering to polymeric matrix getting rubbed against each other. This is equivalent to rubbing two emery papers against each other. To compare this effect with sudden slicing with keen edge, Scanning Electron Microscope (SEM) shown in Fig.3.2 (b) is used to study the typical fractured surface of the propellant as well as sliced surface of propellant using sharp edge like razor blade.

3.7.1 Method

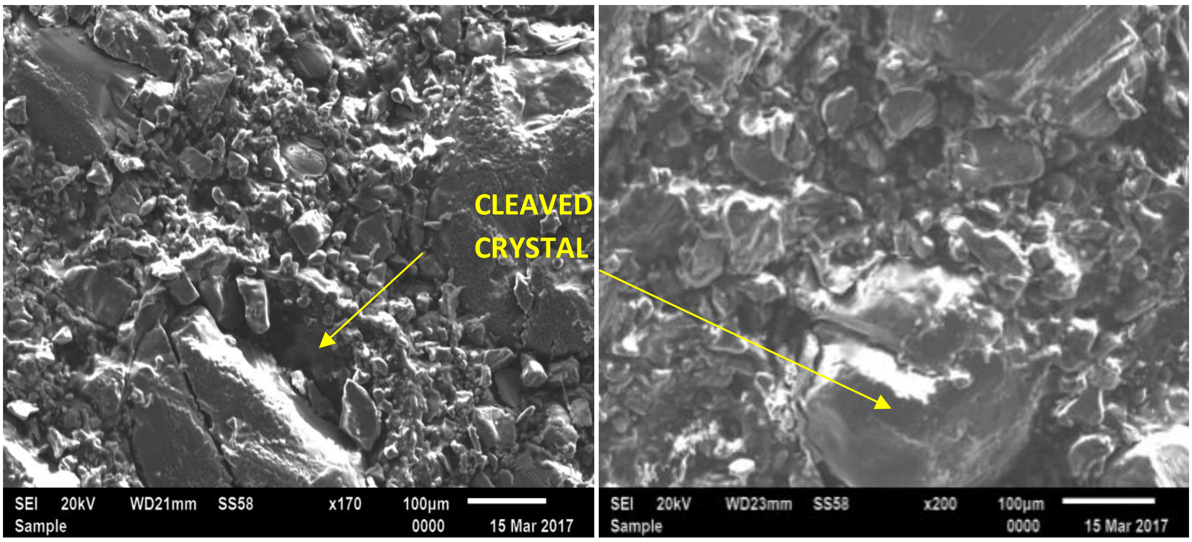
Specimen of the live propellant materials cast in SRM were obtained and studied under both optical and Scanning Electron Microscopes to study the microstructure of propellant material and observe the surface of failure under typical breakage and surface produced by cutting with a sharp and keen cutting edge (Razor blade).

Propellant is a highly filled elastometric material with solid loading of the order of 85%. This clearly indicates that in a properly mixed homogeneous propellant, any cross-section has 85% area filled by solid fillers, which will never deform on stretching. In the initial portion of extension, 15% cross-linked polymeric part of a cross-section is stretched and lateral compression is observed. To observe this effect, scanning electron microscope is used to study the fractured surface of the propellant. Propellant is incompressible for small strain. Specimen were studied under both optical and Scanning Electron Microscopes (SEM) to observe the microstructure of propellant material and observe the surface of failure under typical breakage and sliced/cut surface using sharp and keen cutting edge.

3.7.2 Results



a) Surface as cast condition



b) Typical failure surfaces of propellant under UTM

Fig.3.3: SEM images of propellant surfaces

The selection of both the crystalline particles and the polymer in CSP formulation is not dictated by the optimization of the mechanical resistance. Obviously, the optimum choice of these ingredients has to enhance the energetic/ballistic performance rather than the mechanical properties. Among the possible means, the main failure mechanism in these materials is the debonding process occurring between the binder and the ingredient particles and the adhesion quality is of a crucial importance. When propellant specimen is stretched, propellant specimens behave as rigid solid fillers adhering to polymeric matrix getting rubbed against each other.

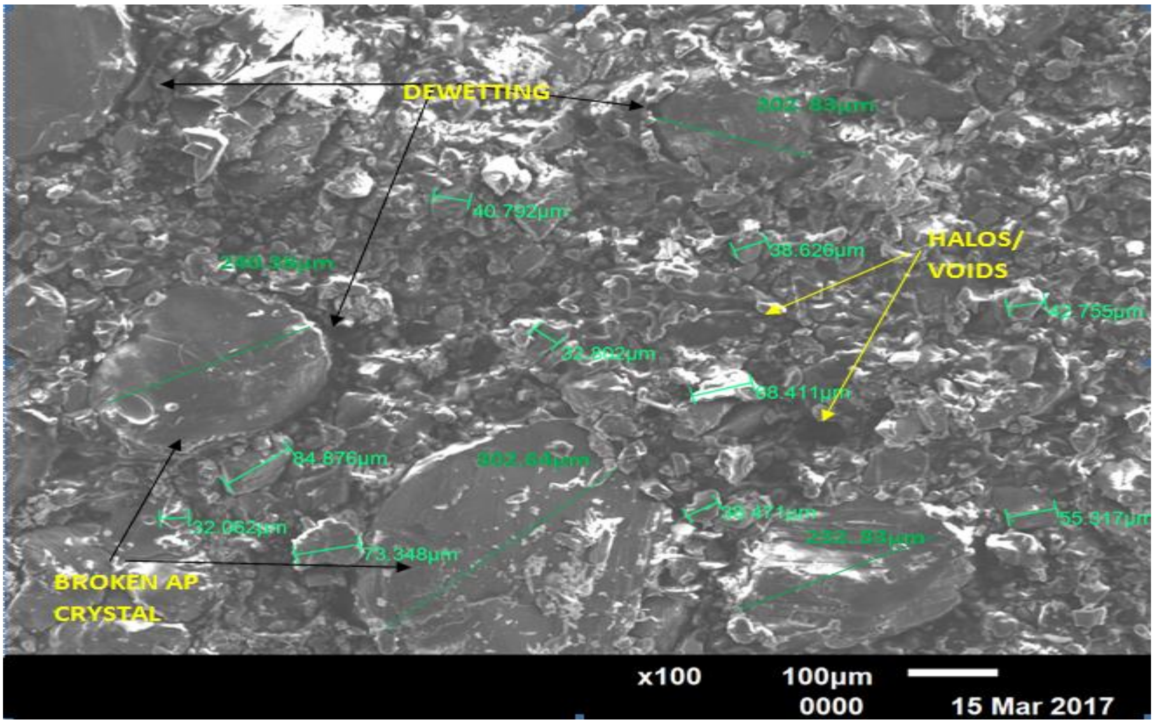


Fig.3.4: Sliced surface of CSP material

The surface of propellant grain, in as cast and cure condition where the filler particles are completely embedded with binder material is shown in Fig 3.3 (a). From the SEM micrographs it is clearly shown that the failure surface is far more irregular and contains numerous broken embedded crystals. This is a feature common to the entire specimen surfaces studied Fig.3.3 (b). The surface produced by cutting a propellant sample is shown at Fig.3.4. The surface is essentially less irregular with only a few cleaved crystals visible on the relatively smooth surface. It can be compared with a typical failure surface shown Fig.3.3 (b).

The close observation of typical large broken crystals in Fig.3.4 on cut surface reveals that the crystals are not only fractured but also cracked into small pieces. This damage of particle was probably caused during the mixing and blending stage of the manufacturing process or due to internal stresses caused during the cool down from the cure temperature during vulcanization.

Sometimes the large crystals present in the bimodal distribution of AP particle in the formulation then broke into two or more pieces or left with a crack in previous mechanical actions during mixing stage of CSP processing. This damage of particle is visible on SEM micrographs as broken particles during the propagation or initiation of the propellant failure by wedge of blade. A large amount of surface damage is visible on all the photographs with small fragments of crystals scattered over the surface.

A propellant sample was broken over a piece of card and considerable amounts of loose crystal fragments are collected are shown in Fig.3.5. The size of particle varies from 25 microns to

300 microns and particle is near sphere shape. Significant difference in surface structure was not observed between the areas of slow crack growth, i.e., near the point of failure initiation by uniaxial loading, and the regions of fast crack propagation caused by razor blade by cutting. But it is found that the accumulation of loose particle increase of surface fracture by cutting using sharp edge blade is more relatively that of failure surface by uniaxial loading. It is because the sharp edge of the cutting blade wipes the particles that were exposed to cutting edge and loose particles separated by dewetting in the matrix on cut plane.

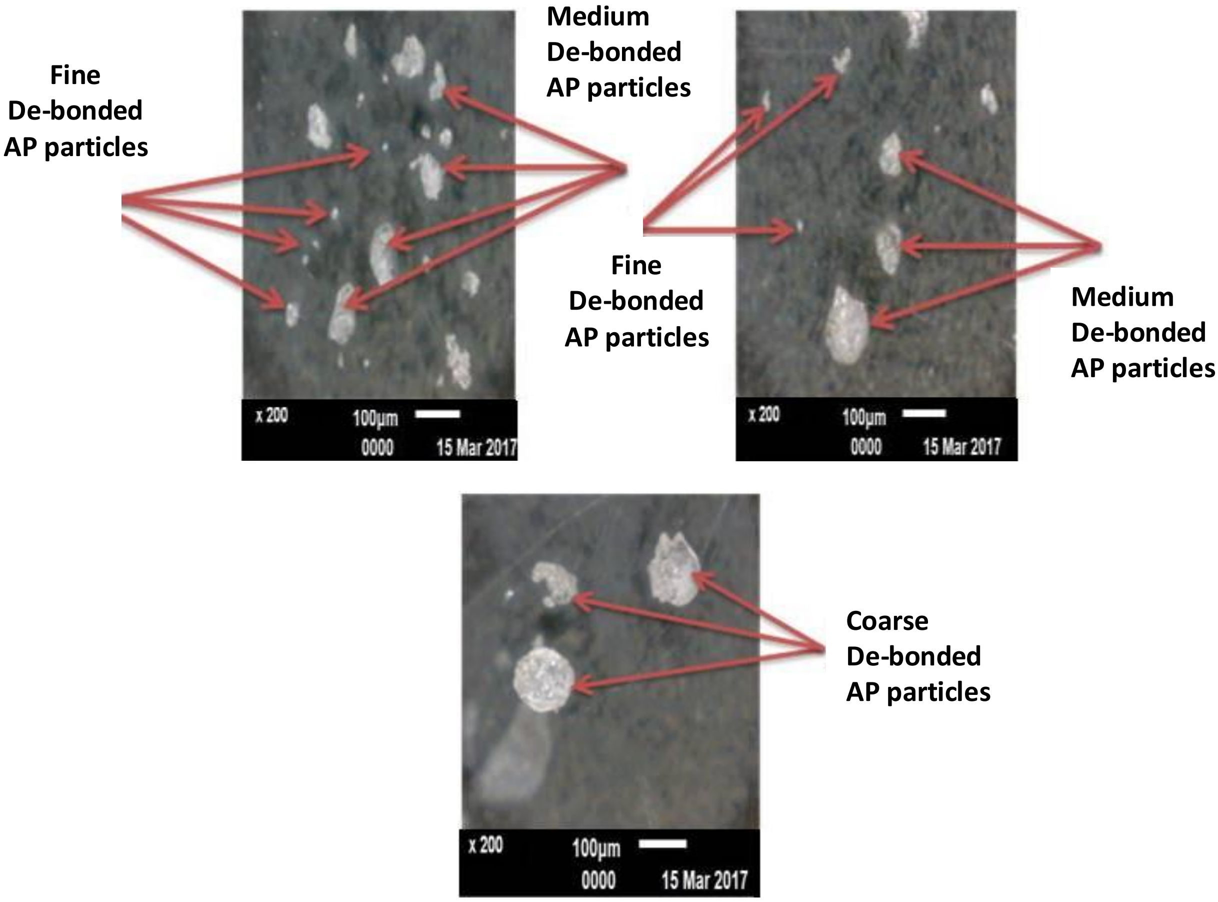


Fig.3.5: Debonded ingredients from fractured surface of CSP (x 200)

3.7.3 Discussion from complete microstructure analysis of HTPB based CSP

It has been found that every component plays a vital role for different aspects of the formulation but their role on machining aspect was not clear. Therefore, before the propellant is machined, a thorough study should be conducted to ensure safe and predicted behaviour of machining. The optimum choice of the ingredients in HTPB/AP/Al based CSP has to enhance the energetic performance rather than the mechanical properties of machining perspective.

a) Ammonium Perchlorate (NH_4ClO_4) covers the major portion of propellant matrix (Approx. 68% by mass as well as volume) and the rest with metallic fuel and binder composition. Cutting edge by and large is exposed to AP particles and metallic Al powder dispersed in Polymer binder during cutting.

b) The grain size distribution and volume distribution is significant for cutting forces, because it is found from SEM micrographs that AP particles are agglomerated into cluster at few locations. The cluster formation has poor interaction between filler and binder that form a larger boundary providing week location for propellant failure locally thereby need low cutting force.

c) The bond between the binder matrix and oxidizer (AP) is not strong in compression with the bond between metallic Al powder and binder which is attributed due to orbicular configuration (near roundness) and large size of AP and irregular and small particle size of Al.

d) The presence of porosity and dewetting of propellant on loading is treated as precedence structural defects in the heterogeneous CSP material which favours for low cutting forces but results relatively poor surface finish. The chances of cutting force fluctuation during machining were speculated due to presence of large number of AP course particles and agglomeration particles and non-uniformity of porosity on the cutting plane.

e) Formation of voids in the specimen cut section can be interpreted as the failure of week adhesive bond between binder matrix and oxidizer particle (AP) hence the deboned particles were found separated while cutting or typical breakage of specimen. Powder of some ingredient (AP) was separated along with chip during machining.

f) Possible formation of AP powder during machining of grain using keen edged cutting tool was observed. Since the propellant chips and powder in tiny form is sensitive, it needs to be evacuated from the cutting zone immediately after the generation for which a provision to be made in the cutter while designing a mechanism to be conceived for instantaneous evacuation during machining.

g) Microscopic studies have shown that propellant rupture occurs by dewetting in two steps, essentially the separation followed by tearing. First the binder separates from the oxidizer when deformed in tension, which results in the formation of voids around the filler particles. Secondly a tear is initiated under conditions of tensile strain in the binder near to the apex of a void and propagates perpendicularly to the direction of straining as shown in Fig 3.4. The dewetting in propellants can occur in localized regions. These dewetting regions are relatively weak and are the sites for the progressive failure of the propellant sample. The dewetting in propellants can occur in localized regions and hence the strain is not uniform throughout the test section

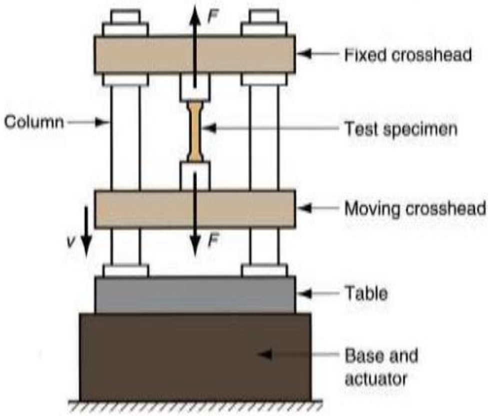
h) Since the low cutting force is the concern than high quality surface finish for the material understudy, the microstructure studies reveal that it is possible to remove the undesired material of propellant grain in the form of chips using conventional cutting tool with the application of reasonably low cutting forces.

3.8 Study on Mechanical properties of HTPB based solid propellant materials

Effective removal of composite propellant material in the form of chips by machining to generate the precise shape and good surface finish on the work piece is technically challenging due to the unique properties of very low elastic modulus and low percentage of elongation before fracture of work material. From the literature [74] it is found that the HTPB based propellants loaded with 80 to 90 percent of particulate solids exhibit nonlinear mechanical properties and its failure process is complex. The uniaxial test was used with the strains applied at various constant rates and then held at a particular constant value to observe the propellant behaviour on 16 samples in two batches. This is to avoid the inconsistency in the results from small batch sample size, as the CSP materials exhibit significant variation in result for mechanical loading. SRM is an integrated structure which is a multilayer adhesive joint involving the propellant, liner, and insulation. The propellant/ insulation interface is considered to be the weakest part of the whole structure [21]. Hence the peel strength of propellant/liner/insulation interfaces to be analysed in terms of its adhesive strength. Propellant and insulation interface bond strength is experimentally investigated to access the failure of the bond due to transfer of cutting forces to interfaces during machining of grain [79]. A batch size of 4 samples are tested for this purpose. As shown in Fig.3.8. The mechanical properties such as Young's modulus, breaking stress and percentage of elongation at the time of break, measured in the tension test are found important along with hardness for machining process analysis.

3.8.1 Method

INSTRON UTM machine (model: 5500) as shown in Fig.3.6 was used to measure tensile strength, Modulus of elasticity, and percentage elongation as per IS 3400 standards. Hardness was measured using Shore's hardness tester on scale-A (Make: Mitutoyo Model: MLR322. The machines available at DRDO-Jagadalpur being used for this purpose.

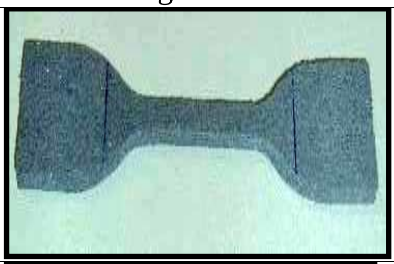


a) Sample in UTM machine

b) INSTRON UTM machine (model: 5500)

Fig.3.6: UTM machine used for mechanical testing of CSP

Table 3.4: Method of testing for mechnical properties

	Mechanical properties	**Peel strength**	Tensile Bond Strength(TBS)
Sample details	Specimen : Dumbbell shape (type-1) as per IS 3400 (part-1)1987 Dimensions: Grip distance= 60mm Gauge length= 45mm Test speed=50mm/min Grip pressure = 1. 2 to 4 Ksc Conditioning = 24 hours	Sample width = 25mm Test speed=50mm/min Conditioning = 48 hours	Thickness = 25mm Width =50mm Speed = 50m/s Conditioning =48 hrs
Specimen			
Experimental setup			

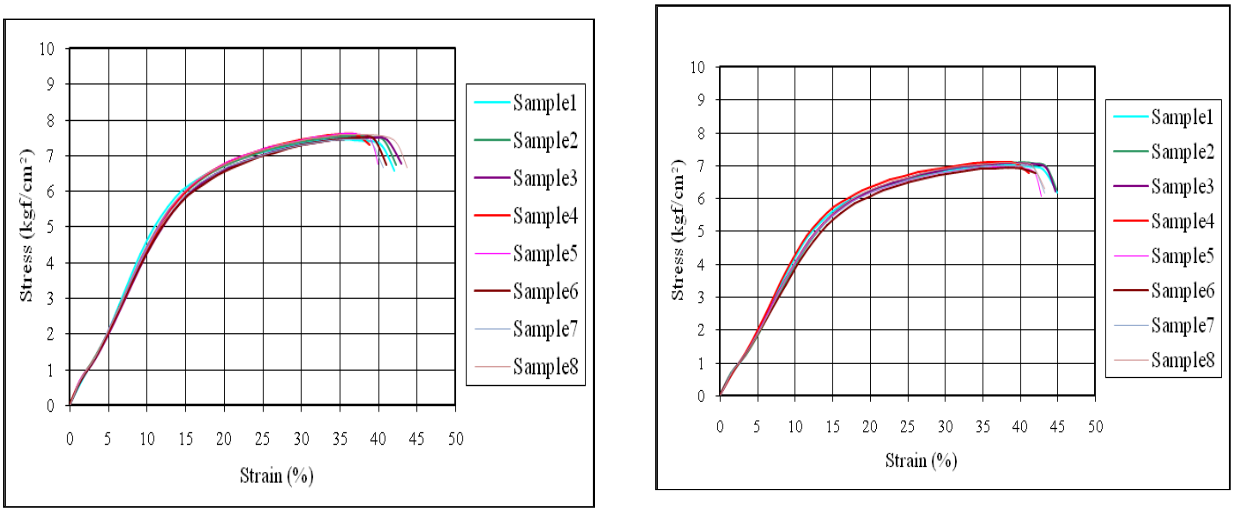


Fig.3.7 :Stress vs Strain curves of CSP material

Table 3.5: Mechanical properties of HTPB/AP/AL based CSP

Properties	**Batch 1 (8 samples)**	**Batch 2 (8 samples)**
Density (gm/cc)	1. 76	1. 76
Hardness (Shore 'A')	79	78
Elongation (%)	**Max 43. 38**/Min 30	**Max 41. 45**/Min 30
Tensile strength (kgf/cm²)	**Max 7. 3**/Min 6. 9	**Max 7. 3**/Min 5
E-Mod (kgf/cm²)	**Max 44**/Min 39	**Max 43**/Min 41

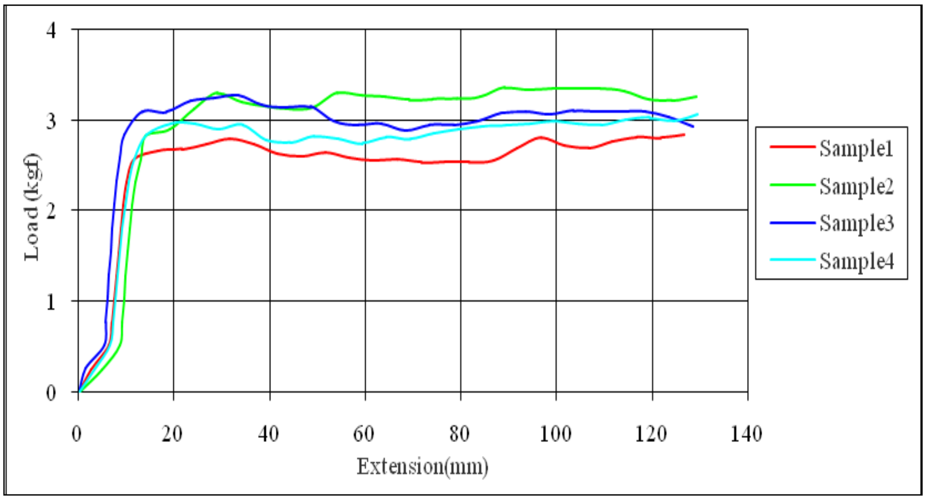


Fig.3.8: Load vs Extension curves for peel strength

Table 3.6: Peel strength results

Specimen No	Width (cm)	Average Load (kgf)	Peel strength (kgf/cm)	Remark
1	2. 61	2. 67	1. 03	**Cohesive Failure In Propellant**
2	2. 65	3. 24	1. 22	
3	2. 66	3. 06	1. 15	
4	2. 60	2. 90	1. 12	
Mean		**2. 97**	**1. 13**	
Standard Deviation		0. 24	0. 08	
COV		0. 08	0. 07	
Minimum		2. 67	1. 03	
Maximum		3. 24	1. 22	
Reqd. Specifications			**Min 0. 6**	

3.8.2 Results

HTPB/AP/AL based CSP being high particulate loaded heterogeneous material, the mechanical properties depends on bonding strength filler and polymeric binder [80-81]. Other factors, such as uniformity of dispersions particle size, shape and distribution of filler and volume fraction also have important influences on the mechanical properties of CSP material [82-83]. In any of the case measured in 16 samples the maximum tensile strength is not more than 8 Kg/cm^2 as shown in Fig.3.7. Hardness measured on all the samples using Shore Hardness tester on Scale-A, and the values are less than 80 . Other mechanical properties relavent to machining studies are summarised in Table 3.5. Specimen tested for peel strength found with cohesive failure in propellant at a load of approximately 3 kgf, as shown in Table 3.6 but not the interface separation by adhesion failure.

Mechanical behaviour of CSP was investigated in terms of uniaxial tensile strength after SEM analyses to estimate the approximate cutting forces and power. The heterogeneity of CSP results in stress concentration between the binder filler, hence when the propellant is deformed the stress distribution is localized in these concentrations. The local stress increases until it exceeds the binder-filler interface bond strength, thus causing dewetting and voids form around the filler particles [82-85]. The strength of the material is influenced by the morphology and the average particle size of the metal powders.

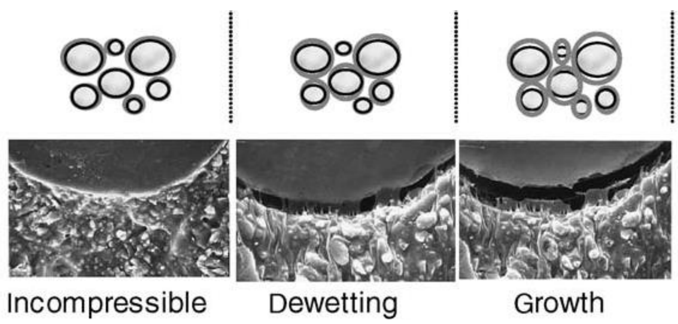
The tensile bond strength and Young’s modules values obtained these experiment will be used to understand requirement of material for tool construction, to estimate the tool signature and to analyse orthogonal cutting of propellant materials. In comparison with metals, CSP materials are complex because of their both material and geometric behaviour are non-linear. CSP materials are isotropic, highly deformable, viscoelastic, and nearly incompressible. The propellant mainly exhibited transgranular fracture damage, augmented porosity and tearing of binder matrix to mechanical loads.

3.8.3 Discussion

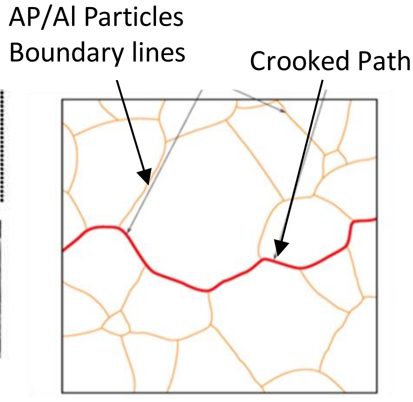
The heterogeneity of composite propellant results in stress concentrations between the filler particles [73].Hence, when the propellant is deformed the stress distribution is localized in these concentrations. The local stress increases until it exceeds the binder/filler interface bond strength thus causing dewetting and voids form around the filler particles. The dewetting phenomenon tends to soften the composite material so that subsequent stretching produces a stress-strain curve which is displaced downwards as shown in Fig 3.7. The dewetting in propellants can occur in localized regions and hence the strain is not uniform throughout the test section [75-76].

Specimen tested for peel strength found with cohesive failure in propellant, but not the interface failure by adhesive failure phenomenon and the failure occurred at a load of approximately 3 kgf. Cohesive failure would occur if the cohesive strength of the binder were exceeded resulting in the formation of small voids in the binder. The similarity between cohesive and adhesive failure is that they both lead to the initiation of voids, the former in the binder and the latter at the interface [72].Since the binder is essentially a thin film around the solid inclusions, any cohesive-failure in it leads directly to an adhesive separation at the interface because the adhesive force in a normal propellant is weaker than the cohesive strength of the binder which can be understood from the illustration shown in Fig.3.9.

The tensile bond strength and Young's modulus values obtained from this experiment will be used to understand the tool material requirement and tentative tool signature and to analyze the cutting process using empirical relation in orthogonal cutting procedures.



a) Dewetting phenomenon in CSP [75]



b) Crock propagation path along the boundaries of ingredients of CSP

Fig.3.9: Failure of CSP for mechanical loading

Dewetting always precedes rupture in propellants which are dilating by binder-oxidizer separation and may be considered to be the first step in-the failure process [76]. These dewetted regions are relatively weak and are the points from where the progressive failure of the propellant sample occurs. Due to the existing defects in CSP material and low values of mechanical properties, it is possible to remove the excess material from SRM using cutting tool of conventional nature using cutting forces that are below the self-ignition forces of CSP by careful design of cutting element. The consolidated list of mechanical properties of HTPB based CSP material of present study is presented in the Table 3.7.

Table 3.7: Mechanical Properties of materials to be machined

Material	**HTPB/AP composite propellant**
Young Modulus (KN/m^2)	4000
Tensile strength (KN/m^2)	600
Hardness on Shore ‘A’ Scale	70-90
% of elongation	30
Density (10^3 Kg/m^3)	1. 76
Poisson’s ratio	0. 499
Coefficient of thermal expansion (/ °c)	0. 0001
Thermal conductivity(W/m K)	0. 389

3.9 Other important properties of CSP relevant for tool design

a. Exhibit nonlinear stress strain relation because of elastometric binder and failure by dewetting

b. The elastic modulus and tensile strength are low compared to metals.

c. Being polymetric material they have low density, low rigidity and their mechanical properties vary considerably.

d. Poison ratio of these materials is 0. 5 and varies in perpendicular direction when measured in orthogonal planes (0. 17 to 0. 3) [77]

e. Coefficient friction of these elastometric material surfaces is relatively high when compared with metal to metal friction.

f. Composite CSP are flexible and offers least rigidity to the applied cutting forces and are dimensionally unstable.

g. The fracture toughness for similar composition corresponding to derived mechanical properties were drawn from the literature [76] and it is 1.94 J/cm^2 .

h. Severe stressing and extreme temperatures induce damage which is manifested in particle cracking, dewetting along polymer binder interface subsequent void nucleation and growth. [77-79]

i. Molecular architecture, ingredients dispersion, size and shape of ingredients, crosslink density, solubility parameter, chin stiffness, monometric friction coefficient, volume fraction filler and volume fraction plasticizer which varies from batch to batch production of SRM, influence the mechanical properties of CSP [77-78].

3.10 Study to understand the Risk/Hazard in Machining of Propellant Materials

In metal cutting a significant portion of the mechanical energy is converted in to heat during the interaction of the tool and work piece. This heat energy is generated due to the friction and shearing action between the tool and the work piece, which gets dissipated by conduction in to the tool, work piece and chip [3].However the heat energy associated in propellant machining should not be transferred to chips and should never reach threshold value/ self-ignition temperature of the material.

3.10. 1 Hazard classification of composite propellant

Machining of composite materials is an area still full of open questions, pertaining to the assessment of machining and thermal aspects compared to metal cutting. Due to the nature of composite materials, precise analysis still lacks progress.

The safety rating for detonation can distinguish propellants as a potentially detonable material (class1.1 - detonation) or as a non-detonable material (class 1.3- mass fire hazard) [65, 67].The constituents of the CSP in pure and original form are classified under hazard class 1.1 for its handling and processing operations, where as in solid composite from in the SRM are classified under hazard class 1.3. Since the deboned AP particles are available in original form at the cutting zone during machining operation, the cutting zone in the vicinity of cutting tool which carries mechanical stimuli to activate the ignition is to be thoroughly studied prior to implementation of cutting tool for precautions of hazard class 1.3. The ignition temperature of major ingredients of CSP such as AP and Al are 700°C and 640°C respectively.

3.10.2 Safety issues in design of tool for CSP materials

Since the ingredients appear at the cutting zone during machining falls under the hazard class 1.1 the following precautions covered under the Safety manuals of Ammunitions and Explosives [86 -87] are to be considered while designing tools and applying it on live propellant material.

a) **Machining of Pyrotechnic Material**

Cutting tools shall be removed from contact with the pyrotechnic material being machined before personnel are permitted to enter the machining area. Frequently cleaning machine tools during operating hours shall prevent residues from accumulating; a thorough cleaning shall conclude each work shift. Vacuum accumulator systems, immersion in liquid coolant streams, or similar automatic means shall remove the pyrotechnic waste products. Only low pressure compressed air may be used as a coolant and only when the scattering of pyrotechnic particles is contained by a vacuum collection system. The coolant delivery tube shall have a metallic tip or nozzle grounded to the machine to reduce static charges.

b) Machining of Explosives and energetic materials

When essential, other high explosives may be machined by remote control, with the operator protected by a suitable operational shield. However, explosives should not be machined if desired shapes or sizes can be obtained by other means, such as forming. The linear and rotational speeds of tools used for the machining of explosives shall be maintained at the minimum necessary to perform the operation safely and efficiently. These shall not exceed 210 linear feet per minute or 525 revolutions per minute [86].The rate of feed should likewise be the lowest consistent with safety and efficiency, based on the explosive materials being machined.

Pneumatically or hydraulically driven machine tools are preferred for all machining operations on high explosives. Control mechanisms for hydraulic and pneumatic equipment shall prevent unauthorized personnel from tampering with speeds. In all machining operations on cased or uncased high explosives; procedures during tool adjustments shall prevent contact between moving parts of the machining equipment and metallic parts of the case or holding fixtures. Machining tools shall be compatible with the explosives being processed. Dull or damaged tools shall not be used for machining high explosives.

The explosives products resulting from machining operations shall be removed by an exhaust system, or by immersion in a stream of water flowing away from the operation. Machining of explosives of reasonable quality during machining process shall be accomplished by remote control, with operators protected by operational shields. The important Limiting values of the energy of CSP material due to mechanical stimuli are shown in Table 3.8

Table 3.8: Limiting values of energy for self-ignition of CSP

Sl. No.	Description	HTPB	Limiting values
1	Impact height to give 50% ignition with 3 kg drop weight	22 cm	Limiting Impact Energy (LIE) < 2J
2	Friction weight for 50% fire / explosion	24 kg	Figure of Friction (FoF) < 3
3	Minimum Ignition Energy (MIE)	200 J	<200 mJ
4	Auto ignition temperature at constant rate of heating (5^o C/min)	260 ^{0}C	< 260 ^{0}C
5	ESD	12. 0 J	Spark Capacity <15 mJ

3.11 Identification of constraints associated in design of tool for machining of CSP grain

On study of microstructure of CSP material, material properties and mechanical properties of CSP the constraints in machining of propellant grain are summarized as follow.

- CSP propellants are sensitive to mechanical stimuli and hazardous for machining
- Safe and instantaneous disposal of hazardous propellant chips and powder as they become more sensitive in tiny form.
- Reference data on range of values fo tool geometry and cutting parameters for machining of 'hazardd to machine' material was seldom available.
- Difficult to achieve close dimension tolerances and surface finish on soft viscoelastic propellant material and high surface finish.
- Complying all the safety considerations and process parameters as per safety guidelines.
- Limited resources on tool design, process parameters and method of experimentation.
- Ensure all metallic parts in the cutter assembly and interface to ensure conductivity of static charge and reduce static charges accumulation.
- Application of vacuum or Low pressure air for evacuation of propellant chips and energetic powder from the machined surface and cooling of cutting tip as well.
- Prevent friction generating / moving / rotary / nonconductive parts in construction of cutter / machining equipment or holding fixtures.

3.12 Summary and Conclusions

The summary of conclusions obtained from the mechanical properties and microstructural studies of CSP are summarized as follows

3.12.1 Important inputs derived from micrographical study of CSP grain

- Cutting edge of the tool largely subjected to Ammonium Perchlorate (AP) particles loosely embedded in binder, followed by Al powder in binder matrix. Therefore cutting wedge is not going to interact with rigid and hard constituents of work material; hence strength of cutting edge do not got much emphasis while design the tool signature.
- The porosity contributes favorably for low cutting force of CSP material. With this precedence structural defect in CSP, conventional cutting tool can be employed to remove the material from CSP in the form of chips even at low cutting force.
- Formation of separated AP powder particles on cutting surface due to low interaction between the binder matrix and oxidizer is possible. Increased sensitivity of the AP in free and powder form demands a special provision in the cutting tool for instant evacuation of propellant chips that will be produced during machining.
- Large number of separated AP particles in slicing /cutting than typical mechanical breakage of specimen was observed, indicating fine and coarse particles of AP will be produced during machining.
- Surface produced by slicing is less irregular than surface produced by typical mechanical breakage and surface finish is governed by maximum size of coarse AP particles in distribution.
- Nose radius of the cutting edge less than radius of coarse AP particle in distribution (150 μm) will produce still finer crystals of AP in the cutting zone by breaking the agglomerated cluster of AP distribution in the matrix. Larger the value of nose radius, higher will be the cutting force which is undesirable because CSP become fire hazardous at elevated cutting forces/ temperatures. Hence nose radius of 0.2 mm is found to be appropriate.

3.12.2 Cutter design inputs obtained from mechanical properties studies

Propellant material fail by process of dewetting that is by particle separation and binder tearing. CSP exhibit low mechanical properties and low hardness in comparison with metals, indicating the requirement of sharp and keen cutting edge for machining. Common tool material with moderate wear resistance and good formability of cutting element meet the shape and size. Suitable grade of HSS tool material will serve the purpose.

3.12.3 Safety features obtained for tool design by hazard assessment study

The initial ignition while applying wedge shaped cutting edge for machining CSP may be due to the following, which needs to be addressed while designing a cutter.

- Friction between cutting tool and foreign material that is entrapped during previous processes before machining while processing of grain will from source of hazard.
- Air borne propellant dust generates by rotation of cutter, and propellant chips subjected to electrostatic discharge in the cutting zone.
- Any spark emanating from electrical systems in close proximity of cutting zone.
- Cutting speed should not exceed 65 m/minor 525 rpm.
- Sharp cutting edge for machining high explosives of 'hazard to machine' materials

The conclusions drawn from the micrographical, mechanical property studies and studies on safety aspects in cutting of CSP material will be used as design inputs for the design and development of prototype hollow contouring cutter which is presented in the subsequent chapter.

4.1 Introduction

Most of the energy associated with chip formation in conventional machining is converted into thermal energy, due to friction between tool rake and work piece, tool flank and machined surface, high rate of deformation of work material along shear plane and impact loads by intermittent cutting action [88].But Solid Rocket Motor (SRM) with CSP material, as studied in previous chapter is sensitive to these mechanical stimuli such as heat, friction and impact loads. Energy associated with mechanical phenomena in machining of CSP , if it is large enough and transferred to propellant grain or powder may be sufficient to initiate the ignition and subsequent massive fire and explosion. This inadvertent burning of grain causes explosive hazard to the human resources and equipment involved in machining. Since these composite propellants are hygroscopic in nature they yield poor mechanical ballistic properties in moisture environment, leading to disqualification of grain for use in SRM. One method to reduce the tool temperature is continuously changing the active portion of the tool cutting part in contact with the chip during machining [44, 88,89]. This was achieved by using multipoint cutting tool with intermittent contact, in place of single point cutting tool. Other method is using Rotary tool [44] where the cutting forces and cutting temperatures in rotary milling operation are low when compared to the conventional milling operation at same conditions due to the rotary motion of the insert.

There is no single, well-defined procedure or method found in literature on designing special purpose cutting tools for 'Hazard to machine' work material like CSP. The approach varies with the amount of available data on design issues, process parameters, type of propellants, propellant grain configuration, given machine setup, emphasis on particular aspect of design like simple construction, economy, less lead time for integration and maintenance etc.

Very few apparatus for milling solid propellant grains were known in the Literature [24-30]. A major functional gap in such cutters was that they can be used only for one particular type of machining operation and carry large number of components offering complexity and excess cost. Therefore, a special purpose contouring cutter to be developed to meet the versatile machining operations required by various profiles of grain configuration at low cutting force as well as to meet the safe removal of chips of CSP material from cutting zone that contain energetic ingredients like $NH_4\ ClO_4$. The approach adopted to conceive the cutter is shown in the Fig4.1 as follows

4.1.1 Why special purpose cutter

- To machine 'Hazard to machine' work material containing energetic ingredients
- To meet the versatile machining requirements
- To comply with safe disposal of hazardous propellant chips and powder
- For bulk volume of material removal and Large MRR
- To achieve close dimension values on viscoelastic material
- To ensure compatibility to existing machine interface
- To overcome the past and obsolete practices for machining present grain configurations

4. 2 Challenges in machining of CSP material

Work material, size and shape of job, profile and accuracy requirements of surfaces to be machined are the primary aspects to be studied for a given job, tool and machine combination [90].Major constraints in machining of propellant grains designed for dry joint assembly as shown in Fig.4.2 and in particular the grain configuration of present interest of study as shown in Fig.4.3are as follows:

a) CSP with AP are sensitive to mechanical stimuli and hazardous for machining. Difficult to achieve close dimensional accuracies and surface finish due to the viscoelastic nature of propellant.
b) Safe and instant disposal of hazardous propellant chips and powder produced during machining as it become more sensitive in tiny form.
c) Literature on reference tool geometry, machining parameters and standard cutting tools for CSP material were seldom found due to strategic nature of its application.
d) Stringent and expensive machine setup requirement for experimentations on live propellants.
e) Large size of the workpiece and bulk volume of material removal.
f) Poor accessibility for the cutter to reach cutting zones and limited visibility to cutting zones while machining
g) Practicing remote machining operations with implemented safety accessories

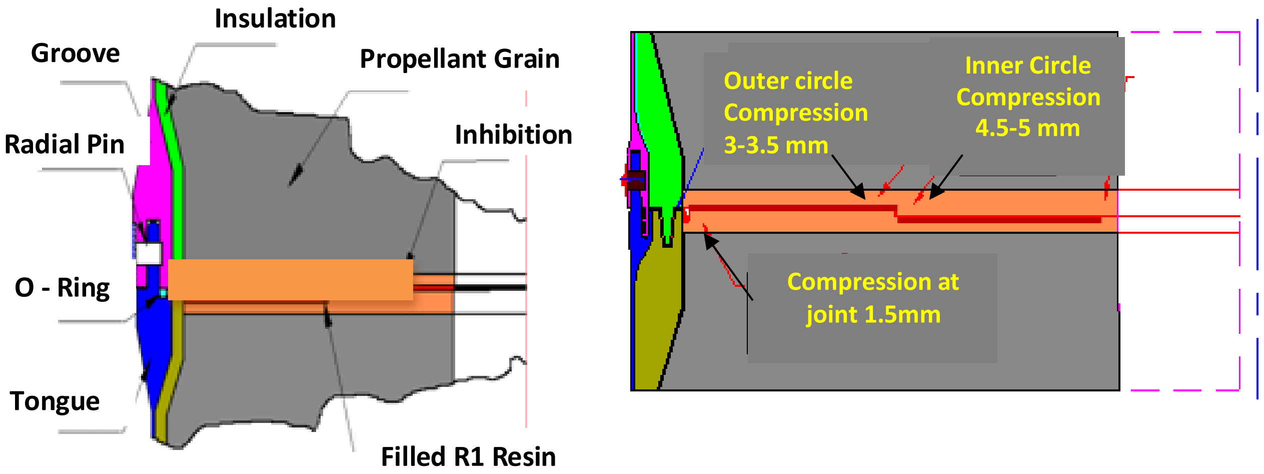
4.2.1 Manual trimming

During the early stages of development of SRM with simple central bore grain configuration and extraction of small specimen from grain for evaluation of mechanical and ballistic properties, manual cutting of propellants in the controlled environment using non sparking hand tool was in practice. This practice caters only simple requirements of making small flat surface or removing simple propellant sample from grain. The material for that non sparking hand tool includes copper beryllium alloys and aluminium bronze alloys. The main source of hazard associated in the manual trimming operation is static charge accumulation and friction by cutting action

Manual trimming practices do not completely eliminate the risk of hazard to the human resources involved in that activity. Time required for completion of propellant trimming is high and quality was inconsistent which depends on the workmanship of operator. It was also infeasible to generate complex profiles with dimensional accuracy by the manual hand trimming/scooping practices. This practice was only adequate for wet joint configuration. This adhesive fill the gap between trimmed surfaces of joint, hence the unevenness of manually trimmed surface and surface disintegrates will be covered by these liquid chemical at joint interface as shown in Fig.4.2(a).But the present grain is designed for ‘Dry joint ‘configuration as shown in Fig.4.2(b)as it is large size SRM.

4.2.2 Present machining requirement

Tight Compression gradient values through flat and inclined surfaces with accurate dimension are essential to form a sound ‘Dry joint’ configuration for assembly of large scale SRM as shown in Fig.4.2(b), which is being commonly adopted for manufacturing of SRM worldwide [2-4].To generate the required grain configuration with multiple transverse slots about the central bore of grain as shown in Fig.4.2(a) and also to remove bulk volume of material from grain, the manual trimming procedures become unviable and even obsolete on safety reasons. Therefore machining of grain with automated machine tool for remote machining practices using suitable cutting tools is inevitable. Machining shall be economical, safe and quality is consistent



a) Wet joint of small scale SRM *b) Dry joint of Large scale SRM*

Fig.4.2: Different joint configurations of SRM

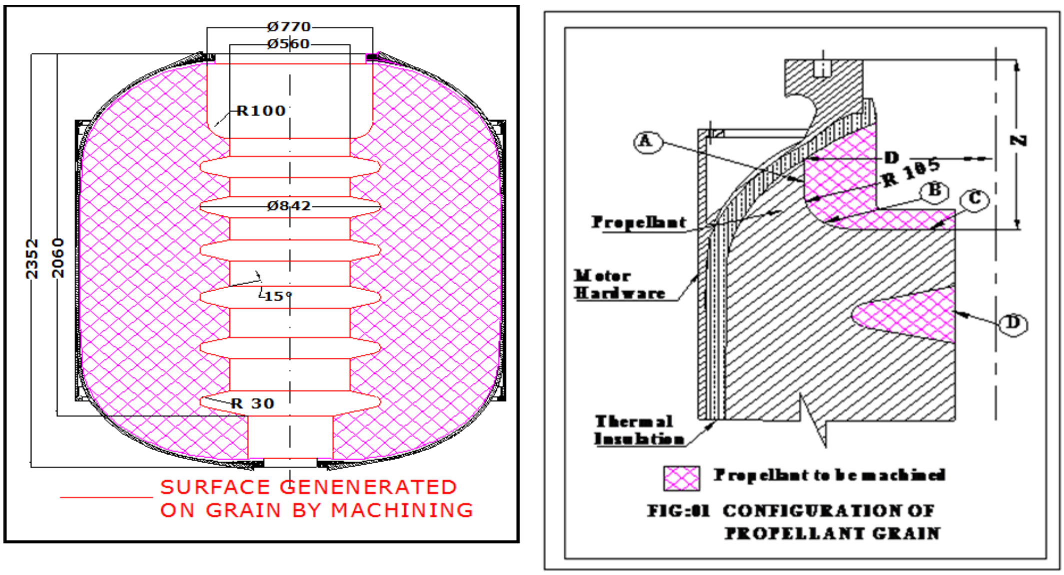
4.3 Features required on new cutting tool

Design and development of custom-built hollow contouring cutter assembly which is versatile in application, yet have a provision to dispose the propellant chips produced during machining, simple in construction, and easy to operate is the requirement. The cutter to be developed should be able to machine high energetic materials particularly AP/HTPB propellants and generate various configurations on propellant grains with low cutting force.

Features to be incorporated in the cutter for safe and effective machining are as follows

a) Should induce minimum mechanical stimuli to work material
b) Versatile in application to generate required profiles as shown in fig 4.3(b) on grain
c) Should have the provision for safe chip evacuation and handle long ribbon like chips
d) Safe and instantaneous chip disposal with a provision of air cooling to the cutting element
e) Cutter should be capable for MMR to remove bulk volume of material
f) Simple in construction, minimum components, easy to assemble and maintain
g) Multiple time usable insert (indexable) [91]
h) Light weight and conductive body to avoid static charge accumulation
i) Feature to address the air borne propellant dust generate by rotation of cutter.
j) Avoid the usage of any spark emanating from electrical and metal to metal rubbing components in the construction of cutter.

The SRM of current research study with dendrite propellant grain configuration and profiles to be machined, for which the versatile and safe cutting tool to be developed is shown in this Fig. 4.3.



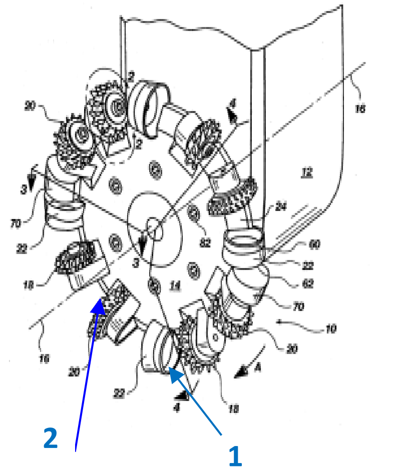
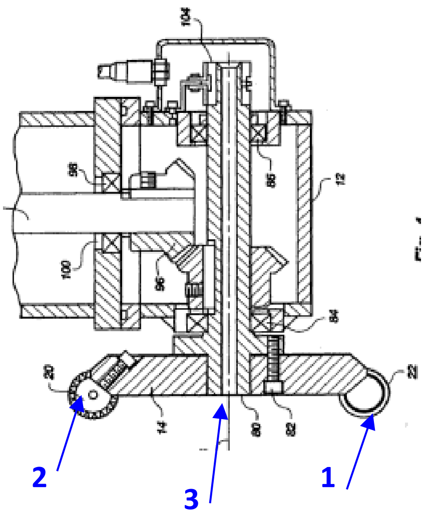
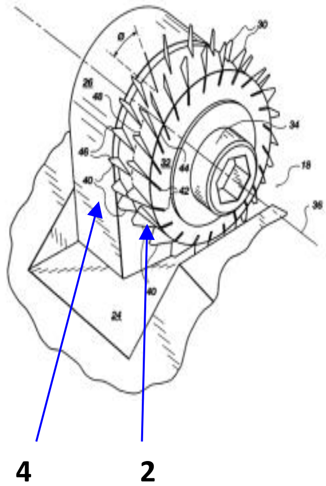
a) Propellant grain to be machined *b) Different profiles in the grain configuration*

Fig. 4.3: Grain configuration and profiles to be machined on the CSP grain

4.4 Inspiration to special purpose contouring cutting tool design

The present cutter development is inspired by a US patent titled "Propellant grain cutting assembly" by Kierstead. B. Wet. Al [29]. This inspired cutting assembly includes four primary cutting wheels (four), four sets secondary cutting wheels (four pairs) and multiple secondary cutters/blades on each secondary wheels and all are mounted to a mounting head. Primary wheel were fixed and secondary wheel were rotary. Function of secondary wheel was slicing of chips with blades for easy handling. Each cutting blade was configured with a radially extending cutting edge for cutting in a direction substantially normal to the axis of rotation of the mounting head. Certain entities of this inspiration that meet the required features as discussed in previous section (4.3), were taken in design and development of the present cutter. The features so drawn from inspiration for present design development of cutter include shape of cutting element, general architecture of cutter assembly, large rake and relief angles on cutting element and number of primary cutting blades to four. Problems such as complex secondary blade, flimsy and weak spikes of slicing blades with tendency to break by tiny forces, presence of source of friction when secondary wheel rotate like round insert in 'Rotary tool' on its axis, lack of instantaneous chip disposal provision, arrangement of secondary blade, shape and orientation of tool holder etc. were identified in the inspiration for its application to machine CSP grain configuration of present interest. Raju et al. [44] used CAD package for modelling for design and development of cutter meant for 'difficult to machine' materials.similar approach will be followed for the present cutter. A research work carried out by Omid Ghahrae et al, [94] in optimizing the rake angles of multipoint cutting tools proposed a large disk shaped tool holder with only 4 inserts to remove bulk sweet sorghum material by intermittent rotary motion of cutter. The cutting elements in the disk were provided with 30°-45° rake angles. Shaw et al [88], and Juneja et al [95] suggested 40^0 rake angle for minimum cutting force and cutting temperature while machining soft and ductile materials which are considered as baseline values for evalution of present cutter through experiments.. Major features rendered from the inspiration for development of present cutter is as shown in Table 4.1.

Table 4.1: Features inspired from "Propellant grain cutting assembly" [29]

Component /Assembly	Reference feature	Features adopted in present cutter	Remarks
Cutter insert	• Large rake angles • 4 Primary cutting wheel • 4 sets (08 No) secondary wheels for chip slicing	• Large rake and relief angles • 4 Primary blades with integrated chip slicing feature	
Cutter body	• Fustrum shaped cutter body with only radially outwardly extended inserts. • Body interfere when the cutter employed for contouring operation with restriction in feed direction.	• Modified disk type body with both axially and radially outwardly extended inserts • Allow contouring with different feed directions • Large size to cover max work surface	
Chip slicer	• Thin knife like cutting edge, extends radially outwardly form its axis of secondary wheel to make only cut marks on material before it is removed as chip by primary wheel.	• New concept of simple chip slicer is conceived by grinding a notch on the cutting edge as integral feature of cutting element. No separate slicing element.	
1. Primary cutting wheel 2. Secondary cutting wheel 3. Cutter body 4. Slicing knife			

4.5 Methodology for construction of prototype cutter

Present chapter describes the development approach adopted for the custom-built prototype contouring cutter to perform the versatile machining operations that are required to meet the grain configuration. The machining operations include contour boring, facing, transverse slots machining, filleting etc. Using a multipoint cutting tool on the existing CNC Vertical Turn Mill (VRM).

Contouring is complex geometry generated by 'intermittent cutting action' by multipoint cutting tool, where each individual cutting insert continuously enters and exit the cut. Custom-built or special purpose cutting tool is as its name offers to quite considerably diverse tool designs. Some of this custom-build tooling can be relatively simple, perhaps just manufactured to mill only one particular feature, while others are very complex and sophisticated in both their design and operation [91].The general notation of 'tool holder' and 'cutting element/tooth' used in cutting technology will be referred as 'cutter body' and 'insert' respectively in the subsequent description of this thesis, because of their wider functional capability. The 'cutter' refers the cutter body/holder and cutting element assembly.

But the Prototype cutter to be developed will be used for the evaluation of tool signature in particular, to fix the rake and relief angles on the insert using Bharat Fritz Werner Ltd (Power 3kW capacity) machine and Kistler Type 9272 quartz four component dynamometer available at NIT Warangal as preliminary machining studies.

4.5.1. Developmental approach for prototype contouring cutter

When designing a special purpose cutter or deciding upon the correct selection of a tool holder /cutting insert for a given application, a range of diverse factors shown in Fig.4.4 and many other variables listed in Table 4.2 to be considered prior to selection of the optimum tool holder /insert. Generally, the fixed conditions presented in the Table 4.2 cannot be modified, but by juggling with the variable conditions, it is possible to accomplish the best compromise tool holder/insert geometry, to optimize these variable conditions for the manufacture of a specific work piece and its intended production requirements. Since the tool holders and cutting inserts are required for a specific manufacturing process, tooling selection procedure is carried out in a logical progression, in order to optimize the best possible tools/inserts for the job in hand.

Since the heat/energy associated in propellant machining should not be transferred to chips and should never reach threshold value/ self-ignition temperature of the CSP material. One method to reduce the tool temperature is continuously changing the active portion of the tool cutting part in contact with the chip during machining [44, 88].This was achieved by selecting a multipoint cutting tool with intermittent contact or a rotary tool in place of single point cutting tool providing cool off time to the insert between cuts and avoid excess rubbing of flank on work material. Side and face milling cutter with round insert is considered in place of rotary tool to avoid the presence of source of friction in the cutting zone due to rotation of rotary insert.

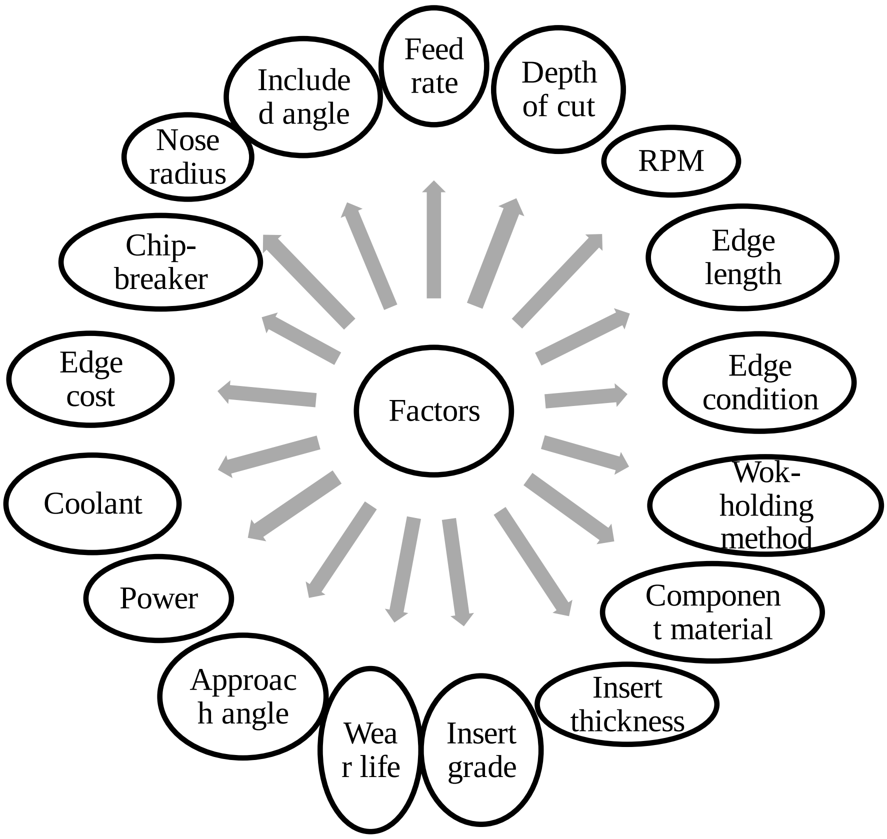


Fig.4.4: Factors influencing the selection of cutter

Table 4.2: Conditions influencing the selection of cutter

Fixed conditions:	**Variable conditions:**
Material specification	Select material grade
Amount of materials to be removed	Select radius
Component dimensions	Select insert shape
Component shape	Select insert size
Hardness	Select insert make
Surface condition	Select tool size
Operation	Select tool-holder size
Finish requirement	Select tool-holder style
Type of machine and condition of machine	
Existing Machine and Power available	
Chucking or clamping method	

4.5.2Cutter body/holder:

Geometry and various parts of prototype cutter in general cutter layout are shown in Fig: 4.5. Size and shape of cutter body, type of holder, method of clamping, cutter density (number of cutting elements) and other safety features to be incorporated are studied as part of cutter body design. A disk shaped cutter body to hold at least four round insert and can rotate around its own axis was conceived as contouring cutter. Contouring cutter body has to hold the equally spaced 4 conical inserts, which requires clamps for positional and rotational locking of insert in addition to locating pin. A stud with left hand and right hand M6 threads to bring the two bush type pads on either side of the disk hole enables to clamp the cutting element on its cylindrical surface when tightened. It will also enhance the positive clamping force to hold the two disks together. One operation of tightening the stud tightly performs functions of holding the cutting elements, disk halves and quick assembly of insert and cutter.

a) Cutter diameter

One of the most important factors affecting the performance of cutting tool is attaining high degree of rigidity in the entire machining system. In the design of cutting tool, there must always be some compromise with maximum rigidity in order to provide adequate chip space to avoid jamming. More chip room and wider tooth spacing are required for the CSP as they produce continuous ribbon like chips. The cutter diameter generally depends on width of cut when viewed for maximum MRR. Quantity of material to be removed and quality of surface finish to be produced, chip room space, machine tool to be used were the factors considered to decide the size of cutter. Since the profiles to be machined are large in size where bulk volume of material to be removed, cutter diameter for face milling should be 1.3 to1.6 times the width of part of job to be machined [91, 96-97]. Symmetrical positioning of the cutter should be avoided when the engagement width is considerably smaller than cutter diameter. The selection of cutter density (number of cutting elements in cutter) and diameter for contouring or pocket milling is more complex because the cutter engagement while machining convex or concave arcs requires thorough prediction of interference of cutter body with work material in place of insert. Taking into consideration of machine capacity, dynamometer specifications and proportional size to final cutter envisaged for actual work piece, the prototype cutter body is a circular disk of diameter 196 mm and thickness is 40mmas shown in Fig.4.5.

b) Cutter Type

Cutter compatible with cartridge type inserts and provision to perform indexing of insert for replenishment of worn out edge is provided through rotation of insert about its own axis. This was ensured with modular cutter assembly [91] and axial symmetry of insert. The cutter is built with minimum number of simple and replenishable components

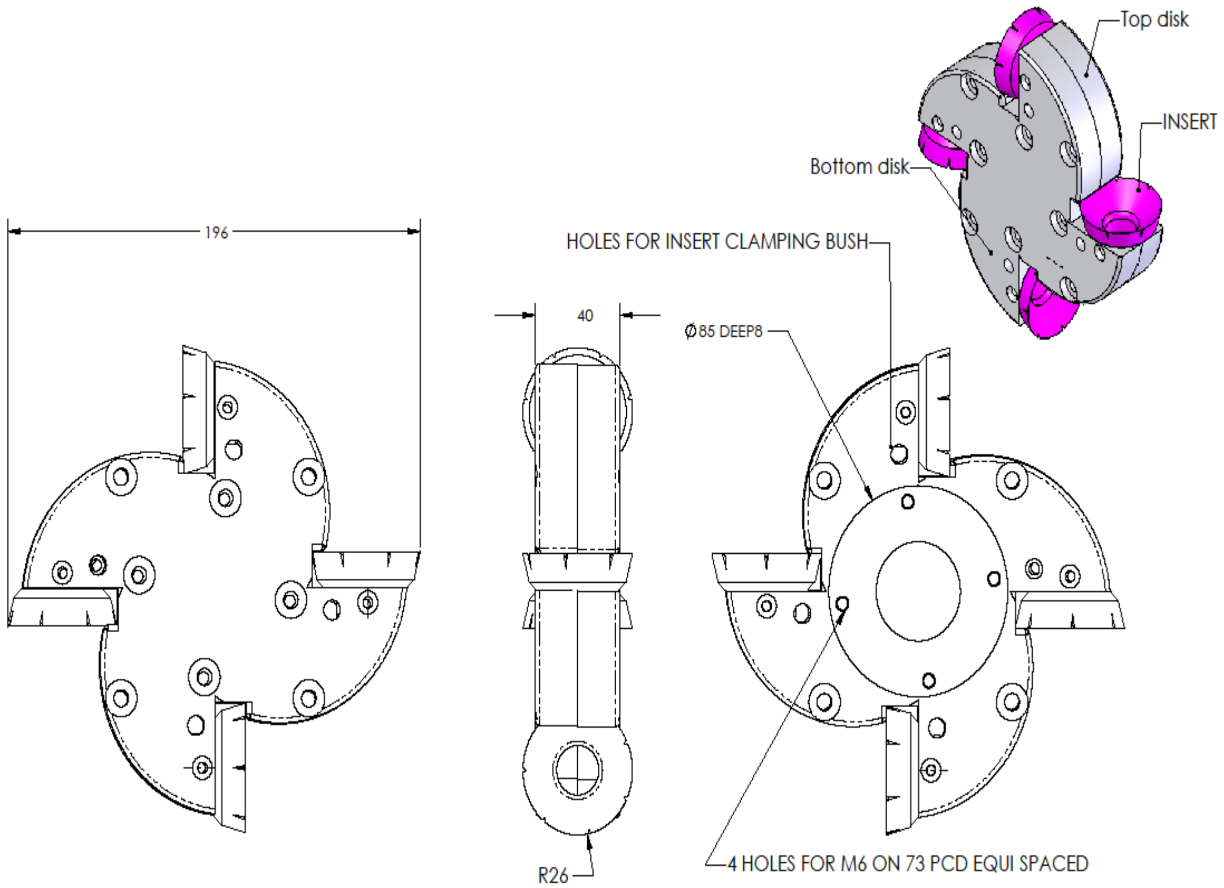


Fig. 4.5: General layout of Prototype contouring cutter assembly

c) Cutter density(Number of teeth)

The driving factors to fix the number of teeth on the present cutter was Max MRR, sufficient space for chips passage, avoid idle rubbing of cutter on CSP grain. CSP being soft material permits heavy feed and depth of cut for max MRR. Sufficient chip room to accommodate chips at heavy cutting conditions is provided by selecting the number of inserts in the cutter. A small increase in depth of cut with round insert will increase the tool engagement which intern increases the cutting force. If too many teeth are in contact with work at same time, the tool part or the machine may be overloaded. Overloading may not only cause decrease in accuracy due to dilation property of the CSP material but also present a source of excess stimuli at cutting zones providing favourable condition to Hazard situation. For milling cutter at least one tooth should be in contact with work at all times to avoid the vibration that occur from varying shock load by the impact of cutter. Inserts are equally spaced on disk periphery to ensure balance during rotation therefore 4 number of round inserts on the cutter is sufficient to meet the discussed requirements and this is in line with the inspiration [29] as shown in Table: 4.2. When the cutter rotates with the 4 inserts at least one insert shall be engaged with the work material at any instant of time to ensure smooth cutting.

Factors considered in optimizing the number of teeth on cutter body:

- Bulk material removal in medium size chip form
- Avoid excess rubbing with work material
- Minimization of insert assembly time to holder
- Rigidity of machine tool
- Minimise the weight of cutter for given power of machine
- Large size and shape of insert enabling more cutting edge engagement length

d) Cutter body material

Aluminium material for cutter body was opted by considering thermal conductivity and electrical conductivity, as the CSP require these two properties to avoid both thermal energy and static charge accumulation. High strength to weight, good damping properties and good machinability to produce desired shape of chip pockets and chip flow passages in the cutter, enables Aluminium Alloy 6351 as potential material for cutter body. The composition of elements in Al 6351 alloy are 0. 7 to 1. 3% Si, 0. 4 to 0. 8% Mg, 0. 4 to 0. 8% Mn, 0. 1% Cu, Al- being the remainder. For machining the given CSP work material, properties of Aluminium alloy Al 6351 shown in Table 4.3 meet the strength and rigidity requirements.

Table 4.3: Mechanical properties of cutter body material

Alloy Designation	Tensile Strength (kg/mm^2)	0.2% Proof stress (kg/mm^2)	% elongation
AA6351/IS64430	31. 5	27. 5	7

e. Summary of cutter body

Cutter Parameter	**Opted for design**
Diameter	196mm
Type	Catridge
Density (No.)	4
Material	AA6351/IS64430

4.5.3 Cutting element/insert:

The main driving factor for insert design was to generate variety of profiles on CSP grain to meet versatile machining operation for combination of profiles of given grain configuration in single setting of cutter and with maximum MRR. The insert should be cost effective, simple in construction and conductive to avoid static charge accumulation due to rubbing. Shape of cutting element is governed by versatility of its application and to withstand the cutting forces envisaged. Size is chosen to cater maximum MRR, large volume for better heat dissipation, and to allow provision for chip extraction by vacuum application. Minimum cutting force, minimum friction and heat shoot-up while machining, prolonged tool life for economy, simplicity in construction, fool proof cutter assembly, easy chip disposal etc. , are also other design drivers for finalizing the insert shape and size. The insert should be featured to mitigate the risk of machining on hazardous propellant material.

a) Insert shape:

Insert capable of producing contours is essential to meet the versatile machining operations. Therefore round shaped inserts are suitable for contouring with different feed directions as shown in Fig. 4.6. The round inserts have two advantages when compared to some other cutter insert geometries; i) inherent strength for minimizing potential points of weakness in the geometry and ii) imparting high shock resistance and fracture toughness and more cutting edges, at least twice as many cutting edges per insert [91].Strength and induced vibration trend for various shapes of insert are shown in Fig. 4.7. Though the round inserts are prone to vibration, when they used on viscoelastic and soft material like CSP, its effect is not significant.

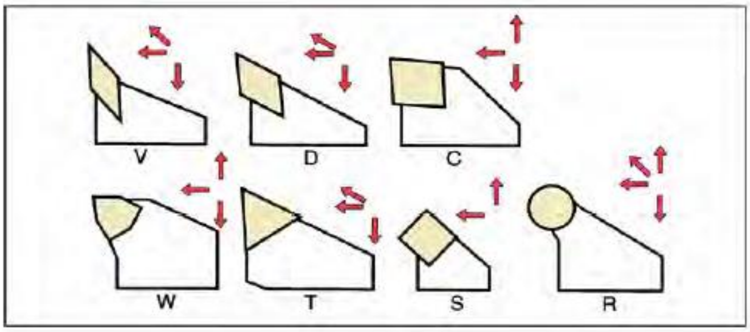


Fig.4. 6: Feed directions for various insert shapes [91]

Advantages of round insert:

i. Strong round cutting edge.
ii. Enable maximum usage of cutting edge.
iii. Suitable for contouring to machine different profiles
iv. Indexable for multiple time usage.
v. Easy tool setting and pool proof clamping.
vi. Offers sufficient space for through feed chip extraction from cutting zone.

vii. Good stability and uniform chip load.

viii. Low cost, low indexing and setting time, less fragile.

Conical insert with round cutting edge was developed as shown in Fig.4.5 corresponds to round insert as shown in Fig. 4.7 to meet strength, functional and safety requirements for machining this 'hazard to machine' material. Cutting element with similar shape was employed for the same material as primary cutting element in the invention [29].

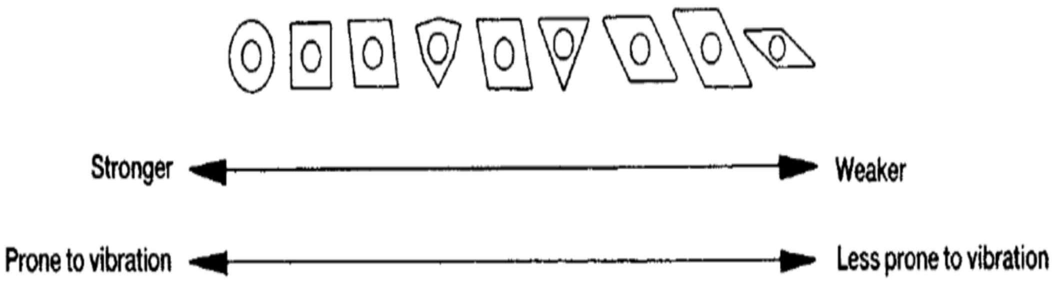


Fig.4.7: Strength and vibration trend for different shapes of insert [91]

b) Insert type:

Cartridge type indexable round insert with proper guiding and seating provision is preferred on the basis of economy of tool and minimum lead time for tool change. Inserts with round cutting edges exhibit rotational symmetry and could continuously indexable in any angular position to accommodate the wear when actually observed on insert. In practice, however, round inserts have also become restricted to use with a discrete number of indexing stations, angularly spaced by an equal shift angle. The angular shift between the indexing stations is referred to as the "angular pitch" of the insert. The angular pitch for the designed insert is 90°, allowing it 4 times indexing before it is disposed.

In order to eliminate the source of friction in the vicinity of cutting zone for this hazard to machine CSP materials, it is desirable to prevent rotation of the insert from its indexed position during the cutting process, thereby limiting the tool deterioration to a defined portion of the cutting edge. This ensures that the portion of the cutting edge presented after repositioning is, in fact, un-used. The shape advantage, application for contouring and bulk material removal using round insert was also proven in earlier developments for difficult to cut materials [44].

c) Insert material

The cutting insert must provide maximum resistance to any tendency of alteration of its geometric shape. To achieve this tool material must be at least 35-50% harder than the work piecematerial. Modified hardness value, taking care of elevated temperatures, at high strain rate in metal cutting as referred in literature [97, 98] is as follows:

$$1.35 < H_{tool}/H_{work} < 1.5$$

The properties of suitable material for CSP material cutting is as follows:

a. Should maintain its hardness more than work material at elevated temperatures
b. Large resistance to wearing action
c. Toughness allows the cutting edge of the insert to absorb the cutting forces and shock loads produced whilst machining, particularly relevant when intermittent cutting operation.
d. High thermal conductivity and high specific heat
e. Low coefficient of thermal expansion
f. Ease of manufacturing to desired shape of insert
g. Low cost and easy availability

Among the commonly used materials for making the cutting tools High Speed Steel (HSS) M2 grade is found most suitable confirming to the above said property and design requirements.

Material Composition:

M2 grade HSS material with HRC 65 and IS designation IS: 7291-1974 is opted to meet the size, shape, and economy and design requirements. Tungsten - 6%, Molybdenum -5 %, Chromium-4%, Venedium-2%, Carbon-0. 85 %, Ferrous (Fe) - being the remainder.

Summary

Insert Parameter	**Opted for design**
Shape	Round insert
Type	Catridge
Material	HSS- M2 grade

4.5.4 Tool signature

The objective of prototype cutter development is to fix the tool signature and to identify the process parameters suitable for the CSP work material. The experimental studies are planned to fix the rake and relief angle on round insert with a fixed nose radius of 0. 2mm as concluded form the material studies of work materials in previous Chapter-3.

a) Rake and relief angles:

Rake and relief angles affect both tool performance and strength of the teeth. High rake ensures free cutting and more efficient machining. High relief angle reduces the rubbing that occur at the flank of tool. These angles cannot be increased without limit, as any increase in either the rake angle or the relief angle, results in a reduction in cutting edge strength. In addition, while high relief angles reduce the temperature resulting from flank friction, they do cause a greater change in size for the development of a wear land of given size. The selection of rake and relief angles therefore requires a compromise.

HTPB composite materials with polymer binder possess relatively low strength and hardness in comparison with metal, which require a sharp cutting edge and not a much stronger cutting edge. As referred from literature [29] extremely large positive rake angles were considered in machining CSP material in comparison with the cutting tools for machining metals, without compromising on strength of cutting edge. The angle so fixed for the application is a trade-off value between minimum cutting force requirements, strength of cutting edge and shape for suction hood of chips for chip evacuation. In view of the dilation of CSP like spring back in metals as investigated in the earlier chapter, low hardness and minimum strength of CSP as work material, relatively large relief angle were selected. But the values are chosen based on the minimum wedge strength requirements. Continuous ribbon-like chips are an indicative attribute for good machinability of material and are associated with a smooth surface finish. For given strength and hardness of work material under study and selected HSS tool material, the wedge angle of 30° is considered sufficient because of greater strength of HSS tool material in comparison with work material. Experiments were conducted as per the run sequence of half fraction factorial method of design of experiments, with four sets of inserts varying rake angle ranging from 40°-55° and relief angles from 5°-20^0, keeping wedge angle at 30° for all inserts, to fix the safe rake and relief angles for minimum cutting force.

Following are the advantages of large positive rake and relief angles converging to the functional requirement of machining of heterogeneous CSP material [94-97]

- Provides sharp cutting edge
- Reduced cutting forces
- Favourable for long ribbon like chips
- Reduced cutting temperature

b) Nose radius

Nose radius of cutting edge must be at least 1. 5 to 3 times the maximum size of ingredients being used in composite propellant grain as discussed in the previous chapter. Surface finish less than that of the maximum size of AP particle is not possible in conventional machining of CSP as investigated from material studies in the previous chapter. As the maximum size of AP particle in coarse distribution is 300 µm, nose radius of the cutting edge less than 150 µm (half the maximum diameter of ingredient) will produce still finer crystals of AP in the cutting zone by breaking the agglomerated cluster of AP distribution in the matrix. Larger the value of nose radius, larger will be the cutting force and friction which is not favourable as the CSP is sensitive to mechanical stimuli. Hence nose radius of 200 µm is considered appropriate.

c) Double-Positive Cutting Edge

Double positive cutting edge, because of positive axial and rake geometries produce low cutting forces, owing to the reduced chip thickness and a shorter length of contact at the chip/tool interface. Positive radial rake provides a sharp cutting edge that tend to pull into the work material, while positive axial rake lift the chips away from finished work surface and towards inside of cutter body enabling the supplementary force towards the centre of round insert to extract the chips through central bore of insert. This geometry allows a relatively ‘free’ cutting/shearing action. As a result, less spindle power is necessary, thus a lower insert strength requirement enabling high-shear cutting availability [90].Double positive cutter reduces cutting pressure, consumes less power, and creates less heat reducing deflection.

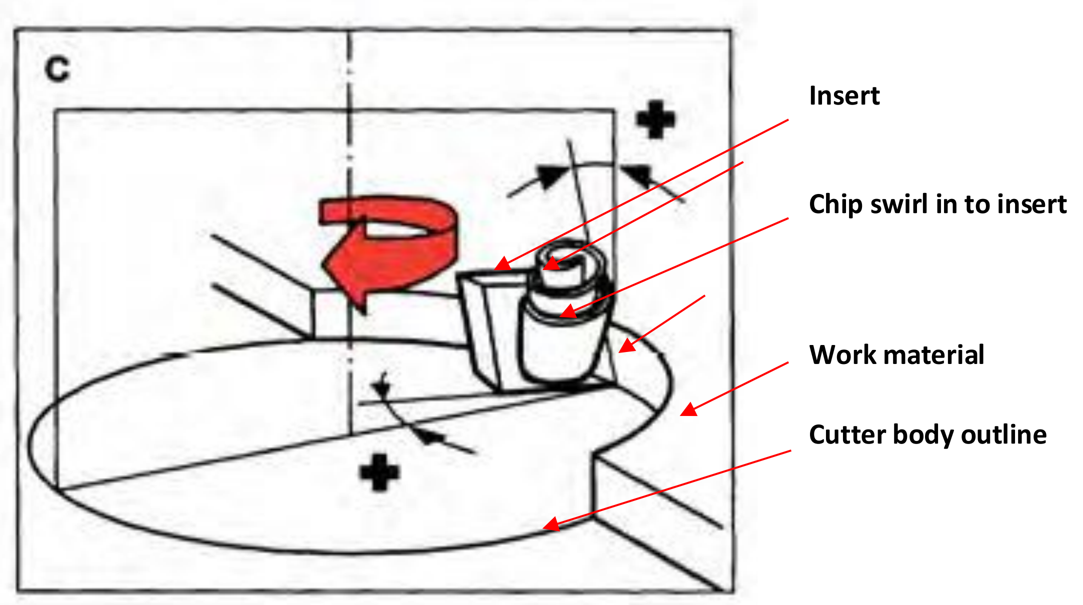


Fig.4.8: Double-positive angled cutting edges

This geometry creates true shearing actions and suitable for finishing operations. Suitable for materials which produce long continuous chips and for work hardened materials. The double positive type insert is shown in during Fig.4.8, which pull into the work material towards its centre enabling easy and instantaneous chip disposal by vacuum application through central hole.

d) Approach/ Entering angle

Entering angle affects the length of the cutting edge engaged in-cut, normally varying from 45°to 90°. The round insert is oriented for orthogonal cutting action, with only a 90° entering angle (i. e. the lead angle reduces to zero), showing a large increase in the axial force component at the expense of the radial force component which is now zero. Circular insert with 3mm depth of cut entering angle has changed to 70° and lead angle is now 20°, these altered angles change the component of forces, with an increase in the axial force while reducing the radial force.

If a 90° approach angle is used, the rate of advance per tooth equals the chip thickness. When there is decrease in the approach angle, the chip volume remains the same, but the length of cutting edge engagement with the work piece will increase as shown in Fig.4.9**.** This results in form a chip which is both smaller and longer than that programmed; hence it is necessary to raise the feed rate to increase the chip thickness to its required level, when the DoC is less than the radius of round insert. It can be said that although the chip created by the round insert geometry has an almost identical chip thickness to that of a 90° approach angled insert, the button-style insert geometry removes work piece material at a considerably faster stock removal rate if the spindle power is greater

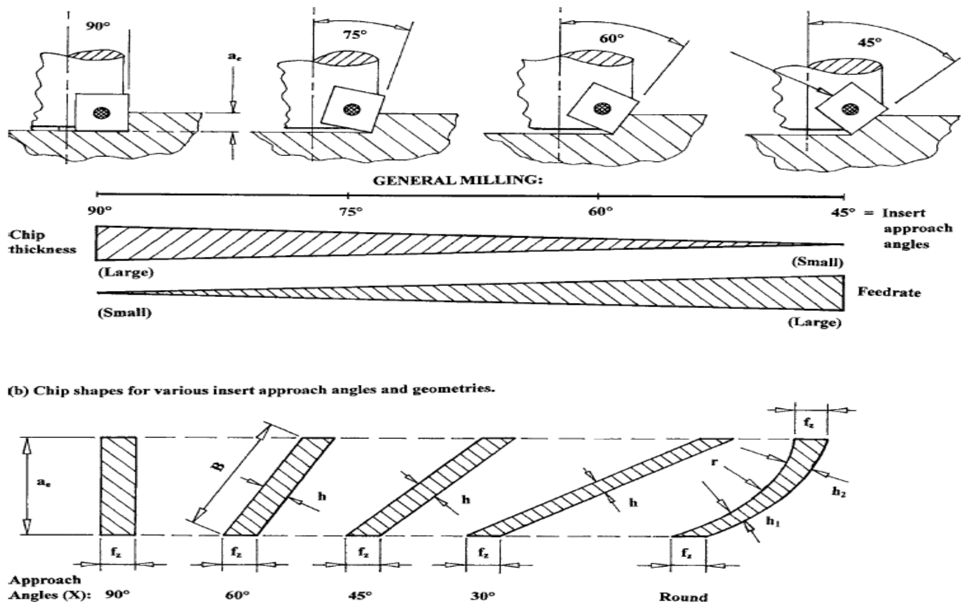


Fig.4.9: Influence of approach angle on chip thickness and feed rate [91]

e) Edge/ insert clamping system:

Among the available three types of clamping systems [89, 91] Pin, Clamp and Lever type, combination of pin and clamp type systems were employed for firm and easy setting of insert. Indexable circular insert (Cartridge type) with proper guiding and seating provision was made for economy of tool and minimum lead time for tool change. Cutting inserts with round cutting edges exhibit rotational symmetry and could theoretically be indexed in any angular position to accommodate wear. However, the insert is designed to use it only four times before its disposal by providing four locating holes on the cylindrical seating surface of the insert as shown in Fig 4.10. The size of round insert segment engaged with work material even for small depth of cut is large which limits the number of indexing cycles of insert. The size of insert (diameter), number of chip slicer on cutting edge and area of damage spread on rake and flank of insert by chemical wear of the insert also limits the number of times the insert can be indexed

In order to make optimal use of a round cutting insert, it is desirable to prevent rotation of the insert from its indexed position during the cutting process, thereby limiting the wear to a defined portion of the cutting edge. Clamping the insert with proper guiding and seating provision is preferred on the basis of economy of tool and minimum lead time for tool change. This ensures that the portion of the cutting edge presented after repositioning is, in fact, un-used.

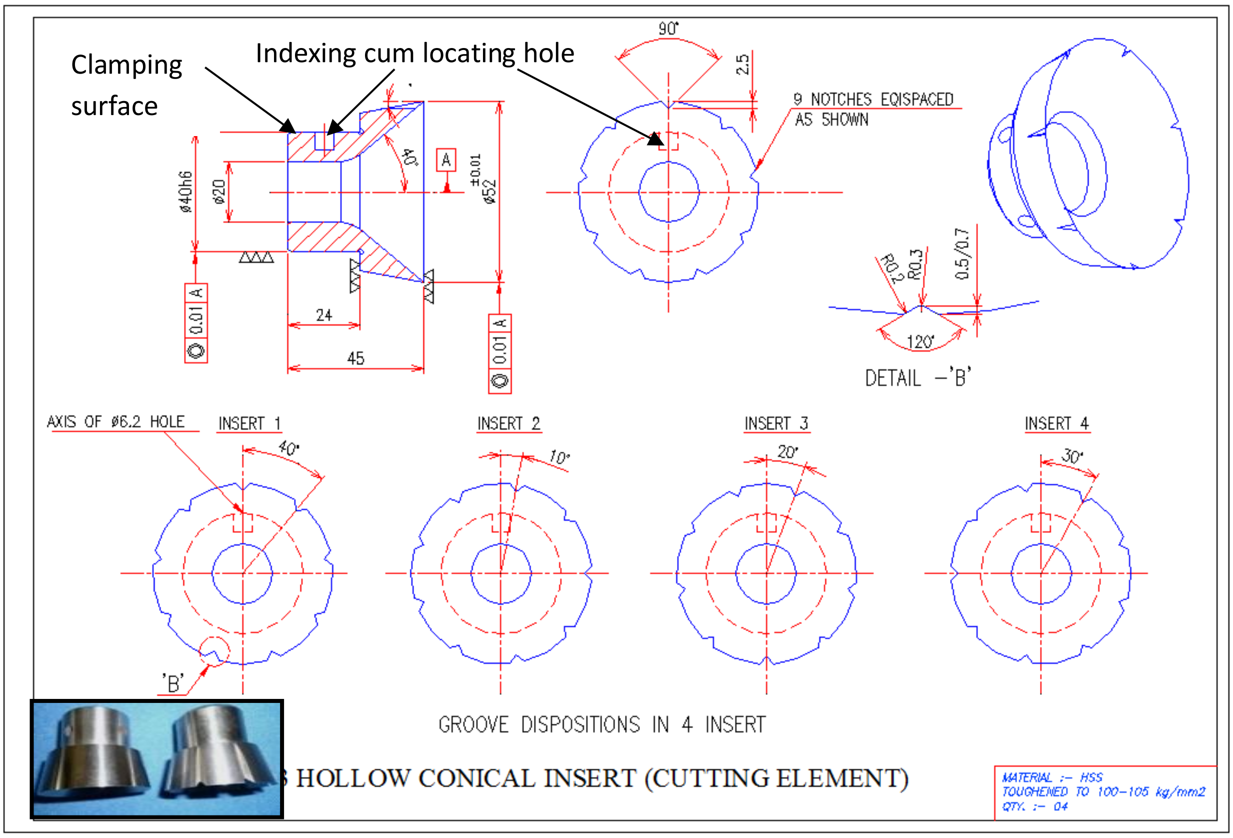


Fig.4.10: Insert design details and Indexing cum locating holes on the insert clamp surface

f) Tool signature of prototype contouring cutter

Concluded tool signature and geometry of the cutter body is shown in Fig. 4.11

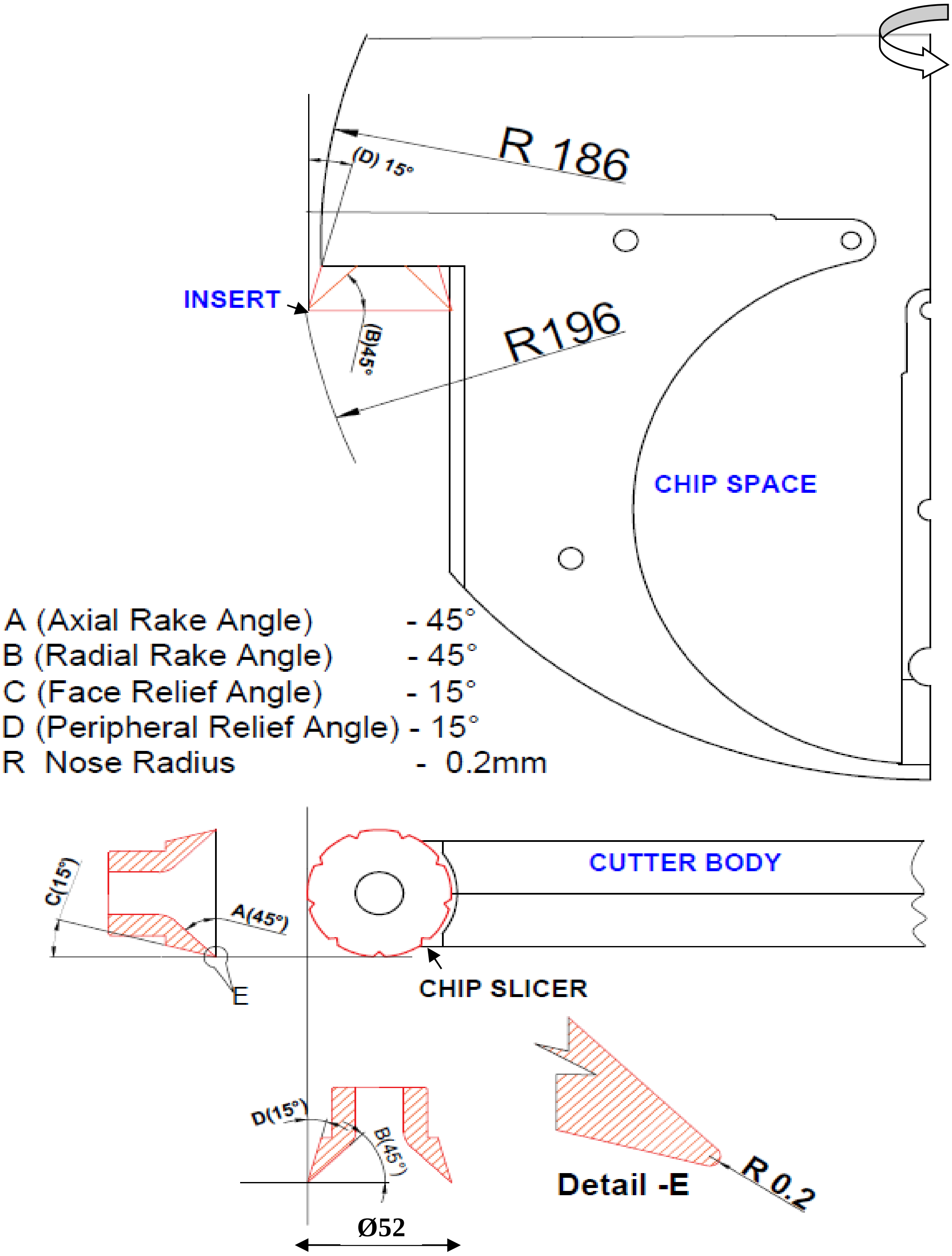


Fig. 4.11: Tool signature of Prototype Contouring Cutter

4.5.5 Safety and functional issues addressed in design of the cutting insert:

a) Round shape of insert for Strength and contouring
b) Sharp cutting edge with large rake and relief angles
c) Small nose radius for minimum cutting force and cutting temperatures as surface roughness is predominantly determined by grain size than nose radius for this heterogeneous CSP material
d) Double positive angle on insert coils the chip toward insert, reduced cutting pressure, good finish on job and perfect for long continuous chips
e) Equally spaced inserts, four in number, for cutter balance
f) Central hole for safe chip disposal and effective machining

4.5.6 Developed prototype cutter assembly

Geometry of cutter and various elements of cutter along with clamping provision of insert are shown in the exploded view of prototype cutter model as shown Fig.4.12 for clear understanding. Contouring cutter is configured with a disc-shaped main body, that comprises a central axial through bore for accommodating drive shaft / arbor, at least two sub-discs being placed coaxially at a predetermined distance and circumferentially sealed with each other so as to form space or passage in between. The cutting elements are tangentially located to the disc shape main body so that the chips formed at the cutting zone of the cutting tool are evacuated through the space between the sub discs and the bore of the main disc body as shown in Fig.4.12.

Cutter body has to hold a round insert and shall rotate around its own axis. Hollow contouring milling cutter body has to hold 4 conical inserts with equal spacing, which requires clamps for positional and rotational locking of insert. A M6 Stud with left hand threads on one end and right hand threads on other end is used to bring the two bush type clamping elements, to firmly clamp the insert at its cylindrical portionwhen tightened. This clamping assembly shall pass through the disk hole to clamp the cutting element on its cylindrical surface when tightened to provide positive clamping force. One operation of tightening the stud brings the two clamping bushes close to insert seating. The solid model assembly of prototype cutter was developed using CATIA, a mechanical modelling tool for design optimisation and simulation design software, adopting the similar approach for development of new tool as found in literature by CS Raju et al [44, 93]. CATIA is feature based parametric solid modelling design tool that the advantage of easy learn windows graphical user interface where we can crease fully associative 3D solid models with or without constraints by utilizing automatic or user defined relation to capture design intent.

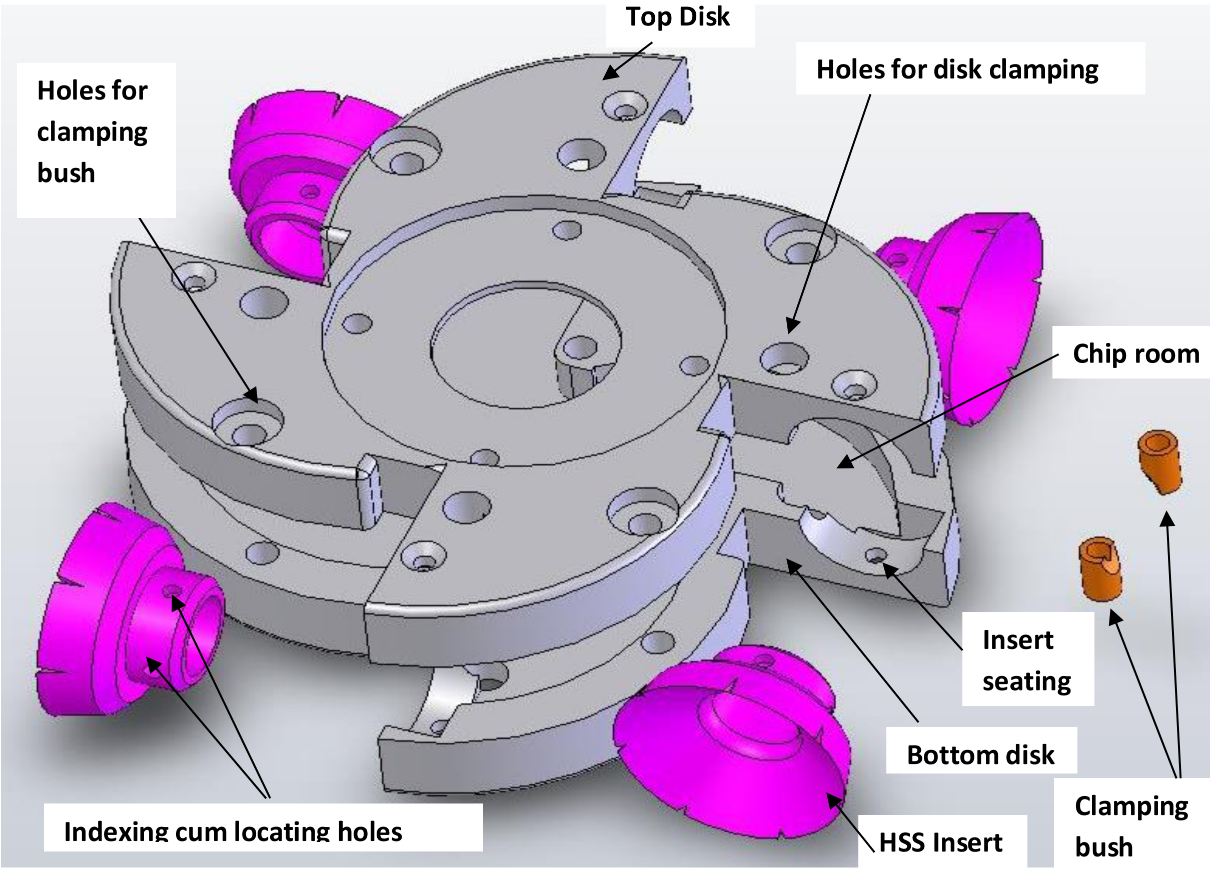


Fig.4.12: Exploded view of developed Prototype contouring cutter

4.6 Experimental evaluation of prototype cuter

The main objective of the experiments is to evaluate the tool signature for minimum cutting force. Conceived Four sets of HSS conical inserts, are made with different rake and relief angles by keeping the wedge angle constant for all the inserts in order to maintain the required strength of tool for given work material. The selected rake and relief angle values are within the range of above discussion and references.

Experiments are conducted based on half fraction factorial (HFF) methods of DOE to identify the cutting parameters between extreme ranges of machine capability where cutting force is stable.

Experiments were carried out at selected cutting parameters using all the inserts, in order to choose the best insert with tool signature for minimum cutting force. The entire procedure is presented in the following section in detail.

4.6.1 Experimental setup

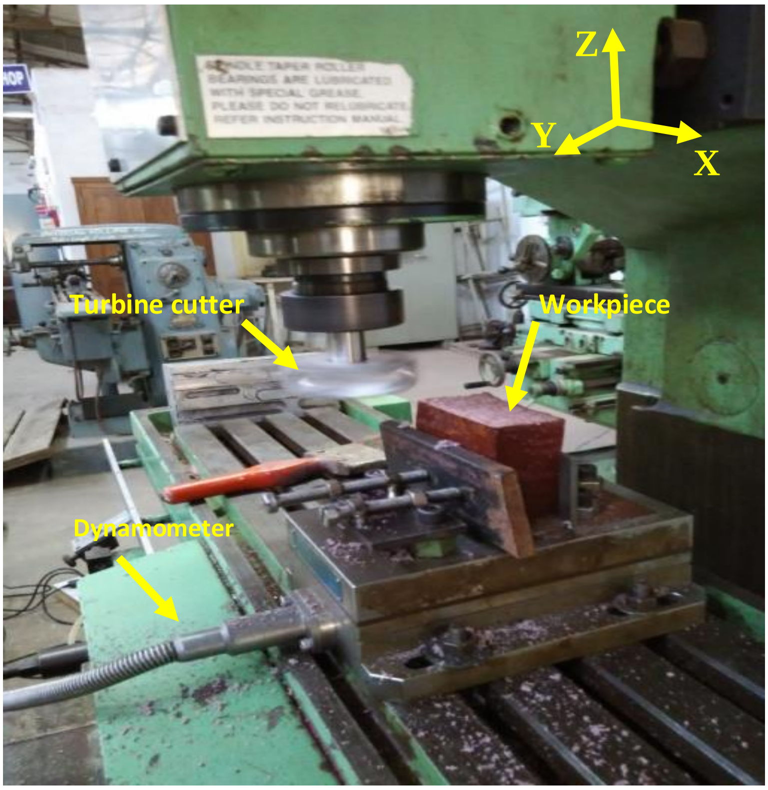


Fig. 4.13: Experimental set-up for tool signature evaluation

a) Machine tool

Since the machine set-up at CNC VTM centre, where actual propellant grain of SRM are to be machined is configured for large six cylindrical jobs (ranging from Ø1000mm x 1.5m length to Ø2200mm x 3.5m length) it is not viable to conduct lab scale experiments on the machine setup and its modification to augments to present preliminary experiments are beyond economy. Therefore experiments in lab scale were conducted on a machine tool which is a three axis vertical milling machine of make Bharat Fritz Werner Ltd (BFWL) as shown in Fig.4.13 here where dynamometer can be mounted with great convenience for measurement of cutting power. The machine tool table of BFWL could be moved in Cartesian coordinates in X, Y and Z direction. Specifications of BAWL machine shown in Table 4.4.

Table 4.4: Specifications of vertical milling machine

Longitudinal movement	560 mm
Transverse movement	250 mm
Vertical movement	390 mm
Speed range	45-2000 rpm
Feed range	16-800 mm/min
Motor power	**3** kW

b) Work piece

The work piece material formulated with non - reactive sodium sulphate ($Na_2 SO_4$) in place of energetic oxidizer (AP) with HTPB binder which yield the same mechanical properties of live propellant (CSP) being used in these preliminary experiments. It is because the CSP with energetic AP is more sensitive, hence replaced with $Na_2 SO_4$. It is also not advised to test the newly developed tool directly on live propellant material on safety reasons without verifying its performance on equivalent non-hazardous work material. A slab of size was 150 × 90 ×75 mm^3 block was as shown in Fig.4.13 being used to conduct experiments. Mechanical properties of this slab includes Max Tensile strength of 7.5 kgf/cm^2, Hardness 85 on Shore-A and Young's modulus 40 kgf/cm^2 when measured the samples using INSTRON UTM as illustrated in Fig.3.6 which is almost equivalent to properties of present CSP material considered.

c) Cutter

Designed prototype Turbine cutter (hollow contouring cutter) as shown in Fig 4.14 with a tool signature as shown in Fig 4.11 was used. The cutter is firmly clamped to the spindle using suitable arbour and it rotates about its axis at specified speed.

Fig 4.14: Prototype Cutter

d) Cutting element

Four sets of HSS conical inserts as shown in Fig.4.15 were used. Rake and relief angle combination for Insert A (Rake 40° - Relief 20°), Insert B (Rake 45° - Relief 15°), Insert C (Rake 50° - Relief 10°) and Insert D (Rake 55° - Relief 5°)were used in the experiment, maintaining wedge angle 30° constant for each Insert.

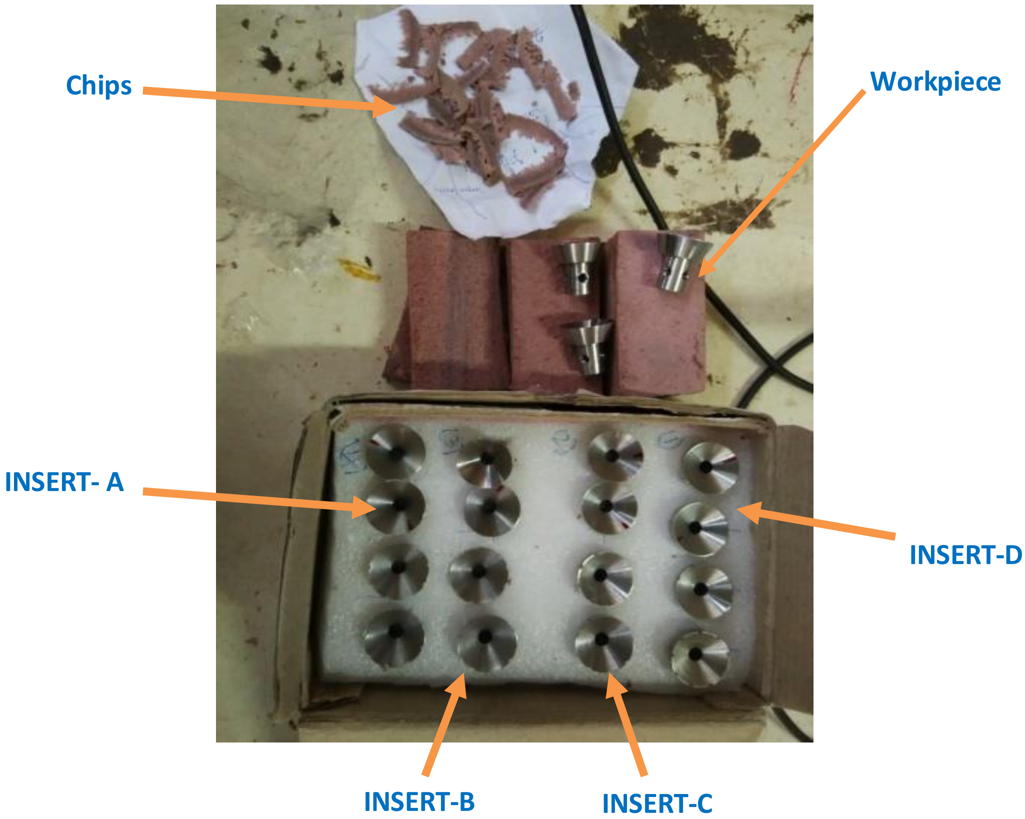


Fig 4.15: Cutting inserts (4 sets)

Table 4.5: Rake and Relief angles on inserts

Name of insert	Rake (Deg)	Relief (Deg)
Insert-A	40	20
Insert-B	45	15
Insert-C	50	10
Insert-D	55	5

e) Cutting force dynamometer

A four component piezoelectric dynamometer, Kistler Type 9272, is used to measure cutting forces. The multi component dynamometer provides dynamic and quasi-static measurement of the 3 orthogonal components of force (feed force Fx, cutting force Fy and axial force Fz) acting from any direction onto the top plate and also moment Mz.

4.6.2 Experimental strategy and Selection of machining parameters

Since the machining parameters are not present in the literature for this work and tool material combination, three important variables of the operating conditions for the multipoint cutting tool are to be studied and adjusted. These are cutting speed, feed per cutting edge and depth of cut as there is no coolant application for this specific case. Of these, the feed is the most important and should be established first [92-95].

It has long been demonstrated that it is more efficient to remove metal in the form of thick chips than in thin ones, so the maximum possible feed per tooth should be used. The maximum feed per tooth is limited by the following factors (i) Cutting edge strength (ii) Rigidity and allowable deflection, (iii) The surface finish required (iv) Tool chip space and (v) The machine capacity. The feed cannot be increased without limit because some point will be reached at which either the tool or the machine will be overloaded. As the feed increases, the cutting force increases presenting a source of fire hazard. The surface finish produced on the work piece usually deteriorates as the feed is increased.

In peripheral milling, the actual chip thickness is affected by the depth of cut. Maximum undeformed chip thickness equal to the feed per tooth is obtained when the width of cut equal to the feed per tooth and width of cut equals to half of the cutter diameter. In the extreme case of peripheral milling, with a shallow width of cut, the undeformed chip thickness may be so low that there is no chip load, which causes the tool to burnish or work harden the material in case of metal but rubbing and heating up the surface in case of the CSP rather than cutting. To prevent this on these shallow cuts, feed rates of three to four times the normal should be used. Since the contouring cutter perform both the side and face milling operations while contouring, theoretical estimation of these operating parameters is difficult, hence attempted to evaluate it by experiments. The obtained parameters will be applied in the machining experiments for deciding the selection of insert.

The rate of feed should likewise be the lowest consistent with safety and efficiency, based on the explosive materials being machined. After maximum allowable feed has been established, the cutting speed should be considered. In the normal operating range, speed has relatively little effect on surface finish, but sometimes a large increase of speed will yield an improvement in surface finish by increasing the temperature such that the work piece is softened, resulting in less tearing. Since heating the work material locally by this practice is not advised for CSP materials. Limiting the Speed not exceeding 500 rpm, the feed at which experiments to be conducted is obtained as follows.

4.6.2.1 Fraction factorial designs of experiments using Minitab software

Factorial design in engineering is used for design the experiments to study the effects of several factors on a response. When conducting an experiment, varying the levels of all factors instead of one at a time, it enables to study the interactions between the factors.

As enough resources to run a Full Fraction Factorial (FFF) design were not available, fraction of the total number of treatments called fraction factorial design of experiments were conducted. Considering the process limitations on parameter imposed by machine capacity, work material and safety, the entire available design space of speed and feed (Range of values over which factors are to be varied) is divided equally into two, the lower half and upper half.

Table 4.6: Bifurcation of complete range of machining parameters

Complete parameter range on machine		
Speed : 100 – 710 rpm	Feed: 160 -800 mm/min	DoC: 1.5 -2.5 mm
	Lower half range (Exp-1)	**Upper half range (Exp-2)**
Speed (rpm)	100 - 355	500 -710
Feed (mm/min)	160 - 300	400 - 800
DoC (mm)	1.5 – 2.5	2.5

The maximum limit of speed is restricted to 710 rpm which is upper limit of machine and entire range of feed rate available in machine is divided in to two halves as shown in Table 4.6 Effects in the lower half range of operating parameters were analyzed in experiment-1, subsequent experiments were conducted to check the effects in upper half range at constant depth of cut of 2.5mm

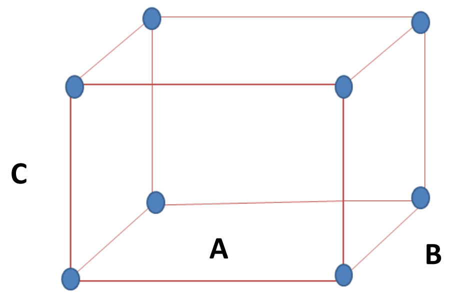
The speed range beyond 500 rpm is not advised as per safety manuals of propellant processing, hence speed range just beyond this was chosen as highest limit to check the performance as the work material being used for this preliminary trials are non - reactive and safe

4.6.2.2 Half Fractional factorial designs

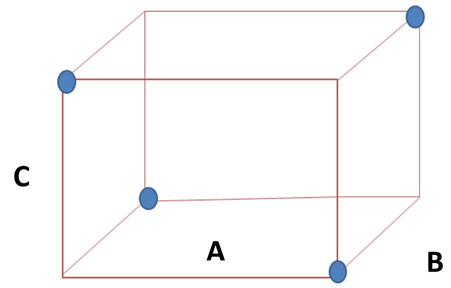
A fractional design is a design in which experimenters conduct only a selected subset or fraction of the runs in the full factorial design. Fractional factorial designs are a good choice when resources are limited or the number of factors in the design is large because they use fewer runs than the full factorial designs.

A fractional factorial design uses a subset of a full factorial design, so some of the main effects and 2-way interactions are confounded and cannot be separated from the effects of other higher-order interactions. Usually experimenters are willing to assume the higher-order effects were negligible in order to achieve information about main effects and low-order interactions with fewer runs. In the following plots, each point represents a unique combination of factor levels for full and half fraction factorial design.

The full factorial design contains twice as many design points as the half fraction design. The response is only measured at four of the possible eight corner points of the factorial portion of the design. However, with this design, the main effects will be confounded with the 2-way interactions. The following Fig 4.16 (a) shows a FFF design versus a HFF design presented in Fig 4.16 (b).



(a) Full factorial design



(b) Half fraction factorial design

Fig. 4.16: Design space of factorial design in DOE

In DoE with HFF and 3 factors 2^{3-1} run or 4 treatments instead of 8 in full factorial , hence the design known as a '½ replicate' or 'half replicate'. A factorial design with centre points, it can test non-linearity in the response surface. However, it cannot model the effect of that curvature anywhere but at the centre point. In other words, it can be said that only calculate the fitted values at the corner points and the centre point of the design, thus cannot create a contour plot. Including centre line repetition and HFF-DoE runs each randomized and repeated, total of 10 runs were conducted in the present study. The run sequence of the HFF with central composition is shown in the Table 4.7

Table: 4.7 DOE, Half fraction factorial experimental list

Exp	**A-Speed (rpm)**	**B-Feed (mm/min)**	**C-DoC (mm)**
1	1	-1	-1
2	0	0	0
3	1	1	1
4	-1	-1	1
5	1	-1	-1
6	0	0	0
7	-1	1	-1
8	-1	1	-1
9	1	1	1
10	-1	-1	1

4.6.3 Results and discussion

Results of experiments are presented as follows

a) Half Fraction Factorial Experiment results in lower half range (Exp-1)

First set of experiments were conducted are conducted to identify the cutting parameters for stable cutting forces based on Half Fraction Factorial (HFF) DoE with center point treatment. Experiments are conducted with three levels as shown in the Table 4.8 in the lower half of the selected range as presented in the Table 4.6 HFF results obtained for cutting forces in all the three directions as summarized in the Table 4.9.

Table 4.8: Level tables (Lower half range) for selection of operating parameters

Level	A (Speed) rpm	B(Feed) mm/min	C(Depth of cut) mm
-1	100	160	1. 5
0	240	250	2
1	355	300	2. 5

Table 4.9: DOE, Experimental results (Experiment 1)

Run	A-Speed (rpm)	B-Feed (mm/min)	C-DoC (mm)	Fx (N)	Fy (N)	Fz (N)
1	355	160	1.5	-51. 91	87. 95	74. 28
2	240	250	2	-63. 96	145. 5	123. 7
3	355	300	2.5	-52. 31	92. 41	65. 25
4	100	160	2.5	-46. 26	106	106
5	355	160	1.5	-47. 79	101. 6	71. 84
6	240	250	2	-72. 63	110. 2	100. 3
7	100	300	1.5	-72. 36	104. 7	146. 3
8	100	300	1.5	-65. 7	115. 2	164. 7
9	355	300	.5	-80. 69	146	127. 4
10	100	160	2.5	-65. 37	103. 2	140. 2

b) Analysis of cutting force

The plots generated from the experimental study were analysed to find the peak value of cutting force of run1/round1 are as shown in below Fig.4.17. Procedure to find out the peak cutting force is repeated for each experiment run using MATLAB. Peak value of cutting force shown in Fig. 4.18 was considered as it is the concern of study because minimum cutting force is key performance characteristic of cutter design for safe machining operations. The Average value of cutting force does not give significant variation for CSP as the change is gradual unlike sudden fall and spikes in metal cutting which can be compared through Fig.4.19 and Fig.4.20.

Only one insert is fixed to the face milling cutter. The feed rate given is used to calculate feed per tooth and that value is given as feed/rev in the experiment. Depth of cut was taken in the range for reasonable MRR. Trial experiments were conducted to determine the stable speed range.

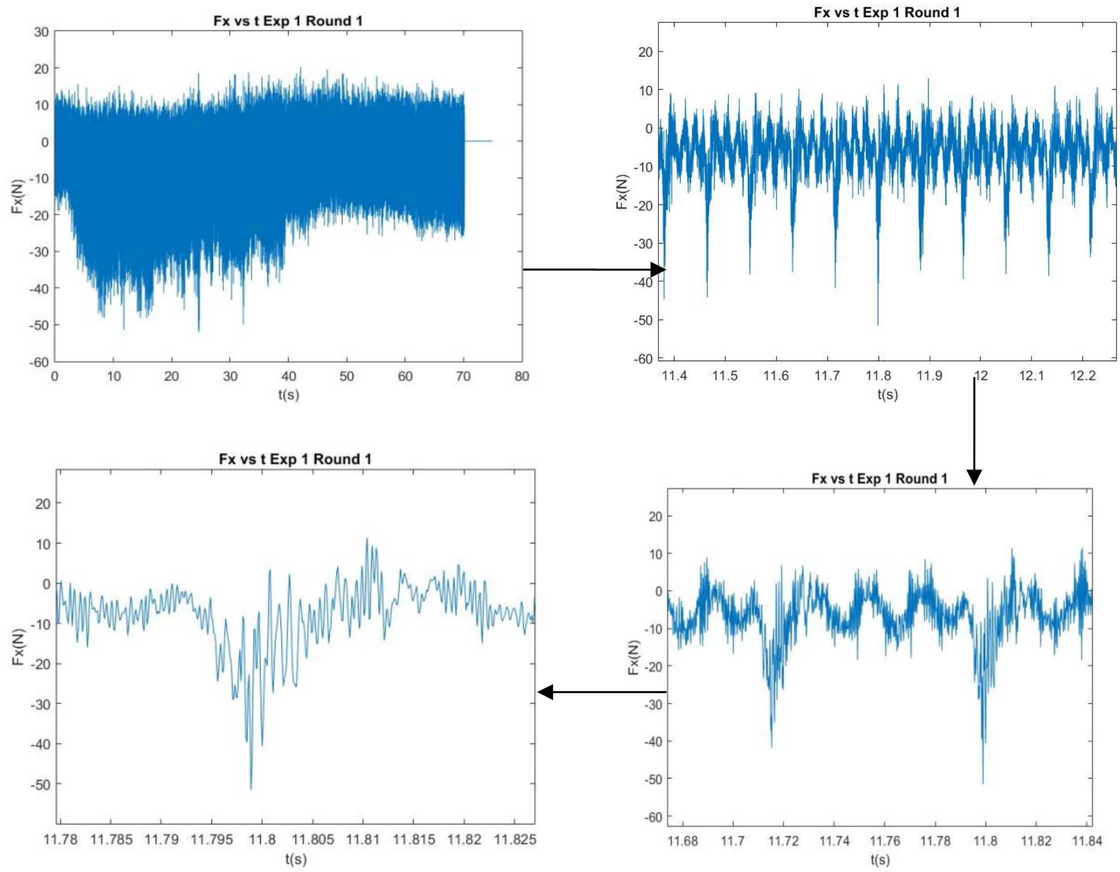


Fig.4.17: Study of cutting force at 355 rpm speed,160 mm/min feed and 1.5 mm DoC

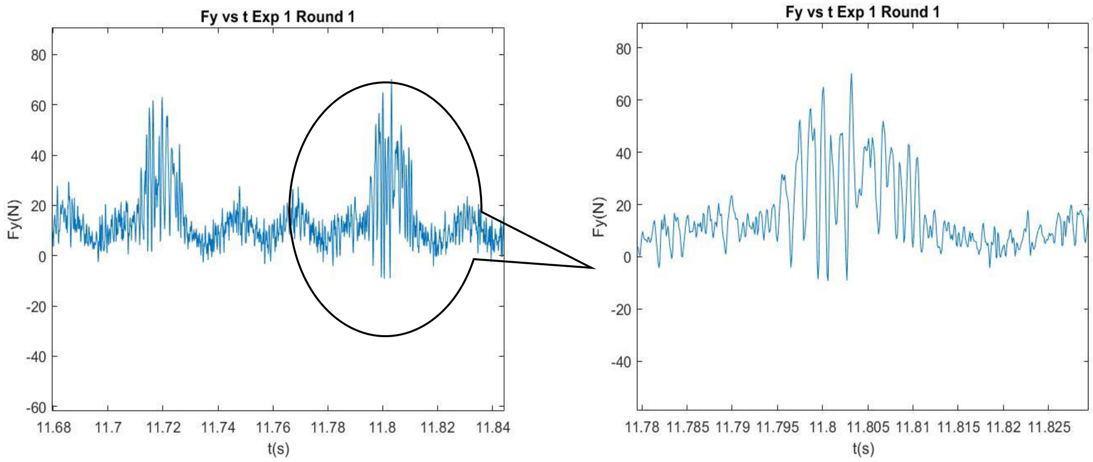


Fig.4.18: Peak value of cuting force

Cutting force plots obtained from dynamometer while machining the CSP material were compared with cutting force plots of metals [92] as shown in Fig. 4.19. The important observations while machining CSP material were relatively small cutting forces, no sharp and clear point of change in cutting forces and change in the cutting force is gradual. Cutting force plots of CSP are shown in Fig.4.20 in all the three directions

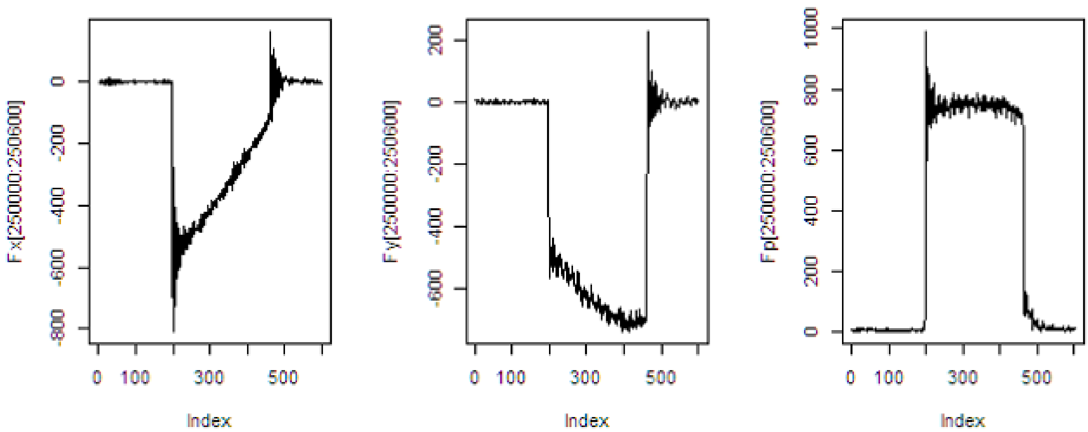


Fig.4.19: Cutting force plots of metals with face milling cutter

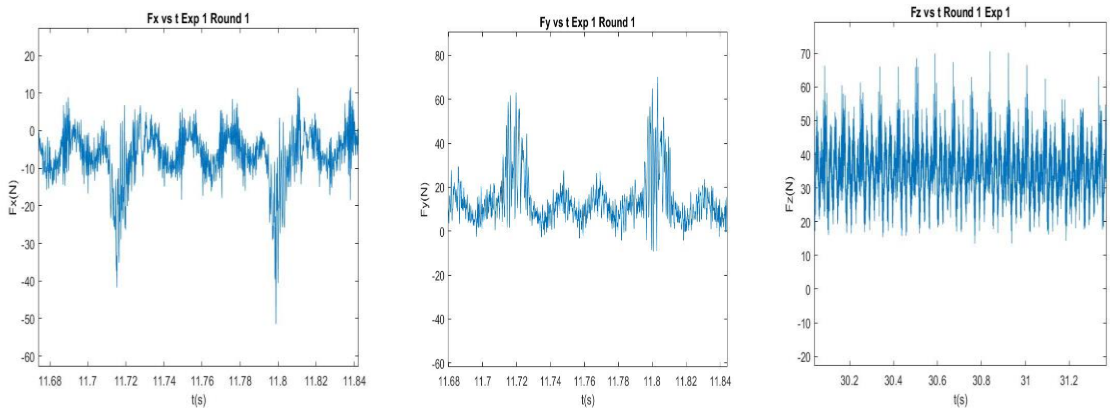
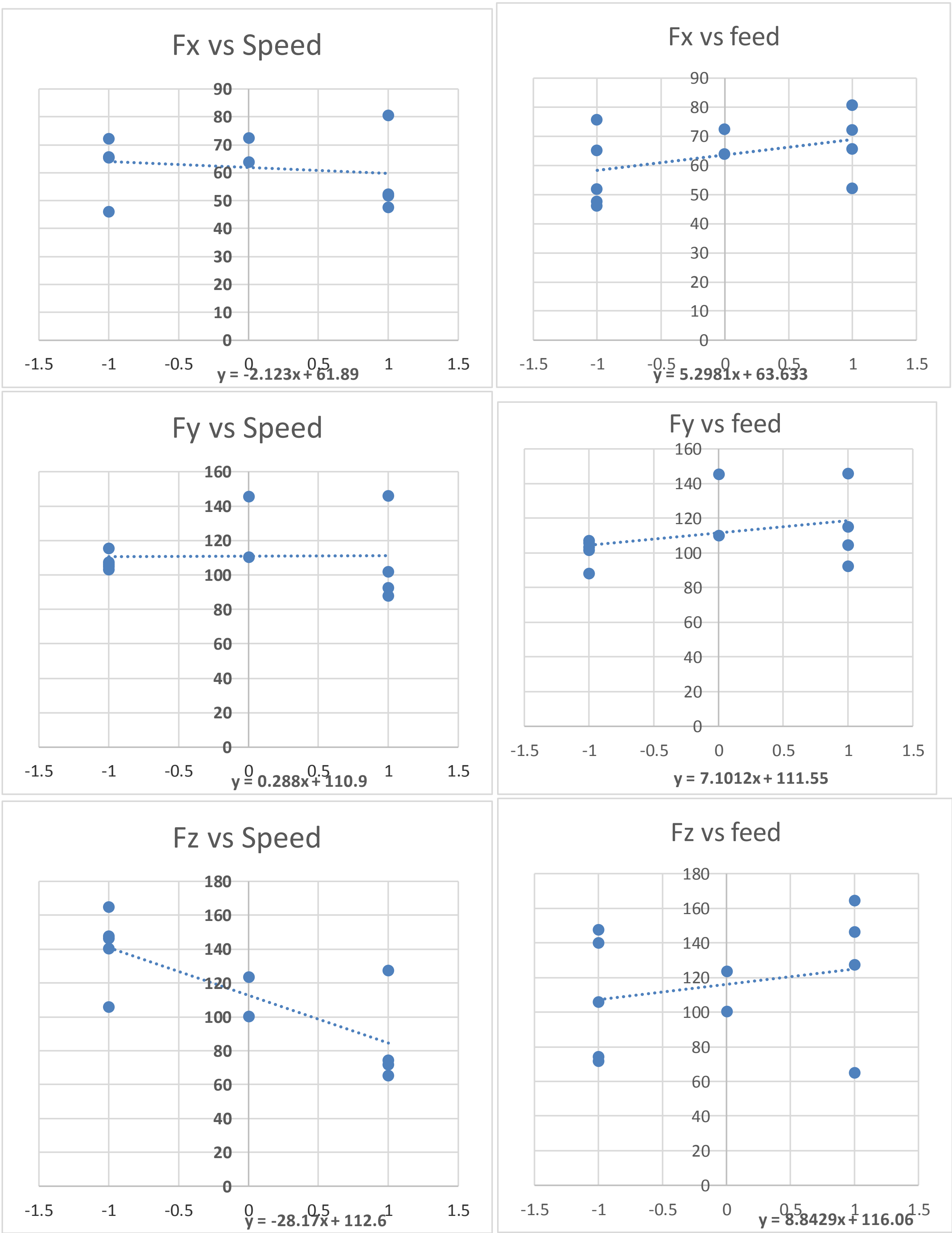


Fig.4.20: Cutting force plots of CSP material with prototype tool in Fx,Fy and Fz direction



a) Speed effect on cutting force *b) Feed effect on cutting force*

Fig.4.21: Speed and feed effects on Cutting force

Fig .4.21 indicates, cutting speed Vs. Cutting force and Table feed Vs. Cutting forces while machining in upper half range. The order of magnitude of cutting force irrespective of levels is $F_z > F_y > F_x$. The slope of speed Vs. Force in all direction gradually decreases. The slope of feed Vs. Force in all direction gradually increases. The trend is similar to metals because the work material is high solid filled composite.

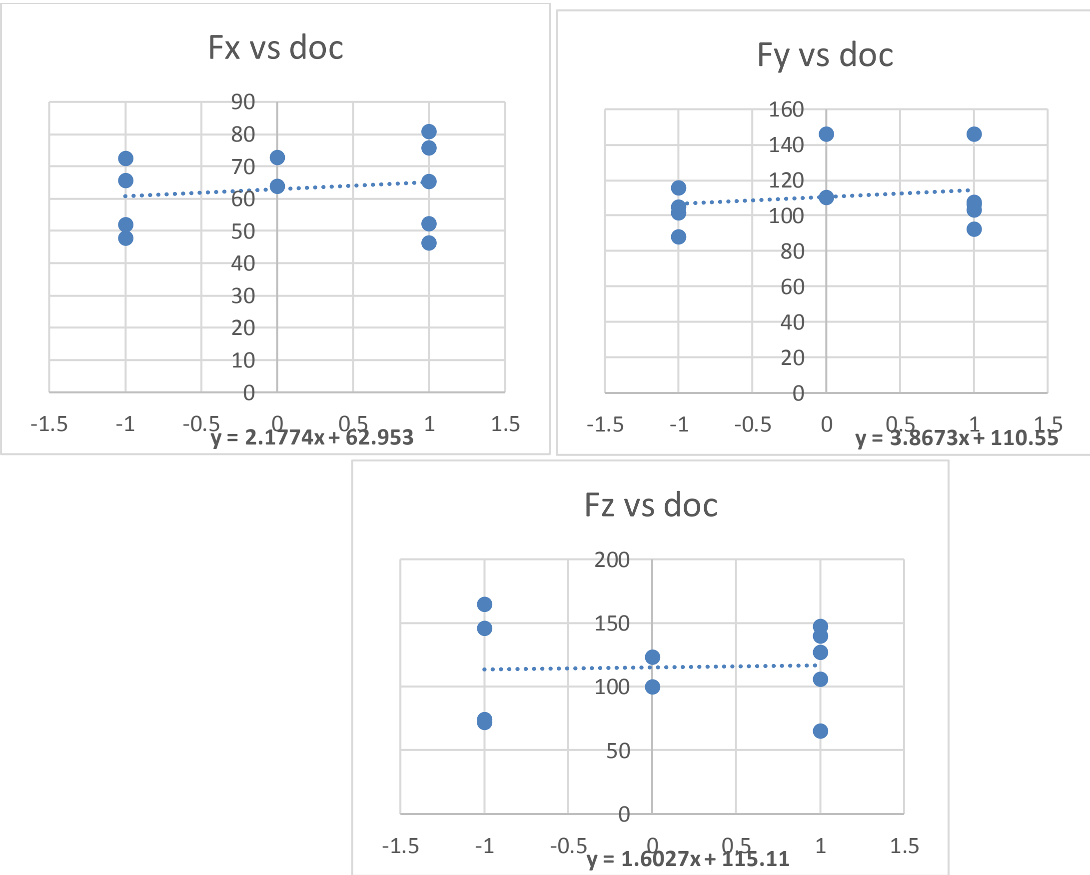


Fig 4.22: Depth of cut effects on cutting force

It can be seen from the Fig 4.22 that the depth of cut does not have significant influence on cutting force and slope of plot was marginally small. Since the main effect of depth of cut on cutting force is not found significant in the experiment-1 (lower half range of cutting parameters) so it is kept constant at maximum value of 2.5 mm for all subsequent runs in experiments-2 when operating in upper half range of parameters.

c) Half Fraction Factorial Experiment results in upper half range (Exp-2)

Keeping the DOC constant at maximum value of 2.5 mm, machining experiments are conducted to identify the cutting parameters for stable cutting forces based on Half Fraction Factorial (HFF) DoE with centre point treatment. Experiments are conducted with three levels as shown in the Table 4.10 in the upper half of the selected range as presented in the Table 4.6. HFF results obtained for cutting forces in all the three directions as summarized in the Table 4.11.

Table 4.10: Level tables (upper half range) for selection of operating parameter

Level	A -Speed (rpm)	B-Feed (mm/min)	C-Depth of cut (mm)
-1	500	400	2. 5
0	640	600	2. 5
1	710	800	2. 5

Table 4.11: DOE, Experimental results (Experiment 2)

Exp	A-Speed (rpm)	B-Feed (mm/min)	C-DoC (mm)	Fx (N)	Fy (N)	Fz (N)
1	640	600	2. 5	-86.24	221.8	255.9
2	710	400	2. 5	-59.6	167	108.3
3	500	400	2. 5	-63.93	140.3	110.5
4	500	400	2. 5	-95.7	163.1	137.6
5	500	800	2. 5	-80.75	125.8	117.2
6	500	800	2. 5	-143.1	275.4	202.5
7	710	800	2. 5	-123.5	226.4	217.4
8	710	800	2. 5	-145.7	209.2	347.8
9	640	600	2. 5	-143.8	255	262.4
10	710	400	2. 5	-71.47	191.6	237.5

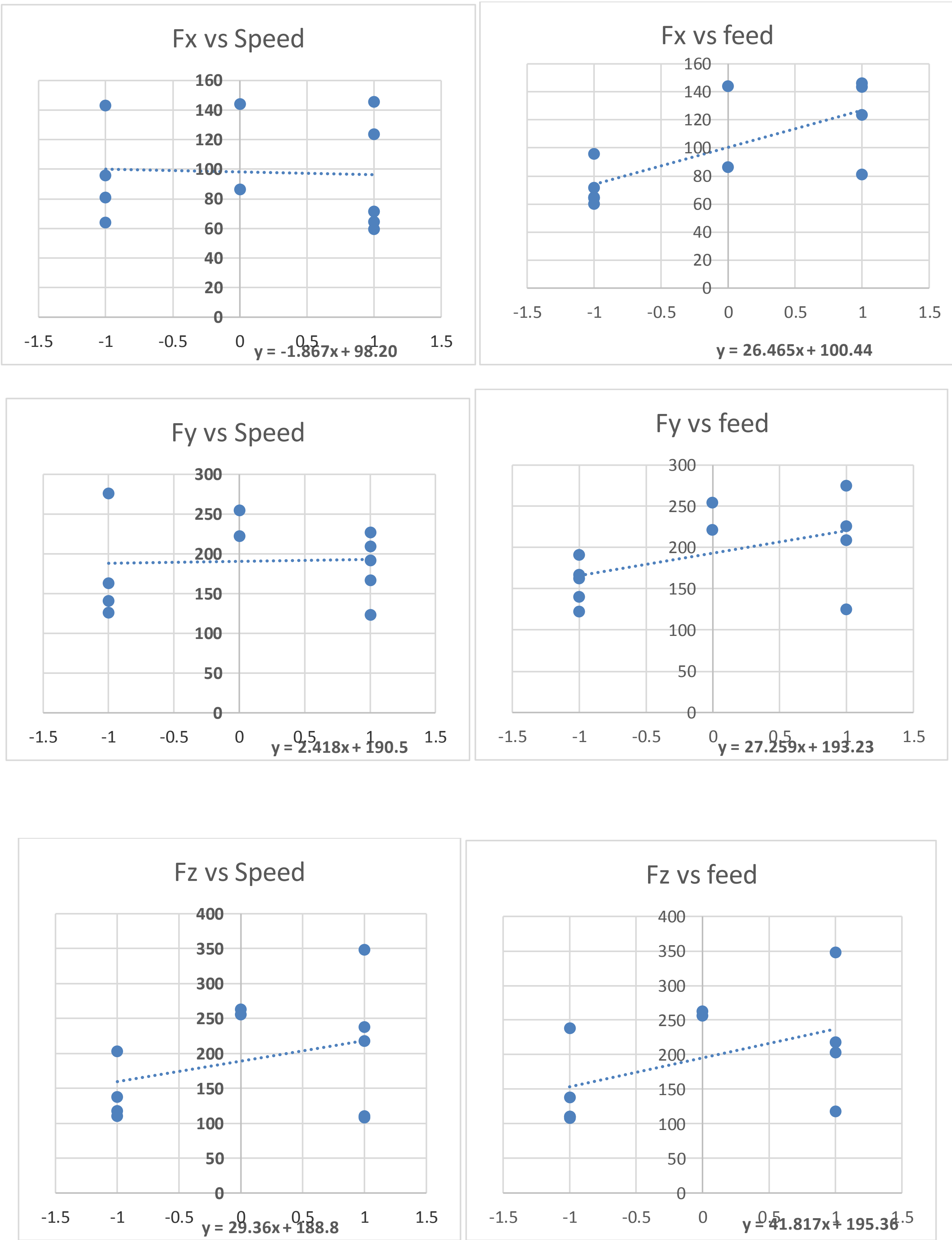


Fig 4.23: Speed and Feed effects on Cutting force at constant DoC (Exp-2)

Observations

From the plots reslted in two experiments based on HFF DoE, following are the observations. Slope of speed versus cutting force were plotted as shown in Fig 4.21 and 4.23, indicating that an increase in speed caused decrease in cutting force till the speed raised up to 500 rpm, beyond which force increasing rapidly. The order of magnitude of cutting force w. r. t speed is $F_z > F_y > F_x$. Higher the speed, larger will be MRR, but the observation indicated a speed of 500 rpm is breakeven point and beyond with cutting force increase is drastic , hence this is choosed as speed for stable cutting force and the same is complied with safety limit as discussed in earlier chapter.

Feed versus cutting force plots showed the same trend in all the plots of experiments-1 and 2 as shown in Fig 4.21 and 4.23 indicating, with an increase in feed rate the cutting force was increased at gradual rate in the lower half range, and at drastic rate in upper half range of parameters. It is also found from the Fig.4.21 and 4.23 the cutting force is lowest at lowest feed rate in first lower half range. Cutting force F_z is Maximum in magnitude in all the experiments. Hence lowest feed rate of 160 mm/min was fixed. Considering maximum MRR, DoC is fixed at highest value .

Conclusions from Experiment 1 and 2

Considering the Maximum MRR, machine capability, size of prototype cutter and complying condition of safety guidelines for machining explosive materials. The following are the conclusions drawn from the experiments

- Maximum speed up to which cutting force follows regular and stable trend were chosen and it was 500 rpm (First level of Esp-2).
- Feed rate of lowest value in lower half of the selected range, i. e., 160 mm/min was fixed based on minimum cutting forces that is observed in entire set experiments (First level of Esp-1)
- Depth of 2.5 mm is picked for Max MRR based on its insignificance effect on cutting force as observed in experiment 1 itself.

Hence these machining parameter values are used to determine the best tool geometry among the conceived 4 sets of inserts as follows

4. 7 Experiments for selection of insert

Experiments to select the rake and relief combination for minimum cutting forces were carried out at the operating parameters that were fixed from previous experiments (Speed= 500 rpm

Feed= 160 mm/min, Depth of cut= 2.5mm). Experiments were conducted in randomized and repeated runs as shown Table 4.8 to minimize errors.

Table: 4.12 cutting force components for different inserts

Exp	Insert	Fx (N)	Fy (N)	Fz (N)
1	C	-73. 94	122	114. 1
2	**B**	**-56. 03**	**83. 53**	**103. 3**
3	**B**	**-58. 31**	**83. 01**	**102. 8**
4	A	-71. 38	108. 2	120. 4
5	D	-59. 36	112. 6	116. 32
6	A	-62. 07	118. 6	164. 3
7	C	-67. 38	123. 7	116. 8
8	D	-58. 35	108. 3	118. 9

Observation

Positive rake angle increases the cutting performance of the tool by decreasing cutting force, work piece deflection. It also makes the edge sharper and weak [99].Large relief angles avoid the rubbing of machined surface with flank of the tool, but strength of cutting edge reduced. A combined increase of both rake and relief angles ensure sharp and keen cutting edge for minimum cutting force but strength of cutting edge is decreased.

HTPB composite materials with polymer binder possess relatively low strength and hardness in comparison with metal, seeking a keen cutting edge but not much stronger cutting edge. For given strength of work material under study and its hardness, the wedge angle of 30° is considered sufficient.

From the experimental results it was found that all the three force components (F_x, F_y and F_z) were lowest for Insert-B with 45° rake and 15° relief angle as shown in Table 4.12. Cutting force analysis for its peak value in each run of experiment was continued as per the procedure shown in Fig 4.17 and 4.18.

Conclusions for selection of inserts

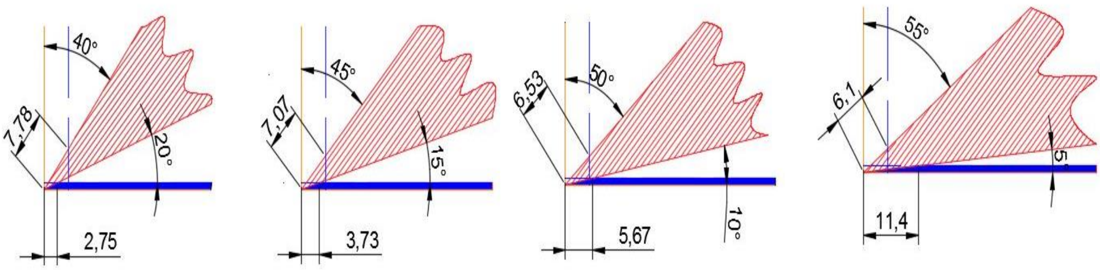
From the experimental studies insert with rake angle 45° and relief angle 15° was best for low cutting forces and will form the main elements in the signature of tool. It is well explained from the Fig.4.24, with an assumption of 1mm dilation and 5mm penetration of wedge into the work material, it is clear theoretically that the Insert-A followed by Insert-B have low Chip equivalent values than C and D (Chip equivalent is the ratio between engaged cutting edge length and area of chip produced). Among Insert-A and Insert-B the chip equivalent is marginally lowest with Insert

-A. But among these two, Low cutting force with Insert-B was found from this experiment. Chip equivalent and unique material properties of CSP were reasoned for this result.

It is observed from the material studies as discussed in previous chapter as well as present cutting trials that propellant damage was mainly in the forms of particle rupture, matrix tearing, and the extended porosity. The greater the impact energy, the more serious the damage [75].

HTPB Propellant material when subjected to local compression and large strain rate near the cutting edge during cutting, polymer may become soft and interactions between the polymer and filler (oxidizer and metal component) fails forming separation around a particle of filler and CSP exhibit dilation and dewetting phenomenon. The combined effect of dilation and dewetting increase the bulk volume of the work material in the cutting zone, both at machined and unmachined surface. This increase in volume of material behind the cutting edge making the flank of the tool in continuous contact with machined surface of work material causing excessive rubbing as shown in Fig. 4.24resulting high cutting forces with reduced relief angle.

Hence the experimental results with low relief angle show relatively large cutting forces. If the clearance between machined surface of work material and flank of cutting tool is sufficient to avoid the excessive rubbing, further increase of relief angle will not have much influence on cutting force which is evidenced in the experimental results. Smaller the chip equivalent, Larger will be the cutting force. This is the reason why Insert-B yield low cutting force than Insert-A.



A (10. 53mm) B (10. 8mm) C (12. 2mm) D (17. 5mm)

Fig.4.24: Interaction of Face and Flank of cutting tool with work material (CSP)

Provision of large relief angles will ensure the clearance between flank face and swelled machined surface lower the resulting cutting forces [94].The large relief angle is also favourable to avoid the inadvertent rubbing and subsequent friction on work material which should be avoided on safety reasons for this HTPB based composites.

4. 8. Summary &Conclusions

a) Design specification of the cutter arrived for safe machining of CSP material is as follows.

Insert signature

Parameter	Value
Axial Rake angle	45°
Radial Rake angle	45°
Face Relief angle	15°
Peripheral Relief angle	15°
Nose radius	0. 2mm
Approach angle	90°
Material	M2 grade HSS material with HRC 65 as per IS designation IS: 7291-1974
Size and shape	**Ø** 52mm and round shape
Type	Cartridge and Indexable
Features	Through flow chip extraction and Indexing

Design details of Cutter

Shape and size	Disk shape/ **Ø** 196 mm x 40mm thickness
Purpose and application	Contouring
Type	Cartridge
Clamping	Pin for Indexing and Bush with stud for clamping
Cutter density	4 HSS inserts
Material	Aluminium alloy: Al 6351
Features	Through flow chip extraction, Large chip room, Light weight and versatile application

b) Conclusions from machining trails

- Among all the three components the values of cutting forces, $F_z > F_y > F_x$ for all the inserts irrespective of tool signature. The maximum value of cutting forces observed among all the experiments is not more than 200N (F_z) in applied operating range
- It is observed that all the three force components are lowest for Insert B with tool signature 45° Rake and 15° Relief and nose radius of 0. 2mm.
- Dilation of work material and chip equivalent are the two factors that contribute for the reason of low cutting force with Insert-B. The large relief angle is also favourable to avoid the inadvertent rubbing of insert flank with finished work materials which is key factor behind the phenomenon of dilating and dewetting of CSP material.

The prototype cutter and the experimental strategy were developed for machining 'Hazard to machine' materials in this chapter. These strategies developed will be implemented for the development of final cutter assembly. In the next chapter, experiments will be conducted for the evaluation of safe and effective machining parameters with the final cutter assembly, keeping the machining parameters evolved in the present chapter as baseline. The actual machine set-up will be equipped with the safety systems to mitigate all the sources of risk associated in machining 'Hazard to machine' materials.

5. 1 Introduction

It is widely accepted by manufacturing engineers that tool geometry, combination of workpiece-tool materials, machine tool, process parameters and coolant application are major influencing factors of machining performance. To design custom-build cutting tool for machining of composite propellant material as work material using special purpose machine tool (CNC-VTM), there is no single, well-defined and established design method. Application of tool, work and tool material combination, safety aspects, MRR, geometry to be produced, quantity of material to be removed are the major design factors considered for designing a custom-build cutter in the present study.

The major design inputs and aspects considered for design and development of custom-build Turbine cutter are summarized as follows. Tool signature values that were concluded on prototype cutter as discussed in previous chapter are considered for implementation in the final cutter assembly.

a) Insert geometry to meet versatile machining operations.
b) Cutter geometry for Maximum MRR
c) Cutter body structure to provide the ample space for chip room and passages for chip evacuation through cutter body
d) Minimum components in comprehensive cutter assembly
e) Positive and firm clamping of cutting element
f) Insertsize to provide sufficient space for chips flow
g) Insert shape to form the mouth of vacuum line for instantaneous chip evacuation
h) Minimum or no modifications to the existing SP VTM machine tool
i) Provision for slicing of chips in the insert
j) Trade-off between tool strength and effective signatures
k) Geometrical symmetry to avoid rotational imbalances and
l) Suitable arbor to access deep slots for machining and chip passage

In order to identify the influence of process parameters such as cutting speed, feed and DoC which are key parameters for safe and effective machining, full factorial experiments were conducted on live propellant material using the developed actual 'Turbine cutter'. The present work also focused to study the effect of process parameters on cutting power, and MRR using DOE, ANOVA and Response Surface Methodology (RSM). The safe and effective cutting parameters were established for machining CSP materials for custom build Turbine cutter. Multi-objective optimization for low cutting power and high MRR using RSM was carried out to find out optimum process parameters [104]. Subsequently formulation of regression models for cutting force and MRR is done for this new tool and work material combination, which is much useful for understanding the machining process of CSP material.

5. 2 Analysis of cutting element and improvement of the prototype cutter

Keeping the shape and geometry of the prototype cutter unaltered, the diameter of cutter was increased to Ø520mm considering the groove radial depth, chip room space in the cutter body, maximum MRR and quantity of material to be removed. Cutter size was determined for given size of work (grain), having web thickness around 850mm. Size of cutter should enough to cover the entire width of work surface in not more than two pass. Accordingly increase in the size of insert resulted to Ø60mm instead of Ø52 mm of prototype cutter. Nine chip slicer on each insert as shown in the Fig.5.1 were provided considering number of indexing cycles, strength of cutting edge, and chip size to be produced. The positional orientation of round insert can be adjusted by indexing it about its own axis and maximum of four indexing cycles ensured with each insert shown in Fig. 5.1with the help of indexing cum locating holes.

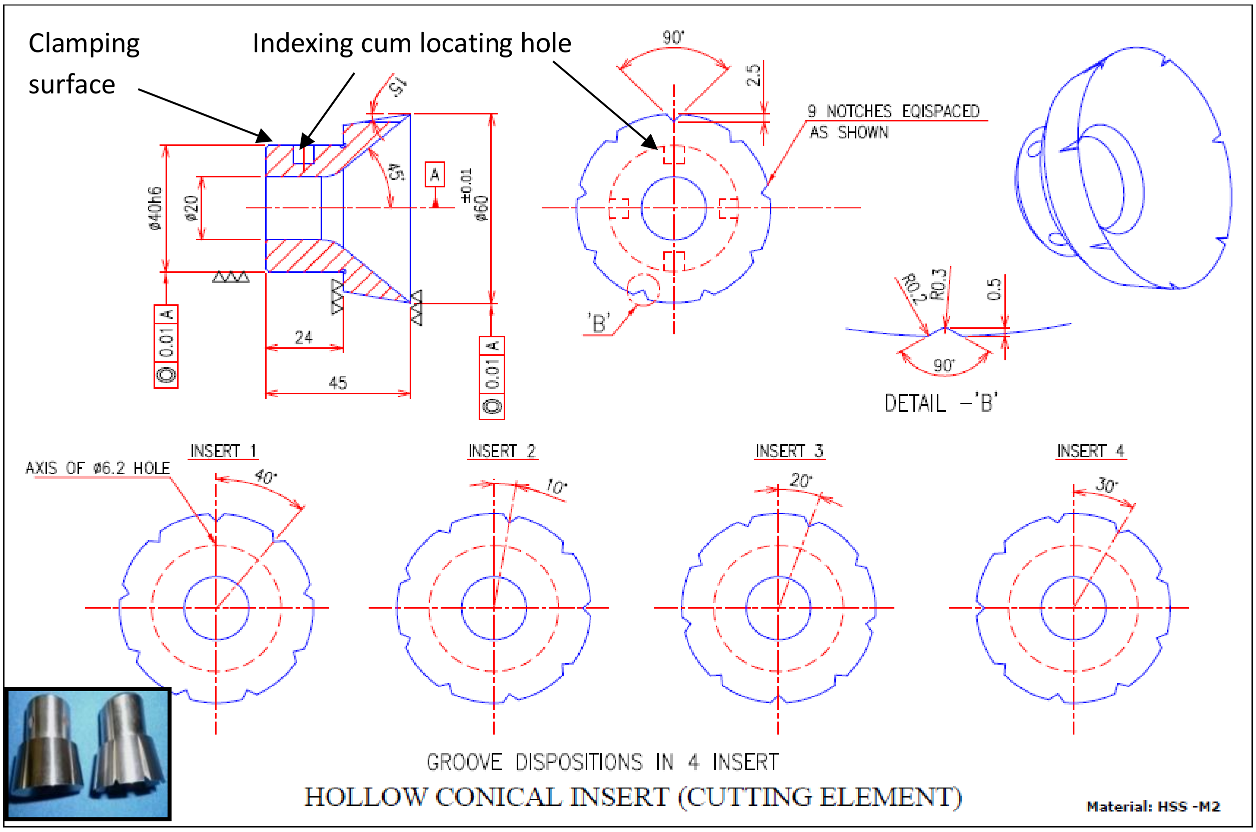


Fig.5.1: Indexing cum locating holes on the insert clamping surface

The number of indexing cycles are limited by the segment area of round insert that comes in engagement with work material at maximum depth of cut. Orientation of chip slicer with respect to first indexing hole on each insert for staggering of chip slicer is also presented in Fig.5.1 as development drawing.

The round insert cutter has a continuously variable entering angle, from zero upwards to 90 degrees, depending upon the cutting depth as shown in Fig.5.2. The round insert provides very strong cutting edge, suitable for high table feed rates (as this is favourable condition for effective machining with the existing CNC VTM machine having large feed rate range), because of the thinner chip generated along the long cutting edge as illustrated in Fig.5.3. This chip thinning effect [91] is favourable for machining CSP material with low cutting force. The change in cutting force direction along the insert radius and the resulting pressure during the cutting will depend upon the depth of cut as illustrated in Fig.5.2. Round insert geometry have made the milling cutters, more widely suitable because of the smoother cutting action, requiring less power and stability from the machine tool. Such cutters were regarded as an efficient roughing cutter, capable of high material removal rates for bulk volume of material to be cut which is requirement in present cuter. Indexing of the insert for replenishment of worn out, with fresh cutting edge shall be ensured with respect to first indexing hole. Indexing of all the four insert to maintain staggered orientation of chip slicer even at least one cutting edge/insert require replacement, for every tool change cycle shall be ensured.

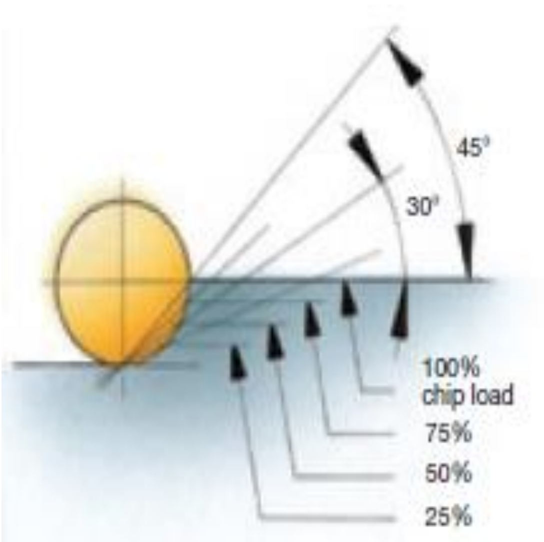


Fig.5.2: Variation of chip loading and entering angle with Depth of cut [91]

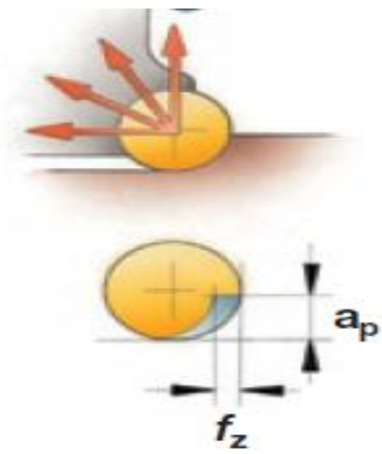


Fig.5.3: Chip thinning effect of round insert [91]

5. 2. 1 Chip slicer:

The number of cutting elements in the multipoint cutter provides multiple entry point passages for the machined chips & powder produced during the machining operation and the chips should be safely evacuated through inner passage and exit center hole of the cutting tool. Due to polymer characteristic of work material wider continuous ribbon like wide chips were produced at moderated DoC, choking chip passage at the suction entry i.e., at central hole of insert when vacuum is applied. To dispose the chips instantly and effectively form the cutting zone, chip slicers are provided on the insert cutting edge to slice the chip in width direction unlike chip breakers on rake face. The chip slicer is discontinuity in cutting edge to slice the width of chip into two and is notch shape in present application. Wider chips were formed because the circular geometry insert cutting edge engagement length is significant even at moderate depth of cut. Long ribbon like chips with minimum width will enable the smooth passage of chips through insert center hole as size of chip become smaller than the diameter of the insert suction hole with slicing effect. To avoid chocking of cutter, slicing of chip is done in width direction of chip unlike in length direction as chip breaker terminology because the chip breaker principles become ineffective due to soft and rubber like physical behavior of polymer work material.

To ensure effective cutting action on propellant material and to prevent the friction between rake face and propellant chips, the rake face of the tool is ground positively more than the corresponding angles on regular tools being used for metal cutting. Similarly, to reduce the rubbing action and intern the friction between flank face and finished surface of propellant grain, the flank face is relieved to 15°. Balancing the cutting edge strength, minimum cutting force and to ensure smooth flow of chips over rake face, machining trials conducted on prototype cutter concluded with rake angle of 45°. The same value was implemented on the insert of final cutter assembly but the size of insert is increased to Ø60mm to suit with increased size of Turbine cutter maintaining the dynamic similarities of cutters. The orientation of the of 'V' shaped grooves on the circumference of the cutting edge is arranged such that in one complete revolution of cutter, the ridges left by chip slicer('V'groove) do not appear on machined surface of the propellant grain. The groove disposition in the insert with respect to locating hole and disk axis ensures staggering of chip slicers in the cutter as shown in Fig.5.4 and 5.5.

Insert is provided with central hole and suction hood shape through 45° rake for passage of chips, when connected to suction system through cutter body and of rotary joint of arbor. Chips enters the suction line from central hole of insert and start flow through passage of cutter body hollow arbor. The convergent angled geometry of rake face provides effective suction hood/mouth ensuring effective and instantaneous suction of chip and powder of work material from the cutting zone. The insert with 45° rake angle provides a convergent angle of 90°at chip entry providing most suitable hood shape for suction.

5. 2. 2 Staggering of chip slicer

Chip slicers on the insert are staggered as shown in Fig.5.5 and 5.6, in such a way that at any point of time of cutting, chip load is disturbed uniformly through all inserts to avoid large cutting forces due to excessive wider chip formation by round geometry. The staggering avoids formation excessive wider chip formation and ridges left by chip slicers. It is calculated that orientation of the chip slicer in each insert with reference to first indexing cum location hole on clamping surface of insert ensured staggering of chip slicers. It is clearly illustrated in Fig.5.5 and 5. 6 in the following section.

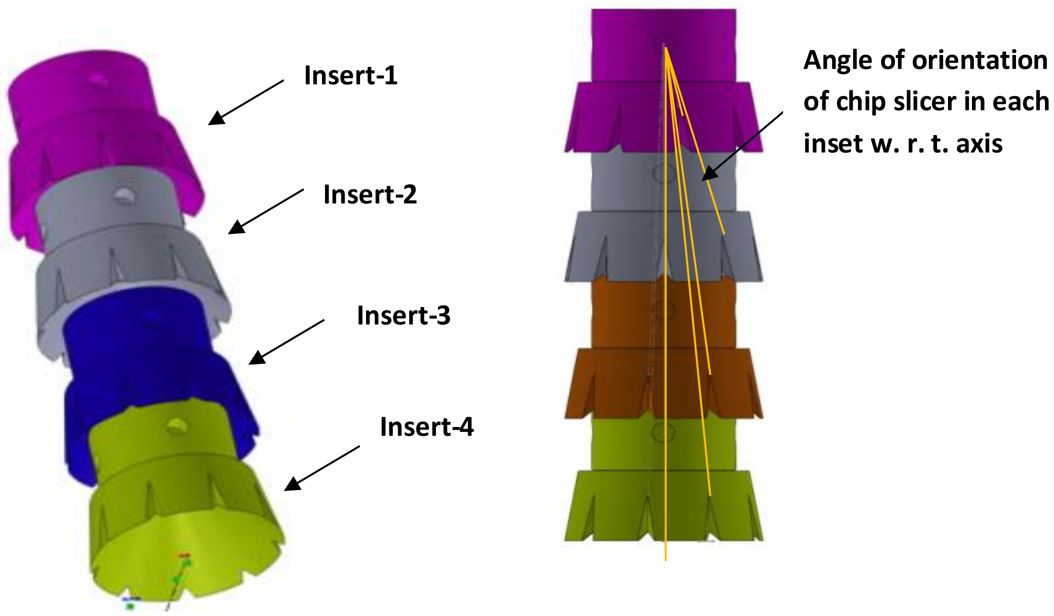


Fig.5.4: Orientation of chip slicer on each consecutive insert for staggering of chip slicer

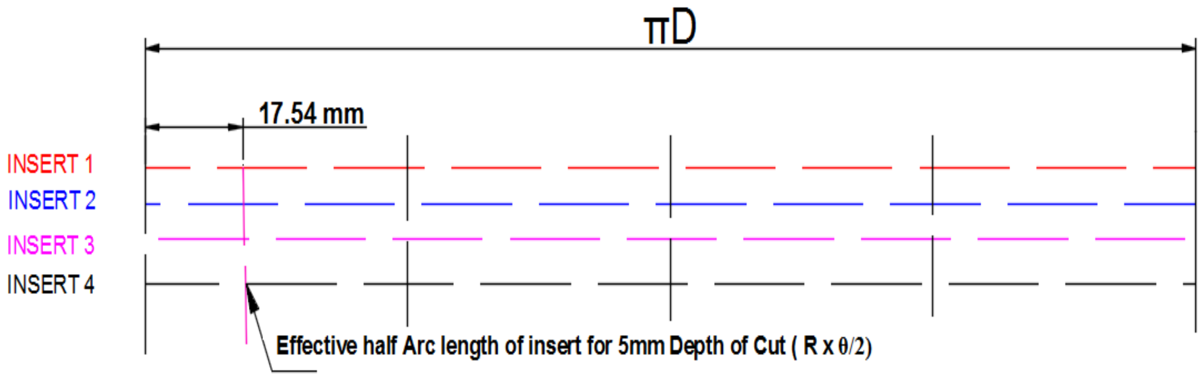


Fig.5.5: Development view of round cutting edge and misalignment of chip slicer groove to avoid formation of ridges (complete set of inserts)

5. 2. 3 Chip width analysis with implemented chip slicer

Since the vertical axis of insert in its side view as shown in Fig.5.6, if aligned with the center of any one chip slicer groove out of total nine chip slicer on the cutting edge, the arc length of cutting edge in engagement with the work material is calculated usingequation5.1. This length is equal to the width of chip to be produced, provided no side spread of chip. Since the total length of cutting edge of insert available for cutting is equal to circumference of the round insert, cutting edge length in engagement with work material at particular depth of cut is given by

Cutting edge length in contact with work material i.e. total width of chip can be calculated as

$$l = R \times \theta \quad \text{-----------------} \quad (5.\ 1)$$

Here θ= $(\theta^{\circ} X \frac{\pi}{180})$ and $\frac{\theta}{2} = cos^{-1}(\frac{R-d}{R})$, Now θ=2x $cos^{-1}(\frac{R-d}{R})$. Substituting these values in (1) we can obtain the value of‘$\frac{l}{2}$, because chip slicer groove symmetrical in position on contact arc about the axis.

Since *‘l’* depends on the depth of cut, and maximum depth of cut envisaged in the cutting trials, discussed in the next part of the chapter is varied not more than 5mm. Calculation is made for maximum width of the chip that generally produced at high depth of cut for assessing these chips effective evacuation through central hole of the insert due to the incorporation of chip slicer.

If depth of cut equal to 5 mm, then $\frac{l}{2}$ is equal to 17. 54 mm as calculated using the empirical relation shown in 5. 1 and it can be ascertained through the Fig.5.6. It is also understood the restriction on depth of cut with this developed round insert geometry is 5mm for effective chip disposal through the central hole of insert. In such case the width of chip with chip slicer will not exceed 17.55mm which can easily get the access to flow though Ø20mm central hole of round insert.

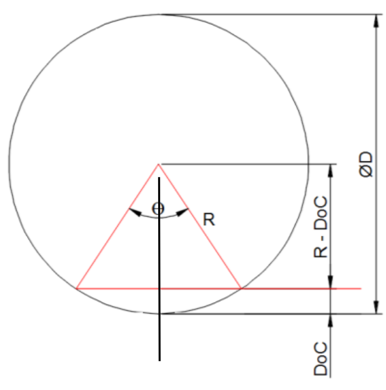


Fig.5.6: Development view of cutting edge circle to calculate the width of sliced chip

5.2.4 Indexing of insert

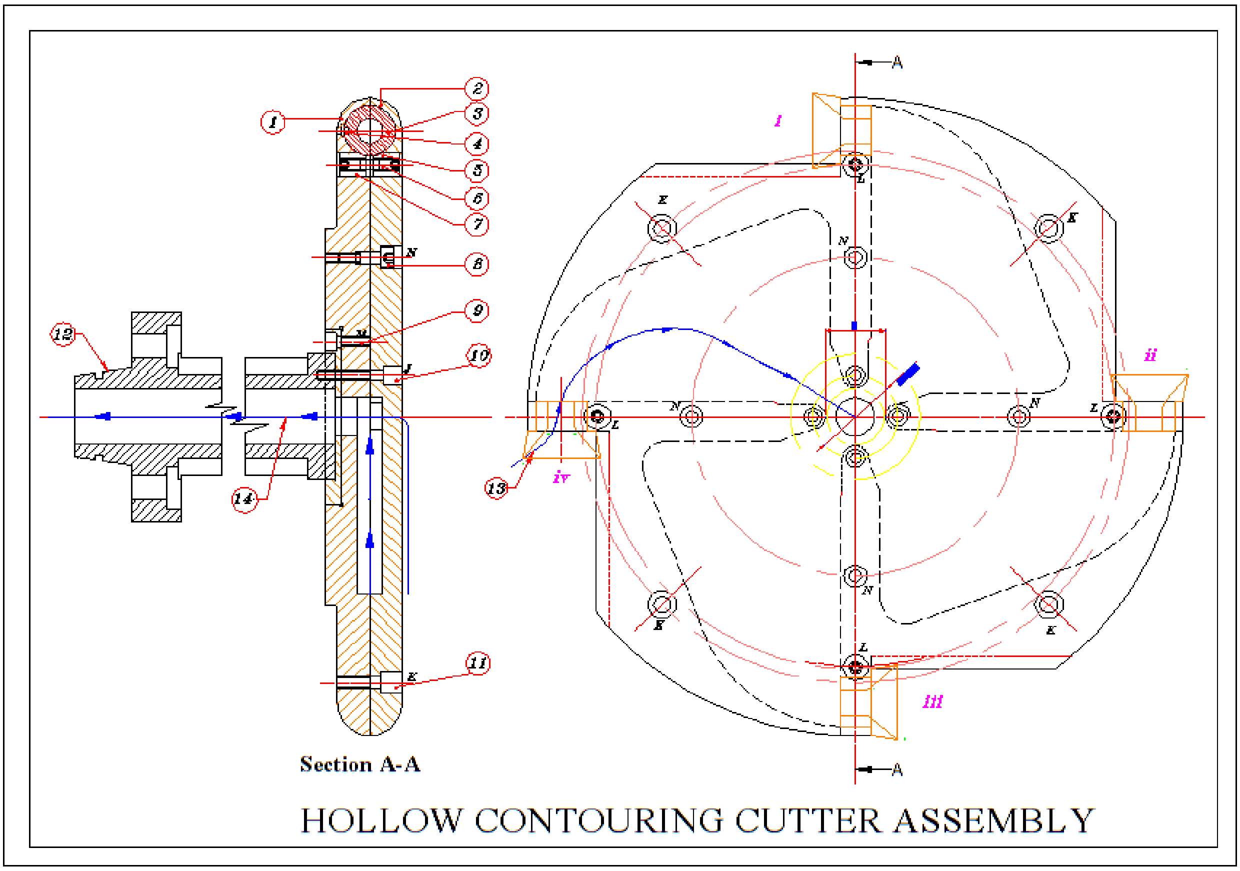
In order to maintain the designed orientation and ensure the effective staggering of chip slicer, indexing of all inserts to be done in assembled set at one go for replenishment of worn cutting edge with new one, if at least one cutting edge reaches end of its tool life.

5. 3 Development of Turbine cutter assembly

To dispose off the propellant powder and chips instantly as soon as they are produced a continuous passage for chip flow through cutting element and cutter body was incorporated which makes the cutter body hollow and light in weight. The exit of chip flow passage in the cutter body is further connected to hollow arbour to extend the vacuum line. In addition to specified safety and functional requirement, the cutter should be capable of performing variety of machining operations to generate different profiles on the propellant grain such as boring, filleting, facing and contouring as required to meet the versatile machining requirement of present grain in single setting of tool.

5. 3. 1 Development of Turbine cutter

In accordance with principle of invention, a hollow side and face milling cutter assembly called 'Turbine cutter' with multipoint cutting inserts and safe chip disposal provision was developed as shown in Fig.5.7. The cutter assembly includes two aluminium hollow halves of disks i.e., top disk (1**)**, bottom disk (2), four conical shaped round cutting elements made of High Speed Steel (HSS)of M2 grade (3), four locating pins (4)**,** four sets of holding fasteners (5) with a pair of LH and RH stud element(6) for positive clamping of cutting elements in correct position and orientation [100].The cutter assembly is rotatable when assembled to the arbor of milling machine and is to be connected centrally to the vacuum pump through hollow arbor (12) and rotary joint before the cutter takes rotation. The cutter body was made hollow with suitable path to allow the chips to pass through smoothly and the conical cutting element have the central hole with hood type geometry at the cutting edge to evacuate the chips by application of vacuum through hallow arbor following smooth path (13). The evacuation of chips from the cutting area is accelerated by the centrifugal force of rotating cutter blades in addition to vacuum application [34, 101] and double positive angle in the tool signature. All the four HSS inserts are placed equidistance on the periphery of the hallow disk assembly. The two hollow halves of Aluminium disks are assembled by means of outer disk clamping fasteners (11)**,** clamping fasteners(9) at Inner Pitch circle diameter (PCD) also being used to assemble the cutter assembly to hollow milling arbor in addition to holding the disks together near the centre ensuring vacuum tight joint between hollow disks. The positions of clamping fasteners (8) at middle PCD ensures leak free joint between disks. The cutter is called turbine cutter because the Propellant chips and powder enters tangentially and leaves axially like the fluid enters and leaves from the turbine as shown in the path (14)and the shape of cutting element (3) resembles the vane of the turbine. To enable easy, quick and fool proof assembly & maintenance of cutter, fasteners are specially configured and all the components are made from suitable materials as listed in Table 5.1. To improve the life of the cutter, all the threads and parts subjected to wear and tear are replaced / composited with SS helicoils / inserts or SS fasteners.



1. **Top disk 2. Bottom portion 3. Cutting element 4. Locating pins 5. Insert Clamping bush –bottom 6. Stud elements 7. Insert clamping bush-top 8. Disks clapping fasteners 9. Flange clamping fasteners 10. Cutter assembly fasteners 11. Outer PCD disk clamp fasteners 12. Arbor Interface 13. Chip flow path in hollow cutter 14. Chip flow path in hollow arbor to exit**

Fig.5.7: Turbine cutter (Hollow contouring cutter) assembly

To ensure effective cutting action on propellant material to prevent the friction between rake face and propellant chips, the rake face of the tool is ground positively more than that the tool used for common metal cutting practice. This shape and rake angle combination in the insert ensured required hood shape of suction inlet for safe and effective evacuation of propellants chips instantly. Similarly to prevent the rubbing action and intern the friction between flank face and finished surface of propellant grain, the flank face is relieved to 15°. Balancing the cutting edge strength, tool life of cutter and smooth flow of chips over rake face, machining trials are conducted with HSS Hollow side and face milling cutting element on sample grain surface to fix the rake angle as 45°.

The orientation of the ‘V’ shaped chip slicer on the circumference of the cutting edge is arranged such that in one complete revolution of cutter the combination of four insert passes clear the machined surface and should not leave the ridge of chip slicers / serration marks on machined surface of the propellant grain. The slicer groove disposition in the insert and insert orientation in the disk assembly enables staggered cutting arrangement in the cutter when it rotates which is thoroughly explained in the previous section of the chapter. The inserts are provided with four transverse holes at the mounting surface to index them at least 4 times before disposed off. Since the inserts are sequenced for staggering and indexing, all inserts at a time to be indexed to maintain staggering sequence when the cutting edge of any insert become blunt / replenished during insert change time. The cutting element edge is ground off to optimum tool angles as shown in Fig.5.1 such that it generates least friction while machining. Through flow application of vacuum to evacuate the propellant chip in the cutting area intern also reduce heat build-up at the cutting zone allowing dry machining conditions at a greatly improved machining rate unlike use of liquid coolant being used in prior arts. Since the cutting elements are detachable, multi time usable and indexable, the cutting hours of cutting element are enhanced before disposed off [99-100].These indexable and disposable cutting inserts yield significant economy to the machining operation.

The circular shape of cutting edge of conical cutting element provides strength and versatile geometry to insert. Inserts with round cutting edges exhibit rotational symmetry and could continuously indexable in any angular position to accommodate actually observed wear

Turbine cutter was configured such that all the sources of risk during propellant cutting could be either eliminated or mitigated to below risk level by multiple provisions. To evacuate the propellant chips and powder generated during machining operation from cutting zone safely and effectively, the exit end of the Turbine cutter assembly at arbor exit is connected to a vacuum pump through a number of filtering components. The flows of vacuum on the rake face of the cutting elements intern keep the temperature of cutting edge at safe range. To achieve maximum material removal rate and impact free engagement and disengagement of cutter with the propellant material, a hollow side and face milling cutter with multipoint cutting is primarily conceived. To make use of the advantage of circular cutting edge for its maximum material removal, significant strength of cutting edge, versatility in application, indexability and ease of fabrication, a hollow conical cutting insert with central hole is designed to allow the chips to pass through it. Inlet for this chip flow from the cutting zone through the divergent portion of the HSS conical insert like hood of the any suction line and the hallow spindle of the turbine cutter is connected to vacuum pump through number of filtering elements.

The rake angle of 45° and relief angle of 15° is provided on conical insert which is the main cutting element. Conical shape of the insert formed by these tool angles is advantageous in tool life point of view also, because round insert can be used number of times by simply indexing it about it axis at its location. The propellant chips generated in this process are considerably wider and may choke the cutter suction line, at the throat of the conical insert. Therefore to slice these chips along its length during cutting, a chip breaker of V-shape (90°) groove is made on the cutting edge up to 0.5 mm depth.

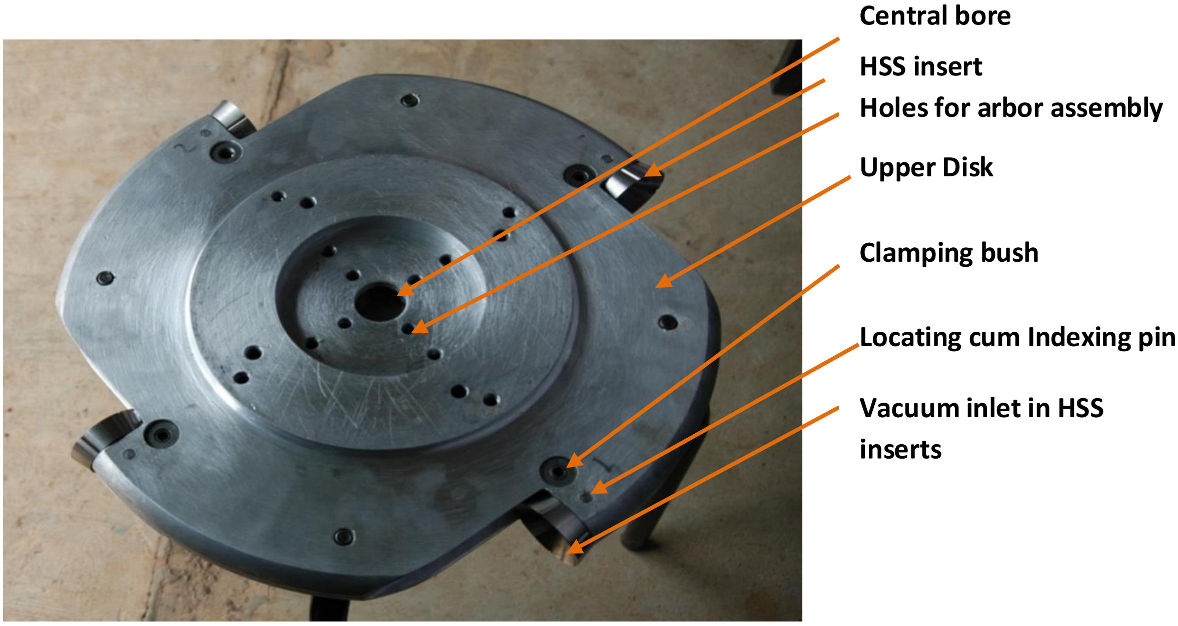


Fig.5.8 :Developed Turbine Cutter for CSP machining

The developed and validated Turbine cutter assembly and conical hollow side and face milling insert equipped in Turbine cutter and various element of the assembly are shown in the Fig. 5.8.

5.3.2Design aspects of extra-long hollow arbor

Double tube type extra-long rigid arbor being used to hold the cutter assembly for slot machining operation, it should be designed for the following design considerations. The long arbor of 2250mm length being used for connecting the cutter assembly with spindle head while generating the slotted grain configuration. The line diagram of arbour assembly is shown in Fig.5.9**.**

5.3.2.1 Design based on strength and rigidity

Since arbor is subjected to both the torsion and bending stresses the resultant stress calculation is essential to approximate the bearing capacity and design specification.

As the arbor is clamped at one to the machine spindle head and other end carry Turbine cutter become a cantilever beam for calculation of the deflection with applied cutting forces without double tube configuration. Due to incorporation of double tube and radial bearings at front and rare end of the arbor it become simple supported and defection values come down.

5.3.2.2 Design for critical speed

Since the arbor is designed for rotating the cutter body along with the inserts, the analytical testing of the arbor critical speed is essential to avoid the accelerated amplitude of vibration which were ensured as per design standards.

5.3.2.3 Design criteria of the extra-long rigid Arbor

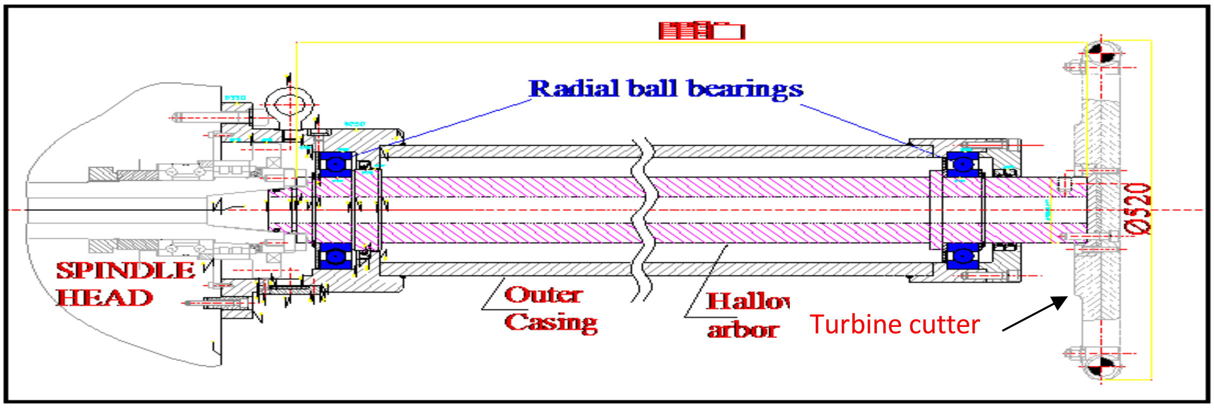


Fig.5.9: Details of extra-long arbor

Design parameter for extra-long arbor being used for the machining operations is as follows

a. Maximum deflection of arbor should not exceed $2x\ 10^{-4}$ times the span between bearings

b. Deflection of arbor where gear is mounted should not exceed 10 times the value of module (in micro meters).

c. Angle of twist should not exceed 0. 25° to 0. 35° per meter length of arbor this equates to a value of between 20 to 60 seconds of arc respectively.

d. Slope of the arbor where gear is mounted should not exceed more than $1x\ 10^{-3}$ radians

e. Maximum slope of the arbor at the bearing support is limited by the permissible misalignment of the bearings [99].

The details of long arbor of 2250 mm length being used for the generating the slotted grain configuration is shown Fig 5.9. Materials of various components of turbine cutter assembly are summarized in Table 5.1.

Table 5.1: Material details of the different elements of the cutter assembly

Sl No	Component in the cutter assembly	Material designation
1	Top and bottom disk (1 &2)	AA6351/ IS64430 (H-30)
2	Inserts/ cutting elements (3)	HSS(IS 7291-1974) M2 Grade
3	Fasteners: Locating cum indexing pins (4), Holding fasteners (5) LH and RH stud element (6)	EN9
4	Clamping bush material	EN24
5	Extra long Arbor	EN24

5.4 Development of accessory system for safe evacuation of chips

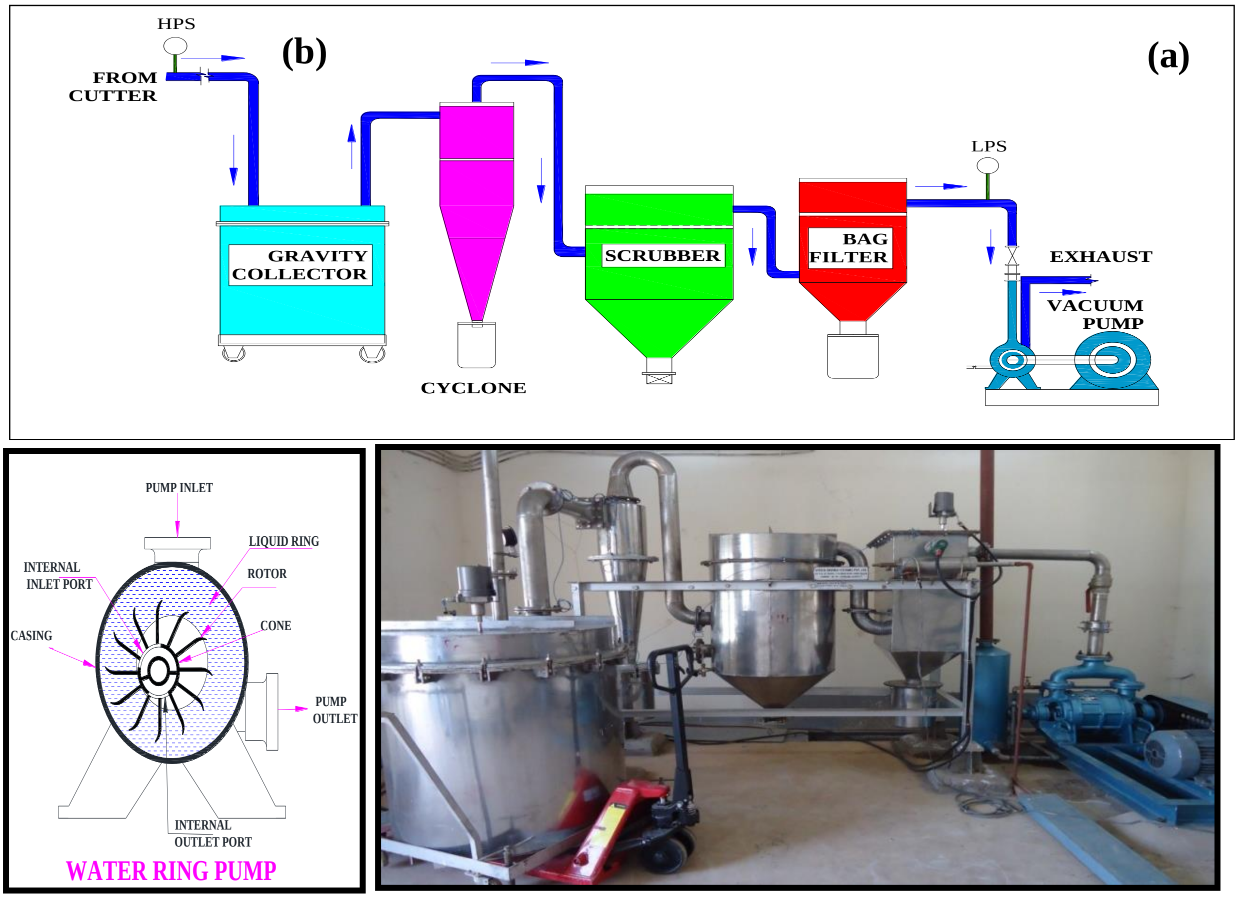
To evacuate propellant chips from cutting zone a special system called Chip and Dust Collection System (CDCS) is integrated to the machine spindle through rotary joint. Ensured continuity of electrical conductivity throughout the suction line prevent static charge accumulation for which suction pipes, flanges and sealing elements are made of metals or metal embedded materials. All the safe industrial filtering elements ranging from gravity separator, cyclone separator, water scrubbers and pleated bag cartridges made of antistatic coated mesh are used for construction of CDCS as shown in Fig 5.10. Utmost care has been taken while configuring this system to eliminate the sources of risk such as friction, heat, impact loads, static charge etc. which are prime stimuli for mass fire and radiation hazard in presence of powder and chips of propellant in fine form.

During the machining of grooves, pockets where the cutting zone is confined and not much accessible to ambient air flow the exhaustion efficiency of CDCS with the developed cutter was near to100%. For rough milling and vertical turning it was found 92% where the chips has tendency to fall due to gravity due to their weight after immediate generation from machined surface, if it is escaped from suction effect, but in the both cases the particles available due to de-bonding at the cutting surface were thoroughly evacuated by applied suction. Machined surface with this system was found free from AP particle cladding. Machining trail was performed on dummy propellant material initially to assess the performance of cutter chip exhaustion then on live propellant. The suction efficiency values explained above are derived from the chips produced during live propellant trials.

The efficiency of CDCS when employed for chip evacuation was calculated by mass of remained chips left in the premises of cutting zone divided by the total mass of chip produced.

$$E = m_e/m_t \text{ X } 100 = (m_t - m_r)/m_t$$

Where m_t = total mass of chip produced, m_e =mass of extracted chips, m_r = mass of non-extracted chips



a) Line diagram of CDCS b) working principle of water ring vacuum pump

c) Developed CDCS system for experimentations

Fig. 5.10: Chip and Dust Collection System (CDCS) for chip evacuation

5.5 Experimental strategy and development of experimental set-up

Safe machining practices have been highly emphasized while machining HTPB based Composite Solid Propellant (CSP) material due to hazardous nature of solid propellant to mechanical stimuli which are inevitable in conventional machining of propellant grain. The viable method for exercising the safe propellant machining experiments on solid propellant grain is to control and maintain the cutting force/power at a prescribed safe level by machining at optimum cutting parameters and implementation of properly designed cutting tool for low mechanical stimuli. The cutter designed for this purpose will also be validated during evaluation of cutting parameter for safe (Low Cutting power) and effective machining (Max MRR) of CSP using the Turbine cutter.

In this particular case material, machine and tool combination, conventional methods and dynamometers for cutting force measurement become unsuitable due to poor rigidity of work material for cutting forces and extreme size of work piece with huge weight which is beyond the measuring capacity commercial dynamometers. The use of recently developed spindle mounted type dynamometers were explored for the experiments, but not become adaptive due to heavier and robust construction of special cutter arbour assembly due to interfacing non compatibility. Rigidity issues of CSP, constraint to place the dynamometers in the vicinity of live propellant material/propellant dust environment on safety reasons as it carries power source are other limitations. Modification or devising a custom-build model of dynamometers will be expensive affair. Downsizing the work piece or machine setup or experimentation to simulate experiments in existing facility needs lot of lead time and expenditure to do so, in compliance with the safety requirements of explosive machining. One simple and economical method to measure the cutting force directly from the power drawn by the servo motor drive of spindle is found most viable solution.

Cutting forces play an important role in all machining operations since they are directly related to power consumption hence the cutting power was measured as output parameter in the experiments. Cutting power is measured in respective Servo drives of the machine parts such as spindle servo drive, Rotary table servo drive etc., and using advanced power analyser having real-time electrical data acquisition system. The Fluke power analyser which can be installed in the AC servomotor drives of machine control panel was used which is having storage and graphical display provision of acquired data.

Experiments carried out in dry conditions using Special purpose VTM machine on HTPB/AP/Al based live CSP material. Tool is custom-build round edge conical insert in the developed Turbine cutter as shown in Fig.5.8 made of HSS M2 grade confirming to IS 7291-1974 is the active cutting element. The present work is focused to study the effect of process parameters such as cutting speed, feed, and depth of cut on Cutting power, and MRR using DOE, ANOVA and RSM.

As the data on machining parameters and modelling of machining of CSP material is not available, attempts are made to generate such valuable data through experimentation using developed Turbine cutter. In machining the CSP with Turbine cutter, the objective of optimization has multiple criteria. In the present study the objectives are low cutting power and high MRR. This makes multi-objective optimization essential for machining studies of CSP material. The present study uses RSM being used for optimization of levels in a given range.

5.5.1 Experimental set-up

A reliable and inexpensive method for indirect measurement of cutting force while machining viscoelastic propellant material become inevitable due to poor rigidity of propellant material for cutting forces and to transmit them to measuring sensor. The measurement of cutting force in machining of propellant grain is essential to assess safety aspect of propellant machining. The maximum value of cutting energy applied while machining the propellant grain with newly developed "Turbine cutter" was measured continuously online in the control panel through cutting power. This experimental method also provides a chance to validate the design and performance of cutter on safety and functional aspect.

In the present research work cutting force was indirectly measured through cutting power measured from the AC drive of spindle motor of CNC VTM machine. The indirect measurement of cutting forces through cutting power is quite reasonable, economical and it has an important application value with high compatibility and stability.

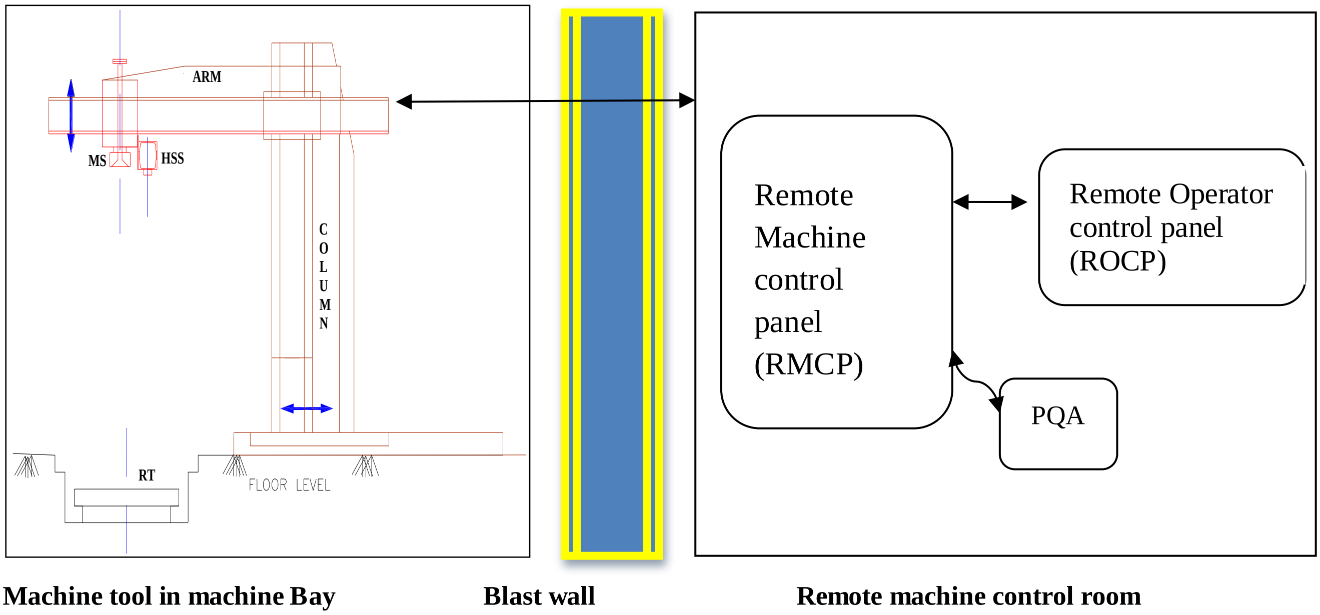


Fig.5.11: Schematic of experimental set-up

5.5.2 General layout of experimentation

The schematic of general layout of experimental set-up is shown in the Fig 5. 11. Detailed description of each system employed in this experimental set-up is explained in subsequent sections. The monitoring and control of machining was done from remote control room through CNC control panels.

5. 5. 2. 1 Machine tool

Fig.5.12: Machine set-up

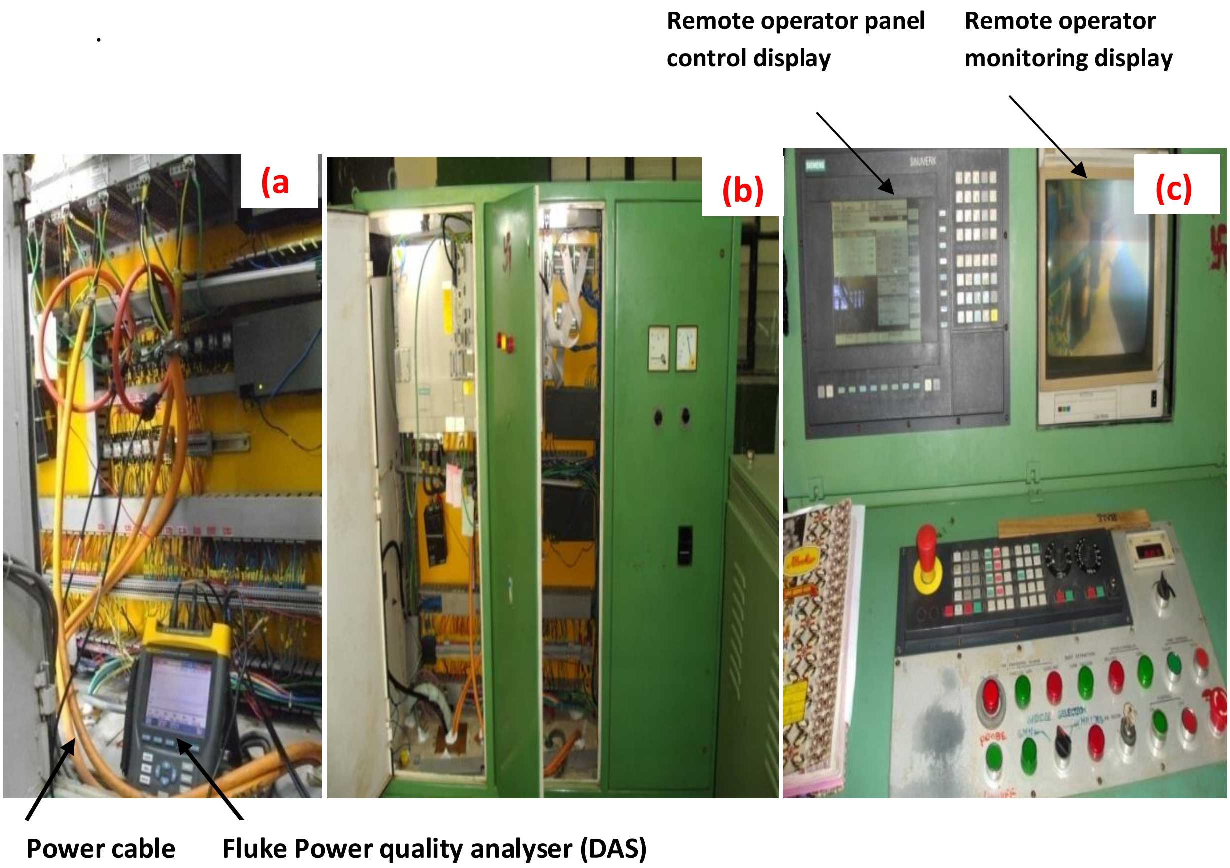
Table 5.2: Specification of CNC VTM

Machine model and make	BECO (Mukund Engineers, Bombay)
Spindle speed range	Up to 2000 rpm
Stroke in X and Y axis	2m in horizontal (X-Axis), 2m in vertical (Z-Axis)
Table dimensions	Ø3 m rotary table
Feed speed range	0-180 °/min
Servo motor details (Spindle)	AC Servo motor, 10 KW, Siemens make
Servo motor details (Table)	AC Servo motor, 15 KW, Siemens make
Controller details	Siemens 840D
Spindle taper details	ISO 50

A CNC VTM machine was used for experimentation whose illustration and detailed specifications is shown in Fig.5.12 and Table 5.2 respectively. CDCS was deployed during machining as accessory system for safe disposal of propellant chips. The remote control panel of machine located in control room behind the blast wall to conduct the machining experiments remotely on safety reasons are shown in Fig 5.11. Power analyser is integrated to power inputs of AC servo drive of spindle and rotary tables at remote control panel in addition to redundant display values of cutting power as default display on operator panel. All the machine control and operator panels were located in remote machine control room. The power variation in rotary table drive is marginal as the magnitude of cutting force in comparison with loaded work material weight (15 ton) on rotary table, hence rotary table power consumption was not considered for study.

5. 5.2.2 Cutting power measurement and monitoring setup

The cutting power measurement scheme, integrated measuring instrument with machine control panel are illustrated in the following Fig.5.13 and the specification of drive units from which the power measurement were made are listed in Table 5.3



a) Integrated power analyser b) Remote control panel of CNC VTM c) Remote operator panel display of Cutting power

Fig.5.13: Cutting power measurement scheme

Table 5.3: Power drives of CNC VTM

X drive	SIMODRIVE, LT-MODUL INT 80A, 1P 6SN1123-1AA00-ODA1	ST-N42037174 GWE-566018901020	Version A
Z drive	SIMODRIVE, LT-MODUL INT 80A, 1P 6SN1123-1AA00-ODA1	ST-P12012467 GWE-566018901020	Version A
Table drive	SIMODRIVE, LT-MODUL INT 80A, 1P 6SN1123-1AA00-ODA1	ST-N42037173 GWE-566018901020	Version A
Spindle drive	SIMODRIVE, LT-MODUL INT 80A, 1P 6SN1123-1AA00-ODA1	ST-N42037170 GWE-566018901020	Version A
SIMODRIVE 611	E/R –MODUL INT 55/71 KW IP 6SN1145-1BA01-ODA1	ST - N 42037383 GWE-566018901560	Version A
Controller	SINUMEIK 8400, NCU-BOX 13A AC 57V, ±5%, 20 KHZ IP 6FC5247 –DAA00-0AA2	GWE-57038901611	Version G

5.5.2.3 Data Acquisition System (DAS) and power quality analyser (PQA)

The detail of Power quality analyser (Make :Fluke)being used in the experiments for measurement and online monitoring of cutting power as Data Acquisition system (DAS) are shown the Table5.4. It is also compared with the machine power consumption values, available in default on the operator control panel. This machine inbuilt feature was provided for monitoring the machining through power consumption to control the machining from remote control room.

Table 5.4: Data acquisition system and power quality analyser (Fluke make)

Make	Fluke
Model	435
Voltage measurement range	1V to 1000V with 0. 01 v resolution and 5% of nominal voltage accuracy
Current measurement range	0. 5 A to 600 A with 0. 1 A resolution and ±0. 5% ±5 counts accuracy
Frequency measurement range	42. 50 Hz to 57. 50 Hz with0. 01 Hz resolution and±0. 01 Hz accuracy
Data handling	LCD Resolution: 320 x 240 pixels Contrast and brightness: user-adjustable, temperature compensated. 8 GB memory for storing data including recordings
Electro-Magnetic-Compatibility (EMC)	EN 61326 (2005-12) for emission and immunity

5.5.2.4 Cutter

Turbine cutter as discussed in the earlier part of this chapter and shown in Fig.5.8 being used in the experimentation of present study.

5.5.2.5 Work piece material

HTPB/AP/AL based CSP heterogeneous material with the formulation and mechanical properties as presented in the previous chapter were used.

5. 5. 2. 6 Accessories

Chip and dust collection system shown in Fig 5.10 is connected through rotary joint to the exit of cutter and arbour assembly for instantaneous evacuation of propellant chip and dust produced during machining experiments.

5. 6 Process parameter selection

The process parameters considered in the present study are cutting speed, depth of cut and feed. These have profound influence on cutting force which is indirectly measured through cutting power [95, 97]. Since the cutting force measurement is not viable in the present case and it can be well measured through Cutting power, the discussion is continued with cutting power in place of cutting force. MRR is calculated from the applied process parameter for each run as side spread of chip is negligible and was in agreement with physical measurement of chip volume rate. The material removal rate (MRR) is the volume of material that is removed per unit time in mm^3/min. For each revolution of the work piece on rotary table, a ring shaped layer of material is removed.

$$MRR = Speed\ X\ feed\ X\ depth\ of\ cut,\ (mm^3/min)$$

5. 6. 1 Effect of cutting speed on cutting power and MRR

Speed is a very important aspect in machining since it considerably affects the tool efficiency and life in machining. Selection of a proper cutting speed has to be made very judiciously because if it is too high, the tool gets over-heated which will be inadvertent and dangerous situation for fire sensitive CSP as work material, causing catastrophic damage of entire machining set-up. If it is too low, too much time is consumed and full cutting capacities of the tool and machine are not utilized, and it results in lowering of MRR /productivity and also increases the time to risk exposure in this particular case of CSP machining and increasing of the production cost. In accordance with safety guidelines of rocket manufacturing as discussed in section 3.10 of chapter-3of thesis, it should not exceed 500 rpm.

At lower cutting speeds, the contact between chip and tool is longer, time of risk hazard is high and productivity is low. At higher speeds, the temperature increases which is undesirable for CSP materials, but duration of contact decreases and causes material softening in the local cutting zone at high speed which are favourable conditions as it reduce cutting force required and time of risk hazard. Material breakage in localised areas in the cutting zone further enhanced by dewetting of CSP at high cutting speed in CSP. At higher speeds, MRR will be high speed and at low speeds, due to high coefficient of friction between tool and rubbery binder of work material cutting forces are significantly high.

5.6.2 Effect of feed on Cutting power and MRR

Feed increases the undeformed chip thickness, thus increasing the area of the chip. But, the specific cutting pressure per unit area will decrease. Thus, the feed increase results in increase in cutting force but the increase is not proportional [95].

Feed ridges are the main reason for surface roughness. Height of the feed ridges increases with feed rate. As the feed ridge height increases, the value of surface finish decreases. To reduce the effect of feed ridges, rather a nose radius tool, a chamfered edge tool is commonly used in metal cutting even at high feed rates to nullify this effect, but it is not advisable for CSP to avoid severe rubbing of chamfered land with finished work material. So the feed in this case is limited by surface finish and machine capacity. With increase in feed MRR will be increased but not linearly proportional due to material viscoelastic, low mechanical properties and microstructure behaviour.

5.6.3 Effect of DoC on Cutting power and MRR

It is the depth or distance parallel to axis of the cutter by which the tool penetrates into the work and measured in length units. In the present case it was considered from 2mm to 4mm considering the trend and results of tested range with prototype cutter. If DoC is large then larger will be the cutting force and MRR

In view of above theoretical aspects, considering the working range of the machine and suction capability, vacuum line size and chip room space in the developed cutter operating range of machining parameters are selected as shown in the Table 5. 5. It was found from the cutting trials on the non-reactive propellant equivalent material as explained in chapter-4 using prototype cutter; the effect in the proposed range was stable. Based on the trial cutting exercises discussed in previous chapter to find the stable process parameters to fix the tool signature on prototype insert, for designed tool size and signature, the maximum speed was limited to 196m/min (125 rpm) keeping safety factor of 4 on suggested safety speed limit of 500 rpm. Feed and depth of cuts have limits based on the insert central bore but beyond the range tested with prototype cutter to sense the entire available band of these two parameters. With the limited and expensive resources the possible approach would be to limit the number of levels to three (the minimum to study the nonlinear effects) and conducted full factorial experiments. However the broad range were chosen in feed, speed range as limited by safety aspects and capabilities of resources.

Table 5.5: Experimental factors and their levels

S. No	Parameters	Notation	Units	Levels		
				1	2	3
1	Cutting velocity	A	Rpm (m/min)	75 (117)	100 (157)	125 (196)
2	Table Feed rate	B	deg/min (m/min)	24 (0. 418)	36 (0. 628)	48 (0. 378)
3	Depth of cut	C	mm	2	3	4

5.7 Design of Experiments (DOE)

Design of Experiment (DOE) is a structured, organized method for determining the relationship between factors affecting a process and the output of that process. It is generally used to quantify the effect of factors and interactions between these factors by analysing data from the experiments and also to develop a good model large dataset is essential. Therefore, in the present study full factorial experiments are planned to develop a large data set. It allows a better analysis of the effects of parameters and the data can be used to develop a mathematical model of process also. Plan of experiments are shown in Table 5.6.

Table 5. 6 DOE, Full Factorial experimental list

S. No.	Coded values			Actual values		
	CV	TFR	DoC	CV	TFR	DoC
1	1	1	1	75	24	2
2	1	1	2	75	24	3
3	1	1	3	75	24	4
4	1	2	1	75	36	2
5	1	2	2	75	36	3
6	1	2	3	75	36	4
7	1	3	1	75	48	2
8	1	3	2	75	48	3
9	1	3	3	75	48	4
10	2	1	1	100	24	2
11	2	1	2	100	24	3
12	2	1	3	100	24	4
13	2	2	1	100	36	2
14	2	2	2	100	36	3
15	2	2	3	100	36	4
16	2	3	1	100	48	2
17	2	3	2	100	48	3
18	2	3	3	100	48	4
19	3	1	1	125	24	2
20	3	1	2	125	24	3
21	3	1	3	125	24	4
22	3	2	1	125	36	2
23	3	2	2	125	36	3
24	3	2	3	125	36	4
25	3	3	1	125	48	2
26	3	3	2	125	48	3
27	3	3	3	125	48	4

5.7.1 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method to determine the existence of differences among several population means. Analysis of variance is effective tool for analysing highly structured experimental data. Different factors affect the defect formation to a different degree and relative effect of the different factors can be obtained by the decomposition of variance, which is commonly called analysis of variance (ANOVA). ANOVA estimates the error variance for the factor effects and variance of the prediction error.

The purpose of the analysis of variance (ANOVA) is to investigate the design parameters that significantly affect the quality characteristic. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SS_T from the total mean S/N ratio can be calculated as:

$$SS_T = \sum_{i=1}^{n} \eta_m - \eta_i)^2$$

Where ‘n’ is the number of experiments in the orthogonal array,

η_i is the mean S/N ratio for the i^{th} experiment and

η_m total mean of S/N ratio.

The total sum of squared deviations of two sources= SS_T

Sum squared deviations due to each design parameter =SS_d

Sum of squared error = SS_e.

The percentage contribution of each of the design parameters in the total sum of squared deviations SS_T is a ratio of the sum of squared deviations SS_d due to each design parameter to the total sum of squared deviations SS_T. In this discussion, the main focus is on developing full factorial experimental design and analysing the data using ANOVA to find significant factors and interactions. For this purpose Minitab 16 has been used for experimental design with randomized order. ANOVA analysis and the related plots were also developed. [103]

Terminology used in ANOVA

i. SS (Sum of squares): It is the sum of squares of deviations. It is calculated for each factor and the total SS is found by adding individual terms.

ii. Seq SS : Sequential sum of squares are obtained by breaking down SS into main effects, interactions, blocks and each co-variate. Seq SS depends on order of the terms entered into the model.

iii. Adj SS: Adjusted sum of squares is the other part of SS which does not depend on the order in which values are entered.

iv. DF: Degree of Freedom is the number of degrees of freedom associated with each sum of squares.

v. MS: Mean square is calculated as MS = Adj SS/DF

F test: It is used to determine whether a given interaction or main effect is significant. Large value of *F* means the factor or interaction is significant.

F= MS Term /MS (Error)

vi. p-value (P): It is also a test similar to F test but can be used to decide whether a parameter needs to be considered significant or not. The common criterion is if the value of P is less than 0. 05, the factor is significant [102, 104].

5.7.2 Mathematical modelling

To obtain applicable and practical predictive quantitative relationships, it is necessary to model the machining responses and the process variables. These models would be of great use during the optimization stage of milling of CSP materials. The experimental results were used to model the various responses using multiple regression method and non-linear fit among the responses and the corresponding significant parameters. In the present work, a commercially available statistical software Design Expert 7.1.0 package was used for the computation of regression constants, parameters and mathematical modelling.

Response surface methodology is a statistical and technique used for modelling of a process in which a response is influenced by a number of variables. The response surface methodology provides plenty of information about the influence of variables and output response with the minimum number of experiments. The exact connection between the response of interest and input factors is typically unknown. In the present study, full factorial design, the most commonly used RSM design, is chosen for modelling and optimization to achieve the maximum MRR and minimum power. In RSM, a suitable approximation has been made to establish the relationship between the dependent and independent variables. The behaviour of the system is explained by the following general quadratic equation with 95% confidence level

$$y = \boldsymbol{\beta}_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<J}^{k} \beta_{ij}\, x_i x_j + \epsilon$$

Where y is the corresponding response and xi,xj are the ith and jth variables related to the machining process parameters. The terms β_i,β_{ii},β_{ij} are the regression coefficients and the residual ϵ represents the experimental error of the observations. So by using the machining parameters, cutting speed, feed rate and depth of cut, the relationship between the response y and these machining parameters can be obtained as follow

5.8 Results and Discussion

Results of experiments after analysis are presented as follows.

5.8.1 Full Factorial experimental results

In this Chapter, the full factorial experimental results obtained for the cutting power, MRR are summarized. The relationship between the cutting power and MRR on the process parameters is discussed. Full factorial design is considered in the present study to understand the interactions effects, which otherwise must be sacrificed in the fractional factorial design [102-103].Based on this, a total of 27 experiments, each having different combinations of different levels of factors as shown in Table 5.6, have been carried out.

Table 5.7: DOE, Experimental results

S. No.	CV	TFR	DOC	Cutting Power (x 10^{-2} KW)	MRR (m^3/min x10^{-6})
1	75	24	2	16. 75	325. 96
2	75	24	3	17. 8	452. 12
3	75	24	4	18. 75	651. 92
4	75	36	2	17. 12	367. 38
5	75	36	3	18. 23	551. 07
6	75	36	4	19. 5	734. 76
7	75	48	2	19. 5	391. 71
8	75	48	3	20. 75	587. 57
9	75	48	4	21. 62	783. 43
10	100	24	2	16. 5	477. 4
11	100	24	3	17. 25	656. 1
12	100	24	4	18. 1	904. 12
13	100	36	2	16. 81	492. 98
14	100	36	3	17. 5	739. 47
15	100	36	4	18. 25	985. 96
16	100	48	2	17. 2	525. 63
17	100	48	3	18. 1	788. 45
18	100	48	4	18. 5	1051. 27
19	125	24	2	13. 75	546. 05
20	125	24	3	14. 12	819. 08
21	125	24	4	15. 75	1092. 11
22	125	36	2	16	615. 44
23	125	36	3	16. 7	923. 16
24	125	36	4	17. 26	1230. 88
25	125	48	2	16. 5	656. 2
26	125	48	3	17	984. 31
27	125	48	4	17. 5	1312. 41

5.8.1.1 Analysis for Cutting power

The main effects of each parameter on Cutting Power (CP) are plotted on graphs shown in Fig. 5.14 (a) to 5.14 (c). These figures clearly indicate how Cutting velocity, Table Feed Rate, Depth of cut affects Cutting Power.

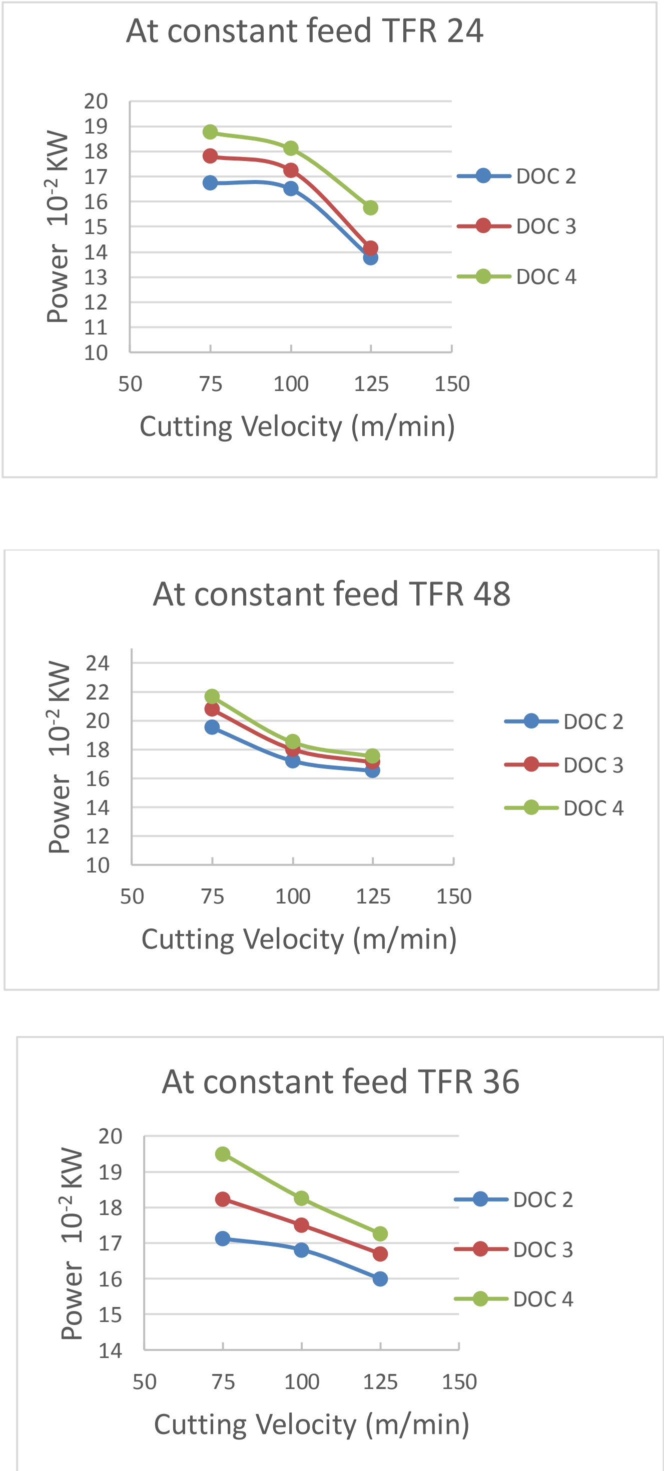


Fig 5.14 (a): Main effects of cutting velocity on cutting power

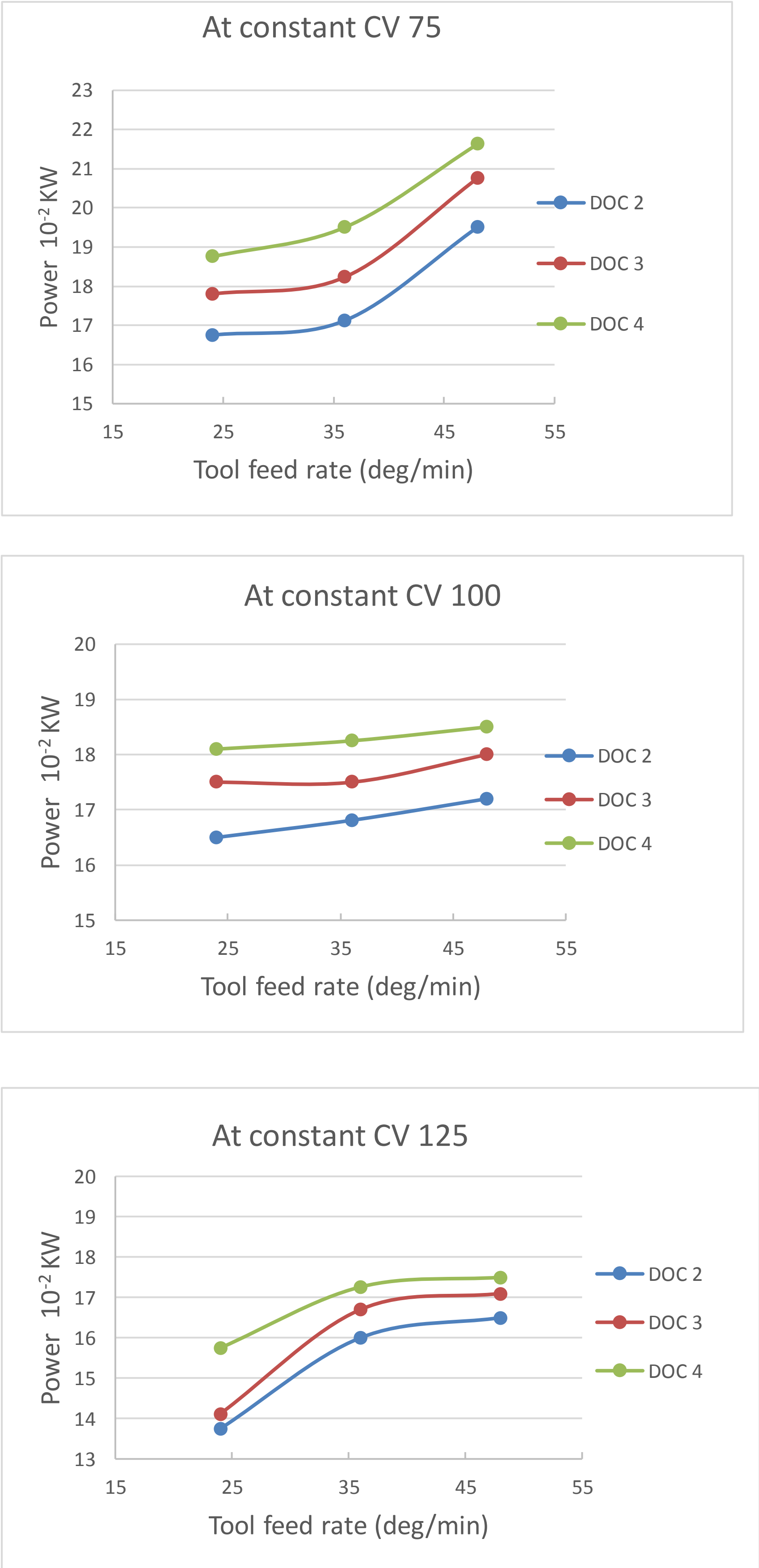


Fig 5.14 (b) Main effects of feed rate on Cutting Power

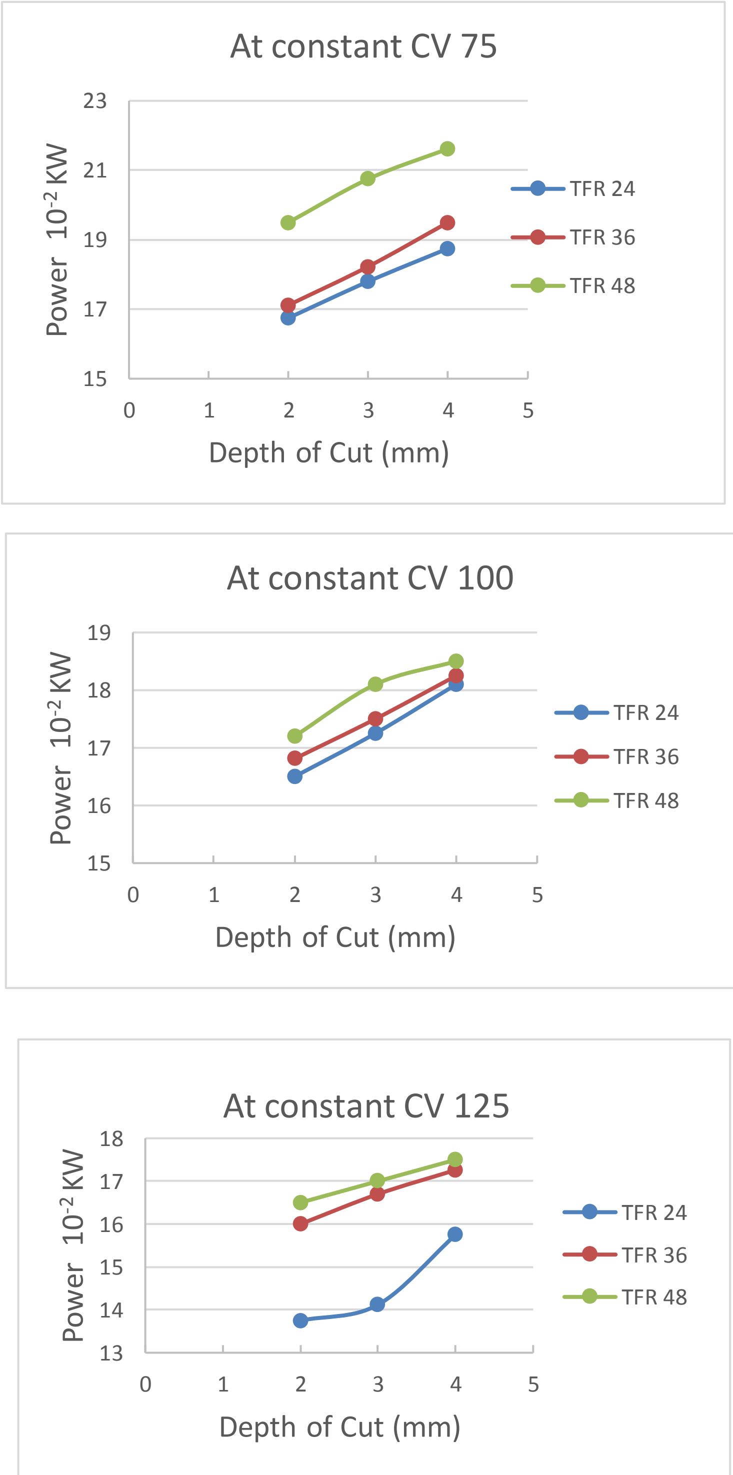


Fig 5.14 (c) Main effect of Depth of Cut on Cutting Power

5.8.1.2 Analysis for MRR:

The main effects of each parameter on MRR are plotted on graphs shown in Fig. 5.15 (a) to 5.15 (c). These figures clearly indicate how Cutting velocity, Table Feed Rate, Depth of cut affects MRR.

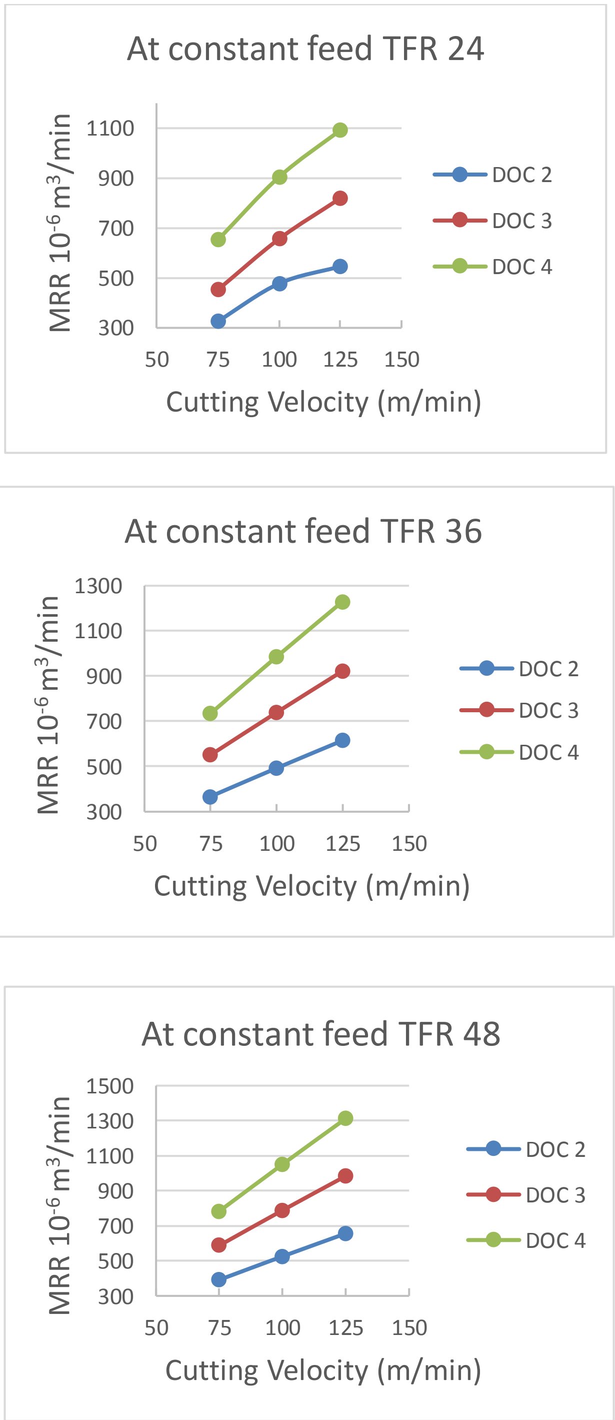


Fig. 5.15 (a): Main effects of cutting velocity on MRR

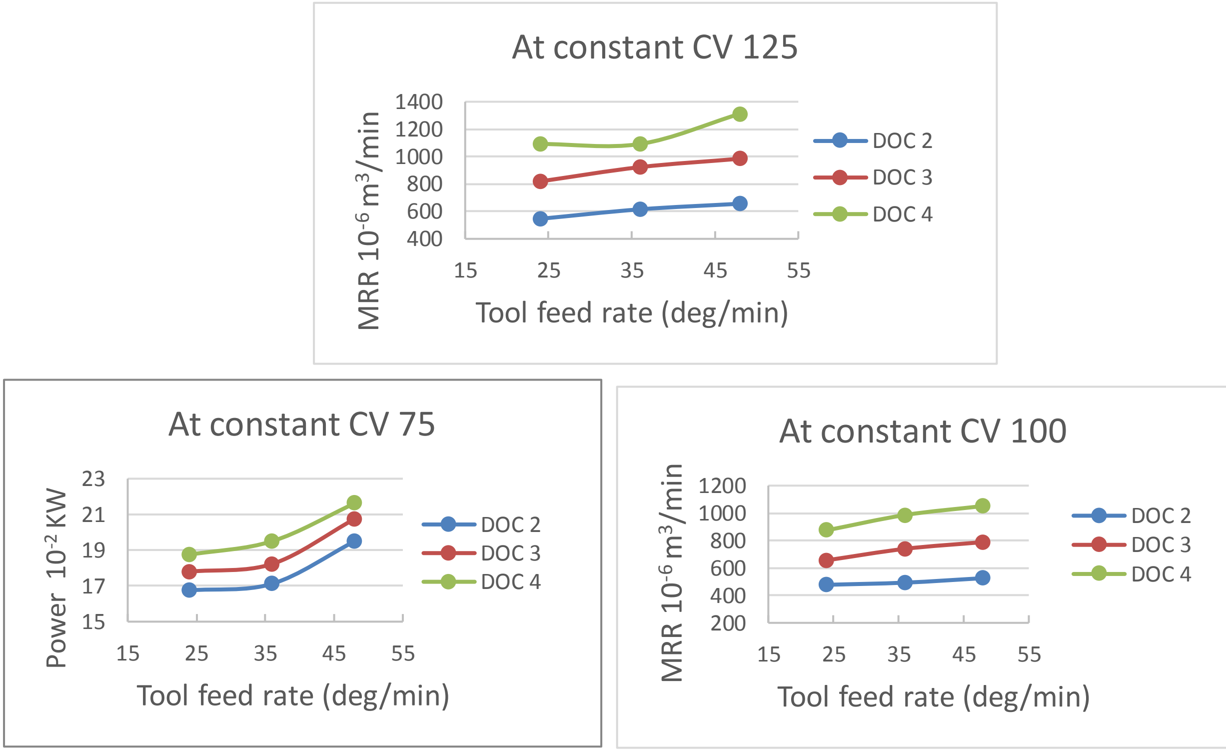


Fig. 5.15 (b): Main effects of Feed Rate on MRR

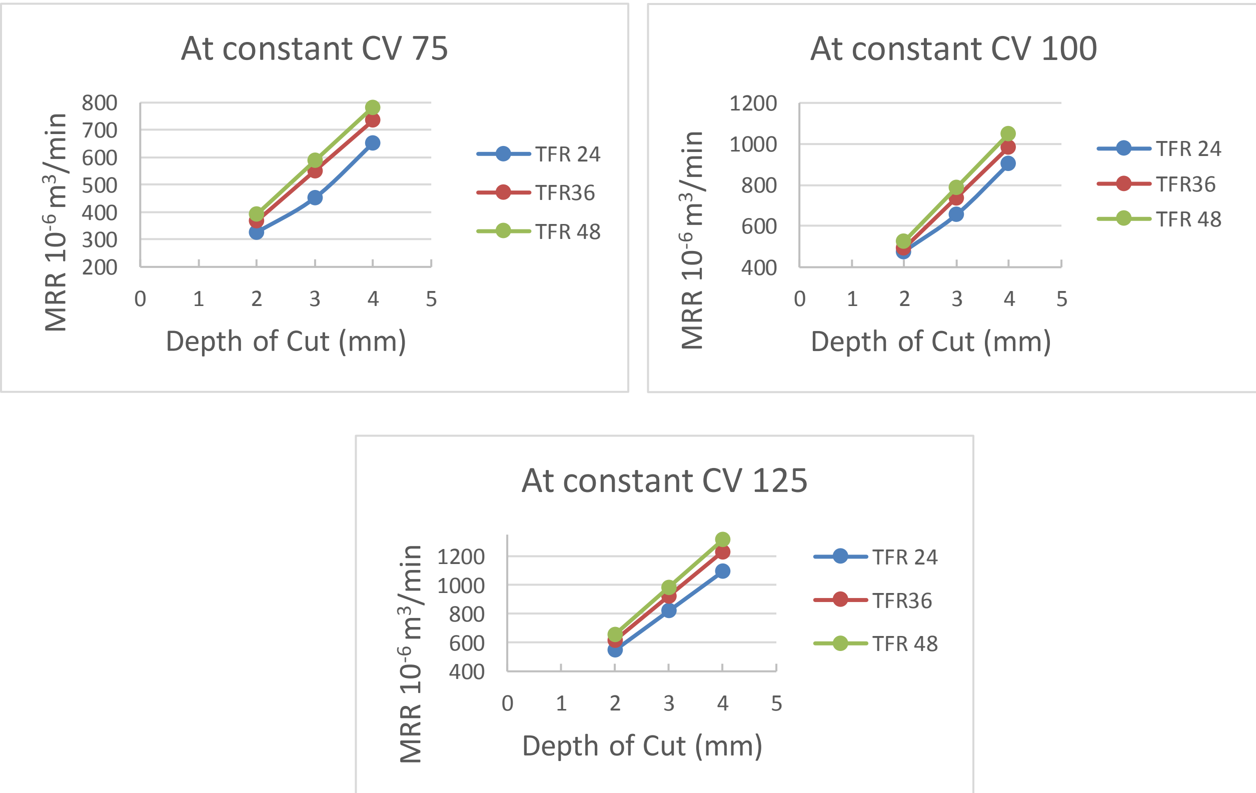


Fig.5.15 (c): Main effects of Depth of cut on MRR

5.8.1.3 Effects of machining parameters on cutting power and MRR

The effects of individual cutting parameter on cutting power and MRR are summarized as follows

a) Effect of cutting speed on cutting power and MRR

At lower cutting speeds, the contact between chip and tool is longer, time of risk hazard is high and productivity is low. At higher speeds, the temperature increases which is undesirable for CSP materials, but duration of contact decreases and causes material softening in the local cutting zone at high speed which are favourable conditions as it reduce cutting force required and time of risk hazard. Material breakage in localised areas in the cutting zone further enhanced by dewetting of CSP at high cutting speed in CSP. At higher speeds, MRR will be high and at low speeds, MRR will be low due to high coefficient of friction between tool and rubbery binder of work material cutting forces are significantly high.

b) Effect of feed on Cutting power and MRR

Feed increases the undeformed chip thickness, thus increasing the area of the chip. But, the specific cutting pressure per unit area will decrease. Thus, the feed increases results in increase in cutting force but the increase is not proportional.

Feed ridges are the main reason for surface roughness. Height of the feed ridges increases with feed rate. As the feed ridge height increases, the value of surface finish decreases. To reduce the effect of feed ridges, rather a nose radius tool, a chamfered edge tool is commonly used in metal cutting even at high feed rates to nullify this effect, but it is not advisable for CSP to avoid severe rubbing of chamfered land with finished work material. So the feed in this case is limited by surface finish and machine capacity. With increase in feed, MRR will be increased but not linearly proportional due to material viscoelastic, low mechanical properties and microstructure behaviour.

c) Effect of depth of cut on cutting power and MRR

Increase in depth of cut increases the cross-sectional area. It does not change specific cutting pressure as it does not affect the chip thickness. This makes the specific cutting pressure constant. As the cross-section area increases, the force too increases proportional to the depth of cut. When comparing feed and depth of cut, depth of cut has a greater influence on force. Depth of cut does not influence the feed ridges. But it can affect the vibrations of the machine tool in combination with feed. This combination is quantified by slenderness ratio (depth of cut/ feed per teeth). If this ratio increases, vibrations increase, and intern increase in surface finish. Large nose radius and small depth of cut increases vibrations and surface roughness. Comparison with feed the depth of cut influence largely on MRR.

5.8.2 Analysis of Variance for Cutting Power

To find out the most influencing process parameter on Cutting Power, Analysis of variance was performed. ANOVA analysis of raw data for Cutting Power is shown in Table 5.8 clearly indicates that Cutting Velocity is strongly influencing the Cutting Power. From the last column from Table 5.8 it can be concluded that Cutting Velocity shows most influencing process parameter on Cutting Power and is followed by Table Feed Rate and Depth of Cut.

Table 5.8 Analysis of Variance for cutting power

Source	***Sum of Squares***	***df***	***Mean Square***	***F Value***	***p-value Prob > F***	***Significant/ Insignificant***	***Percentage Contribution***
Model	0.007474	18	0.000415	96.21745	< 0.0001	significant	-
CV	0.003602	2	0.001801	417.3053	< 0.0001	significant	47. 96
TFR	0.001781	2	0. 00089	206.3511	< 0.0001	Significant	23. 71
DoC	0.001267	2	0.000634	146.8141	< 0.0001	Significant	16. 87
CV X TFR	0.000738	4	0.000185	42.75861	< 0.0001	Significant	9. 83
CV X DoC	6. 16E-05	4	1. 54E05	3.569755	0. 0592	Insignificant	0. 82
TFR X DoC	2. 44E-05	4	6. 11E06	1.414925	0. 3126	Insignificant	0. 32
Residual	3. 45E-05	8	4. 32E06				
Cor Total	0.007508	26					

- ❖ Values of "Prob > F" less than 0. 0500 indicate model terms are significant.
- ❖ In this case CV, TFR, DoC, CV X TFR are significant model terms.
- ❖ Values greater than 0. 0500 indicate the model terms are not significant.

5. 8.2.1 Model Summary

R-Squared	0. 984
Adj R-Squared	0. 974
Pred R-Squared	0. 954

- ❖ Higher R squared values (100) indicate a significant fit for the model. In addition to that as CV X TFR from Table 5.8 is also one of the significant factor therefore the fit be a non-linear fit.

5.8.2.2 Regression equation for cutting power

Power =018+0. 014*CV-0. 0098*TFR-0. 0083*DoC+0. 0069CV*TFR

- ❖ CV X DoC and TFR X DoC are not considered in the generation of regression equation because these interactions are not significant.

5.8.3 Analysis of Variance for MRR

ANOVA analysis of raw data for MRR is shown in Table 5.9 clearly indicates that Depth of cut is strongly influencing the Cutting Power. From the last column from Table 5. 9 it can be concluded that depth of cut shows most influencing process parameter on MRR and is followed by Cutting velocity and Table Feed Rate.

Table 5.9: Analysis of Variance for MRR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significant /insignificant	Percentage contribution
Model	1. 8E-06	18	1E-07	1218. 88	< 0. 0001	significant	34. 32
CV	6. 18E-07	2	3. 09E-07	3767. 01	< 0. 0001	significant	4. 20
TFR	7. 57E-08	2	3. 78E-08	461. 069	< 0. 0001	significant	58. 35
DoC	1. 05E-06	2	5. 25E-07	6403. 51	< 0. 0001	significant	0. 184
CV X TFR	3. 33E-09	4	8. 33E-10	10. 1482	0. 0032	significant	2. 49
CV X DoC	4. 5E-08	4	1. 12E-08	136. 995	< 0. 0001	significant	0. 40
TFR X DoC	7. 23E-09	4	1. 81E-09	22. 0289	0. 0002	significant	0. 03
Residual	6. 56E-10	8	8. 21E-11				
Cor Total	1. 8E-06	26					

- Values greater than 0. 0500 indicate the model terms are not significant.

5.8.3.1 Model Summary

R-Squared	0. 9996
Adj R-Squared	0. 9988
Pred R-Squared	0. 9958

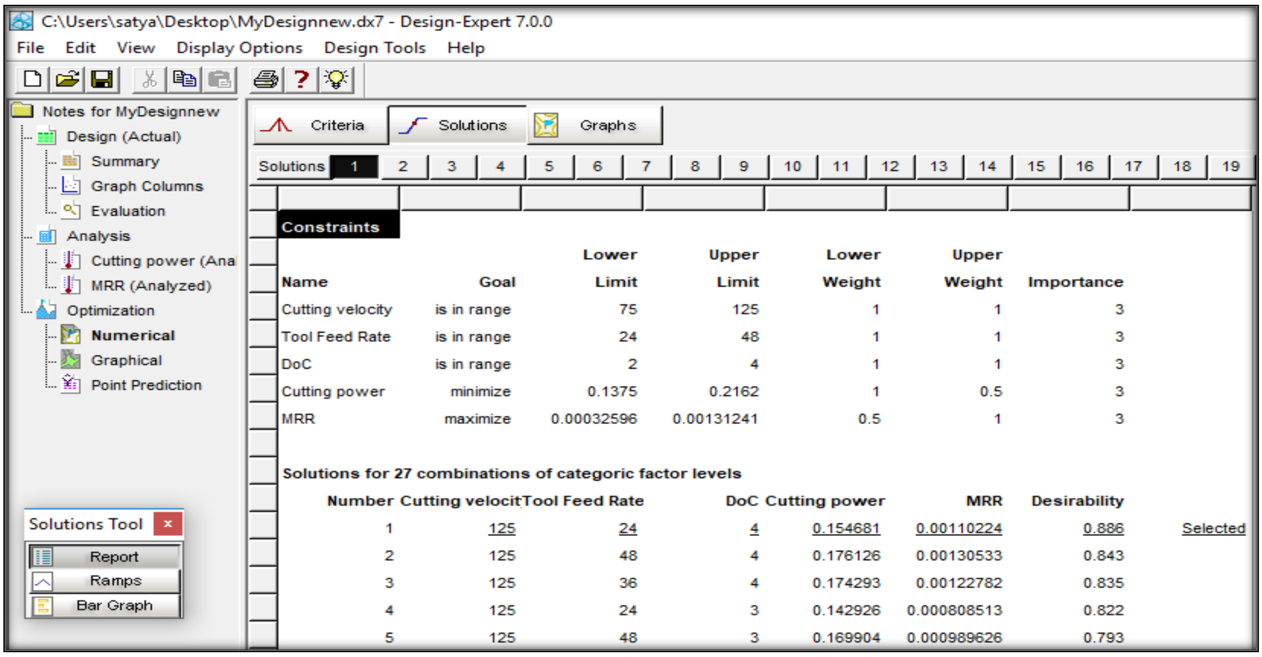
- Higher R squared values (near to 100) indicate a significant fit for the model. In addition to that interactions CV X TFR, CV X DoC, DoC X TFR from Table 5.9 is also significant factors therefore the fit be a non-linear fit.

5.8.3.2 Regression equation for MRR

MRR = 0. 000728-0. 00019CV+0. 00001TFR-0. 00024DoC+0. 0000128CV X TDR + 0. 000062CV X DoC -0. 000011TFR X DoC

5.9 Selection of Optimum levels

In the earlier section, effect of process parameters on individual performance characteristics have been carried out. For optimization of machining parameters, combination of these performance characteristics such as low cutting power and Maximum MRR to be made. Framing the problem with these multiple objectives to find optimum parameters to meet the objectives for safe and effective machining by allocating suitable weightage to each objective was carried out. When all the parameters considered together, it is possible to make a compromise in some properties, while enhancing others so that the desired objective is attained.



Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cutting velocity	is in range	75	125	1	1	3
Tool Feed Rate	is in range	24	48	1	1	3
DoC	is in range	2	4	1	1	3
Cutting power	minimize	0.1375	0.2162	1	0.5	3
MRR	maximize	0.00032596	0.00131241	0.5	1	3

Number	Cutting velocit	Tool Feed Rate	DoC	Cutting power	MRR	Desirability	
1	125	24	4	0.154681	0.00110224	0.886	Selected
2	125	48	4	0.176126	0.00130533	0.843	
3	125	36	4	0.174293	0.00122782	0.835	
4	125	24	3	0.142926	0.000808513	0.822	
5	125	48	3	0.169904	0.000989626	0.793	

Fig 5.16 Constraints for the process parameters and performance characteristics

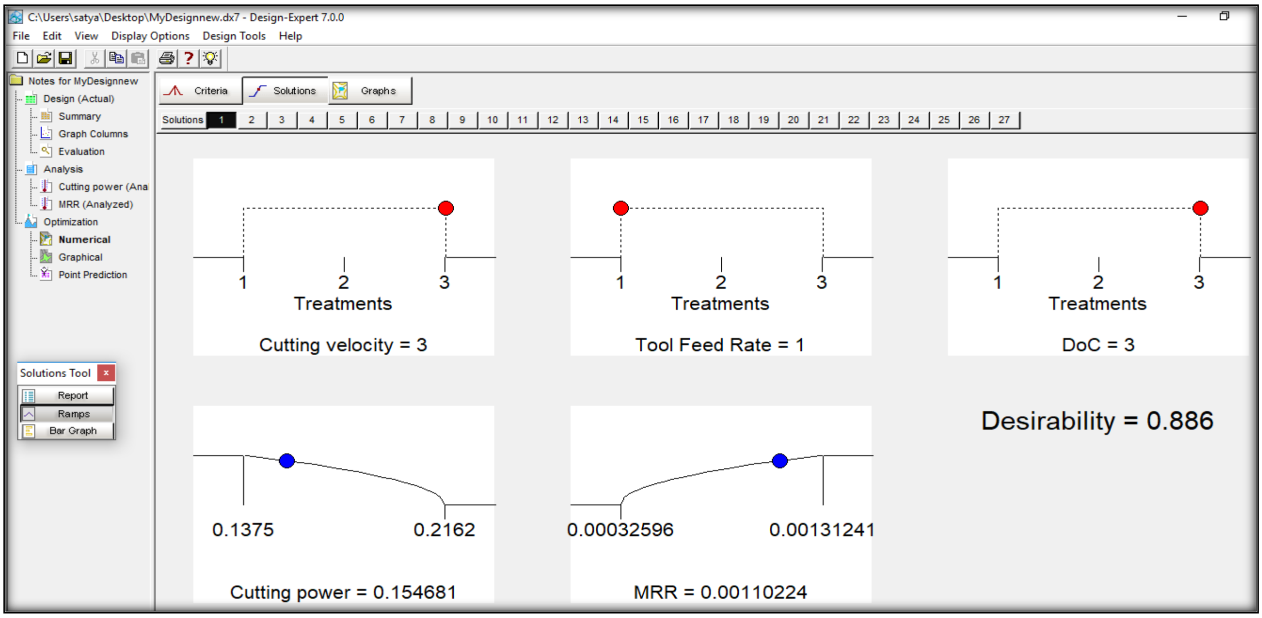


Fig 5.17 Optimal level of process parameters

Here numerical optimization of process parameters for milling of CSP material for Turbine cutter using Design Expert (response surface methodology) is presented. The process parameters considered are speed, feed, and depth of cut are optimized with considerations of multiple process characteristics including minimum cutting power and Maximum MRR. From the Fig 5.16 and 5.17 it can be concluded that for getting optimum condition one can perform experiments at cutting velocity at level 3, Table feed rate at level 1 and Depth of cut at Level 3 with Desirability 0.88

5. 10. Summary and Conclusions

Incorporating the modification of prototype cutter and chip slicer concepts for slicing of chips in width direction a simple, safe and versatile cutter assembly called 'Turbine cutter' developed and implemented for machining of 'Hard to machine' work materials like CSP.

In the present chapter, the 2FI models for Cutting power and MRR have been developed to investigate the influences of machining parameters in machining of CSP material. The experimental plan is based on general full factorial design. The effects of machining parameters such as cutting velocity, table feed rate and depth of cut, have been evaluated by using RSM. The following conclusions are drawn based on this study:

a) Cutting power increases with increase in DoC and TFR, this is because at larger feeds or depths of cut, larger volume of the deformed metal and consequently the resistance of the material to chip formation is greater.

b) Cutting power decreases with increase in CV this is because as CV increases, following chips are thinner and shear angle increases and increase in rake angle leads to decrease in tool-chip contact area.

c) MRR increases with increase in CV, TWR and DoC this is because at lower speeds, due to high coefficient of friction between tool and rubbery binder of work material cutting forces are significantly high. Comparison with feed the depth of cut influence largely on MRR. All the trends observed while evaluating tool geometry with prototype cutter on non reactive material, are in line with the trends resulted in the present experiments. It indicate the experimental methods adopted in earlier chapter are validated.

d) 2FI models developed using RSM are reasonably accurate and can be used for prediction within the limits of the investigated factors.

e) The results of ANOVA have proved that the 2FI models can complete prediction of Power and MRR with 95% confidence interval.

f) 2FI models developed for independent performance characteristic such as Max MRR, Min Cutting power of machining of CSP and combining both the performance characteristics multi objective optimisation carried out to evolve safe and effective process parameters.

g) The results show that the optimal combination of machining parameters is 125 m/min, 24 deg/min and 4 mm for cutting velocity, table feed rate and Depth of cut respectively. The result of optimum condition was correlated with the experiment results of full factorial experiments. The experimental results confirm the predicted results from mathematical modelling. Adopted approach and models for optimizing the cutting parameters were validated.

In the present work, the safe and effective machining parameters for machining CSP material were established. However, tool wear studies have to be performed to understand the mechanism of wear as the work material basically consists of strong oxidisers, which will be the major focus in the next chapter.

6. 1 Introduction

Understanding the science underlying machining of new materials is an important aspect of metal cutting research. HTPB based CSP material show similar mechanical behaviour of filled elastomers when subjected to machining loads but the filler ingredients in CSP are chemically reactive and highly inflammable in comparison with fillers of regular elastomers. Lewiset al [105] has studied end milling of elastomers using woodworking tools, along with cryogenic cooling. Use of induction heated tools at low speed machining of elastomers has been studied by Luo et al [106, 107].Use of cryogenic cooling and induction heated tools is not a possible option in this case of CSP machining due to hydroscopic contamination and fire/explosion hazard due to heat sensitivity of propellants respectively. Hence, a conventional machining process using specially designed cutter called Turbine cutter that carries a set of custom-built HSS inserts was developed. The present chapter focuses on study of tool wear pattern, establishment of predominant tool wear mechanism and fixing the tool life criteria of HSS insert in machining CSP of Solid propellant Rocket Motor (SRM) grain.

Rapid mechanical wearing of the tools has often been attributed to the presence of hard constituent and other abrasive agents in work materials [108-109].However, chemical wear due to extractives such as gums, fats, resins, sugars, oils, starches, alkaloids and tannins in wood/composites and other similar organic work materials has been reported as an important factor in determining the wear characteristics of cutting tools [110-112].

Generally solid propellant grains were vacuum casted with Ammonium Perchlorate as oxidizer and metallic Aluminium as fuel ingredients. The cured strand of solid propellant material exclusive of casing is referred as propellant grain. These propellant grains of rocket motors were remotely machined by Special purpose CNC vertical turn milling machine using 'Turbine cutter' that carried four HSS conical inserts, with integrated safety systems for evacuation of propellant chips that were produced during machining. Vacuum being applied at the cutting zone through insert and hollow cutter body for evacuation of chips. The application of vacuum was also served to cool down the temperature of the insert while machining propellant grains. Visible and irregular pattern of damage was found on insert rake and flank face after a definite period of cutting hours and this damage aggravated further on continuation of machining.

Attempts were made for analysing and concluding the predominant tool wear mechanics on the cartridge type HSS inserts developed Turbine cutter, under prevailing working conditions and the tool & work combination. This chapter is presented with limiting values of tool wear for this specific scenario of machining energetic ingredient CSP with HSS, as it is always important to identify the time for tool change / indexing of insert to replenish the new cutting edge for smooth and safe machining practices. This study also suggested simple but effective measures to delay the wear mechanism for economic and safe machining of SRM grains using the custom build HSS cutting element.

6. 2 Experimental method for HSS tool wear studies

Method adopted for conducting the experiments and various system used are presented in the following section

6. 2. 1 Machine and cutter

Experiments were conducted with a special purpose CNC Vertical Turn Milling (VTM) machine illustrated in Fig 6.1 (make: BECO, model: special purpose VTM-15kW) using developed Turbine cutter whose details were presented in Fig 6.2. Turbine cutter was assembled to Chip and Dust Collection System (CDCS) through arbor and rotary joint as shown in Fig 6.1 for safe chip evacuation while machining. Because of the explosive nature of material, experiments were conducted and monitored remotely form the remote control room of machining facility to comply with safety practices.

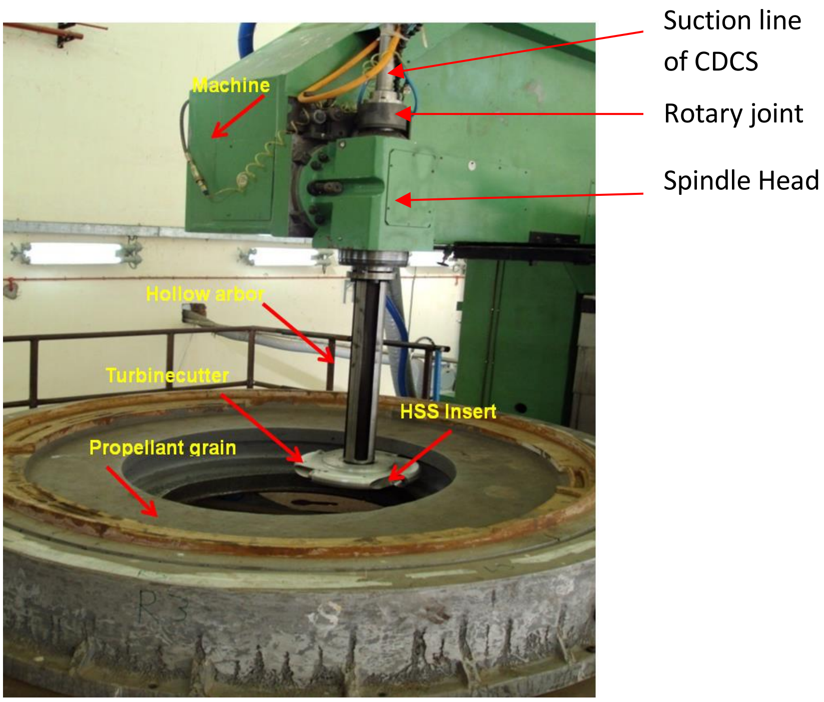


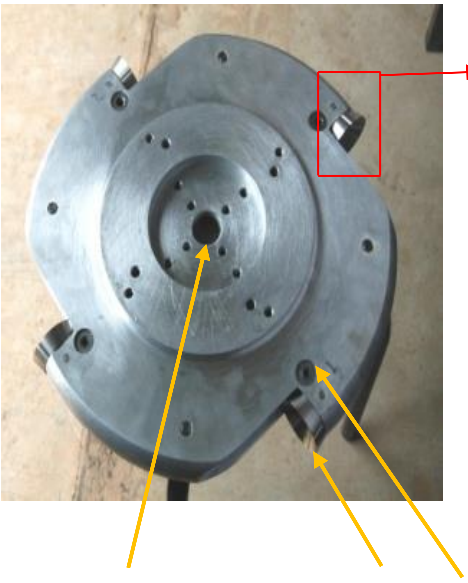
Fig.6.1: Experimental set-up of CNC-VTM with Turbine cutter

6. 2. 2 Cutting element/ insert and machining parameters

Four HSS conical inserts of M2 grade as shown in Fig 6.3 with integrated chip slicer were assembled to the Turbine cutter as illustrated in Fig 6.2 for all the runs. Safe machining parameters were applied throughout the experimental runs at constant values. These cutting parameters were arrived from the optimization studies as presented in earlier chapter and established by monitoring temperature at the cutting zone to be less than 50°C. Temperature was monitored using an infrared thermometer. Machining parameters and environmental factors at which the experiments were conducted are shown in Table 6.1. Experiment was conducted to study the wear on 2 sets of inserts (08 inserts). The optimum machining conditions obtained from the studies in the previous chapter are applied for present tool wear studies

Table 6.1: Machining parameters & environmental factors

Machining Parameters	
Cutting speed	125 m/min
Rotary table feed	24deg /min
Depth of cut	4 mm
Machining environment factors	
Machine bay Ambience Temperature	28 -32° C
Relative Humidity	75-85%
Coolant	Dry machining
Vacuum at the cutting edge	240 mm Hg below Atm



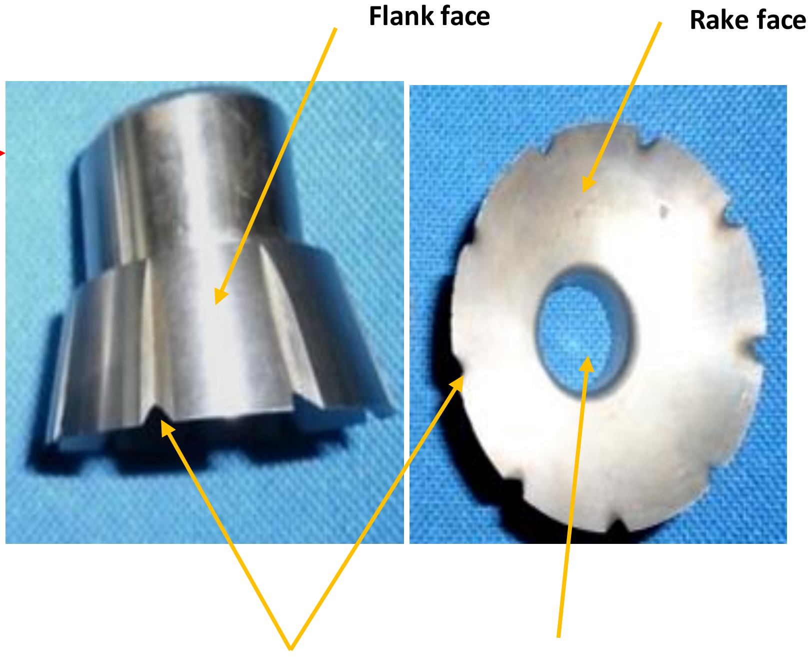


Fig.6.2: Turbine cutter

Fig.6.3: Custom-build HSS conical insert of Turbine cutter

6. 2. 3 Work material:

Work material was already analysed for its composition and their dispersion in the composite matrix using a microscope with an image analyser (Olympus GX71, 200x magnification) in chapter-3, wherein major portion of composite is filled with AP particle as filler which is a strong oxidizer. Mechanical properties were determined to get comprehensive knowledge of the material characteristics. INSTRON UTM machine (model: 5500) was used to measure tensile strength, modulus of elasticity, and percentage elongation as per IS 3400 standards. Density was measured using gravimetric method. Hardness was measured using shore's hardness tester (make: Mitutoyo, Model: MLR322). Mechanical properties of work material being used for this tool wear studies are presented in the Table 6.2.

Table 6.2: Mechanical properties of propellant grain material

Tensile strength	600 kN/m^2
Young's Modulus	4000 kN/m^2
% elongation	30
Hardness	76 on Shore-A scale
Density	1. 17–1. 21×$10^3 kg/m^3$

6. 2. 4 Method:

Machined surface, un-machined as cast surface of CSP, and propellant chips were analysed under microscope to understand the phenomenon of chip formation and investigate the reasons of tool wear. Tool wear progression was analysed by observing and measuring surface damage on the rake and flank surface of insert at regular intervals of time using Vision Inspection System (VIS) as shown Fig 6.4, to measure the tool wear pattern. VIS Measure all geometric 2-D parameters like distances, curves, circles, angular measurements etc., and generate drawings of the measured profiles along with dimension in CAD file format. These CAD files can be imported and exported for the convenience to analyse and compare the measured dimension with actual profile. It offers more flexibility for measuring and recording the wear on inserts. Specifications of vision inspection system were presented in Table 6.3. Both the VIS and USB digital microscope as shown in Fig. 6.4 and 6.5 respectively were used for tool wear and chip morphological studies.

Table 6.3: Specification of Vision inspection system

Measurement range	X-axis 150mm Y- axis 100mm Z-axis 150 mm
Magnification	67x
Resolution	0. 001
Accuracy	0. 005 mm on X and Y traverse
Load capacity	Job weight up to 10 Kg
Manufacturer	Optimech EnggPvt Ltd, Hyderabad

Fig. 6.4: Vision Inspection System (VIS)

Fig. 6.5: USB digital Micro scope for chip morphology Study (Capacity: 2000x)

Surface roughness of the machined surface greater than 400 µm and/or the extraction efficiency of CDCS, less than 95% (where the accumulation of chip in the cutting zone start) was set as the output limiting parameter to sense the limit of HSS insert tool life. Replenishment/replacement of new cutting edge in the Turbine cutter by indexing the HSS insert was carried out when the tool wear on the inserts reaches its maximum / tool wear criteria. These Output values cover the performance, functionality and safety aspect of cutter. Handy surf instrument is used to measure the surface roughness of machined surface of CSP. The surface is measured by moving the stylus of Handy surf across the surface. As the stylus moves up and down along the surface, a transducer converts these movements into a signal which is then transformed into a roughness number along with a visually displayed profile. Efficiency of CDCS was measured as follows.

$E = m_e/m_t \times 100 = (m_t - m_r)/m_t$: where m_t = total mass of chip produced

m_e = mass of extracted chips, and m_r = mass of non-extracted chips

Yet other constrained parameter that should be kept below the limiting value is the cutting temperature which should not exceed 60 °C on the cutting element, and was measured by Infrared thermometer. In all he runs of experiment it was between 52-55°C. It was found that temperature reaching near 60 °C at the end of HSS tool life due to worn out/ damaged cutting edge by corrosion.

6. 3 Understanding the Chip Morphology

a) Type of chips observed

While machining the propellant grain with HSS conical insert using developed Turbine cutter assembly, long continuous ribbon type chips, and powder of propellant ingredients as shown in Fig 6.6 were produced, as speculated in the microstructure studied of the CSP material (Chapter-3). The powder consisting of AP particles were produced along with chips. It is also observed that the ingredient AP powder traces, on the fresh machined surface and on few intricate location of cutting elements particularly in the cleaved chip slicer. The length and width of chips produced by the round edge conical shaped insert were proportional to the width of work piece material engaged with cutter in one revolution (breadth of cutting pass) and depth of cut respectively. The width of chip is approximately equal to chard length of round insert that is engaged with work material. More the number of chip slicer smaller will be the width of chip and more will be the number of chips. The chips are collected and studied for their micro structure and morphology.

(a) **(b)** **(c)**

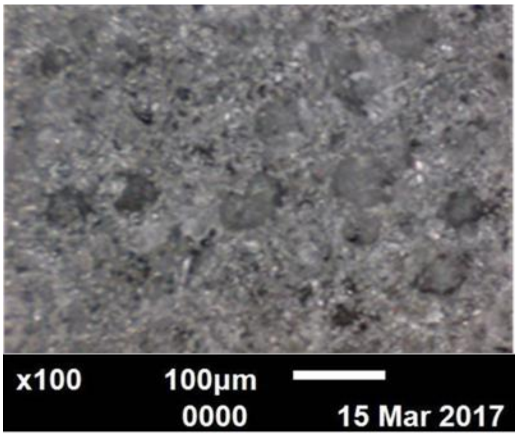
(a) & (b) Long continues ribbon like chips *(c) Tiny chips with powder*

(d) Slender chips produced with increased number of chip slicers during machining of propellant grain

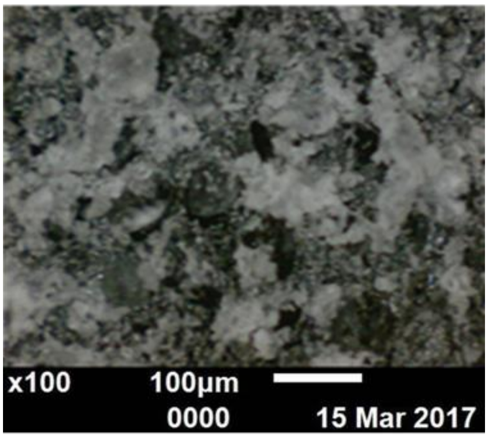
Fig.6.6: Propellant chips

b) Propellant chip analysis

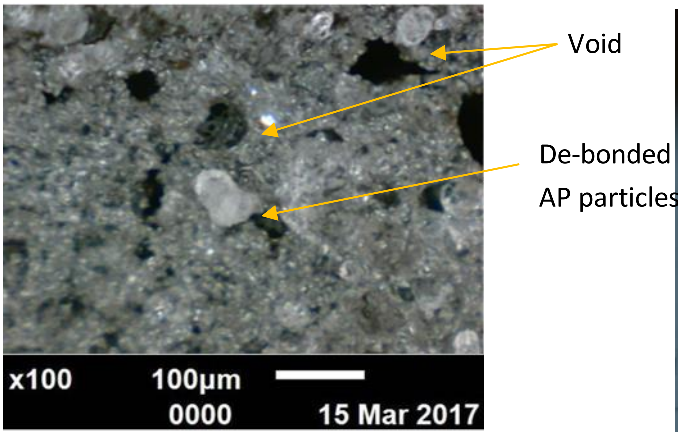
Machined surface (Fig. 6.7(a)) was compared with cast and cured un-machined surface (Fig. 6.7(b)) of CSP material to get an idea of surface transformation. USB digital microscope as shown in Fig.6.5 was used for chip morphological studies. Cluster of AP particle due to agglomeration was found on the machined surface. De-bonding of Ammonium Perchlorate particles from the machined surface was found as shown in Fig.6.7(c) along with dispositional AP particles. The cross section of the chip was found to still have the particles in loose interaction with binder as shown in Fig.6.7 (e). Thin chips were produced at lighter depth of cut (<1mm) looked like a thin sheet of net with see through holes as shown in Fig. 6.7(d) where the through holes on the surface of chip is due to separation of AP particles from polymer binder matrix during cutting. It was checked by passing the light at one surface of chip and observing it other surface shown in Fig. 6.7(d). With increased depth of cut the thicknesses of the chip increased and through holes on the surface were not apparent because of availability of volume of material between the two surfaces of the chip cross section.



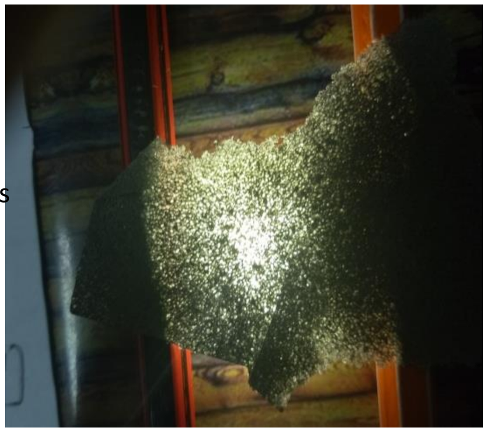
(a) Un machined Surface



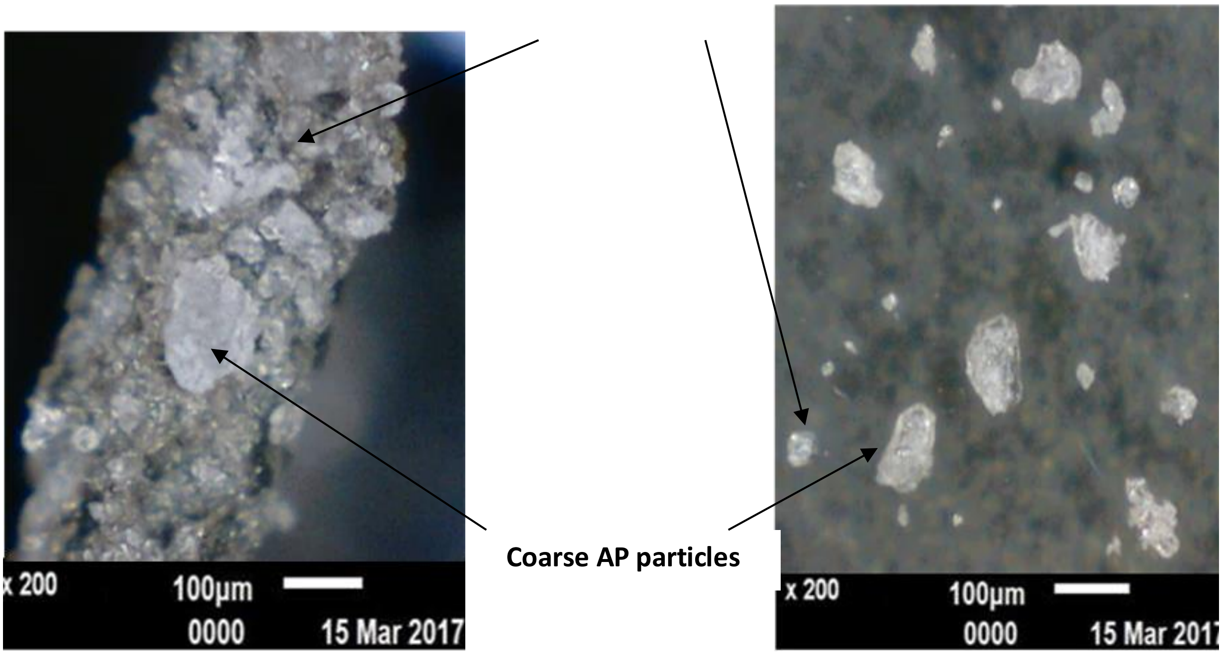
(b) Machined surface



(c) Voids and debonded particles


d) See through holes in thin chip of propellant

Fine AP particles



(e) Chip cross section *(f) AP particles deposited on machined surface*

Fig.6.7: Chip morphological analysis

6. 4 Tool wear and possible tool wear mechanisms in machining of CSP using HSS insert

Cutting tools/inserts can be used as long as they do not reach tool life criteria and can produce parts with desired surface finish and dimensional accuracy [113].Tool wear is defined as a gradual loss of tool material at contact zone of work piece and tool material, resulting the cutting tool reaches its tool life criteria [12].There are several causes and mechanisms of tool wear. Friction on rake face and on the flank of the tool occurs under a close contact of freshly created surface of the work piece material.

When the keen edged HSS insert whose hardness is much higher than the CSP work material (measured on Shore-A hardness scale) penetrates the work material, it allows large area of contact at the tool and work interface at cutting zone. But due to the mere adhesive bond strength of binder with filler AP particles, the loosely emended particles of AP in the composite matrix, the work martial are not capable of abrading the cutting tool. But the cutting edge and faces of insert were found damaged restricting the smooth flow of chips over rake face of insert, which form convergent suction inlet at the cutting zone for effective chip disposal. The damage of cutting edge also resulted rough surface finish on machined surface of CSP material.

6.4.1 Mechanical Wear

Various mechanisms that contribute to the mechanical wear of cutting tool are mechanical over load causing micro breakages (attrition) abrasion, adhesion and diffusion. Attrition is due to breakage of grain boundaries dragging of various components of tool material whereas abrasion is scratches on soft material by hard particles which generally apparent when tool material is relatively low hard in comparison with work material. Adhesion is tight and intimate contact between the tool and freshly created surface of work piece under pressure causing welding of chip in to tool surface and subsequent breakage of these interfaces thus damaging tool surface by build-up edged chip and forming crater on tool faces.

At moderate deformations of HTPB /AP/AL composite material by cutting loads, the material is incompressible and the volume remains constant due to heavy loading matrix with solid particles. Beyond a certain critical level, the particles-binder dewetting process begins particularly between binder and inorganic AP particles and the volume rate increases rapidly with the number of locations where debonding takes place. Once the potential number of particles debonding is reached, the macroscopic volume increases proportionally with the volume of each single void and the response is linear. Since the solid loaded polymer material when subjected to compressive loads by cutting edge of insert, the impregnated particles of AP ploughed out from the composite matrix readily not causing significant mechanical damage to cutting edge / tool rake face. Since the good damping properties of HTPB propellant, the AP particles filled in polymer matrix is not able to make a hard scratch/ abrasion on the HSS insert as binder offer cushioning effect for such severe loading conditions that present during cutting. The hardness of propellant in comparison with HSS is negligible. However annular shaped AL powder particle strongly embedded with binder envelop do not offer its sharp edges to come in contact with tool material directly. In view of above facts and relatively high hardness of HSS material in comparison with given work material and the mere adhesive strength of AP with binder the possibility of mechanical wears of tool material was stroked off.

6.4.2 Electrochemical wear

The corrosion observed on the cutting element during the machining is expected due to electrochemical reaction. Electrochemical reduction is not possible at potentials $E > 1.37$ V, for thermodynamic reasons [108].Since the required potential values which is not present at cutting zone due to straining of work material and continues rubbing of work material with tool the possibility of electrochemical wear is ruled out. Research paper also concludes that corrosion on steels in presence of ammonium perchlorate and moisture is not an electrochemical reaction [108].

6.4.3 Chemical wear

A possible explanation for tool wear while machining CSP work material with HSS cutting tool could be the decomposition of perchlorate to oxygen and chloride in presence of moisture at the interface of the passive layer and the electrolyte. This chloride acts as an aggressive anion causing pitting/ deep in to deep corrosion [108, 111].Chlorate causes breakdown passivity and localized corrosion. All the trials for this observation were conducted at the ambience where Relative Humidity is nearly 80%. To confirm this interpretation, rake and flank surfaces were studied under microscope which reveals its deterioration is by pitting corrosion as shown in Fig.6.8. The possible chemical reaction is as indicated below:

$$NH_4ClO_4 + 4\ H_2O + 4Fe \longrightarrow 4Fe(OH)_2 + NH_4CL$$

6.5 Tool Wear analysis of HSS insert

The experiments were repeated with 2 sets where each set carries four conical inserts in the Turbine cutter. The study and analysis was focused on more damaged insert in both the experiments. One set of inserts photographed during the experiments were shown in the Fig. 6. 8 (a) and (b) indicating the damage inception both on rake and flank faces respectively.

(a) Corrosive damage on rake face of the inserts (b) Corrosive damage on flank face of inserts

Fig.6.8: Tool wear inception in HSS insert of turbine cutter

Fig.6.8 shows the progression of tool wear on flank surface. Fig.6.9 (a) shows formation of local corrosion lines/dendrites on the cutting edge alone. Fig.6.9 (b) shows further dispersion by growth of corrosion lines on the flank close to the cutting edge and its inception appears on the cutting edge which is the weakest part of the structure. Fig 6.9(c) shows the formation of small and irregular crater along with the corrosion lines at the same cutting hours of experiments (38 Hrs) at two different location of the cutting edge.

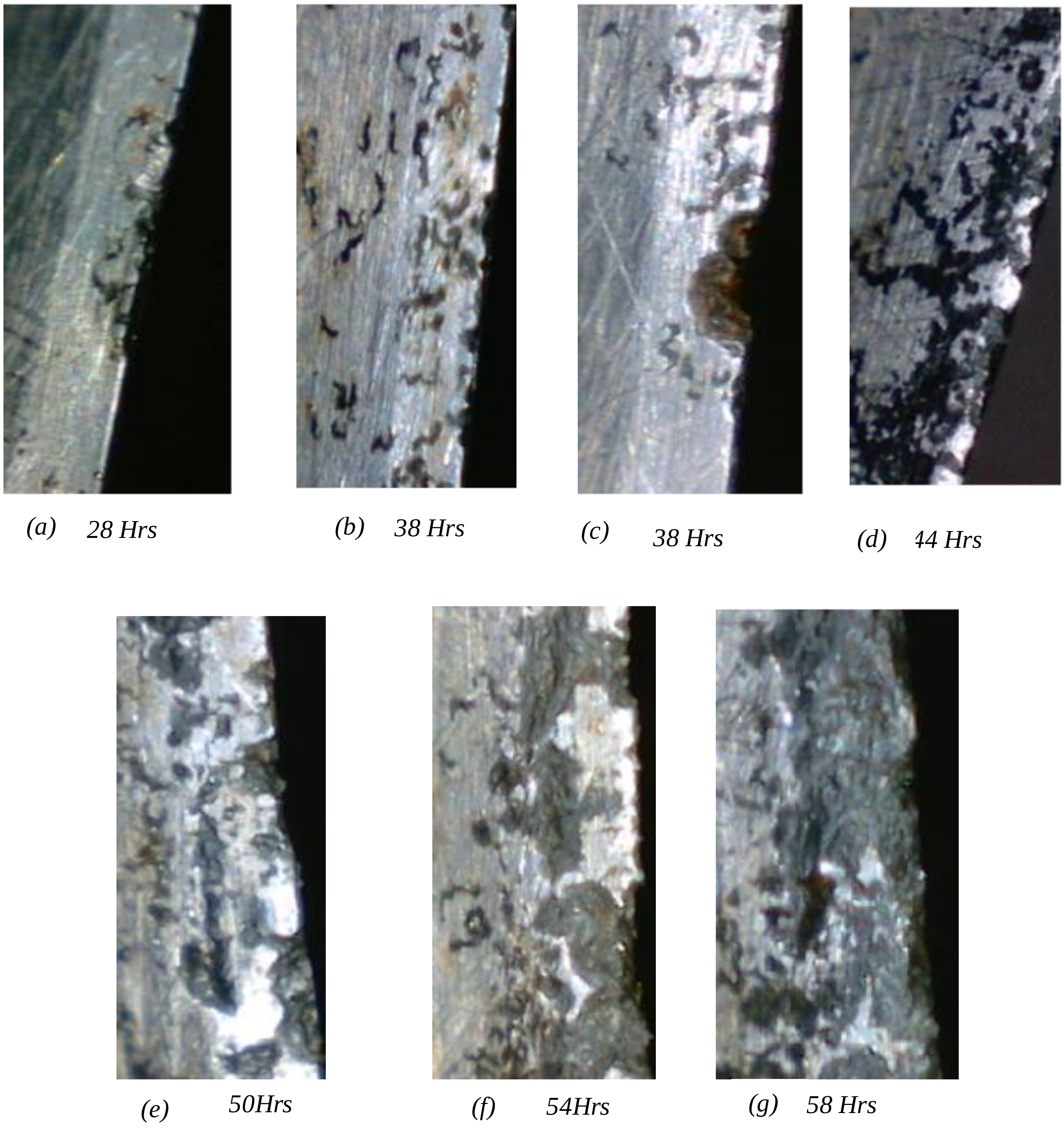


Fig. 6.9: Progression of tool wear on HSS inserts

(Magnification x100)

The tool edge can be seen to have eroded unevenly. Fig.6.9 (d) shows merging of local corrosion lines and spots into a patch of damaged area, but the depth of surface damage was not severe. Fig.6.9 (e) indicates the growth of patches in depth direction and formation of craters and pits by corrosion/pitting due to chemical wear. Fig. 6.9(e) shows deepening of corrosion patches. Fig. 6.9(f) shows growth of pitting patches into large pitting volumes and eaten volumes of tool material weakening the cutting edge significantly. Fig. 6.9(g) shows the final worn out/eaten away area of tool by corrosion action resulting replenishment of fresh cutting edge by indexing all the four inserts. This total damage is observed on the flank face of the tool and along the cutting edge. The cutting hours indicated under each figure represents the rate of tool wear with time. A similar gradual wear on the rake face was also observed. The pattern of wear is irregular at both rake and relief face. Wear volume is more on rake face than flank face. The damage is same in both the experiments and limit for the average tool life was found to be 58 hours.

6. 6 Analysis of tool wear pattern and establishing tool wear criteria

Tools wear by corrosive damage was recorded at regular intervals of time through visual inspection of damage of the insert. The subsequent measurement of damage was also carried out by Vision Inspection System. Limit of tool life is recognized through the surface roughness of machined surface or accumulation of chips in the cutting zone due to uneven and rough rake surface of the insert that resulted by the damage of tool rake face which form the entry hood for chip flow. Surface damage both on rake and flank surfaces of the insert and crater formation by corrosion were measured. The wear pattern observed is converted into a CAD drawing that can be used to measure area of wear and also maximum wear in horizontal and vertical directions as shown in Fig.6.10. These have been used to calculate maximum wear in both X and Y direction as H_x and H_y respectively as shown Fig.6.10. Fig.6.10 (a) and (c) show the magnified images of the tool flank and rake respectively. Fig.6.10 (b) and (d) show the CAD profiles generated from the images produced by Vision Inspection system. The area calculated for these irregular shapes using the Auto CAD tool was used to quantify the surface damage on rake and flank surfaces of the insert and standardized the criteria for tool life not only by depth of crater but also by the area of damage. The averages of maximum tool wear, presented in Table 6.4, on rake and flank surfaces were set as wear criteria in length units. Tool wear criteria in area units (A_d as area of damage) were established as shown in Table 6.4 and explained through Fig.6.11. These limits have to be chosen as wear criteria for defining tool life for HSS insert while machining CSP materials that contain AP as major ingredients.

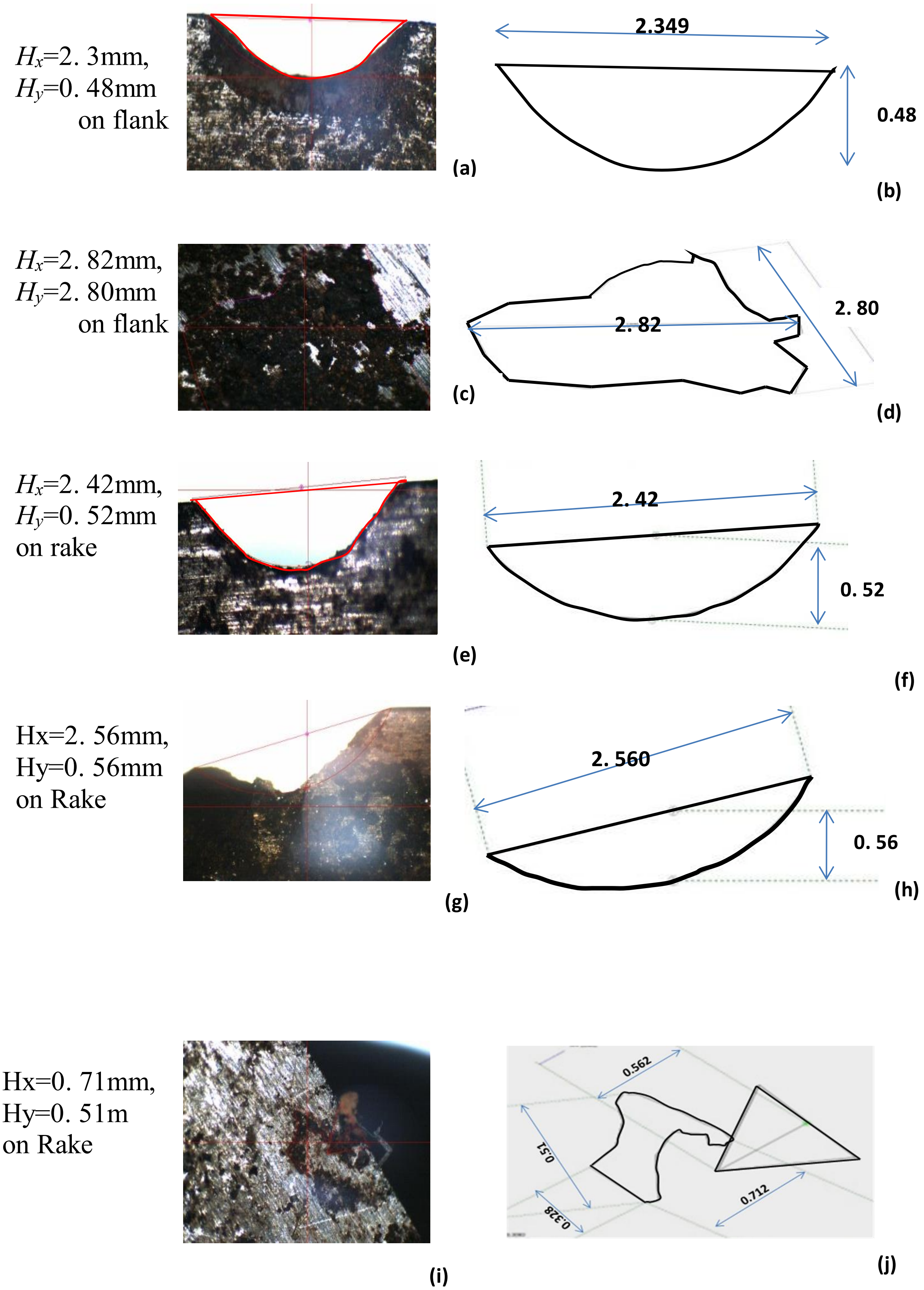
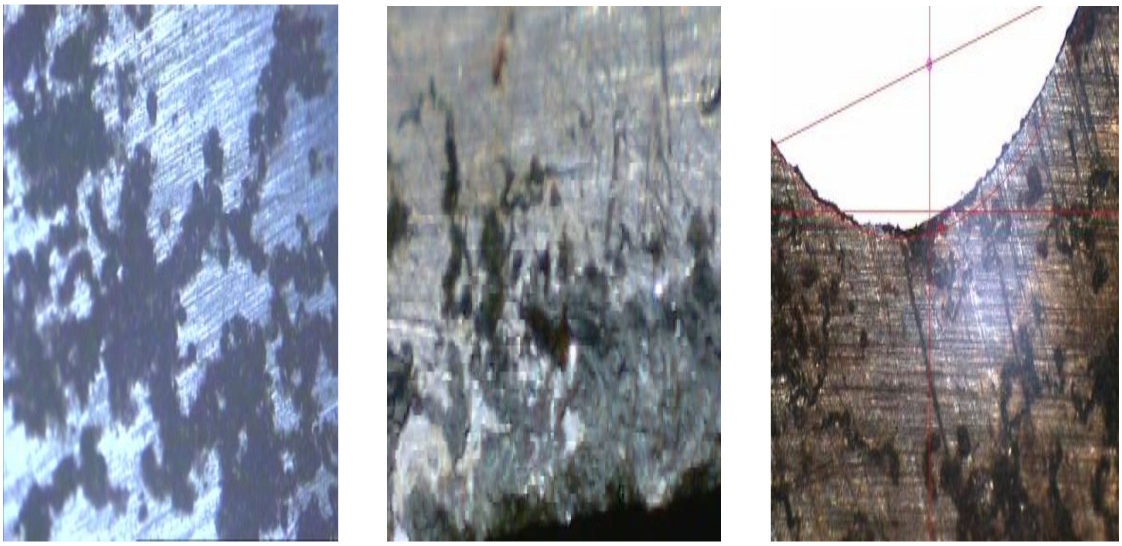


Fig.6.10: Analysis of tool wear pattern (in length unit)



A_d= 55% on rake away from Cutting edge | *A_d = 30 % on rake Immediate to Cutting edge* | *A_d = 10% on cutting edge by Carter*

Fig.6.11: Analysis of tool wear pattern (in Area unit)

Table 6.4: Average of maximum tool wear (tool life criteria)

	$H_{x,\,max}$ (in mm)	$H_{y,\,max}$ (in mm)	$A_{d,\,max}$ (% area) Immediate to cutting edge	$A_{d,\,max}$(% area) Away from Cutting edge
Rake surface	2. 82	2. 8	30 %	55%
Flank surface	2. 48	0. 55	30%	55 %

6. 7 Results and discussion

The ammonium perchlorate present in the propellant forms perchloric acid upon contact with moisture as per the chemical reaction shown below.

$$NH_4ClO_4 + 4\ H_2O + 4Fe \longrightarrow 4Fe(OH)_2 + NH_4CL$$

Perchloric acid ($HClO_4$) is considered as one of the strongest super-acids, which is very reactive with metals, highly corrosive, and a strong oxidizing agent. At room temperature, perchloric acid (up to a concentration of 72%) has properties similar to other strong mineral acids like hydrochloric acid, sulphuric acid, nitric acid, boric acid, etc. Corrosive efficiency of perchloric acid increases with increase the concentration as well as temperature of the test sample. To verify the presence of perchloric acid in the test sample, diphenylamine test was carried out. Diphenylamine is a weak base, and generally forms salt with strong acid which on addition to the test sample containing ClO_4^{-1} anions makes a black coloration. One gram of diphenylamine was dissolved in sulphuric acid to form diphenylamine sulphate [$(C_6H_5)_2NH_2$] [HSO_4] solution. This diphenylamine sulphate solution was added to the test solution using a medicine dropper. It was found that the test sample solution turned black indicating the presence of perchloric acid (HClO4) in high concentration.

From this confirmatory test it is concluded that ammonium perchlorate, present in the propellant chips and on the machined surface in the cutting zone, upon contact with moisture that is present in working environment and elevated temperature of the insert due to cutting action was converted to perchloric acid and primarily responsible for corrosion of the test sample (insert) under study.

It was found through microscopic studies that the traces of propellant material including loose AP particles were deposited in chip slicer groove/clevis at the end of the cutting hours of machining day. Few AP particles were also struck on the rake surface where rough pits produced by corrosive pitting reaction. The presence of this material aggravates the corrosion process on the cutting element, if not cleaned thoroughly. The insert was therefore, cleaned thoroughly with dioctyl adipate (DOA) which is commonly used as plasticizer in HTPB based propellant processing units.

To find the significance of frequent removal of such AP powder cladding on the insert by cleaning initially with DOA wetted cotton cloth, and subsequently with a wet cotton cloth followed by thorough cleaning with dry cloth to ensure complete removal of the AP particles from the surface of the cutting tools practiced in all the cutting days. The propellant traces tightly stick on the insert got weakened by dissolving in DOA and breaking the adhesive bond with insert surface when thoroughly wiped out with DOA wetted cloth. The traces were then removed easily in successive cleaning steps making the active cutting edge free from the materials that cause corrosion of HSS tool. The cleaning activity was carried out at the end of every cutting day in isolation of work material as work material is reactive to these cleaning agents. It was done by retracting the machine spindle head away from cutting zone by programming it to park the spindle in original home position then carried out the cleaning. It is also studied to find out the effect of cleaning of insert on tool life, and it was found that the tool life extended significantly after removal of adhered materials/particles as cleaning the cutting tool delay the corrosion process. Maximum 6-8 hours of extension of tool life was observed in the present study with proper cleaning and management of HSS insert in propellant environment.

6. 8 Conclusions

Normal mechanisms of HSS tool wear [109] were not found while machining propellant grain. As the work piece material being soft, there is no abrasive wear on HSS insert by AP/Al particles that present in the CSP. As can be seen from the images, the wear was spread in a larger area with visible corrosion pits and patches. Due to lack of large electrode potential difference between the tool and work piece material, the possibility of electrochemical wear can be ruled out. Chemical (corrosive) wear can be the predominant wear mechanism.

The predominant wear in HSS insert of turbine cutter while machining of HTPB based composite propellant grain with AP as oxidizer is chemical wear. This can be attributed to the presence of strong oxidizer in large quantities (67. 86%) in work piece and chips and presence of moisture (RH 85%) in the surrounding environment (Table 6.1). The pitting corrosion on rake and flank faces of the HSS insert confirms the same. This wear is further accelerated in presence of high RH values at the cutting zone and application of air stream as vacuum near cutting edge. The knowledge of possible tool wear mechanism enables in designing a suitable inert coating for the tool and in selection of new tool materials. This kind of wear can be prevented by a suitable inert coating on tool or machining in inert environment. However, there is a possibility of adsorption of inert gas by work piece material which prevents application of inert gas in cutting zone. Non corrosive coating on insert is found to be economical on such a large size of insert incorporated with a provision for indexing to use its cutting edge completely before it is replaced.

Thorough clearing of cutting element with DOA, clean water and subsequent cleaning of the insert with dry cloth at the end of every cutting day helped to extend the tool life significantly.

The method used to measure wear pattern in this study established a way to determine various parameters of flank and crater wear, including crater depth. The HSS tool wear studies also established the method to fix the life criteria for HSS insert of Turbine cutter to enable timely replenishment of inserts upon wear. These values serve as reference to avoid inadvertent situations that arise from the usage of blunt cutting edge and rough faces of the insert produced by chemical wear of insert in machining CSP materials with HSS inserts. Tool wear criteria in length units on rake is $H_x = H_y = 2.8$ mm, on flank it is $H_x = 2.5$ mm $H_y = 0.5$mm. Area criteria for HSS tool wear is varying from 10% to 55% depending upon the location of wear and pattern of wear.

7.1 Summary

In the present work, a safe, effective and versatile cutter assembly has been developed for machining of 'Hazard to machine' CSP grain materials of SRM through investigation of microstructure of composite propellant material and evaluation of its mechanical properties. The conclusions drawn from these investigations on machining of CSP material were used as input parameters for design and development of prototype contouring cutter. The tool signature for the prototype cutter is fixed through experimental studies and performance of developed prototype cutter is primarily verified on non-reactive work material whose microstructure, composition and mechanical properties are equivalent to actual CSP work material. It is done as verification procedure before implementing the tool signature in final cutter which is intended to apply on fire sensitive and hazardous live propellant material. The improvements observed in the prototype cutter design were incorporated in the final cutter assembly called 'Turbane cutter' complying with the safety requirements of machining of CSP material.

ANOVA analysis was carried out on full factorial results to find out significant parameters. The effect of speed, feed and depth of cut on output performance characteristics such as Cutting power (P) and Material Removal Rate (MRR) were analysed using 2FI model. Optimisation of parameter levels and mathematical modeling were performed using RSM. With this analysis the safe and effective parameter for machining of 'hazard to machine' CSP material using turbine cutter were established. Experimental method for safe conduct of experiments for machining CSP material was also demonstrated.

Tool wear studies were carried out with developed Turbine cutter to understand the predominant tool wear mechanism in machining of CSP material. The wear in cutting element/insert was analysed using Scanning electron microscope (SEM) and Vision inspection system (VIS). The predominant wear mechanism in machining CSP using HSS insert was concluded as chemical wear. The limiting value of tool wear was established. Simple and effective method to delay the chemical tool wear also suggested.

7.2 Conclusions

The following conclusions can be summarized from the present research work

7.2.1 Investigation on microstructure of CSP for cutting tool design

a) Porosity in CSP is an inherent structural defect in CSP which contributed favorably for low cutting force of CSP material.

b) Nose radius of the cutting edge is determined by the maximum size of coarse AP particle and its distribution in the formulation of CSP material as it affects the surface finish.

c) This study also highlighted the need for provision of suction of chips and air borne propellant dust generated during maching as it leads to fire hazards.

d) The low yield strength and hardness of CSP recommends the use of large rake and relief angles.

7.2.2 Development of prototype cutter and evaluation of tool geometry

A prototype cutter with tool signature 45° Rake and 15° Relief and nose radius of 0.2 mm was developed and evaluated experimentally for low cutting force.

7.2.3 Development of final cutter assembly

A simple, safe and versatile cutter assembly called 'Turbine cutter' was developed by incorporating chip slicer for slicing the chips. This helped in instant, safe and effective disposal of chips from the machining zone.

7.2.4 Evaluation of safe and effective cutting parameters

Optimum machining parametres are analysed based on full fraction factorial results using ANOVA, RSM and 2FI models for low cutting power and maximum MRR .

a. Cutting power increases with increase in depth of cut (DoC) and Table feed rate (TFR), whereas the cutting power decreases with increase in cutting velocity (CV). MRR increases with increase in CV, TFR and DoC. Cutting forces are found to be significantly high with low cutting velocity. This is due to high coefficient of friction between tool and work material at lower speeds.

b. ANOVA results at 95% confidence level, indicates CV is most significant parameter followed by TFR and DoC for cutting power, whereas TFR is most significant parameter than other machining parameters for MRR.

c. RSM being used for development of regression model for prediction of cutting power and MRR within range of cutting parameters considered in the study.

d. 2FI Multi objective optimization results show that the optimal combination of machining parameters is 125 m/min of cutting velocity, 24 deg/min of TFR and 4 mm for depth of cut.

7.2.5 Tool wear studies on HSS insert of turbine cutter in machining CSP materials

a) The predominant wear in HSS insert of turbine cutter while machining HTPB based composite propellant grain with AP as oxidizer is chemical wear.

b) Thorough cleaning of cutting element with DOA (Di octyl adipate) followed by cleaning with water and drying helped in extending the tool life of HSS insert.

c) Tool wear criteria in machining of CSP material with the developed Turbine cutter using HSS inserts has been fixed in length units on rake surface as $H_x = H_y = 2.8$ mm, and on flank surface as $H_x = 2.5$ mm $H_y = 0.5$ mm.

7.3 Scope for future work

a) Study on finite element simulation and modeling of solid filled viscoelastic CSP material to estimate cutting force, evaluate tool signature.

b) Study on coatings of HSS insert to prevent chemical tool wear while machining the CSP is not yet attempted. However the coatings should not only provide anti-corrosive surface on tool in acidic environment but also prevent static charge accumulation.

c) New tool materials with low chemical affinity to the work material can be investigated to address the chemical wear which was identified as one of the major wear mechanisms in machining CSP material.

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List of Publications from this Research work

Patents

1. Kishore Kumar Katikani, Venu Gopal Anne, Santosh Kumar Panigrahi **"A MILLING CUTTING TOOL"** Patent filed with Patent Attorney, New Delhi, India, vide application no: 3023/DEL/2013 dated: 10th Oct 2013 through Director General, DRDO.

Conferences/Proceedings

1. Kishore Kumar Katikani, Venu Gopal Anne, V. Venkateswara Rao **"HSS tool wear mechanism in machining of HTPB based composite propellant grain"**. 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR- 2014), 12th–14th December2014, IIT, Guwahati, Assam, India.
2. Kishore Kumar Katikani, Venu Gopal Anne, V. Venkateswara Rao , **"Development of a Hollow Contouring Cutter for Machining of Solid Rocket Motor (SRM) Propellant Grain"** Proceedings of 10th International High energy material conference and Exhibit (HEMCE-18)11th–13th February2016, ASL, DRDO, Hyderabad, India.

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