Materials and Design 45 (2013) 576–585

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Influence of rotational speed and reinforcements on wear and mechanical properties of aluminum hybrid composites via friction stir processing

A. Devaraju, A. Kumar *, B. Kotiveerachari

Department of Mechanical Engineering, National Institute of Technology, Warangal, AP, India

ARTICLE INFO

Article history:
Received 2 August 2012
Accepted 20 September 2012
Available online 4 October 2012

ABSTRACT

In this paper, the effect of reinforcement particles such as Silicon carbide (SiC), Graphite (Gr) and rotational speed on wear and mechanical properties of Aluminum alloy surface hybrid composites fabricated via Friction stir processing (FSP) was studied. Taguchi method was employed to optimize the rotational speed and volume percentage of reinforcement particles for improving the wear and mechanical properties of surface hybrid composites. The fabricated surface hybrid composites have been examined by optical microscope for dispersion of reinforcement particles and revealed that the reinforcement particles (i.e. SiC and Gr) are uniformly dispersed in the nugget zone. It is also observed that the microhardness at optimum condition is increased due to the presence and pining effect of hard SiC particles. The wear resistance of the surface hybrid composite is increased due to the mechanically mixed layer generated between the composite pin and steel disk surfaces which contained fractured SiC and Gr. The observed wear and mechanical properties have been correlated with microstructures and worn micrographs.

1. Introduction

Aluminum alloy 6061-T6 is widely utilize in aircraft, defence, automobiles and marine areas due to their good strength, light weight and better corrosion properties. But, they exhibits inferior tribological properties in extensive usage [1,2]. In addition, Aluminum based composites were become brittle by the addition of reinforcements such as SiC and Al_2O_3 ceramic particles [3].

A proper technique can be employed to refine the microstructure and homogeneous disperse of reinforcements on metallic surface ever since wear is surface deprivation property [4]. Dispersion of reinforcement particles on metal surface and the control of its dispersal are more difficult to attain by conventional surface modification techniques [5]. Previous researchers [6,7] reported that thermal spraying and laser beam techniques were utilized to prepare surface composites, in which it degrades the properties due to formation of unfavourable phases. These techniques are operated at higher temperatures and impossible to avoid the reaction between the reinforcements and the matrix, which forms detrimental phase. A process can be employed which is operated at below melting temperature of matrix for the fabrication of surface composites which can be avoid the above mentioned complications.

Considering the above problems, FSP best suited for preparation of surface composites and surface modification. In FSP a rotating tool with shoulder and pin is plunged into the surface of material, which creates frictional heat and dynamic mixing of material area underneath of the tool [8]. It leads to incorporate and/or disperse the reinforcement particles in the matrix material such as Aluminum alloys, Magnesium alloys and Copper [9–11]. The authors [12] have achieved in homogeneous dispersion of SiC particles (20 μm average size) on a surface of Aluminum alloy 6061-T6 via FSP. Hybrid composites are prepared by reinforcing with a mixture of two or more different type of particles which combines the individual properties of each type of particle. Essam et al. [13] fabricated Al–1050–H24/(20% Al_2O_3 + 80% SiC) hybrid composite via FSP and exhibited high hardness and superior wear resistance than matrix material.

However, it has not been found that there is no result reported for improvement of wear and mechanical properties by addition of the mixture of SiC and Gr particles as refinements on the surface of Aluminum alloy 6061-T6 via FSP. The optimization of volume percentage of reinforcements and rotational speed for improving the wear properties of Aluminum alloy 6061-T6/(SiC + Gr) surface hybrid composites was not reported. Taguchi method is a systematic methodology intended for design and analysis of experiments to improving the quality characteristics [14–16]. Nowadays, it has become a very popular practical tool for improving the quality of output without increasing the cost of experimentation by reducing the number of experiments. Previous research [17] optimized mechanical properties of TIG welded Ferritic Stainless steel by using Taguchi method. The objective of present investigation is to study the influence of reinforcements and rotational speed on wear and mechanical properties of Aluminum alloy 6061-T6/

* Corresponding author. Tel.: +91 9492783067; fax: +91 08702462834.
E-mail addresses: adepu_kumar7@yahoo.co.in, adepu_kumar7@nitw.ac.in (A. Kumar).

0261-3069/$ - see front matter
http://dx.doi.org/10.1016/j.matdes.2012.09.036

(SiC + Gr) surface hybrid composites were fabricated via FSP and obtain the optimum combinations using Taguchi method.

2. Experimental procedure

The base material employed in this study is 4 mm thick Aluminum alloy 6061-T6. The chemical composition of the base material is given in Table 1. The reinforcement particles which effect on the wear and mechanical properties were identified as SiC, Gr [18–21]. The average size of both reinforcements is 20 μm as shown in Fig. 1. The square groove was made with dimensions of 3 mm width and 3 mm deep tangent to the pin in the advancing side and which is 1 mm far away from the centre line of the tool rotation on the Aluminum alloy 6061-T6 plate. The schematic sketch of Aluminum alloy plate for FSP as shown in Fig. 2. H13 tool steel having screwed taper pin profile with shoulder diameter of 24 mm, pin diameter of 8 mm and 3.5 mm height was used. The reinforcement mixtures of SiC and Gr particles at selected ratios were packed in the groove. The groove opening initially closed by means of the tool which is having shoulder without pin to avoid the escapement of reinforcement particles from groove while processing. The Tool travelling speed of 40 mm/min, axial force 5 KN and tool onward tilt angle of 2.5° along the centre line were used in FSP. The experiments are carried out on a Vertical milling machine (Make HMT FM-2, 10 hp, 3000 rpm).

After FSP, microstructural observations were carried out at the cross section of nugget zone (NZ) of surface hybrid composites normal to the FSP direction, mechanically polished and etched with Keller's reagent (2 ml HF, 3 ml HCl, 20 ml HNO_3 and 175 ml H_2O) by employing optical microscope (OM). Microstructures of the surface hybrid composites were captured and presented. The Scanning electron microscope (SEM) is also utilized for measuring the reinforcement particles size and worn morphology of surface hybrid composites.

Microhardness tests were carried out at the cross section of NZ of surface hybrid composites normal to the FSP direction, samples with a load of 15 g and duration of 15 s using a Vickers digital micro-hardness tester.

The tensile specimens were taken from the surface hybrid composites normal to the FSP direction and made as per ASTM: E8/E8M-011 standard by Wire cut Electrical discharge machining to the required dimensions. The schematic sketch of tensile specimen is shown in Fig. 3. The tensile test was conducted with the help of a computer controlled universal testing machine at a cross head speed of 0.5 mm/min.

Wear test is carried out on a pin-on-disk tribometer as per ASTM: G99-04 standard. Prismatic pins of 8 mm diameter were cut from the NZ, with the axis of the pin normal to the FSP direction. The disk was made of EN31 steel with hardness of 62 HRC. The diameter of the sliding track on the disk surface was 100 mm. The wear tests were performed under dry sliding conditions with a constant load (40 N), rotational speed (650 rpm) and sliding speed (3.4 m/s). The configuration of pin-on-disk is shown in Fig. 4.

Table 1
Chemical composition of Aluminum 6061-T6 alloy (Wt.%).

Element	Mg	Si	Cu	Zn	Ti	Mn	Cr	Al
Amount (Wt.%)	0.85	0.68	0.22	0.07	0.05	0.32	0.06	Balance

Wear rate is calculated by,

$$\text{Wear rate}(\text{mm}^3/\text{m}) = \text{Volume loss}/\text{Sliding distance}$$

2.1. Planning of experiments based on Taguchi's method

Rotational speed is the most important process parameter in FSP which has greater influence in uniform distribution of reinforcement particles, grain refinement and heat input during the process [8,22,23]. Trial experiments were conducted by varying the volume percentage of the reinforcement particles and keeping the others constant to find the working range of volume percentage of reinforcement particles. Feasible levels of the process parameters were chosen in such a way that the surface hybrid composites should be free from defects. The range of the reinforcement particles and the constant process parameters were presented in Tables 2 and 3 respectively.

Taguchi's method is very effective to deal with responses influenced by many parameters. It is a simple, efficient and systematic approach to determine optimal process parameters. It is a powerful design of experiments tool which reduces drastically the number of experiments that are required to model and optimize the responses. Also, it saves lot of time and experimental cost [14–16]. The Taguchi method is devised for process optimization and identification of optimum levels of process parameters for given responses. In Taguchi method, the experimental values of various responses are further transformed to signal to noise (S/N) ratio. The response that is to be maximized is called 'Higher the better' and the response that is to be minimized is called 'Lower the better'. Taguchi uses the S/N ratio to measure deviation of the response from the mean value. S/N ratios for 'Higher the better' and 'Lower the better' characteristics are calculated using Eqs. (1) and (2) respectively,

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \tag{2}$$

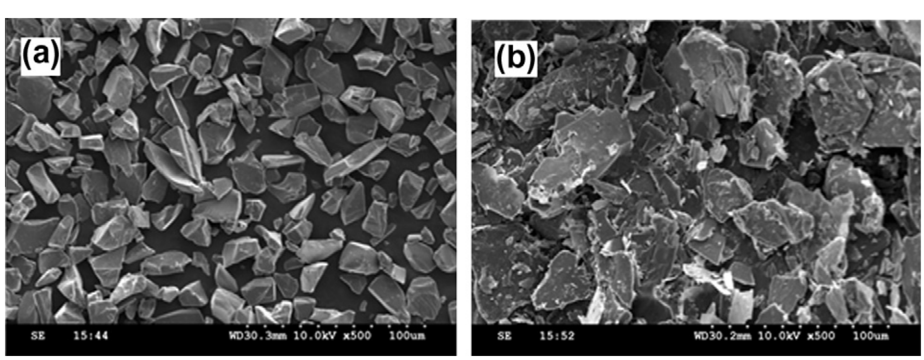

Fig. 1. SEM micrographs of as-received (a) SiC & (b) Gr particles.

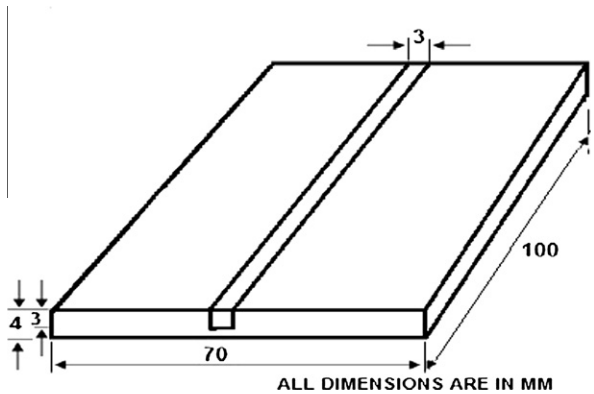

Fig. 2. Schematic sketch of Aluminum alloy plate for FSP.

where η denotes S/N ratio of experimental values, y_i represents the experimental value of the ith experiment and n is total number of experiments.

In the present study, the Taguchi method was applied to experimental data using statistical software MINITAB-15. The number of process parameters considered under this study is three and the level of each factor is three. The degree of freedom of all the three factors is 6. Hence, L_9 (3^4) orthogonal array is selected. Each condition of experiment was repeated twice in order to reduce the noise/error effects. The selected orthogonal array is presented in Table 4. The experimental conditions of all the 9 experiments in Table 4, is denoted as SG1 to SG9 respectively.

The quality characteristics such as wear rate (WR), ultimate tensile strength (UTS), yield strength (YS), percentage of elongation (%EL) and microhardness of surface hybrid composites were evaluated for all the trials and then statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each element in influencing the quality characteristic is evaluated. The optimum element combinations were predicted and verified.

3. Results and discussions

3.1. Microstructure

The optical micrographs of all surface hybrid composites (SG1 to 9) are shown in Fig. 5. The particles of SiC and Gr were observed to be dispersed uniformly in the NZ for all the conditions of composites made by FSP due to rotating tool gives sufficient heat generation and a circumferential force to distribute the reinforcement particles to flow in wider area [12,13]. The reinforcement particles' size after FSP is measured by using SEM and shown in Fig. 6. It is found that reinforcement particles (i.e. SiC and Gr) are reduced in size (∼5 μm) than the as received particles. This is due to the tool provides a shear force to substantial breaking of reinforcement particles in NZ zone and intense plastic deformation [8]. It is also revealed that good bond between reinforcement particle and Aluminum matrix.

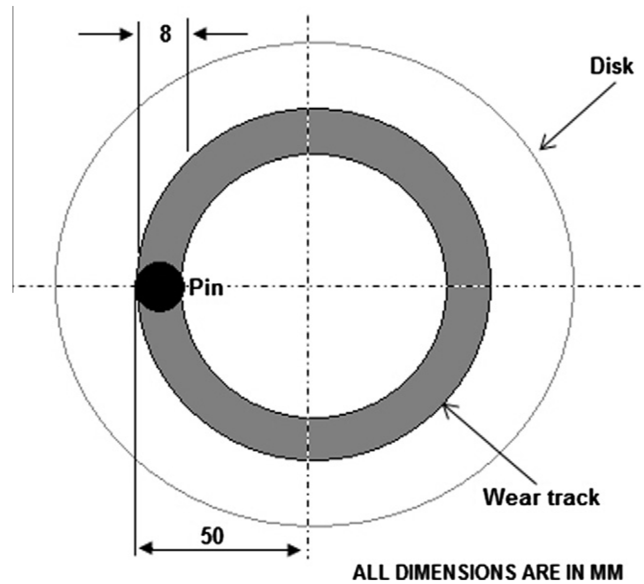

Fig. 4. Schematic configuration of pin-on-disc tribo meter.

Table 2
Working range of the selected parameters.

Symbol	Parameters	Units	Level		
			(1)	(2)	(3)
A	Rotational speed	Rpm	900	1120	1400
B	SiC_p	Vol.%	8	6	4
C	Gr_p	Vol.%	2	3	4

3.2. Mechanical and wear properties

The microhardness, UTS, YS, %EL and Wear rate of surface hybrid composites and base metal were evaluated and presented in Table 5. Regression analysis is used to evaluate the data on all the properties of surface hybrid composite. These developed regression equations are used to predicting the microhardness, UTS, YS, %El and Wear rate within the factorial space exploited.

3.2.1. Development of regression models

The regression model commonly used is represented by $Y = f(A, B$ and $C)$. Y denotes the performance characteristics and A, B and C are the process parameters. The general regression model consist-

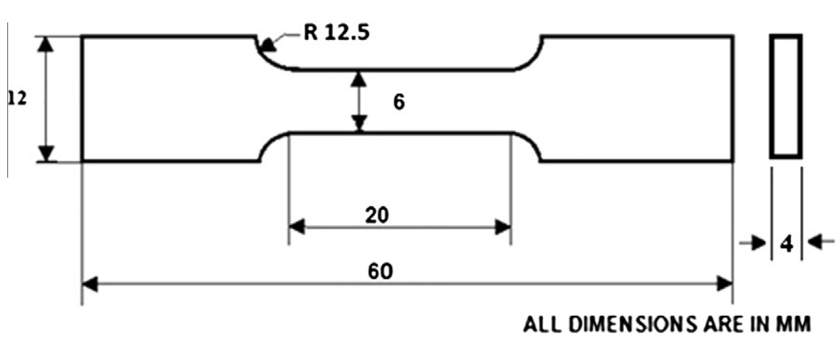

Fig. 3. Schematic sketch of tensile specimen.

Table 3
Constant process parameters.

Parameters	Value
Tool traverse speed	40 mm/min
Tool vertical force	5 KN
Tool tilt angle	2.5°
Tool pin profile	Taper with threaded
Tool shoulder diameter	24 mm
Tool pin diameter	8 mm
D_s/D_p ratio	3
Number of passes	1

Table 4
Experimental layout L_9 (3^4) orthogonal array.

Exp. no	*A*	*B*	*C*
SG1	1	1	1
SG2	2	2	2
SG3	3	3	3
SG4	1	2	3
SG5	2	3	1
SG6	3	1	2
SG7	1	3	2
SG8	2	1	3
SG9	3	2	1

ing of only linear and quadratic effects is given by the following equation:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 A^2 + \beta_5 B^2 + \beta_6 C^2 + \varepsilon \quad (3)$$

where β_0, $\beta_1 \ldots \beta_6$ are regression coefficients of process parameters and ε is the experimental error. The developed regression equations and correlation coefficients for the observed properties were summarized in Table 6. High correlation coefficient indicates good relationship between the process parameters and the observed property data.

The coefficient of correlation (R^2) is defined as the ratio of explained variation to the total variation and measure of degree of fit of the model. When it approaches to unity, the developed model fits the actual data with given confidence. Here all models have higher values of R^2 i.e. above 95%, which means that the regression model provides an excellent explanation of relationship between parameters and responses. All these models are statistically significant at 95% confidence level.

3.2.2. Optimization and validation of process parameters performance characteristics

The optimization of volume percentage of reinforcement particles and rotational speed using Taguchi method permits evaluation of the effects of individual elements independent of other elements on the identified quality characteristics, i.e. microhardness, UTS, YS, %EL and Wear rate. The influence of each reinforcement particles and rotational speed can be evaluated by determining the S/N ratio for each factor at each level. The main effect plots for various responses are shown in Figs. 7–11. From the main effect plots analysis, the optimum parametric combinations for better wear

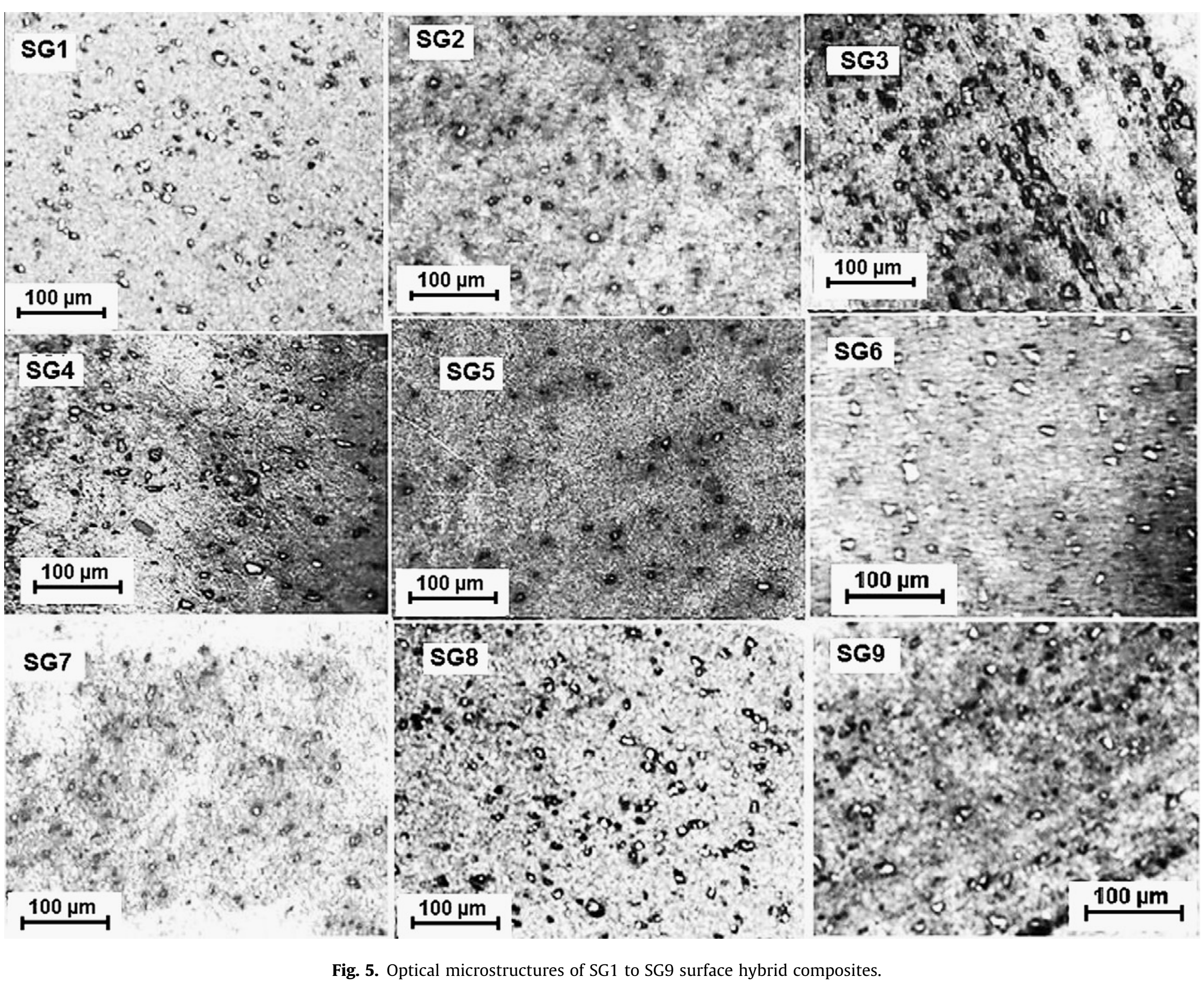

Fig. 5. Optical microstructures of SG1 to SG9 surface hybrid composites.

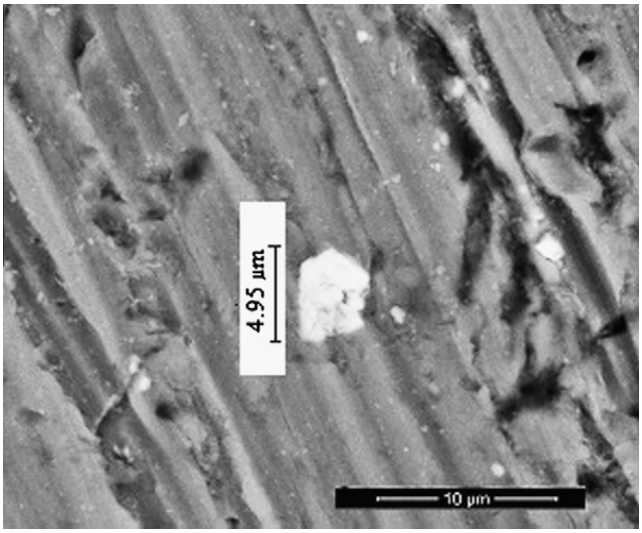

Fig. 6. SEM micrograph of reinforcement particles after FSP.

and mechanical properties are obtained and summarized in Table 7.

The predicted values for various responses at optimum condition are calculated using the predicted S/N ratio (η_{opt}) in the following equation:

$$\eta_{opt} = \eta_m + \sum_{i=1}^{j}(\eta_{jm} - \eta_m) \quad (4)$$

where η_{jm} is the mean S/N ratio of optimum level and j is the number of process parameters that affect the response. For validation of the optimum results, experiments are conducted at optimum condition and the results are presented in Table 8. It is observed that experimental values were closer to the optimum values.

3.2.3. Analysis of variance (ANOVA)

In order to find the effect of process parameters on various responses ANOVA is performed and the results are presented in Table 9. The calculated F-values of the ANOVA for various responses determine the relative significances of different process parameters. Results of ANOVA revealed that the reinforcement particles (SiC and Gr) and rotational speed were significantly effect on all the quality characteristics. It is clear from the ANOVA Table 9 that, the rotational speed has less percentage of contribution on the wear rate compared to SiC and Gr volume percentage and less effect compared to other responses.

3.2.4. Effect of process parameters on microhardness

Fig. 7 shows the main effects plot for microhardness. It is revealed that the increased rotational speed causes small amount of decrement on the microhardness. It is well known that the increasing the rotation speed, increases the heat generation in the nugget zone which leads to more softening of the matrix due to the over aging [22]. This softening of the nugget zone was resulted in coarsening and/or dissolution of strengthening precipitates in the Aluminum matrix, occurs especially in heat treatable Aluminum alloys [24].

It is observed that the increasing the volume percentage of SiC particles immensely increases the microhardness due to the presence and pinning effect of the SiC particles [8,9,12]. The presence of SiC particles is considered for more effective formation of fine grain structure due to the restrain of grain boundary and the enhancement of the induced strain [25]. However the higher hardness is achieved by the SiC particles.

It is also observed that the volume percentage of Gr increases, the microhardness value decreases as a result of weaker Gr phase.

Mainly, the microhardness value depends on the presence and uniform distribution of SiC particles. The optimum microhardness value was obtained at the optimum condition of 900 rpm, 8 vol.% of SiC and 2 vol.% of Gr. This is due to fact that at 900 rpm, tool shoulder supplied enough heat input and shear force to make the reinforcement particles more easily wrapped by the softening metal and rotated with FSP tool which results in well separation and distribution in the nugget zone.

Table 5
Wear and mechanical properties of Aluminum 6061-T6 alloy surface hybrid composites.

Exp. no.	Micro hardness at NZ (Hv)		Ultimate tensile strength (UTS, MPa)		Yield strength (YS, MPa)		% of Elongation (%EL)		Wear rate (mm^3/m)	
	Trail1	Trail2	Trail1	Trail2	Trail1	Trail2	Trail1	Trail2	Trail1	Trail2
SG1	121	119	162	178	134	150	7.3	8.5	0.002503	0.002515
SG2	93	97	159	171	126	138	7.2	7.8	0.001892	0.001908
SG3	89	79	141	159	114	132	6.9	7.8	0.003889	0.003901
SG4	102	94	173	187	147	161	7.9	8.7	0.002988	0.003012
SG5	89	97	164	186	137	159	7.3	8.7	0.003060	0.003074
SG6	96	88	145	159	120	128	7.1	7.5	0.002481	0.002499
SG7	92	100	197	221	163	187	8.6	10.2	0.003510	0.003526
SG8	107	113	126	134	95	103	6.1	6.5	0.002952	0.002964
SG9	95	101	149	163	119	133	6.5	7.9	0.002629	0.002647
Base material	102	106	285	303	263	279	11.5	12.5	0.005274	0.005280

Table 6
Regression equations for the microhardness, UTS, YS, %EL and wear rate of surface hybrid composites.

Sl. no	Response	Regression equation	Coefficient of correlation R-sq (%)
1	Micro hardness (Hv)	$Hv = 172 - 0.007^*A - 2.4^*B - 40.2^*C - 0.000009^*A^2 + 0.54^*B^2 + 6.17^*C^2$	95.5
2	UTS (MPa)	$UTS = 462 - 0.607^*A + 2.4^*B + 78.2^*C + 0.000234^*A^2 - 0.792^*B^2 - 14.2^*C^2$	98.5
3	YS (MPa)	$YS = 494 - 0.674^*A - 0.3^*B + 63.3^*C + 0.0000265^*A^2 - 0.54^*B^2 - 11.7^*C^2$	95.6
4	%EL	$\%EL = 22.3 - 0.0283^*A - 0.325^*B + 3.32^*C + 0.000011^*A^2 + 00.42^*B^2 - 0.583^*C^2$	97.0
5	Wear rate (mm^3/m)	$WR = 0.0187 - 0.000014^*A - 0.00189^*B - 0.00198^*C + 0.000000^*A^2 + 0.000140^*B^2 + 0.000376^*C^2$	95.8

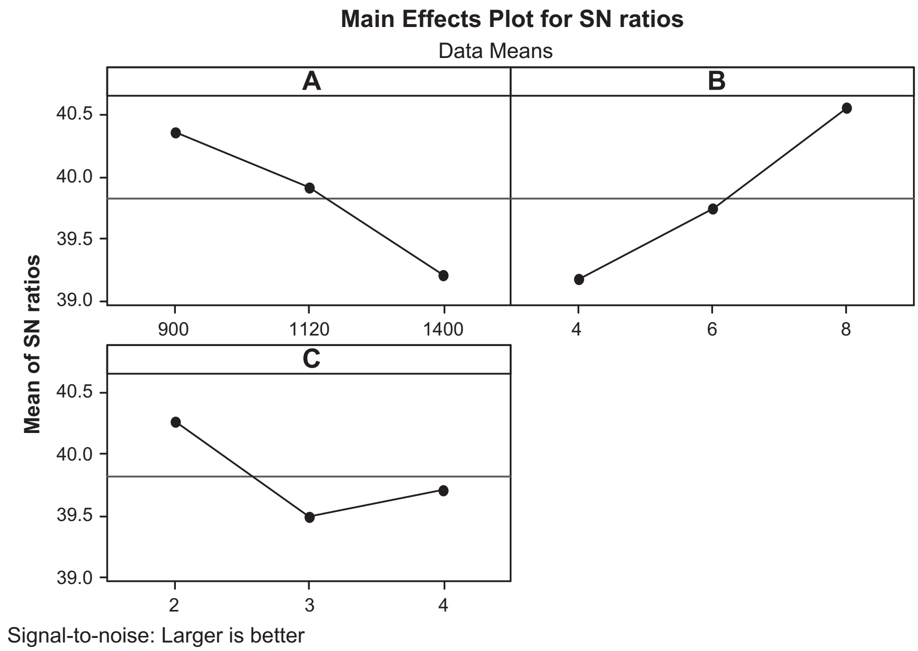

Fig. 7. S/N ratio response graph for microhardness.

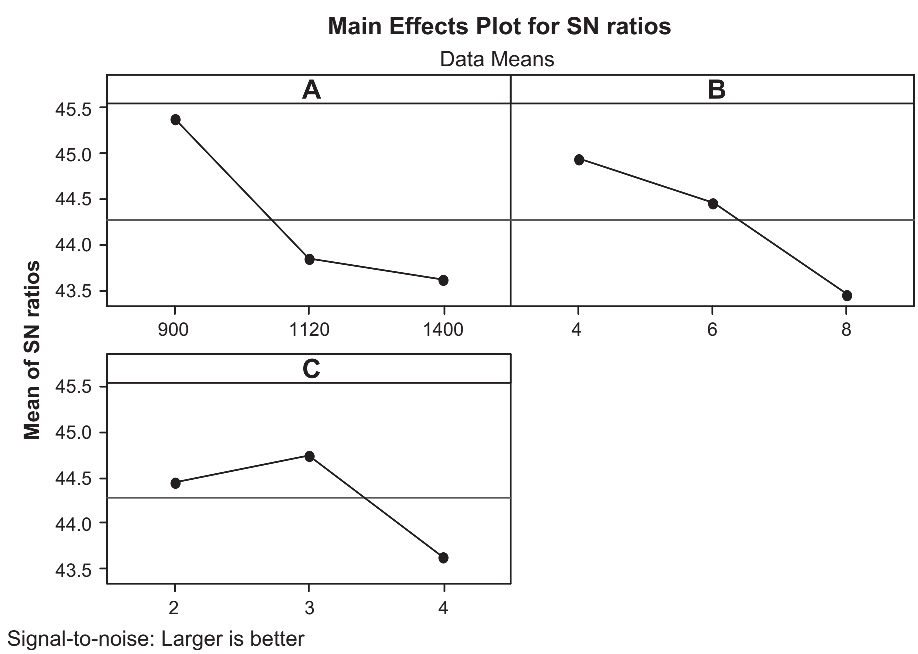

Fig. 8. S/N ratio response graph for UTS.

3.2.5. Effect of process parameters on tensile properties

Figs. 8–10 show the main effects plot for UTS, YS and %EL. It is revealed that the increasing the rotational speed decreases the UTS, YS and %EL. However the earlier mentioned, the heat input increases with increase of rotational speed [22] which resulted in matrix softening. Actually the softening of material will improve the %EL. Contrary in this; the %EL is decreases a very low as rotational speed increases due to loss in strength of the matrix.

It is observed that the increasing the volume percentage of SiC particles, the UTS, YS and %EL immensely decreases. However, increasing the volume percentage of SiC particles increases the interface area between the SiC particles and Aluminum matrix due to low inter particles space area causes the agglomeration of SiC particle results in low tensile properties [26]. The volume percentage of SiC particles increases could be restrict the grain boundary sliding, dislocations and also the weak interfacial bond between the reinforcement particles and the matrix, finally it leads to deteriorate the tensile properties [27,28]. In other words composite has incompatible deformation between the plastically deformed matrix and rigid reinforcement particles caused

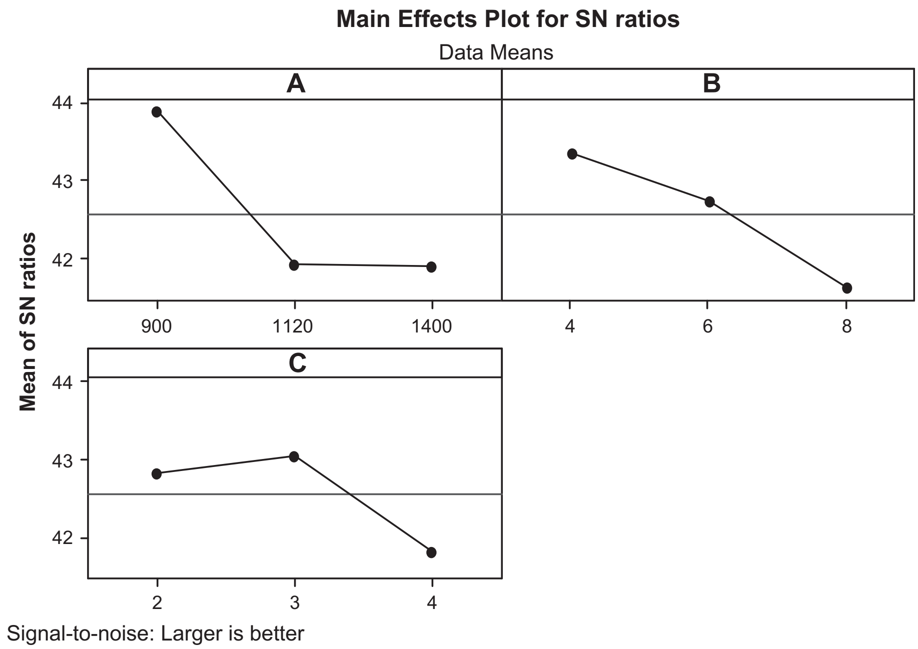

Fig. 9. S/N ratio response graph for YS.

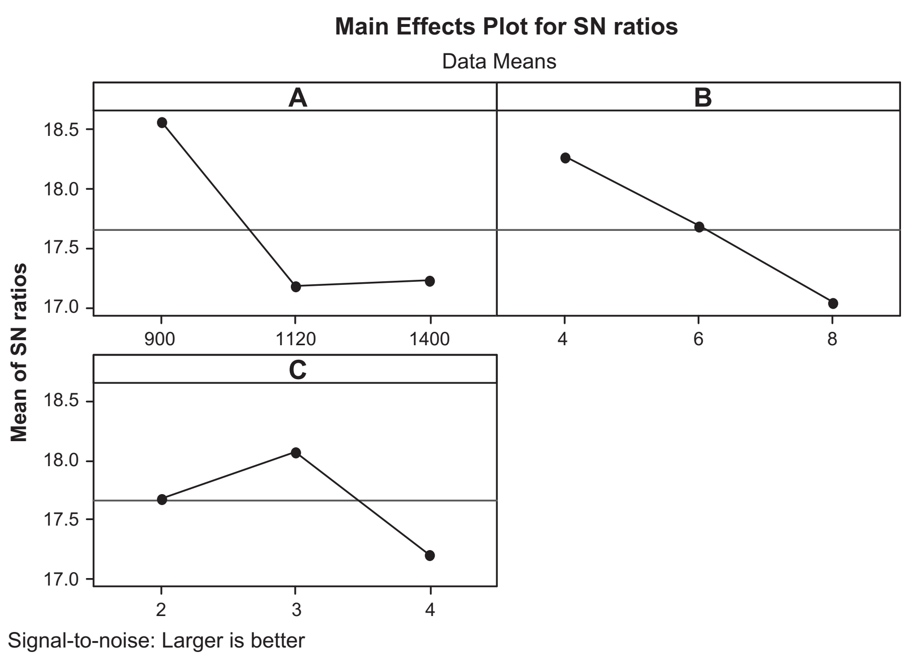

Fig. 10. S/N ratio response graph for %EL.

geometrical dislocations. Besides, increasing the volume percentage of SiC particles increases the effective slip distance of dislocations during deformation, which leads to reduce elongation [29].

It is also observed that the increased the volume percentage of Gr, decreases the UTS, YS and %EL. This may be due to loss in strength of the matrix by the addition of Gr particles and finally reduce the tensile properties.

3.2.6. Effect of process parameters on wear rate

Fig. 11 shows the main effects plot for wear rate. It is revealed that the increasing the rotational speed decreases the wear rate. This is due to the easier and more intense stirring action of the rotating pin causes better dispersion of reinforcement particles which results in decrease the wear rate. Further increasing the rotational speed increases the wear rate. This due to the high heat generation causes matrix softening which results in increase the wear rate.

It is observed that the increasing the volume percentage of SiC particles decreases the wear rate. This is due to the enhanced hardness by the dispersion SiC particles and acted as load-supporting elements [13,30]. At higher volume percentage of SiC particles increases the wear rate due to pulled out of hard SiC particles from the composite pin during the wear process, formed on the steel disk which acts as barrier and further converts the adhesive wear

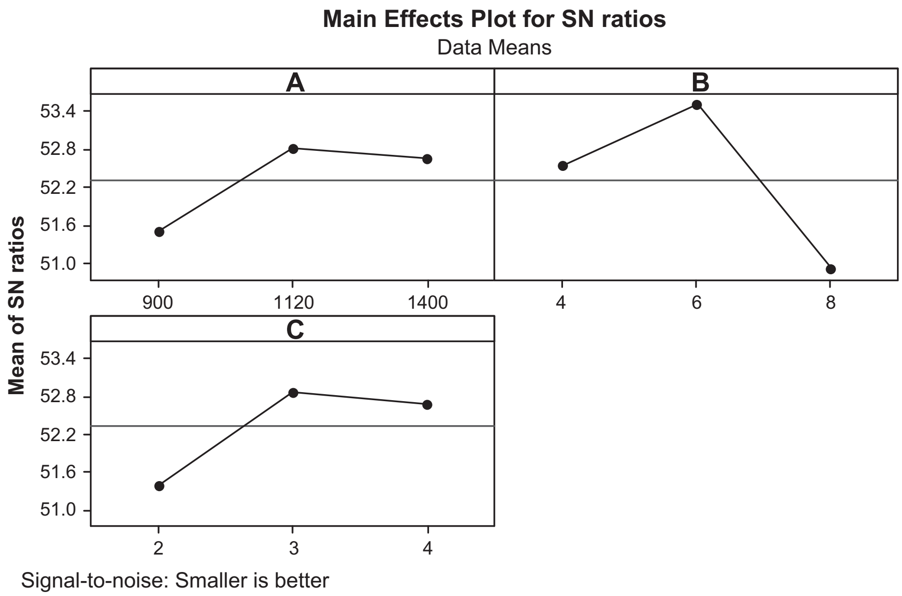

Fig. 11. S/N ratio response graph for wear rate.

Table 7
Optimum values of the quality characteristics.

Quality characteristics	Optimum condition	Optimum value
Micro-hardness at NZ (Hv)	A_1, B_1, C_1 i.e., rotational speed at 900 SiC vol.% at 8 Gr vol.% at 2	119.23
UTS (MPa)	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	211.20
YS (MPa)	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	181.19
%EL	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	9.53
Wear rate (mm^3/m)	A_2, B_2, C_2 i.e., rotational speed at 1120 SiC vol.% at 6 Gr vol.% at 3	0.002028

Table 8
Validation of the optimum results.

Quality characteristics	Optimum condition	Optimum value	[a] Experimental value
Micro-hardness at NZ (Hv)	A_1, B_1, C_1 i.e., rotational speed at 900 SiC vol.% at 8 Gr vol.% at 2	119.23	120
UTS (MPa)	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	211.20	209
YS (MPa)	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	181.19	175
%EL	A_1, B_3, C_2 i.e., rotational speed at 900 SiC vol.% at 4 Gr vol.% at 3	9.53	9.4
Wear rate (mm^3/m)	A_2, B_2, C_2 i.e., rotational speed at 1120 SiC vol.% at 6 Gr vol.% at 3	0.002028	0.00190

[a] Average of two values.

Table 9
ANOVA analysis results for various responses.

Process parameter	Degree of freedom (DF)	Sum of squares (SS)	Adj. Mean sum of squares (MSS)	F-ratio	P	% Of contribution
(a) For microhardness						
A	2	270.22	135.11	3.37	0.229	31.41
B	2	409.56	204.78	5.11	0.164	45.47
C	2	136.22	68.11	1.70	0.371	14.34
Error	2	80.22	40.11			8.78
Total	8	1298.89				100
(b) For UTS						
A	2	2106.89	1053.44	34.99	0.028	49.83
B	2	1224.22	612.11	20.33	0.047	30.75
C	2	681.56	340.78	11.32	0.81	17.71
Error	2	60.22	30.11			1.70
Total	8	4072.89				100
(c) For YS						
A	2	2011.6	1005.78	11.86	0.078	49.09
B	2	1102.9	551.44	6.5	0.013	29.19
C	2	538.9	269.44	3.18	0.239	15.92
Error	2	169.6	84.78			5.8
Total	8	3822.9				100
(d) For% El						
A	2	3.0422	1.52111	17.33	0.055	50.07
B	2	1.8156	0.90778	10.34	0.088	30.94
C	2	0.8822	0.44111	5.03	0.166	15.29
Error	2	0.1756	0.08778			3.70
Total	8	5.9156				100
(e) For wear rate						
A	2	0.000000	0.00000	2.29	0.304	10.58
B	2	0.000002	0.000001	14.49	0.065	55.40
C	2	0.000001	0.000000	6.31	0.137	27.12
Error	2	0.000000	0.000000			6.90
Total	8	0.000003				100

to abrasive wear which results in more amount of material worn-out from the composite pin.

It is also observed that the increasing the volume percentage of Gr particles decreases the wear rate. This is due to the more amount of Gr released on the wear surface during wear process which avoids the direct metal to metal contact and serving as a solid lubricant and thereby reduces the coefficient of friction between the composite pin and the steel disk [19,20]. Further increasing of Gr addition increases the wear rate. This due to the low fracture toughness of surface hybrid composite cause easier fracture during wear process which results in increases the wear rate.

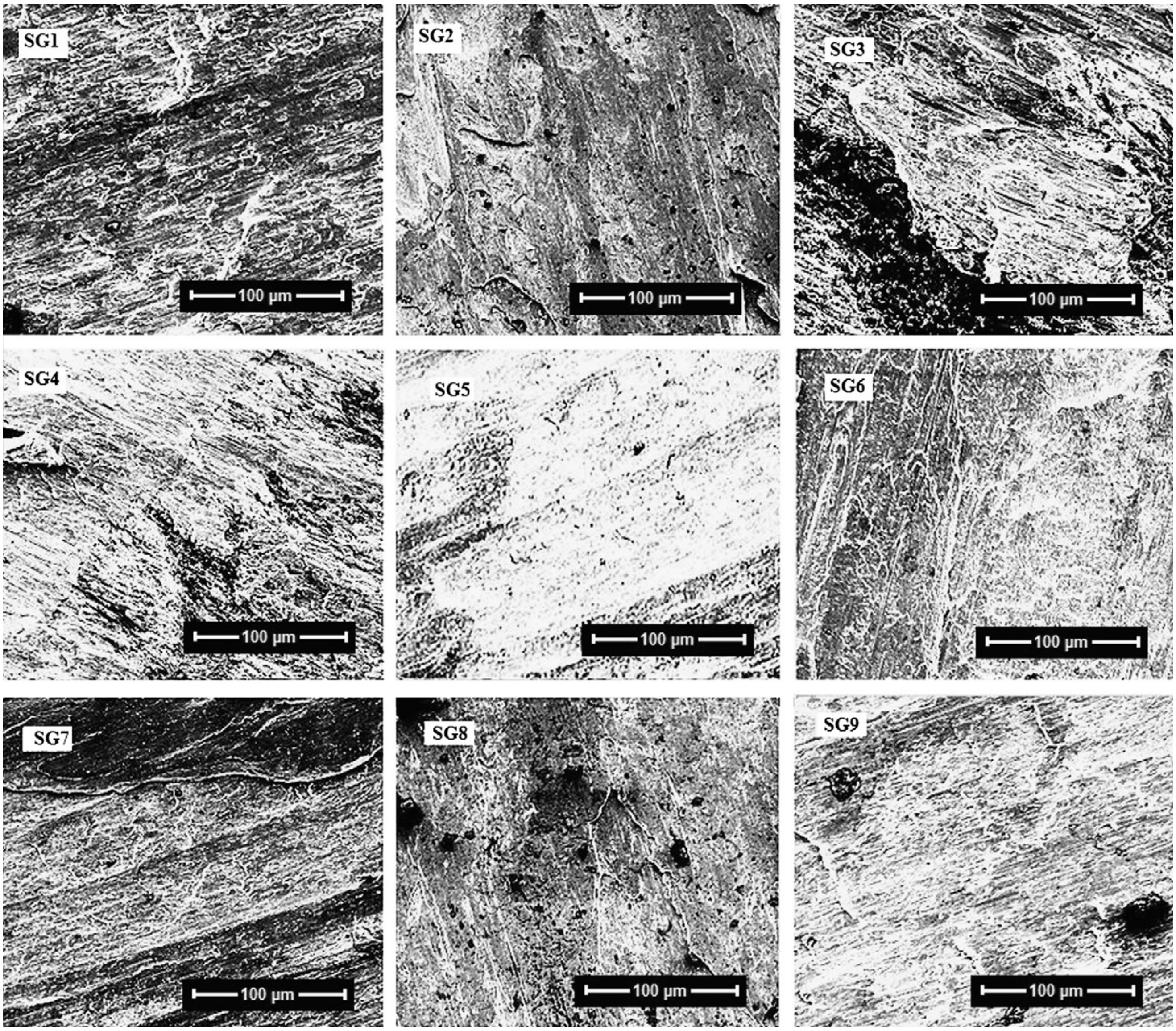

Fig. 12. SEM micrographs of worn surface hybrid composites (SG1 to SG9).

The lower wear rate was obtained at the optimum condition of rotational speed of 1120 rpm, 6 vol.% of SiC and 3 vol.% of Gr.

3.3. Worn morphology

Fig. 12 shows the SEM micrographs of worn surface hybrid composites against a steel disk. The presence of tribo mechanically mixed layer converts the wear manner as of two body to three body wear and decreases wear rate which acts as solid lubricant and lesser coefficient of friction [19,31]. The Al–SiC/Gr surface hybrid composite exhibited high wear resistance than the Al–SiC surface composite due to presence of Gr in the mechanically mixed layer acted as solid lubricant, probably weaken the friction between the disk and surface hybrid composite deformed surface [19]. This resulted in decreases the metal removal during wear test. It is also observed that the worn debris are more at higher content of SiC particles and less at higher content of Gr particles due their hardness. In other words the presence of hard pulled out SiC particles formed on steel disc which acts as barrier and further it converts the adhesive wear mode into abrasive mode.

4. Conclusions

The influence of reinforcements such as SiC and Gr and rotational speed on wear and mechanical properties of Aluminum alloy 6061-T6 surface hybrid composites fabricated via FSP were investigated and the following conclusions are obtained.

- The practical benefit of this study is that, the use of obtained optimum condition improves the wear and mechanical properties of surface hybrid composites.
- Microhardness at optimum condition (i.e. $A_1B_1C_1$) increases due to presence and pining effect of hard SiC particles.
- Wear rate at optimum condition (i.e. $A_2B_2C_2$) is decreased due to mechanically mixed layer generated between the composite pin and steel disk surfaces which contained fractured SiC and Gr. The presence of Gr decreases the wear due to which acted as a solid lubricant.
- Tensile properties at optimum condition (i.e. $A_1B_3C_2$) were lower in small quantity as compare to the base material due to presence of reinforcement particles which make the matrix brittle.

- Regression models were developed to predict the quality characteristics (microhardness, UTS, YS, %EL and wear rate) within the selected range of process parameters (SiC, Gr and rotational speed). The results are validated through ANOVA.

Acknowledgements

The authors would like to thank the authorities of National Institute of Technology-Warangal, Defence Metallurgical Research Laboratory-Hyderabad, Indian Institute of Chemical Technology-Hyderabad and Defence Institute if Advanced Technology-Pune for providing the facilities to carry out this work.

References

[1] Bakes H, Benjamin D, Kirkpatrick CW. Metals handbook. ASM Metals Park, OH; 1979.
[2] Ravi N, Sastikumar D, Subramanian N, Nath AK, Masilamani V. Microhardness and microstructure studies on laser surface alloyed aluminum alloy with Ni–Cr. Mater Manuf Process 2000;15:395–404.
[3] Clyne TW, Withers PJ. An introduction to metal matrix composites. Cambridge: Cambridge University Press; 1993.
[4] Rabinowicz E. Friction and wear of materials. New York: JohnWiley and Sons; 1965.
[5] Budinski KG. Surface engineering for wear resistance. New Jersey: Prentice-Hall; 1988.
[6] Gupta M, Mohamed FA, Lavernia EJ. Solidification behaviour of Al–Li–SiC_p MMCs processed using variable co-deposition of multi-phase materials. Mater Manuf Process 1990;5(2):165–96.
[7] Mabhali LAB, Pityana SL, Sacks N. Laser surface alloying of aluminum (AA1200) with Ni and SiC powders. Mater Manuf Process 2010;25(12):1397–403.
[8] Mishra RS, Ma ZY, Charit I. Friction stir processing: a novel technique for fabrication of surface composites. Mater Sci Eng A 2003;341:307–10.
[9] Ma ZY. Friction stir processing technology: a review. Metall Mater Trans A 2008;39:642–58.
[10] Asadi P, Besharati Givi MK, Faraji G. Producing ultrafine-grained AZ91 from as-cast AZ91 by FSP. Mater Manuf Process 2010;25(11):1219–26.
[11] Dehghani K, Mazinani M. Forming nanocrystalline surface layers in copper using friction stir processing. Mater Manuf Process 2011;26(07):922–5.
[12] Devaraju A, Kumar A. Dry sliding wear and static immersion corrosion resistance of aluminum alloy 6061-T6/SiC_p metal matrix composite prepared via friction stir processing. Int J Adv Res Mech Eng 2011;1(2):62–8.
[13] Essam RI, Makoto T, Tishiya S, Kenji I. Wear characteristics of surface-hybrid-MMCs layer fabricated on aluminum plate by friction stir processing. Wear 2010;268:1111–21.
[14] Ross PJ. Taguchi techniques for quality engineering. New York: Mc Graw-Hill; 1998. p. 24–98.
[15] Montgomery DC. Design and analysis of experiments. New York: Wiley; 1997. p. 395–476.
[16] Phadke Madhav S. Quality engineering using robust design prentice Hall. New Jersey: Englewood Cliffs; 1989. p. 41–229.
[17] Mallaiah G, Kumar A, Ravinder reddy P, Madhusudan reddy G. Influence of grain refine elements on mechanical properties of AISI 430 Ferritic stainless steel weldments-Taguchi approach. Mater Des 2012;36:443–50.
[18] Gurcan AB. Wear behaviour of AA6061 aliminium alloy and its composites. Wear 1995;188:185–91.
[19] Ted Guo ML. Tribological behaviour of self-lubricating aluminum/SiC graphite hybrid composites synthesized by semi-solid powder-densification method. Compos Sci Technol 2000;60:65–74.
[20] Urena A. Effect of reinforcement coatings on the dry sliding wear behaviour of aluminum/SiC particles/carbon fibres hybrid composites. Wear 2009;266:1128–36.
[21] Basavarajappa S. Influence of sliding speed on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite. Wear 2007;262:1007–12.
[22] Olga VF. Microstrucural issues in a friction stir welded aluminum alloys. Scripta Mater 1998;38(5):703–8.
[23] Gupta M, Lai MO, Soo CY. Effect of type of processing on the microstructural features and mechanical properties of Al–Cu/SiC metal matrix composites. Mater Sci Eng A 1996;210:114–22.
[24] Shafiei ZA, Rashani Bozorg SF, Zarei H. Microstructure and mechanical properties of Al/Al_2O_3 surface nano-composite layer produced by friction stir processing. Mater Sci Eng A 2009;500:84–91.
[25] Morisada Y, Fujii H, Nagaoka T, Fucksumi M. Effect of friction stir processing with SiC particles on microstructure and hardness of AZ31. Mater Sci Eng A 2006;433:50–4.
[26] Muratoglu M, Yilmaz O, Aksoy M. Investigation on diffusion bonding characteristics of aluminum metal matrix composites (Al/SiC_p) with pure aluminum for different heat treatments. J Mater Process Technol. 2006;178:211–7.
[27] Barmouz M, Kazem Besharati G, Javad S. On the role of processing parameters in producing Cu/SiC metal matrix composites via friction stir processing: Investigating microstructure, microhardness, wear and tensile behaviour. Mater Charact 2011;62:108–17.
[28] Barmouz M, Asadi P, Kazem Besharati G, Taherishargh. Investigation of mechanical properties of Cu/SiC composite fabricated by FSP: effect of SiC particles' size and volume fraction. Mater Sci Eng A 2011;528:1740–9.
[29] Hai Su, Wenli G, Zhaohui F, Zheng L. Processing, microstructure and tensile properties of nano-sized Al_2O_3 particles reinforced aluminum matrix composites. Mater Des 2012;36:590–6.
[30] Kumar S, Balasubramanian V. Developing mathematical model to calculate wear rate of AA7075/SiC_p powder metallurgy composite. Wear 2008;264:1026–34.
[31] Kumar A, Devaraju A, kotiveerachari B. Wear properties of Al–SiC/Gr surfaces composites prepared via friction stir processing. WASET 2012;63:748–52.