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# Application of Taguchi Method on Biaxial Stretch Forming of Friction Stir Processed Mg AZ31B Alloy

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**Abstract** The present study describes the effect of friction stir processing parameters on formability of Mg AZ31B sheet under biaxial stretching. The formability of friction stir processed sheet was studied by limiting dome height test in biaxial strain deformation mode. The experiments were carried out as per the Taguchi parametric design concepts and an L9 orthogonal array was used to study the influence of various combinations of process parameters. Statistical optimization technique, ANOVA was used to determine the optimum levels and to find the significance of each process parameter. The results indicate that the traverse speed is the most significant factor followed by the rotational speed and the tilt angle in deciding the formability of friction stir processed magnesium alloy. In addition, mathematical model was developed to establish relationship between the different process variables with formability by regression analysis.

**Keywords** Biaxial stretching · FSP · Mg AZ31B alloy · Taguchi

## 1 Introduction

Magnesium alloys are attractive for light weight structural components in the aerospace, electronics and automotive industries due to their low density, specific strength and stiffness. Hence, numerous research works have been carried out on magnesium alloys throughout the world in recent years. However, due to their hexagonal closely packed crystal structure, magnesium alloys have low ductility at room temperature and require high temperatures to increase ductility and formability [1]. The poor formability of magnesium alloys has been attributed to highly anisotropic dislocation slip behaviour. Critical resolved shear stress (CRSS) has been reported for three different slip systems in single crystals of magnesium [2]. According to reported data the CRSS for basal plane slips in magnesium single crystal is 100 times lower that for non basal plane slip (prismatic, pyramidal planes) near room temperature. Therefore, it is noted that the plastic deformation in polycrystalline alloys occurs almost by basal slip. In this case, the base slip provides only two independent slip systems but at least five independent slip systems are required for homogenisation that may result in lack of active slip systems causing poor formability of magnesium alloys at room temperature.

Many researchers indicated that the formability can be improved in magnesium alloys by refining grain structure [3–5]. The improvement of formability was due to activity of non basal dislocation slip systems and dynamic recovery induced by plastic compatibility stress [6]. Moreover, twins and small angle grain boundaries formed during the dynamic recovery process at the time of room temperature deformation. These mechanisms are responsible for the improvement of ductility and formability in the fine-grained magnesium alloys [7]. Refinement of grains and homogenisation can be done by a number of severe plastic deformation techniques like equal channel angular processing (ECAP) [8], high pressure torsion (HPT) [9], and accumulative roll bonding (ARB), [10]. But all are

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complex and time consuming processes and resulting products are in a rod shape of finite dimensions. Recently, friction stir processing (FSP) has been developed to be an effective and efficient new method for microstructure modification [11, 12], providing intense plastic deformation as well as higher strain rates than other methods. FSP produces equiaxed homogeneous microstructure consisting of fine grains [13–17], resulting in enhancement of formability of the material. The objective of the present work is to investigate the effect of FSP parameters on the formability in biaxial stretching mode and also to find the statistical significance of each process parameter on the formability using Taguchi and ANOVA statistical methods. In addition, a mathematical model has been developed to establish the relationship between the process parameters and formability.

## 2 Methodology

Taguchi methods developed by Dr. Genichi Taguchi refer to the quality engineering techniques that incarnate both statistical process control (SPC) and the quality related to management techniques. Taguchi analysed the engineering problems with a statistical approach. He proposed that the engineering optimization of a process should be carried out in the three step approach, namely the system design, the parameter design and the tolerance design [18]. The Taguchi method uses orthogonal arrays from the design of experiments theory to study a large number of variables with a small number of experiments. The orthogonal arrays reduce the number of experimental configurations to be studied. Furthermore, the resulting conclusion from the analysis will be true within the range of the experimental region defined by the control factors [19]. Orthogonal arrays are not unique to Taguchi [20]. However, Taguchi has modified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects [21]. The experimental results are then transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values. There are three categories of quality characteristics in the analysis of the S/N ratio, i.e. the lower-the-better, the higher-the-best, and the nominal-the-best.

### 2.1 FSP Process Parameters

The FSP parameters such as the tool rotational speed (RS), the traverse speed (TS) and the tool tilt angle (TA) play a major role in influencing the formability. In the present investigation, these three process parameters have been considered. Pilot experiments were carried out on 4 mm thick rolled sheet of magnesium AZ31B to determine the working range of FSP process parameters.

When the tool RS is lower than 900 rpm, the worm hole defect was observed due to insufficient heat generation and insufficient metal transportation whereas a tunnel defect was found due to excessive heat generation when the RS is higher than 1,400 rpm. When the TS is lower than 24 mm/min, pin holes were observed due to excessive heat generation and a tunnel defect was found, due to insufficient heat input, caused by inadequate flow of metal, when the TS is >40 mm/min. Defect free surface was obtained, for a tool TA of 0° to 2°. Based on the above experiments, the range of process parameters is fixed as 900–1,400 rpm for RS, 24–40 mm/min for TS and 0°–2° for tool TA.

### 2.2 Selection of Orthogonal Array (OA)

Experiments have been carried out using Taguchi's L9 orthogonal array (OA) experimental design which consists of nine combinations of RS, TS and tool TA. It considers three process parameters to be varied in three discrete levels. The nonlinear response of the formability of the material can only be known if more than two levels are chosen. Therefore, each parameter was analysed at three levels. However, more than three levels have been omitted as it will increase the number of experiments for the analysis. Moreover, previous literature has revealed that the interaction parameters are not having an influence on the properties of the present analysis chosen.

As per Taguchi experimental design philosophy, a set of three levels assigned to each process parameter, has two degrees of freedom (DOF). This gives a total of six DOF for three process parameters. Thus, we have a total of eight DOF for the factors in the present experiments. The nearest three level orthogonal arrays available satisfying the criterion of selecting the OA is L9, having eight DOF. The experimental design is shown in Table 1.

### 2.3 Friction Stir Processing

An alloy Mg AZ31B of composition (in wt%): Al-3.02, Zn-0.89, Mn-0.29, Si-0.026, Ni-0.0009, Fe-0.0025, Mg-balance, in wrought condition supplied by Yuchen Metal Products Co., Ltd, China was used as the base metal for friction stir processing. The FSP was done on a vertical milling machine with the position of the tool fixed relative to the surface of the sheet as shown in Fig. 1. The work piece (150 × 150 $mm^2$) was firmly clamped to the bed and a specially made tool was plunged into the selected area of the material sheet for sufficient time in order to plasticize the material around the pin. After adequate plasticization, the tool is traversed across the surface of the material for a single pass. The entire sheet was processed with the

**Table 1** Formability (LDH) data for the base and FSPed samples

| Specimen no. | Rotational speed (RPM) | Traverse speed (mm/min) | Tool tilt angle (Degree) | Full dome height (mm) | S/N ratio |
|---|---|---|---|---|---|
| 1 | 900 | 24 | 0 | 6.6 | 16.3909 |
| 2 | 900 | 32 | 1 | 9.1 | 19.1808 |
| 3 | 900 | 40 | 2 | 7.6 | 17.6163 |
| 4 | 1,150 | 24 | 1 | 8.6 | 18.6900 |
| 5 | 1,150 | 32 | 2 | 9.3 | 19.3697 |
| 6 | 1,150 | 40 | 0 | 8.8 | 18.8897 |
| 7 | 1,400 | 24 | 2 | 7.9 | 17.9525 |
| 8 | 1,400 | 32 | 0 | 10.1 | 20.0864 |
| 9 | 1,400 | 40 | 1 | 8.5 | 18.5884 |
| | Base metal | | | 6.4 | |

number of passes. A non consumable taper threaded tool made of high carbon steel, H13 with a shoulder diameter of 18 mm, pin diameter of 6 mm, and a pin length of 3 mm was used. The FSP experiments were conducted on the sheet in the rolling direction as per the selected orthogonal array.

### 2.4 Limiting Dome Height Test (LDH)

Limiting dome height (LDH) [22] test and the Ohio State University (OSU) [23] test can be used to investigate the stretchability of friction stir processed samples. These tests are designed to simulate stretching, in plane-strain, with minimal bending strain. The LDH test can also be used to impose biaxial stretching on a sheet specimen, which is referred to as a full-dome test. In this work, the biaxial stretch forming was used to find the formability of the friction stir processed Mg alloy. The schematic arrangement of LDH tools (lower die, upper die and punch) is shown in Fig. 2. Square specimen sizes of 100 × 100 $mm^2$ were blanked from the friction stir processed sheets for LDH test. Circular lock beds were provided on the dies, to restrict the flow of material from the flange region into the die. All LDH tests were carried out in dry condition at a punch speed of 0.3 mm/Sec on a 50 ton hydraulic press. An optimum blank holding force in the range of 3–4 tons was applied. The punch was stopped immediately when the initiation of fracture was found on the specimen. The load—displacement data of the specimens were recorded and stored using data loggers.

Fig. 1 Friction stir processing set-up

### 2.5 Microstructural Analysis

Samples of size 10 × 8 $mm^2$ were cut from the FSPed specimens for optical metallography to study the influence of microstructural modification on the formability. The samples were prepared as per the standard technique used for Mg and its alloys and etched with a mixture of 4.2 g picric acid, 10 ml acetic acid, 70 ml ethanol and 10 ml diluted water solution for ~10 s at room temperature.

## 3 Results and Discussions

### 3.1 Influence of Process Parameters on Formability

FSP is one of the severe plastic deformation techniques that have been developed to modify the microstructure of the materials and enhance the properties of metal by localised grain refinement and homogenisation of metal. The FSP process parameters exert significant effect on the temperature generation and material flow pattern, thereby influencing the microstructural evolution of the material. The most influential process parameters affecting the microstructure and the formability are the tool RS and the tool traverse speed. The influence of FSP process parameters on the formability of magnesium sheets has been studied using stretch forming test. The friction stir processed stretch formed samples are shown in Fig. 3. The formability of the friction stir processed samples and base metal was studied in terms of LDH obtained in biaxial strain condition. The formability of Mg AZ 31 sheets for the "as-received" material and the FSP processed samples done with different process parameters combination is presented in Table 1. The microstructures of the "as-received" and FSPed AZ31B magnesium alloy are shown in Fig. 4. The "as-received" Mg alloy sheet shows coarse grain microstructure with an average grain size of 16.5 µm (Fig. 4a). The microstructures of the friction stir processed samples reveals that grain refinement has taken place due to the dynamic crystallization process during the friction stir processing. It can be observed from Table 1 that the FSP process parameters namely the tool RS, tool TS and TA play a greater role to enhance the formability of the

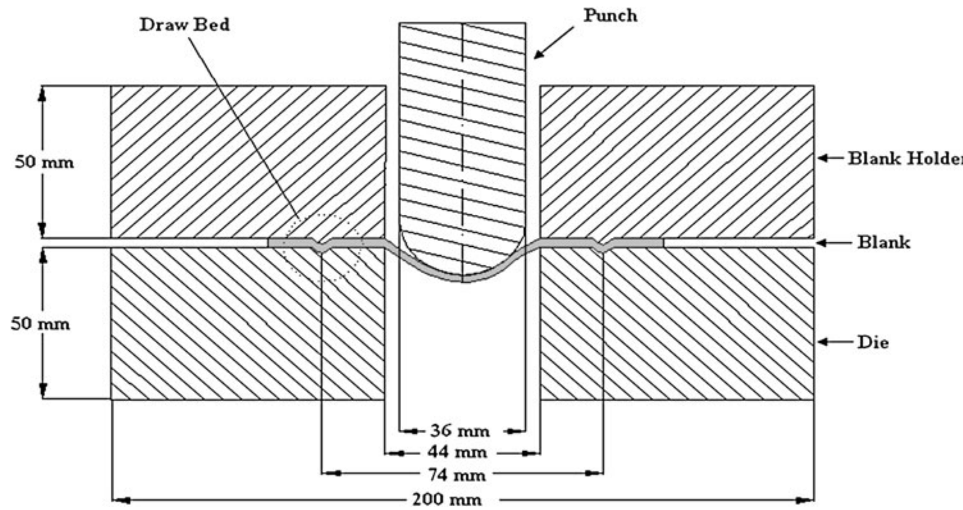


**Fig. 2** Schematic diagram of LDH test

magnesium alloys. Figure 4b shows that lower RS, TS and lowest TA have only marginally refined the grain, due to insufficient heat generation and forging force, resulting in inhomogeneous microstructure with a mixture of coarse and fine grains. As a result of this, specimen 1 exhibits only a slight increase in the formability than the "as-received" material. The increase in TS and TA has resulted in a refined microstructure (Specimen 2, Fig. 4b). The extent of inhomogeneity in the sample 2 has been reduced considerably, compared to that of the specimen 1. The specimen 2 shows better formability than specimen 1 and the "as-received" material. A further increase in the TS and the TA (40 mm/min, 2°) has produced coarse and inhomogeneous microstructure (Fig. 4c, Specimen 3). As a result, this specimen exhibits lower formability.Increase in RS from 900 rpm to 1,400 rpm results in enhancement of formability due to the greater refinement of grains and greater homogenization of the material. The microstructures of the specimens 4, 5 and 6 show homogeneous, fine grain structure (Fig. 4d, e, f). This is because, due to the increased RS, an increased frictional heating and stirring has occurred resulting in an adequate temperature and forging force for the complete deformation. The only marginal difference in the formability was found between these specimens. However, further increase in the RS has resulted in excessive heat input than the optimal, resulting in the deterioration of the formability. For example, samples processed with a RS of 1,400 rpm, a tool TS of 24 mm/min and a TA of 2° has produced inhomogeneous and coarse microstructure (Fig. 4g, specimen 7) and poor formability. This can be attributed to the excessive grain growth that has happened due to the low flow of the stirred material in the stirred zone and the higher heat input. The increase in the TS and decrease in TA at a higher RS has produced uniform microstructure (Fig. 4h, specimen 8). The change in the microstructure in this specimen is attributed to lower heat generation due to the increase in the traverse speed. As a result, this specimen exhibits higher formability than other specimens. The increase in TS and TA has again resulted an inhomogeneous microstructure (Fig (i), specimen 9) due to insufficient heat generated for optimum grain growth. As a result, this specimen displays marginally lower formability than that of the specimen 8.

### 3.2 Signal to Noise Ratio

Taguchi recommended a logarithmic transformation of mean square deviation called signal-to-noise ratio (S/N ratio) for the analysis of the results. Signal-to-noise ratio (SNR) is utilized to measure the deviation of a quality characteristic from the target. In this investigation, the "larger-the-better" S/N ratio method has been used to maximise the responses. The S/N ratio for the "larger-the-better" target for all the responses has been calculated as follows. The formula used for the computing S/N ratio is given by:

$$\text{Larger the better, S/N ratio } (\eta) = -10\log_{10}\frac{1}{n}\sum_{i=0}^{n}\left[\frac{1}{Y_i^2}\right] \quad (1)$$

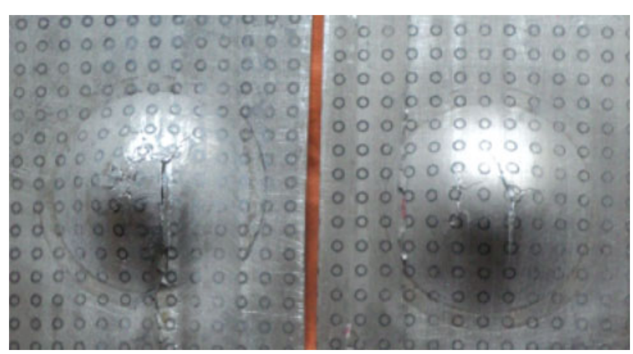

**Fig. 3** Deformed specimens in biaxial stretching

where $n$ is the number of experiments ($n = 1$ for a single set of parameters) and $Y_i$ is the response for the ith experiment. In this study, S/N ratio is used to analyse the effect of FSP parameters on the responses.

In the present study, LDH of friction stir processed magnesium sheet were analysed to determine the effect of FSP parameters. The experimental results were transformed into a signal-to-noise (S/N) ratio using the statistical Minitab software. The S/N ratio values of all levels are calculated and presented in Table 1. Main effects at all the levels are calculated and listed in Table 2. The main effect for mean and S/N ratio is plotted in Figs. 5 and 6,

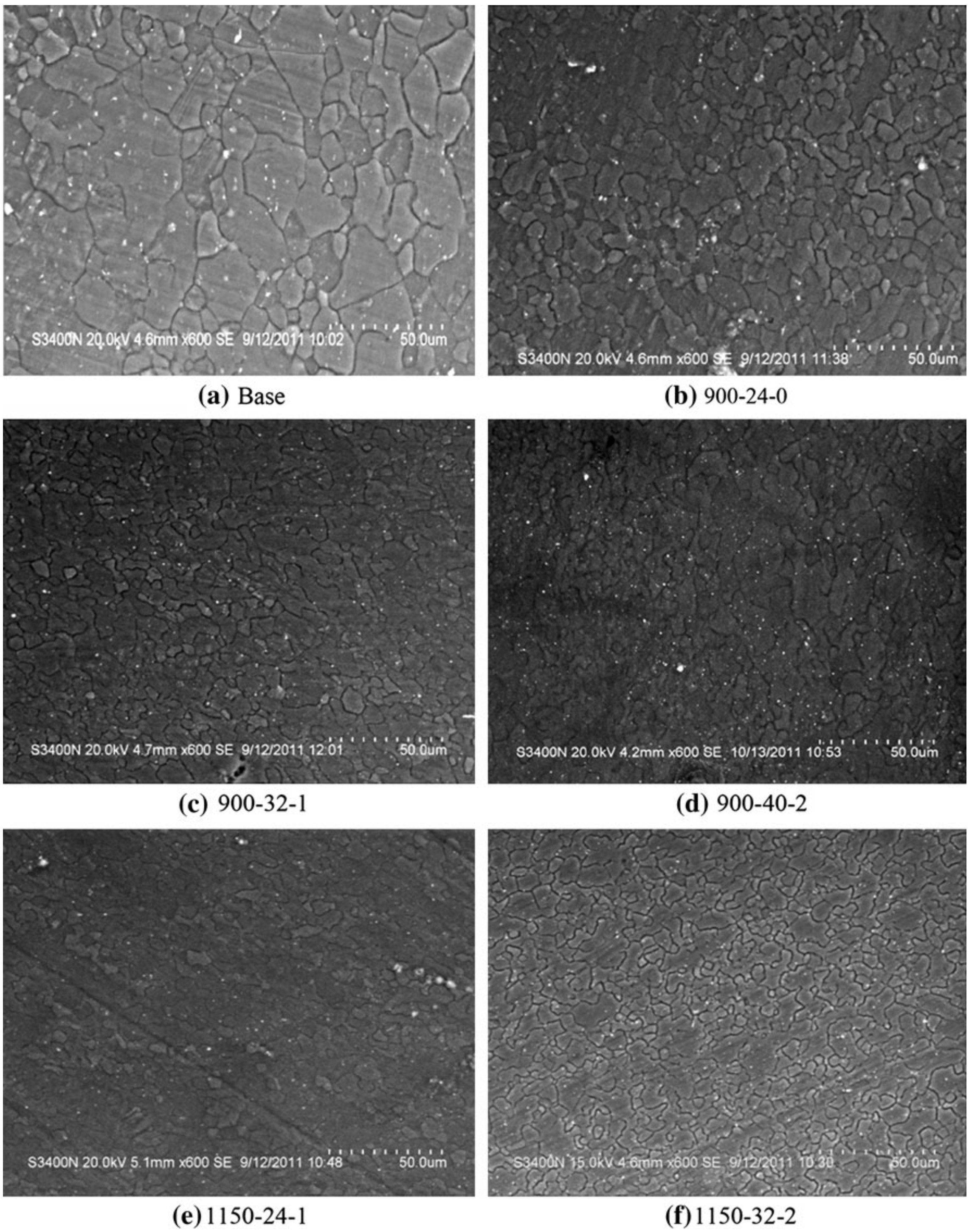


**Fig. 4** Optical microstructures of as received and FSPed specimens

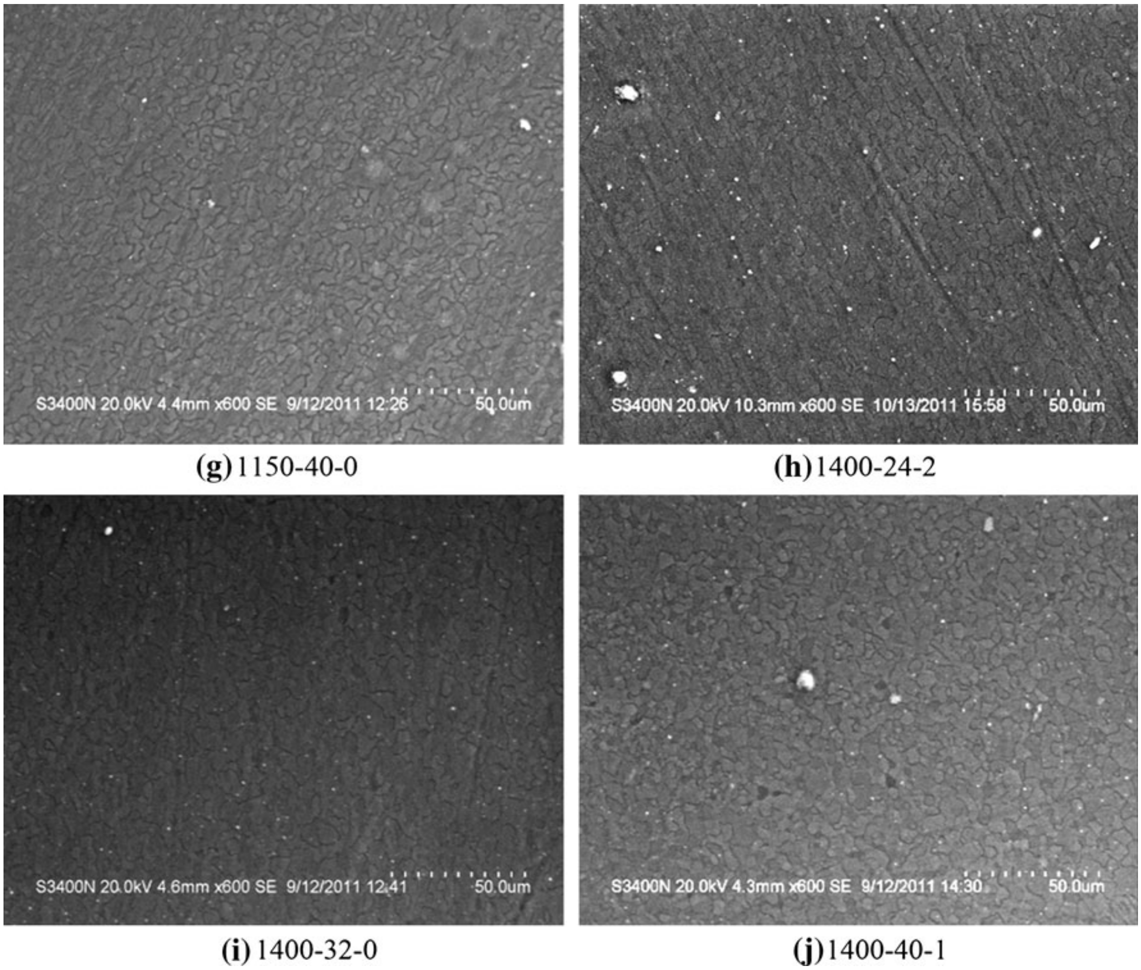


**Fig. 4** continued

respectively. Both mean effect and S/N ratio values indicate that the formability is at maximum when the RS, TS and tool TA are at level 2, i.e. RS at 1,150 rpm, TS at 32 mm/min and tool TA at 1°.

## 3.3 ANOVA (Analysis of Variance)

ANOVA (analysis of variance) is a statistical technique for determining the degree of difference or similarity between two or more groups of data. It is based on the comparison of the average value of common components. The percentage contribution of various process parameters to the selected performance characteristic can be estimated by ANOVA.

Table 3 shows the results of ANOVA for LDH of friction stir processed magnesium alloy. It is observed that the RS has 28.753 % contribution, TS has 59.715 % contribution and tool TA has 3.87 % contribution to the variation in the LDH FSPed Mg alloy.

**Table 2** Main effects of LDH (means and S/N ratio)

| Level | Means | | | S/N ratio | | |
|---|---|---|---|---|---|---|
| | RS | TS | TA | RS | TS | TA |
| L1 | 7.767 | 7.700 | 8.500 | 17.73 | 17.68 | 18.46 |
| L2 | 8.900 | 9.500 | 8.733 | 19.98 | 19.55 | 18.82 |
| L3 | 8.833 | 8.300 | 8.267 | 18.88 | 18.36 | 18.31 |
| Delta | 1.133 | 1.800 | 0.467 | 1.25 | 1.87 | 0.51 |
| Rank | 2 | 1 | 3 | 2 | 1 | 3 |

## 3.4 Regression Model

Regression analysis is a statistical technique used to find relationships between the variables for the purpose of predicting intermediate values within the range of the level. In this investigation, the relationship between process parameters for a given response or outcomes was modelled. Nonlinear regression models are developed based on the experimental results to predict the formability. It is found

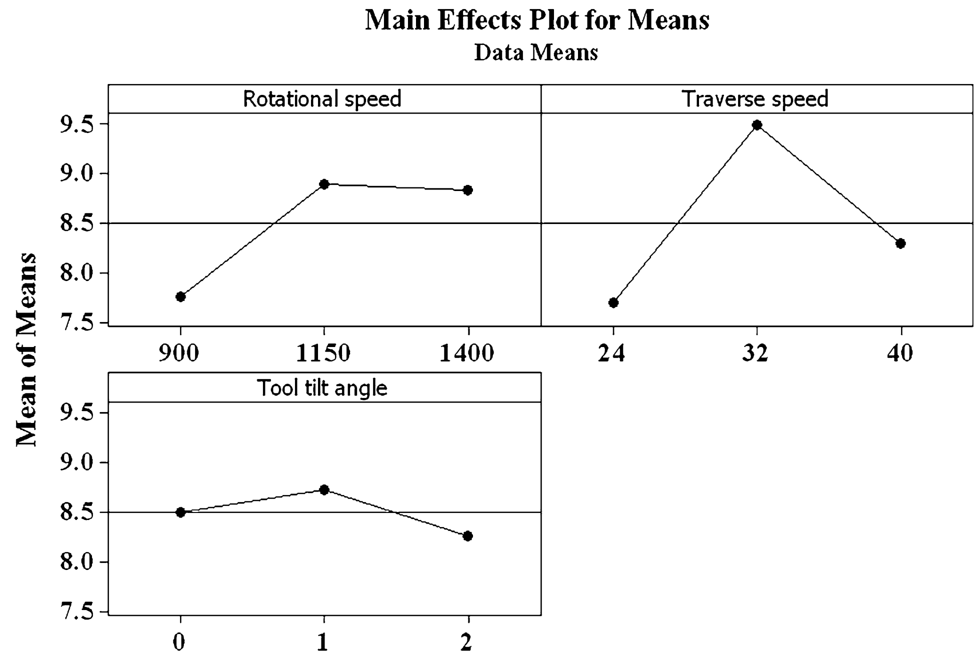


**Fig. 5** Main effects plot for Mean

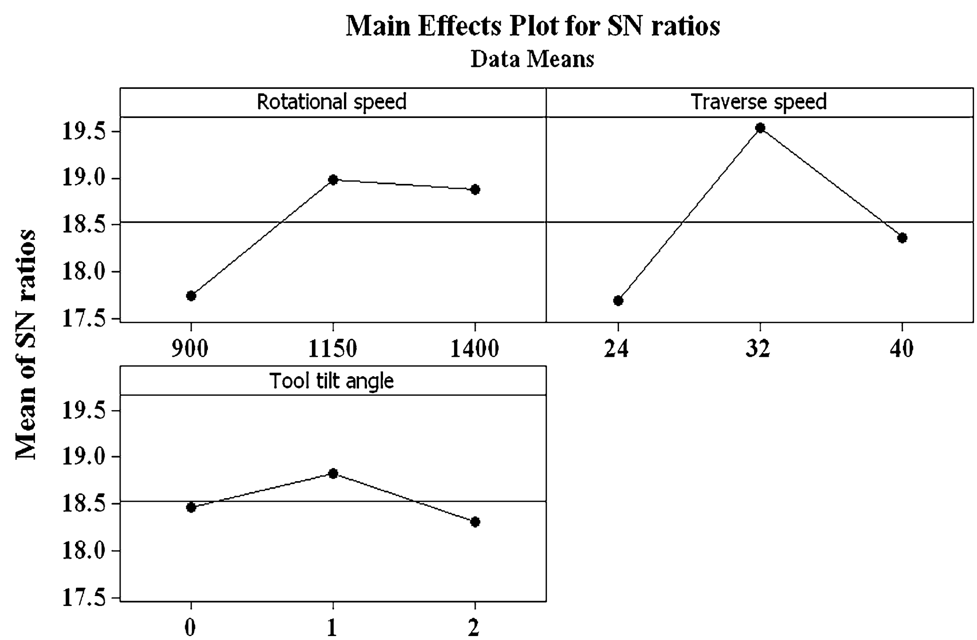


**Fig. 6** Main effects plot for S/N ratio

**Table 3** ANOVA for dome height

| Source | DF | Seq SS | ADJ SS | Adj MS | F | Contribution (%) |
|---|---|---|---|---|---|---|
| RS | 2 | 2.4267 | 2.4267 | 1.2133 | 3.75 | 28.753 |
| TS | 2 | 5.0400 | 5.0400 | 2.5200 | 7.79 | 59.715 |
| TA | 2 | 0.3267 | 0.3267 | 0.1633 | 0.51 | 3.870 |
| Error | 2 | 0.6467 | 0.6467 | 0.3233 | | 7.662 |
| Total | 8 | 8.4400 | | | | 100 |

that a second order polynomial curve best fitted the experimental values. The dependent variable is expressed as a function of the process variables as given below.

Dependent Variable (LDH) = f (RS, TS, TA)

$$\text{Limiting Dome Height LDH} = 0.0242133\text{RS} + 1.53750\,\text{TS} + 0.583333\text{TA} - 9.60000\text{E}-06\text{RS}^2 - 0.0234375\text{TS}^2 - 0.350000\text{TA}^2 - 30.44933 \quad R^2 = 92.44\% \qquad (2)$$

### 3.5 Confirmation Test

Confirmation experiments were carried out by setting the process parameters at optimal levels to validate the model developed for optimum results. The tool RS, TS and tool angle were set at level 2 and the dome height of friction stir processed Mg AZ 31 B alloy was found to be 10.31 mm.

## 4 Conclusions

1. Friction stir processing significantly improved the formability of magnesium alloy by refining the grains having equiaxed homogeneous fine grains.
2. The FSP process parameters were optimised using Taguchi analysis and the optimum value of the process parameters were found to be at a RS of 1,150 rpm, at a TS of 32 mm/min, and at a tool TA of 1°
3. An ANOVA analysis test was conducted to determine the significance of each FSP process parameter on the formability. It is found that the tool TS (59 %) has a significant influence on the formability followed by the RS (28 %)
4. Regression models were developed in this investigation to predict the formability and formability for various tool rotational speeds, traverse speeds and tool angles without requiring experimental tests.

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