Full length article

Taguchi optimization of process parameters in friction stir processing of pure Mg

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Abstract

Taguchi experimental design technique was applied to determine the most influential controlling parameters of FSP such as tool rotational speed, travel speed, tilt angle and penetration depth on hardness value of Mg. In this case, 9 combinations of these 4 essential processing parameters were set and Taguchi's method followed exactly. Signal to noise ratio (S/N) analysis showed that maximum hardness achieved when rotational and travel speeds, penetration depth and tilt angel were chosen as 1600 rpm, 63 mm/min, 0.1 mm and 2°, respectively. In addition, analysis of variance (ANOVA) technique indicated that tilt angle and rotational as well as travel speed are the significant influential parameters in the hardness value of the treated samples, respectively. Finally a model for hardness values based on FSP parameters was calculated by design expert which was also confirmed by experimental results.
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Keywords: Mg; FSP; Hardness; Taguchi; ANOVA; Design-expert

1. Introduction

Magnesium and its alloys have received considerable attention as biodegradable implants during recent years. However, their biomedical applications are still limited due to their poor mechanical and corrosion resistance [1,2]. High degradation rate of Mg based materials deteriorates their mechanical integrity during the healing process. Many techniques have been applied to improve corrosion resistance of magnesium alloys, such as alloy modification [3], producing composites [4,5] and surface treatment [6–8]. Among this variety of methods, the one which can improve both corrosion and mechanical properties of magnesium would be more promising. Previous studies have shown that

the grain refinement can enhance mechanical properties [9,10] and corrosion resistance simultaneously [11–13]. Different severe plastic deformations have been used to modify the structure of materials [14–17]. Friction stir processing (FSP), which can significantly refine structure [18,19] and fabricate composites [20,21] can be considered as a severe plastic deformation to modify the structure of materials. FSP requires a precise design of process parameters in order to achieve a defect free workpiece that is consistently reproducible. Since magnesium holds hexagonal close packed structure, the successful achievement of fine grains in Mg by FSP might be very sophisticated due to its limited slip systems. In addition, there are several FSP parameters that affect the structure and mechanical properties of Mg; therefore, a large number of experiments should be done to achieve a fine grained Mg structure with enhanced mechanical properties.

Jayaraman et al. [22] determined optimum welding condition for maximizing tensile stress of cast aluminum alloys by

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ANOVA and signal to noise ratio. S. Rajakumar et al. [23] focused on the development of empirical relationship to predict tensile strength of friction stir welded AA 1100 aluminum alloy joints. The results showed that rotational speed is more sensitive than tool hardness, followed by axial force, shoulder diameter, pin diameter and welding speed on tensile strength. Lakshminarayanan et al. [24] indicated that the rotational speed, welding speed and axial force are the most influential parameters on the tensile strength of aluminum alloy joints. Nourani et al. [25] confirmed that Taguchi's orthogonal design can be successfully used to minimize both the HAZ distance to the weld line and the peak temperature in aluminum alloys. M. Salehi et al. [26] applied design of experiment (DOE) to determine the most important factors of friction stir processing which influence ultimate tensile strength (UTS) of AA6061/SiC nanocomposites. Analysis of variance revealed that the rotational speed has significant impact. The statistical results depicted that higher UTS achieves by threaded pin, higher rotational and lower the transverse speed.

This work has been conducted to find optimal FSP parameters, such as rotational (W) and travel (V) speeds, tool penetration depth (PD) and tilt angle (Θ) in order to fabricate fine grained magnesium workpiece. Analysis of variance (ANOVA) along with the Taguchi technique and design-expert software was used to interpret experimental data.

2. Experimental design and procedure

The Design-Expert, statistical software along with Taguchi design with L9 orthogonal array which composed of 3 columns and 4 rows were employed to optimize the FSP parameters (Table 1). The selected FSP parameters for this study were: rotational speed (W), travel speed (V), tilt angle (Θ) and penetration depth (PD). The Taguchi method was applied to the experimental data and the *signal to noise ratio* (S/N) for each level of process parameters is measured based on the S/N analysis. Regardless of the category of the quality characteristic, a higher S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio [27]. A detailed ANOVA framework for assessing the significance of the process parameters is also provided. The optimal combination of the process parameters can be then predicted. Finally, a model for hardness values based on FSP parameters is offered by design expert.

As cast Mg workpieces (100 × 50 × 7 mm) were prepared and FSP were applied on the surface of the workpieces using a conventional miller machine. A triangle FSP tool with shoulder diameter of 20 mm was machined from H13 tool steel. A Vickers microhardness tester (HV-5, Laizhou Huayin Testing Instrument Co. Ltd) with an applied load of 200 gf for 10 s was used to measure the hardness of the workpieces. In this study, the hardness value of stir zone which experiences the highest strain and heat input by FSP, is determined for optimizing the FSP parameters.

3. Results and discussion

3.1. Signal to noise ratio (S/N) analysis

Signal to noise ratios (S/N) for each control factor were calculated, in order to minimize the variances in hardness values. The signals indicate that the effect on the average responses and noises are calculated by the influence on the deviations from the average responses, which will disclose the sensitiveness of the experiment output to the noise factors. The appropriate S/N ratio must be chosen according to previous knowledge, expertize and understanding of the process. When the target is determined and there is static design, it is possible to choose the S/N ratio based on the goal of the design. In this study, the S/N ratio was chosen based on the criterion the-higher-the-better, to minimize the responses and it was calculated according to Eq. (1) [27];

$$\frac{S}{N} = -10 \text{Log} \left(\frac{1}{n} \sum_{i=1}^{3} \frac{1}{Y_i^2} \right) \tag{1}$$

where n is repetitions that in this study is equal to 3 and Y_i is the hardness result for the ith experiment.

The Taguchi experimental results are summarized in Table 2 and presented in Fig. 1.

As is seen in Fig. 1, the highest hardness was achieved when W, V, Θ and PD were chosen according to level 3, 3, 2, and 1, respectively.

FSP encourages recrystallization phenomena due to high strain and heat input and refines the structure. Higher strain and lower heat input result in finer microstructure and enhance hardness value. Induced strain rate and heat input during FSP can be calculated by Eq. (2) [18] and Eq. (3) [28]. Too high value of rotational to travel speed ratio (W/V) for a relatively

Table 1
FSP parameters and design levels.

Parameters	Code	Unit	Level 1	Level 2	Level 3
A: Rotational speed	W	rpm	1000	1250	1600
B: Travel speed	V	mm/min	25	40	63
C: Tilt angle	Θ	degree	1.5	2	3
D: Penetration depth	PD	mm	0.1	0.2	0.3

Table 2
Standard orthogonal arrays of 9 different groups following Taguchi's suggestion.

Test number	W (rpm)	V (mm/min)	Θ	PD	HV0.2			S/N
1	1000	25	1.5	0.1	38	34	42	31.49
2	1000	40	2	0.2	37	35	34	30.94
3	1000	63	3	0.3	33	33	35	30.53
4	1250	25	2	0.3	33	35	37	30.85
5	1250	40	3	0.1	38	35	37	31.27
6	1250	63	1.5	0.2	29	34	38	30.38
7	1600	25	3	0.2	31	34	36	30.49
8	1600	40	1.5	0.3	30	32	34	30.06
9	1600	63	2	0.1	46	48	49	33.55