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A Characterization Study of the ZE41 Magnesium Alloy Using Abrasive Waterjet Cutting †

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Abstract: ZE41 is a magnesium alloy used in heat exchangers, condensers, reactors, and pressure vessels where good surface qualities are required. This current research focuses on the investigation of the striation angle (SA), surface roughness (SR), and striation zone (SZ) in ZE41, using abrasive waterjet cutting. Significant variables in the investigation were jet pressure, traverse speed, mass flow rate, and stand-off distance. In accordance with Taguchi's L18 orthogonal array, the responses for each cut test were studied. In addition, the principal component-based grey incidence (PGI) technique successfully combined the strengths of the optimization tool to identify the ideal parameter condition. The confirmation results revealed that the PGI technique improved SR by 4.02%, SZ by 6.67%, and 1.48% in the SA.

Keywords: ZE41 alloy; magnesium alloy; AWJC; PGI technique

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1. Introduction

Waterjets in their pure form, or when coupled with abrasives, can machine materials that are tough to cut, such as brass, nickel-chromium alloys, and titanium. Unlike cutting procedures involving plasma or laser, abrasive water jet cutting (AWJC) is distinguished by the absence of microcracking and thermal impacts on the cut surface [1]. To conduct the desired activity, the principle consists of converting water's available pressure energy into kinetic energy by passing it through a small hole (orifice) [2]. Abrasive performance was discovered to be significant while taking cuts, and proper abrasive recharging improved the penetration depth of waterjets at a lower cost [3]. In addition, a good surface finish was observed when AWJC of a metal alloy was compared to AWJC of pure metal as a parent [4]. Furthermore, cutting factors such as abrasive water jet pressure (AWJP), cutting speed (CS), abrasive flow rate (AFR), jet angle (JA), and standoff distance (SOD) were discovered to play a vital influence in defining the quality features of the cut surface [5]. For offline quality control, research factors and their impacts on quality characteristics were critical, and an appropriate combination of factors was required to achieve improved cut surface characteristics [6,7]. SZ characteristics in the PGI method (zone length and SA) directly impact surface texture; hence, lowering the SZ and its angle was critical for producing a superior cut surface [8,9]. It is possible to think of the AWJC technique as a multiple-input procedure that necessitates the simultaneous optimization of several answers [10,11]. A survey of the available literature revealed that little is known about the properties of the SZ and that little has been done to research the SZ in ZE41, a magnesium alloy AWJC. As a result, a factor design attempt has been undertaken in AWJC using the PGI method to reduce SR, SZ, and SA.

2. Materials and Methods

ZE41 was selected as the workpiece material. It is mainly composed of zirconium, rare-earth elements, zinc, and magnesium. The experiments were run on a dual amplifier and pump system-equipped three-axis AWJM (Waterjet Germany Pvt. Ltd., model: S30155, Bad Nauheim, Germany). The device operated a 0.28 mm diameter (sapphire) injection nozzle that can discharge the water jet at a maximum pressure of 3600 bar using a PLC-based system. During several cutting trials, garnet (80 mesh) was utilized as the abrasive, and the nozzle was held at a right angle to the cut surface. Figure 1 depicts the machine setup and machined samples. The AWJC factor levels were chosen based on the available literature and pilot experiences. Taguchi's L18 OA was employed for experimentation, with each factor being varied at five levels. After the numerous trial cuts, the SZ, SA, and SR were observed as representatives of surface texture. Lower SZ, SA, and SR values might improve the surface texture. Therefore, all of the observed responses were treated as smaller-than-better characteristics. The cutting surface has two distinct zones: one has no striations, indicating cutting wear, and the other has striations, revealing deformation wear to the bottom 15. It features a predetermined square on the screen with a built-in transparent protractor for measuring angles. The length of the bottom section chosen as the SZ was measured using an optical microscope and an optical micrometre, and the SA was calculated using the program MB Ruler 4.0′. The SR was determined using a smartsurf roughness tester with a contact stylus (Model: SE500A, Fukuoka, Japan). The roughness profile's arithmetic mean deviation (Ra) was measured for a sampling length of 4 mm and measured at a speed of 0.1 mm/s16.

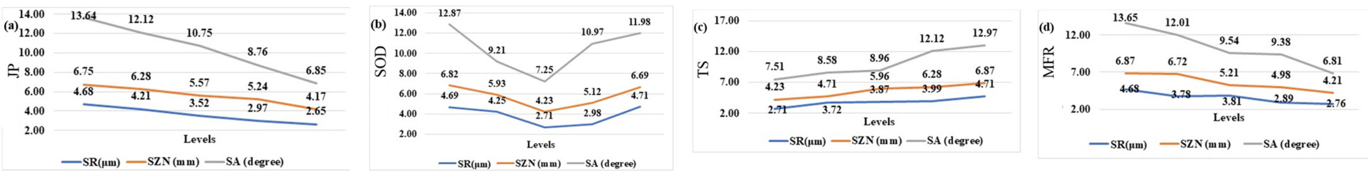

Figure 1. (**a**–**d**) Effect of JP, SOD, TS, and MFR on the responses.

3. Results and Discussion

Using the combination of inputs recommended by the L18 OA, the metallurgical surface treatment of carbonitriding was applied to all material substrates. Further analysis was performed on the replies that were received. The effects of individual factors on the response are displayed in Figure 1a–d. The higher level of JP 350 MPa gives a lower range of SR of 2.65 μm, SZ of 4.17 μm, and SA of 6.85 degree, as shown in Figure 1a. The lower level of JP 150 MPa gives a higher spectrum SR of 4.68 μm, SZ of 6.75 mm, and SA of 13.64 degree, as shown in Figure 1a. Figure 1b reveals that the moderate level of SOD 2 mm gives a lower range of SR 2.71 μm, SZ 4.23 mm, and SA 7.25 degree. The initial and higher SOD 1 mm and 3 mm level provides a greater range of SR 4.71 μm, SZ 6.69 mm, and SA 11.93 degree. The lower level of TS 50 mm/min gives a lower range of SR 2.71 μm, SZ 4.23 mm, and SA 7.51 degree, as shown in Figure 1c, and it also indicates that the higher level of TS 110 mm/min produces a higher range of SR 4.41 μm, SZ 6.87 mm, and SA 12.97 degree. The higher level of AFR 400 g/min gives a lower range of SR 2.76 μm, SZ 4.21 mm, and SA 6.81 degree, as shown in Figure 1d. Similarly, the lower range of AFR 200 g/min produces a higher range of SR 4.68 μm, SZ 6.87 mm, and SA 13.65 degree.

3.1. Principal Component-Based Grey Incidence (PGI)

An efficient method for offline quality control is the simultaneous optimization of a number of responses. The simultaneous optimization of many responses in manufacturing is challenging and requires additional experimental trials and compound analysis. In an innovative (PGI) methodology, an attempt has been made to combine the advantages of Eigenvector analysis and grey incidence theory. Two stages are used to present the various PGI technique steps.

3.2. Pre-Processing and Normalization of the S/N Ratio

A necessary solution was used to compute the requisite signal (process average) to noise (standard deviation), quantified as the S/N ratio, for different quality factors. The S/N ratio was the reciprocal coefficient of variation, which reflected the relative dispersion of data and was used as an initial indicator. The first stage of data pre-processing was finished, and the pre-processed data are shown in Table 1 along with the experimental results. Equation (1) predicts response values and DPI values [12]. Table 2 summarizes the results of the confirmation tests. In the validation trials, the difference between anticipated and actual responses was less than 5%, indicating that the L18 Taguchi models developed for AWJM on ZE41 is a magnesium alloy were acceptable. At the initial condition, JP = 150 MPa, SOD = 0.5 mm, TS = 110 mm/min, and MFR = 200 g/min, and in the optimal condition, JP = 300 MPa, SOD = 1 mm, TS = 72 mm/min, and MFR = 400 g/min; the performance of the AWJM process on the ZE41 magnesium alloy was observed.

$$\gamma_{pred} = \gamma_m + \sum_{k=1}^{nq} (\overline{\gamma} - \gamma_m) \tag{1}$$

Table 1. Experimental results with GIC and DPI grades.

S.No	Run	Input Factors				Response			GIC			DPI Grade
		JP	SOD	TS	AFR	SR	SZ	SA	SR	SZ	SA	
		MPa	mm	mm/min	kg/min	µm	mm	Degree				
1	26	350	0.5	50	400	3.11	4.928	7.575	0.457	0.489	0.943	0.630
2	15	350	0.5	110	400	2.68	4.899	8.598	0.496	0.428	1.000	0.641
3	6	350	2.5	50	400	4.13	5.057	7.974	0.392	0.516	0.765	0.558
4	22	350	0.5	50	200	3.50	5.057	8.065	0.418	0.477	0.875	0.590
5	23	350	2.5	110	400	3.52	5.232	8.151	0.417	0.476	0.863	0.585
6	17	350	2.5	50	200	3.86	5.363	6.726	0.458	0.639	0.728	0.608
7	3	350	0.5	110	200	4.18	5.340	8.231	0.373	0.490	0.800	0.554
8	7	300	1.5	80	300	3.90	4.159	8.421	0.431	0.511	0.707	0.550
9	1	350	2.5	110	200	3.96	5.716	6.786	0.380	0.552	0.923	0.618
10	13	150	0.5	50	400	4.09	4.587	9.151	0.367	0.444	0.808	0.540
11	10	250	1.5	80	350	4.12	5.780	9.335	0.375	0.448	0.765	0.529
12	27	250	1.5	65	300	4.14	6.033	8.579	0.355	0.455	0.869	0.560
13	16	250	1	80	300	4.16	5.715	9.845	0.369	0.430	0.758	0.519
14	24	250	1.5	80	300	3.88	6.432	9.879	0.364	0.408	0.854	0.542
15	19	250	1.5	80	300	4.23	5.879	6.758	0.379	0.582	0.840	0.600
16	9	250	1.5	80	300	4.25	6.432	9.785	0.350	0.421	0.806	0.526
17	25	250	1.5	95	300	3.59	5.489	7.186	0.440	0.551	0.821	0.604
18	14	250	2	80	300	4.34	6.472	11.433	0.347	0.386	0.745	0.493

Table 2. Experimental validation.

Confirmation	SR	SZ	SA
Initial setting	3.40	5.80	9.24
DPI setting	2.98	5.24	8.75
Actual	2.86	4.89	8.62
Improvement (%)	4.02	6.67	1.48

3.3. Surface Topography Analysis

Due to the irregular surface roughness towards the bottom, the surface quality was primarily impacted. The aqua jet's high abrasive pressure sufficiently sheared the material at the bottom region. By contrast, the particle with lesser energy created a rough surface by plastic deformation. Figure 2a depicts the smoother surface quality generated in the centre region of the ZE41, which is a magnesium alloy machined surface with peck and scratch at a higher jet pressure JP (350 MPa), whereas Figure 2b depicts the rough surface with embedding and ploughing at a lower jet pressure (150 MPa) due to ductile erosion. Microscopic analysis was performed on FESEM images observed at the higher levels of each factor, with the remaining parameters maintained at a medium level. The SEM images of factors such as JP, TS, SOD, and MFR are shown in Figure 2c,d.

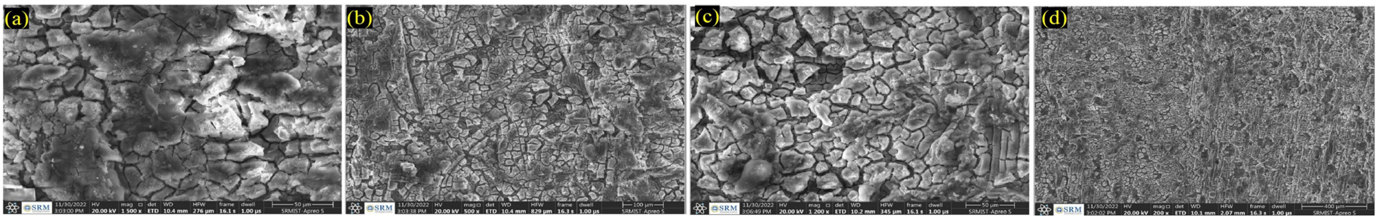

Figure 2. SEM image, (**a**) JP 350 MPa, (**b**) JP 150 MPa, and (**c**,**d**) Optimum condition JP 250 MPa, SOD 1 mm, TS 72 mm/min, and MFR 400 g/min.

4. Conclusions

The PGI methodology successfully predicted the optimal conditions at SOD = 1 mm, TS = 65 mm/min, MFR = 400 g/min, and JP = 350 MPa. The relative impact of variables in lowering SR, SZ, and SA was investigated using ANOVA statistics on the DPI response. A significant variable was JP at 44.31%. The other process variables, MFR, SOD, and TS, had a minor impact. The confirmation results revealed that the PGI technique improved SR by 4.02%, SZ by 6.67%, and 1.48% in the SA. The SEM analysis shows that the smooth SR was achieved with a maximum JP, MFR, and minimum SOD and TS.

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