Wear Investigation of Aluminum Alloy Surface Layers Fabricated through Friction Stir Welding Method

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In this research paper, an effort was made to investigate the dry sliding wear rate of friction stir welded AA6262/AA5456 composite performed by the Taguchi approach. Wear experiments are carried out by selecting suitable process parameters such as load (LD), sliding speed (SS), and sliding distance (SE) to recognize the individual and combination effects of parameters. Orthogonal array L27 mode is applied to make numbers of experiments to find the extreme and minimum wear amount. The experimental works are conducted on Pin on Disc (POD) apparatus and measured the weight of samples before and after test for calculating wear rate (WR) and then various analyses are performed such as ANOVA, interaction plot between parameters, and regression model with support of MINITAB software. The results revealed that maximum wear rate is found as 0.01215 mm³/Nm at LD of 50 N, SE of 600 m, and SS of 4 m/s, whereas minimum 0.00414 mm³/Nm at the grouping process parameters which are LD of 30 N, SE of 400 m, and SS of 6 m/s. From the observation of ANOVA, the most significant factor is identified as load, followed by sliding distance, sliding speed, and combination of each parameter. The load is considered as main parameter which contributes about 83.75% to achieve the maximum wear rate of developed AA6262/5456 composites. The contribution of sliding distance and speed are 3.75% and 1.85%, respectively.

1. Introduction

Aluminum alloy's importance in the automotive and construction sectors may be attributed to their low density and high rigidity. AA6XXX rated components have better physical qualities and strength, making them desirable in applications such as missiles, weapons, and automobiles [1]. AA6262/5456 is a higher-grade alloy with a higher amount of magnesium, silicon, and iron components, all of which have been carefully regulated to improve resistance to oxidation and mechanical characteristics [2]. Different techniques including stir casting [3], squeeze-casting, metallurgy method, and friction stir process (FSP) are used to create aluminum matrix composites based on size of particles, volume fraction, and shape of reinforcing components [4]. Friction stir welding (FSW) is a production method for combining metals, steels, and aluminum alloys [5–7]. It is really energy-efficient and perfect example of create composites from two metallic phases as per several researchers point of view [8, 9]. FSW factors of Al 6061/7075 alloys were examined by Ravikumar's team. They chose three distinct pin tools in the shapes of square, cylinder, and square thread shapes [10]. According to the study conducted by Bhushan and Gupta, wear is caused by friction between two comparable or different metals when they come into contact [11]. Singla et al. exposed AA6061/SiC composite made using the
SC process with modifications in silicon carbide volume %, and the wear examination was conducted via a POD device [12]. Sesharao et al. studied on the effect of sliding distance on the response of wear rate for Al6066/HSS-Cu produced by the heat treated casting method [13]. The maximum wear resistance is attained in 24 hrs milling powder method performed by Guler and team. They compared the ZA27/B4C/graphite composites with and without milled process and found corrosion resistance is more in milling powder technique [14]. Singh et al. studied about wear and friction performance of panama oil lubricants at various levels of sliding speed, and the results conclude that this kind of biolubricant mainly applicable in automobile enterprise [15]. Natarajan et al. studied wear rate of Al 2014/flyash on the brake pads. When they compared with grey cast iron, Al-based composite provides superior wear resistance [16]. Panneerselvam et al. used the Taguchi approach to examine wear performance of Al-HMMC by employing input variables of load, slide speed, and MoS₂ particles. The influence factor was identified through the ANOVA technique [17]. Hemanth Reddy and Perumal used compression moulding to prepare samples of (C3H6)n/Nylon/Honeycomb Al-based composite and preferred Taguchi-L9 orthogonal array on wear experiments [18]. To conduct the wear experiment on POD device, AA5052/ZrO2/Al2O3 specimens are made as according to ASTM standards using the stir process. The MINITAB software was used to examine the design of experiments for wear parameters [19, 20]. From other research works, many scholars selected almost 3 to 5 input factors such as load, sliding speed, time, distance, and reinforcement percentage to perform wear examination. The wear rate of Al 7075-SiC-graphite reinforced matrix is lower in the composite than in the nonreinforced alloy, according to a parametric investigation (load, speed, and sliding distance). With the exception of sliding velocity, where a transitional velocity was seen, the wear rate was shown to rise with the increase in process parameters [21]. The wear behaviour of B4C particles reinforced with aluminium that were manufactured using the friction stir procedure is revealed by Mehta et al. A variety of specimen passes were tested. One advantage of reverse pass is that the base metal is well-reinforced uniformly [22]. Wu et al. assessed the wear rate (WR) and friction coefficient (FC), finding that WR values was improved when Nd was at 0.5% of weight and subsequently dropped when Nd was at 1.0 w.t%, when a load was applied from 30 to 160 N [23]. In the absence of reinforcement particles, the composite hardness reduced in contrast to the basic metal, according to Barmouz et al.’s study, who generated Cu/SiC composites by dispersing 5 mm and 30 nanometers SiCp into the surface of pure Cu using FSP [24]. Trimble’s team used a postweld experiment and monitoring force to pick a combination of welding

Table 1: Mechanical properties of Al6262 and Al5456.

| Material | Tensile strength, TS (MPa) | Yield strength, YS (MPa) | Elongation, δ (%) | Hardness (HV) |
|----------|---------------------------|--------------------------|------------------|---------------|
| Al6262   | 260                       | 206                      | 12               | 85            |
| Al5456   | 305                       | 244                      | 15               | 110           |

Table 2: Wear test parameter levels.

| Parameters | Level 1 | Level 2 | Level 3 |
|------------|---------|---------|---------|
| LD (N)     | 30      | 40      | 50      |
| SE (m)     | 400     | 500     | 600     |
| SS (m/s)   | 2       | 4       | 6       |
process parameters for producing sound welds and strength at higher speeds. Variations of rotating speeds and tool speed were used in the AA 2024-T3 research. However, they discovered that tool geometry with a scrolling shoulder and a triflute shape for the pin produced superior results [25]. Prado et al. investigated the influence of rotational speed on tool wear in FSW of AA6061-20% alumina and discovered that tool wear was not linear [26]. Lee et al. compared WR of AZ91-10% wt of SiC with base composite to that of FSW and discovered a reduction in the wear rate. However, he was not trying to attempt to link the influence of FSW parameters on wear amount [27]. Krishnan et al. [28] studied the effect of stirrer blade design on mechanical properties of AMCs and performed simulation through the CFD method. The result revealed that four blade stirrers give more tensile strength and hardness amongst 5 different blades. Krishnan and team [29] prepared different aluminum matrix composites by stir-squeeze casting. Microstructural investigations such as optical microscopy, XRD, and EDS were carried out, and mechanical proprieties exposed that UTS around 126 MPa was obtained at scrap Al/Alumina composites. Rayapandi Thevar et al. [30] used the Taguchi approach with L9 orthogonal array to conduct experimental study of Al–Al2O3 composites. Based on various literature articles, the effects of weld speed and tool tilt angle while joining different Al-based alloys were found and explored. As the tool rotating speed (TRS), tilt angle (TA), and weld speed (WS) are the
primary sources of heat generation, the weld strength and quality typically depend on the heat generated and material mixing during welding. Our objective is to create AA6262/AA5456 composites with help of these parameters (TRS, TA, and WS) in the FSW method and prepared 27 specimens for conducting the wear test. With the support of the Taguchi technique and MINITAB software [31], significant parameter was identified to increase the wear rate. The fabrication of pressure vessels, screw machine products, nuts, oil line fittings, and valve components are applied for the development of FSW of Al5456/6262 composites.

2. Materials and Methodology

The plates of AA6262 and AA5456 are preferred to make a joint via friction stir welding (FSW). 6262 alloy which possess 91–92% of aluminum along with some other elements such as 5.2–5.7% of magnesium, 0.4–0.5% of iron, 1.5–1.75% manganese, 2.08–0.35 of copper, 0.2–0.4% of silicon [32]. Similarly, 5456 alloy has 95.5% of Al and other chemical contents such as Mg-1.2%, Mn-0.15%, and Si-0.9% [33]. The mechanical properties of base metal AA5456 and AA6262 alloys are shown in Table 1. Vertical milling machine and H13 pin were used as machine and welding tool to complete the FSW process as shown in Figure 1. Al plates with a dimension of 100 × 50 × 6mm³ are connected by inserting pin tool with 25 mm of shoulder diameter and 4 mm length. Figure 2 shows Pin on Disc (POD) unit which utilized to conduct dry sliding wear test size of specimens Ø12 mm × 35 mm length (ASTM-G99) was removed from the FSW sample. Before the carryout experiment, we cleaned the specific sample by acetone and then measure its weight through electronic digital device. After that, the specimen is placed in pin, then make sample to touch on rotating disc of diameter 75 mm. The wear test is performed by varying parameter of load (30N), slide distance (400m), and slide speed (2m/s). The load is applied on the arm to make contact with revolving disc till the sample surface is wear off. Due to movement of arm with disc which creates wear on composite. Afterward, the experiment is completed, and take out specimen and calculate weight loss by measuring weight of the specimen. In this dry wear examination, we did not use any lubricants. This procedure is followed for the remaining 26 parameter levels on the wear test. Design of Experiments (DOE) is frequently used to examine the input process variables or parameters with their stages to attain objectives. The conduction of experiments was performed with the aid of parametric combinations and their levels. The number of experiments is to be established according to the Taguchi design [34, 35]. In this task, we have selected three parameters of LD, SS, and SE at 3 levels as shown in Table 2. The optimization software MINITAB

| Table 3: ANOVA wear rate. |
|---------------------------|
| Considerations | Dof | SS       | MS       | F        | P value | Contribution level (%) |
| LD            | 2   | 0.000134 | 0.000067 | 72.02    | 0.000   | 83.75                |
| SE            | 2   | 0.000006 | 0.000003 | 3.40     | 0.085   | 3.75                 |
| SS            | 2   | 0.000003 | 0.000002 | 1.68     | 0.246   | 1.85                 |
| LD * SE       | 4   | 0.000004 | 0.000001 | 1.08     | 0.428   | 2.12                 |
| LD * SS       | 4   | 0.000002 | 0.000001 | 0.55     | 0.704   | 1.25                 |
| SE * SS       | 4   | 0.000003 | 0.000001 | 0.79     | 0.563   | 1.85                 |
| Residual error| 8   | 0.000007 | 0.000001 |          |         | 5.43                 |
| Total         | 26  | 0.000160 |           |          |         |                      |

Table 4: Response output for WR.

| Level | LD    | SE    | SS    |
|-------|-------|-------|-------|
| 1     | 0.005006 | 0.006972 | 0.007173 |
| 2     | 0.007472 | 0.007864 | 0.007964 |
| 3     | 0.010454 | 0.008096 | 0.007794 |
| Delta | 0.005449 | 0.001123 | 0.000791 |
| Rank  | 1     | 2     | 3     |
helped to generate the combination of three factors as per L27 OA, and it allows to establishing and understanding a significance of the process variables on output response of the wear rate. DOE examination, ANOVA [36], regression model, response of SN ratio, and plots were examined after collection of experimental results from the wear test which performed on POD apparatus.

3. Result and Discussion

3.1. Influence of FSW Parameters. The equipment is called pin disc which assisted to perform the wear behavior test on friction stir welded (FSW) samples of AA6262/AA5456 composites. For joining both the surfaces of chosen materials, we utilized steel pin tool and maintained the tool rotational speed of 1400 rpm, weld speed of 30 mm/min, and tool angle of 2° to carry out FSW joints. Wear rates (WR) have been measured by variation of three important process parameters such as application of load (LD), sliding speed (SS), and sliding distance (SE). Totally, 27 experiments are conducted with change of LD, SS, and SE factors. 1 to 9 experiments are performed by kept LD (30 N) and variation of SE (400–600 m) and SS (2–6 m/s), respectively. Figure 3 shows that the lowest wear rate (0.00414 mm³/Nm) was achieved at SE (400 m) and SS (6 m/s) whereas the maximum WR was attained at 0.00615 mm³/Nm at SE (500 m) and SS (4 m/s). 10–18 wear tests were conducted by increasing the applied load from 30 to 40 N. The wear rate varies from 0.00635 to 0.00822 mm³/Nm as shown in Figure 4. Low intensity of WR is at SE of 400 m SS of 2 m/s and highest wear intensity is acknowledged at SE (500 m) and SS (6 m/s). The final (19–27) tests are carried out by increasing LD as 50N. As mentioned in Figure 5, minimum (0.00849 mm³/Nm) and maximum (0.01282 mm³/Nm) WR were accomplished at SE (500 m) and SS (2 m/s) and SE (500 m) and SS (6 m/s), respectively. The overall wear results are declared in Figure 6 and noticed that among 27 experimental outcome, the highest (0.01215 mm³/Nm) and lowest (0.00414 mm³/Nm)
wear rate are acknowledged at specimen 27 and specimen 3 that the combination of process parameters levels are LD3-SE3-SS2 (50 N, 600 m, and 4 m/s) and LD1-SE1-SS3 (30 N, 400 m, and 6 m/s), respectively. The outcomes revealed that WR is almost directly proportional to applied load and sliding distance. When the load and sliding distance are increased, the wear rate also is improved more.

3.2. Analysis of Variance. The Taguchi-GRA method was used to identify the optimize process parameters [37]. ANOVA is one of the essential steps in the optimization process which is to investigate an effect of individual parameters of LD, SS, SE, and influence of combined factors such as LD × SS, LD × SE, and SS × SE on wear quantity. Table 3 shows the contribution of each input variables, representing their influence level on outcome of the wear amount. The AA6262/5456 surface layer is subjected to rubbing under altered loads, slide speeds, and slide distances. From Figure 7, it is observed that the load is the most influencing factor contributing 83.75%, second significant is to be considered as sliding distance of 3.75% to improve wear rates and remaining individual (SS) and joint factors are involved as negligible or low significant factors on the wear performance. Residual error is obtained as 5.43% due to machine and operational mistakes.

The influenced input parameters are being analyzed by generating effect of plots through optimal software. Figure 8 and Table 4 exhibited that the sliding distance is moderate at 600 m compared to other two factors of load and sliding speed. At the same time, load is major contributor in wear rate increment. The maximum WR is seen at LD of 50 N. The optimal significance of each wear parameters have been identified as per Taguchi analysis. LD3 is the most influenced factor when increasing wear rate of 0.010454 mm³/Nm trailed by 0.008096 mm³/Nm and 0.007964 mm³/Nm at SE3 and SS2, respectively.

The mathematical equation or regression model is established with the aid of regression design as showed in (1) in order to know the relation between input variables and output response of WR and also it helps to find the approximate reading of the wear rate by submitting process factors of load, sliding speed, and distance.

\[
\text{WearRate} = 0.00668 + 0.000272LD + 0.000006SE
\]

\[+0.000155SS.\]

3.3. Optical Microscope Investigation. The optical microscropic images of base metals, heat affected zone (HAZ), and weld nugget in specimen L24 are shown in Figure 9. It is noticed that the large number of dark spots and occurrence of massive quantity of strengthening precipitates in Figure 9(a). The grains of Al6262 are oriented along the rolling direction of the plates in Figure 9(b), and it is evident that the grains have become rougher in the HAZ region compared to the base metal of Al5456 in Figure 9(c). From Figure 9(d), we observed that the grain growth and Mg2Si precipitates magnitude in the HAZ-Al6262 are decreased. Figure 9(e) shows the grains are broken down into finer grain size in weld nugget due to mixing of two dissimilar Al alloys.

4. Conclusion

In the present work, wear rate of FSW 6262 and 5456 Al alloys are examined by the Taguchi L27 method, and analysis of variance, regression equation, and plots between selected variables are carried out by using the MINITAB software. This research work is to identify the highest and lowest wear rate of FSW composites. According to effects of plots and interaction between parameters graph, increasing of load and sliding distance increase dry wear rate. However, the WR reduces when increasing the sliding speed. The maximum quantity of wear is reached in LD of 50 N, SE of 600 m, and SS of 4 m/s and minimum at LD of 30 N, SE of 400 m, and SS of 6 m/s. ANOVA result concluded that apply load on the sample is the most significant parameter which contributes around 83.75% to achieve maximum wear rate, followed by sliding distance of 3.75%, sliding speed of 1.85%, and remaining percentage are contributed by combined parameters.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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