Parametric optimization of friction stir process for developing high strength and wear-resistant chromium reinforced NiAl bronze composite

Varun Dutta\textsuperscript{1,2,\ast}, Lalit Thakur and Balbir Singh\textsuperscript{1}

\textsuperscript{1} School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra-182320, India
\textsuperscript{2} School of Energy Management, Shri Mata Vaishno Devi University, Katra-182320, India
\textsuperscript{3} Mechanical Engineering Department, National Institute of Technology Kurukshetra, Kurukshetra-136119, India

\textsuperscript{\ast} Author to whom any correspondence should be addressed.
E-mail: varun.dutta@smvdu.ac.in

Keywords: friction stir processing, NAB, Cr, tensile strength, wear

Abstract

The present study focuses on fabricating a chromium-reinforced nickel aluminium bronze (NAB) composite using an optimized multi-pass friction stir processing (FSP) technique. The tool rotation, tool traverse speed, and volumetric concentration of the reinforcement were taken as input process parameters, whereas the ultimate tensile strength (UTS), yield strength (YS), percentage elongation (%E), microhardness, and sliding wear rate were taken as output responses. Taguchi-Grey relational analysis (GRA) was utilized for optimizing the input process parameters, which were 1000 r.p.m., 28 mm min\textsuperscript{-1} and 15.7\%, respectively. The most significant parameter was traverse speed, followed by tool rotation and volumetric concentration of the reinforcement. FE-SEM, EDS, and XRD analyses were performed to characterize the as-cast NAB, chromium powder, and FS-processed composite. The tensile strength and wear resistance of the processed composite are enhanced compared to the base NAB alloy on account of significant grain refinement due to the stirring action of the tool pin in the processed zone and the dispersion of chromium reinforcement. The wear rate of the composite was reduced as the tool rotation, traverse speed, and Cr particle volume concentration were increased. The maximum UTS of the prepared composite was 701 MPa, whereas the UTS of the as-cast NAB was 620 MPa. It was observed that as-cast NAB exhibited a hardness value of 286 HV, which was improved to 385 in the FSPed prepared composite. It was found that as-cast NAB exhibited $7.0 \times 10^{-6}$ gm m\textsuperscript{-1} of wear rate, whereas the FSPed composite showed a minimum wear rate of $5.5 \times 10^{-6}$ gm m\textsuperscript{-1}. The microstructural examination revealed that the wear mechanism in the case of as-cast NAB was primarily adhesion, whereas the abrasion was found to be the governing mechanism of material removal in the processed composite.

Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| ANOVA        | Analysis of Variance |
| EDS          | Energy dispersive spectroscopy |
| GRC          | Grey relational coefficient |
| GRG          | Grey relation grade |
| %E           | Percentage elongation |
| SEM          | Scanning Electron Microscope |
| S/N          | Signal to Noise ratio |
| SZ           | Stir zone |
| TR           | Tool rotation |

© 2022 The Author(s). Published by IOP Publishing Ltd
1. Introduction

Wear is the gradual removal of material from solid surfaces. Wear in industries leads to massive losses, and when it comes to the shipping industry, this can also result in colossal failure of the components due to the aggressive environment. These failures may also lead to poor performance and increased maintenance costs of marine vessels. In ships, components like propellers and rudders are subjected to considerable wear and tear due to difficult sea conditions. Conventionally, marine propellers are fabricated from manganese aluminium bronze (MAB) or NAB alloys [1].

NAB alloy is one of the common materials used for many decades to fabricate ship propellers due to its better mechanical properties. The typical NAB configuration is Copper (80%)—Aluminum (10%)—Iron (5%) Nickel (5%). Due to its ability to maintain its properties even after extensive use, NAB has a high-efficiency factor rating. NAB’s use as a propeller and rudder material is justified by its ability to withstand breakdown and failure under impact loads [2].

In the past, different surface modification methods have been developed to fabricate the surface metal-matrix composite. These are high-energy electron beam irradiation [3], cast sinter [4, 5], high-energy laser processing [6–8], casting [9] and plasma spraying [10]. These fabrication processes of the surface composites are based on liquid-phase processing at very high temperatures. It is difficult to avoid the interface reaction among the metal matrix & reinforcement particles, thereby leading to unwanted phases. Moreover, significant control over the process parameters is important for obtaining flawless microstructure in the surface composite. In this case, the processing must be done below the material’s melting point to avoid these problems. The friction stir process (FSP) is one such solid-state processing technique developed by Mishra et al [11–13] for surface modification of metallic materials.

FSP technology of severe plastic deformation (SPD) has been widely used for surface transformation in the last few years, resulting in the refinement of homogenous grains and the eradication of surface imperfections. A revolving tool is a specially fabricated pin and shoulder that is placed inside the workpiece and moved across the surface of the base material in the desired direction. Because of the friction created by this contact, heat is generated, and the material experiences a significant plastic deformation, which helps in the refinement of grains [14–17]. To achieve the desired defect-free material and microstructure, FSP must be carried out, but first, it is crucial to have a good understanding of the individual and combined impacts of the friction stir processing factor [18, 19]. Various process factors, such as (a) tool rotation, (b) tool geometry, (c) tool tilt angle, (d) tool traverse speed, and (f) axial force, influence the microstructure development and, as a result, the mechanical properties of FSP samples. Traverse speed and tool rotation speed significantly influence the heat input to the material [20].

FSP is ideal for surface modification leading to improvement in characteristics. In friction stir processing, the substrate and the particles may be ferrous or non-ferrous, compatible or incompatible. The process creates ultrafine grain structure and improves the alloy’s localized microstructure and associated mechanical properties. FSP also enhances the grain size-dependent properties like superplasticity. The multi-pass processing of the alloy has significantly improved the alloys’ superplasticity [21]. Mishra et al [22] fabricated Al-SiC composite layer of 50–200 μm with excellent bonding with aluminium substrate. It was found that the microhardness of the surface composite was doubled with SiC reinforcement. Thapliyal and Dwivedi have reported the effects of friction stir processing on the sliding wear characteristics of NAB. The wear resistance of NAB was found to have been improved by FSP [23]. Hanke et al [24] recorded a decrease in the wear rate of the single-layer coated NAB processed by friction surfacing.

Thapliyal and Dwivedi [25] fabricated NAB/graphite surface composite by FSP. It was shown that the addition of graphite improved wear properties and surface hardness. Moreover, by measuring the stacking fault energy (SFE), it was revealed that in comparison to the unprocessed surface, the FSPed surface resulted in a decrease in SFE. Lv et al [26] obtained the optimal microstructure of FSPed NAB alloy using different FSP tools. It was observed that during the FSP process, both temperature gradient and plastic deformation gradient co-exist from the top to bottom surface. Ni et al [27] performed FSP on cast NiAl bronze (NAB) using different tool revolving rates and tool traverse speeds. The initial coarse microstructure of NAB was seen to be changed into a fine structure, and porosity defects were also reduced. The results showed considerable improvement in hardness, tensile strength, and ductility as compared to the base metal. It was also noticed that the second pass
Further increased the microstructural homogenization. This shows that multi-pass FSP enhances grain refinement, thus, leading to improved properties.

Bheekya et al. [28] fabricated the Cu-Cr alloy by reinforcing Chromium (1.0 wt%) in the copper plate using the FSP technique. With the increase in tool traverse speed along with the addition of Cr, it was observed that both mechanical and tribological properties were improved significantly, while the thermal conductivity was decreased. According to numerous recent research, the FS process is a useful tool for enhancing copper and copper-based alloys’ mechanical and tribological behaviour. Mazaheri et al. [29] studied the influence of pre-rolling and FSP on copper’s microstructure and mechanical behavior. It was observed that the rolling and FSP showed enhancement in hardness, YS and UTS due to grain refinement. Kumar et al. [30] produced Cu-SiC composite by FS technique and observed the enhancement in strength, ductility, hardness and wear resistance compared to pure copper. Sabbaghian et al. [31] employed FSP to fabricate the Cu/TiC composite and observed an enhancement in its microhardness and wear resistance. Sarmadi et al. [32] used FSP to produce Cu/graphite surface composite. They used different tool pin profiles to perform FSP and found that the triangular pin profile gave better dispersion of graphite particles. Also, with the addition of graphite, the wear rate was also decreased. Akramifard et al. [33] fabricated Cu/SiC composite via the FSP route and observed fine and equiaxed grains in the stir zone. Furthermore, the microhardness and wear resistance were enhanced compared to pure copper. Kumar et al. [34] fabricated zirconia particle reinforced copper surface composite by the FSP method and observed that microhardness and wear resistance improved significantly compared to copper.

Aydin et al. [35] reported that the Taguchi technique is an effective instrument for optimizing the friction stir welding (FSW) process with less experimentation. Sindu et al. [36] employed Taguchi-GRA to optimize rotary ultrasonic machining parameters for quartz glass. This method has been found to be particularly effective in solving multi-objective issues. Taguchi GRA was used by Sahu et al. [37] to accomplish multi-objective optimization of process parameters in FSW of Mg alloy. The use of GRA in conjunction with Taguchi to enhance the welding quality of Mg alloy was examined.

The literature review shows that the researchers have undertaken less work on the friction stir processing of NAB than other alloys. Moreover, the effect of adding Cr reinforcement on the mechanical and tribological characteristics of NAB material using the FSP has not been explored very well. Further, parametric optimization for the FSP of NAB is scarce in the literature. In this study, the Taguchi-GRA approach is used to optimize the multiple response characteristics of a multi-pass FSP on NAB material. This work attempts to optimize the input process parameters simultaneously and combine multi-objective responses into a single integrated numerical value known as Grey relation grade (GRG). Experimental studies were performed using the Taguchi L9 factorial design of the experiments. Furthermore, the analysis of variance (ANOVA) was used to analyze the influence of all the process parameters on responses, namely tensile strength, microhardness and wear resistance.

2. Experimentation

The current study employs multi-pass FSP on NAB material with Chromium (Cr) as reinforcement. The as-cast NAB (C95800) plate of size 150 mm × 90 mm × 8 mm was used for the study. The chemical composition of the NAB alloy as given by the supplier (Govind Metals Co, Gujarat, India) is shown in table 1. Drilled holes of 2.0 mm in diameter and 6.0 mm deep on the NAB plate surface were filled with Cr particles with an average size of 40–50 μm (supplied by Om Enterprise, Gujarat, India) for the FSP.

The plates were properly fixed in the special fixture, as shown in figure 1. A pin-less tool was used to close the powder-filled holes by plastic deformation of the surface material. The four-pass FSP was performed using a vertical milling machine (Make: Batliboi BFV-5 Vertical Milling Machine). This was accomplished by employing a tapered pin-type tool with a 4 mm tip diameter, a 6 mm base diameter, and a 5 mm length. Due to its significant mechanical properties at high temperatures, the tool material was chosen as Inconel 718 (supplied by Bharat Aerospace Metals, Mumbai, India).

The trial runs were performed to finalize the significant input parameters and their ranges. Tool rotation (TR), Traverse speed (TS) and Volume concentration of the reinforcement (VC) were chosen as input variables for the experimental analysis based on the trial experimentations. The volume concentration of the reinforcement was calculated by using the formula [38, 39]:-

\[ VC = \frac{m_{\text{reinforcement}}}{m_{\text{matrix}}} \times 100 \]

Where \( m_{\text{reinforcement}} \) is the mass of reinforcement and \( m_{\text{matrix}} \) is the mass of matrix.
The input parameters with their levels are shown in Table 2. The levels of the input variables were chosen by conducting the trial runs. The experiment was designed using Taguchi L9 orthogonal array (DOE), and each experiment was repeated three times with the same parametric setting to compensate for the error in the experimental procedure.

UTS, % E, YS, average hardness, and wear rate were measured as shown in Table 3. Specimens for tensile testing were sectioned from the processed zone with the help of wire cut EDM as per E8 ASTM standard and tested using a universal testing machine (Dak Inc., Model 7200). The as-cast and FSPed plates were sectioned, embedded in resin and polished with different silicon carbide papers (grades 320 to 1500). The specimens were further subjected to cloth polishing followed by etching with a solution (98 ml ethanol, 2 ml HCl and 5 gm FeCl₃)

\[ VC = \frac{\text{number of holes} \times \text{volume of one hole}}{\text{volume of stir zone}} \times 100 \]
for microstructural analysis. The micro-hardness (Digital Micro Hardness Tester, model: HVD-1000MP) tests were also performed for all the polished samples with a load of 300 gm and a dwell period of 20 s.

The effect of FSP on the wear characteristics of the prepared composite was examined on a pin-on-disk setup (TR-20LE-PHM400, Ducom Instruments Pvt. Ltd., India). Cylindrical pins of diameter 6 mm and length 8 mm were prepared from the as-cast NAB and FSPed samples for all the parametric settings with the help of the wire-EDM process, as depicted in figure 2. The holder was used to keep the pin in position against the rotating disk made of EN 31 carbon steel (Ra ≈ 0.2 μm, 62 HRC). The experiments were performed at 1 m s⁻¹ sliding speed, 20 N constant load, and 1000 m sliding distance. The samples were initially weighed using the electronic weighing machine, having 0.0001 gm as the least count. After testing, the sample pin was taken off the holder, cleaned with acetone to eliminate worn-off particles, dried and weighed again to determine the weight loss. The sliding wear rate was calculated using the difference in the initial and final weights.

The surface morphology of the worn-out surface and fractured surface of the as-cast NAB and processed composite were analyzed using a field emission scanning electron microscope (JOEL JSM 7900F). In order to determine the elemental composition of the as-cast NAB, Cr powder, and fabricated composite, energy dispersive spectroscopy (EDS) analysis was carried out. The phases present in the as-cast NAB and treated composite were identified by XRD analysis using a Bruker D8 Advance Diffractometer. The XRD analysis was conducted using Cu-Kα radiation of 1.54 Å source with a scan range of 10°–100° and a scan speed of 2° per min.

Wear rate was calculated by considering the initial weight (w1), final weight (w2) and sliding distance (sd) of the wear samples using the equation given below:

\[
\text{Wear Rate} = \frac{(w_1 - w_2)}{sd}
\]  

3. Parameter optimization by taguchi- grey relational analysis (GRA)

Taguchi’s approach was used to design experiments and examine the effects of factors on the output responses. It was established on the orthogonal grouping of experiments for optimizing the process parameters. The Taguchi technique evaluates process parameters using a statistical measure of performance known as the signal-to-noise (S/N) ratio. The ratio of mean signal to standard deviation is called as S/N ratio. The conventional Taguchi technique is combined with GRA to evaluate the multi-response optimization problem. In 1982 Deng proposed the Grey system theory to analyze the uncertainties in arrangement models, study relations between parameters, and create models to make predictions and decisions. This technique evaluates process parameters using a statistical degree of performance known as the S/N ratio. This ratio gives the degree of robustness used to diminish variability in a product or process by reducing the outcome of uncontrollable elements [36, 37, 40].

In GRA, experimental data should initially be normalized between 0 to 1, known as the grey relation generation. The Grey relational coefficient (GRC) is calculated using normalized data to correlate the expected and actual experimental results. Furthermore, the complete grey relation is evaluated by calibrating the GRC for the respective feedback. As a result, changing the multi-response problem to a single response optimization problem with a complete GRG as the objective function is advantageous. Finally, the optimum GRG value is determined using an ANOVA. All of the stages for carrying out the GRA are listed below:
i. S/N ratio calculation

The initial step in this process is to apply the following rule to get the S/N ratio of correlated responses. Higher, the better approach

\[ -10 \log 10 \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{Q_{ij}} \right) \]  

(2)

\( Q_{ij} \) = experimental responses with \( i = 1, 2, 3, \ldots n \); \( n \) = total number of repetitions and \( j = 1, 2, 3, \ldots k \)

This approach is applied when the responses are to be maximized. In the present study, it has been used for maximizing the UTS, % E, YS and hardness of the material. Lower the better approach

This approach is applied when the responses are to be minimized. In the present study, it has been used for minimizing the wear rate.

\[ -10 \log 10 \left( \frac{1}{n} \sum_{i=1}^{n} Q_{ij}^2 \right) \]  

(3)

ii. S/N ratio normalisation

Once the S/N ratio is calculated, normalization or standardization of the measured S/N ratio is performed. Standardizing the data is a significant step, as data series units and ranges can vary. Therefore, transferring the original sequence into a comparable sequence is prepared by performing the linear standardization of data. Here, \( Q_{ij} \) is transformed into a comparable sequence \( P_{ij} \) using the equations (4), (5).

Higher the better approach (tensile strength and hardness)

\[ P_{ij} = \frac{Q_{ij} - \min(Q_{ij}, i = 1, 2, 3, \ldots n)}{\max(Q_{ij}, i = 1, 2, 3, \ldots n) - \min(Q_{ij}, i = 1, 2, 3, \ldots n)} \]  

(4)

Smaller the better approach (Wear rate)

\[ P_{ij} = \frac{\max(Q_{ij}, i = 1, 2, 3, \ldots n) - Q_{ij}}{\max(Q_{ij}, i = 1, 2, 3, \ldots n) - \min(Q_{ij}, i = 1, 2, 3, \ldots n)} \]  

(5)

iii. Calculation of grey relation co-efficient (GRC)

The next step is calculating the GRC to develop the relationship between the final and real experimental outcomes. The value of GRC is calculated by using equation (6).

\[ \beta(z_o(k), z_j(k)) = \frac{\Delta \min + \xi \Delta \max}{\Delta_{j}(k) + \xi \Delta \max} \]  

(6)

where:

\* \( j = 1, 2, 3, \ldots n; k = 1, 2, 3, \ldots m \) where \( n \) and \( m \) are the number of experimental data items and responses, respectively.

\* \( z_o(k) \) is reference sequence; \( z_j(k) \) is the specific comparison sequence.

\* \( \Delta_{oj} = || z_o(k) - z_j(k) || \) is the absolute value of the difference between \( z_o(k) \) and \( z_j(k) \).

\* \( \Delta \max \) and \( \Delta \min \) are the highest and lowest value of \( z_j(k) \).

\* \( \xi \) is known as distinctive co-efficient, and its value ranges from 0 to 1, and its value is taken as per the requirement.

iv. Calculation of weighted GRG

The next step is to calculate GRG. GRG is the mean sum of obtained GRC in the previous step.

\[ \delta (z_o, z_j) = \frac{1}{P} \sum_{i=1}^{P} \beta(z_o(k), z_j(k)) \]  

(7)

where, \( \beta(z_o, z_j) \) denotes GRG of \( j \)th experimental trial and \( p \) represents the total number of output responses.

v. Determination of optimum parameters and their corresponding levels
Based on the values of GRGs generated in the previous step, the effect of the factors can be assessed. The higher-the-better approach is used in this case to determine the optimum parameter levels. Equation 8 predicts the optimum GRG value, where $\delta m$ is the total mean, $p$ is the no. of input variables, and $\delta_{i}$ is the mean GRG value at the optimal level for the $i$th parameter.

$$\delta E = \delta m + \sum_{i=1}^{p} (\delta_{i} - \delta_{m})$$

4. Results and discussion

The microstructure analysis was performed on the samples of base NAB alloy, chromium powder and FSPed composite. The FE-SEM and EDS images of the chromium powder are demonstrated in figures 3(a)–(b), which revealed the irregular morphology and confirmed the presence of chromium. Moreover, the particle size was measured by the image analysis software, and it was around 40–50 $\mu$m, which corroborates the information provided by the supplier.

4.1. Grey relational analysis

In the current study, the UTS, YS, % E, hardness and wear rate were optimized simultaneously with TR, TS and VC as the input variables. The input variables and output responses for all the trials are shown in table 3. Normally, higher UTS, % E, hardness, and lower wear rate are preferred. The S/N ratios for all the output responses are determined using equations (2) and (3), and their values are shown in table 4. Normalized data of the S/N ratio for all the runs was calculated using equations (4) and (5), as shown in table 5.

After normalizing the S/N ratio data, the next step is to compute GRCs using equation (6). Here, the value of distinctive co-efficient $\xi$ is taken as 0.5 (since all the input variables are given equal weightage). GRCs for the responses are shown in table 6.
Then, GRGs for each level of the factor were computed. Higher GRG indicates better characteristics. The GRG values are listed in table 6. The mean GRG and response plot for GRG versus process variables are given in figure 9, respectively.

4.2. Influence of process parameters on the responses

It is observed that with the decrease in TS, the UTS enhances, as depicted in figure 4. It may be accounted for by less heat input and high compressive stress on the prepared composite, which leads to further grain reduction. The maximum UTS of the prepared composite is 701 MPa, whereas the UTS of the as-cast NAB is 620 MPa. The F value indicates the significance of each factor affecting the process response in the ANOVA table. The higher the F value, the larger the concerned factor’s significance. In table 7, the significance of the TR and TS is higher and plays a major role in UTS, as represented by the corresponding higher F value. Figure 5 represents the

| Run order | Normalized values of S/N ratio |
|-----------|------------------------------|
|           | UTS | % Elongation | YS | Hardness | Wear rate |
| 1.        | 0.1672 | 0.6503 | 0.1688 | 0.2130 | 0 |
| 2.        | 0.0909 | 0.5151 | 0.0641 | 1 | 0 |
| 3.        | 0.3027 | 1 | 0.4424 | 0.5548 | 0.6498 |
| 4.        | 0.1016 | 0.1062 | 0.0641 | 0.5138 | 0.3170 |
| 5.        | 0.1240 | 0 | 0.3034 | 0.0961 | 1 |
| 6.        | 0.5092 | 1 | 0.6153 | 0.1543 | 0.7645 |
| 7.        | 0.0571 | 0.1604 | 0.0641 | 0.8915 | 0 |
| 8.        | 0.7861 | 0.6656 | 0.9202 | 0.3920 | 0.2631 |
| 9.        | 1 | 1 | 1 | 0.5961 | 0.4261 |

Table 5. Normalized values of S/N ratio.

| Run order | GRC | GRG |
|-----------|-----|-----|
| UTS | % Elongation | YS | Hardness | Wear rate |
| 1.        | 0.749 | 0.435 | 0.748 | 0.701 | 1.000 | 0.727 |
| 2.        | 0.846 | 0.493 | 0.886 | 0.333 | 1.000 | 0.712 |
| 3.        | 0.623 | 0.333 | 0.531 | 0.474 | 0.435 | 0.479 |
| 4.        | 0.831 | 0.825 | 0.886 | 0.493 | 0.612 | 0.729 |
| 5.        | 0.801 | 1.000 | 0.622 | 0.839 | 0.333 | 0.719 |
| 6.        | 0.495 | 0.333 | 0.448 | 0.764 | 0.395 | 0.487 |
| 7.        | 0.898 | 0.757 | 0.886 | 0.359 | 1.000 | 0.780 |
| 8.        | 0.389 | 0.429 | 0.352 | 0.560 | 0.655 | 0.477 |
| 9.        | 0.333 | 0.333 | 0.333 | 0.456 | 0.540 | 0.399 |

Table 6. Computed GRCs and corresponding GRGs.

Then, GRGs for each level of the factor were computed. Higher GRG indicates better characteristics. The GRG values are listed in table 6. The mean GRG and response plot for GRG versus process variables are given in figure 9, respectively.

4.2. Influence of process parameters on the responses

It is observed that with the decrease in TS, the UTS enhances, as depicted in figure 4. It may be accounted for by less heat input and high compressive stress on the prepared composite, which leads to further grain reduction. The maximum UTS of the prepared composite is 701 MPa, whereas the UTS of the as-cast NAB is 620 MPa. The F value indicates the significance of each factor affecting the process response in the ANOVA table. The higher the F value, the larger the concerned factor’s significance. In table 7, the significance of the TR and TS is higher and plays a major role in UTS, as represented by the corresponding higher F value. Figure 5 represents the
experimental stress-strain curve of the as-cast NAB alloy and FSPed composite showing maximum UTS. It is observed from the curve that FS-processed composite exhibits increased UTS compared to as-cast NAB on grain refinement and reinforcement of Cr particles. The fitted model of UTS is given by equation no (9).

\[
UTS = 717.1 - 0.0636 \times TR - 1.799 \times TS + 6.77 \times VC
\] (9)

As-cast NAB has shown 12% elongation, whereas FSPed processed composite exhibited 16.4% elongation. As demonstrated in figure 6, increasing TR from 710 rpm to 1000 rpm increases the percentage elongation, whereas increasing TR from 1000 rpm to 1400 rpm decreases it marginally. However, with the increase in traverse speed, % elongation is further reduced, accountable to less heat generation and stirring, thus, resulting in less grain refinement. Moreover, the increased VC of the Cr particles resulted in increased % elongation. The
traverse speed has major significance, followed by volume concentration and tool rotation as interpreted from the F value in table 8. The fitted model of % E is given by equation no. (10).

\[
\text{Percentage Elongation} = 14.10 + 0.000414 \text{ TR} - 0.845 \text{ TS} + 0.261 \text{ VC} \quad (10)
\]

The YS has increased from 250 MPa to 335 MPa with the processing of as-cast NAB, which shows significant improvement. With the increase in TS, yield strength decreases due to reduced stirring producing less grain refinement, as demonstrated in figure 7. Moreover, with the increase of volume concentration of Cr particles, yield strength increases, which shows the influence of reinforcement in enhancing the strength. The traverse speed of the tool has major significance, followed by tool rotation and volume concentration, as represented by the F value in table 9. The fitted model of YS is given by equation no. (11).

\[
\text{YS} = 360.7 - 0.0438 \text{ TR} - 1.470 \text{ TS} + 1.93 \text{ VC} \quad (11)
\]

It was observed that as-cast NAB has a hardness value of 286 HV, which is increased to 385 HV as obtained from FSPed prepared composite in experiment no. 5. As the TR increases from 700 rpm to 1000 rpm, the hardness increases and further decreases with TR from 1000 rpm to 1400 rpm due to more heat generation, as shown in figure 8. With the decrease in volume concentration of the Cr particles, hardness decreases. It was observed that tool rotation and volume concentration were the most governing factors that affected the hardness, with a percentage contribution of 35.2% and 43.3%, respectively. In table 10, the significance of the volume concentration and tool rotation is higher and plays a major role in hardness, as shown by their F value. The annealing and refinement of grains influence the microhardness of the stir zone. Reduced grain size increases hardness and, as a result, inhibits the commencement of material flow. The stirring action of the pin causes dynamic recrystallization in the stir zone (SZ), which decreases grain size, increases dislocations, and

---

Table 8. ANOVA for % E.

| Source                | DF  | SS      | MS    | F       | P      | Fraction contribution (%) |
|-----------------------|-----|---------|-------|---------|--------|---------------------------|
| Tool rotation         | 2   | 2.4450  | 1.2225| 69.86   | 0.014  | 16.7                      |
| Traverse speed        | 2   | 9.3800  | 4.6900| 268.00  | 0.004  | 64                        |
| Volume concentration  | 2   | 2.7650  | 1.3825| 79.00   | 0.012  | 18.9                      |
| Error                 | 2   | 0.0350  | 0.0175| 0.4     |         | 0.4                       |
| Total                 | 8   | 14.6250 |       |         |        |                           |

Table 9. ANOVA for Yield Strength.

| Source                | DF  | SS      | MS    | F       | P      | Fraction contribution (%) |
|-----------------------|-----|---------|-------|---------|--------|---------------------------|
| Rotation speed        | 2   | 1432.7  | 716.3 | 2.62    | 0.276  | 27.2                      |
| Traverse speed        | 2   | 2616.7  | 1308.3| 4.79    | 0.173  | 49.7                      |
| Volume concentration  | 2   | 672.7   | 336.3 | 1.23    | 0.448  | 12.8                      |
| Error                 | 2   | 546.0   | 273.0 |         |        | 10.3                      |
| Total                 | 8   | 5268.0  |       |         |        |                           |
improves hardness values. The increased hardness of the composite is attributed to grain refinement in the SZ as per the Hall-Petch relationship \[41-43\]. Moreover, with the reinforcement of Cr particles in the as-cast NAB, the hardness value of the composite is increased. This could be owing to the pinning effect and the presence of Cr particles. The addition of Cr particles increases the dislocation density of the as-cast alloy. The interaction of Cr particles with dislocations enhances the composite’s hardness \[42\]. The fitted model of hardness is given by equation no.(12).

\[
\text{Hardness} = 389.7 - 0.0055 \text{TR} + 0.178 \text{TS} - 1.99 \text{VC}
\]  

(12)

It was found that as-cast NAB exhibited \(7.0 \times 10^{-6}\) gm m\(^{-1}\) of wear rate, whereas the FSPed composite showed a minimum wear rate of \(5.5 \times 10^{-6}\) gm m\(^{-1}\). As observed in figure 9, the wear rate decreases as the tool rotation increase from 710 rpm to 1000 rpm, then increase from 1000 rpm to 1400 rpm. At a moderate value of tool rotation, the reinforcement particle distributes more evenly, and lower agglomeration of the reinforcement particle occurs. Increased tool rotation results in grain boundary clustering and agglomeration along the grain boundaries, which has the opposite effect on the characteristics \[44-47\]. The increase in tool rotation resulted in
improved hardness value and reduced wear rate of the FSPed specimens, as explained by Archard’s wear law [48]. Moreover, with an increase in TS, there is a decrease in wear rate. Further, it is noticed that with the increase in the VC of Cr particles wear rate of the composite decreased. As the reinforcement particles are uniformly distributed, the load is efficiently transferred from the matrix to the particulates. Furthermore, the wear rate decreases when the VC of Cr particles in the FSPed composite increases. All of these effects contribute to less composite’s wear [49]. As indicated in Table 11, TR and TS were shown to be the significant factors influencing wear rate, with a percentage contribution of 41.5 percent and 38 percent, respectively.

The Cr particles increase the wear resistance of the composite significantly and thus reduce the wear rate. Moreover, with the improvement in bulk hardness of composite, sliding wear decreases as per the Archard law of wear [50]. With the reinforcement of Cr particles, the effective contact area between the wear pin and counter disc surface decreases. There is the formation of oxides of chromium during sliding, as also reported by Paulmier et al [51]. This oxidized debris gets separated during the wear process and comes in between the specimen and counter disc surface. This occurrence of oxides changes the process of wear of a two-body system to a three-body system, thereby leading to point contact from surface contact [52]. With this reduction, the load applied is taken by the reinforcement particles rather than the base material, decreasing the frictional coefficient at the sliding surface. The fitted model of wear rate is given by equation no. (13).

### Table 11. ANOVA for Wear Rate.

| Source                | DF  | SS    | MS    | F     | P     | Fraction contribution (%) |
|-----------------------|-----|-------|-------|-------|-------|---------------------------|
| Tool Rotation         | 2   | 0.36167 | 0.18083 | 5.56  | 0.152 | 41.5                      |
| Traverse speed        | 2   | 0.33167 | 0.16583 | 5.10  | 0.164 | 38                        |
| Volume Concentration  | 2   | 0.11167 | 0.05583 | 1.72  | 0.368 | 12.8                      |
| Error                 | 2   | 0.06500 | 0.03250 |       |       | 7.7                       |
| Total                 | 8   | 0.87000 |        |       |       |                           |

### Table 12. Output responses of as-cast NAB and FS processed composite.

| Output parameters | As-cast NAB | FS processed composite |
|-------------------|-------------|------------------------|
| UTS (MPa)         | 620         | 701                    |
| Percentage Elongation (%) | 12          | 16.4                  |
| YTS (MPa)         | 250         | 335                    |
| Hardness (HV)     | 286         | 385                    |
| Wear rate (gm m⁻¹) | 7.0 × 10⁻⁶  | 5.5 × 10⁻⁶             |

### Table 13. ANOVA table of results for grey relation grade.

| Source                | DF  | SS    | MS    | F     | P     | Fraction contribution (%) |
|-----------------------|-----|-------|-------|-------|-------|---------------------------|
| Tool Rotation         | 2   | 0.01629 | 0.008145 | 1.13  | 0.469 | 9.4                       |
| Traverse speed        | 2   | 0.12881 | 0.064406 | 8.96  | 0.100 | 74.3                      |
| Volume concentration  | 2   | 0.01377 | 0.006884 | 0.96  | 0.511 | 7.9                       |
| Error                 | 2   | 0.01438 | 0.007189 |       |       | 8.4                       |
| Total                 | 8   | 0.17325 |        |       |       |                           |

### Table 14. List of responses for GRG.

| Symbol | Factor          | Level 1 | Level 2 | Level 3 | Max-Min | Rank |
|--------|-----------------|---------|---------|---------|---------|------|
| A      | Tool rotation   | 0.639   | 0.645   | 0.552   | 0.093   | 2    |
| B      | Traverse speed  | 0.745   | 0.636   | 0.455   | 0.290   | 1    |
| C      | Volume concentration | 0.564 | 0.613   | 0.659   | 0.096   | 3    |

The overall mean of the GRG is 0.612.
The result of the ANOVA showed that the traverse speed is the main significant variable affecting the output responses, followed by tool rotation and volume concentration, as observed in table 13.

Considering the optimum level of process parameters for the FSP, the anticipated GRG is calculated using equation no (7). Based on the list of responses and plot for GRG, as shown in table 14 and figure 10, the optimum

$$\text{Wear rate} = 7.324 + 0.000041 \text{ TR} - 0.01639 \text{ TS} - 0.0415 \text{ VC}$$ (13)
parametric settings are obtained at levels 2, 1 and 3 for tool rotation, traverse speed and volume concentration, respectively. Thereafter, confirmatory testing was performed using the optimum parametric combination. Table 15 summarises the outcomes of the confirmation experiment. After calculating the GRG value from the optimum parametric combination, it was found that there is an increase of GRG by 0.14 as compared to the preliminary parametric condition. It was also calculated that the % error with the predicted value is only 4.6% while validating with confirmatory data.

4.3. Microstructural analysis

The refinement of as-cast microstructure was observed in the FSPed specimen (extracted from the stir zone with optimum parametric setting) as coarse α and κ phases were considerably broken and refined with the uniform dispersion. The grain refinement was observed after the FSP process, as shown in figures 11(a) and 12(a). Recrystallization caused by intense plastic deformation resulted in a fine and equiaxed grain microstructure in the SZ [27, 28]. A heterogeneous structure was marked across the stir zone with primary α, β, κII (globular shape), κIII (lamellar shape) and κIV (globular shape) phases. However, no iron (Fe)-rich κI phase (rosette shape) was found, which occurs only when Fe content in the alloy is more than 5%. The HAZ region comprises elongated α and κII phases, as shown in figure 12(a).

The analysis by energy dispersive spectra (EDS) verified the existence of Cr particles in the NAB matrix of the stir zone after the FSP process, thereby corroborating the Cr reinforcement NAB composite, as shown in figure 12(b).

The EDS elemental mapping was performed on the NAB-Cr prepared composite, as shown in figure 13. The mapping has revealed the presence of all major elements, and the Cr reinforcement is seen evenly dispersed in the NAB matrix of the SZ. The images obtained from an optical microscope were analyzed for the base alloy and prepared composite. In comparison to the NAB alloy, the microstructure of the prepared composite was refined, as observed in figure 14(a). The grains were recrystallized by severe plastic deformation, as shown in figures 14(b) and (c). The grains can be observed properly disbursed in the base NAB substrate. Moreover, the grain size was reduced from 20 μm to 7.1 μm in the heat-affected zone (HAZ) and observed as 6.3 μm in the nugget zone.

The x-ray patterns of as-cast NAB and FSPed prepared composite are shown to identify the phase structure during the process. Due to this rapid cooling, more phases are present, which can be observed in the dark-coloured layers in figures 12 and 14(b) [33, 54].

For semi-quantitative examination of the various phases present in the as-cast and FSPed composite, the normalized intensity ratio (NIR) of the phases was determined using the following relation:

\[
\text{NIR}_a = \frac{I_a - I_{\text{back}}}{I_a + I_b + I_c - I_{\text{back}}}
\]

Where \(I_a\), \(I_b\), and \(I_c\) are the intensities of the first, second, and third phases, respectively, and \(I_{\text{back}}\) is the intensity of the background intensity. The above equation was then used to get the NIR value for all phases. For determining the NIR of distinct phases, the main peak corresponding to that phase was taken from the XRD
spectrum. The approximate values of phases are shown in table 16. Cu, NiAl/Fe3Al, and CrO2 had phase intensities of 67.61%, 21.04%, and 11.34%, respectively. On the other hand, the as-cast NAB had phase intensities in Cu and NiAl/Fe3Al of 95.15% and 4.85%, respectively.

Fractography image of the tensile fractured specimen of the as-cast NAB revealed the mixture of ductile and brittle fracture, with micro-voids as observed in figure 16(a). The figure shows the fractured surface of the base material, which presents the brittle mode of failure and the cracking of the partially dissolved eutectoid constituent accompanied by creating a micro-void. Figure 16(b) exhibits the fractography image (FI) of the tensile fractured surface of the specimen corresponding to experiment no. 4 (TR 1000 rpm, TS 28 mm min−1, VC 12.6%), where a high value of output responses is observed. Figure 16(c) shows the FI of the tensile fractured surface corresponding to the optimum parametric setting. Figure 16(d) shows the FI of the tensile fractured surface of the specimen corresponding to experiment no. 9 (TR 1400 rpm, TS 56 mm min−1, VC 12.6%), where low values of output responses are observed. On the tensile fractured surface, as illustrated in figures 16(b)–(d), there are few dimples with large and consistent diameters on the fractured surface, indicating significant elongation. The tensile sample did not show any significant necking in the tensile test [55, 56]. Despite the considerable % E (16.4%), the fracture occurred in the normal stress plane with no evidence of macroscopic plastic deformation. Patel et al [57] showed that the increase in mechanical strength in the stir zone is due to uniform microstructural refinement in the FSP process.

After the wear testing, the specimens of a-cast NAB and prepared composites were inspected by SEM to evaluate the wear mechanisms. The SEM image of the NAB exhibited more surface damage than the prepared composite. In the case of unprocessed NAB alloy, the sliding contact between the tip of the pin and the counter surface experiences adhesive wear [58]. The adhesive wear is marked by delamination, larger wear scar and wrinkles on the surfaces, as observed in figure 17(a).

Figure 17(b) demonstrates the SEM image of the worn-out surface of the composite processed at the setting of experiment no. 4 (TR 1000 rpm, TS 28 mm min−1, VC 12.6%), which resulted in high values of output responses. Figure 17(c) shows SEM images of the worn-out surface of the fabricated composite corresponding to
Figure 14. Optical images of (a) as-cast NAB (b) Cross-section showing the interface between unprocessed and processed (c) FS processed stir zone showing the distribution of particles.

Figure 15. XRD graph of As-cast and FSPed processed composite.

Table 16. FSPed composite relative phase intensities.

| S. No. | Phase       | $I_a$  | $I_b$  | $I_c$  | $I_{back}$ | NIR (%) |
|--------|-------------|--------|--------|--------|------------|---------|
| 1      | Cu          | 37.96  | 3.34   | 67.61  | 3.34       | 67.61   |
| 2      | NiAl/Fe3Al  | 14.11  | 3.34   | 21.04  | 3.34       | 21.04   |
| 3      | CrO$_2$     | 9.14   | 3.34   | 11.34  | 3.34       | 11.34   |
the optimized parameters. Figure 17(d) demonstrates the SEM image of the worn-out surface of the prepared composite corresponding to experiment no 9 (TR 1400 rpm, TS 56 mm min\(^{-1}\), VC 12.6%), where the low value of output responses is observed. The development of small pits characterized the observed surface.

It was also observed that grooves, micro-cutting, ploughing, and wear debris exists in some surface areas, which denote the abrasive nature of wear that occurred on the material surface. The wear rate of FS-prepared composite was reduced due to grain refining, which increased the hardness value. The existence of debris acts as nano-bearing between the sliding elements and leads to a decrease in wear [59].

In figures 17(b)–(d), the main wear mechanism is due to abrasion, as supported by the existence of debris and microchipping on the surface. The high wear rate in the as-cast alloy is confirmed by deep grooves and extremely deformed areas, as shown in figure 17(a). The minimum wear rate in the case of Cr reinforced NAB surface composite is confirmed by the presence of smoother, shallow scratches and fewer grooves. The intensity of the wear rate that occurred in the FSPed composite is less than the as-cast surface when exposed to wear testing under the same conditions. Moreover, the presence of Cr particles can also be observed in the images.

### 5. Conclusions

Taguchi GRA was successfully applied to optimize the process parameters of FSP for fabricating a Cr-reinforced NAB surface composite. The inferences can be concluded as follows:

1. FSP was effectively utilized to fabricate Cr reinforced NAB surface composite. It resulted in refinement of grain structure, leading to enhancement in strength, hardness and wear resistance compared to as-cast NAB. The average grain size of the prepared composite alloy reduced significantly from 20 \(\mu\)m to 6.3 \(\mu\)m.

2. The optimized process parameters were tool rotation 1000 r.p.m., traverse speed 28 mm min\(^{-1}\) and volume concentration 15.7%.

![Figure 16. Fractography SEM image of (a) as-cast NAB (b) composite at experiment no. 4 (c) composite at optimal setting (d) composite at experiment no. 9.](image-url)
3. The utmost effective process parameter was the traverse speed affecting the output responses, followed by tool rotation and volume concentration. In the case of tensile strength, TR and TS were the significant variables. It was observed that tool rotation and volume concentration were the most dominant factors affecting the hardness. However, the most dominant factors for wear rate were TR and TS.

4. The microstructure of the FSPed composite exhibited $\alpha$ (FCC), $\beta$, $\kappa_{II}$ (globular shape), $\kappa_{III}$ (lamellar shape), and $\kappa_{IV}$ phases (globular shape).

5. The tensile strength of NAB was increased from 620 MPa to 701 MPa by FSP, and all the specimens fractured without any sign of necking formation.

6. With the FS process on as-cast Nickel Aluminum Bronze alloy, the wear mechanism changed from adhesive to abrasive type.

The composite can also be fabricated using modified process, which includes inserting reinforcements by grooving method and compared with the current study for evaluating their dispersion. Moreover, FSP can be performed in a submerged cold medium to enhance the material’s performance by removing excess heat from the processed zone. A low-temperature Charpy impact testing can also be done to evaluate the material toughness at different low temperatures, which is generally experienced by the propellors of the ships travelling in oceans.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
References

[1] Swain B, Bhuyan S, Behera R, Sanjeeb Mohapatra S and Behera A 2021 Wear: A Serious Problem in Industry Tribology in Materials and Manufacturing – Wear, Friction and Lubrication ed A Patnaik et al (IntechOpen) (https://doi.org/10.5772/intechopen.94211)

[2] Fuller M D, Swaminathan S, Zhiluyaev A P and McNelley T R 2007 Microstructural transformations and mechanical properties of cast NiAl bronze: effects of fusion welding and friction stir processing Mater. Sci. Eng. A 463 128–137

[3] Choo S H, Lee S and Kwon S J 1999 Effect of flux addition on the microstructure and hardness of TiC-reinforced ferrous surface composite layers fabricated by high-energy electron beam irradiation Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 30 3131–41

[4] Wang Y, Zhang X, Zeng G and Li F 2000 Cast sinter technique for producing iron base surface composites Mater. Des. 21 447–52

[5] Wang Y, Zhang X, Zeng G and Li F 2001 In situ production of Fe-VC and Fe-TiC surface composites by cast-sintering Compos. Part A Appl. Sci. Manuf. 32 281–6

[6] Hu C, Xin H and Baker T N 1995 Laser processing of an aluminium AA6061 alloy involving injection of SiC particulate J. Mater. Sci. 30 5985–90

[7] Pantelis D, Tissandier A, Manolatos P and Ponthiaux P 1995 Formation of wear resistant Al–SiC surface composite by laser–melt–particle injection process Mater. Sci. Technol. (United Kingdom) 11 299–303

[8] Hu C and Baker T N 1995 Laser processing to create in situ Al-SiCp surface metal matrix composites J. Mater. Sci. 30 891–7

[9] Attia A N 2001 Surface metal matrix composites Mater. Des. 22 451–7

[10] Gui M and Kang S B 2000 6061 Al/Cr2O3 bi-layer composites produced by plasma-spraying process Mater. Lett. 46 296–302

[11] Mohan A, Yuan W and Mishra R S 2003 High strain rate superplasticity in friction stir processed ultrafine grained Mg-Al-Zn alloys Mater. Sci. Eng. A 362 69–76

[12] Mishra R S and Malhoney M W 2001 Friction stir processing: a new grain refinement technique to achieve high strain rate superplasticity in commercial alloys Mater. Sci. Forum 357–359 507–14

[13] Mehdi H and Mishra R S 2021 Effect of multi-pass friction stir processing and SiC nanoparticles on microstructure and mechanical properties of AA6082-T6 Adv. Ind. Manuf. Eng. 3 100062

[14] Mishra M K, Rao A G, Balasundar I, Kashyap B P and Prabhu N 2018 On the microstructure evolution in friction stir processed 2507 super duplex stainless steel and its effect on tensile behaviour at ambient and elevated temperatures Mater. Sci. Eng. A 719 82–92

[15] Sharma D K, Patel V, Badheka V, Mehta K and Upadhyay G 2020 Different reinforcement strategies of hybrid surface composite AA6061 (B4C + Mo52) produced by friction stir processing Materwiss. Werkst. 51 1493–506

[16] Patel V, Badheka V, Li W and Akkreddy S 2019 Hybrid friction stir processing with active cooling approach to enhance superplastic behavior of AA7075 aluminum alloy Arch. Civ. Mech. Eng. 19 1568–80

[17] Patel V, Li W, Liu X, Wen Q, Su Y, Shen J and Fu B 2020 Tailoring grain refinement through thickness in magnesium alloy via stationary shoulder friction stir processing and copper backing plate Mater. Sci. Eng. A 784 1–10

[18] Lakshminarayan A K and Balasubramanian V 2010 An assessment of microstructure, hardness, tensile and impact strength of friction stir welded ferritic stainless steel joints Mater. Des. 31 4592–600

[19] Patel V, Li W, Vairis A and Badheka V 2019 Recent development in friction stir processing as a solid-state grain refinement technique: microstructural evolution and property enhancement Crit. Rev. Solid State Mater. Sci. 44 378–426

[20] Mehdi H and Mishra R S 2020 Effect of friction stir processing on microstructure and mechanical properties of TIG welded joint of AA6061 and AA7075 Metallogr. Microstruct. Anal. 9 403–18

[21] Barmour M, Besharati Givi M K and Seyfi J 2011 On the role of processing parameters in producing Cu/SiC metal matrix composites via friction stir processing: Investigating microstructure, microhardness, wear and tensile behavior Mater. Charact. 62 108–17

[22] Mishra R S, Ma Z Y and Charit I 2003 Friction stir processing: a novel technique for fabrication of surface composite Mater. Sci. Eng. A 341 307–10

[23] Thapliyal D and Dwivedi D K 2016 Study of the effect of friction stir processing of the sliding wear behavior of cast NiAl bronze: a statistical analysis Tribol. Int. 97 124–35

[24] Hanke S, Fischer A, Beyer M and dos Santos J 2011 Cavitatin erosion of NiAl-bronze layers generated by friction surfacing Wear 273 32–7

[25] Thapliyal D and Dwivedi D K 2016 Microstructure evolution and tribological behavior of the solid lubricant based surface composite of cast nickel aluminum bronze and its effect on friction stir processing of friction stir processed J. Mater. Process. Technol. 238 50–8

[26] Li Y, Nie B, Wang L, Cai H, Li L, Wang R and Lyu F 2020 Optimal microstructures on fatigue properties of friction stir processed NiAl bronze alloy and its resistant fatigue crack growth mechanism Mater. Sci. Eng. A 771 138577

[27] Ni D R, Xue P, Wang D, Xiao B L and Ma Z Y 2009 Inhomogeneous microstructure and mechanical properties of friction stir processed NiAl bronze Mater. Sci. Eng. A 524 119–28

[28] Sheekya Naik R, Venkateswara Reddy K, Madhusudhan Reddy G and Arockia Kumar R 2021 Microstructure, mechanical and wear properties of friction stir processed Cu-1.0%Cr alloys Fusion Eng. Des. 164 112202

[29] Mazaheri H, Aival H J and Jamaati R 2021 Pre-strain assisted low heat-input friction stir processing to achieve ultrafine-grained copper Mater. Sci. Eng. A 826 141958

[30] Kumar H, Prasad R and Kumar P 2020 Effect of multi-groove reinforcement strategy on Cu/SiC surface composite fabricated by friction stir processing Mater. Chem. Phys. 256 123720

[31] Sabbaghian M, Shaniamin M, Akramifard H R and Esmaizadeh M 2014 Effect of friction stir processing on the microstructure and mechanical properties of Cu–TiC composite Ceram. Int. 40 12969–76

[32] Sarmadi H, Kokabi A H and Seyed Reihani S M 2013 Friction and wear performance of copper-graphite surface composites fabricated by friction stir processing (FSP) Wear 304 1–12

[33] Akramifard H R, Shaniamin M, Sabbaghian M and Esmaizadeh M 2014 Microstructure and mechanical properties of Cu/SiC metal matrix composite fabricated via friction stir processing Mater. Des. 54 838–44

[34] Kumar H, Vashista M and Yusufzai M Z K 2018 Microstructure and wear behavior of zircon reinforced copper base surface composite synthesized by friction stir processing route Trans. Indian Inst. Met. 71 2025–33
[35] Aydin H, Bayram A, Esme U, Kazancoglu Y and Guven O 2010 Application of grey relation analysis (GRA) and Taguchi method for the parametric optimization of friction stir welding (FSW) process | Uporaba greyjeve analize (GRA) in Taguchijeve metode za parametrično optimizacijo varjenja z vrtlino-tornim procesom (F Mater. Tehnol. 24 405–11

[36] Sindhu D, Thakur L and Chandna P 2019 Multi-objective optimization of rotary ultrasonic machining parameters for quartz glass using taguchi-grey relational analysis (GRA) Silicon 11 2033–44

[37] Sahu P K and Pal S 2015 Multi-response optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis J. Magnes. Alloy. 3 36–46

[38] Girish G and Anandakrishnan V 2020 Determination of friction stir processing window for AA7075 Mater. Today Proc. 21 557–62

[39] Girish G and Anandakrishnan V 2021 Fabrication of Al-Zn-Mg-Cu matrix composite by multi-pass recursive friction stir processing and its characterization J. Mater. Eng. Perform. 30 5868–88

[40] Sindhu D, Thakur L and Chandna P 2020 Parameter optimization of rotary ultrasonic machining on quartz glass using response surface methodology (RSM) Silicon 12 629–43

[41] Barmouz M, Givi M K B and Jafari I 2014 Evaluation of tensile deformation properties of friction stir processed pure copper: Effect of processing parameters and pass number J. Mater. Eng. Perform. 23 101–7

[42] Bauri R, Yadav D and Suhag S 2011 Effect of friction stir processing (FSP) on microstructure and properties of Al-TiC in situ composite Mater. Sci. Eng. A 528 4732–9

[43] Sathiskumar R, Murugan N, Dhinaharan I and Vijay S J 2013 Characterization of boron carbide particulate reinforced in situ copper surface composites synthesized using friction stir processing Mater. Charact. 84 16–27

[44] Kumar D and Thakur L 2022 A study of processing and parametric optimization of wear-resistant AZ91-TiB2 composite fabricated by ultrasonic-assisted stir casting process Surf. Topogr.: Metrol. Prop. 10 25024

[45] Sharma D K, Patel V, Badheka V, Mehta K and Upadhyay G 2019 Fabrication of hybrid surface composites AA6061/(B4C + MoS2) via friction stir processing J. Tribol. 141 1–10

[46] Fuse K, Badheka V, Patel V and Andersson J 2021 Dual sided composite formation in Al6061/B4C using novel bobbin tool friction stir processing J. Mater. Res. Technol. 13 1709–21

[47] Sharma D K, Badheka V, Patel V and Upadhyay G 2021 Recent developments in hybrid surface metal matrix composites produced by friction stir processing: a review J. Tribol. 143 050801

[48] Archard J F 1953 Contact and rubbing of flat surfaces J. Appl. Phys. 24 981–8

[49] Habibnejad-Korayem M, Mahmudi R, Ghasemi H M and Poole W J 2010 Tribological behavior of pure Mg and AZ31 magnesium alloy strengthened by Al2O3 nano-particles Wear 268 405–12

[50] Lloyd D J 1994 Particle reinforced aluminium and magnesium matrix composites Int. Mater. Rev. 39 1–23

[51] Paulmier D, Bouchoucha A and Zaidi H 1990 Influence of the electrical current on wear in a sliding contact copper–chrome steel, and connection with the environment Vacuum 41 2213–6

[52] Nak R B, Reddy KV, Reddy GM and Kumar R A 2020 Development of high strength and high electrical conductivity Cu-Cr-Zr alloy through friction stir processing Fusion Eng. Des. 161 111962

[53] Ding D, Pan Z, van Duin S, Li H and Shen C 2016 Fabricating superior NiAl bronze components through wire arc additive manufacturing Materials (Basel). 9 1–12

[54] Shen C, Pan Z, Ding D, Yuan L, Nie N, Wang Y, Luo D, Cuiuri D, van Duin S and Li H 2018 The influence of post-production heat treatment on the multi-directional properties of nickel-aluminum bronze alloy fabricated using wire-arc additive manufacturing process Addit. Manuf. 23 411–21

[55] Li Y, Wang L, Han Y, Xu X and Lu W 2015 Investigation of microstructure and mechanical properties of hot worked NiAl bronze alloy with different deformation degree Mater. Sci. Eng. A 643 17–24

[56] Dharmendra C, Amirizh B S, Lloyd A, Ram GDJ and Mohammad M 2020 Wire-arc additive manufactured nickel aluminum bronze with enhanced mechanical properties using heat treatments cycles Addit. Manuf. 36 101510

[57] Patel V, Li W, Liu X, Wen Q and Su Y 2019 Through-thickness microstructure and mechanical properties in stationary shoulder friction stir processed AA7075 Mater. Sci. Technol. (United Kingdom) 35 1762–9

[58] Li J, Wongsa-Ngam J, Xu J, Shan D, Guo B and Langdon T G 2015 Wear resistance of an ultrafine-grained Cu–Zr alloy processed by equal-channel angular pressing Wear 326–327 10–9

[59] Zhang Y, Tang H, Ji X, Li C, Chen L, Zhang D, Yang X and Zhang H 2013 Synthesis of reduced graphene oxide/Cu nanoparticle composites and their tribological properties RSC Adv. 3 26086–93