Investigating the influence of single-pass and double-pass friction stir processing on mechanical and wear behaviour of AA5083/Al2O3 surface

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Abstract. Friction Stir Processing (FSP) has established itself as an efficient technique to manufacture surface composite. Since the development of FSP, a variety of surface composite coatings have been produced with the help of this technique. Surface composite provides an enhancement in the material’s properties by providing a coating layer of composite material on the parent material. Various FSP process parameters can affect the produced surface composite and its properties. One of the important FSP parameters includes the number of passes over the surface of a material. In this paper surface composite of AA5083/Al2O3 was produced using FSP. Single-pass and double pass FSP were employed to understand its effect on microhardness, tensile strength, microstructure coefficient of friction, and wear rate. It was observed that the double pass aided to produce the homogeneously dispersed reinforcement particles in the surface composite along with fine grain microstructure. FSP helped to enhance the microhardness from 79.5 HV in the parent material to 136.5 HV in double pass FSP. Moreover, FSP helped to increase the tribological properties after two passes. However, the ultimate tensile strength was reduced after FSP.

Keywords: Friction Stir Processing, Multipass, Surface composite, AA5083, Al2O3, Tensile strength

1. Introduction
In most industries, aluminum alloys are widely used as the preferred material due to their lightweight. Industries like automobiles, aerospace, marine, etc. use aluminum to build their product parts. However, due to the reduced surface properties like wear and hardness, industries limit their use in wear and mechanical applications. These mechanical and tribological properties of aluminum can be enhanced by producing metal matrix composite (MMCs). However, if the application requires only the improvement in the surface of the aluminum then it becomes costly to produce the MMC of the entire aluminum material. Therefore the concept of the surface composite was developed in which only the surface of the material was made to MMC. Friction Stir Processing (FSP) is considered to be a reliable method by which surface composite can be made. FSP is considered to be a solid-state process that was built on the basic principle of Friction Stir Welding. In FSP, a rotating tool is inserted into the workpiece and then provided with a transverse motion which further produces the dynamic recrystallization of the stir zone and thus helps in developing the fine-grain microstructure which further enhances the microstructural, mechanical, and tribological characteristics in the workpiece.
To produce the MMCs composite coating on the workpiece, different researchers used different ceramic reinforcements in their study and improved the properties by making surface composite. Satyanarayana et al.[1] investigated FSP on AA6061 with 5 FSP passes and concluded that the ductility, as well as the corrosion behaviour of the workpiece, were enhanced after the process. Similarly Suganeswaran et al.[2] investigated the process on AA7075/SiC and observed that the microstructural, hardness, and wear behaviour of the material were enhanced after the process. Prabhu et al.[3] investigated FSP on AA6082/SiCp and observed that the three passes of FSP assisted the composite coating in enhancing the microhardness, tensile, and wear resistance of the material. Similarly, many other studies[4–7] show that FSP provides an optimum solution to produce a surface composite with better properties.

Based upon the literature review it has been observed that the process parameters of FSP perform a crucial part in deciding the workpiece properties. One of the FSP process parameters includes the number of FSP passes over the material. In this paper, single-pass FSP and double pass FSP were used to manufacture surface composite of AA5083/Al₂O₃. The effect of the FSP passes on microstructure, microhardness, tensile strength, wear rate and coefficient of friction were studied.

2. Material and Methodology

2.1. Material

2.1.1. Base Material. In the present investigation, AA5083 (Aluminum alloy 5083) was employed as the parent material. Aluminum plates with 300mm length, 50mm width, and 5mm thickness were used for the process.

The spectrography test was conducted at Divine Metallurgical Services, Ahmedabad to check the chemical composition of as-received AA5083. Table 1 represents the composition of parent material AA5083, tested using Optical Emission Spectroscopy. Fig.1 represents the optical micrograph of as-received AA5083.

| Element | Al | Mn | Cr | Sn | Cu | SiC | Fe | Zn | Mg | Pb | Ti | Ni |
|---------|----|----|----|----|----|-----|----|----|----|----|----|----|
| wt. %   | 94.5 | 0.61 | 0.089 | 0.0001 | 0.06 | 0.2 | 0.00 | 4.2 | 0.002 | 0.02 | 0.004 |
| %       | 9 | 6 | 3 | 5 | 7 | 1 |

Figure 1. Optical Microscopy of AA5083 at 200× magnification
Holes with the zigzag pattern were made in the AA5083 plates to fill the reinforcement particles for the surface composite. This type of pattern was employed to avoid any agglomeration or clustering of Al₂O₃ particles. CNC vertical milling machine was employed to drill the holes into the workpiece with the dimensions of diameter 2 mm and depth of 3 mm. Fig. 2 shows the AA5083 plate and holes pattern.

![Figure 2](image_url)

Figure 2. (a) as-received AA5083 plate, (b) Hole pattern in as-received AA5083, and (c) Schematic representation of holes dimensions

2.1.2. Reinforcement Particles. Aluminum Oxide (Al₂O₃) was used in this experiment as the reinforcement particles. The average particle size of Al₂O₃ was 15 μm. Fig 3 shows the optical microscopy of Al₂O₃ particles.

![Figure 3](image_url)

Figure 3. Optical Microscopy of Al₂O₃ at 200x magnification [8]

2.2. Processing
A simple vertical head milling machine of BFW make of the UF-1 model was used for the process. Clamping was used for holding the material to avoid any kind of vibrations during the process. The experimental setup and clamping are shown in fig. 4. Single-pass FSP and Double pass FSP were performed over AA5083

![Experimental setup (left) and clamping arrangements (right) for FSP](image)

The surface composite of AA5083/Al₂O₃ was made by providing a tool rotating speed of 1000rpm and a constant traverse speed of 25mm/min. A constant tool tilt angle of 3° was provided during the process. The tool was made with the hardened H-13 steel material. Two types of tools were used for the experiment. The first tool consists of a pin whereas the other tool is made pinless. The pinless tool was first employed for settling and covering the reinforcement material into the holes while the tool with pin was implemented to reinforce AA5083 and Al₂O₃ to produce a surface composite. The tool was made with a taper cylindrical pin profile with pin length of 4 mm, pin diameter of 4 mm, and shoulder dia of 18 mm.

Both the single pass and the double pass were used to process the material in this experiment. Different samples which were obtained after the process is described in table 2 (Each of the samples was also cut in transverse section and cross-section). The processed AA5083/Al₂O₃ surface composite samples with different FSP passes are illustrated in fig. 5.

| Sample code | Sample Name       | Number of passes | Presence of Reinforcement Particle(Al₂O₃) |
|-------------|-------------------|------------------|-----------------------------------------|
| A           | As-received       | -                | -                                       |
| B           | AA5083 - 1        | 1                | No                                      |
| C           | AA5083 - 2        | 2                | No                                      |
| D           | AA5083/Al₂O₃ -    | 1                | Yes                                     |
EAA5083/ Al2O3 - 2 2 Yes

Figure 5. Photographs of fabricated AA5083/ Al2O3 surface composite: (A) as-received AA083, (B) FSPed AA5083-1 pass without reinforcement (C) FSPed AA5083-2 pass without reinforcement (D) FSPed AA5083/ Al2O3-1 pass, and (E) FSPed AA5083/ Al2O3-2 pass

2.3. Characterization
To study the microstructure in the processed specimens, the specimens were grounded firstly with the help of emery papers having grit sizes from P100 to P2000. Samples were then grounded using the double-disc polishing machine and diamond paste having the size of 3μm and 1 μm. After the grounding process, the samples were then etched using the Keller reagent (HNO 3 – 5ml, HCl – 3ml, HF – 3ml, H2O – 190 ml) etchant was used. To analyze the microstructure of the prepared samples, optical microscopy was used in this study. Specimens were obtained from both transverse and cross-section areas.

To study the influence of FSP on the mechanical aspects of the prepared samples, microhardness and tensile tests were performed over the prepared samples. For the microhardness study, Vicker’s microhardness investigation was executed at a load of 200g for a dwelling period of 15 sec. Hardness was tested from both the cross-section and transverse sections of the processed samples. Ultimate tensile strength (UTS) test was done on Universal Testing Machine (UTM), according to the ASTM E8 standards at Divine Metallurgical Services, Ahmedabad.

In order to study the effect of FSP on the wear behaviour of the prepared specimen, tribological investigations were conducted on the pin on disc tribometer. The results were achieved using a constant load of 10N, track diameter of 80mm, and sliding distance of 1000m. The mass difference of the specimens before and after the test were measured. Coefficient of friction (COF) and wear rate against the sliding distance were measured during the test.

3. Results and Discussion
3.1 Parameter optimizing
FSP tool speeds were chosen based upon the literature review[4,9–11]. It was found that the higher rotating speed of the tool and lower traverse speed resulted in more heat generation which helps the material to limit the growth of grains and thus helps in the smaller grain size. The goal of this investigation is to investigate the effect of single pass and double pass FSP. Therefore a constant tool speed was selected for all the experiments so that a better understanding of the comparison between
the studies could be done. For all the experiments a constant tool traverse speed of 25 mm/min, 1000rpm rotational speed, and tool tilt angle of 3° were selected.

3.2 Microstructural analysis
To analyses the microstructure of the prepared specimens, an optical microscope was used and images were captures at 100X, 200X, 500X, and 1000X. However, the best images were observed at 200X and 500X therefore these images are used in the paper. The grain size was measured using ASTM E112/E1382-91 standard using the line intercept method with 10 lines at 1°. The low magnification image of sample D (FSPed AA5083/ Al₂O₃-1) and sample E (FSPed AA5083/ Al₂O₃-2) are shown in figure 6. The Unaffected Zone (UAZ), Heat Affected Zone (HAZ), Thermomechanically affected Zone (TMAZ), and nugget zone (NZ) are also labeled in the figure.

Figure 6. Optical image of FSP samples (a) Sample D, and (b) sample E with different processing zones

Optical Microscopy of TMAZ, HAZ, and UAZ in sample E is shown in figure 7. The transformation from UAZ to TMAZ is shown in the figure. The dispersed Al₂O₃ particles in the FSPed specimen in TMAZ is also shown in fig 7(a)

Figure 7. Optical micrographs of (a) TMAZ, (b) HAZ, and (c) unaffected zones in sample E

Figure 8 represents the optical micrographs of stir zones in samples A to E. Images from both transverse section and cross-section was taken for a better understanding of the microstructure. As-received AA5083 has average grain size of 7.9μm in transverse section whereas sample E showed average grain size of 2.75μm in transverse section. The reduction in the grain size in nugget area is due to the phenomenon of recrystallization. The combined action of heat generation because of friction and the plastic deformation in the processed area helped the material to undergo dynamic
recrystallization[12]. Hence the dynamically recrystallized grains were obtained in the processed region. Table 3 shows the grain size at the stir zone in samples A to E.

Table 3. Average grain size at stir zone

| Sample | Av. Grain Size (μm) | Av. Grain Size (μm) |
|--------|---------------------|---------------------|
|        | Cross Section       | Transverse Section  |
| A      | 4.60                | 7.90                |
| B      | 4.37                | 3.85                |
| C      | 4.25                | 3.25                |
| D      | 3.85                | 3.25                |
| E      | 3.25                | 2.75                |

From Table 3 it has been observed that the average size of grains in the samples was reduced with increasing the FSP passes. FSP helps in the reduction of grain size even at the single pass without any reinforcement particles. However, additional reinforcement particles and increased passes help the grain size to get further reduced[13]. The reduction of grain size with the addition of Al₂O₃ particles
can also be related to the Zener Pinning effect. The single-pass FSP produced a non-uniform dispersion of coarser Al₂O₃ particles which was reduced with another FSP pass. Similar types of results were also reported in the previously published articles[3,14–16] where the increased passes of FSP helped the material to get finer grain size and thus produce a surface composite with finer reinforced particles.

3.3 Mechanical

3.3.1. Microhardness analysis. The average microhardness values for samples with single pass and double pass FSP at transverse section (TS) and cross-section (CS) are presented in figure 9. The microhardness values of the as-received AA5083 was observed to be 79.5 HV. It has been observed that all the samples showed better microhardness near the nugget region as compared to the base material. All the FSPed samples at CS showed a gradual hardness enhancement with the distance from the base material. The microhardness value of all the samples seems to be in perfect agreement with Hall Petch equation according to which microhardness is inversely proportional to the grain size. Maximum Vicker hardness number of 136.5 HV was achieved at the nugget zone of sample E at TS as compare to the base material with ~80 HV microhardness. The reason for the enhancement in microhardness is because of the uniform scattering of Al₂O₃ particles at double pass FSP and the grain refinement due to stirring. The Al₂O₃ particles behave as the precipitate through the dislocation which helps to enhance the microhardness value of the prepared specimens. In TS with single-pass FSP, the Al₂O₃ particles were coarser in size and were not dispersed homogeneously due to which the microhardness was more towards the retreating side as compared to the advancing side. It can be said that increasing the FSP passes helps the material to undergo better dispersion of reinforced particles and hence enhance the microhardness values. The result can be validated by the articles[17–20] in which increased FSP passes helped to enhance the microhardness values.
3.3.2 Tensile behaviour. The UTS test was performed in accordance with the ASTM E8 standard to understand the influence of FSP and its number of passes on the Ultimate Tensile Strength (UTS), Yield Strength (YS), and Elongation (El) in specimens during the test. Fig 10 shows the results obtained after tensile testing. The test was performed for all the samples A-E for their UTS, YS, and El (%). It has been observed that with the addition of Al\(_2\)O\(_3\) particles, UTS of specimens reduced as compare to the base material. The base material showed UTS of 300.9 MPa whereas the 2 pass FSP with Al\(_2\)O\(_3\) showed UTS of 257.17 MPa. In other sample D, a similar result was found. It occurs due to the reason that the Al\(_2\)O\(_3\) particles act as separate particles and thus the specimen behaved as the brittle material. Similar observations were observed by Zayed et al. [21] and Aruri et al. [22] who observed a decrease in tensile strength after FSP.
Figure 10. UTS, Yield Strength (YS), and Elongation (%) behaviour

3.4 Tribological behaviour

3.4.1. Friction analysis. Fig 11 shows the Coefficient of friction (COF) plot against the sliding distance for samples A to E. The average COF for base material was found to be 0.393 whereas the least COF was observed for sample E with an average COF of 0.284. It is observed that the samples gradually decreased the COF with the FSP and number of passes. A relation between hardness and COF could be observed in the figure that the samples whose hardness was more have the least COF. The reason behind the decrease in COF with an increase in hardness is because the harder surface provides a smaller area of contact and resists the scratch during the test. Similar results were observed in the recently published articles[23–25] where specimens showed lower COF with an increase in microhardness values. Therefore it can be said that increasing the FSP passes helps to increase the microhardness that further helps to reduce the COF.
3.4.2. Wear study. Table 4 shows the mass loss of the specimens after the wear test. Specimen A (base material) showed the maximum mass loss of 0.007 g after 1000 m sliding distance as compared to sample E with 0.001 g mass loss. It is observed that FSPed specimens showed a reduced mass loss in the test. It can also be observed that the presence of Al₂O₃ and increased FSP passes helped to reduce the mass loss during the test. A similar pattern was observed in the plot of wear rate of specimens A-E which is shown in fig. 12. It was also observed that the specimen E showed least wear rate of 205.88 μm/mm as compared to the base material with a wear rate of 261.75 μm/mm. With an increase in the FSP passes and adding Al₂O₃ particles, the specimen showed a better wear rate. The reason behind the reduced wear rate and least mass loss after FSP can be explained by the grain refinement and increased microhardness phenomenon. According to Archard’s equation:

\[ Q = \frac{K F D}{H} \]

Where \( Q \) is wear rate, \( H \) is the microhardness of the material, \( D \) is the sliding distance, \( K \) is COF, and \( F \) is the applied load. From this equation, it can be clearly stated that the enhancement in
microhardness value helps to improve wear rate and COF. Similar results were observed in many recent articles[18,22,26] where FSP helped to increase microhardness and thus reduced wear rate and COF.

Table 4. Mass loss during the wear test

| Specimen | Mass before wear test (g) | Mass after wear test (g) | Mass difference (g) |
|----------|---------------------------|--------------------------|---------------------|
| A        | 0.227                     | 0.22                     | 0.007               |
| B        | 0.268                     | 0.265                    | 0.003               |
| C        | 0.244                     | 0.241                    | 0.003               |
| D        | 0.272                     | 0.27                     | 0.002               |
| E        | 0.224                     | 0.223                    | 0.001               |

Figure 12. The plot of wear rate against sliding distance for different samples.
4. Conclusion
In this paper, the effect of number of FSP passes on microstructural, tribological, and mechanical behaviour of the prepared AA5083/Al₂O₃ surface MMCs were investigated. FSP was employed over AA5083 without Al₂O₃ and with Al₂O₃ reinforcement particles. FSP passes and the presence of Al₂O₃ particles in AA5083 and their effect on the prepared surface composite were studied. Some of the conclusions made from the study are as:

1. Increased FSP passes helped in the homogeneous scattering of the Al₂O₃ particles. Double pass helped the material to undergo dynamic recrystallization and thus produced a fine grain-sized microstructure.
2. Multi-pass FSP helped to enhance the microhardness of the workpiece. Double pass FSP enhanced the microhardness value to 136.5 HV as compare to the 79.5 HV in the base material.
3. Prepared AA5083/Al₂O₃ surface composite showed reduced UTS after the FSP. The reinforcement particles act as separate hard particles and increased the brittleness of the surface composite due to which the tensile strength of the specimens reduced after FSP.
4. The COF of the prepared specimens showed a gradual reduction with the rise in the FSP passes. This occurs because of the increased hardness of the specimens. The increased hardness helped to resist the specimens against scratch and thus helped to reduce the COF.
5. The wear rate of the prepared specimens was improved with the presence of Al₂O₃ reinforcement and increased FSP passes. An increase in FSP passes helped in the homogeneous dispersion of the Al₂O₃ reinforcement and the stirring action of the tool helped to produce fine grain microstructure which furthermore facilitated to improve the wear properties of the FSPed specimens.

These results show that the prepared surface composite AA5083/Al₂O₃ can be helpful in the areas where hardness and tribological properties are of great importance. The increase in FSP passes can help the material to further enhance the microstructural, microhardness, and tribological properties. However, further investigation is needed to enhance the tensile property of the prepared surface composite.

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