Effect of Ti/SiC Reinforcement on AA5083 Surface Composites Prepared by Friction Stir Processing

Md. Ziyaur Rahman¹, Arshad Noor Siddiquee¹, and Zahid A. Khan¹

¹ Department of Mechanical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi 110025, India

er.ziyaurrahman@gmail.com

Abstract. Al alloys because of their desirable characteristic properties have made them predominant materials in lightweight design structures such as the aviation, automotive, and shipbuilding industry. However, their applications are limited due to their lower strength at higher operating temperature and difficulty in their welding. One of the alternatives to enhance the surface properties of aluminium alloys is coating metallic substrates. In the present experimental study, the effect on surface properties by introducing titanium and silicon carbide reinforcement into AA5083 alloy using friction stir processing (FSP) was investigated. Additionally, bead geometry such as the width of SZ, depth of SZ, and area of SZ in all the specimens were also analyzed. FSP was performed at different combinations of rotational speeds, traverse speeds, and shoulder diameter sizes using Taguchi L4 orthogonal array. Experimental results indicated that the highest value of hardness was observed at tool rotational speed of 355 rpm, traverse speed of 63 mm/min, and shoulder diameter size of 17 mm. Moreover, at such combination of process parameters, the lowest value of width to depth ratio was observed.

1. Introduction
Al alloys find potential applications in aerospace, automotive, and shipbuilding industry owing to their desirable characteristic properties such as lightweight, high specific strength, better corrosion resistance, and appreciable toughness. However, their applications are limited due to their poor surface properties such as lower wear resistance and lower hardness. On the other hand, aluminum alloys lose their strength/functionality at higher operating temperatures due to their low melting point temperature (656 °C) [1-2]. To encounter such problems, one of the alternatives to enhance their properties is to introduce hard components such as SiC, W and Ti to the surface of base alloy [3]. A significant study related to introduction of hard particles in the base material (BM) surface was performed by researchers using a fusion route. However, this technique was associated with various limitations such as the formation of undesirable phases and separation of micro phases during processing [4]. On the other hand, techniques such as conventional casting and powder metallurgy are effective in the fabrication of metal matrix composites (MMC) than fusion routes but are subject to certain limitations such as lack of uniform distribution of reinforcements [5]. To address, the limitations of such MMC fabrications process, friction stir processing (FSP) is one of cost-effective alternatives for fabricating MMC. FSP is an alternative to friction stir welding (FSW) and is widely used to tailor the surface
properties of BMs. In FSP, the reinforcements are introduced into the well-packed groove of predetermined size. Thermo-mechanical and stirring action of FSP tool plasticizes the BM and leads to uniform distribution and embedment of reinforcement into the matrix. The plasticized MMC is subsequently forged at trailing side of tool due to axial force applied by FSP tool.

Significant literature is available attributed to the enhancement of surface properties of AA5083 using FSP [6-7]. In contrast, little research work has been performed on the influence of process parameters on the surface quality during FSP of AA5083 [8-9]. However, no study is available in open literature exploring the influence of process parameters in friction stir processed (FSPed) Ti+SiC reinforcement on surface properties. The central aim of the present experimental investigation is to obtain optimum process parameters for obtaining the best surface properties such as hardness. Moreover, the bead geometry of the stir zone (SZ) was measured at various process parameters. Taguchi L4 orthogonal array was designed for characterizing the surface properties of friction stir processed AA5083 using three predictors, tool rotational speed (rpm), traverse speed (v), and shoulder diameter size (ϕ).

2. Experimental Set-Up

In this experimental investigation, the BM was aluminium alloy 5083 (AA5083) with chemical composition listed in Table 1. Plates of dimensions 200mmx70mmx7mm were cut along the rolling direction. Grooves of dimensions 2.5mmx2mm were made on the surface of AA5083 plates along the longitudinal direction using a computer numerical controlled (CNC) machine. Reinforcement, Ti/SiC in the ratio of 10:3 was introduced into the groove (refer Figure 1(a)). Before FSP the reinforcement in the groove was well-packed with the aid of a pin less flat shouldered cylindrical tool. After compact packing of precisely placed reinforcement, the well-designed profiled tool of suitable dimensions having cylindrical pin (with right-hand threads) (refer Figure 1(b)) was introduced axially into the previously well-packed reinforcement to fabricate the MMC (refer Figure 1(a)). The surface MMC was fabricated using a retrofitted vertical milling machine. After FSP, the specimens were cut in the transverse direction for metallographic examination. The specimens were subsequently polished with emery papers up to 2000 grit sizes and were finally polished with diamond paste using a velvet cloth. The specimens were subsequently etched with a solution of 34 ml of distilled water, 16 ml HNO$_3$, 12 ml HCl, and 1 ml HF, and 4.8 grams of CrO$_3$ for 65 sec for revealing the microstructural characteristics and distribution of reinforcement in the processed zones. The microstructural images of the processed region were revealed with the aid of an optical microscope (OM). The Vickers microhardness readings were measured in a direction perpendicular to the weld cross-section using a microhardness hardness tester.

Table 1. Elemental composition of AA5083 BM.

| Elements | Mg  | Mn  | Fe  | Si  | Cr  | Cu  | Ti  | Zn  | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt.%     | 4.365 | 0.5 | 0.16 | 0.08 | 0.07 | 0.031 | 0.013 | 0.002 | Bal. |

In this experimental study, Taguchi L4 orthogonal array was used. The experimental plan of the present study is listed in Table 2. Two levels each of ϕ (17 and 20mm), rpm (355 and 450rpm), and v (63 and 80mm) were employed in this investigation. In this study, the optimal combination of process parameters was investigated for which the highest values of hardness were obtained. Moreover, the bead geometry of SZ of the processed specimen for which higher value of hardness obtained was investigated in detail.
Figure 1 shows (a) the principle of FSP and (b) the FSP tool with the nomenclature.

Table 2. Experimental plan

| Experiment No. | ϕ (mm) | rpm  | v (mm/min) |
|---------------|--------|------|------------|
| S1            | 17     | 355  | 63         |
| S2            | 17     | 450  | 80         |
| S3            | 20     | 355  | 80         |
| S4            | 20     | 450  | 63         |

3. Results and discussion

3.1. Macrostructure and Microstructure

Figure 2 shows the macrostructure of various weld regions in S1, S2, S3, and S4 specimens produced during FSP. Microhardness indents (vertical line) can be observed on the cross sectional surface of FSPed region. In all the specimens the agglomeration of Ti+SiC powder can be observed by visual inspection. This agglomeration indicates the improper distribution of reinforced particles with the base alloy matrix. Figure 3 represents the optical microstructure of FSPed specimens fabricated at tool rpm of 355, v of 63mm/min, and ϕ of 17mm. Four characteristic zones were recognized in the FSPed region: stir zone (SZ), thermomechanically affected zone (TMAZ), heat affected zone (HAZ), and BM. In SZ, the grains were fine and equiaxed owing to dynamic recrystallization due to intense plastic deformation in this region. On either side of SZ is TMAZ having elongated and large grains owing to partial plastic deformation in this region. Adjacent to TMAZ is HAZ where grains are more or less similar to the base material and are only subjected to a thermal cycle with no plastic deformation. In general, the increase in grain size occurs as one moves from SZ to TMAZ then HAZ due to progressive removal of plastic deformation from SZ to HAZ. In SZ the highest values of hardness are observed due to the presence of fine and equiaxed grains formed during FSP. In Figure 3E, the agglomeration of reinforcement particles can be observed in SZ. This condition is attributed to the improper mixing and distribution of reinforcement particles in the base matrix during FSP.
Figure 2 shows the macrostructure and friction stir processed region in FSP specimens.

Figure 3 shows the microstructure of various zones formed during FSP in S1 specimen

3.2. Micro hardness

The average hardness value of as received base alloy (AA5083) was 80 HV. Figure 4 represents the microhardness profiles of SZ measured perpendicular to processed cross-section. The microhardness was measured at a continuous spacing of 0.4 mm under the load of 0.5 kgf acting for 15 sec using a microhardness tester. In general, the FSP does not result in softening of the FSPed specimens. The hardness profiles were more or less uniform in the SZ. There is an overall increase in hardness in SZ in comparison to base matrix which is attributed to dynamically recrystallized grains formed during FSP in this region. Besides, the hardness value is inversely proportional to grain size according to Hall-Petch Law. From the microhardness profiles, significant variation in hardness can be observed as one moves towards the bottom surface. On the other hand, the higher values of hardness can also be contributed to the uniform distribution of intermetallic during FSP.

The maximum hardness value of 124.5HV (refer Figure 4) was observed in specimen S1 with a tool rpm of 355, v of 63 mm/min, and φ of 17 mm. This highest value of hardness was observed at a depth of 2mm from shoulder surface. The reason for higher values of hardness is due to the distribution of reinforcement (Ti+SiC) particles which also restrict the grain growth during processing. Furthermore, the formation of plasticized zone beneath the tool shoulder results in the fabrication of MMC resulting in higher values of hardness. Besides, the existence of large force near the tool shoulder causes the
severe dynamic recrystallization and formation of fine equiaxed grain leading to an overall increase in hardness near to tool shoulder surface.

Figure 4 Represents the microhardness profiles obtained from S1, S2, S3, and S4 FSP specimens.

3.3. Bead Geometry Analysis

Figure 2 shows the macro images of the FSPed region. The bead geometry of SZ i.e., width, depth, and the area are shown in Figure 2. In all the specimens the dimensions of SZ i.e., the width of SZ, depth of SZ, and area of SZ was calculated from macroscopic images of the FSP region using ImageJ software (refer to Table 3). For specimen S1, the highest values of microhardness were obtained at tool rpm of 355, v of 63 rpm, and φ of 17mm. The corresponding value of the width, depth, and area of SZ was calculated as 17.23 mm, 5.743 mm, and 52.629 mm2 respectively (refer to Table 3). Moreover, the maximum value of hardness was obtained at 2mm from the top surface of SZ in specimen S1. This indicates that optimal results are obtained at lower tool rpm (355), lower v (63mm/min) and small φ (17mm) results in proper and uniform distribution of reinforcement within the metal matrix. Moreover, it can be observed that specimen S1 has the lowest width/depth ratio. The lowest width to depth ratio resulting in high hardness values owing to distribution of reinforcement in the specific area which ultimately leads to high density of reinforcement particles and hence higher hardness value.

Table 3. Presents the numerical values of width, depth, and area of SZ measured from micrographs using ImageJ software.

| Sample No. | Width of SZ (mm) | Depth of SZ(mm) | Area of SZ (mm²) | Width/Depth ratio |
|------------|-----------------|-----------------|-----------------|------------------|
| S1         | 17.230          | 5.743           | 52.629          | 3.0              |
| S2         | 17.855          | 5.863           | 55.988          | 3.045            |
| S3         | 20.164          | 5.707           | 59.272          | 3.533            |
| S4         | 20.586          | 5.603           | 59.922          | 3.67             |

4. Conclusions

From the above experimental study, the following main conclusions can be drawn:
1. Macrostructure of FSPed specimens indicates the improper distribution of reinforced particles.
2. Microstructure of processed regions indicated the significant variation in grain size in various regions. The highest value of hardness was obtained in SZ owing to dynamic recrystallization of grains and more or less uniform distribution of reinforcement particles.
3. The highest value of hardness was obtained for specimen S1 at tool rpm of 355, v of 63 mm/min, and φ of 17 mm.
4. The highest value of hardness was obtained at a depth of 2 mm from the upper surface of processed region. Moreover, the maximum hardness value observed in S1 specimens bears the lowest width to depth ratio.

5. References
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