Processing and wear properties of aluminium surface composites using friction stir processing

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Abstract: Friction stir processing (FSP) was employed to fabricate Aluminium Surface Composites (SC) by reinforcing boron carbide (B₄C) particles with AA6082 aluminium matrix alloy. The role of reinforced particles on the microstructure and mechanical behaviour of the prepared surface composites was studied. The microstructure of the produced composite was examined utilising optical microscopy, scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD). The micrographs of the processed zone revealed fine grains and uniform dissemination of B₄C particles with good interfacial bonding. Microhardness and wear resistance tests were conducted on the matrix alloy, FSPed matrix and produced surfaced composites with the different volume fraction of B₄C particles. The microhardness and wear resistance showed the higher values compared to aluminium matrix and friction stir processed aluminium without B₄C particulates. It was seen that the wear resistance of the FSPed surface composite was improved significantly as compared to that of the AA6082 matrix alloy.

Key words: Surface composites - Rotational speed - Processing speed – Microstructure - Microhardness - Wear rate

1. Introduction
Aluminium Matrix composites (AMCs) are most wanted materials in aircraft, marine and automobile industrials. Generally, AMCs are having some important properties such as their higher specific Strength, low density, and wear resistance. However, reinforced hard ceramic particles reduced the ductility and toughness [1-3]. Research is being carried out to retain the interior properties and enhance the mechanical properties of the surface layer of materials in the desired thickness level (Surface Composites).

Several methods such as powder metallurgy, cast sintering, electron beam irradiation, plasma spraying, and high energy laser melt injection, have been used to produce surface composites. These processes are performed under the elevated temperatures, which causes the interfacial reaction between particles and alloy, and produced intermetallic products. A simple novel process, Friction stir processing (FSP) is introduced to fabricate surface composites using the principles of Friction stir welding (FSW). The reinforcement particles are packed in grooves or holes on the top surface of the material. A non-consumable rotating tool with a pin is plunged in to the top of the material and travelled longitudinally along the groove. Due to the rotation of the tool, heat is generated and plasticize material and surface composites is produced with reinforced particles [4, 5]. Maxwell et al [6] fabricated TiC and B₄C particles reinforced hybrid surface composites with various volume ratios. The increased fraction of volume ceramic particles increased the mechanical properties. Qiang et al [7] stated the influence of
different vol. % of multi-walled carbon nanotubes incorporated into the aluminium matrix using FSP. You et al [8] fabricated aluminium surface composites with Mg and CuO are reinforcements using FSP and enhanced the tensile strength of the matrix alloy. Hashemi & Hussain et al [9] fabricated TiN Nanoparticles reinforced with AA7075 surface composites with different tool profiles using FSP. TiN particulates and threaded profile tool enhanced the wear properties. Shahraki et al. [10] fabricated surface composites using AA5083 as matrix and ZrO$_2$ as reinforcing particles and observed the improved microstructure and mechanical properties. Bahrami et al. [11] fabricated AA7075/SiC composite and evaluated the effect of tool pin shape on microstructure and mechanical properties. Maza-heri et al. [12] fabricated A356/Al$_2$O$_3$ surface composites and examined the microstructure and tribological behaviours. Khodabakhshi et al. [13] developed AA5052-TiO$_2$ composites and observed the role of annealing on the solid state chemical reactions. Zhao et al. [14] processed Aluminium Surface composites reinforced with boron carbide particles and observed that how the number of passes affect the distribution of particles. Therefore, in this work, an endeavour is made to produce aluminium surface composites with addition of B$_4$C particles as reinforcement and investigate the microstructural and mechanical features.

2. Materials and Methods
The chemical composition of AA6082 aluminium alloy plate size 100 mm x 50 mm x 10 mm was used for this study is shown in Table 1. A rectangle 5.5 mm deep groove and different size width was created along the middle portion line of the plate by wire cut Electrical Discharge Machining. The B$_4$C powder was packed in a groove. A tool made of H13 without pin was used to close the top layer of the rectangle groove after packing with B$_4$C particles to inhibit the particles from sprinkling during FSP. An aforesaid material tool which has shoulder diameter of 18 mm, pin diameter of 6 mm and 5.7 mm pin length was plunged into the closed groove along the longitudinal direction. The process was performed with the tool rotating speed of 1200 rpm, 60 mm/min processing speed and 10 kN axial force. The aforesaid process parameters were chosen according to the results inferred from the past works and trial experiments conducted by the corresponding author. The procedure for the production of surface composites was explained elsewhere [15].

| Element | Si | Mg | Mn | Fe | Cu | Cr | Zn | Ti | Al |
|---------|----|----|----|----|----|----|----|----|----|
| wt.%    | 1.06 | 0.78 | 0.55 | 0.21 | 0.09 | 0.03 | 0.06 | 0.01 | 97.20 |

The samples under study were attained from the middle line of the processed zone and polished as per metallographic procedure. The Keller’s reagent was used for the purpose of etching. An Olympus-BX51M optical microscope was used to obtain the micrographic images. The reinforced particle dissemination was observed by FESEM, Carl Zeiss-SIGMA HV and EBSD. The microhardness of the stir zone was measured using a Mitutoyo MVK-H1 Vickers microhardness testing machine at 500 grams load applied for 15 seconds. A pin-on-disc wear apparatus (DUCOM TR20 - LE) was used to evaluate the wear behaviour of the processed surfaced composites.

3. Results and Discussion
The optical micrographs of the parent material and processed zone are shown in figure. 1(a) - (d). From the micrograph of the processed matrix material, it is noticed that the reinforced particles influence the grain size of the aluminium matrix. Aluminium matrix grain refinement takes place due to the effect of pinning of hard B$_4$C particles. The irregular grain development of matrix alloy is hindered by sliding of
the grain boundary. Moreover, aluminium matrix grains are further reduced, because of nucleation locations that are developed by the dynamic recrystallization process. The dynamic recrystallization phenomenon contributes to the grain refinement and modification of grain structure. The size and shape of the incorporated B₄C is shown in figure 1(b). The FESEM images reveal that B₄C particles are uniformly disseminated in the stir zone. The load - posture capacity of the material depends on the interface between matrix and reinforcements. Figure 1(c) depicts a very good interface bonding between matrix and ceramics particle is obtained. There is no pores and cavities found in the microstructure as in the case of liquid casting processes. Figure 2 (a & b) depicts the EDS spectrum analysis of surface composites. The results of the EDS analysis suggest that the layer formation at the stir zone interface are Inter - Metallic Compounds (IMCs) layer with the average chemical composition (wt. %) of 70.99% B/14.43% C/10.57% Al/3.42% Si, and 0.6% O. It can be noticed that the microvoids are not located around the reinforced particles. In the processed zone, there is no evidence for the presence of third phase particles.

Moreover, the microstructure was further studied by EBSD is shown in figure 2 (c &d). The figure clearly shows the EBSD grain boundary map images of the stir zone. It is noticed that the grain structure is recrystallized and equiaxed fine grains which are finer than matrix alloy. The heat generated during the process and plastic deformation leads to dynamic recrystallization and ensures the fine structure of grain.

The average microhardness and wear rate of surface composites are shown in Table 2. The average microhardness value of matrix alloy was found to be 62 HV. FSPed matrix alloy average hardness value had enhanced and a maximum of 75 HV was achieved. The increased hardness value is due to the grain refinement and fragmentation and dissemination of intermetallic particles. These dispersed particles may enhance the mechanical properties of the alloy through Orowan strengthening mechanism (16). The reinforced B₄C particles improved the hardness of the composite. The maximum hardness value of 125.6 HV is reached in the composites. Furthermore, the B₄C particles have better Cohesion between the aluminium grains. The applied load is transmitted to B₄C particles and has got higher load posture capacity compared to aluminium alloy.
Figure 2: (a & b) FESEM image and EDS analysis of AA6082/B₄C composites, (c & d) EBSD grain boundary map of AA6082/B₄C surface composite

From the observations made on Table 2, the wear resistance of the surface composite has significantly improved. The wear rate of the composites depended on the microstructural characteristics and wearing condition such as applied load, sliding distance, temperature and ceramic particle size. In this case, the incorporation of B₄C particles and microstructure modification done by the processing play a vital role in wear resistance improvement. The wear rate was evaluated to be $536 \times 10^{-5}$ mm$^3$/m at 0 vol. % and $352.3 \times 10^{-5}$ mm$^3$/m at 22.9 vol. %. The wear rate was evaluated to be $536 \times 10^{-5}$ mm$^3$/m at 0 vol. % and $352.3 \times 10^{-5}$ mm$^3$/m at 22.9 vol. %.

Table 2. Influence of volume fraction on mechanical properties

| Sample No. | Volume fraction % | Microhardness (VHN) | Wear rate ($\times 10^{-5}$ mm$^3$/m) |
|------------|-------------------|----------------------|---------------------------------------|
| 1          | 0                 | 75.30                | 536.17                                |
| 2          | 3.8               | 88.40                | 463.87                                |
| 3          | 8.5               | 103.88               | 424.50                                |
| 4          | 14.6              | 117.62               | 384.40                                |
| 5          | 22.9              | 125.60               | 352.30                                |

4. Conclusions
Aluminium alloy AA6082 reinforced with boron carbide composites were produced with help of FSP and the influence of B₄C particles and its fraction of volume on microstructure, hardness and sliding wear properties were analysed. The incorporated particles were uniformly dispersed and a clean
interface was observed between B₄C particles and matrix alloy. B₄C particles strengthened the surface composites. Both the hardness and the wear resistance were enhanced when the B₄C particles volume fraction was increased.

5. References
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