Fabrication of AA1050/B₄C surface composite by friction Stir processing (FSP) and investigation on mechanical and wear characteristics

Hemendra Patle¹⁺, Ashish Gupta¹, P Mahendiran², Ravikumar Dumpala¹

¹Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India
²Jawaharlal Nehru Aluminium Research Development and Design Centre, Nagpur

Corresponding author: hemendrapatle876@gmail.com

Abstract. Friction stir processing (FSP), derived from the friction stir welding (FSW) process, is an energy efficient processing technique to fabricate surface composite. In the present study, FSP technique is applied for the development of surface composites, using AA1050 aluminum as base metal and Boron Carbide (B₄C) powder as reinforcement particles. The mechanical and wear characteristics were compared with the base metal characteristics. Pin-less tool for capping pass and threaded cylindrical pin tool for subsequent passes was used for FSP experiments. Tool rotational speed and traverse speed were kept 1400 rpm and 25 mm/min respectively. It was observed that the Friction stirred processed (FSPed) specimens with B₄C particles showed higher hardness (45 VHN) in comparison to the base material hardness (25 VHN). Wear behavior of the fabricated surface composite has been investigated using linear reciprocating tribometer. Wear resistance of fabricated surface composite has shown significant improvement in comparison to that of the base metal.

Keywords: Friction stir processing, AA1050, B₄C particles, Surface composite, Hardness, Wear

1. Introduction
Aluminum alloys are most widely used for automobile and aerospace applications because of lightweight and high strength. However, aluminum alloys have poor wear resistance and the surface properties can be improved by incorporation of secondary phase particles. TiC, SiO₂, SiC, Al₂O₃, B₄C, etc. are most commonly used hard ceramic particles for making aluminum-based matrix composite. A variety of techniques are available for the fabrication of surface composite where the particles are dispersed only on the surface of the base metal while the bulk material properties remain as it is. Some of the surface modification techniques such as plasma spraying, electron beam irradiation, high energy laser beam, etc. are used for the development of surface metal matrix composites (SMMC) [1-4]. However, these techniques require liquid phase transformation of materials at elevated temperature, which causes interfacial reaction between matrix material and reinforcement particles. Detrimental phases form due to these interfacial reactions and it can be avoided if process is done in solid state. Friction stir processing (FSP) is one of most popular solid state processing technique used to fabricate
SMMC [5, 6]. FSP causes high plastic deformation and uniform distribution of particles in matrix material which results significant improvement in microstructure of matrix material and homogeneous processed zone. Owing to these features, FSP has been extensively used in the development of light metals such as aluminium and magnesium based surface composite with better surface properties. R.S. mishra et al [7] first developed AA5083/SiC based surface composite by FSP and revealed better material properties than base material. Many investigations have been carried out in development of 2xxx and 7xxx series based surface composite through FSP.

In this present study, AA1050/B₄C surface composite was developed using FSP technique. Subsequently, mechanical and wear characteristics of the developed surface composite were investigated.

2. Experimental Details

Commercially available AA1050-O aluminium sheets of 6 mm thickness were used as matrix material. Table 1 shows the chemical composition of AA1050-O aluminium sheet. B₄C (average particle size of 18 µm) were used as reinforcement particles to fabricate surface metal matrix composite.

Table 1. Nominal composition of AA1050-O alloy (wt. %).

|   | Si   | Fe  | Cu  | Mn  | Mg  | Zn  | Cr  | Pb  | Sn  | Ti  | Al  |
|---|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 0.161| 0.303| 0.009| 0.013| 0.004| 0.005| 0.001| 0.002| 0.002| 0.005| Bal.|

Sheets of size 150 mm x 100 mm were used for FSP experiments. On the centerline of sheet surface, series of small holes of 3 mm diameter and 2.5-3.5 mm deep were drilled in regular intervals to hold the B₄C particles and also to prevent the sweeping of B₄C particles by the tool movement and as shown in ‘figure 1’. To remove any dirt, organic material and fine particles left after the cutting and drilling process, the work pieces were cleaned by acetone thoroughly.

![Figure 1. Work piece for FSP experiments.](image)

Friction stir processing experiments were conducted in a vertical milling machine (Model: VF3, BFW). The FSP tool used for experiments was made of H-13 tool steel hardened to 55 HRC. FSP tool consist of simple threaded straight cylindrical pin with 6 mm pin diameter, 4.5 mm pin length and 18 mm shoulder diameter is shown in ‘figure 2’.
Pin-less tool (tool without pin) was used for capping pass to close the drilled holes. Threaded cylindrical pin was used for subsequent stirring passes. If FSP is directly performed without capping pass then there will be loss of powder particles during stirring. It can be efficiently reduced by applying a single capping pass with cylindrical tool without pin to cover the holes. FSP tool rotational and traverse speed was kept 1400 rpm and 25 mm/min respectively and tool tilt angle was fixed as 3°. Two stirring passes were performed to fabricate surface composite. High rotational and low traverse speed reduces the chances of agglomeration of reinforcement particles [8].

Metallographic studies were performed on the cross section of the Friction stirred processed (FSPed) sample perpendicular to the FSP tool traverse direction. Samples were polished upto 1200 grit emery paper and followed by disc cloth polishing with a diamond suspension of particle size 3 and 1 μm in order to obtain a mirror finish surface. Metallographic samples were used for microstructural observations and hardness measurements. Optical microscope (Carl Ziees AXIOTECH100) was used for microstructure examination on the transverse section of specimens to analyze the reinforcement particle distribution in the matrix and also to observe the presence of micro defects such as micro cavities, micro cracks, particle agglomeration or segregation, particle free zones, etc.

To investigate the mechanical properties of surface composite samples, microhardness test was carried out. Hardness measurements of the developed surface composites were carried out using Vickers Micro Hardness tester (INSTRON TUKON 2100). Microhardness measurements were taken across the processed zone at regular intervals (0.5 mm) with 300 gf load and a dwell time of 10 seconds as per the ASTM E10 standard to analyze the hardness distribution of the developed surface composite.

To investigate tribological behavior of fabricated surface composite, dry sliding wear test was conducted using a linear reciprocating tribometer (DUCOM TR-281). Type of contact was ball on plate geometry (point contact), so that ball moves on to and fro motion on FSP processed surface. Wear test specimen were cut from base metal and FSPed specimens with the dimension of 20 mm x 20 mm x 5 mm using wire EDM. Ball material was AISI 52100 steel with 6 mm diameter. The dry wear test were conducted at the normal load of 10N, sliding velocity of 0.06 m/sec for the distance of 50 m. Wear test were conducted at room temperature and 40-50% humidity. After conducting wear test samples were cleaned with acetone and weight loss was measured using a balance with least count of 0.1 mg.
3. Results and Discussion

‘Figure 3’ shows the top surface of produced surface composite. The holes filled with B$_4$C are perfectly closed during FSP. Defects like cracks and voids are not detected on the surface due to tool’s stirring action.

![Macro image of FSPed AA1050-B$_4$C surface composite.](image)

**Figure 3.** Macro image of FSPed AA1050-B$_4$C surface composite.

3.1. Microstructure

‘Figure 4’ shows the macrostructure image of cross section of FSP processed specimens. Due to the frictional force between tool and matrix material, sufficient heat generates which plasticizes the matrix material [6]. The continuous stirring action of FSP tool distributes the B$_4$C particles uniformly within the matrix material. Thus, a defect free AA1050-B$_4$C is obtained by FSP.

![Macrograph of transverse section of AA1050-B$_4$C surface composite.](image)

**Figure 4.** Macrograph of transverse section of AA1050-B$_4$C surface composite.

It can be seen from ‘figure 4’ that tunnel defect, voids, warm hole are not observed in the cross section of fabricated surface composite which are typical defects of FSW. However, particle free zone and particle mixed zone can be observed and it can be eliminated by increasing the number of stirring passes.

Optical Micrograph of AA1050-B$_4$C surface composite is shown in ‘figure 5’. Though there was a particle free zone on macro level, B$_4$C particle has mixed uniformly in the stir zone as evident from the microstructure. Uniform distribution of B$_4$C particle in matrix is due to the stirring action of the tool. Also, grain refinement and uniform distribution of secondary phase particles was observed which are required to gain enhanced mechanical properties in composite. Mixing of hard ceramics particles in Aluminum alloy was investigated in FSP studies [9-11]. These investigators reported the Al$_2$O$_3$, SiC particles clustering within matrix material. Small clusters of particles on micro level were observed in processed zone as shown in the ‘figure 5’. This indicates that the stirring action of the threaded cylindrical tool is not sufficient to break the particle clusters at micron level.
3.2. Microhardness

‘Figure 6’ shows the microhardness distribution across the AA1050-B₄C surface composite. The microhardness of the base metal was in the range of 25 VHN. The hardness in the surface composite was ranging from 40-50 VHN and average hardness was 45 VHN. Though there was slight variation in hardness observed along the surface composite layer, the average hardness has drastically improved. The incorporation of B₄C particles and grain size refinement due to FSP the hardness of base metal was drastically improved.

Increase in hardness can be justified by Orowan mechanism and grain strengthening [12-14]. In fact, presence of B₄C particles (according to Orowan mechanism) and grain boundaries (according to grain strengthening mechanism) work as barriers for dislocation movement. Hence, the presence of B₄C particles and reduction in grain size results increase in microhardness of fabricated surface composite.

3.3. Wear resistance

‘Figure 7’ illustrates the variation of coefficient of friction (COF) versus sliding time for 50 m sliding distance for base metal AA1050 and fabricated AA1050-B₄C surface composite. This figure shows that FSPed sample has less friction coefficient than base metal. The results revealed that average value
of coefficient of friction for base metal AA1050 and AA1050-B$_4$C surface composite are 0.79 and 0.71 respectively. It is evident from figure 7, there are some changes in the COF because of periodical accumulation as well as elimination of wear debris on the tested worn surface and continuous banding structure in FSP tool traverse direction[15-16].

![Figure 7](image7.jpg)

**Figure 7.** Variation of coefficient of friction for base metal AA1050 and FSPed AA1050/B$_4$C surface composite.

‘Figure 8’ illustrates the wear rate for both specimens under 10 N load for 50 m sliding distance. Wear rate observed in base metal AA1050 and FSPed AA 1050/B$_4$C are 2.2 and 1.4 mg, respectively. Surface composite samples showed less wear rate than base metal sample.

![Figure 8](image8.jpg)

**Figure 8.** Wear rate for base metal AA1050 and FSPed AA 1050/B$_4$C surface composite samples for 50 m sliding distance.

In fact, addition of B$_4$C particles results in the decrease in the weight loss of AA 1050/ B$_4$C based surface composite. Presence of B$_4$C particles increases strength and hardness of the base metal, which reduces the plastic deformation of material during movement of counter surface. It has been experimentally proved that hardness of any material can be correlated with its wear resistance.
AA1050/ B₄C surface composite has more hardness than base metal AA 1050 and thus shows less wear rate. It is evident from the results that distribution of B₄C in AA1050 improved the tribological behavior of material. ‘Figure 9’ shows the worn track of both specimens. ‘Figure 9’ clearly indicates that base metal specimen is more prone to wear and observed with wider and deeper groove than surface composite specimens.

![Figure 9](image)

(a) Worn track of base metal AA1050  
(b) Worn track of FSPed AA1050/B₄C surface composite

**Figure 9.** Macrograph of worn surface of BM and Surface Composite.

4. Conclusion
Fabricated AA 1050/ B₄C based surface composite by FSP technique. Investigated the mechanical and tribological characteristics of the developed surface composite and compared with unprocessed alloy. Following conclusions were derived from this study:

1. AA 1050-B₄C surface composite was successfully fabricated by FSP with simple threaded cylindrical pin tool.
2. Uniform distribution of B₄C particles was observed with significant microstructural refinement. However, particles clustering and particle free zones were observed in the stir zone.
3. Higher microhardness of 40-50 HV was observed in AA 1050/ B₄C surface composite as compared to that of unreinforced AA 1050 (25 HV) base metal, which is attributed to the higher wear resistant.
4. Wear resistance of the fabricated surface composite was improved in comparison to that of the base metal. Friction coefficient and weight loss of AA 1050/ B₄C based surface composite were less in comparison to the unreinforced AA1050 base metal. This is attributed to the enhanced hardness of the surface composite (AA 1050/B₄C).

5. References

[1] Han Y et al. 2018 *Appl. Surf. Sci.* **431** 48-54
[2] Zhu J, Ma Z, Gao L, Liu Y and Wang F 2016 *Mater. Des.* **111** 192-97.
[3] Mishra S and Yadava V 2015 *Opt. Lasers. Eng.* **73** 89-122.
[4] Hong L and Vilar R M 1997 *J. Mater. Sci.* **32** 5545-50.
[5] Ma Z Y 2008 *Met. Mater. Trans. A* **69** 642-58.
[6] Mishra R S and Ma Z Y 2005 *Mater. Sci. Eng. R* **50** 1-78.
[7] Mishra R S, Ma Z Y and Charit I 2003 *Mater. Sci. Eng. A* **341** 307-10.
[8] Akramifard H R, Shamanian M, Sabbaghi M and Esmailzadeh M 2014 *Mater. Des.* **54** 838-44.
[9] Marzoli L M, Strombeck A V, Santos J F D, Gambaro C and Volpone L M 2006 *Compos.Sci. Technol.* **66** 363-71
[10] Ceschini L, Boromei I, Minak G, Morri A and Tarterini F 2007 Compos. Sci. Technol. 67 605-15
[11] Nami H, Adgi H, Sharifitabar M and Shamabadi H 2010 Mater. Des. 32 976-83.
[12] Devaraju A, Kumar A and Kotiveerachari B 2013 Trans. Nonferrous. Met. Soc. China. 23 1275-80
[13] Sabbaghian M, Shamanian M and Esmailzadeh M. 2014 Ceram. Int. 40 12969-76
[14] Salehi M, Farnoush H and Aghazadeh M 2014 J. Mater. Des. 63 419-26
[15] Zahmatkesh B, Enayati M H and Karimzadeh F2010 Mater. Des. 31 4891-96
[16] Anvari S R, Karimzadeh F and Enayati M H 2013 Wear 304 144-51