Enhancement of wear and ballistic resistance of armour grade AA7075 aluminium alloy using friction stir processing

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Abstract

Industrial applications of aluminium and its alloys are restricted because of their poor tribological properties. Thermal spraying, laser surfacing, electron beam welding are the most widely used techniques to alter the surface morphology of base metal. Preliminary studies reveal that the coating and layering of aluminium alloys with ceramic particles enhance the ballistic resistance. Furthermore, among aluminium alloys, 7075 aluminium alloy exhibits high strength which can be compared to that of steels and has profound applications in the designing of lightweight fortification structures and integrated protection systems. Having limitations such as poor bond integrity, formation of detrimental phases and interfacial reaction between reinforcement and substrate using fusion route to deposit hard particles paves the way to adopt friction stir processing for fabricating surface composites using different sizes of boron carbide particles as reinforcement on armour grade 7075 aluminium alloy as matrix in the present investigation. Wear and ballistic tests were carried out to assess the performance of friction stir processed AA7075 alloy. Significant improvement in wear resistance of friction stir processed surface composites is attributed to the change in wear mechanism from abrasion to adhesion. It has also been observed that the surface metal matrix composites have shown better ballistic resistance compared to the substrate AA7075 alloy. Addition of solid lubricant MoS2 has reduced the depth of penetration of the projectile to half that of base metal AA7075 alloy. For the first time, the friction stir processing technique was successfully used to improve the wear and ballistic resistances of armour grade high strength AA7075 alloy.

Keywords: Armour grade aluminium alloy; Friction stir processing; Boron carbide; Molybdenum disulphide; Wear; Ballistic resistance

1. Introduction

Steel is globally accepted as primarily used material for the construction of military and non-military vehicles. It is attributed to the features associated with steel, such as high energy absorbing properties, high strength, greater notch toughness and high hardness [1–3]. Selection of suitable armour materials for defence applications is very crucial with respect to increasing mobility of the systems as well as maintaining safety. Therefore, determining the material with the lowest possible areal density that resists the predefined threat successfully is required in armour design studies. A number of various material systems can be considered in this perspective, especially substituting the steels with light metal and alloys [4]. The aluminium and its alloys have profound application in the design due to their of lightweight fortification structures and integrated protection system low density, high specific strength, high specific energy absorption capability, good corrosion resistance, good thermal conductivity, less sensitivity to adiabatic shear banding and thermoplastic
Backman et al. [6] and Corbett et al. [7] revealed that aluminium and its alloys possess Young's modulus, strength and ductility, lower melting point and less sensitivity to strain rate fords it's usage as armour material. Multi-layering of target or spaced structures, in extruded products or in combination with other materials, is effective measures towards improving the penetration resistance. It can be inferred that an effective combination of surface hardness to blunt or deform the projectile and subsequent dissipation of kinetic energy by supporting tough layer is primary requisite for an armour material [8–11]. Discontinuously reinforced metal matrix composites are typically a two-component system consisting of a dispersed ceramic phase in a metallic matrix, which exhibits desirable mechanical properties, including high specific stiffness, high plastic flow strength, good thermal expansion, thermal stability, creep resistance, and good oxidation and corrosion resistances, suitable for automobile, aerospace, and defence industries [12]. Earlier investigations on incorporating the sandwich of hard facing alloy and depositing a soft buttering layer in between base metal (Austenitic stainless steel) improved the ballistic immunity of steel armour welds by hindering the affect of hydrogen induced cracking (HIC) and heat affected zone (HAZ) softening introduced during weld thermal cycle used in combat vehicle construction [13–19]. Coating metallic substrates with carbides is an effective solution in prolonging the service life of a metallic component in abrasive or erosive environments. The mechanical performance of carbide coating strongly depends on the degree of dissolution of carbide in the matrix and the type of reaction layer [20]. Extensive work has been carried out for production of protective coating of silicon carbide (SiC) and tungsten carbide (WC) using surface modification techniques such as high energy laser melt treatment, high energy electron beam irradiation and plasma transferred arc process. Among these techniques, laser melt treatment is the widely used surface modification process. During this process, laser melts the surface of substrate along with the deposited material which is usually either carbide powder (SiC, or WC) or combination of carbide powders and a binding material (Co, Al, or Ni) [21–30]. In aforesaid techniques (liquid phase processing or fusion route), it is difficult to avoid the interfacial reaction between reinforcement and metal matrix, and the undesirable and detrimental phases may form at the surface. It also leads to defects such as pores, pin holes, shrinkage cavities, segregation, and grain coarsening [31]. Hence those cited problems can be addressed by adopting such a technique which is based on solid state. A technique that is receiving renewed attention and development all over the world is friction stir processing, which is a solid state process. Surface composite fabricated by incorporating nano sized alumina into AA6082 aluminium alloy revealed the existence of defect free interface and the perfect bonding between surface composite and substrate. It was also found that the wear rate is reduced to one third of that of as received AA 6082 [32]. Silicon carbide reinforced AA 2024 alloy composite has been introduced onto the surface of A356 Al–Si alloy using friction stir processing. The obtained surface composite exhibited excellent wear resistance and metallurgical bonding with the substrate [33]. Wear characteristics of surface hybrid composites processed through friction stir processing revealed the significant improvement in wear resistance compared to that of substrate [34,35]. Keeping the afore mentioned in view, the present investigation assumes significance as studies on enhancement of wear and ballistic resistances by using friction stir processing, which have not been reported on this class of armour grade AA 7075 aluminium alloy.

2. Material and methods

Base metal AA7075-T6 aluminium alloy (substrate) of size 500 × 500 × 40 mm was used in the present investigation and its chemical composition is given in Table 1.

The surface of substrate was subjected to a depth of 3 mm using friction stir processing with a specially designed friction stir welding machine (make — ETA Technology, Bangalore, India). It was done with the help of two hot working tools made of high carbon steel (H13). The first tool, a straight cylindrical friction stir tool, having shoulder Ø 20 mm without pin was employed to compact the powder in the previously drilled holes on the substrate surface and to avoid scattering of the boron carbide particles during FSP. The second tool, a straight cylindrical friction stir tool (3 mm in pin length, Ø 6 mm in pin diameter, Ø 20 mm in shoulder diameter), was inserted into already processed surface, i.e., first step of friction stir processing of flat cylindrical surface. Tool rotational speed of 960 rpm, transitional speed of 50 mm/min, and plunging speed of 30 mm/min were employed.

A section cut from unprocessed and friction stir processed alloys, i.e., surface composites were prepared for microstructural examination. The polished surfaces were etched with Keller's reagent. Microstructural examination was carried out using optical microscope. The friction stir processed material was subjected to micro hardness testing employing Vickers indentation at 0.3 kgf load. The pin specimens (in the form of cylinders of Ø 4 mm and 25 mm in length) were subjected to dry slide wear test using Ducom pin-on-disc wear tester. The counterpart disc was made of hardened alloy steel with surface hardness of 65Rc. The applied load was 0.5Kgf and the sliding speed was kept constant at 640 rpm. The total sliding distance for the test was 6 km. Surface composites (targets) produced by incorporating different sizes of boron carbide particles using friction stir processing for ballistic testing are shown in Fig. 1.

Ballistic testing of friction stir processed plates was carried out as per the military standard (JIS.0108.01). The experimental setup is given in Fig. 2. The target plates were tested with 7.62 mm lead projectiles located at 10 m from the

Table 1
Nominal composition of AA7075 alloy.

<table>
<thead>
<tr>
<th>Element</th>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Cr</th>
<th>Mn</th>
<th>Ti</th>
<th>Si</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight/%</td>
<td>5.6</td>
<td>2.5</td>
<td>1.6</td>
<td>0.23</td>
<td>0.3</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>rest</td>
</tr>
</tbody>
</table>
projectile exit region. The striking velocity of the projectile was measured using infrared light emitting diode photovoltaic cells by measuring the time interval between the interceptions caused by the projectile running across two transverse beams being spaced apart from one another at a fixed distance. The probes were placed at 6 m and 8 m from the nozzle of the gun barrel, respectively. The first probe activates the timer and the second probe de-activates it. Few numbers of preliminary experiments were performed and the adjustments were made to obtain the required impact velocity of the projectile onto the target. The velocity of projectile was measured to be $830 \pm 10$ m/s.

3. Results and discussion

3.1. Microstructure

Base metal AA7075-T6 plate exhibits elongated matrix grain morphology (pan-caked grains) along the rolling direction as evident from optical micrograph shown in Fig. 3.

Optical micrograph of friction stir processed AA7075 alloy with boron carbide is shown in Fig. 4(a) and (b). From the microstructure it can be observed that there is a fine scale microstructural region in which the second phase particles are uniformly distributed in the matrix. After FSP, the boron carbide particles are dispersed homogenously within the stir zone and lead to the formation of defect free and adherent $\text{B}_4\text{C}$ particles in substrate. The average size of the boron carbide particles in the stir zone is estimated significantly to be smaller than that in the as received powder. Grain refinement in the stirred region is due to dynamic recrystallization during friction stir processing. Presence of uniformly distributed $\text{B}_4\text{C}$ particles in the composite layer leads to severe grain refinement. Besides, the grain refinement in stirred region can be attributed to restricted grain growth as result of grain boundary pinning by the $\text{B}_4\text{C}$ particles.

The depth of processed zone was observed to be around 3 mm, which is almost close to pin height, and the FSP zone exhibits thorough material mixing and a more uniform distribution of intermetallic particles as compared to base metal AA7075 alloy. Fig. 4(b) shows the interface between the boron carbide particles and the substrate without any defect. It needs to mention that the interface between the ceramic particles ($\text{B}_4\text{C}$) and matrix plays a crucial role in determining the properties of the friction stir processed composite layer.

3.2. Hardness testing

The hardness data of base metal and friction stir processed alloy under different conditions is presented in Fig. 5. There is no significant improvement in the hardness of the friction stir processed alloy without carbide powders as compared to base metal. But a considerable improvement in the hardness of friction stir processed alloy with boron carbide powders was observed. Irrespective of carbide particles, the grains undergo mechanical rupture of inherent grain boundaries due to stirring action during friction stir processing and results in result in the formation of high angle grain boundaries. These high angle grain boundaries will impede the free movement of dislocations and enhances the strength and hardness of surface composites.

Addition of carbide particles leads to inhomogeneous local deformation that assists the breakup of the grains. Increase in
hardness may be due to individual higher hardness of carbide particles and Orowan mechanism. This mechanism explains the interaction of the dislocations with the non-shearable carbide particles. Dislocations make loops and bypass the particles which act like barriers to the movement of dislocations. This leads to the increase in strength and hardness of the composite layer on the surface of the alloy. Grain boundary pinning by the carbide particles and associated dispersion hardening may also contribute to the improvement in the hardness of composite layer. It is evident from hardness test that there is threefold increase in the surface hardness of the AA 7075 alloy after friction surfacing with carbide powder with finer size of 30 μm. However, addition of solid lubricant molybdenum disulphide (MoS₂) to boron carbide has not resulted in significant improvement in surface hardness, which may be due to the softness of the MoS₂ powder.

3.3. Wear testing

Wear rates of the base metal and the friction stir processed alloy with surface composites under different conditions are shown in Fig. 6. This reveals that the wear resistance is significantly improved with incorporation of carbide particles reinforcement. The improvement in wear resistance of friction stir processed carbide composites could be explained by considering its wear mechanism different from that of the substrate. It is observed that the base metal AA7075 aluminium alloy exhibited higher wear rate while the friction stir processed surface composites experienced lower wear rate.

It can be mentioned that the presence of carbide particles in the matrix of AA7075 aluminium alloy decreases the direct load between matrix portion of specimen and counter disc. In fact, the load bearing capacity of the hard carbide particles decrease the direct load between the surface of wear specimen and counter face and reduces wear rate significantly. This is attributed to localized deformation and selective removal of materials from the softer matrix, occupying the intermediate position between the mating surface and disc which acts as lubricant. From the results of hardness and wear test, it is noted that, although the hardness of boron carbide surface composite layer was only improved by around 44% and 50 VHN in comparison with that of base metal, which was increased from 90 VHN in base metal AA7075 to 140 VHN in friction stir processed B₄C-160 μm (AA7075 aluminium alloy). The wear resistance of the same coating is significantly more than that of base metal.

A detailed study of the variation of the coefficient of friction and the SEM micrographs of the worn surface of samples were undertaken to understand the wear mechanism. At the beginning of the tests, the friction coefficient of AA7075 alloy increases to a peak value (initially at a very high rate), followed by a gradual steady state value as shown in Fig. 7.
The increased coefficient of friction is attributed to localizing adhering of the worn debris to the surface as reported in Refs. [36,37]. It is considered that the rupture of the welded micro-parts and the occupancy of the mating surface contributed to a gradual steady value of coefficient of friction with time [38]. From the variation of the coefficient of friction,
it may be concluded that the predominant wear initiation mechanism for AA7075 alloy is adhesive, which converts to abrasion at a later stage. Fig. 7 shows that the friction stir processed surface with boron carbide powders exhibits lower coefficient of friction compared to that of base metal.

With finer carbide powder particles, the coefficient of friction decreased significantly and the result is in good agreement with the observed hardness data of friction stir processed surface composites. Differences in the extent of localized plastic deformation at real contact areas may lead to the deficiencies in friction coefficient. The friction stir processed surface composites have exhibited lower friction as they are harder and undergo less plastic deformation \[39\]. Addition of solid lubricant has further decreased the friction coefficient and increased the wear resistance of AA7075 alloy significantly. This may be attributed to the possible formation of lubricant film on the deposited coating of boron carbide which reduces the tangential stresses on the surface and decrease the severity of asperity.

Fig. 10. (a) Base metal target (b) Friction stir processed AA 7075 alloy targets with B$_4$C powder 160 $\mu$m (c) 60 $\mu$m (d) 30 $\mu$m (e) 30$\mu$m + MoS$_2$. 
contact. The above results are consistent with the scanning electron micrographs of the worn tracks of AA7075 alloy. Fig. 8(a) shows the SEM micrographs of the worn tracks of AA7075 alloy. The abrasive component of the wear mechanism is evidenced by the ploughed grooves inside the wear tracks. Fig. 8(b) shows the worn tracks observed in the surface composites. Detailed examination of the wear tracks of friction stir processed surfaces revealed the features associated with adhesive and abrasive mechanisms. It is evident that the extent of adhesive and abrasive wears in friction stir processed AA7075 alloy decreased due to a comparatively lower coefficient of friction and higher hardness, respectively. Fig. 8(c) shows the typical SEM micrographs of the worn surface of the friction stir processed boron carbide composite produced by FSP. The worn surface appeared comparatively smooth and had some grooves on it. It is clear from Fig. 7 that the coefficient of friction of surface composites is fairly low. The low coefficient of friction indicates that the mechanism of wear is predominantly adhesive in nature due to the harder (steel disk) surface scratch on the softer (pin) surface.

3.4. Ballistic behaviour

Front end appearance of targets after ballistic testing is shown in Fig. 9. Ballistic testing with lead projectile has resulted in damage, in the form of a perforation hole with measurable depth of penetration, width and cracks around the hole. Cracks were generated due to transfer of high impact energy of projectile onto the surface which results in tangential shear stresses on the coating. The ballistic performance was characterized by the depth of penetration of the projectile in the target plate, width of hole and total crack length. The depth of penetration was measured by taking cross section of damaged targets.

After ballistic testing, the macrographs were recorded and are shown in Fig. 10. Width of the perforation hole and total crack length were measured for each target. Tested targets were cut and the macrographs of the cross sections were recorded and are shown in Fig. 11. Depth of penetration was measured and is presented in Table 2. It gives the comparative data of the ballistic testing of base metal and friction stir processed coating with boron carbide powder.

It can be seen from Table 2 that the friction stir processed AA7075 alloy plate is able to stop the projectile whereas the uncoated base metal is perforated completely. Depth of penetration of projectile into the boron carbide surfaced base metal decreased significantly with the decrease in particle size, and the observed result is in agreement with hardness data. Further, it can be noted that the addition of solid lubricant MoS2 decreased the depth of penetration of projectile and resulted in complete stopping of projectile in the thick target plate. Projectile can be seen clearly in the perforation shown in Fig. 10(e). Hence it can be concluded that friction surfacing can be successfully used to deposit hard boron carbide powder on the surface of armour grade AA7075 alloy. Thus the metal matrix surface composite layer improved the ballistic efficiency/performance of AA7075 alloy.

4. Conclusions

1) Friction stir processing of AA7075 aluminum alloy resulted in fine and uniform microstructure consisting of carbide particles in matrix.
2) The friction stir processing of AA7075 alloy with boron carbide powder significantly improved the wear resistance over that of the base metal. Particle size of boron carbide was found to affect the wear resistance of substrate, and the maximum wear resistance was achieved with particle size of 30 μm.
3) Addition of solid lubricant molybdenum disulphide into boron carbide has further improved the wear resistance of the alloy.

Table 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Width of hole/mm</th>
<th>Total crack length/mm</th>
<th>Depth of penetration/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>30</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>B1C-160 μm</td>
<td>9</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>B1C-60 μm</td>
<td>10</td>
<td>45</td>
<td>29</td>
</tr>
<tr>
<td>B1C-30 μm</td>
<td>8</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>B1C-30μm + MoS2</td>
<td>8</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>
4) Significant improvement in ballistic performance has achieved after friction stir processing of AA7075 alloy along with boron carbide particles and molybdenum disulphide. Observed result is attributed to the improvement of hardness and wear resistance, and very low friction coefficient.

5) For the first time, the present work demonstrated successfully that the friction stir processing route is an effective strategy for enhancement of ballistic performance of AA7075 aluminium alloy which finds wider range of defence applications.

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References

[38] Santella ML, Engstrom T, Storjohann D, Pan TY. Improvement in tribological properties of surface layer of an Al Alloy by friction stir processing. Scr Mater 2005;53:201.