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ENHANCEMENT OF TRIBOLOGICAL PERFORMANCE OF 6061 ALUMINUN ALLOY BY SECOND PHASE HARDENING VIA FRICTION STIR PROCESSING

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ABSTRACT

The properties of metallic alloys can be substantial modified by the addition of a second phase particles. This is especially noticeable when hard particles are incorporated in a relatively soft matrix, often resulting in improved mechanical and tribological performance. This paper presents the results of our study on mechanical and tribological performance enhancement of 6061 Aluminum alloys by incorporation of B_4C particle via Friction stir processing (FSP). Unidirectional ball on flat friction and wear tests were conducted with a base material, friction stir processed 6061-Al and 6061-Al doped with B_4C particles via FSP against 52100 bearing steel balls under dry sliding conditions. The incorporation of particles not only reduced friction by 30% but also reduced wear by 2 orders of magnitude compared to unprocessed base and FSP material without particles incorporation. FSP alone without particles addition did not have a significant effect on the tribological behavior of the tested aluminum alloy.

INTRODUCTION

Alloy 6061, one of the most versatile of the heat treatable aluminum alloys, is popular for its medium to high strength, good toughness and excellent corrosion resistance. Applications for the material range from transportation and machinery components to consumer durables. Percent weight composition of this alloy is: (0.4-0.8) Si, (0-0.7) Fe, (0.15-0.4) Cu, (0-0.15) Mn, (0.8-1.2) Mg, (0.04-0.35) Cr, (0-0.25) Zn and Al (remainder). Its microstructure consist of an Al matrix, with grain size of 50-200 μm and a magnesium rich second phase particles with grain size of 1-4 μm (Fig. 1a).

Friction stir processing (FSP), a variant of friction stir welding (FSW), is a new technique used to modify the microstructure of the surface layer of metallic materials [1, 2]. FSP uses a rotating and translating tool that imposes severe plastic deformation of the near surface material. The processed microstructure is usually more homogenous, defect free and refined grains, often resulting in enhanced surface properties such as ductility, fatigue life, and fracture toughness.

Al alloys may represent the largest application of FSW and FSP to date, because of its softness and ease of plasticity. It is precisely for this reason, that Al alloys are often further reinforced with second phase hard particles such as SiC, Al_2O_3, etc., to fabricate aluminum based metal matrix composites (e.g. Al-SiC, Al-Al_2O_3). Such composites have higher hardness, strength and perhaps wear resistance.

In terms of tribological application, the surface layer is the relevant region for performance. Because of its versatility, FSP has the potential to be used for producing a metal matrix composite by incorporating hard particles into the Al matrix. Such surface composite is expected to have higher hardness and strength, and maybe better tribological performance.

This study evaluates the incorporation of B_4C particles into the near surface region of Al 6061alloy. The impacts of particle incorporation on hardness, friction and wear behavior were assessed.

NOMENCLATURE

FSP, hard particles, second phase, Al alloy,

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EXPERIMETAL PROCCEDURE

Materials

B_4C particles (Fig. 1), with av. size of 10-0.2 µm were incorporated into Al 6061 alloy by FSP. The Al plates (4”x4”x1”) were modified by inserting groves (3mm x 3mm x 4”) as a reservoir for the B_4C particles. The material was processed at Friction Stir Link Inc. using a Tungsten alloy tool. Processing with done in a single pass and/or 2 passes with 50% overlap along grooves filled the reinforcing powder.

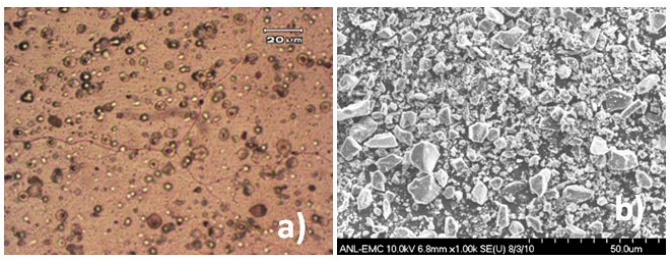

Fig. 1: a) optical image of base material with second phase particle, b) SEM micrograph of B_4C particles.

In order to compare the effect of particle incorporation and FSP processing alone on performance, another plate without particles was processed with the same parameters. The properties of both processed plates were compared to the base material.

Friction and Wear testing

Friction and wear tests were conducted with a ball-on-flat contact configuration under dry unidirectional sliding. 52100 hardened steel balls (ǿ 0.5”) and 35 nm Ra surface roughness were slid against the various Al alloy flat specimens: base material, FSP without particles and FSP with particles. Flat specimens were ground to same surface finished of (200 nm Sa.). All tests were run for an hour, at room temperature and with 2N load and linear speed of 1cm/s. Friction coefficient was continuously monitored during the duration of the test.

RESULTS AND DISCUSSIONS

In order to compare microstructural changes produced during the processing, metallographic sample of the cross-section areas for the base and FSP materials were prepared by standard techniques: mounting, polishing and etching in Keller’s reagent (1% HF, 1.5 % HCl, 2.5 % HNO_3, 95% water) to reveal grain boundaries. Fig. 2 shows the microstructure of surface layer for the base and processed material. Note that grain size is reduced during FSP by an order of magnitude (baseline grain size of 200-50 µm to FSP grain size of 5-10 µm).

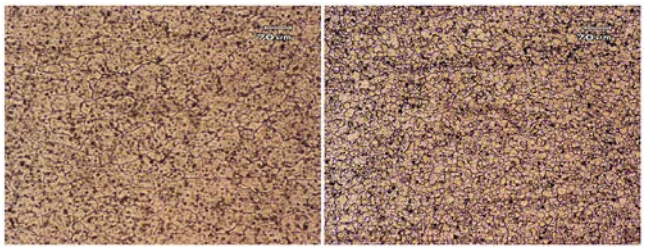

Fig. 2: optical image of base material (left) and FSP material (right) with significant grain refinement.

Particle incorporation was also evaluated using Scanning electron microscopy. Fig. 3 shows the top surface of the processed specimen after polishing to remove the residual grooves left behind by the processing. All range of particle sizes were effectively incorporated into the aluminum matrix. Grinding and polishing of the specimen caused removal of matrix material exposing the particles and making them sticking out of the surface (Fig.3b). Good bonding particle-matrix was observed for all particle sizes.

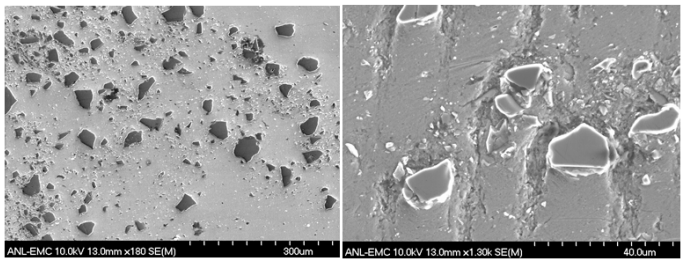

Fig. 3: SEM image of FSP material with B_4C particles incorporated. Good bonding matrix-particle was observed.

Micro-hardness measurements (using a Wilson Tukon Vicker indenter) were conducted for the 3 specimens. Hardness results indicated that grain refinement by FSP did not improve hardness as observed in other material [3]. A 10% hardness reduction in the FSP specimen was observed when compared to the base material. This may be attributed to dynamic recovery during friction stir processing. B_4C particle incorporation by FSP, on the other hand, increased the hardness by a factor 6 compared to the base and FSP material. This hardness increase for the composite surface layer is in good agreement with the rule of mixture analysis for a 5-6% of particle incorporation. Analysis of the different region of the Al-B_4C surface composite produced by FSP showed that particle incorporation can be up to 15% although the average was 5-10%.

Friction results

Variation of friction with time in test with the various Al alloy flat is shown Fig. 4. Friction coefficient for the base material is almost constant at about ~0.55 and noisy for the duration of the test. The friction coefficient for the FSP material with no particles started at a higher value (µ~0.9) but decreased to a near steady value of µ~0.65, exhibiting the highest and noisiest friction coefficient. The addition of B_4C

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particles by FSP not only reduced friction to the lowest level (μ~0.4) but also reduced the noise in the friction.

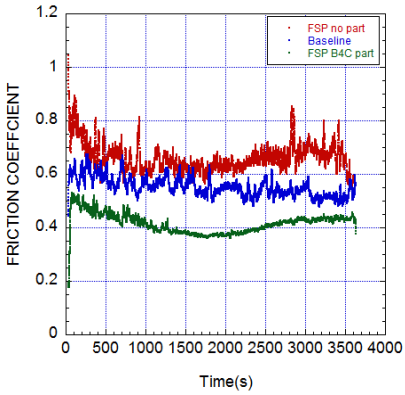

Fig. 4: Friction coefficient for the base material, FSP and FSP with incorporation of B_4C particles.

In many instances, friction behavior is indicative of the operating wear mechanisms. Optical micrographs of the wear tracks for the base material, FSP and FSP with B_4C particles incorporated are shown in Fig. 5. The wear mechanisms in the base material is mostly abrasion with periodic particles embedment, which accounts for noisy and high friction values as observed in the Fig 4. Similar wear mechanisms were observed in the FSP Al alloy material without particles. The reduction in hardness of this material compared to the baseline, can accounts for the higher and noisier frictional behavior as there is more abrasion and more particle embedment. The FSP Al Alloy with B_4C particles addition showed minimal abrasion compared to the other two specimens materials. The B_4C particles, which are standing out in the surface, provide load bearing capacity and thus less material is removed and the friction coefficient is minimal and less noisy.

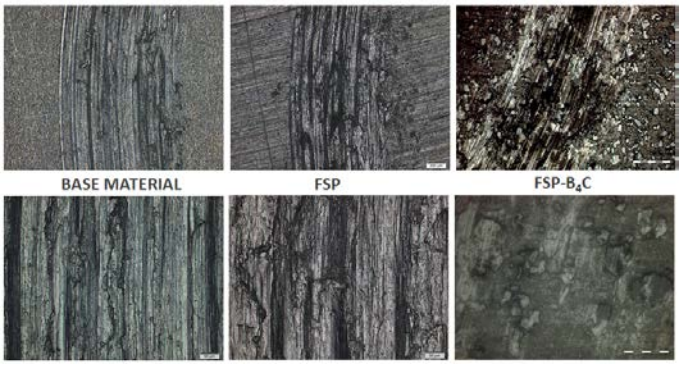

Fig. 5: Optical micrographs of the wear track for the base material, FSP and FSP with incorporation of B4C particles.

Wear Results

Wear results for the 3 material tested are summarized in Fig. 6. Due to the above mechanisms, wear in FSP-B_4C is around 2 orders of magnitude less than FSP alone, and 75 times less than the base material. The aluminum matrix – B_4C particle composite is a more wear resistant material due to the contribution of the hard particle as a load bearing capacity.

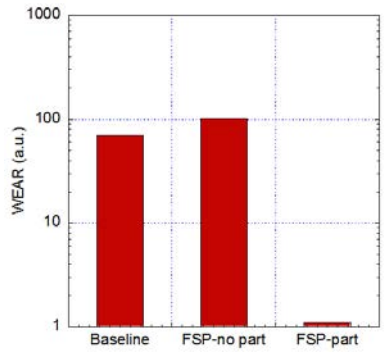

Fig. 6: Wear comparison for the base material, FSP and FSP with incorporation of B4C particles.

CONCLUSIONS

Friction stir processing was applied to 6061 Al alloy with and without B_4C particles. Up to 15% particle incorporation was achieved. FSP alone reduced the hardness of the material by 10% compared to the base material, while the addition of particles increased hardness by a factor 6.

Friction behavior of the base and FSP material are similar to one another when sliding against 52100 steel balls. Relatively high (μ~0.6), and noisy friction was observed for the duration of the test. This behavior is attributed to the operating wear mechanism, which consist of abrasion and periodic particle embedment. Friction in FSP with B_4C particles was lower (μ~0.4) and less noisy. This is due to B_4C particles sticking out of the surface and bearing the load.

In addition to friction reduction, B_4C particle incorporation by FSP reduced wear by more than 75 times compared to the base material and 2 order of magnitude compare to the FSP alone. Further work is needed to elucidate details of the mechanisms for tribological properties improvement and optimization.

ACKNOWLEDGMENTS

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