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Development of surface composite based on Al-Cu system by friction stir processing: Evaluation of microstructure, formation mechanism and wear behavior

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ABSTRACT

In this study, friction stir processing (FSP) was used to fabricate in-situ surface composite based on Al-Cu system on 1060 Al substrate. The effects of the number of FSP passes on phase compositions, microstructure and wear behavior of the resulting surface composites were investigated. The XRD analysis showed that with increasing the number of FSP passes, only Al_2Cu phase was formed, irrespective of FSP passes, and its amount increased. This was in a good agreement with the SEM and TEM results, which showed that during multi-pass FSP, there were two types of in-situ formed particles, including fine Al_2Cu particles and relatively coarse core-shell structured Cu-Al_2Cu particles, until most of core-shell structured Cu-Al_2Cu particles were converted into small Al_2Cu particles. Moreover, increasing FSP passes, with the opposite travelling direction of FSP tool between the consecutive passes, increased the area of the stir zone, decreased the particle size, improved the particle dispersion homogeneity, and favored the grain refinement. The formation mechanism of in-situ Al_2Cu/Al surface composite produced by multi-pass FSP was also clarified based on the thermodynamic and kinetic standpoints as well as the process characteristics of FSP. The FSPed AMC layers exhibited significantly improved hardness and wear resistance as compared with as-received Al (~24 HV), which were both improved with increasing FSP passes. The maximum microhardness was achieved in the 5-pass FSPed AMC layer, reaching a level as high as ~75 HV. Particularly, the wear mechanism was transformed from adhesive wear in the as-received Al to the combination of abrasive and delamination wear in 5-pass FSPed AMC layer.

1. Introduction

The outstanding properties of aluminum and its alloys, such as high specific strength, good stiffness and excellent formability, promote their extensive utilizations in aerospace, petrochemical, marine, automotive and many other fields [1]. However, both pure Al and Al alloys possess low hardness and poor wear resistance, which limit their potential applications [2–4]. Thus, the improvement in the hardness and wear resistance of Al alloys is considered to be a significant work to promote their further utilizations. Since the hardness and wear resistance are surface properties governed by the microstructure and composition of the near-surface region in the material, it will be sufficient just to modify the composition and microstructure of the surface without affecting the properties of bulk Al alloys. This will help to retain the ductility of the inner Al matrix and improve the wear resistance of the surface simultaneously.

Traditionally, the surface properties of Al alloys can be significantly improved by fabricating hard coating over the substrate using surface techniques like physical vapor deposition, hard anodizing and ion beam enhanced deposition [5–8]. Nevertheless, the prepared coating by these methods is too thin to sustain the applied high load since the thin film is easy to break with a deformation of Al alloy substrate. Moreover, these techniques are costly, time-consuming and not environmentally friendly due to their expensive consumables, long processing time and toxic emissions. Also, fabrication of aluminum matrix composite (AMC) layer reinforced with hard ceramic or intermetallic particle over Al substrate is another effective method to improve the surface properties of Al alloys. So far, various techniques, including laser cladding [2,4], plasma spraying [9] and micro-arc oxidation [10], have been used to fabricate surface AMC layer. However, the laser cladding for surface composite fabrication involves the metallic melting, which can easily cause several defects such as cracking, porosity, anisotropic and dendritic grain coarsening and the formation of some detrimental phases due to the interfacial reaction between reinforcement and metal matrix. When using spraying or micro-arc oxidation techniques, there is an obvious stratification between the surface composite layer and the

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substrate and the interfacial bonding strength is limited. In order to overcome the problems associated with these aforementioned techniques, more advanced technologies are still desirable.

Recently, a relatively new solid state surface modification technique, friction stir process (FSP), has been recognized and applied widely to material processing with aim to modify microstructures of the metallic surface [11]. Also, it has been demonstrated to be an effective method of introducing the reinforcements into metal matrix to fabricate surface/bulk metal matrix composites [12]. In the case, grooves and array of holes are machined on the surface of metal plates and packed with reinforcing particles. Then a non-consumable rotating tool with a pin and shoulder is plunged into the workpiece and traversed along the path of the grooves or holes. The frictional heat generated between the tool and the workpiece softens the materials around the tool and the combination of tool rotating and traversing induces significant material flow and thus results in sufficient mixing of the reinforcement and the matrix, finally forming composites. Based on the characteristics and rules of preparation of surface composite by FSP, the main advantages of preparing surface AMC layer by FSP are summarized as follows:

1) The whole preparation process is energy conservation, environmental protection and low cost;
2) Low processing temperature with short thermal cycle, below the melting point of Al alloys, can avoid many defects associated with metal melting and limit the interfacial reaction between reinforcement and Al matrix;
3) The thickness of the composite layer can be optionally adjusted by changing the designed length of FSP tool-pin under the premise of adopting appropriate introduction mode of reinforcing particles, which can reach a few millimeters;
4) No delamination, debonding and interlayer reaction between the upper AMC layer and beneath Al substrate occur because of the inherent material continuity during FSP.

In general, hard ceramic particles such as SiC [13,14] and Si_3N_4 [15], and carbon nanomaterials such as graphite [16] and CNT [17], as reinforcements are incorporated into Al alloy matrix to fabricate AMC by FSP. However, the AMC reinforced with these aforesaid reinforcements have a few drawbacks, such as great difference between the coefficient of thermal expansions (CTE) of Al matrix and these reinforcements and their high brittleness. Intermetallics have low density, high modulus and melting temperature [18]. Also, intermetallics have much closer CTE to Al matrix and are less brittle in comparison with the aforesaid reinforcements. Therefore, using intermetallics particle as reinforcements has been an attractive field of early developments [19]. Among the families of intermetallics, aluminum intermetallics are one of the most important materials with many attractive properties, such as excellent wear resistance, high hardness and stability at an elevated temperature. Consequently, they are expected to serve as the reinforcing phase in AMC.

Currently, there are two ways to prepare the aluminum intermetallics particle reinforced AMC by FSP: (a) ex-situ approach and (b) in-situ approach. The in-situ route has several advantages over the ex-situ approach. The AMC fabricated by in-situ approach have more homogenous microstructures and also are more stable thermodynamically. Especially, the interfacial reactions between reinforcements and Al matrix provide metallurgical bonding between them allowing load to transfer through reinforcements/matrix interface, which is supposed to be essential for obtaining excellent tribological properties [20]. Kao and co-workers have successfully used the indirect FSP method to obtain in situ AMC of Al-Al_2Cu [21], Al-$Al_{13}Fe_4$ [22] and Al-Al_3Ti [23]. For this purpose, relevant powders (Al with Cu or Fe or Ti) were mixed, hot pressed, and sintered to form a bulk billet. Then, FSP was applied to produce in situ intermetallic particulate reinforced AMC. In recent years, some studies [24,25] have reported the feasibility of direct FSP method to fabricate the AMC reinforced with in-situ intermetallic particles. Khodabakhshi et al. [24] created grooves on the surface of 5052 Al-Mg alloy matrix and embedded the Ti particles with an average particle diameter of 40 μm, and subsequently performed four passes of FSP. Their results showed that Ti reinforcements would react with Al substrate to form the Al_3Ti. Also, Khodabakhshi et al. [25] used the same method to fabricate hybrid intermetallics (Al_3Ti/MgO) reinforced surface composite based on the Al-Mg-TiO_2 system. This direct FSP method has some advantages over the indirect FSP. Through this technique, the need for consolidation and sintering steps before FSP is eliminated. This can be an important issue in the view of decreasing the energy consumption and also saving the time.

Copper is one of the ideal elements to be added to aluminum for in situ formation of the reinforcing phases because of its low cost and high wear resistance of the Al-Cu intermetallics. So far, few attempts have been made to fabricate Al-Cu intermetallics particle reinforced AMC by indirect or direct FSP method [21,26]. In these studies, only Al_2Cu was in situ formed whether by means of direct or indirect FSP method and the role of these in-situ formed Al_2Cu particles on the microstructural evolutions and mechanical properties was clarified. However, in these works [21,26], studies on the reason why only Al_2Cu was formed was not carried out. Also, there is limited information about the wear behavior of the AMC reinforced with in situ formed intermetallic particle based on Al-Cu alloy system at room temperatures. The main goals of this paper were to use the direct FSP method to fabricate surface AMC layer reinforced with in situ formed intermetallic particle based on Al-Cu alloy system on Al substrate and investigate the effect of the number of FSP passes on the phase compositions, microstructure, microhardness and wear behavior of the FSPed surface AMCs layer. In particular, the thermodynamic and kinetic of Al/Cu interfacial solid state reactions was discussed in detail.

2. Experimental procedure

2.1. Materials

In the present study, commercially available 1060-H14 pure aluminum plates and pure copper powder (99.0% purity) with the average particle size of 5 μm were used as the initial materials. The microstructures of the raw copper particles are provided in Fig. 1. As shown in Fig. 1, the raw copper particles are irregular in shape and show aggregated state before processing.

2.2. Fabrication of the surface composite layer

The presetting method of reinforced particles is a key controlling factor for obtaining composites with excellent properties. Now, the

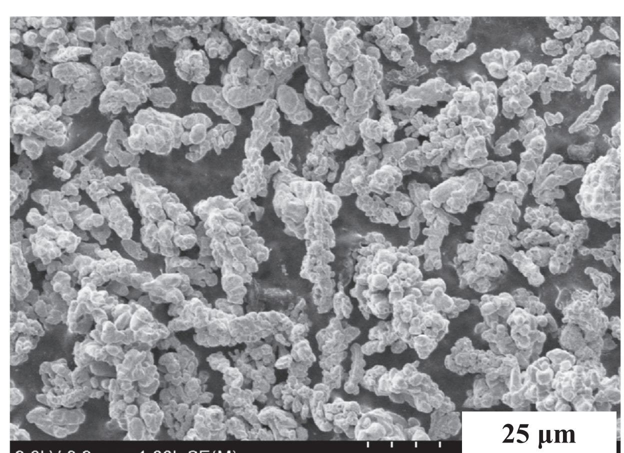

Fig. 1. Morphology of as-received Cu powders.