Faculty of Engineering - Papers (Archive)   Faculty of Engineering and Information Sciences

2010

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Effect of nano-sized particles on bond strength in accumulative roll bonding

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Abstract—**Effect of nano-particles on bond strength of aluminium alloy 5050 produced by ARB was investigated. Experimental results indicated that nano-particles can significantly enhance the bond strength of aluminium alloys. Several kinds of nano-particles with different particle size were compared. The hardness of the particles and the particle size are the two factors that decide the strengthening effect.The results showed that 50 nm Al_2O_3 particles have the best strengthening effect.**

Keywords-accumulative roll bonding; bond strength; nano-particles; strengthening mechanism

I. INTRODUCTION

Accumulative roll bonding (ARB) as a kind of severe plastic deformation (SPD) has been drawing much attention since it was first introduced by Saito et al [1]. As using the same equipment as conventional rolling, ARB is considered to be one of the most promising methods for manufacturing ultrafine grained (UFG) sheet materials [2-4]. During ARB, rolling is conducted on two layered sheets which have the exact same dimensions and have been stacked together beforehand. The rolling process not only provides large plastic deformation but also has an effect of bonding the two layers together. The bonded specimen of each cycle is conducted to cutting, surface degreasing, brushing, and stacking together for the next cycle [1-2, 5-6]. The multi-layered materials obtained from ARB are quite different from materials manufactured by other SPD methods such as equal channel angular pressing (ECAP) or high pressure torsion (HPT) as the materials after ARB are more like a layered composite [5,7,8]. Although it's very common for ARB-processed metals to obtain a grain size of several hundreds of nanometers and the enhanced strength by a factor of more than 2.5, the bond strength between two layers of the sheet has a crucial influence on the properties and applications of the ARBed materials [6, 9-11].

Conventionally, bond strength was enhanced through surface treatment of the materials before ARB [1-3]. The authors have proposed to use nano-sized SiO_2 particles in the ARB process to enhance the bond strength [12]. It has been found that the bond strength was significantly improved by using nano-sized SiO_2, compared to wire-brushing method. In the present work, several kinds of commercially available particles with different size, including 14 nm fumed silica, 50 nm aluminium oxide, 5 nm silicon carbide, 2 μm silicon carbide and 20–40 μm silicon carbide, have been compared in terms of enhancement of the bond strength.

II. EXPERIMENTAL MATERIALS AND PROCEDURES

The materials used in this work were aluminium alloy 5050. The samples were cut parallel to the original rolling direction, having the dimension of $2.4 \times 100 \times 250$ mm^3 (thickness×width×length). Prior to each rolling cycle, the roll was cleaned by acetone and the roll gap and speed were set to the required setting. Two pieces of the original samples were degreased by acetone and wire-brushed. The particles were uniformly spread between the two pieces. The samples were then stacked and heated in a furnace at 250 ºC for 5 min and then rolled with a nominal reduction of 50 % under dry condition. The rolled samples were cut into two halves and the edges were trimmed to avoid propagation of edge cracks. The above procedure proceeded for four cycles.
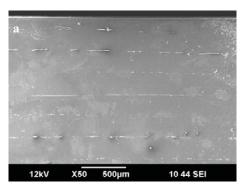
As the rolling cycle increases, the number of the interface increases. The authors' former research showed that the central interface which is the newly formed interface is the weakest among all the interfaces [12]. Therefore, we use the bond strength of the center interface to evaluate the bonding properties of the whole workpiece. A procedure proposed by Krallics and Lenard [10] were used to test the bond strength. A rectangular sheet was first machined from the ARBed materials. Two narrow slots were milled to the center interface along the thickness direction from opposite surfaces. Tensile tests were conducted to the specimen and the bond strength was calculated according to

$$\tau_B = F_B / (L_B \times W_B) \tag{1}$$

where F_B is the measured load and W_B is the sample width.

III. RESULTS AND DISCUSSION

Fig.1 showed the images of the cross-section of an eight layered 14 nm SiO_2 enhanced specimen. As can be seen from Fig.1 (a), the bonded interfaces between the sheets can be seen clearly. However, after magnification of the center interface,
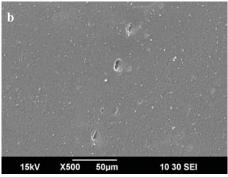
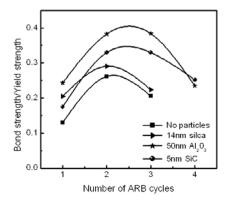Fig.1 Cross-section of an eight layered specimen, (a) Overall view, (b) Magnification of the center interface

Fig.2 Ratio of bond strength to yield strength of samples with different particles

Fig.3 Ratio of bond strength to yield strength of samples with different size SiC particles

only a few unbonded parts of interfaces can be seen in the specimen. The other parts exhibit very good bonding as if the specimen is one piece originally. This means that the roll-bonding was almost attained by ARB.

Fig.2 shows the ratios of bond strength to yield strength for three different types of nano-sized particles: 14 nm fumed silica, 50 nm aluminium oxide and 5 nm silicon carbide. The downward parabolic curves in Fig. 1 indicate that as the ARB cycle increases, the bond strength/yield strength ratio increases first, reaches the maximum values at the second or the third cycle, and then decreases. The magnitude of the bond strength tends to be stable after the second or third cycle. However, the yield strength still increased, resulting in the parabolic curves of the bond strength/yield strength ratio. It can be seen t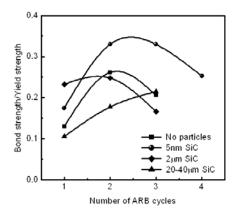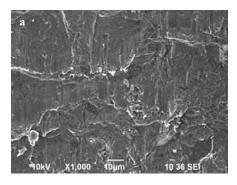hat the bond strength has been enhanced with the assistance of all three types of nano-sized particles. The 5 nm SiC particles exhibit higher bond strength/yield strength ratios than the 14 nm slica particles except for the first cycle. The 50 nm Al_2O_3 particles give the largest amount of enhancement in the bond strength of the materials except for the smaller value at the fourth cycle than SiC particles.

Fig.3 shows the effect of the particle size on the bond strength/yield strength ratios. SiC particles with three different sizes (5 nm, 2 μm and 20–40 μm) have been compared. As the particle size increase, the bond stringy/yield strength ratio roughly decreases with two exceptions (2 μm SiC sample after the first ARB cycle and 20–40 μm SiC sample after the third ARB cycle). It can be found that compared to the sample with no particles, the addition of nano-sized SiC particles enhances the bond strengths for all ARB cycles, while adding micro-sized particles results in lower bond strengths for most cases.

The nano-sized particles are thought to improve the bond strength by two mechanisms. First, when shear deformation is applied to the contact interface the nano-sized particles impede the movement of dislocations and lead to the pile-up of dislocations around the particles. This serves to locally harden the interface and enhance the bond strength. The nano-sized particles used at the interface play the same role as the second phase in composite materials, which induce the dispersion hardening. Second, since the particles are harder than the materials being bonded the particles can break the oxides layer that exists at the surfaces of the aluminium sheets to be roll bonded. Wire brushing has a similar effect, but time lag between wire brushing and roll bonding enables the oxide layer to re-form on the surface hence reduce the strengthening ability. However, the particles cause fresh surfaces to be exposed and, without sufficient time to re-form an oxide layer, the surfaces are bonded more effectively. The hardness of the particles and the particle size are the two factors that decide the strengthening effect. SiC is the hardest while SiO_2 is the softest among the three kinds of particles used in the experiment. SiO_2 has the weakest strengthening effect among the three particles, which is in agreement with the results in Fig.2. However, the bond strengths of samples strengthened by SiC particles are smaller than those strengthened by Al_2O_3 particles, which is because the particle size of SiC is too small for effective strengthening.
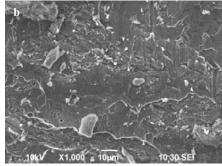
Fig.4 The shearing failure surfaces of two typical samples (a) with 50 nm Al_2O_3 particles (b) with 2 μm silicon carbide particles

Fig.4 shows the shear failure surfaces of 50 nm Al_2O_3 and 2 μm SiC strengthened samples after 3 ARB cycles. Scratches along the shearing direction can be seen in both figures. The particles acted as obstacles during shearing, and the scratches were left when the particles passed through sample interfaces. Fig.4 (a) exhibits the failure surface of the sample with addition of 50 nm Al_2O_3 particles. The scratches made by Al_2O_3 particles were evenly distributed in the interface, indicating that strengthening by nano-particles is effective, which is consistent with the curves shown in Fig.2. Fig.4 (b) shows the failure surface of the sample with 2 μm SiC particles. As can be seen from the figure, the scratches are distributed in some area of the figure, while the other areas shows shearing morphologies of metal materials or even no contact. It has been known that the interdiffusion between the particle and the interfaces occurs during the bonding process. If coarser particles are used, the micro-voids will be created on faster diffusing part and weaken the interfacial bond [13]. Therefore, the nano-sized particles allow two interfaces to come into intimate contact. In addition, the adhesion between the different types of particle and aluminium sheets may be different. This will also influence the bond strength. Molecular dynamics model is currently under development to investigate the adhesion phenomenon.

IV. SUMMARY

The bond strength of aluminium alloy 5050 after ARB was investigated through addition of several kinds of commercially available particles with different size. Adding nano-sized particles between aluminium layers enhances the bond strengths of materials after ARB process compared with those with no particles addition, while adding micro-sized particles results in lower bond strengths for most cases. The hardness of the particles and the particle size are the two factors that decide the strengthening effect. Adding 50 nm Al_2O_3 particles give the largest amount of enhancement in the bond strength in this experiment. The impeding effect of nano-sized particles for the movement of dislocations and fresh metal surface exposed after breaking the oxide layer are the major mechanism for the strengthening of bonding.

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