MODELING AND COMPARISON OF STRAIN BEHAVIOR DURING SYMMETRIC AND ASYMMETRIC ACCUMULATIVE ROLL BONDING OF ALUMINUM SHEETS

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Abstract

Accumulative roll bonding (ARB) is one of the severe plastic deformation methods of producing ultrafine grained laminated metal composites (LMCs). This paper is focused on LMCs consisting of dissimilar bimetal system of aluminum alloys AA1050/AA6061. One difficulty of roll bonding two dissimilar materials is obtaining of elevated strain at the interface of the composite in order to provide the ultrafine grain structure and superior bonding strength between the stacked layers. Compared to conventional ARB the asymmetric accumulative roll bonding is more appropriate for the production of dissimilar bimetal composites. This paper presents the results of the finite element simulation and comparison of strain behavior during symmetric and asymmetric accumulative roll bonding of AA1050/AA6061 bimetal composites at cryogenic temperature. Influence of rolls speed ratio (5…50 %) and contact friction coefficient (0.1…0.4) on strain distribution through composite thickness, especially on interface between the AA1050 and AA6061 layers, during asymmetric ARB were analysed by FEM in details.

Keywords: Finite element method, asymmetric accumulative roll bonding, cryogenic temperature, aluminum, bimetal composite

1. INTRODUCTION

Accumulative roll bonding (ARB) is a severe plastic deformation (SPD) process invented in order to fabricate ultrafine grained (UFG) metallic materials [1]. In the ARB process, 50 % rolled material is cut into two, stacked and then rolled again. By repeating this procedure, very high strain can be introduced into the material and as a result significant structural refinement can be achieved. In order to obtain one body solid material, the rolling in ARB is not only a deformation process but also a roll-bonding process. Large-scaled sheets with laminated structures, which are denoted as laminated metal composites (LMCs), can be realized by ARB process [2]. ARB technique can be applied to generate LMCs consisting of layers of the same one material or several dissimilar materials. Aluminum alloys are particularly suitable for the ARB process due to its high light-weight potential and good cold roll-bonding capability. Lately, more and more studies have been focused on UFG LMCs consisting of bimetal systems fabricated by ARB, such as AA6014/AA5754 [3], AA1050/AA6061 [4], AA1100/AA7075 [5], AA5005/AA6061 [6], AA2219/AA5086 [7]. Compared to conventional ARB the asymmetric accumulative roll bonding can be more appropriate for the production of dissimilar bimetal composites. The difficulty of roll bonding dissimilar materials is necking and finally rupturing of the harder layer with increasing ARB cycles caused by the difference in plastic flow behavior. The main disadvantage of ARB process is a low productivity because of a lot of cycles needed for achieving of certain amount of strain and high bond strength. Since accumulative or effective strain “e” plays a key role in grain misorientation, an increase e may accelerate the evolution toward an ultrafine microstructure subdivided by high angle boundaries (HABs). In other words, if a certain amount of strain is required for the formation of ultrafine grains surrounded by HABs, an increase in e might result in a decrease in the number of passes and hence in a higher productivity of ARB process. Moreover, the grain refining effectiveness of the ARB process would be higher with increasing e. Finally, increasing e leads to a superior bonding strength between the stacked layers. In order to obtain a higher accumulated strain, the ARB process should have an additive shear component. A small amount of shear strain is observed for conventionally rolled materials because of contact friction between sheet and rolls. However, during conventional ARB, shear strain is restricted only to the near surface region. Moreover, during conventional ARB the contact friction should be kept at a low level in order to prevent excessive rolling force. Elevated shear strain can be introduced into the material by asymmetric rolling in which the speeds of the top and bottom rolls are different [8-9]. Yu et al. [10] studied the bonding strength of ultrathin UFG bimetal foils produced using ARB followed by asymmetric rolling. The interface bonding strength was found to increase as the number of rolling passes increased. TEM inspection showed that the interface quality was the best when the roll speed ratio was 1.2. There were no noticeable residual voids at the interface of the AA1050/AA6061 bimetallic foils for this roll speed ratio; however, residual voids were observed when the roll speed ratio was 1.0 or 1.4. Combination of the ARB technique with asymmetric cryorolling and ageing was suggested in [11]. It was shown significant improvement in both the ductility and the strength of the processed AA6061 sheets in comparison with conventional ARB process. Investigation of asymmetric ARB of Al/Ti composite sheets was presented in [12]. Multi-layers of AA1050 and commercially-pure Ti sheets were alternatively stacked and rolled-bonded with varied roll diameter ratios ranging from 1 to 2, for up to four passes. Mechanical tests revealed that both tensile strength and ductility of the sheets increase systematically with applied asymmetry. It was shown that asymmetric ARB lead to a more refined grain size of the Al matrix and also it promotes the development of a nanostructured surface layer on Ti that comprised crystallites of 50-100 nm in size, which were otherwise absent in the case of symmetric ARB. The asymmetrically processed sheets exhibited a larger thickness of the interdiffusion layer at the Al/Ti interfaces than the counterparts processed via the symmetric ARB route, the difference being in excess of 15% [12]. As shown by the literature review some experimental investigations on the microstructural and mechanical properties evolution of bimetal system of aluminum alloys processed by asymmetric ARB, including combination with cryorolling, have been already done. However, no research on finite element simulation of asymmetric ARB at cryogenic temperature has been found. The goal of this paper is the finite element simulation and comparison of strain behavior during symmetric and asymmetric accumulative roll bonding of AA1050/AA6061 bimetal composites at cryogenic temperature.

2. RESEARCH METHOD

Simulations of the asymmetric ARB was carried out using the commercial FEM code DEFORM 2D. The geometry model and FE meshing of asymmetric ARB process are shown in **Figure 1**. Bimetal composite consisted of AA1050 and AA6061 with an initial thickness of 0.5 mm each layer. So the bimetal composite was 1.0 mm initial thick. Sticking boundary conditions, which prevented sliding or separation on interface between the AA1050 and AA6061 layers, were defined. Asymmetric ARB process was performed by a single pass with a thickness reduction of 50 %. So the final thickness of bimetal composite was 0.5 mm. The modeling of the process was performed at temperature of liquid nitrogen (77 K) without taking into account the increment of the metal’s temperature due to the thermal effect of deformation and friction. This assumption is applicable for conditions when the roll temperature is 77 K, and the rolling speed is very low, e.g., 1.0 rpm (≈1.0 m/min). The diameters of the rolls were 300 mm, and the rolls were considered as rigid. The bottom roll in contact with the AA6061 layer was rotated at the higher speed (1.0 rpm) in all calculation variants. Speed of the top roll in contact with the AA1050 layer was reduced by 5…50 % with step 5 %. A Coulomb friction model with constraint was used between rolls and strip in accordance with equation (1).

$$\tau = fp \leq k \tag{1}$$

where:

τ - frictional stress (MPa)

f - friction coefficient

p - contact pressure (MPa)

k - shear yield stress (MPa)

The number of initial brick elements was about 3000 for each layer of AA1050/AA6061 bimetal composite. Very small finite elements with thicknesses of 5 micron on top and bottom surfaces as well as on interface between the AA1050 and AA6061 layers were generated (**Figure 1**). AA1100 and AA6061 were chosen as hardened rigid-plastic materials. The stress-strain curves of the materials at the temperature 77 K are shown in **Figure 2**. The stress-strain curves for 77 K were approximated with using data from [13].

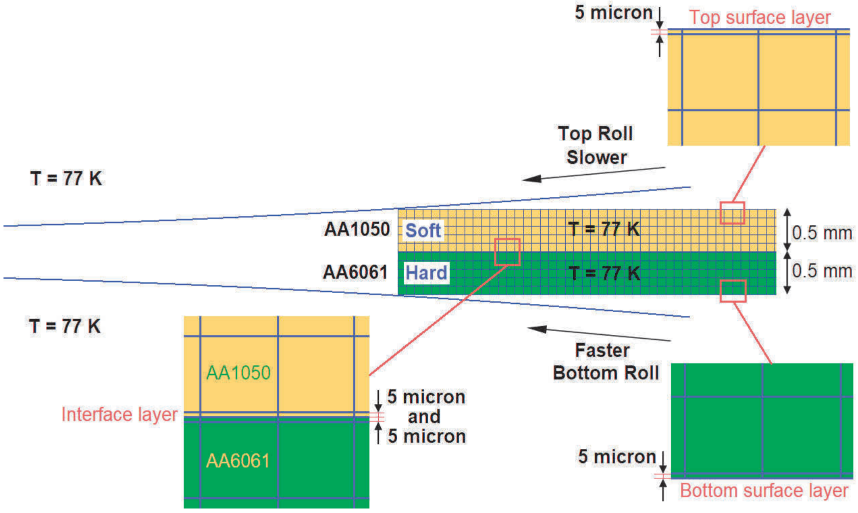

Figure 1 Geometry model and FE meshing of AA1050/AA6061 bimetal composite during asymmetric ARB

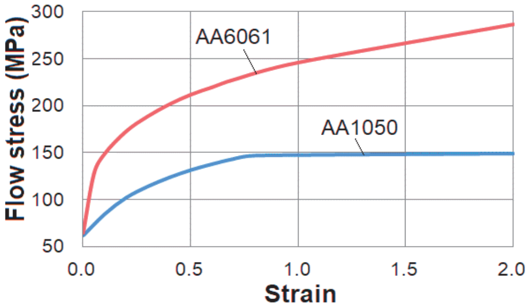

Figure 2 Stress-strain curves of aluminum alloys at 77 K

Influence of rolls speed ratio (5…50 %) and contact friction coefficient (0.1…0.4) on strain distribution through composite thickness, especially on interface between the AA1050 and AA6061 layers, during asymmetric ARB were analysed by FEM in the present study.

3. SIMULATION RESULTS AND DISCUSSION

The increasing friction coefficient from 0.1 to 0.4 leads to increasing of the strain from 0.9 to 1.7 on the top surface of AA1050 layer and from 0.8 to 1.6 on the bottom surface of AA6061 layer of the composite during conventional ARB (**Figure 3**). However, the strain at the interface is varied little (**Figure 4**). Strain in the soft layer (AA1050) was higher than that in the hard layer (AA6061). Mean strain e_m at the interface of thickness 10 micron was considered at the exit plane from deformation zone (**Figure 5**) in accordance with equation:

$$e_m = \left(\sum_{i=1}^{20} e_i / 20 \right) \tag{2}$$

where:

e_i - effective strain of point i (i = 1-20, see **Figure 5**)

Thereby the increasing friction coefficient during conventional ARB leads to serious increasing of the strain only at the top and bottom surfaces of the composite AA1050/6061, but the strain at the interface remains almost unchanged. Another situation occurs during asymmetric ARB with simultaneous increasing of the friction coefficient and the rolls speed ratio. The results of the numerical simulations have demonstrated that the right combination of friction coefficient and the optimal ratio of work roll speeds leads to very high mean strain at the interface (**Figure 6**), while the strain at the top and bottom surfaces of the composite remains almost unchanged. At low friction coefficient, e.g. f = 0.1, there is no effect of the rolls speed ratio on mean strain at the interface (**Figure 6**).

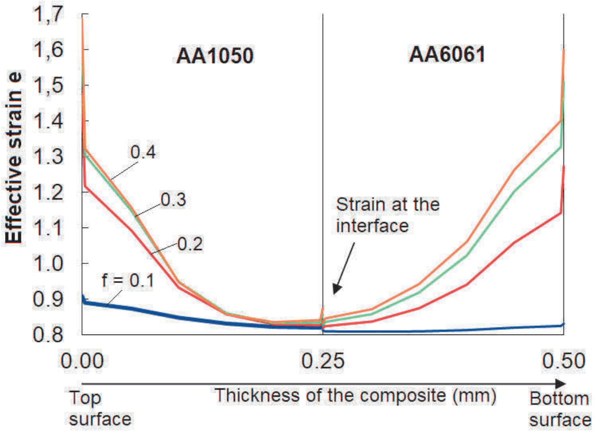

Figure 3 Influence of friction coefficient on strain distribution through thickness of the composite AA1050/6061 during conventional ARB

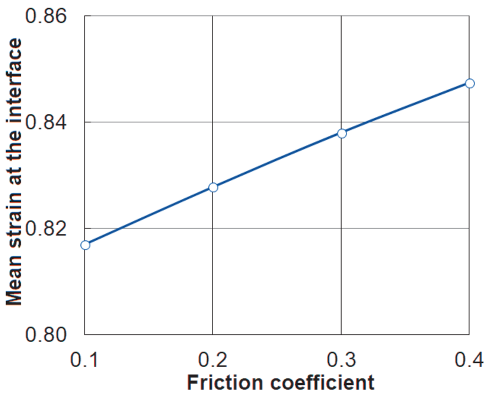

Figure 4 Influence of friction coefficient on mean strain at the interface of the composite AA1050/6061 during conventional ARB

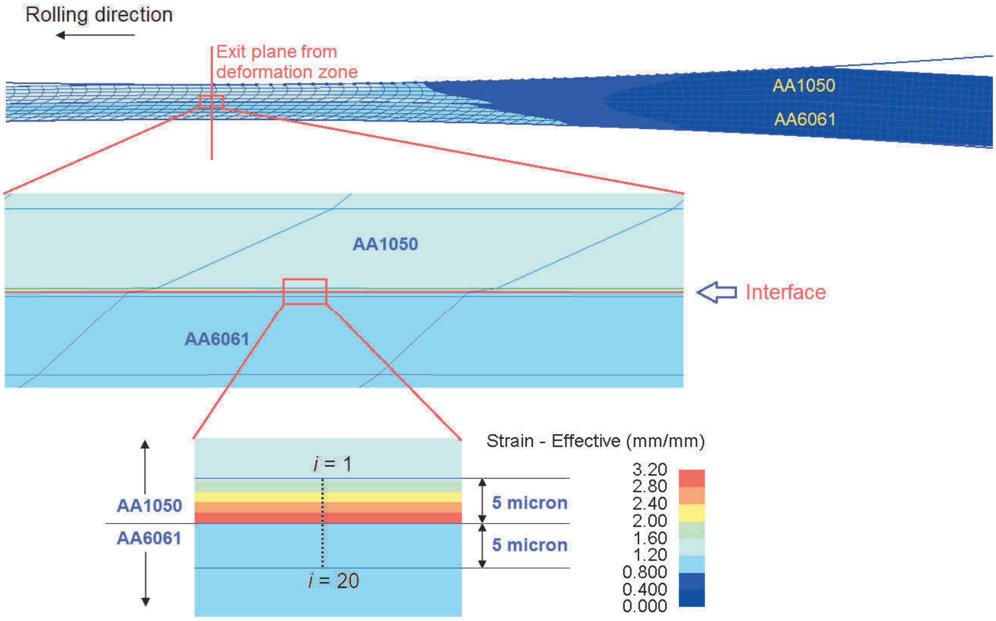

Figure 5 The field of effective strain and the selected points at the interface of the composite AA1050/6061 (asymmetric ARB, *f* = 0.3, ΔV = 20 %)

Increasing the contact friction leads to non-linear changing of the strain depending on the rolls speed ratio. At first the mean strain at the interface is increased to the maximum value with increasing of the roll speed ratio. However after reaching the optimal value the mean strain is sharply decreased (**Figure 6**). The optimal ratio of the work rolls speeds corresponds to some friction coefficient, which together can provide the maximum mean strain at the interface (**Figure 6**). Mean strain at the interface can be increased up to e_m = 10…11 when friction coefficient *f* = 0.4 and the rolls speed ratio ΔV = 40…45 %.

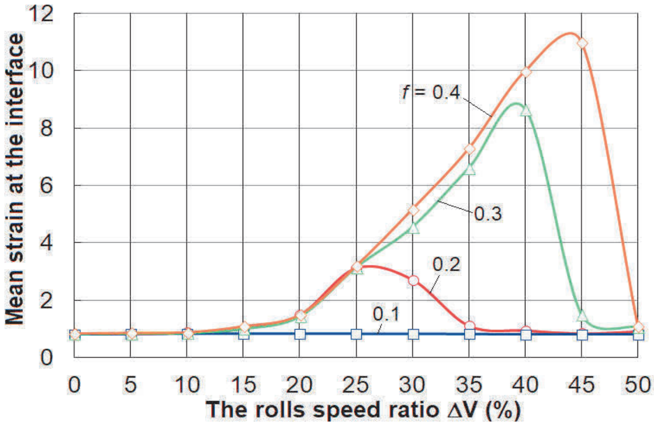

Figure 6 Influence of the rolls speed ratio and the friction coefficient on mean strain at the interface of the composite AA1050/6061 during asymmetric ARB

Detailed description of strain distribution through thickness of the composite AA1050/6061 during asymmetric ARB with different rolls speed ratios and high friction (*f* = 0.3) is shown in **Figure 7**. The increasing the rolls speed ratio from ΔV = 0 to ΔV = 40 % leads to decreasing of strains from e ≈ 1.6 to e ≈ 1.1 on the top surface of AA1050 layer (**Figure 7a**) and from e ≈ 1.5 to e ≈ 1.2 on the bottom surface of AA6061 layer (**Figure 7c**). At the same time the strain at the interface in soft material (AA1050) is extremely increased up to *e* ≈ 40 while the strain in hard material (AA6061) remains almost unchanged (**Figure 7b**). Since the strain at the interface can be seriously increased, than the ultrafine grain size and the superior bonding strength between the stacked layers are expected during asymmetric ARB.

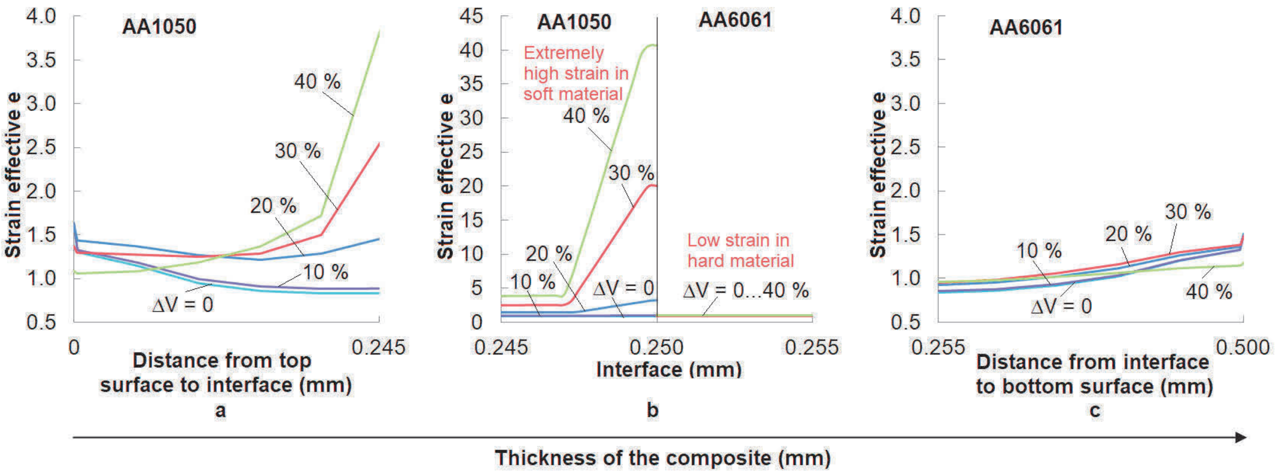

Figure 7 Influence of the rolls speed ratio ΔV (%) on strain distribution through thickness of the composite AA1050/6061 during asymmetric ARB (*f* = 0.3): a - layer of AA1050, b - interface, c - layer of AA6061

4. CONCLUSION

The increasing friction coefficient from 0.1 to 0.4 during conventional ARB leads to serious increasing of the strain only at the top and bottom surfaces of the composite AA1050/6061, but the strain at the interface remains almost unchanged. Elevated strain can be introduced at the interface of the composite AA1050/6061 by asymmetric ARB in which the speeds of the top and bottom rolls are different. It was numerically shown that the strain in soft material (AA1050) of the interface can be extremely increased up to $e \approx 40$ while the strain in hard material (AA6061) remains almost unchanged and is about $e \approx 0.8\ldots1.0$. Since the strain at the interface can be seriously increased, than the ultrafine grain size and the superior bonding strength between the stacked layers are expected during asymmetric ARB. Cryogenic conditions can be used for increasing ductility of the processed materials and for increasing grain refinement. The FEM results of investigation of the influence of the rolls speed ratio and friction conditions on strain distribution through composite thickness, especially on interface between the AA1050 and AA6061 layers, can be useful for the development of the improved ARB process of AA1050/AA6061 bimetal composites with UFG structure and high bond strength. Further experimental investigations are required.

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