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Investigation of bonding properties of Al/Cu bimetallic laminates fabricated by the asymmetric roll bonding techniques

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Abstract. In this study, 2-mm Al/Cu bimetallic laminates were produced using asymmetric roll bonding (RB) process. The asymmetric RB process was carried out with thickness reduction ratios of 10%, 20% and 30% and mismatch rolling speeds 1:1, 1:1.1 and 1:1.2, separately. For various experimental conditions, finite element simulation was used to model the deformation of bimetallic Al/Cu laminates. Specific attention was focused on the bonding strength and bonding quality of the interface between Al and Cu layers in the simulation and experiment. The optimization of mismatch rolling speed ratios was obtained for the improvement of the bond strength of bimetallic laminates during the asymmetric RB process. During the finite element simulation, the plastic strain of samples was found to reach the maximum value with a high quality bond for the samples produced with mismatch rolling speed 1:1.2. Moreover, the peeling surfaces of samples around the interface of laminates after the peeling test were studied to investigate the bonding quality by scanning electron microscopy.

Keywords: asymmetric roll bonding; bond strength; peeling test; bimetal laminates; finite element method

1. Introduction

Aluminum/copper (Al/Cu) bimetal laminates have been become increasingly popular for engineering applications since for cost reduction, combining the advantages of high specific conductivity and good resistance to corrosion. Especially, these bimetal laminates have high formability, electrical and thermal conductivity, making it a favorite material for specific application in automobile, military and electronic industry (Chang *et al*. 2009, Chen *et al*. 2006). There are several processes to fabricate bimetal clad sheets, including diffusion welding, explosive welding, roll bonding and friction stir welding (Saito *et al.* 1999). However, the roll bonding (RB) is more applicable and economical than other processes (Sedighi *et al*. 2016). Bonding is achieved when surface deformation breaks up the oxide layers and contamination layers and roll pressure causes the extrusion of virgin material through any cracks normal to the rolling direction (Reihanian *et al*. 2016). Many studies about asymmetrical rolling technique as a new noble process to fabricate bimetal laminates indicate that the cross shear deformation zone, caused by the displacement of neutral plane of upper and lower roll, provides a severe deformation for materials

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and lowers the power consumption. Also, asymmetrical roll bonding technique improves the bonding of dissimilar component metals, especially for which are difficult to deform (Yu *et al*. 2014). Saito *et al*. (1999) proposed the ARB process for the first time in 1999. Many research studies have been carried out to investigate the effective parameters to understand the behavior of the bonding mechanism. It has been reported that the roll bonding of metals is affected by various factors such as rolling thickness reduction (Heydari Vini *et al*. 2017a), bonding temperature (Yan *et al*. 2004), annealing treatment before and after the roll bonding (RB) process (Shabani *et al*. 2012), welding time, rolling direction, metal purity (Jamaati and Toroghinejad 2010), lattice structure, and the metal under investigation (Hsieh *et al*. 2007). To explain the bonding mechanism in the roll bonding process, four theories have been proposed i.e. the film theory, energy barrier theory, joint recrystallization theory and diffusion bonding theory. The film theory has been the major mechanism in the roll bonding process. Based on the film theory, during the rolling process, two opposing brittle surface layers break up coherently and the virgin material is extruded under the action of normal rolling pressure through widening cracks from both sides of strips (Heydari Vini *et al*. 2017b).

Some researchers have investigated the asymmetrical rolling process. For example Hwang *et al*. (1996) used mathematical and mechanical approaches to investigate the asymmetrical roll bonding process with different diameters rolls. Yu *et al*. (2014 and 2016) used asymmetric cryorolling to produce nanostructured aluminum alloys, and found that with increasing difference between the upper and lower roll speeds, the grain size undergoes refinement. There have been many finite element method investigations conducted based on the asymmetric rolling process. Reyds *et al*. (2003) used FEM to predict the outgoing curvature of bimetallic aluminum-copper sheets. Tadanobu *et al*. (2013) developed a finite element simulation for the accumulative roll bonding process. In his simulation which have been developed for three cycles of the ARB process, the effect of ARB cycles on the equivalent plastic strain of laminates have been investigated. However, the mechanism of improvement of interfacial bonding as well as the metal flow in deformation zone by asymmetrical roll bonding has not been apparent. In this study, we reported an investigation of the asymmetric roll bonding of bimetallic Al/Cu laminates. The mismatch ratio of lower to upper roll speed was quantitatively analyzed by the finite element (FEM) and experimental method. Also, the bond strength of Al/Cu bimetallic laminates produced by the RB process with various thickness reduction ratios and mismatch roll speed. Cross section and peeling surfaces of the peel test specimens were observed by scanning electron microscopy (SEM). The observations were used to improve the bond strength.

2. Materials and processing

2.1 Experimental investigations

The asymmetrical roll bonding technique is used to fabricate bimetallic Al/Cu laminates. Asymmetric RB process samples were sheets of annealed commercial aluminum alloys Al and Cu with initial dimensions of 100 × 30 × 1 mm where annealed preciously. The mismatch ratio of lower to upper roll speed controlled by the transmission gear unit was set to 1:1, 1:1.1and 1:1.2, while the speed of lower roll was constant as 36 rpm. There might be some greases, oxides, adsorbed ions and dust particles to exist on the metal surfaces. So, it is essential to remove contaminants from the surface of strips to be joined. Thus, the metal surfaces were degreased in

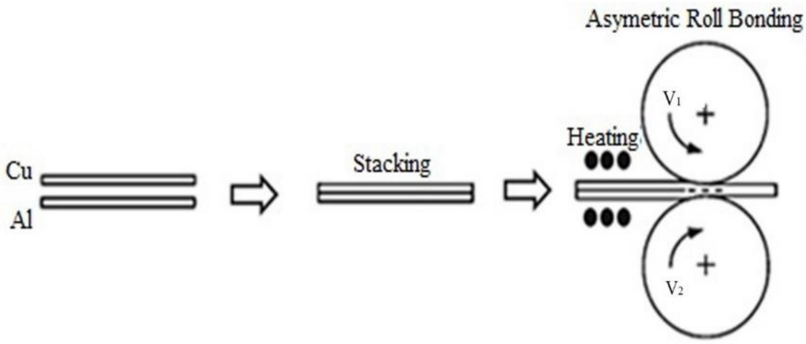

Fig. 1 Schematic diagram of asymmetrical RB process

acetone bath and scratch brushed with a 90 mm diameter stainless steel circumferential brush with 0.35 mm wire diameter and speed of 2500 rpm in order to remove the oxide layer on the surfaces of strips. One strip of Al and the other of Cu were stacked together to achieve 2 mm thickness. Then, according to Fig. 1, the stacked strips were fastened by steel wires at both ends and were roll-bonded with thickness ratios 10%, 20% and 30% at 300°C, respectively.

To set up the asymmetric RB process, the peeling test was performed using an Instron tensile testing machine with 100 kg load cell. The mean peeling force was measured by a clamping configuration shown in Fig. 2. The speed of the crosshead in the peeling test was 20 mm/min. The bond strength of Al and Cu bimetal laminates was measured using the peeling test according to ASTM-D903-93. In the peeling test, the average peel strength was taken as (Heydari Vini *et al.* 2017b),

$$Average\ peel\ strength = \frac{Average\ load}{Bond\ width}$$

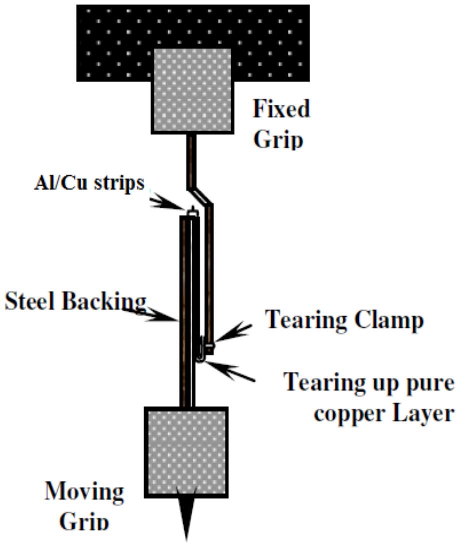

Fig. 2 Schematic illustration of the peeling test fixture

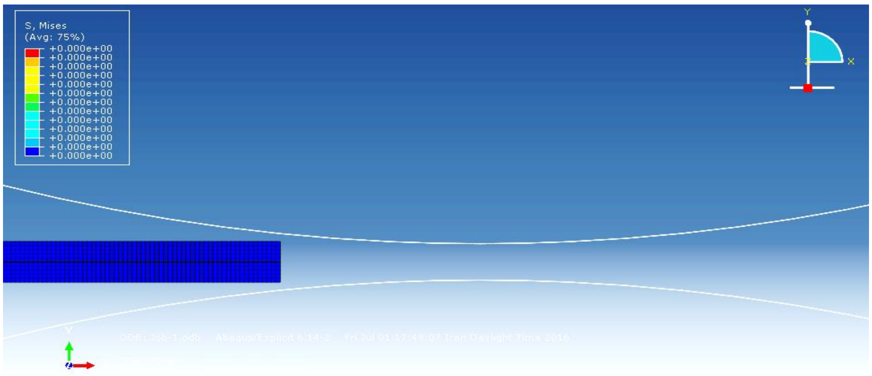

Fig. 3 Geometry and FE meshing of the asymmetric roll bonding process

Table 1 Physical and mechanical properties of Cu and Al strips

Elastic modulus(GPa)	Poisons ratio	Density (kg/m^3)	Strip
110	0.3	8900	Cu
70	0.3	2700	Al

2.2 Numerical simulation

The Roll Bonding (RB) technique was used to fabricate bimetallic laminates. Fig. 3 shows a schematic diagram of the asymmetric rolling process of Al/Cu bimetallic laminates. In Fig. 3, the horizontal and vertical directions are the longitudinal and normal directions. In the two dimensional FE model of RB process set up in ABAQUS software, the initial thickness of both layers (Al and Cu) was 1 mm. Dynamic explicit solver is used to solve the process and work rolls. The center of works rolls were regarded as a center for applying the boundary conditions. Also, as mentioned before in the experiments, the thickness reduction ratios chosen were 10%, 20% and 30% at 300°C with the roll speed ratios (mismatch ratios) 1: 1, 1: 1.1 and 1: 1.2, respectively. During the rolling process, the plastic deformation was regarded as plane strain condition and rolls were regarded as rigid and strips have been meshed with CPE4R elements (Heydari Vini *et al*. 2017a). The isotropic material model was used for modeling Al and Cu layers. During the rolling process, temperature change and sheet width spread were neglected. The geometric models were meshed with square elements and after doing the mesh sensivity analysis, the model contained 1200 elements. The FE meshing of bimetallic strips for the roll bonding process is shown in Fig. 3. As mentioned before in the experiment, the rolls rotated with a constant angular velocity 36 rpm in the rolling process. Then, Al/Cu strips entered the gap between the rolls with an initial velocity and exited under the action of frictional forces. The physical and mechanical properties of Cu and Al strips used in this study are presented in Table. 1.

3. Results and discussions

3.1 FE simulation results

Fig. 4 shows the asymmetrical roll bonding process of bimetal Al/Cu laminates. According to Fig. 4, due to the difference of the yield stress of Al and Cu strips, the rolling process is not

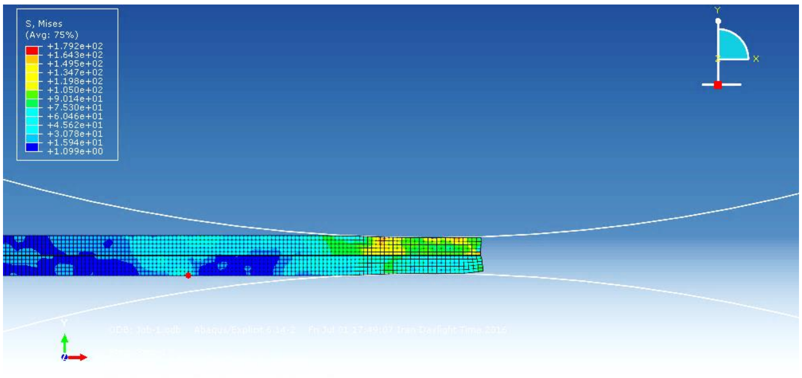

Fig. 4 Asymmetric rolling process of bimetal Al/Cu laminates

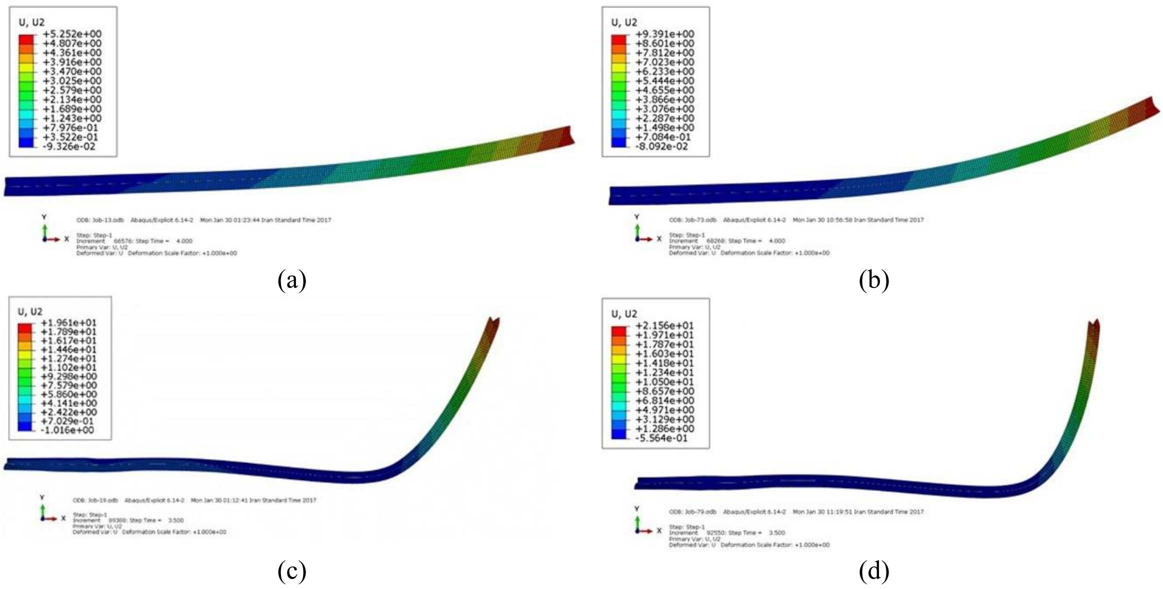

Fig. 5 Maximum vertical strain exerted on the bimetal strips with. (a, c) 1:1 and (b, d) 1:1.2

symmetrical along the thickness of strips due to the longitudinal direction. So, there is an asymmetrical stress distribution along the thickness length.

Figs. 5(a-d) show the vertical strain amount of Al/Cu strips after rolling with mismatch speed ratios1:1 and 1:1.2, for the reduction ratios of 10% and 30%, respectively. As can be seen in Fig. 5, increasing the mismatch speed ratios leads to increasing the radius of the final rolled bimetal curvature. When the roll speed ratio reaches up to 1.2, the curvature radius attains a maximum amount. Increasing the radius generates higher shear at the interface of Al/Cu strips.

Fig. 6 shows the maximum rolling pressure for the roll bonding process of bimetal Al/Cu laminates with 10%, 20% and 30% of reduction ratio and with different mismatch speed ratios. According to Fig. 6, by increasing the mismatch speed ratios, the forming stress increases lightly. According to Fig. 6, increasing the mismatch speed ratio leads to increasing the shear stress along the rolling length of contact which improves the normal rolling pressure.

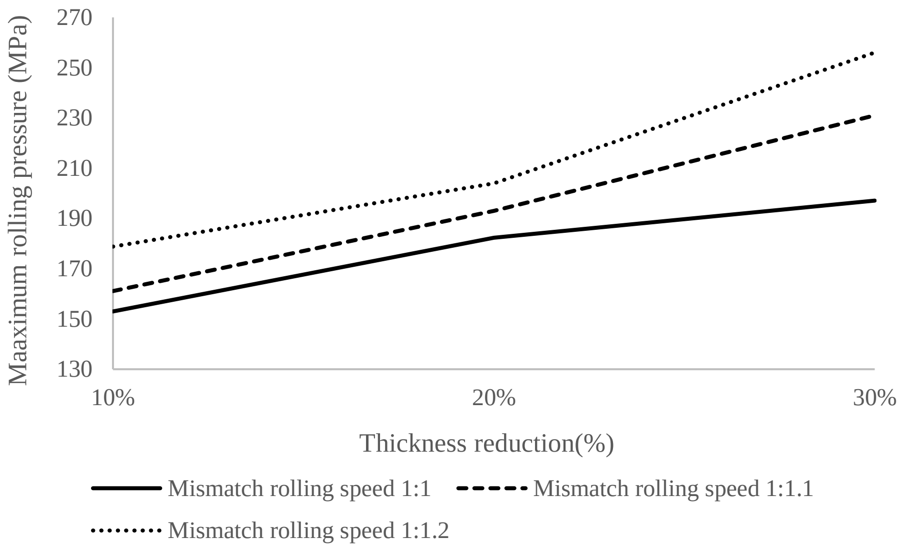

Fig. 6 Maximum stress exerted on the bimetal strips with different mismatch speed ratios

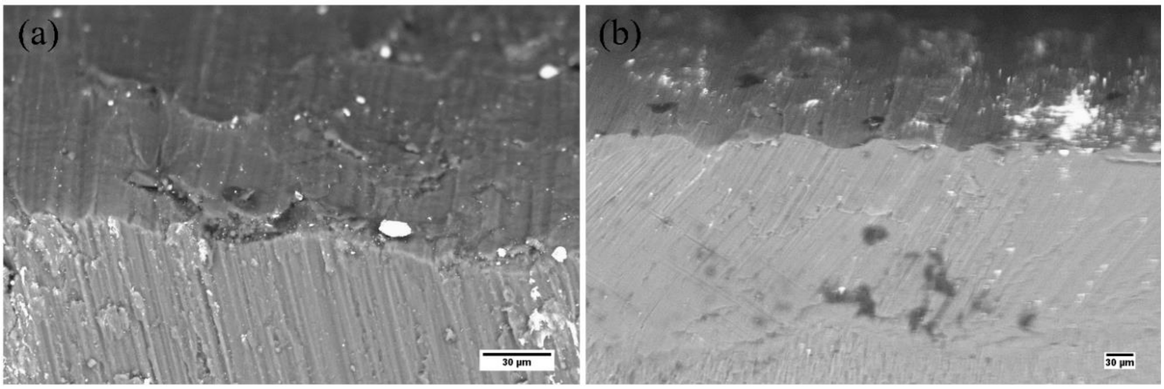

Fig. 7 SEM microstructure of as-rolled clad sheet with different mismatch speed ratios (a) 1:1 and (b) 1:1.2

3.2. Bonding interface

It is useful to investigate the interface of samples which was studied by SEM. Figs. 7(a, b) show the interface between Al and Cu with different mismatch speed ratios 1:1 and 1:1.2 with the thickness reduction ratios 30%. As can be seen in Fig. 7(a), by increasing the mismatch speed ratio, the interface gap becomes more and clear and the interface contains some residual voids.

Also, by increasing the mismatch speed ratio up to 1.2, the interface bond quality between Cu and Al component improves greatly. Thus, the interface gap vanishes and the microstructural analysis shows an apparent soundness (no pores or cracks). According to Fig. 7, the interfaces are all very thin (less than 1 μm) and are influenced by three parameters of roll bonding process, (I). Rolling thickness reduction ratio, (II). Roll bonding temperature and (III). Mismatch speed ratios. In fact, the higher mismatch speed ratios favor the bonding process enabling to achieve sound

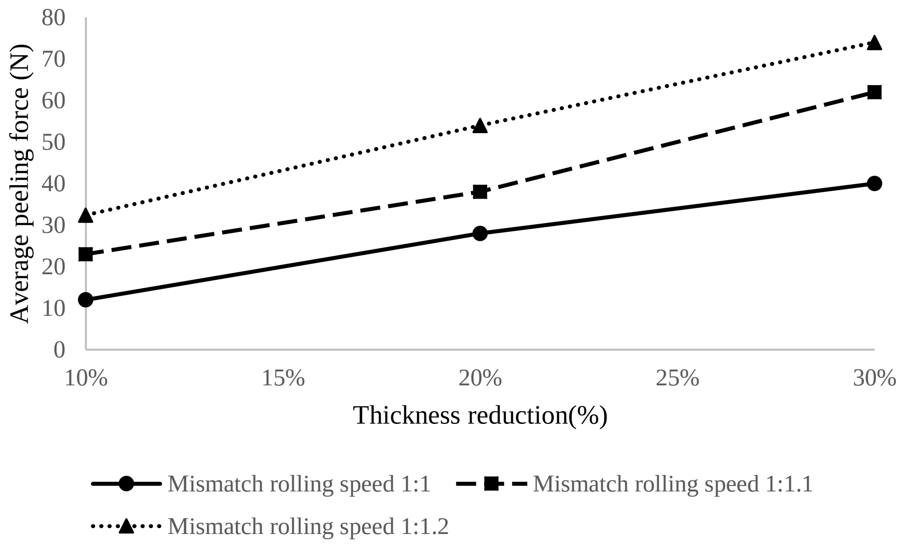

Fig. 8 Effect of mismatch speed ratio on the average peeling strength of samples

joints (Li *et al*. 2017). Also, the results are good consistent with the analysis of stress state of asymmetric RB shown in Fig. 5.

3.3. Effect of mismatch speed ratios on the peeling strength

Fig. 8 shows the breaking off forces of clad sheets in the peeling test. The larger mismatch speed ratio causes an improvement in the peeling force and hence the bond strength. Also, According to Figs. 5 and 6, FE simulation shows that by increasing the mismatch rolling speed ratio, the rolling pressure increases considerably. For example, the average peeling strength of Al/Cu samples improves from 12 N up to 32.4 N and 40 N up to 74 N for samples fabricated with mismatch rolling speed 1:1 and 1:1.2 and with 10% and 30% of thickness reduction ratio registering 170% and 85% improvement, respectively. As can be seen in Fig. 8, its improvement caused by the (I): enhancement of shear deformation at the interface of Al/Cu strips, (II): surface expansion of metals normal to the rolling direction and size of crack and finally (III): extrusion of the virgin metal (extrusion channel) during the asymmetrical roll bonding process.

3.4. Effect of mismatch speed ratios on the peeling surface

Fig. 9 shows the microstructure of peeled surface of asymmetric roll bonded Cu/Al clad sheet. According to Fig. 9, the size of extrusion of the base metal and consequently the bond strength improves with increasing the rolling mismatch speed ratios. As can be seen in Figs. 5 and 8, increasing the mismatch rolling speed ratio leads to increasing the plastic strain and the normal rolling pressure which generates higher surface expansion. Also, according to the film theory, higher surface expansion along the rolling direction leads to generation of more cracks on the metal surfaces which are the extrusion channels during the rolling process. Thus, a lot of underlying virgin metal is extruded by the rolling pressure and the number and area of bonding areas increase which are looking like isolated islands.

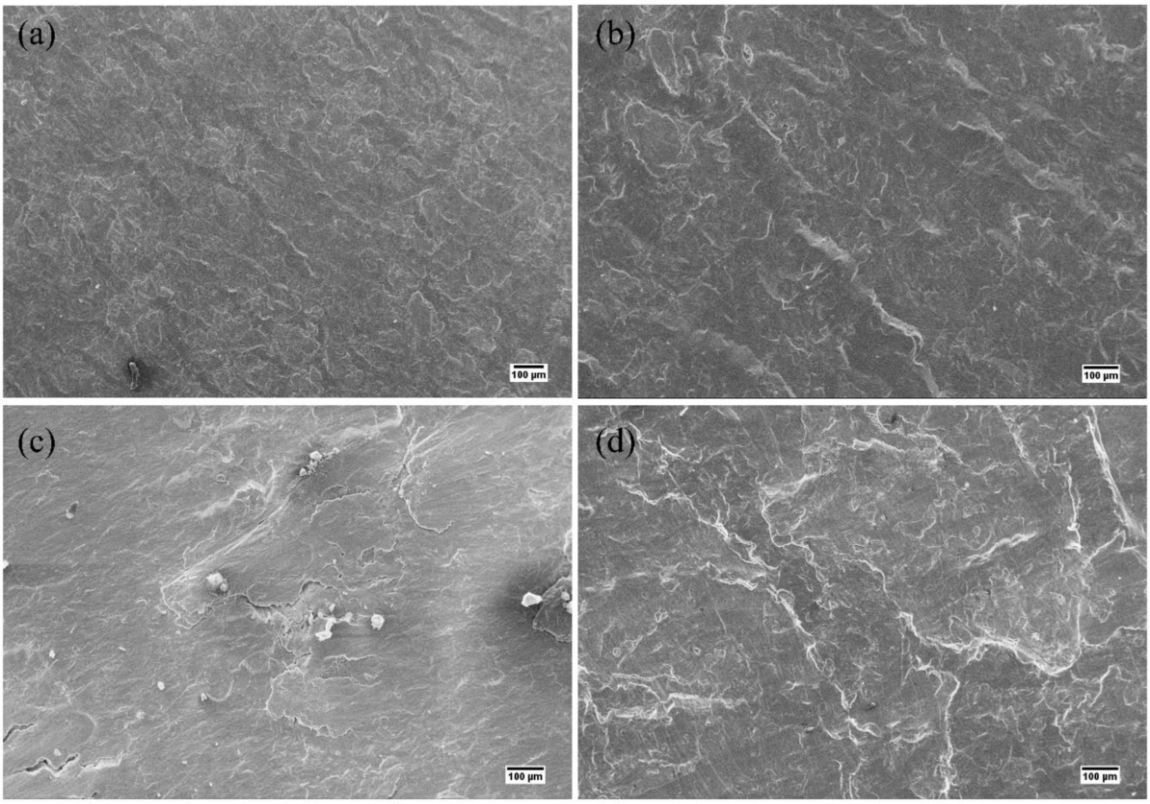

Fig. 9 SEM microstructure of peeled surface of samples with thickness reduction ratios (a, b) 10% and (c, d) 30%. Also, with different mismatch ratios as (a) 1:1, (b) 1:1.2, (c) 1:1 and (d) 1:1.2

4. Conclusion

In this study, the experimental investigation and finite element simulation of the asymmetric roll bonding process of bimetal Al/Cu laminates in ABAQUS software were successfully conducted. The following points can be concluded:

- The asymmetric bimetal Al/Cu roll bonding process is an asymmetrical process with asymmetrical stress distribution along the thickness of strips. This asymmetric stress distribution affects the final geometry of the rolled product.
- According to the stress state of deformation zone, asymmetrical roll bonding provides a remarkable cross shear strain and promotes the metal surfaces to deform and extend.
- A number of residual voids are seen at the interface of Al/Cu bimetallic laminates. With increasing the mismatch speed ratio from 1:1 up to 1:1.2, the interface bonds quality improves and has no visible cracks. So, number of bonding areas which are looks like isolated islands increases considerably.
- By increasing the mismatch speed ratio, the plastic strain at the interface increases. Increasing the plastic strain increases the rolling pressure and as a result the bonding quality improves.

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