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An Investigation on the Bond Strength of Aluminum Strips in the Presence of Brass Mesh after Cold Roll Bonding

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Abstract: In this study, the presence of brass mesh on the bond strength of aluminum (AA1050) strips in the cold roll bonding (CRB) process was investigated. The influence of various process parameters including reduction in thickness, pre-rolling annealing, initial thickness of the strips, and post-rolling annealing was also considered. After CRB process, peeling test was carried out and peeled surfaces were examined by optical and scanning electron microscopes (SEM). Energy dispersive spectroscopy (EDS) analysis also, revealed that there was neither diffusion zone, nor formation of intermetallic at the interface of aluminum and brass wires after annealing at 643 K. It was found out that, by increasing the amount of reduction and initial thickness, the bond strength of the layers was increased. Furthermore, pre-rolling and post-rolling annealing treatments at 643 K increased the bond strength.

Keywords: Bond strength, Cold roll bonding, Peeling test, Composite

1. Introduction

Aluminum-based metal matrix composites (AMMCs) are beginning to find increased applications in aerospace, marine, automobile, compressor, and turbine due to their light weight, high strength, stiffness, and resistance to high temperature [1]. There are different manufacturing processes to fabricate metal matrix composites (MMCs) materials such as powder metallurgy, spray deposition, casting, and cold roll bonding (CRB) [2]. CRB process, despite other mentioned processes offers no undesirable problems such as high temperature, formation of disadvantages component, defects and porosity. Moreover, CRB is a novel low temperature process for fabrication of multilayered composites [3], and is a type of pressure welding or solid state welding where bonding is established by joint plastic deformation of the metals [4]. Although different methods are used to manufacture these composites, CRB has proved to be more efficient and economical. Recently, multilayered structures have been fabricated successfully by CRB process including Al-St [5], Ag-Cu [6] and Al-Pt [7]. It has been reported that various factors as reduction of thickness, annealing treatment before and after the CRB process, rolling speed, rolling direction, and initial thickness of strips can affect the roll bonding of metals [8].

Among many parameters preparation of the metal surfaces is one of the most important factors governing bond formation [9]. The surface film theory [4], can truly describe the main mechanisms involved in joining the two strips at low temperature in CRB process. According to this theory, the brittle surface layers are fractured during rolling deformation. Then, virgin metals are exposed and extruded under the action of normal rolling pressure through expanded cracks in the surface layers from both sides of the interfaces [10-12]. In the recent decades, the tendency for producing composite with uniform distribution of reinforcement in the matrix has been increased. Uniform distribution of second phase in the matrix created the isotropy properties in the composites and caused increasing of composite application.

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There are different methods to produce composite with network structure. In some research [13, 14], fiber glass or polymer woven meshes in the aluminum matrix were used to produce network structure composite by autoclave process. In a new study, Tayyebi et al. [15] made an aluminum-stainless steel composite by accumulative roll bonding. They used stainless steel meshes as reinforcement in the composite.

In this study, CRB process was utilized to produce primary sandwich composite for ARB process. A review of literature on the subject shows that although CRB process has been carried out on many aluminum alloys, the formation and strength of bonds have not been sufficiently studied in composites produced by this technique. In this study, brass mesh was used as the network reinforcement between aluminum layers to fabricate composite with uniform distribution of second phase. The aim was to produce Al-brass composite with ARB process. Before ARB process, investigations of peeling parameters that affect the bond strength are necessary. Accordingly, in the present paper, some key parameters including initial thickness of strip, reduction in thickness, annealing treatment before and after CRB process are considered.

2. Materials and Experimental Procedures

2.1. Materials

Commercial purity aluminum (AA1050) and brass mesh with the specification given in Table 1. were used. Strips of dimensions 120 mm long, 30 mm wide, and 2 mm thick were cut parallel to the original rolling direction of the sheet. All strips were annealed at 643 K for 2 h followed by air cooling to room temperature. The brass mesh was made by wires 0.15 mm in diameter and 30 networks in each square inch. It should be noted that brass wires were woven and not welded at the intersections. As received sheets were used in order to investigate the effect of pre-rolling annealing, and then post-rolling annealing were performed in 643 K for 2 h.

Table 1. Chemical composition of aluminum strips and brass mesh (wt%).

Element	Al	Cu	Si	Fe	V	Ni	Zn
Al strips	99.5	0.01	0.051	0.136	0.022	0.23	0.008
Brass mesh	—	67.1	—	—	—	—	32.9

2.2. Surface preparation

In order to create bonding between two strips, it is necessary to remove contaminations like oxide scale, moisture, grease, and dust particles from the surface. Aluminum strips and brass mesh were degreased by acetone. Preparation process was continued by scratch brushing on the surfaces of the strips parallel to the rolling direction with stainless steel wires 0.23 mm in diameter. It has been observed that amount of scratching would affect the formation of brittle layers and thereby, the bond strength. After preparation of surfaces, rolling process must be carried out immediately after degreasing and scratch-brushing to avoid any re-oxidation of the surfaces [8].

2.3. Cold roll bonding and peeling test

After surface preparation, aluminum strips and brass mesh were fixed by steel wires at the edges and rolling process was performed. CRB process was carried out with no lubricant using a laboratory rolling mill with a loading capacity of 20 tons. The rollers had a diameter of 125 mm and the rolling speed was set at 2 m/min. Fig. 1a-c shows a schematic of CRB process of aluminum and brass mesh. Fig. 2 depicts the rolling direction-normal direction (RD-ND) cross section of CRBed sample after 60% reduction. Bond strength was measured by peeling test according to ASTM D1876-08, as shown schematically in Fig. 1d. The peeling test was performed using a Hounsfield H50KS tensile testing machine with a 50 kg load cell and a crosshead speed of 20 mm/min. In this test, breaking-off forces were measured as shown in Fig. 3 for the aluminum strips in presence of brass mesh, subjected to 70% reduction in thickness. After the peeling test, the bond strength was calculated by using following equation [4].

$$\text{Average peel strength} = \frac{\textbf{average load (N)}}{\textbf{bond width (mm)}} \tag{1}$$

In order to examine the surfaces of layers after peeling test, optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) analysis were used.

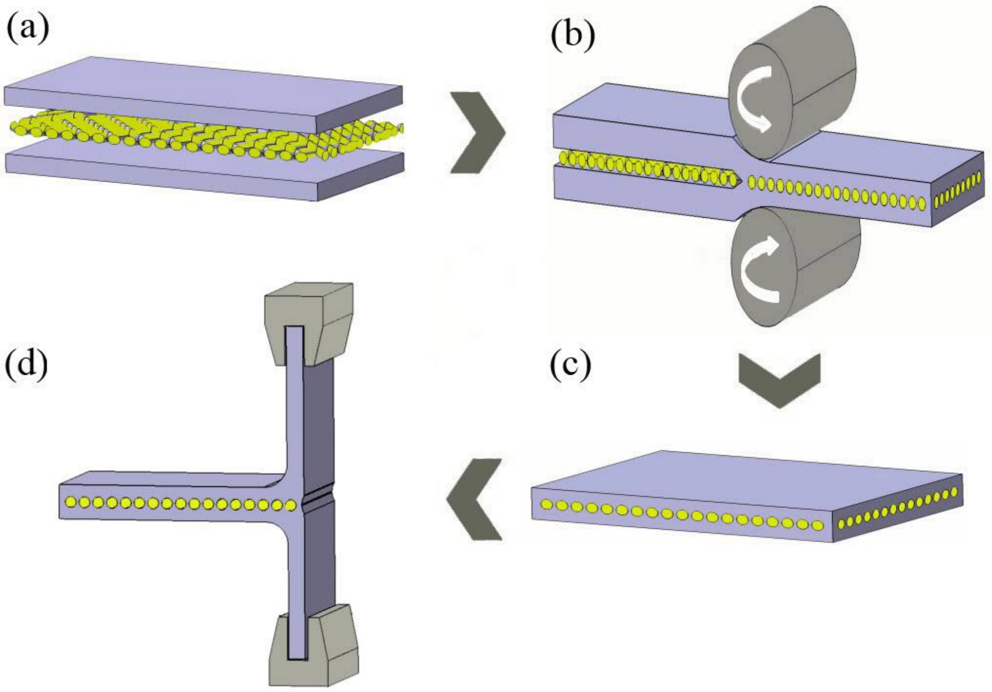


Fig. 1. Schematic of CRB process of aluminum and brass mesh (a-c) and peeling test (d).

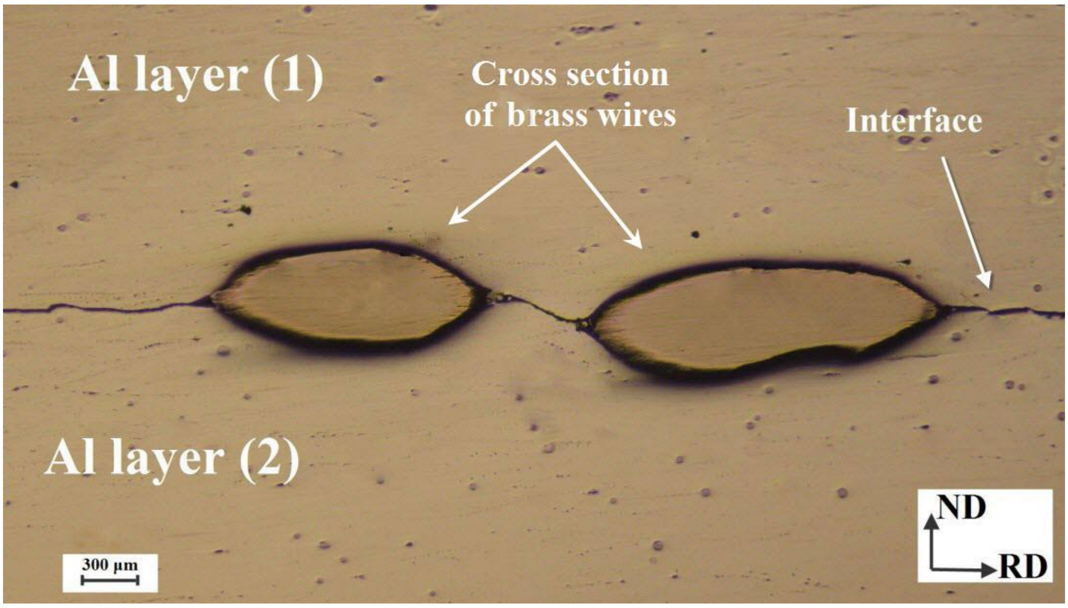


Fig. 2. Optical micrograph of RD-ND section of aluminum strips and brass mesh after CRB.

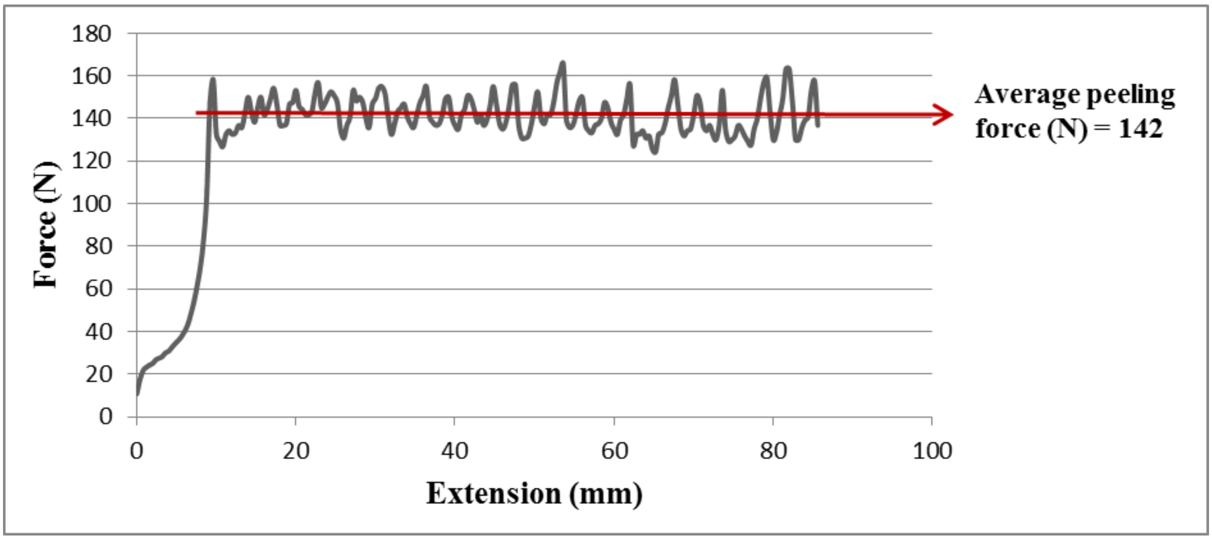


Fig. 3. Typical curve of peeling force versus peel distance after 70% reduction.

3. Results and Discussion

3.1. Effect of reduction

The results of peeling tests obtained for different reductions in Fig. 4 illustrate that there is no adequate bonding for reduction values less than 30%. The amount of threshold deformation required for bonding was about 40% and by increasing roller pressure or higher reduction, greater bond strength was obtained. In order to investigate the bonding in more details, peeled surfaces were examined by SEM. Figure 5 confirms that by increasing the reduction in thickness, the number and width of cracks (shown by black arrows) grow as well as the amount of extruded virgin metal thus, leading to stronger bonding. Some research [16-17] indicated that, by increasing the deformation, the number of cracks increased and therefore more virgin metal surfaces were exposed in contact surfaces. Wright et al. [18] also suggested that, during a rolling deformation, the cracks between the scratch brushed areas grew in size rather than in number. Comparison between Fig. 5b and c shows the intensifying number of cracks obviously and the comparison between Fig.5c and d shows that the grow in crack size is more significant rather than the number of cracks.

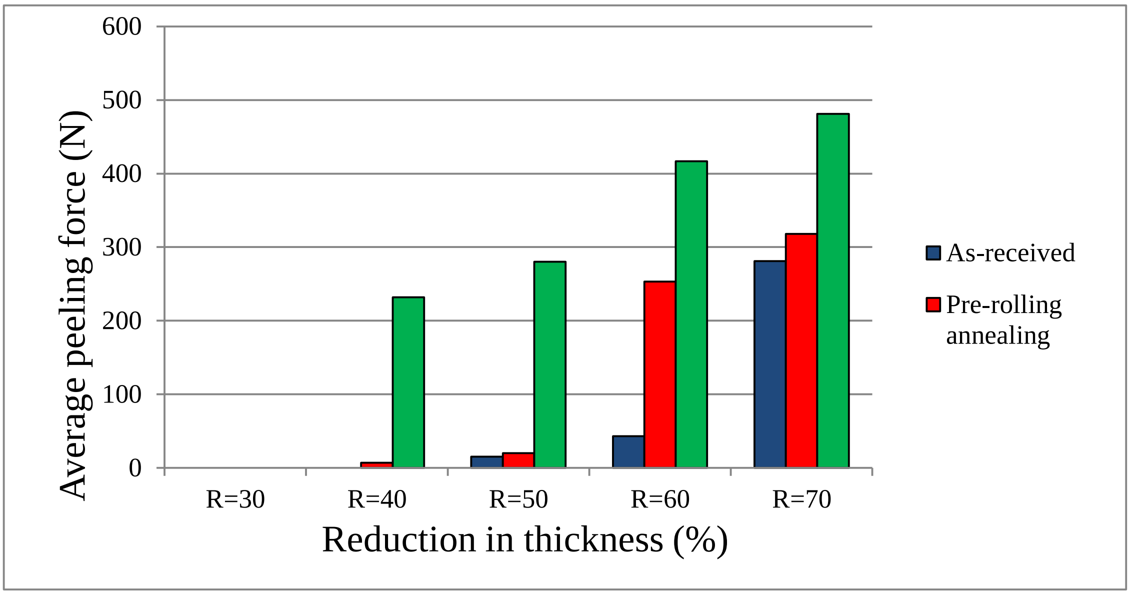


Fig. 4. Effect of annealing treatments and reduction on the bond strength of Al strips in presence of brass mesh.

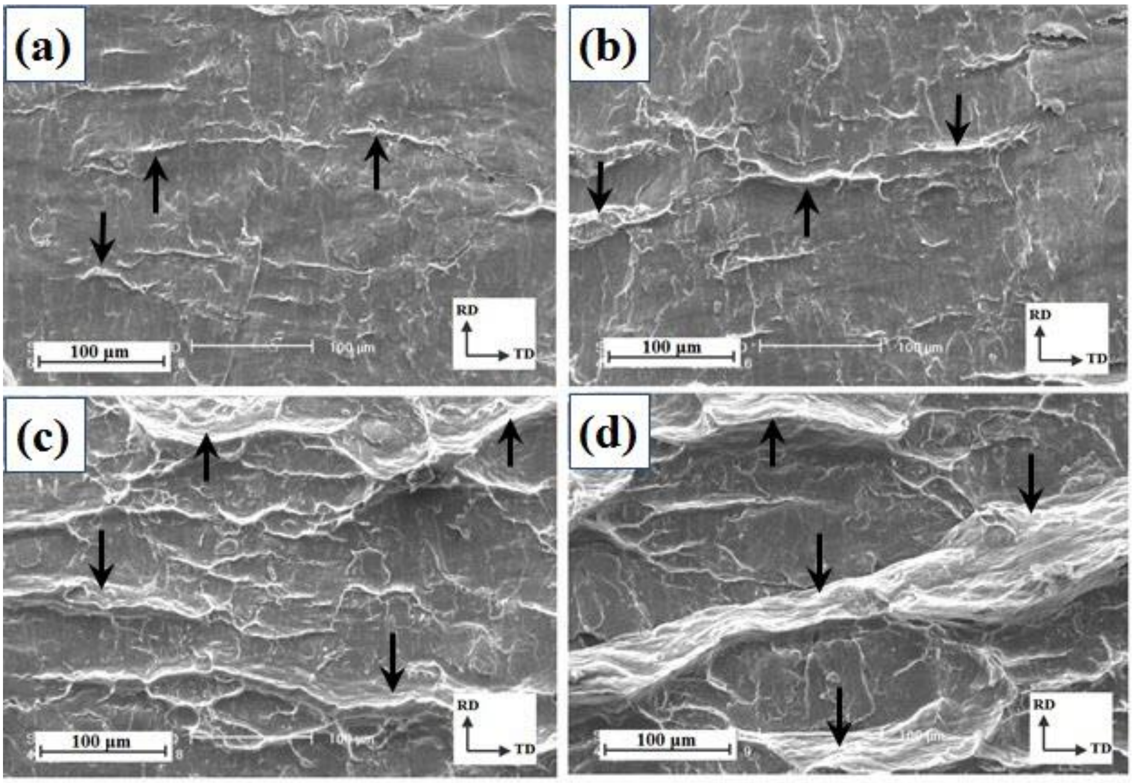


Fig. 5. SEM micrographs of aluminum surface after the peeling test for different reductions; (a) 40%, (b) 50%, (c) 60% and (d) 70%.

Figure 6 depicts SEM micrograph of aluminum and brass wire interface in two magnifications. Figure 6b shows that, there are some micro cracks at the interface in aluminum surface without any microstructural interaction between aluminum and wire. It appears that the brass wires reduced the welded areas between the two aluminum strips. However, due to stress concentration, cracks were nucleated around the brass mesh especially near the intersections of wires. Bond points have been developed around these areas, as shown by arrows in Fig. 7.

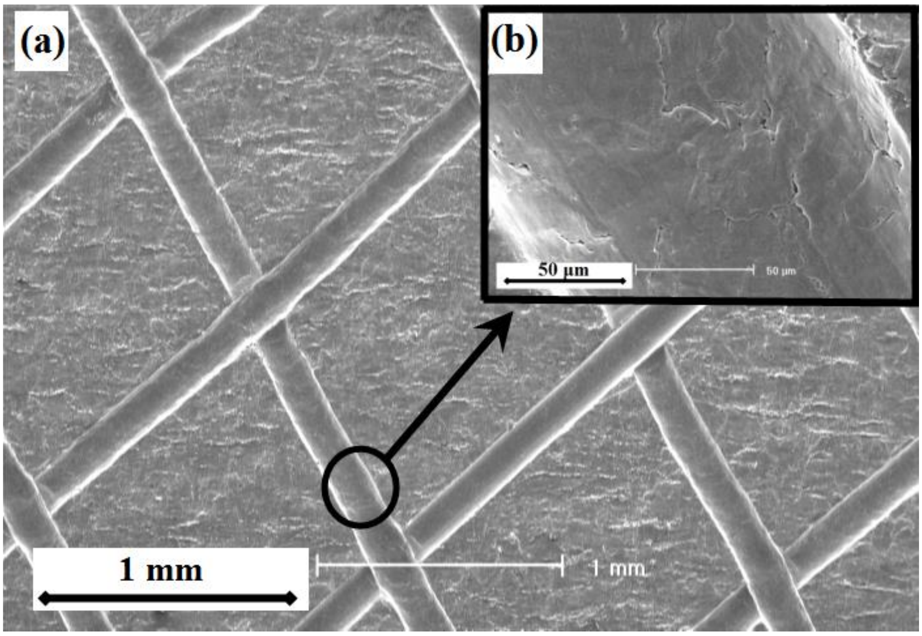


Fig. 6. SEM micrograph of the interface between aluminum and brass wire in different magnifications (a) 24X and (b) 500X.

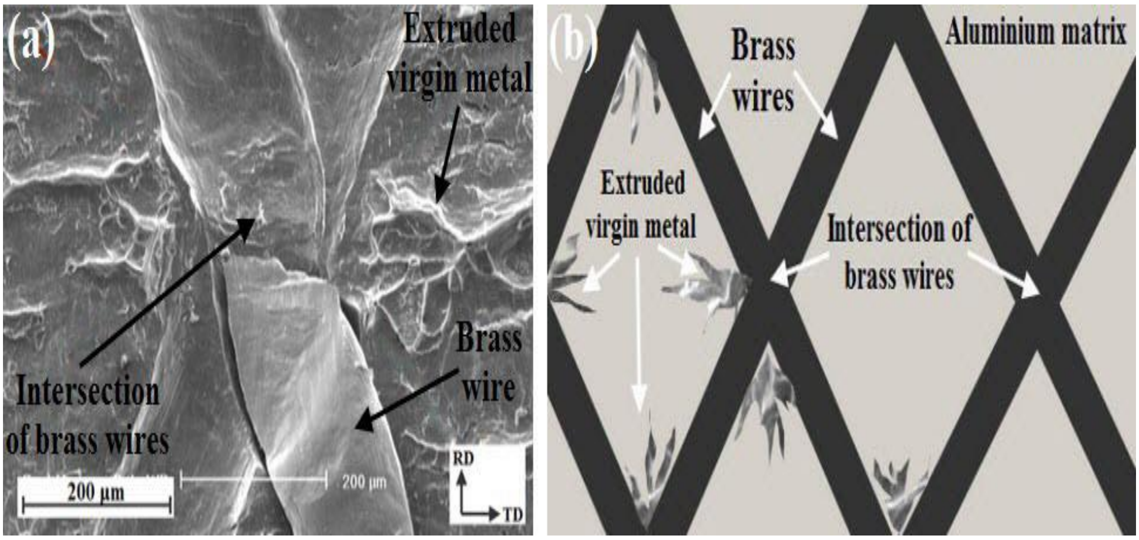


Fig. 7. SEM micrograph of aluminum surface after the peeling test and extruded virgin metal around the intersection of wires (a), and schematic picture (b).

Four mechanisms have been proposed for bonding during CRB process including surface film theory [4], energy barrier [11], diffusion bonding and joint recrystallization [19]. Among these mechanisms, the surface film theory presents a better description of the bonding in CRBed strips. Based on the film theory, there is a brittle layer on the surface of strips which formed during scratch brushing as a result of a heavily work hardened surface layer. The brittle cover layer is fractured during surface expansion caused by rollers pressure and, fresh metal is extruded through cracks leading to formation of metallic bonds between opposing surfaces. By increasing the thickness reduction, wider cracks were produced and the amount of extruded virgin metal was increased thereby, stronger bonding was formed. It has been reported that bonding between the layers is not initiated until an energy level, termed energy barrier [19]. Such energy barrier may come from a number of sources including flow of virgin metals, rearrangement of atoms to achieve a boundary configuration, surface contaminations like adsorbed water vapor and trapped air at the interface and the activation energy needed for bond formation [4]. Accordingly, by increasing the pressure, more atoms obtained the activation energy for providing atom-to-atom bonding.

3.2. Effect of pre-rolling and post-rolling anneal

In order to examine the effect of annealing treatment on the bond strength before CRB, samples were cut from the as-received sheet and rolling was carried out without annealing treatment. Fig. 4 depicts that there is no bonding at the thickness reductions that are less than 50% in the received samples. This means that threshold reduction was 50% without annealing prior to rolling process. In addition, the average peeling force was less than that for pre-annealed and post-annealed samples at the same reduction (Fig. 4).

There are few published research works on the effect of pre-rolling annealing treatment, on the bond strength [20]. It has been noted that, formability of strips is the key factor involved in the bonding process. Pre-rolling annealing facilitated breaking of the surface layers and increased formability of virgin metals within the underlying surfaces [20-21]. Therefore, enhancement of extruded virgin metal caused creation of more bond points at the interface. Moreover, pre-annealing treatment reduced hardness of aluminum from 37 to 22 VHN and therefore, increased bond toughness. Improving bond toughness required more force to separate and discontinuity between two strips in peeling test. Jamaati et al. [16] also reported, pre-rolling annealing provided energy as more atoms obtain the activation energy required for the bond formation.

In order to examine the effect of post-rolling annealing on the bond strength, samples were annealed at 643 K for 2 h after CRB process and then, the peeling test was performed. Fig. 4 reveals an increase in bond strength of aluminum strip as an effect of post-rolling annealing. The level of increase in bond strength was higher at low reductions. Fig. 8 illustrates the effect of post-rolling annealing on the surface of peeled strips after 70% reduction. After annealing the bond points were complete and as it can be seen in areas A and B (Fig. 8b), the atomic diffusion between aluminum layers near the cracks was observed after annealing treatment. Diffusion phenomena improve bond point in the CRB process. Moreover, there are some dimples in area C as shown in Fig. 8b, which indicates the increasing ductility of fracture during peeling test. By decreasing the residual stress during post-rolling annealing, the tendency of ductile fracture is increased and caused increasing bond toughness. In contrary, appearance of diffusion phenomena near the cracks and dimples were not observed in fractured surface of sample without post rolling annealing as shown in Fig. 8a. To study the effect of diffusion between aluminum strips and brass wires and also formation of any intermetallic at the interface, point EDS analysis was employed. Based on the results of microanalysis in Fig. 9, there is neither sign of diffusion nor formation of intermetallic phases at the interface between aluminum and brass after annealing.

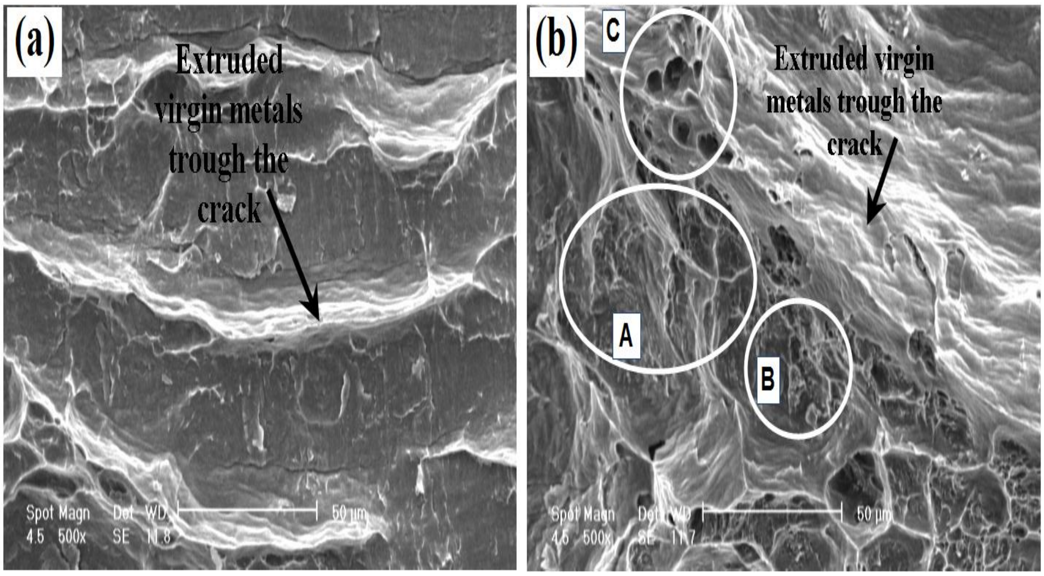
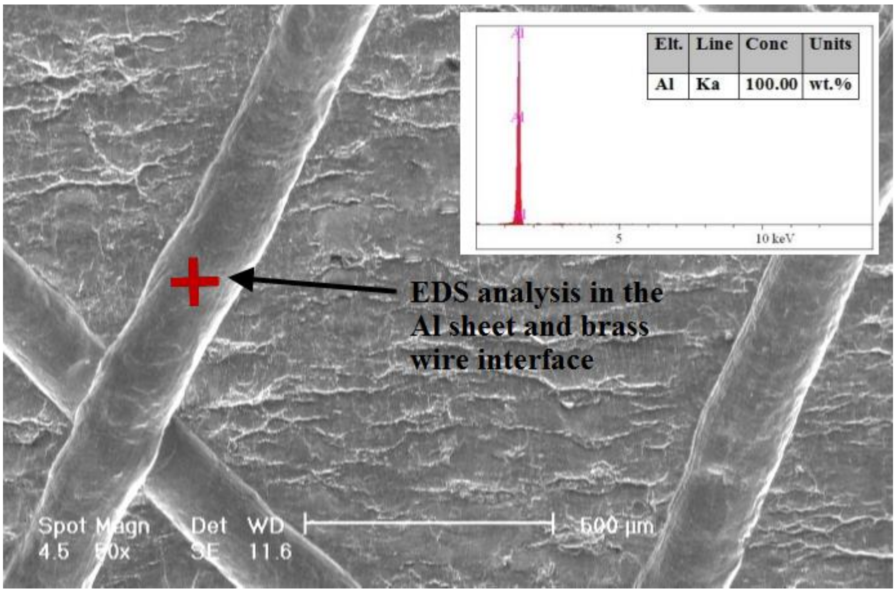


Fig. 8. Effect of annealing on the surface of peeled strips; (a) without post-rolling annealing, (b) after post-rolling annealing at 643 K.



Elt.	Line	Conc	Units
Al	Ka	100.00	wt.%

Fig. 9. EDS elemental analysis at the interface of aluminum and brass wire after annealing.

Some researchers [16-22] reported that, post-rolling annealing increased bond strength due to several phenomena including improvement of atomic diffusion, reduction of residual stresses between the layers, enhancement of toughness of bonding, and reduction of the hardness of pure aluminum strips. On the contrary, other published works [19, 23] have reported that post-rolling annealing decreased the bond strength for three main reasons. The first phenomenon is the kirkendall effect between two different materials that created a layer of defects and voids. The second reason was mentioned as formation of brittle intermetallic compounds with covalent and ionic bonding at the interface. The third issue was the difference in the coefficient of thermal expansion (CTE) between dissimilar strips that could induce thermal stresses.

Regarding the results of EDS analysis, increasing the bond strength after annealing in the present work is more related to atomic diffusion phenomena between aluminum strips and, decreasing the stress and hardness of strips. At lower reductions, the virgin metal is only partially extruded as it is shown in Fig. 5a with black arrows. It has been shown that annealing treatment after the CRB process would lead to more complete bonding therefore, improved the mechanical properties [20]. The experimental results in the present work suggest that effect of annealing is more obvious at lower reduction values.

3.3. Effect of initial thickness of the strip

In order to examine the effect of initial thickness on bond strength, three thicknesses of aluminum strips (0.5, 1 and 2 mm) with the same brass mesh in different reductions were rolled. Figure 10 illustrates the variations of initial thickness versus average peeling force. Figure 10 shows that, by increasing the initial thickness of Al strips, the bond strength was increased. Optical micrographs prepared from the peeled surfaces of aluminum strips are shown in Fig. 11. It is obvious that, by increasing the initial thickness of strips, wider cracks were formed on the peeled surfaces and finally leading to higher amount of extruded virgin metal and stronger bonding.

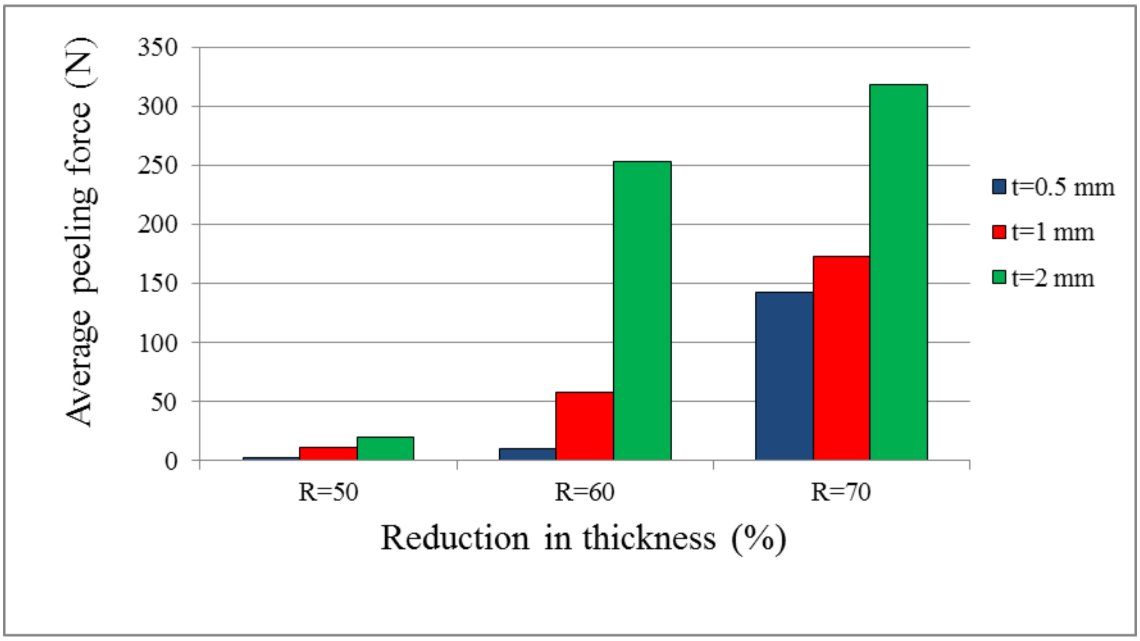


Fig. 10. Effect of initial strip thickness on the average peeling force of aluminum strips and brass mesh for different reductions.

Our experimental findings in the present research are in contradiction with some previous works [1, 24, 25, 17]. They showed that, by decreasing the initial thickness, the bond strength was increased. According to Equation (2), by decreasing the initial thickness, the length of roll contact is reduced and the required pressure to reach a certain reduction is increased.

$$P = \frac{F}{WL} \tag{2}$$

In this equation, P is contact pressure and L, W, and F are length of the roll contact arc, strip width, and rolling force respectively [25]. A theoretical analysis on the effect of initial thickness on the bond strength performed by Yong et al. [17] showed that some parameters such as rigid-plastic boundary (Γ^*) and contact boundary at the interface (L^*) affected the time for which the normal pressure was acting and thereby, determine the bond strength. In the present study, the brass mesh produced a gap of 0.3 mm between two aluminum strips and a gap was filled out by extruded virgin metal. Increasing the initial thickness caused more amount of extruded virgin metal in the gap between the layers. Further analysis of the results suggested that the presence of brass mesh probably affected Γ^* and L^* parameters defined by Yong et al [17]. However, this must be confirmed by quantitative data in order to identify the dominant mechanism in bond strength.

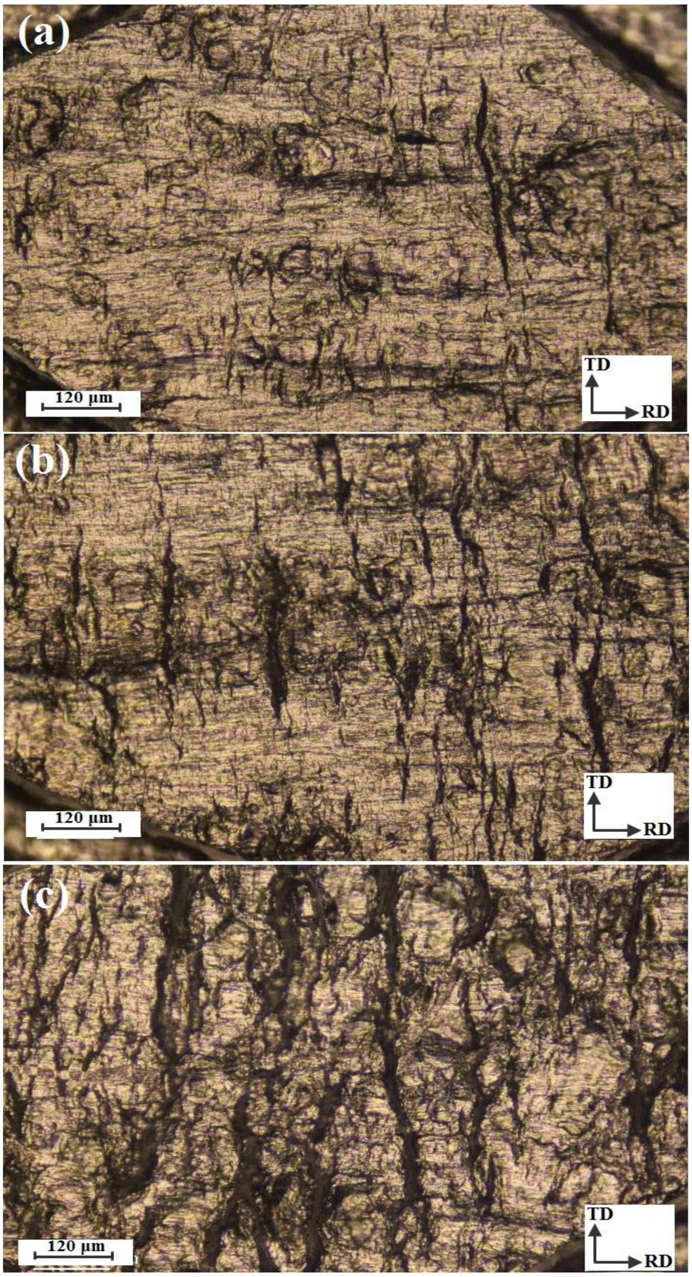


Fig. 11. Optical micrographs of peeled surface of different thickness aluminum strips after 60% reduction; (a) 0.5 mm thickness, (b) 1 mm thickness, (c) 2 mm thickness.

4. Conclusion

In this work, similar aluminum strips were successfully joined together using a brass mesh layer between them by CRB process. Bond strength between the layers at different levels of reduction, initial thickness and annealing treatment was evaluated by peeling test. The conclusions from this study are summarized as follow:

1. Cold roll bonding was shown to be a successful process to produce aluminum-brass multilayered composites with network structure.
2. By increasing the reduction in thickness and initial thickness, the peel strength was increased. The effect of initial thickness was unlike the previous research due to a gap creation by mesh between Al layers.
3. Annealing treatment before and after CRB process increased the bond strength.

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ارزیابی استحکام چسبندگی ورق‌های آلومینیوم در حضور توری برنجی پس از فرایند نورد سرد پیوندی

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چکیده: در این تحقیق، حضور توری برنجی بر استحکام چسبندگی ورق‌های آلومینیوم (1050) در فرایند نورد سرد پیوندی مورد بررسی قرار گرفت. تاثیر پارامترهای مختلف شامل کاهش ضخامت، آنیل قبل از نورد، ضخامت اولیه ورق‌ها و آنیل پس از نورد نیز مورد بررسی قرار گرفت. پس از فرایند نورد سرد پیوندی، آزمون پیلینگ انجام شد و سطوح شکست آزمون پیلینگ توسط میکروسکوپ نوری و میکروسکوپ الکترونی روبشی مورد بررسی قرار گرفتند. آنالیز طیف سنجی پراش انرژی نیز نشان داد که پس از آنیل در دمای 643 درجه کلوین در فصل مشترک آلومینیوم و سیم‌های برنجی هیچ نفوذی صورت نگرفته و هیچ ترکیب بین فلزی تشکیل نشده است. مشخص شد، با افزایش میزان کاهش ضخامت و ضخامت اولیه، استحکام چسبندگی لایه‌ها افزایش یافت. علاوه بر این، آنیل قبل از نورد و آنیل بعد از نورد در دمای 643 درجه کلوین استحکام چسبندگی را افزایش می‌دهد.

کلمات کلیدی: استحکام چسبندگی، نورد سرد پیوندی، آزمون پیلینگ، کامپوزیت