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ORIGINAL ARTICLE

Experimental and numerical investigation of the solid cold-welding properties of the APB process of Al/Cu bulk composites

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Abstract

Nowadays, the use of bimetallic laminates with special capabilities is increasing and has experienced high growth. These properties include high mechanical properties, corrosion resistance, lightweight, and thermal stability. Among the technologies of multilayer composite materials, Accumulative Press Bonding (APB) as a solid-phased method of welding is one of the most common techniques for the production of multilayer composites. One of the most important aims for this choice is the press pressure, which can create a strong and suitable mechanical connection between produced metal layer components. In this study, the APB method has been used to produce bimetal aluminum/copper bulk composites as its novelty for the first time. After that, the effect of pressing parameters such as strain and number of layers on the stress distribution has been investigated. The shear stress among the layers reached 4 MPa for the samples with eight layers which is a good condition to generate a successful bonding. With increasing the thickness reduction ratio, the stress applied to the layers has also increased. As the thickness decreases, the interlayer shear stresses also increase which leads to a better bonding between layers. With increasing the thickness reduction ratio, the amount of layers sinking in each other was greater than before, which led to the crushing of copper layers along the entire length of the sample. During the process, as the number of passes increased, the volume of virgin material in the direction of the press rose, which led to increased compaction and better adhesion of Al and Cu layers to each other. The bonding strength enhances from 47 to 95 N for samples manufactured with one and four cycles of APB due to the increment of virgin metal normal to the pressing direction showing a 102% enhancement.

Keywords Metal matrix composite · Solid welding · Bimetal · Accumulative press bonding · FEM

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1 Introduction

In solid-state welding methods, creating continuity in parts is done without melting the base metal. In these methods, no fillers are used and metals do not lose their original properties [1–4]. Also, in all types of solid-state welding, the edges of the parts are interlaced with heat or in some cases without heat due to the application of high pressure [4–7]. The main governing mechanism in non-fusion welding methods is solid-state penetration. Although a very thin layer of molten metal may be formed in the intermediate stages of the joining operation between the surfaces it is mostly ignored [8–11]. Press welding is one of the oldest methods of welding as a type of solid welding approach. This process has practical and historical value because it helps us understand why and how advanced welding methods were developed [11–13].

One of the most up-to-date and innovative methods of severe plastic deformation (SPD) is the accumulative press bonding method (APB), in which strain accumulation leads to severe plastic and microscopic changes in materials [4, 6]. In APB, for the production of metal composites, two or more different sheets are used as the base and reinforcing phases, which are pressurized and the connection operation is performed using a high pressure [10, 14–19]. The outcomes of microstructural studies show that by repeating the process, the final strength of composite samples is increased at higher passes. Also, fracture studies have shown that the type of composite failure is the soft shear failure [11]. Nowadays, the use of computer simulation software to improve the performance of various systems has become very common [12, 13]. Notable advantages of this method include reduced costs, reduced sample review time, the possibility of reproducibility, and the ability to understand the performance of the research [20–24]. Based on the simulation technique, the actual physical response can be predicted and estimated under various conditions, and the effect of variables can also be observed [23–28]. Usually about the APB process, experimental studies are prominent, and no other numerical simulation has been done yet. So, in this study and for the first time, the combination of experimental investigation and numerical simulation of the APB process has been conducted as its novelty for the first time [16, 17]. The main purpose of this study is to simulate the APB process of Al/Cu bimetallic composites in Abaqus software as its novelty. The next step is to fabricate Al/Cu bimetal bulk composites via the APB process as its other novelty for the first time. The final step is the investigation of the APB parameters on the press bonding quality and value using SEM microscopy and peeling tests.

2 Experimental investigation and numerical simulation

2.1 Experimental procedure

The contamination removal from the surfaces to be bonded is vital to generate a desirable bonding, Fig. 1. As can be seen in Fig. 1, these layers are composed of illuminations which are essential dames against the creation of a successful metallic bonding. So, surface preparation prior the pressing is necessary.

A pressing machine with a tonnage of 100 tons is used to set up the APB process. Also, the composite samples were machines based on ASTM E8M for the tensile test along the rolling direction with 6 and 25 mm in width and length, respectively [14–19]. To measure the bonding strength, a H50KS testing machine at a strain rate of $1.67\times10^{-4}\mathrm{S}^{-1}$ was utilized for the peeling test at the ambient temperature using a 100 kg Instron tensile testing machine with a peeling speed of 20 mm/min according to ASTM-D903-93. So, the average peel strength was taken as, [19, 20]:

$$Average\ peel\ strength = \frac{Average\ load}{Bond\ width} \tag{1}$$

First of all, pure aluminum and copper strips are modeled in the Abaqus environment in dimensions of $40\times20\times3$ mm to conduct the APB process. Table 1 shows the properties

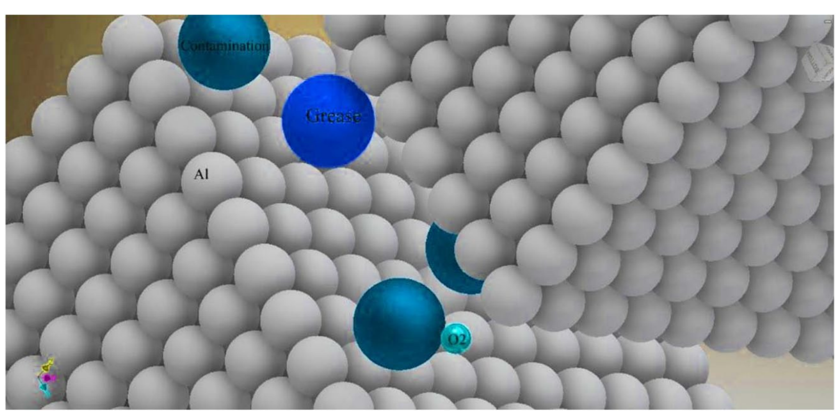


Fig. 1 The presence of illumination on the surface of samples before the bonding

Table 1 Mechanical properties of primary Al and Cu strips

Element	Poisson's ratio	Density (Kg/m^3)	Plastic Strain	Yield Stress	Young's modulus (GPa)
Cu	0.34	0 to 0.83	8900	0.3	70
Al	0.31	0 to 0.83	2700	0.3	90

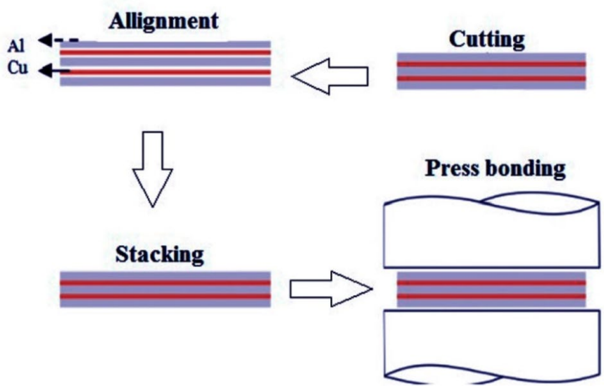


Fig. 2 The schematic illustration of the APB process

Fig. 3 The processed composite sample after cycle one

Fig. 4 Warming of the bottom mold to start the APB process

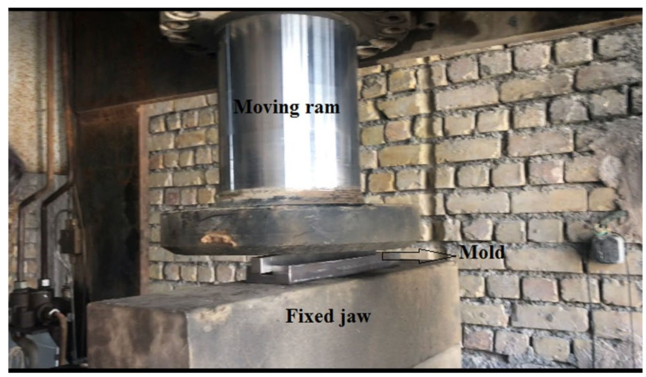


Fig. 5 Pressing of composite samples

of primary materials used for the fabrication of composite samples. Figure 2 shows the experimental setup for the APB process. Figure 3 shows the composite sample produced after the first cycle. Also, Figs. 4 and 5 shows the die which is used for the pressing of composite samples. During all the experiments, the ambient humidity and temperature were 30% and 25 °C, respectively.

2.2 Numerical simulation

2.2.1 Modeling

In the present study, the APB process has been modeled in Abaqus software. The number of composite layers and stress parameters are modeled in Abaqus. Pure aluminum and copper were used as primary raw materials. The physical and mechanical of them are illustrated in Table 1. Figure 6 shows the flowchart of the fabrication steps of bimetal samples. The properties of each of the strips (Al and Cu) are entered separately in the relevant table and introduced to the software because the layers used in this project are made of two parts. These properties are such as Poisson's ratio, Young's modulus, density, and material properties in the plastic deformation range. The APB process is performed at the ambient temperature with one up to three cycles containing two, four, and eight layers, respectively.

Three simulation environments have been conducted in Abaqus software to model the APB process of samples with two, four, and eight layers, respectively. The subsequent steps were assembling one layer of Cu and the other of Al on each other, positioning the layers under the press machine, determining the processing type, defining the contact behavior and tribological specifications between the layers, boundary conditions (displacement and loading), meshing and finally, solving step applied to perform the APB process. Figure 7 shows the contact properties of bimetal layers during the numerical simulation in Abaqus software.

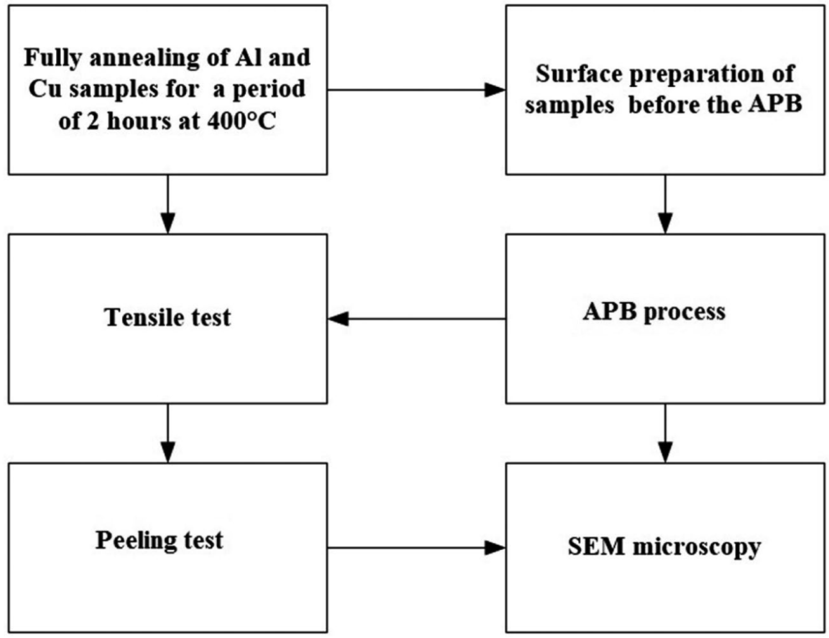


Fig. 6 Flowchart of the fabrication steps of bimetal samples

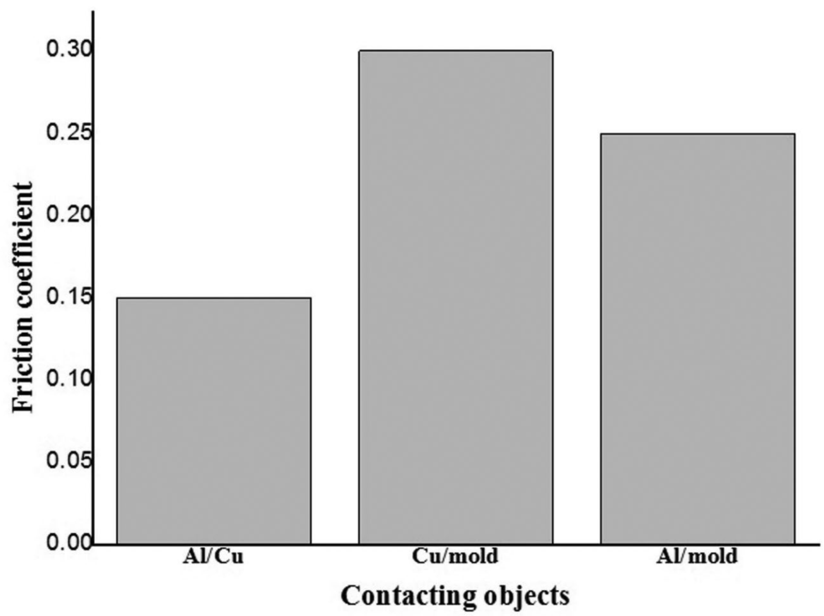


Fig. 7 Friction coefficients between composite layers

The lower mold is modeled as a fixed bed and the upper one is moving toward the fixed mode. During the meshing step, the modeled geometry was meshed for final analysis containing two, four, and eight layers.

2.2.2 Assumptions

Some assumptions are taken into account throughout the study. The plane strain condition is considered for the rolling process. Al and Cu strips are assumed to be perfectly rigid plastic parts with no strain hardening. The molds were regarded as rigid rectangles with a uniform velocity distribution and a constant coulomb friction coefficient is applied among the surfaces touched together.

3 Results and discussions

3.1 Bonding interface

Through the composite matrix, the strain hardening of copper is greater than aluminum. So, thinning the of both of these metals is the same for samples fabricated with one and two APB cycles. Also at higher cycles, copper layers have

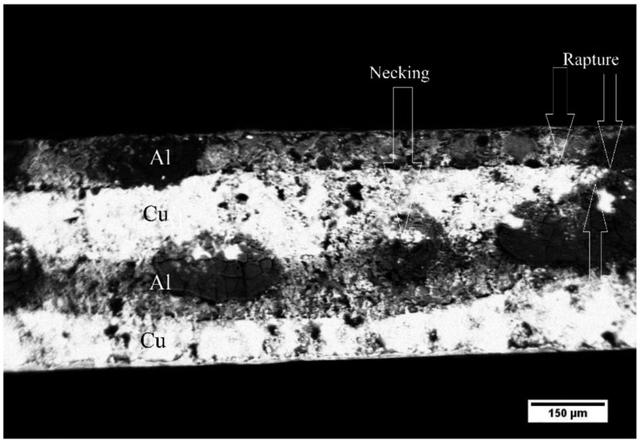


Fig. 8 Cross section of a composite sample after three cycles

inhomogeneous deformation and wavy shape and start to neck in some regions, Figs. 8 and 9.

The composite interface after the tensile test is illustrated in Fig. 10. According to Fig. 10(a) and for samples fabricated via one cycle, many voids and splits are visible along the interface between adjacent layers.

The aluminum and copper interfaces display reducing splits as a result of high-quality bonding, by increasing the number of cycles, Fig. 10(b). According to Fig. 10(b), the number of extrusion channels for the virgin metal increases by increasing the cycles which improves the bonding strength. So, the bonding interface cannot be viewed easily, Fig. 10(b).

The stress distribution contour equivalent to Al/Cu sheets fabricated by APB while analyzing finite elements in two, four, and eight-layer passes is shown in Fig. 11. Figure 11 shows that as the thickness decreases, the amount of stress applied to the sheets increases. To cause more deformation of the sheets at the same time, it is necessary to spend more energy. The plastic deformation is quite uniform and continuous and has been able to create a good relationship

Fig. 9 Schematic micrographs of specimens after **(a)** stacking, **(b)** two, and **(c)** four cycles

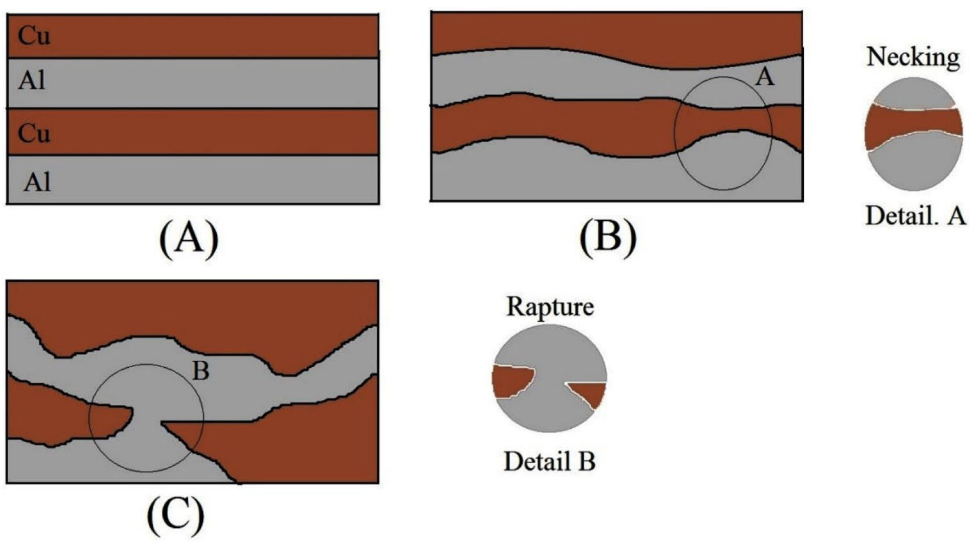
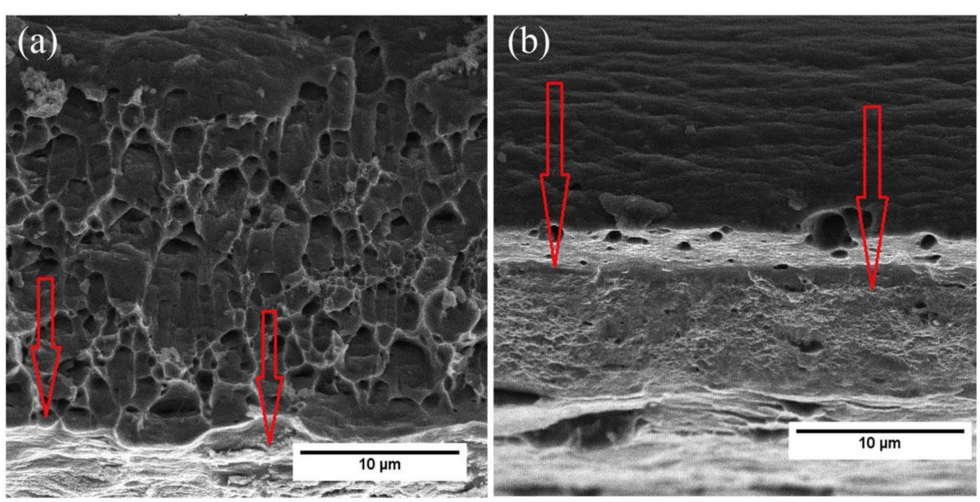


Fig. 10 The rapture morphology around the bonding interface of Al/Cu layers with (a) one and (b) four APB cycles



between the composite layers. Therefore, with increasing the number of passes which is associated with increasing the number of layers, this uniformity becomes more and more considerable. In other words, the higher the number of passes, the higher the volume of the virgin metal in the direction of the pressing, which causes the layers to adhere better to each other. Increasing the number of passes, on the one hand, reduces the size of the holes created at the joint of the two sheets of aluminum and copper, and on the other hand, this good connection causes the layers to adhere during the extrusion of the virgin metal. Figure 11 shows the plastic deformation of two-, four-, and eight-layer composites during the pressing.

Figure 12 shows the effect of a number of layers (passes) on the shear stress distribution. According to Fig. 12, the maximum amount of shear stresses has been done in the bonding interface of the sheet and mold, and in the bonding interface of the layers. As can be seen in Fig. 12, the dead zone is the middle of bars which has the least pressing pressure. Shear stresses have a very good effect on the forming behavior of the virgin metal between the layers. Therefore, the higher the amount of these stresses in the joint of the layers, the more the interlayer adhesion and ultimately, the strength between the layers increases.

Then, the bonding quality among the copper and aluminum layers is investigated to find the connection between the layers. The outcomes show that owing to the higher strength of copper, the strain hardening of copper is greater than that of aluminum alloy through a composite matrix. Therefore, for fabricated samples, the thinning of both of these metals is the same, and in more passes of the APB process, the copper thickness begins to change due to the heterogeneous deformation. As shown in Fig. 13 [22, 27, 28], after each step, the Cu layer begins to necking in many areas with more distortion.

Figure 14 represents shear stresses in the bonding interface between composite layers. The amount of shear stress decreases by increasing the number of passes due to the work hardening of composite layers. In other words, increasing the shear stress between the layers leads to a decrease in the amount of virgin metals. However, it should be noted that for the third pass, the overall rate of shear stresses is equal to Fig. 14. In this case, the total shear stress increases by increasing the number of passes.

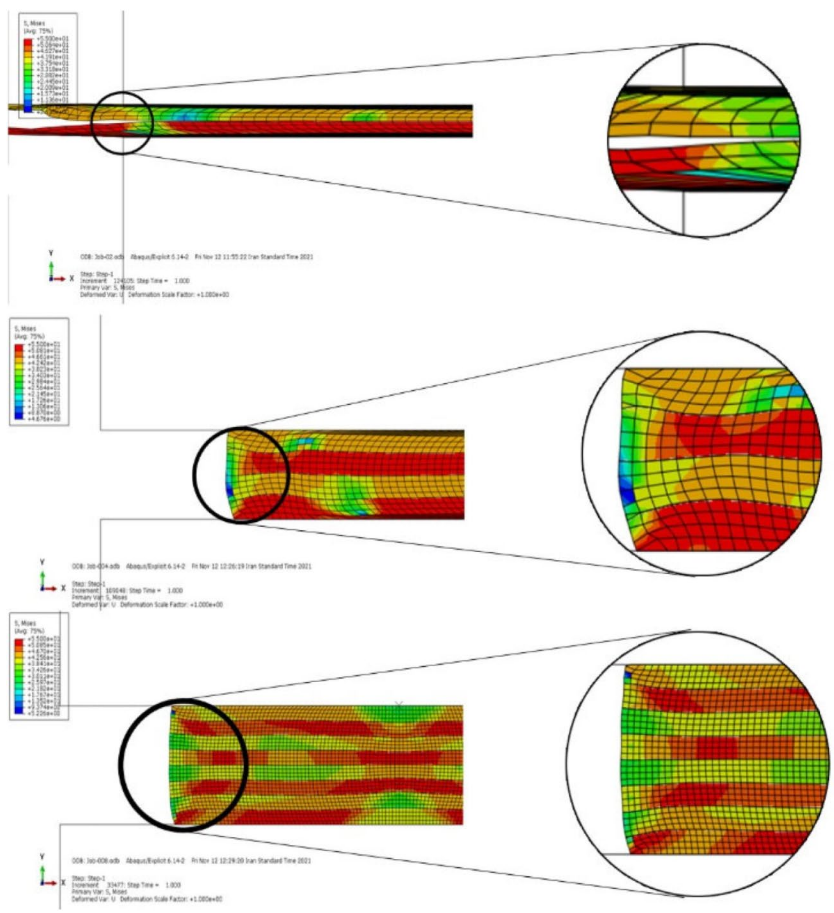


Fig. 11 The plastic strains of composite sheets during the APB

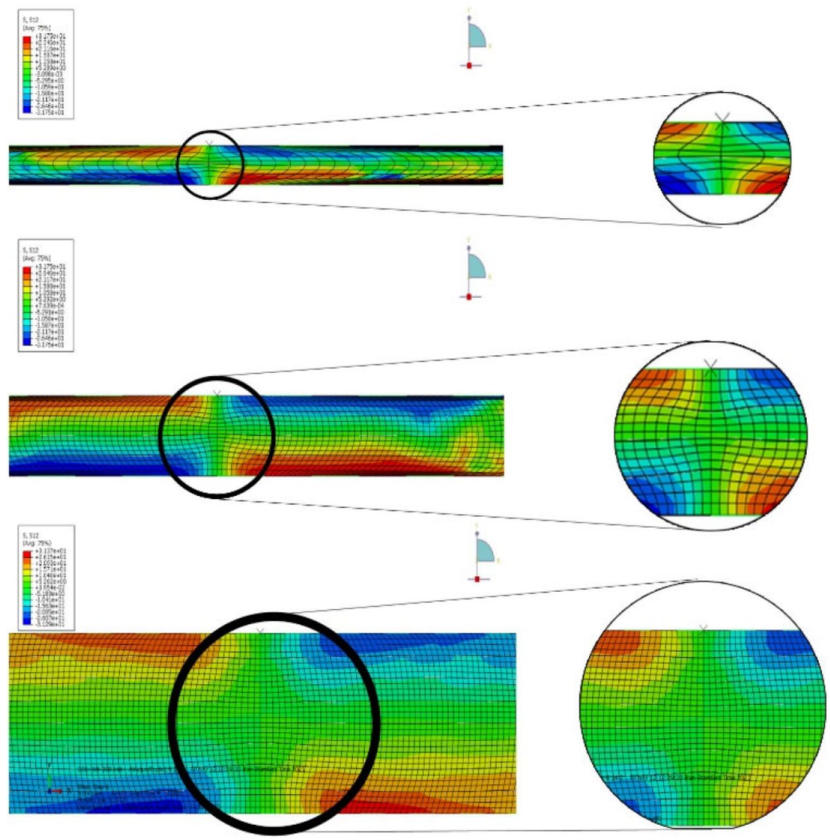


Fig. 12 The distribution of shear stresses vs. number of layers

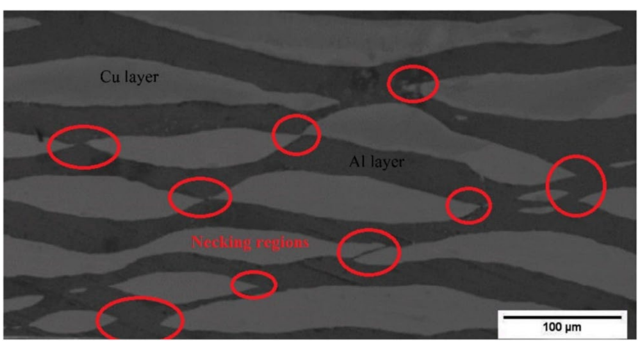


Fig. 13 Schematic creation of a metallic connection between layers

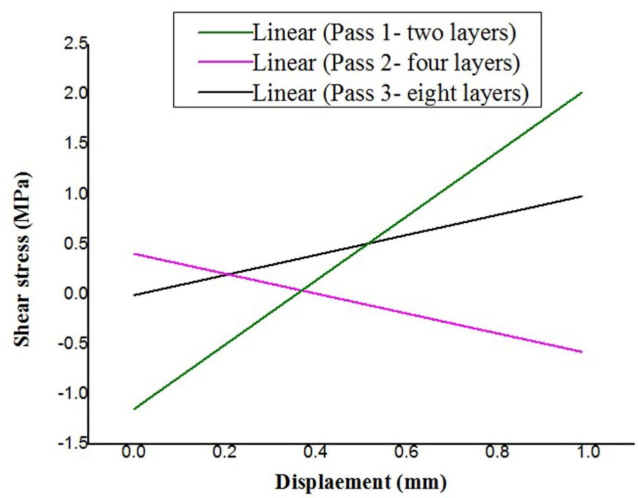


Fig. 14 Shear stresses between Al/Cu layers (along the pressing length) vs. number of APB passes

3.2 Bonding strength

The bond strength of samples was measured using a peeling test according to ASTM-D903-93 and for each sample, the test was repeated 3 times. In the peeling test, the average peeling forces were measured, and the average bond strength was taken as Fig. 15.

Figure 16 illustrates the peeling strength of samples vs. the pressing steps. As can be seen in Fig. 16 and based on the finite element simulation results, the bonding strength improves with growing the APB cycles. For example, the bonding strength enhances from 47 to 95 N for samples manufactured with one and four cycles of APB due to the increment of virgin metal normal to the pressing direction showing a 102% enhancement.

3.3 Bonding quality

The peeled surface morphology of composites manufactured with one and three pressing cycles is shown in Fig. 17. Based on Fig. 17, the cross-section of the virgin metals

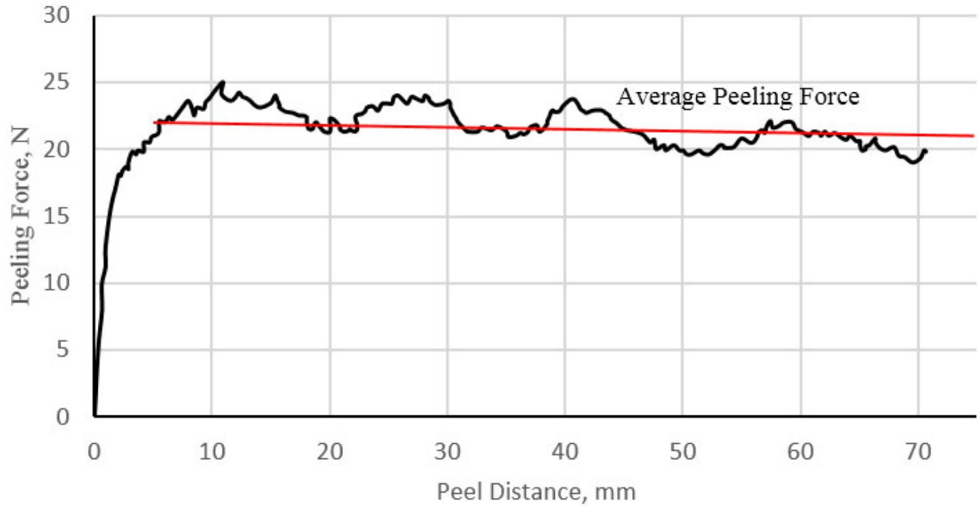


Fig. 15 Typical plot of peeling force versus peel distance

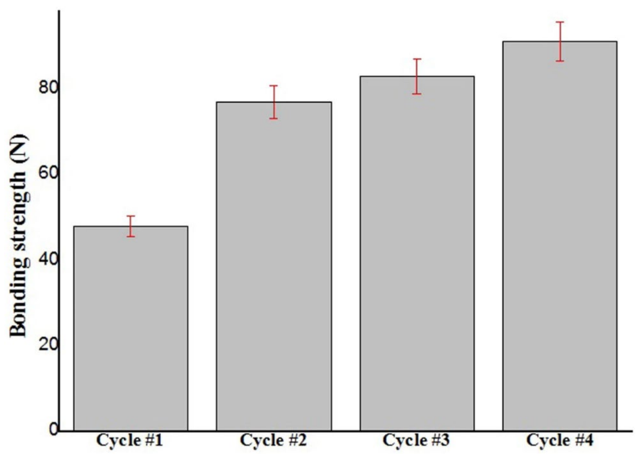


Fig. 16 The bonding strength of composite samples vs. APB cycles

(bonded regions) looks like isolated islands. The cross-section area of these islands depends on the number of APB cycles. So at a higher number of pressing cycles due to the higher amount of plastic strain, the virgin metal has more energy to break the surface oxide layers, extrude through them, and create a successful bonding [22–26].

4 Conclusions

In this study, the numerical and experimental investigation of the APB process of Al/Cu bimetal laminates has been conducted. The following results can be concluded as:

1. The results show that plastic deformation has continuity and uniformity, which has led to an acceptable relationship between copper and aluminum layers. It is also observed that the number of passes increases the size of the virgin metal in the direction of the press has grown. This leads to rising compression and better adhesion of the layers to each other.
2. By increasing the number of passes, reducing the size of the cavities created in the bonding interface of composite sheets occurs and the results also confirm this hypothesis.
3. Due to higher copper strength, the Al strain is more than Cu. Therefore, at higher passes of APB, copper thickness changes, due to heterogeneous shape changes, and begins to break.
4. Along with the progression of the transplantation between composite layers, the pressure rate increases. Therefore, the range of hardness gradually increases through this process.

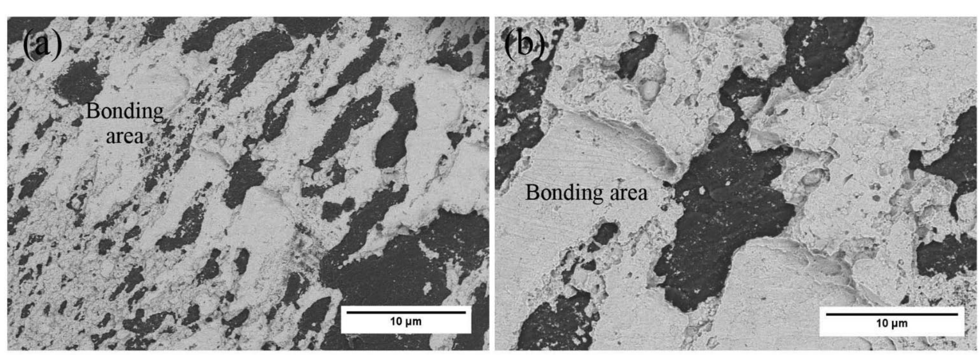


Fig. 17 SEM morphology of the peeling surface of composites produced via **(a)** one and **(b)** three APB cycles

5. The results indicate that shear tensions have increased in the bonding interface of Al/Cu layers.
6. Owing to the hardness of the Al and Cu layers, the amount of shear stress decreases by increasing the number of passes.
7. Finally, The total shear stress increases with increasing number of passes.

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Data availability The data used to support the findings of this study are included in the article.

Declarations

Conflict of interest /Competing interests.
The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

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