Preprint of: Davood Rahmatabadi , Moslem Tayyebi, Ramin Hashemi & Ghader Faraji. (2018). Evaluation of microstructure and mechanical properties of Al5052/Cu multi-layered composite fabricated by the ARB process. Powder Metallurgy and Metal Ceramics. DOI: 10.1007/s11106-018-9962-4

Evaluation of microstructure and mechanical properties of Al5052/Cu multi-layered composite fabricated by the ARB process

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Abstract

In the present study, Al5052/Cu multi-layered composite is prepared through accumulative roll bonding (ARB) and the microstructure and mechanical properties is evaluated using optical microscopy (OM), scanning electron microscopy (SEM), tensile tests and micro-hardness measurements. The results showed that the thickness of copper layers of 1000 μm at the initial sample was reduced to ~7 μm after the fifth cycle of ARB cycles while the thickness of Al layer increases. By increasing the number of ARB cycles, the microhardness of both aluminum and copper layers was significantly increased. The tensile strength of the sandwich was enhanced continually, and the maximum value of 566.5 MPa was achieved. The higher strength of 566.5 MPa and ductility of 9.61% were achieved which were about 47% and 21 % greater than the maximum values resulted in the literature. Investigation of the tensile fracture surfaces during the ARB process, indicated by increasing the number of the ARB passes, the fracture mechanism changed to shear ductile.

Keywords: Multi-layered composite, Al/Cu, ARB, Fractography, Mechanical properties, Microstructure.

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1. Introduction

Metal matrix composites (MMC) have attracted the interest of many designers due to high strength and low density [1, 2] because of their extensive usage in various industries [3]. Aluminum alloy are used much more than other light alloys such as Mg and Ti to fabricate MMC due to the simultaneous presence of appropriate strength, ductility, and good corrosion resistance [4]. 5XXX aluminum alloy is generally classified as a non-heat treatable alloy, and its nominal chemical composition consists of Mg, Fe, Si, Cu, Mn and other elements. In AA 5052 aluminum alloy, the main addition element is Mg, with the content ranging from 2.2% to 2.8% which strengthens the alloy by forming a solid solution. A few of researches have been carried out on enhancing mechanical properties of AA 5052 aluminum alloy to meet the needs of modern sheet production. High electric conductivity and low electric resistance caused Copper as well as aluminum to be further utilized in multi-layered composites. It is known that the Al-Cu composites exhibit desirable properties of both copper and aluminum. So, low density, high ductility, good corrosion resistance, and high electric conductivity could simultaneously merge which make Al-Cu composites suitable for use in different industries of electrical, automotive, and aerospace [5]. For example, Al-Cu composites are used in aircraft cylinder heads, diesel engine pistons, and cylinder blocks because of higher strength and wear resistance at elevated temperatures [6].

In the last decade, fabrication of bulk multi-layered composites by severe plastic deformation (SPD) processes was considered and developed quickly because of some advantages of SPD over other processes such as casting, deposition and powder metallurgy [7]. So far, different successful SPD methods [8] were developed such as equal channel angular pressing (ECAP) [9] and rolling (ECAR) [10], tubular channel angular pressing [11, 12], high-pressure torsion (HPT) [13, 14] and accumulative roll bonding (ARB) [15]. The common features all of SPD methods are no change in the sample cross section after and before the process, capability to produce ultrafine grained (UFG) structures with high angle grain boundary and useable for different metals and alloys [16]. The accumulative roll bonding (ARB) is a type of SPD method suitable for processing sheet samples introduced by Saito et al. in 1998 [15]. In recent years, this method was used as a novel approach for manufacturing of multilayered MMC composites [17, 18]. The main advantageous of ARB process are the simplicity of the process, relatively accessible and inexpensive equipment, high production rate, and continuous production which increase its industrial capabilities. During the last years, though several metallic laminated composites, for example, Al/Ni [19], Al/Cu [20, 21], Al/Zn [22], Mg/Al [23] and Al/Cu/Ni [24] were successfully processed using ARB method. However, almost no study was done on producing Al alloy/Cu composites especially Al5052/ Cu composite.

In this study, Al5052 is bonded to pure copper at the room temperature by ARB process, and an Al5052/Cu multilayered composite is produced. Then, the microstructure and mechanical properties of the produced multi-layered composite were evaluated after different ARB cycles.

2. Experimental Procedure

2.1 Materials

Materials used in this study included 5052 aluminum alloy (Al bal., Mg 2.2, Fe 0.4, Cr 0.2, Si 0.2, Mn 0.1, Zn 0.1, Cu 0.1) and commercially pure copper sheets with initial dimensions of 120 mm in length, 50 mm in width and 1 mm in thickness.

2.2 ARB Process

Fig. 1 demonstrates schematic illustration of the ARB process in two steps. At first, a primary sandwich was fabricated and then the accumulative roll bonding process was carried out. To fabricate the primary sandwich, at first, two aluminum sheets, and Cu were prepared at same dimensions. Then, these three sheets were degreased in acetone, dried in the air, and were scratch brushed and stacked on each other as shown in Fig. 1. Then, the sheets were assembled as a sandwich stack included aluminum layers as the outer surfaces and one copper layers as the inner one. To prevent slippage, the stack was clamped through copper wires at four edges. Finally, to fabricate primary sandwich, a 60% reduction in thickness was applied so that the thickness of sandwich stack reaches 1.2 mm from 3 mm by using rolling at room temperature. After fabrication of the primary sandwich, the samples were cut into half and then surface treatment including degreasing with acetone, drying in the air, and roughing with a steel brush was applied. Finally, the roll-bonded sheets with a 50% reduction in thickness value were created after clamping. The ARB process repeated up to five cycles (accumulative strain of about 5.058). The process was performed using a laboratory rolling mill with 107 mm in roller diameters at room temperature in which no lubricant was used. During the ARB process, the samples are assumed to be deformed in a plane strain condition. Therefore, the equivalent strain after n cycles can be determined using the following Eq [25]:

$$\varepsilon_{eq} = \frac{2}{\sqrt{3}} N ln \frac{t_0}{t} = \frac{2}{\sqrt{3}} N ln \frac{1}{1-R}$$

Where t_0, t, N, and R are the initial thickness, thickness of samples after ARB process, number of ARB cycles, and reduction thickness in each pass, respectively. The reduction per ARB cycle was 50%, which resulted in an equivalent strain of about 0.8/cycle.

2.3 Microstructure

The microstructures of unprocessed and processed specimens were evaluated by optical microscopy (OM). Specimens after each pass were cut using wire electro discharge machining in the parallel to the rolling direction. Then, they were grinding using sandpaper numbers 180 to 4000 and polishing by use of alumina powder with a size of 1 μm and 3 μm. Also, to evaluate the rupture mode, failure surfaces of the uniaxial tensile test samples were investigated through VEGA TESCAN scanning electron microscope (SEM).

2.4 Mechanical properties

Mechanical properties of Al/Cu composite fabricated by the ARB process were studied through uniaxial tensile tests and microhardness measurements. The uniaxial tensile test samples were prepared for the unprocessed and ARB processed sheets oriented along the rolling direction according to the ASTME8/E8M-9 standard. The gauge length and width of the tensile test specimens were 6.92 and 2.5 mm, respectively. The uniaxial tensile tests were performed at a nominal initial strain rate of 1×10^{-4} s^{-1} at room temperature using SANTAM tensile testing machine. Also, the difference between gauge lengths before and after uniaxial tensile test defined the total elongation for each sample. The Vickers microhardness tests were done for initial, and ARBed samples using JENUS apparatus under a load of 200 gr applied for 10 s. Microhardness tests had been implemented to the both aluminum and copper layers at ten different points randomly on the cross-sections perpendicular to the rolling direction. Then, for each copper and aluminum layers the minimum and maximum hardness were disregarded.

3. Results and discussion

3.1 Microstructure

Fig. 2 illustrates the microstructure of Al5052/Cu multi-layered composite as a function of the equivalent strain (at different cycles of ARB process). Copper layers are continuous and coherent in an aluminum matrix at the end of the second cycle (accumulative strain of about 2.658). There is almost no plastic instability approximately up to the second pass. By increasing the number of ARB passes (equivalent strain) from third (accumulative strain of about 3.458) to the fifth cycle (accumulative strain of about 5.058), the plastic instability was observed in copper layers. However, copper layers are distributed in the continuous aluminum matrix. According to the conducted researches, the formation of plastic instability between dissimilar metals such as Al and Cu is influenced by different mechanical properties of them in which the harder layer (Cu) start necking and failure first [21, 22, 26, 27]. Fig. 3 demonstrates the microstructure of Al5052/Cu multi-layered composite after the ARB process through the fifth cycle. It can be seen that the copper and aluminum layers bonded together completely and no separation at the interface is seen. Though, plastic instability (i.e., necking) is observed at none of the ARB cycles except at the fifth cycle. As is realized the value of the critical strain for fracture of the layers is high enough, which would be provided with the higher number of ARB passes [32, 35, 36]. Fig. 4 demonstrates the thickness variations for copper layers as a function of the equivalent strain (at different passes of the ARBed Al5052/Cu composite). By increasing the number of the ARB passes (accumulative strain), the thickness of the copper layers decreased significantly due to the applied high strains. Finally, at the fifth pass (accumulative strain of about 5.058), the minimum thickness of copper layers is achieved. Also, the copper layers were distributed uniformly along the aluminum matrix layer. As is known from the literature, the thickness reduction value to reinforce layers at the early ARB passes is more than that in the last ARB cycles in which layers are experienced separation and distribution [32, 34].

3.2 Mechanical properties

Fig. 5 illustrates the micro-hardness variation of copper and aluminum layers individually as a function of the equivalent strain (at various ARB passes). As shown, it is apparent that by increasing the number of the ARB passes, microhardness of both layers (aluminum and copper) is increased. The microhardness after the first step is enhanced 1.3 and 2 times compared to the initial samples. Accordingly, a sharp rise in the microhardness at the early passes can be explained by work hardening or increasing the dislocations density and the subsequent formation of a subgrain boundaries [21, 22, 24, 28]. Increasing the number of ARB passes from the second to the fourth leads to increase in the value of microhardness of both aluminum and copper layers. Though, the rate of increase is less than early cycles. This may be because the work hardening and grain refinement are larger in early stages of SPD processing [29, 30]. At the intermediate passes, the rate of work hardening is less than the initial passes [24, 31-33]. Finally, the microhardness reached a saturated value resulted from saturation in the grain size. At the last pass, the value of microhardness of aluminum and copper layers reaches to 142HV and 169.6HV, respectively. By comparing them with the initial samples, the value of microhardness of aluminum and copper layers increases 1.55 and 2.27 times, respectively after the second step. The main reason of increasing microhardness is grain refinement [21, 22, 24, 28]. Also, the difference in thermal expansion coefficient between the matrix and reinforcement due to the heat caused by the friction of the rollers and the subsequent production of dislocations can be involved in increasing of microhardness [24, 34].

The engineering stress–strain curves of the multilayer composite Al5052/Cu after ARB process through a different number of passes were shown in Fig. 6. It is clear that by raising the number of the ARB cycles, the strength increases. The results are in good agreement with the other research results on Al/Cu and Al/Cu/Ni composites processed by ARB [21, 24].

Fig. 7 represents the variation of tensile strength and elongation of the multilayer composite Al5052/Cu processed by ARB as a function of the equivalent strain. As shown, the tensile strength increases continuously up to fifth cycles. The maximum value of tensile strength is achieved after the fifth cycle ARB process reached 566.5 MPa. This strength value is 2 and 5 times higher than that of initial Al5052 and Copper sheets, respectively. However, elongation of initial and final sandwich remains almost unchanged. The trends of tensile strength and elongation are in good agreement with the results of last investigations about the fabrication of multi-layered or metallic matrix composite by ARB [21, 22, 24, 28]. Researchers reported that several major factors affects to change the tensile strength of metal matrix composites with and without reinforcing including work hardening, grain refinement, shape, type and size of the particle, the amount of applied deformation, quality of bonding layers, and distribution of reinforcements [21, 22, 24, 28, 31, 34].

At the early ARB passes, strengthening is mainly due to work hardening, the formation of low angle subgrain boundaries and increasing the density of dislocations and according to Fig. 2(f) [21, 22, 24, 31]. Then, the mechanism of strengthening is mainly due to grain refinement so that at the last cycles of ARB process, the value of strength increased because of the fine-grained microstructure and the distribution of the copper reinforcements. Increase the number of ARB passes from the second to the fifth, the quality of the connection layers improves due to the distribution of reinforcing the material, and also cracks are closed and crack propagation would be delayed.

Table 1 compares the strength and ductility of multilayered Al5052-Cu composite achieved from this study with those from previous works. It could be realized from Table 1 that the higher strength and ductility is obtained from Al5052-Cu ARB processed composite in comparison with those from previous studies including Al/Cu, Al/Cu/Al_2O_3, Al/Ni/Cu and Al/Cu/Mn composites processed by ARB. The strength of 566.5 MPa and ductility of 9.61% were achieved which are about 47% and 21 % greater than the maximum values obtained in the literature. This means that using 5052 Al alloy instead of pure Al is recommended for processing of Al/Cu multilayered metallic composites with or without particulate reinforcements. Also, plastic instability and fracture of copper layers take place at early stages of ARB processing of pure Al/Cu composites while they take place at the final stages of ARB processing of Al5052/Cu composites. There was seen different strain hardening behavior in Al5052/Cu composite in comparison with Al/Cu composite because Al 5052 alloy have lower stacking fault energy than pure Al.

3.3 Fractography

Fig. 8 illustrates the tensile fractured surfaces of Al and Cu sheets after the uniaxial tensile testing. The basic fracture mechanism of the most coarse-grained metals with FCC crystal structure is a ductile fracture. Ductile fracture appears slowly after plastic deformation and necking with the creation of small dimples and coalescence to each other and ultimate failure [35].

Fig. 9 shows tensile fractured surfaces of Al5052/Cu multi-layered composite at Al and Cu layers after primary sandwich. As shown, the ductile fracture mode with formation and coalescence of dimples is seen at both cases. SEM micrographs of tensile fractured surfaces of Al5052/Cu multi-layered composite produced via multipass ARB were presented in Fig. 10. It was reported that early ARB cycles exhibit lower bonding between the layers compared to the last cycles. Also, there is a lamellar structure between matrixes and reinforcing that disappears by the increasing number of ARB cycles [34]. For this reason, micro cracks may nucleate at the interfaces between matrix and reinforcement which caused failure [21, 24, 34]. By increasing the ARB cycles, bonding between copper and aluminum layers is stronger, though still lamellar structure is considered after fifth cycle according to Figs. 10a-10f. It can also be seen that the fractured surfaces of Al and Cu layers at the primary sandwich exhibited ductile mode and composed of coaxial dimples. Ductile fracture is occurred in the materials having low dislocation density and at grain boundaries with hemispherical and gray holes. By increasing the number of the ARB cycles in comparison with initial sandwich, the depth and size of dimples decrease, and finally, stretched dimples form and fracture mechanism change from ductile to shear ductile mode (see Fig. 10 (f)). These results are confirmed by the previous work results [21, 24, 26].

4. Conclusions

In the present study, Al5052/Cu multi-layered composite was fabricated through the accumulative roll bonding process up to five cycles, and the results are concluded as follows:

- Copper reinforcement layers are continuous along the aluminum matrix, and there is almost no plastic instability at early cycles.
- By increasing the number of ARB cycles to the fifth cycle (accumulative strain of about 5.058), the plastic instability (necking and fracture) were observed at copper layers, and multi-layered composite with uniform Cu distribution was fabricated.

- The thickness of copper layers of 1000 μm at the initial sample was reduced to ~7 μm after the fifth cycle of ARB cycles.
- By increasing the number of ARB cycles (equivalent strain), the microhardness of both aluminum and copper layers was increased.
- The tensile strength of the sandwich was enhanced continually, and the maximum value of 566.5 MPa was achieved.
- Investigation of the tensile fracture surfaces during the ARB process, indicated by increasing the number of the ARB passes, the fracture mechanism changed to shear ductile.

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Table 1. Comparison of strength and ductility of the multilayered composite obtained in this study with those from previous works.

Materials	Reference	R and ε_{eq} at sandwich	Maximum value of El (%) - ε_{eq}	Maximum value of UTS (MPa) - ε_{eq}
Al5052-Cu	present study	60% - 1.058	9.61 – 5.058	566.5 – 5.058
Al-Cu	[21]	50% - 0.8	7.93 – 4.8	365 – 4.8
Al-Cu-Al_2o_3	[34]	50% - 0.8	5 – 4.8	361 – 6.4
Al-Ni-Cu	[24]	66% - 1.2457	7.8 – 10.04	346 – 10.04
Al-Cu-Mn	[31]	66% - 1.2457	6.9 – 3.6457	355 – 8.445

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Figure 1. Schematic illustration of ARB for processing Al5052/Cu multilayered composite.

Figure 2. The microstructure of ARB processed Al5052/Cu multi-layered composite (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles and (f) fifth cycles.

Figure 3. Fracturing and necking of copper layers after five ARB cycles.

Figure 4. Thickness variations of copper layers as a function of the equivalent strain **(**at different cycles of ARB) processed Al5052/Cu composite.

Figure 5. Microhardness variation of copper and aluminum layers individually as a function of the equivalent strain **(**at different cycles of ARB processing of Al5052/Cu composite).

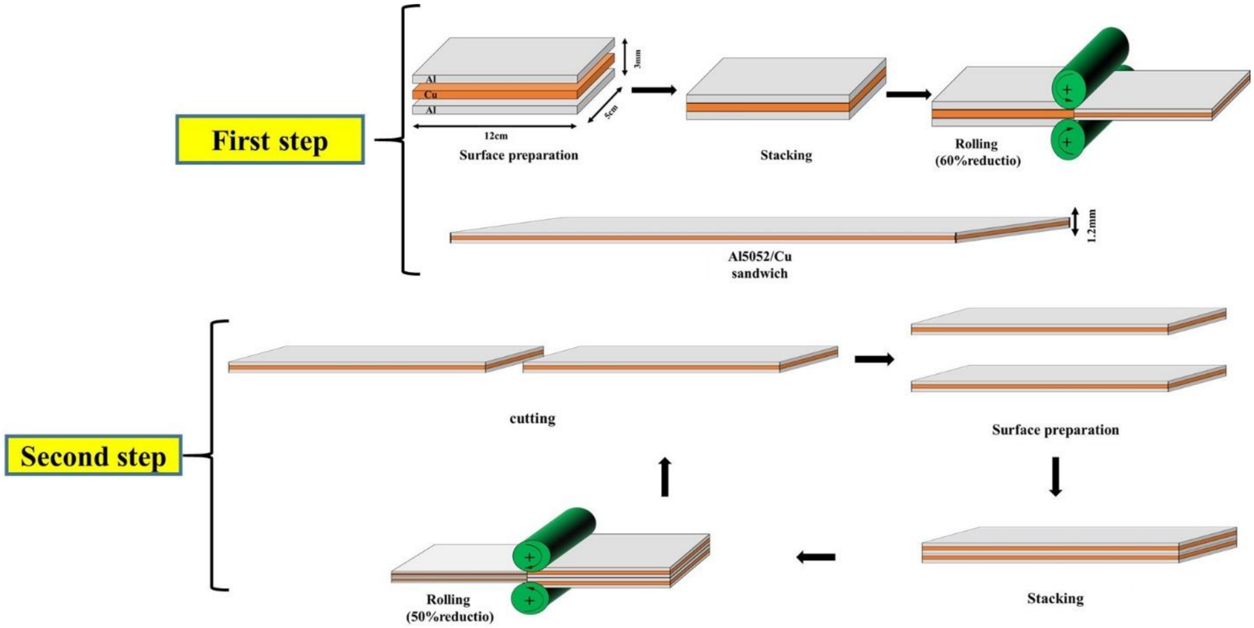
Figure 6. Engineering stress-strain curves of ARB processed Al5052/Cu composite.

Figure 7. Variations of the tensile strength and elongation of Al5052/Cu composite as a function of the equivalent strain **(**at different cycles of ARB).

Figure 8. Tensile fractured surfaces of initial sheets before ARB process.

Figure 9. Tensile fractured surfaces of Al5052/Cu multi-layered composite: (a) Al layer after primary sandwich (b) Cu layer after primary sandwich.

Figure 10. Tensile fracture surfaces of Al5052/Cu multi-layered composite: (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles and (f) fifth cycles.



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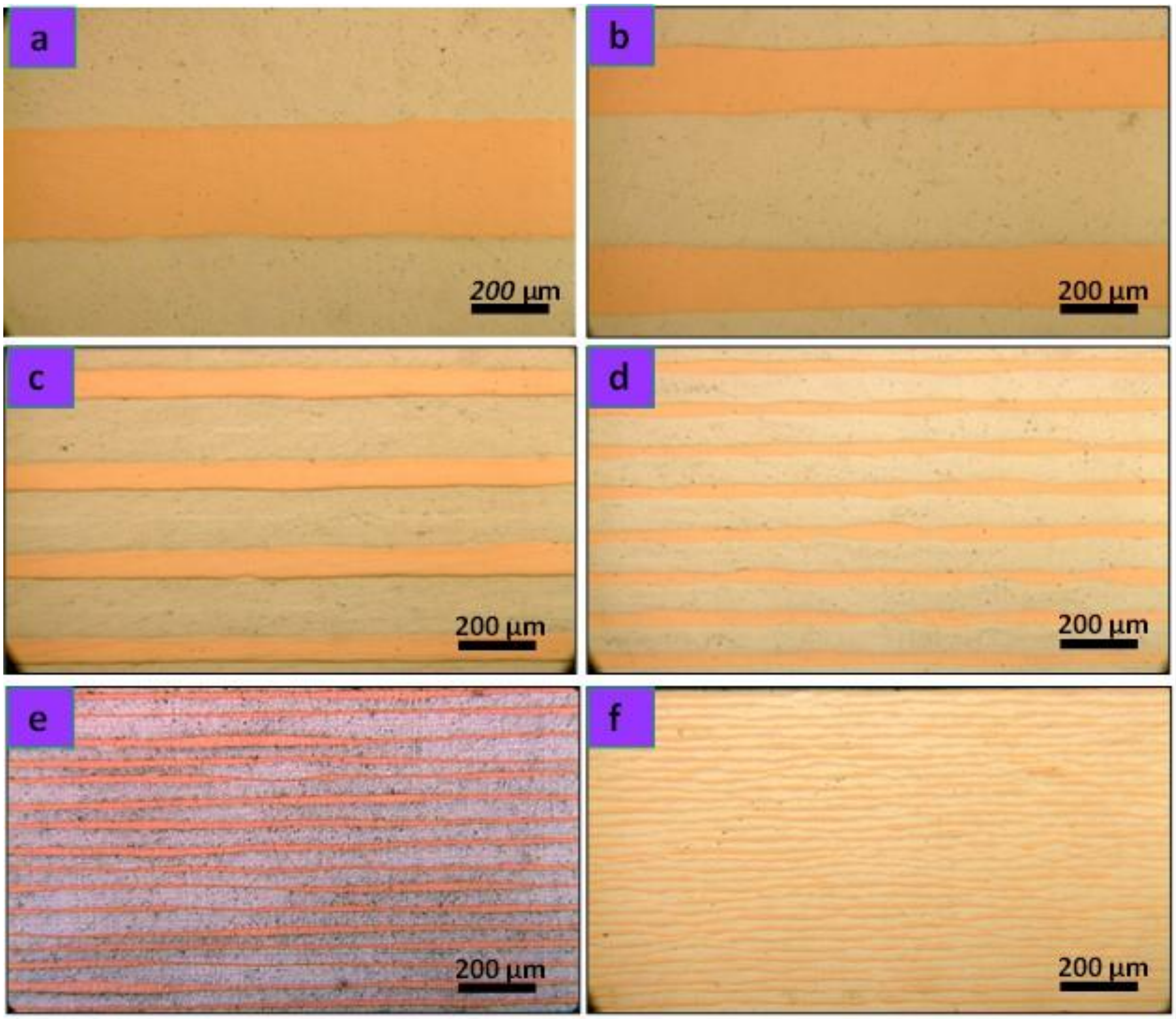

Figure 10. The microstructure of ARB processed Al5052/Cu multi-layered composite (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles and (f) fifth cycles.

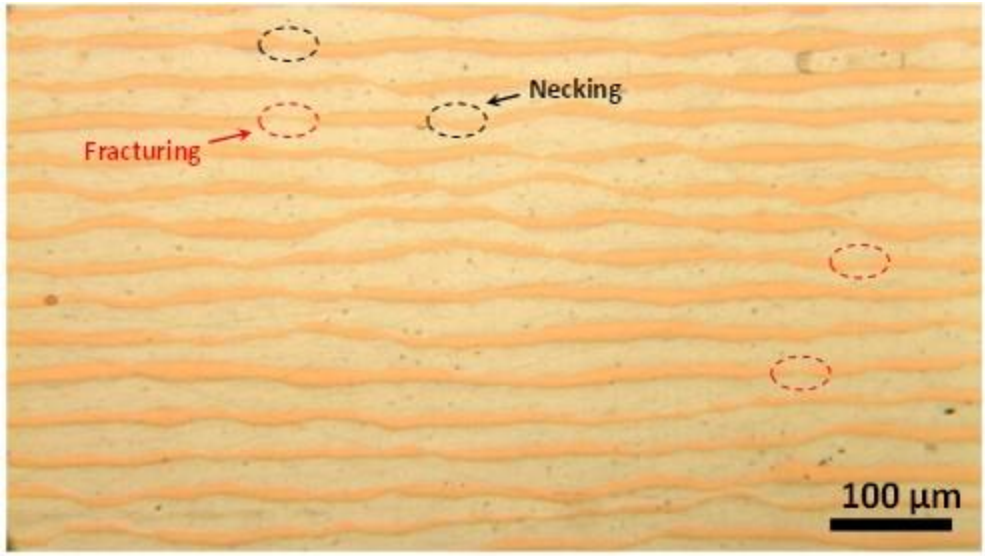

Figure 11. Fracturing and necking of copper layers after five ARB cycles.

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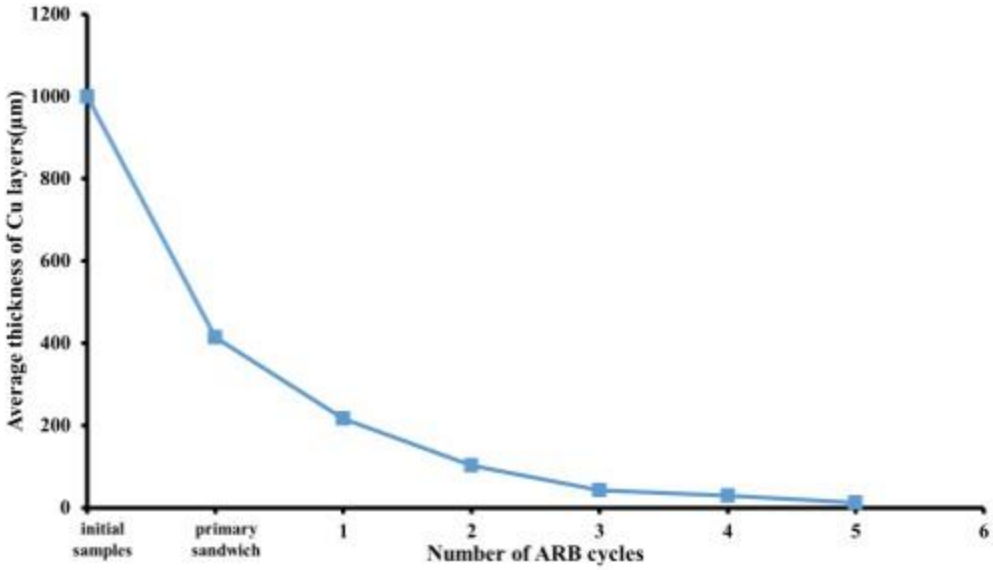

Figure 12. Thickness variations of copper layers as a function of the equivalent strain **(**at different cycles of ARB) processed Al5052/Cu composite.

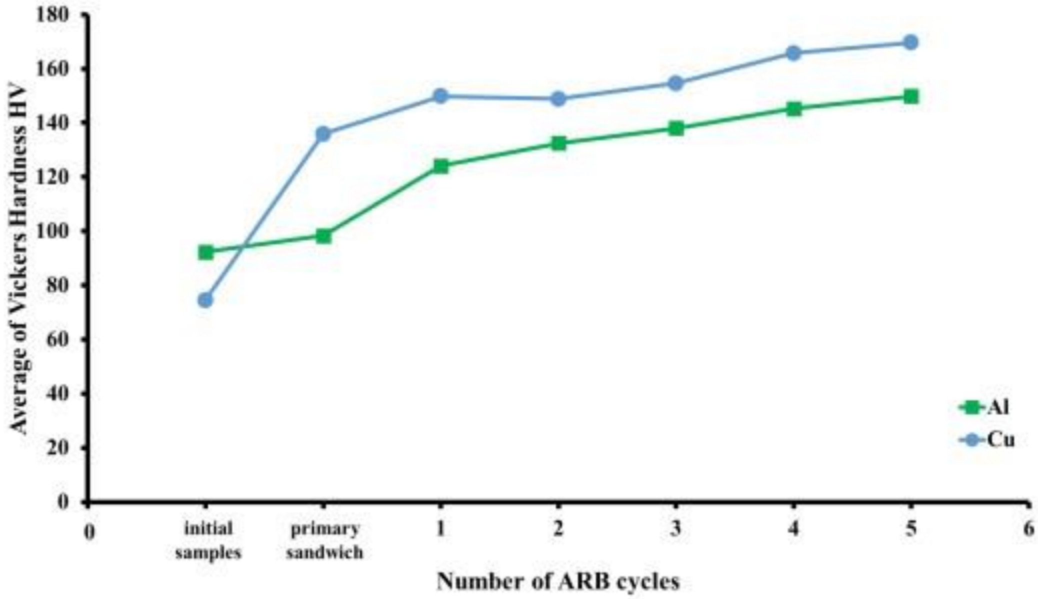

Figure 13. Microhardness variation of copper and aluminum layers individually as a function of the equivalent strain (at different cycles of ARB processing of Al5052/Cu composite).

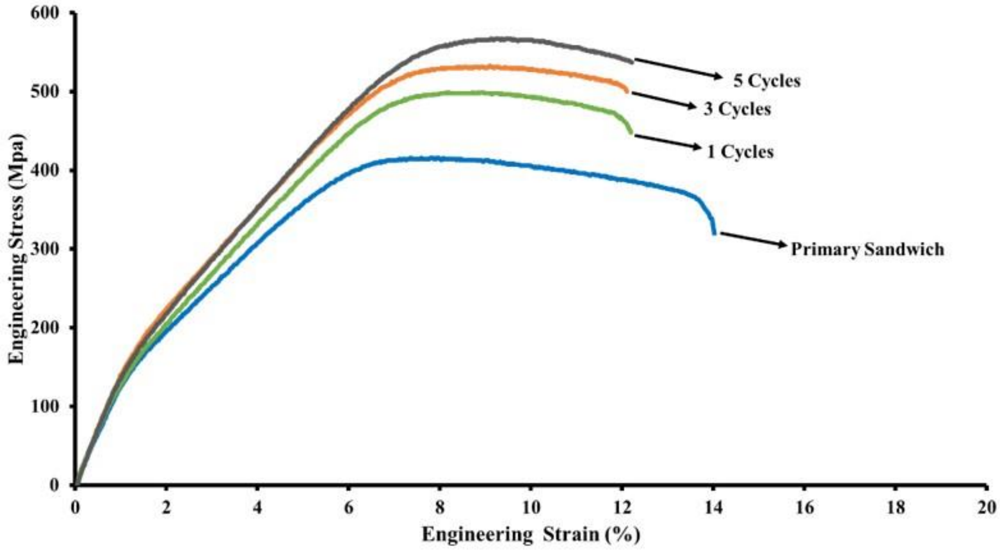

Figure 14. Engineering stress-strain curves of ARB processed Al5052/Cu composite.

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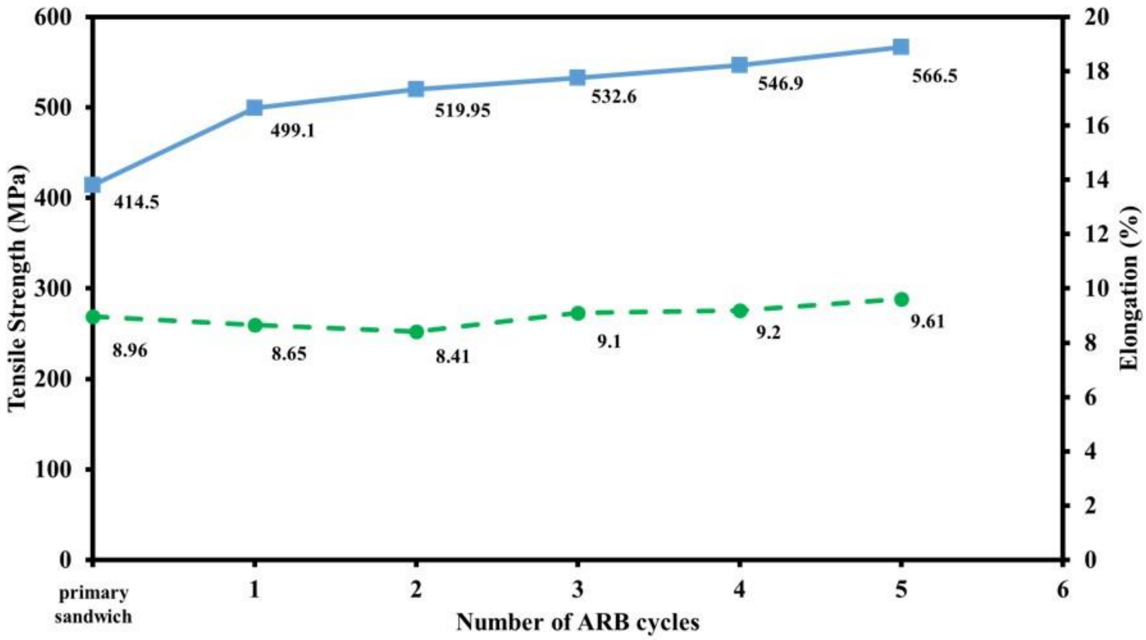


Figure 15. Variations of the tensile strength and elongation of Al5052/Cu composite as a function of the equivalent strain (at different cycles of ARB).

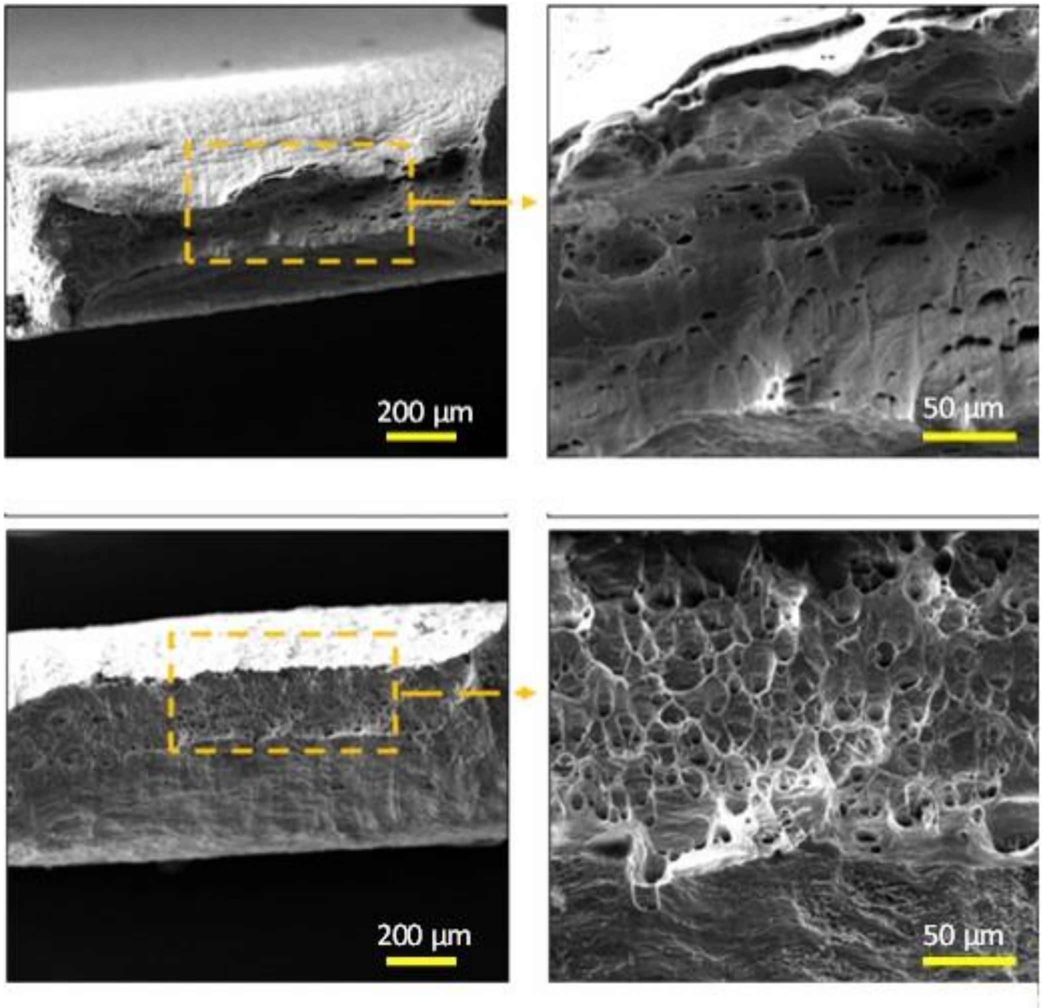
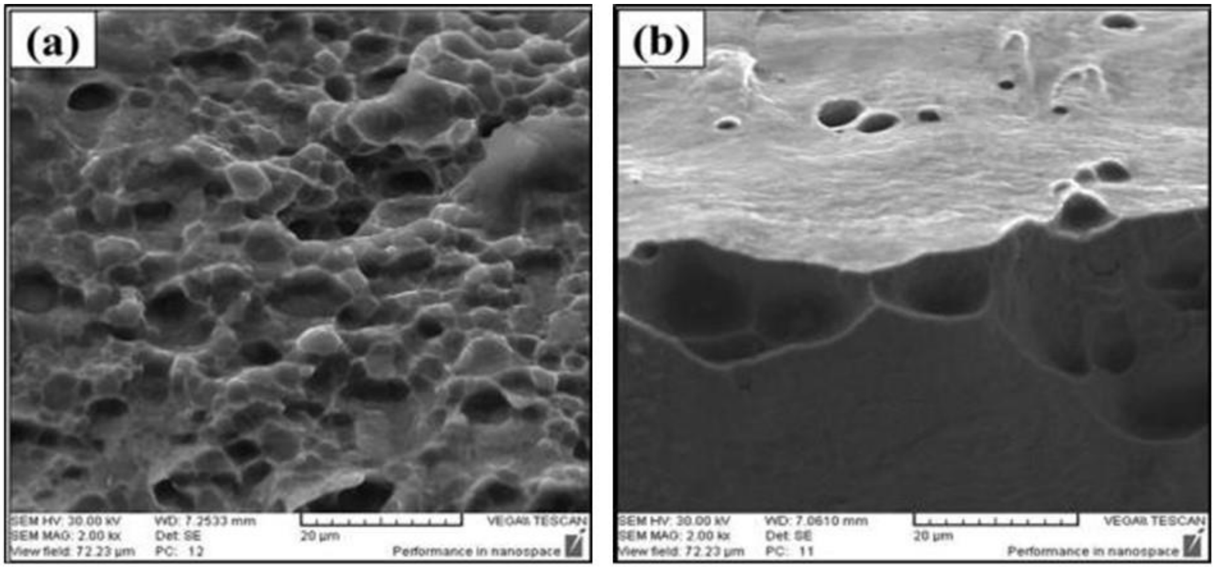


Figure 16. Tensile fractured surfaces of initial sheets before ARB process.



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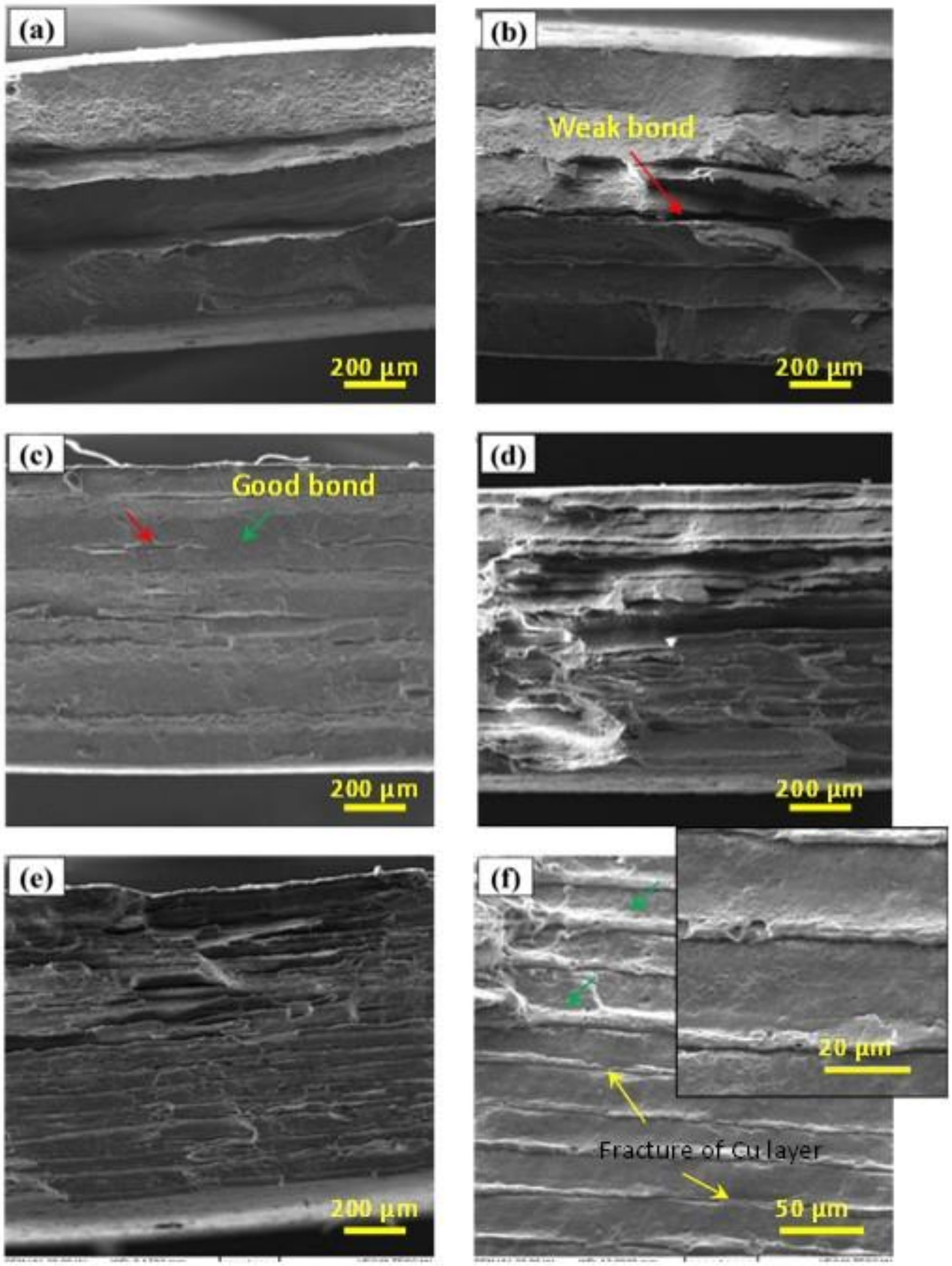

Figure 10. Tensile fracture surfaces of Al5052/Cu multi-layered composite: (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles and (f) fifth cycles.