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Fabrication of MMC Strip by CRB Process

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In this study, Al/Al_2O_3 composite strips were produced by the cold roll bonding (CRB) process. Microhardness, tensile strength, and elongation of composite strips were investigated as a result of changes in thickness reduction, quantity of alumina particles, and the production method used. It was found that higher values of reduction and quantities of alumina improved microhardness and tensile strength but decreased elongation. Furthermore, as-received strips exhibited the highest values for microhardness and tensile strength but the lowest for elongation. In contrast, post-rolling annealed strips recorded the lowest values for microhardness and tensile strength but the highest for elongation. Finally, it was found that pre-rolling annealing was the best method for producing this composite via the CRB process.

Keywords joining, mechanical testing, metal matrix composites, rolling

1. Introduction

A wide and growing interest has been witnessed in developing metal matrix composites (MMCs) due to their unique mechanical properties such as light weight and high elastic modulus. The common fabrication routes of particulate-reinforced MMCs include spray deposition, liquid metallurgy, and powder metallurgy (Ref 1). Since expensive equipment is required and the processing routes are usually complex, the cost involved in producing MMCs by these methods is high, which has limited the applications of MMC materials.

Among the current composite material technologies, cold roll bonding (CRB) for producing composite sheets has experienced a rapid growth and development in recent years due to its efficiency and economy as compared with other processes. To date, this method has been widely used for producing dissimilar layered composites including Al/Steel (Ref 2), Al/Zn (Ref 3), Al/Ti (Ref 4), and Al/Ni (Ref 5). However, there is no conclusive research on the production of particulate-reinforced composites by the CRB process.

The aim of this study is to manufacture the Al/Al_2O_3 composite via the CRB process and to investigate the composite's microstructure and mechanical properties such as tensile strength and microhardness. Also, the effects of pre- and post-rolling annealing treatments will be examined.

2. Experimental Procedures

2.1 Materials

As-received commercial purity aluminum sheets were cut into 100 mm × 40 mm × 1 mm sheets parallel to the sheet rolling direction. Also, some of the specimens were annealed at 643 K for 2 h (specifications are given in Table 1). Al_2O_3 particles (<50 μm) were then uniformly spread between two strips by a brush.

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2.2 Surface Preparation

To produce a satisfactory metallurgical bond by the CRB process, it is essential to remove any contaminations that may be present on the surfaces of the metals to be joined. These surfaces are composed of oxides, adsorbed ions, greases, moisture, and dust particles. A number of authors have claimed degreasing followed by scratch brushing with a rotating steel brush to be the best method for surface preparation (Ref 6, 7). Therefore, the preparation processes for the specimens in this study included degreasing in an acetone bath followed by scratch brushing the surfaces using a stainless steel brush with wires 0.26 mm in diameter. The initial surface roughness of the specimens was 0.5 μm, which, after scratch brushing, rose to about 4.2 μm in the longitudinal and transverse rolling directions. It is important not to touch the cleaned surfaces, because grease or oil on the faying surfaces impairs the formation of a strong joint. To avoid any oxide formation or interference with bonding, the CRB process must be carried out immediately after degreasing and scratch brushing.

2.3 Cold Roll Bonding (CRB) Process

After surface preparation, the specimens were carefully handled to avoid renewed contamination. To prevent the formation of any surface oxides and formation of a strong bond between layer strips, the specimens were rolled as soon as surface preparation was complete. In general, the time between surface preparation and rolling was kept to less than 120 s. Care was taken to properly align the two strip surfaces before rolling. The CRB experiments were carried out with no lubrication, using a laboratory rolling mill, with a loading capacity of 20 tons. The roll diameters were 125 mm, and the rolling speed was set at 2 m/min. The schematic illustration of the CRB process with the presence of Al_2O_3 particles is shown in Fig. 1. The high reduction by this process generates a great amount of heat and bonds the two surfaces together. For the prepared specimens, a series of rolling experiments were carried out using the rolling reductions between 50 and 80%.

Table 1 Specifications of commercial purity aluminum

Material	Chemical composition, wt.%	Temperature	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Hardness, HV
Al 1100	99.11Al, 0.17Si, 0.49Fe, 0.12Cu,	As-received	186.4	169.1	6.02	57
	0.02Mn, 0.09 others	Annealed	92.5	47.3	29.2	22

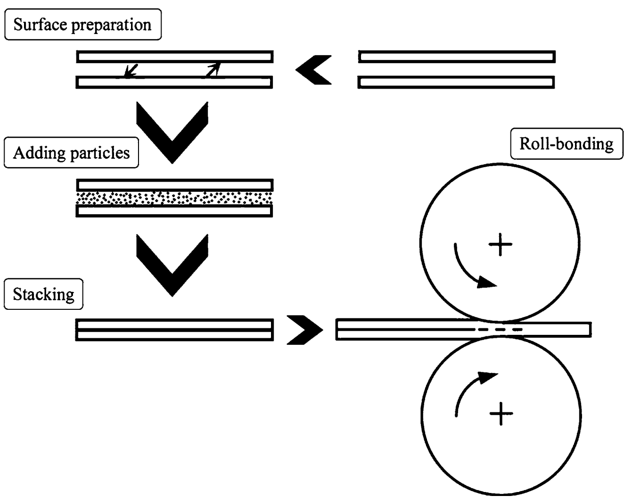

Fig. 1 Schematic illustration of the principle of CRB in the presence of Al_2O_3 particles

The amount of Al_2O_3 particles varied between 0 and 1.0 wt.%. A number of specimens were annealed at 643 K for 2 h before or after the CRB process to investigate the effects of pre-rolling and supplementary annealing on mechanical properties.

2.4 Mechanical Properties

2.4.1 Microhardness Test. Vickers microhardness test was performed using a Boehleer apparatus under a load of 100 g and time of 20 s on composite's cross sections perpendicular to rolling direction. Microhardness test was measured randomly at 10 different points for each sample, the maximum and minimum results were disregarded, and the mean microhardness value was calculated using the remaining eight values.

2.4.2 Tensile Test. The tensile test specimens were machined from the rolled strips conforming to the ASTM E8M tensile specimen, oriented along the rolling direction. The gage width and length of the tensile test specimens were 6 and 25 mm, respectively. The tensile tests were conducted at ambient temperature on a Hounsfield H50KS testing machine at an initial strain rate of 1.67×10^{-4} s^{-1}. Total elongation of the specimens was measured as the difference in the gage length before and after testing.

2.5 Microstructure Evaluation

The microstructures of the CRB-processed composite strips at various conditions were evaluated by scanning electron microscopy (SEM). To evaluate alumina distribution in matrix and bonding condition of the CRB-processed composite strips, the SEM examination of the strips was conducted. All SEM microstructures were observed along the RD-TD planes of the strips.

3. Results and Discussion

3.1 Microstructure Observation

The produced composites have a three layer sandwich structure including two thick pure aluminum layers and one thin MMC layer with a high volume fraction of alumina particles. The thin MMC layer consisted of bonding interface and Al_2O_3 particles. Figure 2 illustrates the SEM microstructures of the thin MMC layer with 1.0 wt.% alumina produced by CRB process with 70% reduction for various production methods. For the as-received and post-rolling annealed samples, the alumina particles are distributed non-uniformly in matrix compared to pre-rolling annealed sample. Furthermore, the porosity content between the aluminum matrix and the alumina particles in pre-rolling annealed sample decreased compared with other samples.

The alumina layer opens up into particles during rolling process (because the metal plastically deforms and extends), and as a result is uniformly distributed in the aluminum matrix. Then, the aluminum flows through the opened alumina regions because of the cracks that open up in the oxide layer. The interface, therefore, is a combination of alumina particles and bonded areas of extruded aluminum. Consequently, the opening of the oxide layer allows metal-metal contact and roll-bonding to take place. Therefore, due to high plasticity of the matrix of the pre-rolling annealed sample, the oxide layer can open easily, and which subsequently allows stronger bonding and more uniformity to take place compared with as-received and post-rolling annealed samples.

The bond strength of aluminum/alumina composites in the presence of various Al_2O_3 quantities (0, 0.1, 0.5, and 1.0) was previously investigated by the present author (Ref 8). It was found that the bond strength between strips decreases with an increase in the amount of Al_2O_3 particles. However, when the reduction of thickness increased, the bond strength between the aluminum strips increased. In other words, increasing the thickness reduction can eliminates the influence of the alumina particles on the bond strength.

3.2 Microhardness

Figure 3 shows variations in microhardness versus reduction for different amounts of alumina particles for the as-received, pre-, and post-rolling annealed strips. It can be seen that the strip microhardness increases with increasing thickness reduction. This can be related to the higher strain hardening due to dislocations at higher reductions. Also, it is evident that microhardness increases by increasing Al_2O_3 particles between two strips. These fine particles act as a barrier to dislocation movement, causing the enhancement of microhardness. Furthermore, the number of microhardness error bars increases with increasing alumina particles. In other words, the values of microhardness obtained for a CRBed strip without alumina particles are similar together. This can be related to the

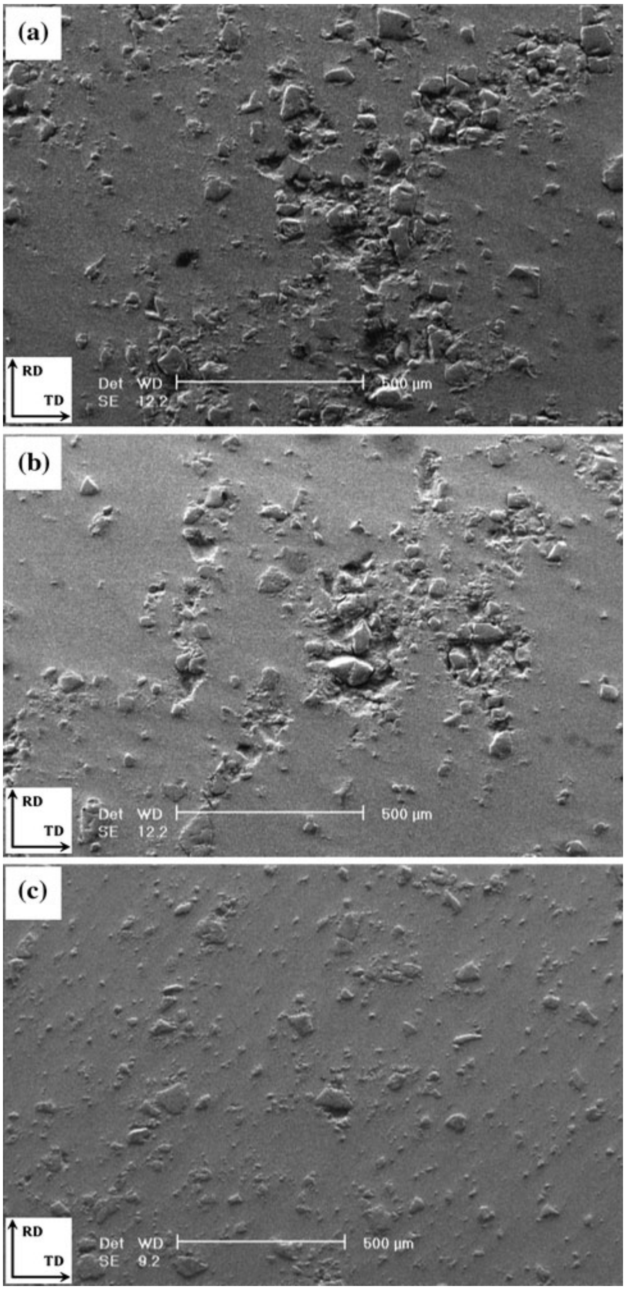

Fig. 2 SEM micrographs of the microstructures of the composite strips with 1.0 wt.% produced by CRB process with 70% reduction for various method: (a) as-received, (b) post-rolling annealed, and (c) pre-rolling annealed

non-uniform distribution of particles with higher quantities of Al_2O_3 particles.

Figure 4 shows variations in microhardness versus quantity of alumina with different treatments for 80% reduction. It can be seen that maximum and minimum microhardness values are obtained for the as-received and post-rolling annealed strips, respectively. In other words, the largest value of microhardness was achieved when the strip was rolled without pre- or post-rolling annealing treatment. This may be related to the significantly decreased amount of dislocations and dislocation debris after annealing treatment and the consequent decrease in work hardening. Also, no great difference was observed between the microhardness values of the as-received and pre-rolling annealed strips. For post-rolling annealed strips, a remarkable decrease was achieved in microhardness, which was almost three times that of the strip before post-rolling annealing treatment.

From the above results, it may be concluded that the CRB process increases hardness. This can be apparently attributed to strain hardening (because of the density of dislocations and the interaction between them).

3.3 Tensile Strength and Elongation

3.3.1 Effect of Alumina Particles. Figure 5 indicates the effects of alumina particles on the UTS and elongation of strips after the CRB process, respectively. Figure 5(a) shows that UTS increases negligibly due to the presence of alumina particles. These fine particles act as a barrier to dislocation movement, causing enhancement of strength. As seen in this figure, the increased UTS values (as a result of increased alumina quantity) for the as-received, post-, and pre-rolling annealed strips are 0, 3 and 6%, respectively. Therefore, pre-rolling annealing is a better treatment option compared with as-received and post-rolling annealed samples.

Also, it is seen in Fig. 5(b) that elongation decreases as a consequence of increasing alumina particles. This result is in total agreement with almost all the available literature of particulate-reinforced MMCs which shows that increasing volume fraction of particles decreases the elongation. This may be attributed to the presence of reinforcement/matrix interfaces in the composite samples. During tensile test, the interfaces are suitable sources for crack propagation and therefore, the elongation values of composites decreased. The decreased values of elongation (in consequence of increasing alumina) for the as-received, post- and pre-rolling annealed strips are 47, 23, and 15%, respectively. Again, pre-rolling annealing is a better treatment option compared with as-received and post-rolling annealed samples.

As expressed by the present authors previously (Ref 9, 10), two following major phenomena influence the strength and elongation values in the composites produced by CRB process: (a) the particle distribution is an effective parameter for determining the strength and elongation of the metal matrix composites. With pre-rolling annealing treatment (Fig. 3), the uniformity of alumina particles in the aluminum matrix improves, and therefore, strength and elongation increase compared with as-received and post-rolling annealed samples; (b) the bonding quality of alumina/aluminum and aluminum/aluminum is another important factor that affects both strength and elongation of the MMCs. As expressed by the present authors previously (Ref 8, 11), with pre-rolling annealing, the adhesion between alumina/aluminum and aluminum/aluminum becomes stronger due to the greater rolling pressure and higher plasticity of the matrix, which imparts a higher strength and elongation to the product.

3.3.2 Effect of Reduction in Thickness. One of the most important aspects of the CRB process is the tensile properties it provides in the product. Figure 6 presents the effects of thickness reduction on the UTS and elongation of strips after the CRB process. It can be seen that by increasing the amount of deformation, UTS increases. In the CRB process, strain hardening or dislocation strengthening plays a main role in increasing the strength. Elevation in UTS can be justified by work hardening. Large values of plastic deformation may occur in samples by the CRB process. These plastic deformations

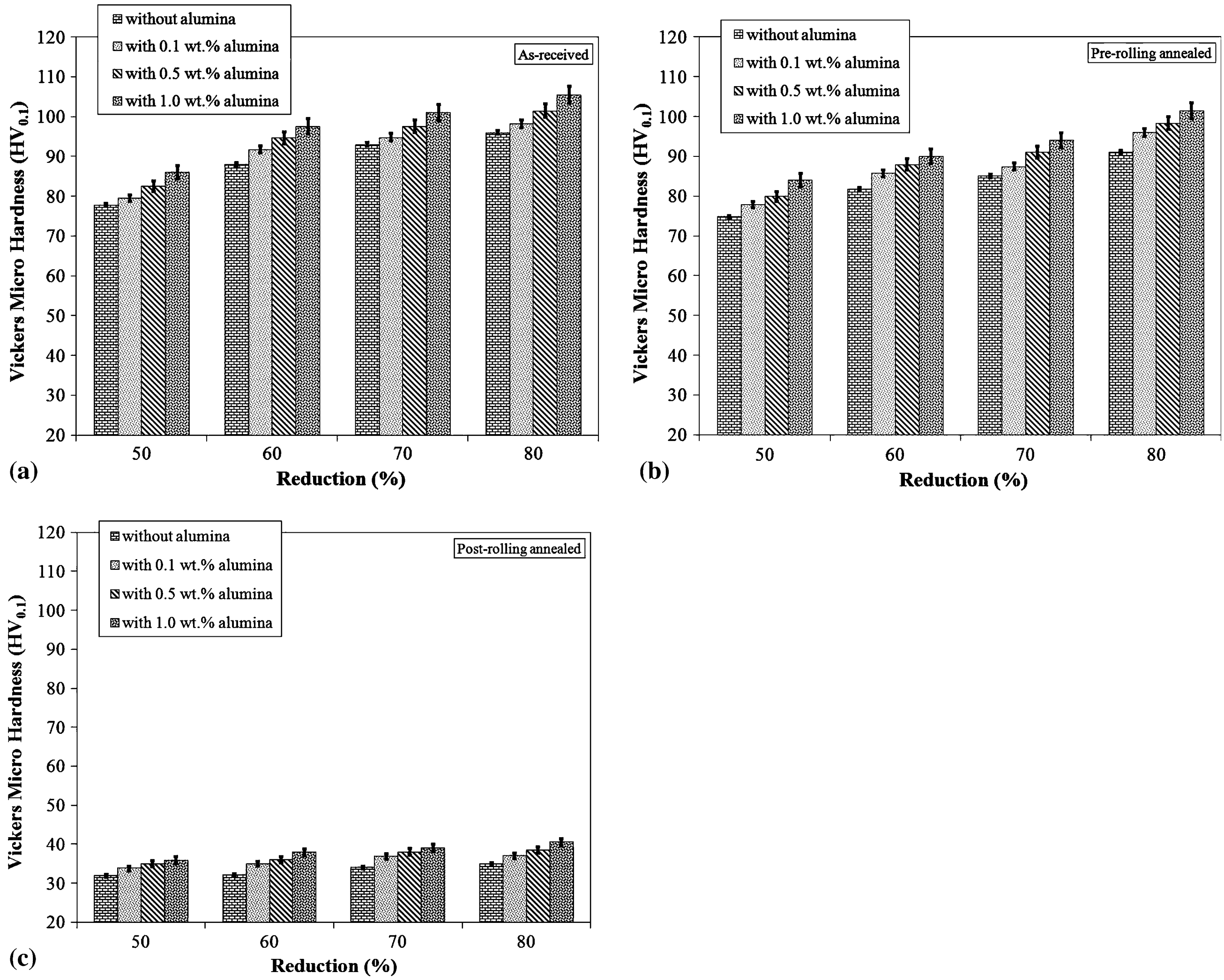

Fig. 3 Variations in microhardness vs. reduction for different amounts of alumina particles for (a) as-received, (b) pre-rolling annealed, and (c) post-rolling annealed strips

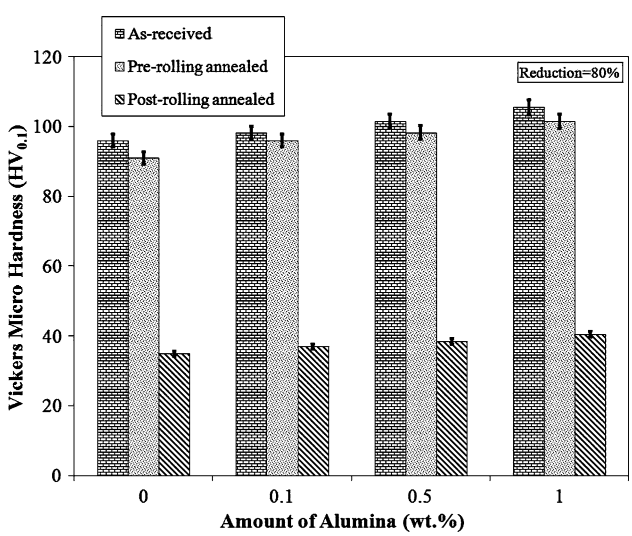

Fig. 4 Variations in microhardness vs. alumina quantity with different treatments for 80% reduction

cause work hardening. Figure 6(a) revealed that the increased UTS values (due to increasing thickness reduction) for the as-received, pre-, and post-rolling annealed strips are 7.1, 6.4, and 2.9%, respectively. Also, it is obvious from Fig. 6(b) that the increases in thickness reduction match decreases in elongation. Decreased elongation in strips can be justified by work hardening, too. The values obtained for decreases in elongation (due to increasing reduction of thickness) for the as-received, pre-, and post-rolling annealed strips are 13.2, 9.8, and 5.6%, respectively. All these results are in agreement with those obtained from the microhardness test.

3.3.3 Effect of Annealing Treatment. Figures 5 and 6 demonstrate the effects of different composite production methods on the UTS and elongation of strips, respectively. It can be seen in Fig. 5(a) and 6(a) that the as-received strips had the highest UTS while the post-rolling annealed strips had the lowest UTS values for any reduction level and any quantity of alumina. Also, it is evident from Fig. 5(b) and 6(b) that the as-received strips underwent the least elongation while the post-rolling annealed strips experienced the highest elongation for any reduction level and any quantity of alumina.

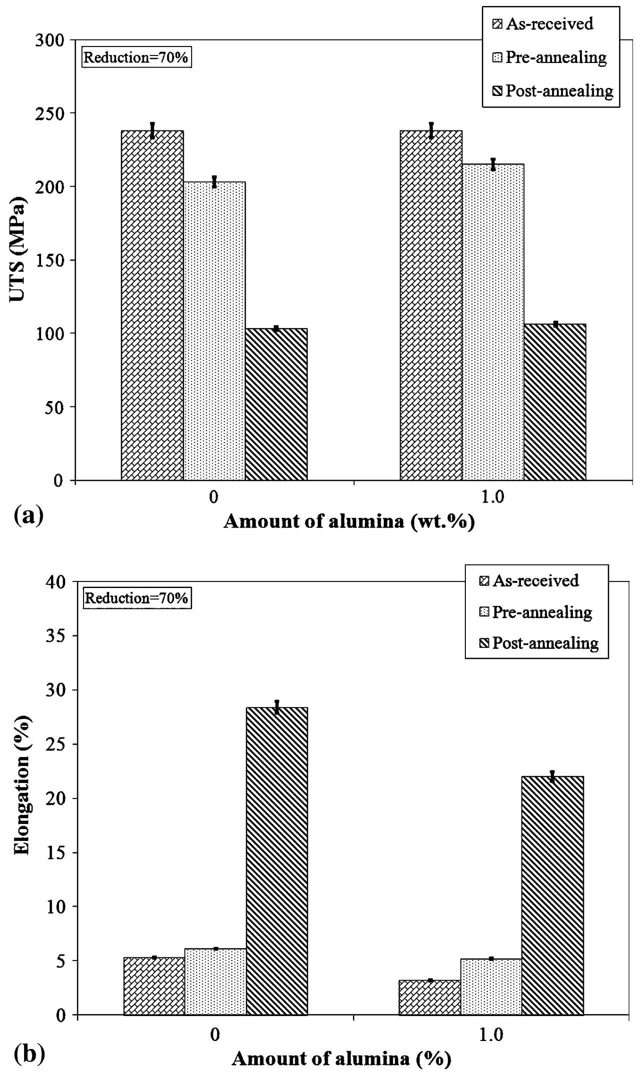

Fig. 5 Variations in (a) UTS and (b) elongation for different amounts of alumina

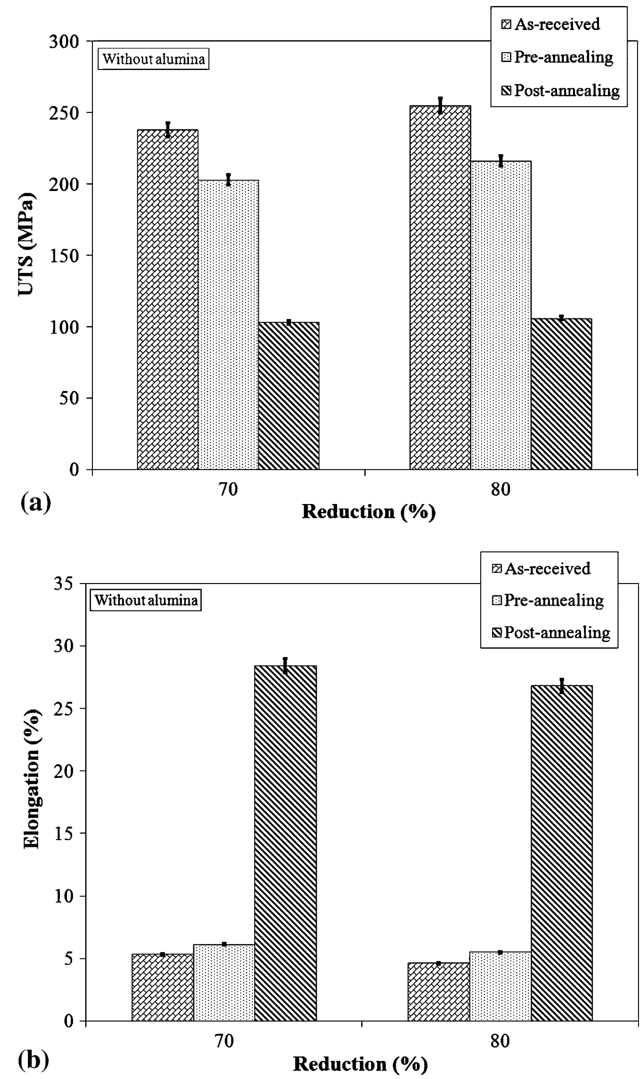

Fig. 6 Variations in (a) UTS and (b) elongation for different reduction levels

The as-received strips had the maximum strain hardening: hence, the highest UTS and the lowest elongation. Also, the post-rolling annealed strips had the minimum work hardening and, hence, their lowest UTS and largest elongation.

Referring to Fig. 5(a) and 6(a), the post-rolling annealing caused a great decrease of UTS values. Also referring to Fig. 5(b) and 6(b), the as-received samples caused a great decrease of elongation values. Furthermore, referring to Fig. 3, the matrix of the pre-rolling annealed sample, due to high plasticity, can be extruded more easily, which subsequently results in stronger bonding and more uniformity compared with as-received and post-rolling annealed samples. Therefore, based on all the results reported above in sections 3.1, 3.2, and 3.3, it is concluded that pre-rolling annealing is the best method for producing Al/Al_2O_3 by the CRB process.

Alumina particulate-reinforced aluminum matrix composites have been well developed over the past few decades, because of their excellent properties such as light weight, high elastic modulus and wear resistance, low thermal expansion coefficient, etc., and also because of the possibility of their fabrication by many well-known methods (Ref 1, 12). Thus, these composites are expected to have many applications in aerospace, aircraft, automobile, electronic industries, etc. (Ref 12, 13). Aluminum/alumina metal matrix composites are produced using both solid-state route (blending, compacting and sintering of powders) and liquid-state route, such as infiltration, stir casting, squeeze casting, and spray forming (Ref 1, 12, 13). However, those MMCs produced by the above mentioned traditional processes suffer from some drawbacks, such as the non-uniform distribution of the reinforcement, undesirable chemical reaction, and poor adhesion between the reinforcement and the matrix. Also, since expensive equipment is required and the processing routes are usually complex, the cost to produce MMCs by these methods is high, thereby having limited the applications of MMC materials.

Also, aluminum/alumina metal matrix composite strip can be produced by conventional method through ingot casting followed by metal-working processes. However, it becomes very expensive due to high rejection rate during mechanical working. In this study, a low-cost technique (cold roll bonding—CRB) was used to fabricate an aluminum/alumina matrix composite dispersed with three different volume fractions of alumina particles. This novel manufacturing has the high mechanical properties and the flexibility of controlling the volume fraction of the MMCs by varying the alumina particles between the aluminum strips. Furthermore, this method is very simple and can be easily automated.

4. Conclusion

This study investigated the effects of reduction in thickness, quantity of alumina particles, and Al/Al_2O_3 composite production method by the CRB process on the microstructure and mechanical properties of the product. The findings can be summarized as follows:

1. With pre-rolling annealing treatment, the distribution of alumina particles in the aluminum matrix changes to yield a more uniform product compared to the as-received and post-rolling annealed samples.
2. Microhardness increased with increasing reduction and alumina content. Furthermore, the highest values were obtained for microhardness with the as-received strips (without pre- and post-rolling annealing treatments).
3. The tensile strength of the CRBed strips increased with increasing thickness reduction and alumina quantity. Also, the highest values of tensile strength were obtained with the as-received strips (without pre- and post-rolling annealing treatment.
4. Elongation increased with decreasing thickness reduction and alumina content. Furthermore, the highest values of elongation were obtained with post-rolling annealed strips.
5. Pre-rolling annealing was the best method for producing Al/Al_2O_3 composite strips via the CRB process.

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