The role of applied strain and volume percentage of components on mechanical properties and fracture toughness in multilayered Al/Mg composite fabricated by the accumulative roll bonding process

M Delshad Gholami, D Rahmatatabadi, T Shojaee, R Hashemi and B. Mohammadi
School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran
E-mail: rhashemi@iust.ac.ir

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Abstract
In this study, for the first time, the effect of applied strains and volume percentage of components of layered composite on the mechanical properties and fracture toughness of Al/Mg were investigated experimentally. The multilayered Al/Mg were produced by the accumulative roll bonding (ARB) process. For the investigation, three Al/Mg composites with different volume percentages (25%, 50%, and 66.6%Al) at different applied strains (0.8–3.2) were produced. The experimental evaluation included microscopic examination by optical microscope imaging, uniaxial tensile test, and plane strain fracture toughness. As the applied strain for all three composites increased, plastic instability in the magnesium reinforcement intensified, but due to the low thickness of the Al layers compared to the Mg layer, uniform structure of Mg distribution in Al for all three composite was not achieved. Also, by adding Al layers to the primary composite, a lower shear strain was applied to the magnesium reinforcement, and instability intensity in the reinforcement layer decreased. For this reason, as Al layers increased, plastic instability diminished. By raising the exerted strain, the values of tensile strength increased, and by adding Al layers, the elongation increased. The maximum amount of tensile strength and elongation for each composite was achieved in the same ARB pass (last pass) and the highest values of UTS and elongation were reached to 384.1 MPa and 1.95% for Al25%Mg, respectively. However, the highest amount of fracture toughness for each composite was obtained in the different exerted strains and the maximum value of 41.4 MPa·m^{1/2} was achieved for Al33.3% in the third pass. The present phenomena indicated that many factors such as higher Mg volume with higher energy absorption, plastic instability, thickness ratio, plastic instability, and value of applied strain affected the fracture toughness. In summary, the relationship between fracture toughness with applied strain and also with volume percent of Al was not always straightforward. It depends on other factors, such as how the reinforcement was distributed, the thickness of the layers, the workability, and the addition of aluminum. Also, the applied strain has a more significant effect on increasing fracture toughness in multilayered composite if they cause a uniform distribution of reinforcement particles in the field or continuity in the reinforcement layer.

1. Introduction

Today, the production of multilayer metal composites has been accomplished because of the appropriate mechanical properties and high strength to weight ratio [1]. Magnesium, because of its unique properties such as suitable machining ability, good corrosion resistance, and excellent creep resistance, has abundant uses in industry, especially in the aerospace and automotive industries [2–4]. Magnesium, with a purity of 99%, is rarely used in engineering, so it is used as an alloy. AZ series magnesium alloys such as AZ31 and AZ91 have the highest percentage of magnesium, aluminum, and zinc in their chemical composition [5, 6]. Aluminum is also the most important and widely used metal in the world after steel, and its use in diverse industries is soaring [7].
limitations of using magnesium are its high cost and its low ductility at ambient temperature. According to what was said, aluminum-magnesium multilayered composite can have many applications in industries due to the favorable properties of the two metals [8, 9].

One of the simplest methods for the production of layered composites is the accumulative roll bonding (ARB) technique and today, the production of metal matrix composites (MMC) by the ARB process has become a research topic of interest to researchers. ARB, despite its low cost and applicability to all metals, is a subset of the severe plastic deformation (SPD) and has all the advantages of these methods [10–12]. So far, much research has been done on the mechanical and metallurgical properties of composites made by this method. Researches have shown that the ARB process boosts the mechanical and metallurgical properties of different metals and composite [13–15]. This process is affected by many factors such as crystallite structure of metals [16], surface preparation and roughness, coefficient of friction, rolling direction, rolling speed, presence of particles, particles material, strain rate, heat treatment between passes, process temperature, annealing before and after rolling, temperature and time of annealing, the percent reduction in thickness, the thickness of the primary sheet layer, etc. [16–19]. In most SPD processes, strength and hardness improvements are accompanied by a sharp drop in ductility [15, 20–23]. Therefore, studying the parameters of toughness and energy absorption can be a more attractive parameter in these processes, which has recently received more attention. Fracture toughness is an essential and main engineering parameter used to estimate component life. The fracture toughness indicates the amount of energy absorbed by the material before the fracture [24, 25]. To date, research has been conducted on the fracture toughness of composite materials.

Xia et al have reviewed the role of grain size on rupture mechanism and fracture toughness in Equal Channel Angular Pressed (ECAPed) AZ31 magnesium alloy [26]. They realized the amount of fracture toughness of AZ31 magnesium alloy processed by ECAP was affected by grain size and by rising the number of ECAP passes the grain size and fracture toughness decreased and increased, respectively. [26]. Samekawa and Mukai reported that the equal channel angular extrusion (ECAE) process increased the fracture toughness of Mg alloy [27]. They said that with the implementation of the ECAE process, the amount of plastic area, which is affected by the three factors of strength, strain hardening exponent, and elongation, has increased. They also found that reducing grain size and improvement dispensation of basal texture is affected by the amount of fracture toughness [27]. In 2017, Rahmatabadi et al assessed the role of the ARB process on the fracture toughness of pure Al [1]. Their result also showed a significant improvement in the amount of fracture toughness with increasing applied strain. In other studies, they evaluated the fracture toughness of Al/Cu and Al/Cu/Mg composite processed by ARB process [14, 28]. Results showed that the fracture toughness of both composite increases by increasing the applied strain. Also, its value reaches its maximum at the end of the third pass.

Although much research has been done so far on the fabrication and mechanical properties of Mg-Al multilayer composites, however, there is still no comprehensive investigation on the fracture toughness of this type of composite made by the ARB process. Also, there are no investigations into the fracture toughness of the ARBed specimens, which have investigated the effect of strain on material and composite with a specified volume percentage. In contrast, the bulk percentage of the metal in MMCs can have a significant impact on the fracture toughness and properties.

In the present research, Mg-Al composite was fabricated by the accumulative roll bonding process (ARB) at ambient temperature in four passes and, for the first time, the effect of applied strains and volume percentage of components of layered composite on the mechanical properties and fracture toughness of Al/Mg processed were investigated. To this end, three composites with different volume percentages of aluminum and magnesium (Al50%Mg, Al33.3%Mg, Al25%Mg) were produced by the ARB process at ambient temperature. The identical conditions were considered thoroughly (e.g., reduction thickness, preparation condition, temperature, speed rolling, etc.). The experimental tests were performed according to standards such as tensile, microhardness, microscopic and optical imaging, and drawing of pre-crack compacted tensile specimens, which created with wire cut machines for each sample.

2. Production of Al/Mg composite

2.1. Materials and methods

In this study, three Al-Mg composites with different volume percentages (25%, 50%, and 66.6%Al) in different passes via the ARB process were produced. The first composite was produced with the same percentage of 50% Al and 50% Mg (Al50%Mg) in the four ARB passes. In the second pass, two Al layers were added to composite No. 1, and the second composite was produced (Al66.6%Mg) and in the same way, in the second pass, two more layers of aluminum were added to composite No. 2, and third composite (Al66.6%Mg) was processed, and the processing of all three composites proceeded to the fourth pass. For this purpose, two Al 1050 sheets and one Mg AZ31 sheet with thicknesses of 0.5 mm and 1 mm were prepared, respectively. The chemical composition and
mechanical properties of the sheets used are listed in table 1. Before performing any ARB process, to remove the hardness created in the sheet resulting from the production process and to achieve a more uniform structure, the sheets annealed in the furnace at 385 °C for 75 min.

The first step in the ARB process was the preparation of sheets. After degreasing and washing using acetone, sheets were brushed using steel wire brushes. This eliminated the surface oxide layers and created a hardened layer on the sheet. After the sheets were prepared, they were lined up in such a way that their prepared surfaces came in contact with each other [29]. To make the primary sandwich, a sheet of magnesium was placed in the middle and two aluminum sheets on either side. To prevent the sheets from slipping over each other during rolling, the four corners of the sheets were fastened with thin copper wire. Then by rolling, a 50% thickness reduction was applied, and sheets bonded to each other. Next, the rolled sheet was cut longitudinally in the middle and divided into two equal parts, and the same steps were repeated. Therefore, by increasing the number of these cycles, a large amount of plastic strain could be applied to the material [30]. The operation was carried out by laboratory rolling consisting of two rollers with a diameter of 250 mm, and a motor of 22 KW capable of producing a maximum speed of 40 rpm at room temperature, no lubrication and no heat treatment between the cycles were performed. Figure 1 shows the schematic of the accumulative roll bonding process.

The second composite was produced using the first composite in the first pass. For producing the second composite (Al33.3%Mg), two Al layers with equal thickness as the outer layers on both sides were welded to the Al-50%Mg composite in the first pass by applying a 50% strain during rolling, and the Al33.3%Mg composite was also produced in four passes. The same process was repeated for the third composite, such that by welding two Al sheets to Al33.3%Mg composite in the second pass, Al25%Mg composite was produced. The ARB process also processed the composite until the fourth pass. All other conditions were considered equal in the

| Table 1. Chemical composition and mechanical properties of both Al 1050 alloy and Mg AZ31. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material | Chemical composition (wt. %) | Hardness (HVN) | Elongation | Yield strength (MPa) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Al 1050 | 99.44 Al, 0.406Fe, 0.121Si, 0.033Cu | 24 | 55 | 61 |
| Mg AZ31 | 95.7Mg, 3Al, 1Zn, 0.3Mn | 60 | 18 | 168 |
production of composites with accumulative roll bonding processes such as strain applied per pass, the thickness of sheets used, rolling temperature, rolling speed, preparation conditions, and so on.

2.2. Examination of microstructure, plastic instability, and mechanical properties
To investigate the bonding of the layers, plastic instability, and how the shear bands were formed, the specimens were imaged in the thickness by optical microscope (OM). For this purpose, after mounting the specimens, their surface should be thoroughly sanded and polished. Uniaxial tensile tests were required to determine the mechanical properties, including tensile strength and maximum elongation. After preparing the tensile test specimens, based on the ASTM-E08 standard (The gauge length and width of the tensile test specimens are 25 and 6 mm, respectively) in the rolling direction, the test was performed at room temperature with a strain rate of $1 \times 10^{-4}$/s. Vickers microhardness tests were also performed for each layer at different passes at more than ten points, and the average of achieved data was reported. The value and time of the applied force for all layers were assumed to be 100 gr and 10 seconds, respectively.

2.3. Fracture toughness
In order to investigate the fracture toughness of the specimens, three samples were prepared from each sheet according to the ASTM E647 standard using a wire cut machine. The test of plane strain fracture toughness was performed by compressive-tensile (CT) samples. Therefore, fasteners were designed and manufactured according to ASTM E399 for fracture toughness specimens. The loading was quasi-static at a speed of 0.5 mm min$^{-1}$ at ambient temperature. According to ASTM E-561, the plane strain fracture toughness of the specimens ($K_c$), can be obtained. It should be noted that the value of $K_c$ for different ARBed specimens must be determined at the instability condition from the tangency between the R-curve and the applied K-curve of the samples. The crack grows resistance ($K_Q$) for the CT specimens, can be calculated as follows:

$$ k_r = \frac{P_t}{b\sqrt{w}} \times f_i\left(\frac{a}{w}\right) $$

$$ f_i\left(\frac{a}{w}\right) = \left[\frac{2 + \frac{a}{w}}{\left(1 - \frac{a}{w}\right)^2}\right]\left[0.886 + 4.64\left(\frac{a}{w}\right) - 13.32\left(\frac{a}{w}\right)^2 + 14.72\left(\frac{a}{w}\right)^3 - 5.6\left(\frac{a}{w}\right)^4\right] $$

Applied $K_{curve}(P_t) = \frac{P_t}{b\sqrt{w}} \times f_i\left(\frac{a}{w}\right)$

Figure 2. Effect of applied strain on the microstructure of RD-ND section of Al50%Mg composite: (a) first pass, (b) second pass, (c) third pass, and (d) the fourth ARB pass.
Where, \((p_i)\), \((w)\), \((B)\), and \((a)\) are the variable force in terms of crack growth, sample width \((19\, mm)\), sample thickness \((1\, mm)\) and crack growth size during the test, respectively and it is valid for \(\frac{a_w}{w} \geq 0.35\). The coefficient \(f\left(\frac{a}{w}\right)\), which only dependents on the specimen geometry and based on the standard, the given expression for \(f\left(\frac{a}{w}\right)\) is considered.

### 3. Results and discussion

#### 3.1. Microstructure and plastic instability

In figure 2, optical microscope images of the Al/Mg composite are presented in equal volume percentage (Al 50\%Mg) in terms of the number of ARB passes. According to figure 2, plastic instability (necking) was observed in the Mg layer from the first pass. As the number of passes of the ARB process raised, the thickness of the Mg layers decreased, and more severe plastic instability was observed (necking and fracture) due to the high strain applied at each pass at ambient temperature. As shown in figures 2(c) and (d), the composite layered structure...
was not destroyed even at the end of the fourth pass; the Mg layer was seen indentation and waveform. According to previous researches in the ARB process, the small difference in the two main factors of the flow properties and the thickness of matrix and reinforcement in metal matrix composite preserved the layered structure \([13, 31]\). In figures 3 and 4, the second (Al33.3%Mg) and third composites (Al25%Mg) microstructure are presented from the second to the fourth and third to the fourth ARB passes, respectively. It can be seen from the images that with the addition of one and two pairs of Al layers and rising the applied strain, the layered structure was gradually decreased. It was foreseeable that the addition of Al layers would result in increases the thickness ratio of the matrix to the reinforcement layers, and by reducing the Mg volume ratio, more severe plastic instability would occur and according to figure 4, plastic instability is also apparent in the Al25%Mg composites and plastic instability, thickness reduction and discontinuity of magnesium layers are more severe. In summary, for all three composites with layered structures, waveform and center core, the increase in the applied strain increased the amount of plastic instability in Mg and other factors such as the thickness of the outer Al layers and the thickness ratio were affected to the applied shear strain \([32]\). In figure 5, the last two ARB passes for all three composites are presented in order to investigate the effect of the volume percentage of the constituent layers, and a layered structure is seen for Al33.3% Mg and center core in the third pass of the Al25% Mg composite. In Al50%Mg, although required shear strain was applied for Mg, there was no uniform distribution of Mg in the matrix due to the higher thickness of the primary Mg layer compared to the Al layers. In figures 5(c) and (f), white layers are seen in the Al interfaces. The results showed that the alumina oxide layer was formed in the Al interfaces, which is based on previous results due to the low thickness of the Al layers and the heat generated when the high thickness during rolling was done \([30, 33]\).
3.2. Mechanical properties

Engineering stress-strain diagrams for the Al/Mg composite for different modes are presented in figures 6 and 7. In figure 7, the behavior of Al/Mg composite with different volume percentages in different ARB cycles under uniaxial tensile test are presented. In other words, in figure 7, the applied strain effect for the three Al/Mg composites is presented, and the tensile strength value is improved for almost all three composites by increasing the applied strain. For quantitative and detailed evaluation, the values of ultimate tensile strength and elongation from stress-strain diagrams are extracted and presented in table 2. According to table 2, for Al50%Mg composites, by rising the exerted strain during cold roll bonding, at the beginning (i.e., second pass) ultimate tensile strength (UTS) and elongation values decreased and then for third and fourth ARB cycles increased. The decrease is due to severe plastic instability in the second pass and loss of layer structure in the magnesium layer and then improving the uniform magnesium distribution not so ideally causes a slight increase in UTS. Based on table 2, for Al33.3%Mg and Al25%Mg composites, strength and elongation sored with increasing exerted strain. It is noteworthy that the changes of elongation relative to the strength during the ARB process are negligible, and the amount of elongation did not change much with rising the applied strain due to the cold work and high reduction thickness in each rolling pass. According to these results and previous studies, cold work and grain refinement are responsible for changes in mechanical properties [34–36]. Cold work at lower strains and grain refinement at high strains play this role. These are two of the main strengthening mechanisms in all SPD processes [1, 37]. Plastic instabilities, oxide layers, and reinforcement particles also affect the mechanical properties changes, which are further investigated in this study [38]. In layered composites produced by the ARB method, usually, if the reinforcement distribution is continuous or homogeneous, the amount of strength increases continuously with increasing the number of ARB passes and the thickness of the reinforcement layer. However, in this study, due to the lack of uniform distribution and preservation of the layered structure, increasing magnesium has reduced the strength and increasing magnesium has reduced the strength and brittle pieces of magnesium are the main source of crack growth and covering surfaces with aluminum has reduced.

Table 2. Variations of UTS and elongation during different ARB cycles for Al%50 Mg, Al33.3%Mg, and Al25%Mg composite.

|                | Al (Vol%) | Pass 1 | Pass 2 | Pass 3 | Pass 4 |
|----------------|-----------|--------|--------|--------|--------|
| UTS (Mpa)      | 50        | 151.5  | 123.0  | 245.2  | 293.0  |
|                | 66.7      | **     | 208.5  | 209.8  | 307.9  |
|                | 75        | **     | **     | 285.9  | 384.1  |
| El (%)         | 50        | 0.63   | 1.02   | 1.19   | 1.16   |
|                | 66.7      | **     | 1.27   | 1.02   | 1.27   |
|                | 75        | **     | **     | 1.21   | 1.95   |

Figure 8. Force displacement diagrams during different ARB cycles for: (a) Al50%Mg, (b) Al33.3%Mg and (c) Al25%Mg composite.
brittleness and increased strength. The highest strength was reached to 384.1 MPa for the lowest percentage of magnesium and at the highest applied strain.

In figure 7 and table 2, the tensile strength and elongation of the three Al/Mg composites are presented in the third and fourth ARB passes. In both passes, the Al25%Mg composite has much higher strength and elongation, indicating that with the addition of more Al layers, the strength and ductility are increased. However, this conclusion cannot be generalized, and the comparison of the other two composites (Al50%Mg and Al33.3%Mg) shows that other factors are involved. Comparison of the two composites revealed that in the third (the same strain), the Al50%Mg was stronger, and in the fourth pass, the Al33.3%Mg composite was stronger. However, the magnitude of elongation at both passes is higher for Al33.3%Mg. Adding two layers of annealed Al to the primary composite (Al50%Mg) resulted in the production of the second composite (second pass of Al33.3%Mg), indicating that the outer Al layers were less cold work than the inner layers, resulting in higher formability and lower strength. By increasing the applied strain (fourth pass), this effect decreases, causing the composite containing new Al layers (Al33.3%Mg and Al25%Mg) to have a higher hardening rate, and by doing one pass, the strength of the composite with added Al will be increased with the higher trend.

3.3. Fracture toughness

Figure 8 shows the force-displacement diagrams during the tensile of compact tension specimens for Al/Mg composites at different volume percentages of components. The values of the fracture toughness calculated by the $R$ curve method are also presented in table 3. According to figure 8(a) and table 3, the Al50%Mg composite has the highest force in the second cycle or, in other words, has more resistance to crack initiation. The resistance value is upward in the first and second passes, and in the third pass due to discontinuity and failure in the magnesium layer is descending. Also, based on table 3, the maximum fracture toughness is achieved at the last pass, and except for the third pass, there is an upward trend in the other passes. The fracture in the magnesium layer and its heterogeneous and uneven distribution of magnesium in the composite causes the fracture to occur precisely in these areas due to the lower strength of Al compared to magnesium. The most important parameters in the resistance to crack opening in MMCs are related to the strength of the material, the elongation, and the plastic deformation of the crack opening [14, 28]. The process of change of all of them depends on many parameters such as hardening, shape, and size of the reinforcement particles, grain refinement, dislocation density, and the quality of the connection of the layers [29, 39–41].

Similarly, according to figures 8(b) and (c) and table 3, Al33.3%Mg in the third pass, and Al25%Mg in the fourth pass showed the highest resistance at crack initiation and fracture toughness. Based on figure 6(b), in the fourth pass, the fracture toughness of the Al66.6% composite reduced over the third pass due to excessive brittleness. Considering all the results (table 3), At first glance, there is no logical relationship between the applied strain and the maximum force and fracture toughness for the three composites, and each composite reaches its maximum strength in a different pass. On closer examination, however, we observed that for each sample maximum crack resistance and fracture toughness were reached in one pass after that Al layers were added, that is, for Al50%Mg in the second pass, for Al33.3%Mg in the third pass, and Al25%Mg in the fourth pass. The addition of Al makes the surface layers very soft. It also does not allow more shear strain to be applied to the magnesium core, which prevents fragmentation and distribution of magnesium in the field but improves ductility.

On the other hand, excessive strain results in excessive brittleness of the specimens resulting in a severe loss of toughness. All of these factors influence fracture toughness and are the main keys for determinants of fracture toughness. In summary, the relationship between toughness and applied strain is not always straightforward and this trend has been reported in previous researches [42, 43]. It depends on other factors, such as how the reinforcement is distributed, the thickness of the layers, and the workability of components [15]. Somekawa reported, in addition to improving mechanical properties in the SPD process, anisotropy, grain size,
recrystallization, and basal texture distribution are very influential on the amount of fracture toughness [27, 44–46].

The results of the access of the effect of volume percentage of the component in Al/Mg composite on the amount of resistance to crack initiation and fracture toughness are presented in figures 9–11. In both third and fourth passes, Al50%Mg has the lowest strength and fracture toughness due to its low UTS and elongation as well as the heterogeneous dispersion of Mg layers. On the other hand, by adding two and four layers of Al to the Al50%Mg composite, the amount of fracture toughness for Al33.3%Mg increased and decreased for Al25%Mg, respectively. Magnesium has a higher energy absorption than aluminum, and as its composite volume decreases, the amount of fracture toughness decreases. In addition to the difference in the percentage of components, the two composites differed in the layering of the layers in the third and fourth passes. Also, the strength of the surface Al layers was different. Magnesium is not applicable because of its brittle structure at ambient temperature, and the addition of Al improves the mechanical properties, although the maximum of the toughness was obtained for the Al33.3%Mg (MPa·m$^{1/2}$). Al33.3%Mg composite has the highest fracture toughness at the same strain due to more uniform dispersion of magnesium layers than Al25%Mg and higher formability due to the presence of more Al than Al50%Mg composite. Therefore, the percentage of aluminum used in Al/Mg composite has an optimum value, and its further addition causes a decrease in the mechanical properties and toughness.
4. Conclusion

In this paper, nine layered Al/Mg composites were produced by accumulative roll bonding (ARB) method with the same thickness (1 mm) with different volume percentage (Al50%Mg, Al33.3%Mg, and Al25%Mg) and applied strain (0.8–4) and then the plastic instability, mechanical properties, and fracture toughness were investigated, and the following results were highlighted:

1. By raising the exerted strain, more plastic instability in the magnesium layers appeared, however, in all three composites, no uniform structure of Mg in the Al field was observed: in the Al50%Mg due to the low thickness of Al compared to magnesium in the composite, in the Al33.3%Mg and Al25%Mg due to reduction of shear stress applied to magnesium by the addition of annealed aluminum layers, but with increasing the thickness ratio of the layers, the instability is more and the thickness of the magnesium layer is less.

2. As the number of ARB increased, the amount of strength and elongation increased, and the best mechanical properties were obtained in the last cycle for all three composites. Two mechanisms of work-hardening and fine-graining are the main reasons for the increase in mechanical properties in plastic deformation processes; however, the plastic instability and the discontinuity of the reinforcing layers in some of the passes caused a decrease in strength.

3. In both the third and fourth pass, Al50%Mg has the lowest strength and fracture toughness due to its low UTS and elongation as well as the heterogeneous dispersion of Mg layers. The highest amount of fracture toughness was not obtained in the highest applied strain or greatest volume percentage of aluminum, but in the third pass for Al33.3%Mg composite was obtained.

4. The percentage of Al used in Al/Mg composite and applied strain have an optimum value, and its further addition causes a decrease in the mechanical properties and toughness. Also, many other parameters such as layering, thickness ratio, flow properties, plastic instability, microstructure, etc. are very effective on fracture toughness.

ORCID iDs

D Rahmatabadi @ https://orcid.org/0000-0002-6898-3061
R Hashemi @ https://orcid.org/0000-0001-8369-0390
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