Original Article

Influence of ARB technique on the microstructural, mechanical and fracture properties of the multilayered Al1050/Al5052 composite reinforced by SiC particles

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A B S T R A C T
In this paper, Al1050/Al5052/SiC composite was manufactured via accumulative roll bonding (ARB) technique, and the fracture toughness for the different passes was experimentally investigated. The microstructure, mechanical properties, and fracture behavior were determined through Optical Microscopy (OM), Scanning Electron Microscopy (SEM), tensile test, microhardness, and plane stress fracture toughness. The results of OM showed that local necking and failure of Al5052 reinforcement layers happened at the 1st pass and after that by raising the exerted strain the shape of the layers varied from the lamellar to particle form, and finally, Al1050/Al5052/SiC composite was provided via perfect dispersion of layers and particles reinforcements. The microhardness variations were ascending for both Al layers in terms of ARB cycles, and this trend was observed for UTS variations except for the third and fourth passes so that in the both passes the strength was downtrend. Finally, the best UTS and elongation values were obtained on the last pass. The results of SEM demonstrated that by raising the exerted strain, the kind of fracture mechanism varied to shear ductile from ductile. From zero pass (primary sandwich) to the second pass, the rate of changing in fracture toughness was ascending and then drastically reduced. Also, maximum and minimum values are achieved at second and third ARB cycles respectively. Due to the higher variation in the strength compared to elongation, as in previous researches, the trend of toughness was similar to that of strength, with this difference that the presence of ceramic particles at the interfaces was causing the brittleness in the composite.

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1. Introduction

Today, due to the industry’s need, the use of multilayered composites with different qualities compared to the monolayer, including lightweight, higher mechanical properties, corrosion resistance, good wearing stability, and thermal stability are felt more than ever before [1,2]. In the meantime, pure Al and Al alloys are the most widely utilized in multilayered composite materials due to their favorable properties, low cost and easy access [3]. In recent years, ceramic particles such as SiC, WC, B₄C, TiC, ZrO₂, and SiO₂ also were utilized as reinforcing particles in MMCs with similar and dissimilar metal layers [4–6]. Ceramic reinforcement powders were used to increase hardness, tensile strength and increase thermal resistance in various applications. Different methods were used to make metal-based composites, which included powder metallurgy, stir and squeeze casting, compocast and spray-forming as the most widely used methods [7–9]. Indeed, the use of ceramic powders with small grain sizes could produce a microstructure with a more uniform distribution of particles and a strong bond between the reinforcement and the metal matrix [6]. Moreover, it ultimately could improve mechanical properties. Usually, in all of these methods (e.g., powder metallurgy and different casting methods), coarse grain particles with a size greater than 5 μm were usually used. These particles tend to become non-uniform distribution and clustering, which has a negative influence on the electrical and mechanical behaviors of the composites [7]. For solving these problems, different methods such as mechanical alloying or quick compression were made to overcome the accumulation and clustering to achieve scattered nanoparticles, but in most cases, these methods caused an increase in contamination, porosity, and costs [10,11]. In recent years, the different severe plastic deformation (SPD) processes were attracted by many researchers [12,13]. SPD methods result in a dramatic improvement in mechanical properties and microstructure. During the SPD processes, due to the constant geometric dimensions and the application of the hydrostatic pressure to the sample during the process, it is possible to apply a high plastic strain to the samples [14–17]. These two characteristics (constant geometric dimensions and the application of the hydrostatic pressure) are the main characteristics of SPD [14,18]. Of course, the parameter of the hydrostatic pressure is somewhat restrictive of applied strain, and the applied strain in various processes is different [14,19]. By increasing the applied strain, achieving a better microstructure with ultrafine-grained (UFG) or nanostructure (NS) and subsequently high mechanical properties is provided. So far, many successful SPD processes for sheets have been introduced. SPD processes that are most considered and used include high-pressure torsion (HPT) [20], equal channel angular pressing (ECAP) [21–24] and accumulative roll bonding (ARB) [15,25,26], etc. [27–31]. The ARB process was introduced by Saito in 1998, and then it was attracted by many researchers [25]. This process was capable of industrialization and production of UFG and nanostructured multi-layered composite with excellent mechanical properties [1,26,32]. Also, in the ARB process, ceramic powders could be used as a composite reinforcement phase [33–35]. So, the ARB technique was used for the fabrication of UFGe and NSed materials, multilayered metal matrix composite and metal matrix composite reinforced with reinforcing particles [36–39]. This technique was also used to remove imperfections such as porosity and agglomeration. The ARB technique was also used to improve the microstructural and mechanical features of samples produced via casting methods [40]. Kitazono et al. were the first persons that used the ARB process to add and distribute TiH₂ reinforcing particles to the Al field for the production of closed Al foams [36].

The fracture toughness is one of the essential parameters that has recently been taken into consideration by researchers in the field of severe plastic deformation. So far, the fracture toughness of metals produced by various SPD techniques such as HPT [41], CGP [42], ECAP [43,44] and ARB [45–47] have been accomplished. Rahmatabadi et al. examined the fracture toughness of Al, Al/Cu, and Al/Cu/Mg composites produced by ARB process in three distinct articles [45–47]. The results of all these studies showed that with increasing exerted strain, fracture toughness increased [45–47]. In this article, the influence of fracture toughness and absorption capacity of metal matrix composite reinforced with ceramic particles has been investigated which for the first time, the fracture toughness parameter for composite with reinforcement particles has been investigated. Multilayered Al1050/Al5052/SiC composite was processed by the ARB technique through six cycles at ambient temperature, and the microstructure and mechanical properties of the produced multilayered composite were investigated during different ARB cycles. As the main part of the article, the influence of SiC particles to the fracture toughness studied by plane stress fracture test and capacity adsorption energy of CT specimens were also examined in the primary sandwich, first to the third ARB passes.

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<th>Table 1 – The chemical compositions and mechanical properties of Al1050 and Al5052.</th>
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<td>Material</td>
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2. Experimental procedures

2.1. Initial materials

Initial materials utilized in the present article include Al 1050, Al 5052 (without annealing), and SiC microparticles. Table 1 demonstrates chemical composition, tensile strength, microhardness and initial size of unprocessed materials. Also, scanning electron microscopy (SEM) image of SiC powders that was used in this study with a size of 20 μm is shown in Fig. 1.

2.2. ARB process

Fig. 2 demonstrated a schematic illustration of the ARB method in two parts. At first, fabricated primary sandwich and then repeated accumulative roll bonding for six cycles. Initially, three Al1050 and two Al5052 strips were prepared at the same dimensions to manufacture the primary sandwich. Then, these strips were cleaned up in acetone and after drying in the air, were scratched with stainless steel circumferential brush. Then, the five sheets were stacked to be 5 mm in thickness, while 2 vol.% SiC at 4 interfaces, each with 0.5% volumes of powders were spread between Al1050 and Al5052. Finally, the strips were assembled as a sandwich stack included three Al1050 and two Al5052 layers and 2 vol.% SiC powders that Al1050 layers as the outer surfaces. For prevent sliding on each other, the stack was fixed through steel wires at four edges. Finally, 70% reduction thickness value (Von Mises equivalent strain of 1.39) was applied to fabricate primary sandwich, and the thickness of sandwich stack was received from 5 mm to 1.5 mm by using rolling at room temperature.

After fabricating the primary sandwich, the fabricated samples were cut in half and then surface treatment was applied. Surface treatment included some steps such as degreasing with acetone, drying in the air, and scratching with a steel brush. After performing all of these steps, the layers were stacked on each other and to avoid sliding; two sheets were fixed with steel wire at four edges. Finally, a 50% reduction thickness value (Von Mises equivalent strain of 0.8) was applied to create roll-bonded material. The ARB process repeated for six cycles by using laboratory rolling mill with 107 mm of rollers diameters in room temperature and without using a lubricant.

2.3. Microstructure and local plastic instability

The microstructures of metallographic samples (after a primary sandwich and each pass) were evaluated using optical microscopy (OM). The produced strips after primary sandwich and each pass were prepared in the parallel to rolling direction on RD–ND plane. Making of metallographic strips included sectioning by wire cut, cold mounting grinding by using sandpaper numbers 180–4000 and polishing by use of alumina powder with a size of 1 and 3 μm. To separate Al1050 and Al5052 layers before polishing, NaOH solution was used to remove oxides. However, no etch solution has been used, and no etching has been made.

2.4. Mechanical properties

To specify the mechanical behaviors of Al1050/Al5052/SiC composite which was produced via ARB, uniaxial tensile test and Vickers microhardness test were utilized in the different ARB cycles. The uniaxial tensile test samples were prepared from the initial and ARBed sheets in the rolling direction, based on the ASTM-E08 standard. The width and a gauge length of the standard tensile test samples were 2.5 and 6.92 mm, respectively. This examination was done at a nominal initial strain rate of 1 × 10^{-4} s^{-1} at environment temperature via SANTAM machine. Vickers microhardness test was done for initial, and ARB processed samples via JENUS apparatus. Vickers microhardness was applied on both Al1050 and Al5052 layers at more than ten various points randomly under a load of 20 g and time of 10 s on the surface of the cross-section of specimen’s perpendicular to the rolling direction. Finally, by deleting the irrelevant data the values of micro-hardness were calculated by averaging the remaining values for each sample. VEGA TESCAN scanning electron microscope (SEM) was utilized for comparing the fracture mechanism of tensile rupture areas for unprocessed and processed materials.

2.5. Fracture toughness and the absorption energy

In this paper, plane stress fracture toughness and absorption energy were investigated for raw materials (Al1050 and Al5052), primary sandwich and first to third ARB cycles of Al1050/Al5052/SiC composite produced by ARB process. Fracture toughness was performed experimentally by preparing fixtures, compact tension (CT) specimens and drawing R-curves based on ASTM-E561, ASTM-E399 and ASTM-E647 [48,49]. The standard CT samples are presented in Fig. 3. These specimens and pre-cracks were made using a Wire cut machine in a completely identical and distinct dimension. The method of pre-cracks preparation with Wire
Fig. 2 – A schematic illustration of the ARB process for processing Al1050/Al5052/SiC multilayered composite.

Fig. 3 – The prepared CT specimens, fixture and undeformed and deformed CT specimens.
cut has been considered in recent years and is used for materials with low thickness and strength [16,45,46,48]. The experimental fracture examination was carried out by displacement control by loading the first mode (perpendicular to the crack growth direction) at a head speed of 0.5 mm/min. Finally plane stress fracture toughness and absorption energy were calculated by drawing R-curves and the area under the force-displacement curve during fracture test.

3. Results and discussion
3.1. Microstructure observation

Provided optical microscopy of multilayered Al1050/Al5052/SiC composites processed in different passes of the ARB are shown in Fig. 4. Based on Fig. 4(a) (in the primary sandwich) the Al1050 and 5052 layers as well as the SiC particles (red arrows) are observed. By increasing the applied...
strain, the number of layers increased, and no local plastic instability was found in Al layers until the third pass. In the third pass, and after that, the local plastic instability and local necking (red ellipses) and failure (blue ellipses) are visible (Fig. 4(c)). It has been reported that in composites consisting of several layers of different metals due to differences in the mechanical properties of the layers, layers break down and neck (local necking faster in the harder layer). In summary, the local plastic instability depends on the difference in the initial thickness ratio, the strain hardening exponent (n), and the strength coefficient (k) of the composite layers [1,6,17,32,45,50].

Also, SiC particles can act as stress concentrations in the Al/SiC interfaces and based on Fig. 4(c), create imperfections such as cavities, porosity, etc., in the interfaces [6,10,34,35]. By raising the number of ARB cycles, the distribution of Al5052 reinforcement layers in the Al1050 matrix improved and became more uniform (Fig. 4(e)).

In Fig. 5, the variation of layer thickness for Al5052 reinforcement are presented. According to this image, by rising the number of applied strain, the layer thickness decreased, as it happens in first cycles at high rates and then at low rates.

3.2. Distribution of SiC particles reinforcement

Fig. 6 demonstrates microscopic pictures of the reinforcement particles distributions in the Al1050/Al5052/SiC composite during various ARB cycles. In Fig. 6(a) and (b), we can clearly show the SiC particles, the porosity, and the cluster particles at the interface of the Al1050 and Al5052. In most composite areas, the distribution of the SiC particles is uniform. It has been presented that there are cavities and porosity between the cluster particles as well as the SiC particle/Al layer interfaces in multilayered Al1050/Al5052 composited reinforced by SiC produced via ARB process and this phenomenon is more evident in the initial ARB passes. According to the film theory, the extraction of pristine metal from the pores of these cavities leads to a better distribution of particles and reduction of cavities. With the advent of virgin metals from the cavities, the particles become better distributed, and the cavities can be reduced [6,10,34,35].

The ARB process changes the length and thickness of the layers, as well as increases the number of layers, which this will increase the distance between the clusters, break down the clusters, and eventually reduce the areas free of particles and distribute the particles in the matrix [6,7,10,34,35].

3.3. Mechanical properties

Fig. 7 demonstrates the engineering stress–strain diagrams of the unprocessed materials (Al1050 and Al5052) and Fig. 8 demonstrates the engineering stress–strain diagrams of processed Al1050/Al5052/SiC composites during various ARB passes. According to previous studies, the strengthening in the various passes of the ARB technique can be explained by three cold working mechanisms (at primary passes), grain refinement (end passes) and the role of reinforcing particles in various passes [1,6,17,32,51–53]. Fig. 9 shows the variation of elongation and ultimate tensile strength of Al1050/Al5052/SiC during different ARB cycles. It can be seen that in the primary sandwich and the initial ARB passes, the strength has increased and the elongation has decreased. The increase in strength can be related to increasing the cold work rate, as well as the continuation of the 502 reinforcement layers in the Al1050 matrix [2,16,26,54]. According to previous works, it was observed that the discontinuity and separation of the reinforcing layers in the matrix resulted in the loss of mechanical properties [6,45,55]. It has also been reported that non-deformable particles increase the sliding systems of the matrix. This results in the creation of a high density of dislocation and thus strengthening. Elongation reduction can be related to imperfections such as porosity, cluster particles, cavities, non-uniform particle distributions, and the low bonding quality of layers in the elementary ARB passes [7,10,34,35].

In the third and fourth ARB cycles, the reducing strength is because of the non-uniform distribution of the both metal and ceramic reinforcements (Al5052 and SiC particles), the separation of the Al5052 reinforcement layers, porosities, clustered particles, and the creation of fine interfacial cavities, in particular in the reinforcement-particle corners, which are areas of high stress concentration [7,56].

In the end, ARB passes (5 and 6), due to the improvement of the distribution of reinforcing particles, the role of fine-graining mechanism, development of bonding strength between layers, and reducing defects, strength and elongation compared to previous cycles were improved. The dominant strengthening mechanism, in the end, ARB passes is fine grainning.

In the finale ARB passes, grain refining can be occurred due to some reasons such as increasing the number of layers, the presence of reinforcing particles (SiC), the friction between the rollers and the workpiece (creating a shear strain), increasing the dislocation density due to cold working of the brushing the surface of the sheets during the primary preparation of samples before rolling, the difference between the coefficient of thermal expansion of the metal layers in the composite and the reinforcing particles [10,51,52]. Also, due to the incompatibility between particles and layers, a large number of essential geometric dislocations can be formed. By the better distribution of the reinforcing particles (the end ARB passes of ARB process), the number of these dislocations increases and
strength improves by rising the volume fraction of the high angle boundaries [7,10,34,35]. Finally, the maximum of both UTS and elongation as mechanical properties are obtained in the last ARB pass which these values are 326 MPa and 14% for UTS and UTS value is about 3.58 and 1.49 times higher compared to Al1050 and Al5052 as unprocessed materials, respectively.

Fig. 10 demonstrates the average of the microhardness variations of both Al1050 and Al5052 layers in the multilayered Al10/Al5052/SiC composite during different ARB cycles. According to Fig. 9, the values of microhardness for both Al layers increased continuously by raising the number of ARB cycles. The microhardness of the Al1050 and Al5052 increased from about 89 and 31 to 76 and 142 after the sixth cycle of ARB technique, respectively. In the last related researches reported that work hardening as a principal mechanism increases the microhardness during the ARB process. Next to it, grain refinement is also an essential factor in improving microstructure which grain refinement had less impact relative to cold working [57,58]. In this research, due to the use of reinforcement SiC particles, increasing microhardness has occurred at a higher rate. Another point to consider is the difference of microhardness increasing rate for Al1050 and Al5052 that can be related to the cold working rate of the both raw materials during the ARB process. Of course, the difference in the cold work rate is also associated with the stacking fault energy (SFE) that way metals with higher SFE the distance between the dislocation is less as a result, the locking of the dislocation and slip of plane occurs in fewer tensions [55,58,59]. Also, during the ARB process due to the contact between the surface layers and rollers and even high rate of plastic deformation, shear stress and high temperature are created. When rolling is done, some temperature rises due to friction between the surface of rollers and samples. Due to the difference
in the thermal expansion coefficient between the layers, the thermal stresses when the samples are cooled are created, which causes thermal stresses to create new dislocations and increase the density of dislocations [6,17,32,45].

3.4. Fracture toughness

In Fig. 11, the force-displacement diagrams of CT samples of multilayered Al1050/Al5052/SiC composite during fracture test are presented in various cycles of the ARB process. Based on this image, by increasing the applied strain from primary sandwich to the second pass, \( P_{\text{max}} \) increases and after the third pass severely decreases so that's the smallest force value. This trend (variation of the \( P_{\text{max}} \) of the sheet with crack) is similar to the variation of maximum tensile strength (UTS) values in terms of ARB cycles. This process has also been observed in other composite samples produced by ARB such as Al, Al/Cu and Al/Cu/Mg [16,45,46]. Usually, CT specimens have two types of elastic and plastic deformation during fracture test that the purpose of elastic and plastic deformation are resistance to the beginning and growth of the crack respectively [48]. Therefore, according to Fig. 12, the maximum force (\( P_{\text{max}} \)) is a measure of material resistance to crack origin and is the elastic parameter of materials. According to the microstructural and mechanical results, in the third ARB pass, the Al5052 reinforcement layers are broken and discontinuous, and the most critical factor in reducing the strength of MMC was the discontinuity and failure of reinforcement layers, which reduced the resistance of the material to the crack starting. Generally, via rising the applied strain, the thickness of both matrix and reinforcement layers decreased, and in the third pass, local plastic instability occurred that it is in addition to reducing strength, exacerbates the separation of the layers, agglomerate, and porosity in the interfaces.

In Fig. 13, the absorbed energy of CT samples (the area under the force-displacement curves during the fracture test) are shown in various cycles of the ARB. The energy absorption parameter can be a measure of the material’s resistance to crack growing. According to Fig. 13, after the primary sandwich and first cycle, absorbed energy increases and then after the second and third pass decreases. Of course, the amount of absorbed energy, such as \( P_{\text{max}} \), in the third pass decreases sharply, and the smallest amount is obtained in this pass. In the second ARB pass, the lowest amount of ductility has been achieved, which expresses the excessive brittleness of Al1050/Al5052/SiC composite processed by ARB due to non-uniform distribution of SiC ceramic particles in the matrix/reinforcement interfaces. Therefore, it seems logical to reduce the amount of absorbed energy in the second compared to the first ARB pass by increasing the brittleness and decreasing the ductility [48,60,61]. The same trend is true for the third ARB pass and where absorbed energy is reduced due to the lowest strength in the various ARB passes.

After fracture test and reading the values of crack growth of CT samples in terms of force by the visual method, the plane stress fracture toughness values of multi-layered Al1050/Al5052/SiC were calculated according to the ASTM-E561 standard and the following equations [16,45,46]:

\[
k_i = \frac{P_i}{b\sqrt{w}} \times f_i \left( \frac{a}{w} \right)
\]

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

In these equations, \( a \) is the amount of crack growth corresponding to the applied force \( (P_i) \), \( b \) and \( w \) are thickness and width of CT specimens which are constant for various ARB passes and \( f(a/w) \) is a geometric coefficient in terms of crack growth. Also, \( k_i \) is the crack growth resistance in terms of \( P_i \) and \( f(a/w) \) during fracture test and \( P_{1,2,3} \) are \( k_i \) in the constant forces which makes it possible to a tangent to the R-curve and obtain the amount of fracture toughness at the contact point [16,45,46,48].

In Fig. 14 R-curves for different ARB cycles are exhibited. Using Fig. 14, changing in the fracture toughness in terms of the number of ARB cycles and unprocessed materials are presented in Fig. 15. Based on Fig. 15, fracture
toughness values of multilayered Al1050/Al5052/SiC composite during different ARB cycles are more than unprocessed Al1050 and Al5052 materials. From primary sandwich to the second pass the rate of changing in fracture toughness is ascending and then drastically reduced. Also, maximum and minimum values are achieved at second and third ARB cycles respectively which that highest amount is more than 2.88 and 1.33 higher than Al1050 and Al5052 respectively. According to last studies that none of them used ceramic reinforcement particles, fracture toughness depends entirely on tensile strength and elongation and because the strength variations are much higher than elongation variation (almost constant, or the rate of change is low), trend of changing in fracture toughness is similar to strength [16,45,46]. The same trend is observed in this research, but there is a major difference between previous studies and current research, which is the reduction of toughness in the third cycle. In the fracture toughness investigation of ARB processed materials, by increasing the cycles, the fracture toughness has increased continuously but for Al1050/Al5052/SiC after the third pass decreases sharply [45,46]. This, of course, goes back to the strength drop that occurs due to the instability of the Al5052 reinforcement layers. In general, by increasing the number the ARB cycles, the number of layers increases and due to the decrease in thickness, the strength and crack growing
resistance each layer decreases. On the other hand, due to the presence of SiC ceramic particles in the interfaces and the non-uniform of particle distributions, by increasing the strain not only the strength increase, but also in the interfaces is a suitable place for the growing and diffusion of the crack. Therefore, the reinforcing particles play a crucial role in the variation of plane stress fracture toughness and reduction in toughness will intensify in the third pass. With all these interpretations, the main factor in the reduction of fracture toughness is the instability and separation in the Al5052 reinforcement in the third pass (according to Fig. 4(c)). The presence of detachment and instability in the first stage reduces strength and then reduces fracture toughness. Of course, as noted above, the role of reinforcing particles and the lack of uniform distribution of them, are also very effective.

3.5. Fractography

Fig. 16 demonstrates the Al1050/Al5052/SiC multilayered composite after uniaxial tensile test during the ARB process. We found that the outstanding failure mechanism of the raw materials (Al1050 and 5052) with the face centered cubic (FCC) crystal structure to be dimple creation and ductile rapture [32]. According to Fig. 16(a), in the initial ARB passes, due to the weak bonding between the Al1050/Al5052 interfaces and accumulation of SiC particles in the interfaces, the fracture occurred at these places. By rising the number of ARB passes, the quality of bonding at the interfaces enhanced. According to Fig. 16, both the rupture surface of the Al1050 matrix (Al1050) and Al5052 reinforcement (Al5052) remained ductile and had dimples. The major difference between raw material and processed Al layers are that after the ARB process dimples had smaller and shallower. This trend has also been
observed in previous related researches that do not change the failure mechanism for different Al alloys by applying ARB processes, and only affects the shape, number, and size of dimples. In other words, due to the application of non-uniform strain during ARB process, the co-axial and the spherical dimples become asymmetric and are drawn in different directions, and the so-called ductile fracture mechanism changes to the shear ductile fracture. The reinforcement SiC particles also have a significant influence on the fracture mechanism. Based on Figs. 16(a)–(c), the reinforcing particles are observed in the center of the dimples and the Al1050/Al5052 interfaces, which causes germination and growth of the crack.
4. Conclusions

In this article, multilayered Al1050/Al5052/SiC composite was prepared via the ARB method until six passes, and for the first time fracture toughness values were investigated for multilayered composites reinforced by ceramic particles. Also, microstructural and mechanical properties during different ARB cycle were evaluated via OM, uniaxial tensile test, microhardness, and SEM. The bold results of mechanical properties and microstructure were concluded as follows:

At first, ARB passes, the trend of changing the Al5052 reinforcement thickness were very fast and gradually reached a constant thickness, in the end, ARB cycles, and via soring the exerted strain, the Al5052 reinforcement layers varied to uniform stated from the lamellar form. Local plastic instability was observed at third ARB cycle, and then Al1050/Al5052/SiC composite was provided via an almost uniform dispersion of Al5052 layer, and SiC particles reinforcements and the distribution of the hard layers was more homogeneous due to work hardening and decreasing formability of the layers.

Fig. 16 – The fracture surfaces of Al1050/Al5052/SiC composites: (a) after first, (b) third and (c) after sixth cycle.
SEM images showed that in the initial ARB passes, the quality of bonding between layers was weak due to the Al1050/Al5052 interfaces and accumulation of SiC particles in the interfaces. Also, the fracture occurred in these places. Via soaring the number of ARB passes, the quality of bonding at the interfaces enhanced. Investigation of the tensile rupture areas for Al1050 matrix during the various ARB cycles demonstrated that via rising the performed strain, the size and shape of the dimples varied, but the ductile fracture mechanism remained and varied to shear ductile at the last cycles. 

The Vickers microhardness values of two Al1050 and Al5052 layers were increased, continuously and the maximum values 76 and 142 were obtained at the end cycle for Al1050 and Al5052, respectively. The best tensile strength and elongation values were, in the end, ARB cycle which these values were 336 MPa and 14% for UT and elongation, respectively. By adding the applied strain during ARB, the values of absorbed energy for CT samples during fracture test at first increased and then in the 2nd and 3rd cycle decreased. The minimum values of elongation and UTs were achieved at second and third ARB cycles, respectively and this caused a drop in absorbed energy in the second and third passes. 

Variation of the crack initiation resistance and fracture toughness as in other previous studies was in terms of the material's strength, as the tensile strength increased from the primary sandwich to the 2nd cycle, and in the third pass, it is sharply reduced. Mild increase and severe reduction, due to the cold work and local plastic instability of the Al5052 reinforcement layers, respectively. Maximum values of fracture toughness for Al1050/Al5052/SiC processed by ARB was obtained in the 2nd cycle which improved by 187% and 33% compared to Al1050 and Al5052 as raw materials, respectively.

Conflicts of interest

The authors declare no conflicts of interest.

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