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# Characteristics of thin Al/steel/Al sandwich produced via accumulative roll bonding technique for electromagnetic shielding applications

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## Abstract

Tri-layered Al/steel/Al composites with 0.2 mm thickness were produced by accumulative roll bonding (ARB) process at room temperature using Al-1050 sheets and a commercial low carbon steel DC01 up to four cycles. The effect of ARB cycles on the microstructure, mechanical properties and magnetic shielding of the ARBed sandwiches is investigated. The microstructural results obtained using SEM and EBSD techniques showed that the steel layers were necked and fractured as the strain increases and a small part of steel fragments was observed in some points of Al matrix. Further, the outer Al layers tend to disappear and to be replaced by steel layers, which may be due to the softening of the Al alloy resulting from the intermediate annealing performed at 400°C for 10 min between each ARB cycle. During ARB cycles a pronounced decrease of the grain size is observed in Al layers and the HAGB of both Al and steel layers showed a little increase with respect to primary sandwiches. The tensile tests revealed a significant reduce in tensile properties of the sandwich after 2 passes due to the fragmentation of steel inside the Al matrix. The shielding effectiveness (SE) of multi-layered Al/steel/Al composites is evaluated from 20 Hz to 20 KHz versus the cycle number. The SE of ARB processed sandwich showed a similar behavior as steel shielding at low frequency and gradually increases with increasing frequency.

**Keywords:** *Al/steel/Al composites, accumulative roll bonding (ARB), magnetic shielding*

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## 1. Introduction

Nowadays, electronic devices such as computers, smart phones and Wi-Fi systems are extensively used in our daily lives. Such devices emit electromagnetic waves (EMW) which may cause disturbance, noise and malfunctions for other devices. Thus, it is crucial to use shielding materials that act as obstacles against occurrence of electro-magnetic interference (EMI) and suitable shielding for specific frequency ranges. Light weight, less thickness and good shielding effectiveness (SE) are prerequested for shielding materials over a wide range of frequencies [1]. In this regard, research to develop EMI shielding material increased promptly during the last two decades [2]. Multilayer composites have been of great interest to use as adequate shielding materials

against EMI at low frequencies owing to their new magnetic, optical and electronic property [3, 4]. Aluminum matrix composites (AMCs) have received an attractive attention thanks to their low density, high solidity, low rate of erosion, and good corrosion [5].

Accumulative roll bonding (ARB) process as a severe plastic deformation SPD method has been regarded as an effective tool for the production of diverse multi-layered metal composites in the forms of sheets [6]. As respect to the other SPD techniques, ARB takes more advantages process for its simple equipment and accessible to process the huge volume of piece [5]. The principal purpose of ARB process is to impose a very large plastic strain within the material, resulting in structural refinement and increase its strength without changing sample dimensions. Therefore, numerous studies have been done in this field and several AMCs have been successfully fabricated through ARB process including Al/Sn [6], Al/Zn [7], Al/Ni [8], stainless steel/Al/Cu [9], Al/Ni/Cu [10], Al/Cu/Mn [11], Al/Mg [12], and Al/Sc [13]; acceptable results have been achieved.

To date, very few works have been done to estimate the SE for the Al/steel/Al sandwiches produced using ARB [14]. In this study, the thickness of the prepared sandwiches was 1mm. In the current study, shielding efficiency is evaluated for a very thin tri-layered Al/steel/Al with 0.2 mm in thickness fabricated using ARB process up to 4 cycles at room temperature. The SE values were taken at low frequencies between 20 Hz to 20 kHz; that are generally emitted by power supplies, switches and motors that enable cause distortions in the form of noise and disruption to the sensitive devices. The evolution of microstructure and related mechanical properties during ARB cycles of the produced sandwiches were also investigated by means of optical microscopy, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) techniques and tensile tests.

## 2. Experimental Section

### 2.1 Materials and processing

The raw materials used in this study were commercial Al-1050 (state H18) and low carbon steel DC04 sheets with 0.1 mm in thickness. The chemical composition of these sheets is given in Table 1.

**Table 1** Chemical composition (wt. %) of the materials used in this study.

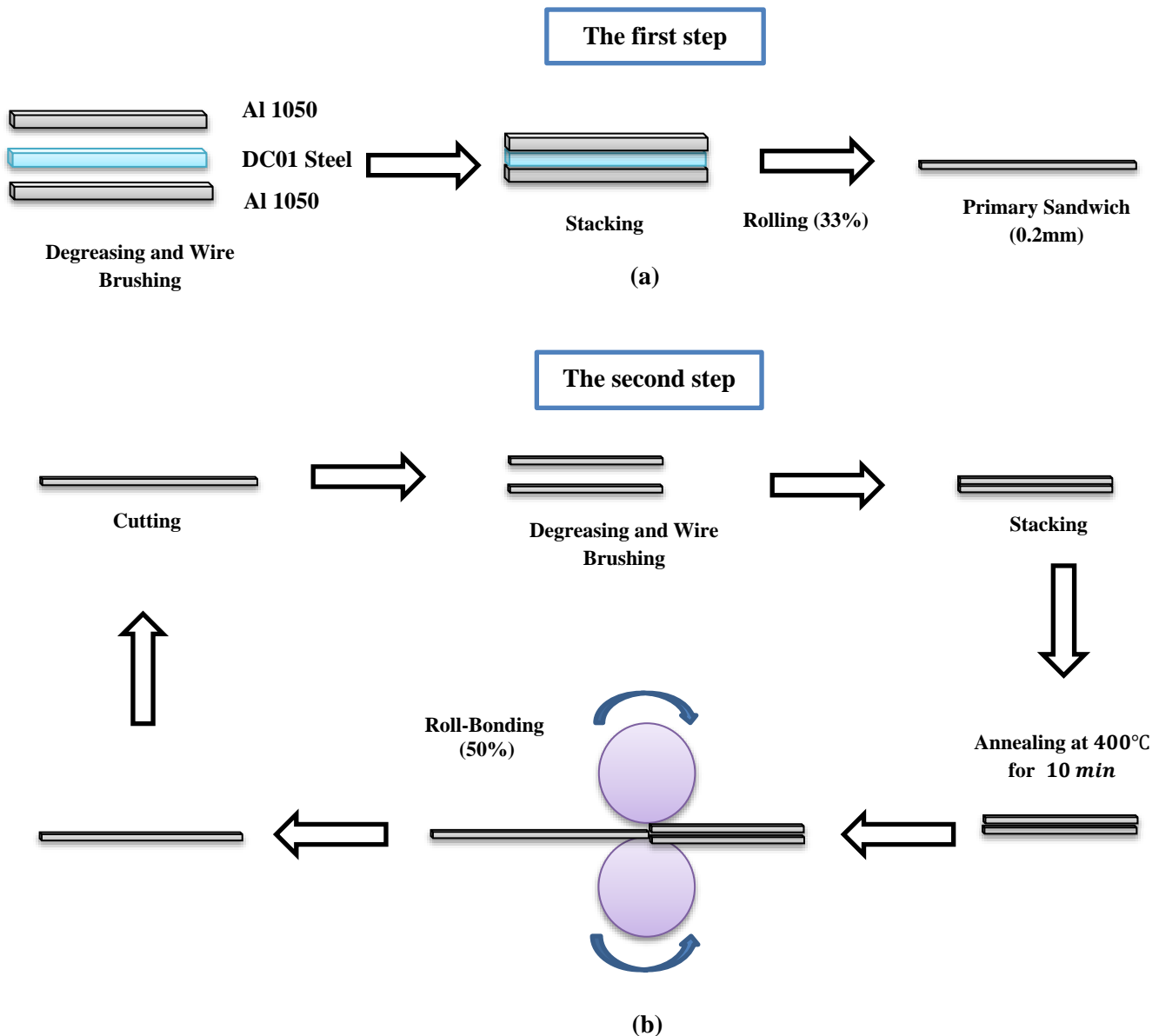
<i>Material</i>	<i>Chemical composition (wt. %)</i>									
	Al	Fe	Si	Cu	Mn	Mg	Zn	C	P	S
Al-1050	98.81	0.69	0.31	0.16	0.005	0.001	0.07	-	-	-
Steel DC04	0.05	-	0.025	-	-	0.33	-	0.08	0.03	0.02

Fig. 1 shows the schematic diagram of ARB process. The multilayer composites were made in two steps: first, a primary Al/steel/Al sandwich structure was formed by bonding two Al sheets (0.1mm thick) with a steel sheet of 0.1mm thickness between them. The three strips were degreased with acetone and wire-brushed with a circular steel brush. In order to avoid sliding on each other, the sheets were fixed together by iron wires from the edges and then conducted through a 33% reduction in thickness (0.2 mm) at room temperature (Fig. 1a). In the second step, the Al/steel/Al sandwich structure was cut into two halves, fastened together and then roll-bonded with reduction

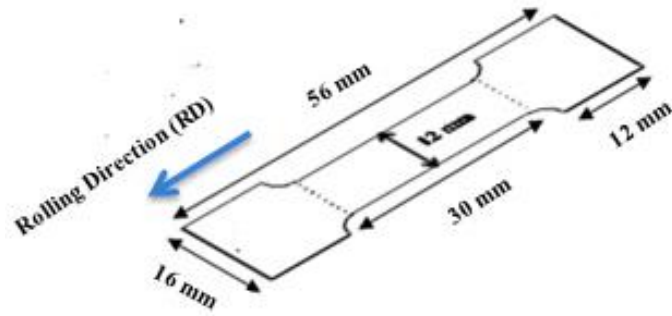
in thickness of 50% (Fig. 1b). The process was carried out at room temperature and repeated up to four cycles without using any lubricant. An intermediate annealing for 10 min at 400°C was carried out at each cycle before cold-rolling. Finally, the sheet surfaces were degreased and wire-brushed before stacking among ARB cycles to achieve good bonding.

## 2.2 Characterization techniques

The microstructure of the composites during the ARB process was examined using a scanning electron microscope (ZEISS SUPRA 55 VP) operating at 20 kV with a TSL orientation imaging system, OIM™ software. The samples for EBSD analysis were first mechanically ground and then electrolytically polished with an A2 Struers solution. The tensile tests were conducted at room temperature using Zwick Roell Z010 with the initial strain rate of  $6.7 \times 10^{-7} s^{-1}$ . The tests were collected along the rolling direction on the samples with the gauge dimensions as shown in Fig. 2.



**Fig. 1** Schematic diagram illustration of (a) primary sandwich preparation and (b) ARB processes

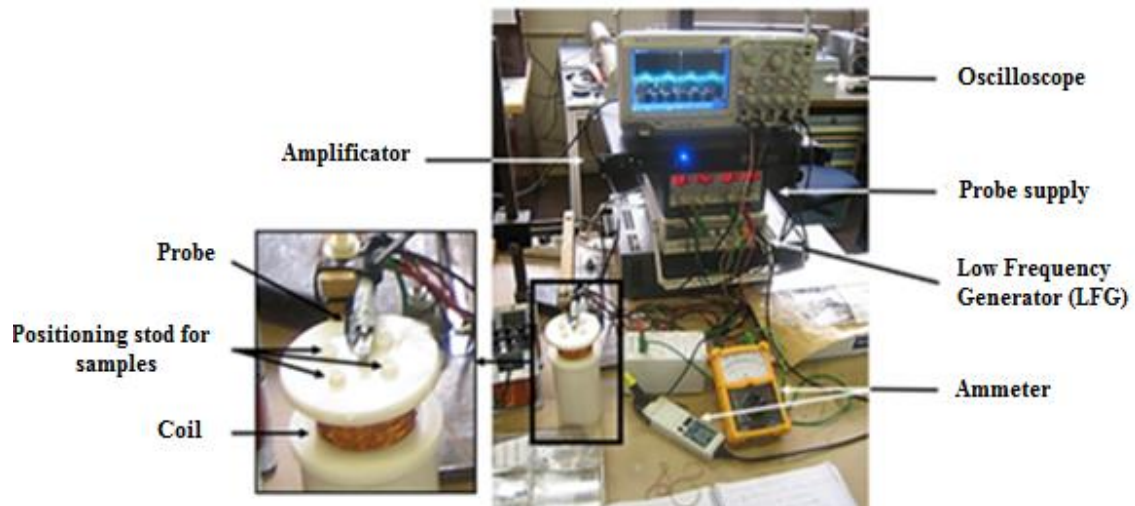


**Fig. 2** Gauge dimension for tensile test

The magnetic shielding is the ability of a given material or composite to reduce the amount of emission of electromagnetic waves transmitted through it and generally given in dB [15]. To measure the SE of Al/steel/Al multilayered composites at low frequencies (20 Hz -20 kHz), an ad-hoc device was elaborated represented in Fig. 3a with the principle of shielding measurement (Fig. 3b). A 100 turn copper wire coil of 90 mm diameter aligned by a low frequency generator of 400 mA and generate the magnetic field  $\vec{B}$  which is proportional to the applied voltage V. The samples with a parallelepiped shape of 30 mm side length and 1 mm thick were placed above the coil (10 mm) and centered on its revolution axis (Fig. 3a). By measuring the applied voltage above the sample ( $V_s$ ) and the applied voltage of the same position without sample ( $V_{air}$ ), the SE can be evaluated using the following formula:

$$SE (db) = 20 \log\left(\frac{V_{air}}{V_s}\right) \quad (1)$$

The values obtained are proportional to the tensions measured by a Hall probe which was positioned above the sample (Fig. 3b).



**(a)**

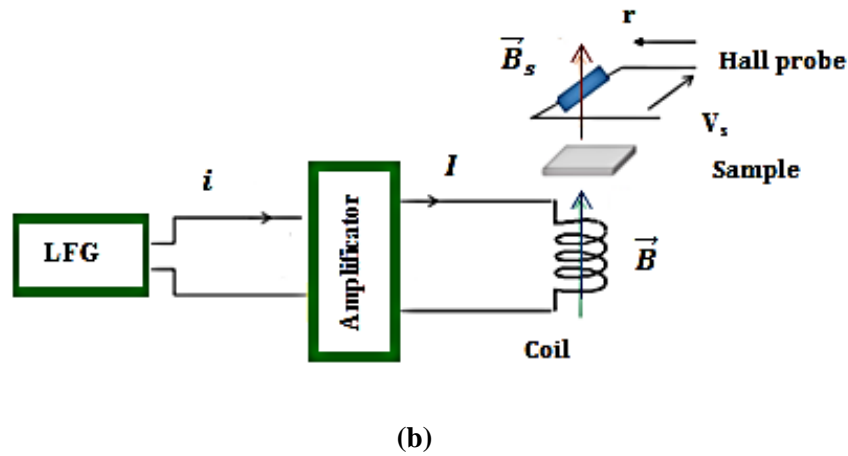


Fig. 3 (a) Equipment set-up and (b) principle of shielding measurement

### 3. Results

#### 3.1 Effect of ARB process on microstructure

Fig.4 illustrates the optical micrographs of composites in the RD-ND plane of the primary sandwich (Fig. 4a) and the samples processed through 1, 2, 3 and 4 cycles (Fig. 4b-e) correspond to total strains of 0.8, 1.6, 2.4 and 4, respectively. According to these images, the superposition of 3 layers is observed in the primary sandwich (Fig. 4a). After the first cycle, the layers keep their continuity and aligned in straight line along the rolling direction. In the composite processed through the second cycle, the steel layers forfeiture their straightness and undergo local necking. As the ARB cycle number increases up to 4 the steel is completely fractured and the fragments act as reinforcements in the Al matrix (Fig. 4d). As ARB cycle number increases, the Al alloy is removed from the outer layers (up and down), probably due to its low yield stress compared to the steel alloy.

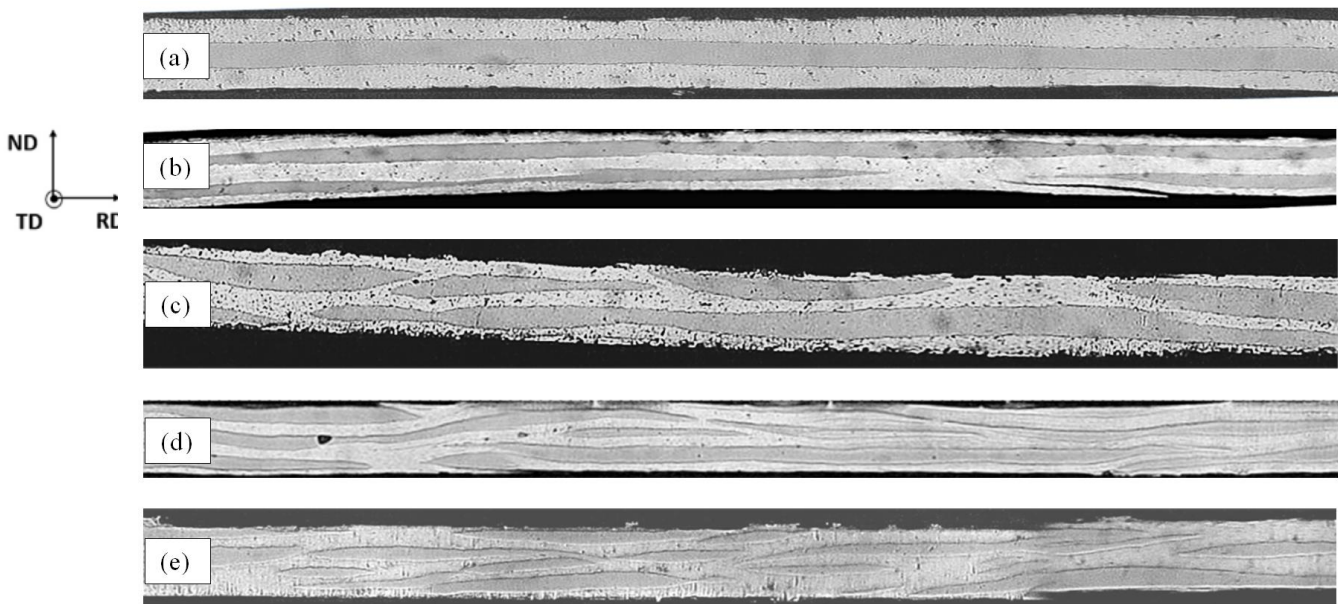
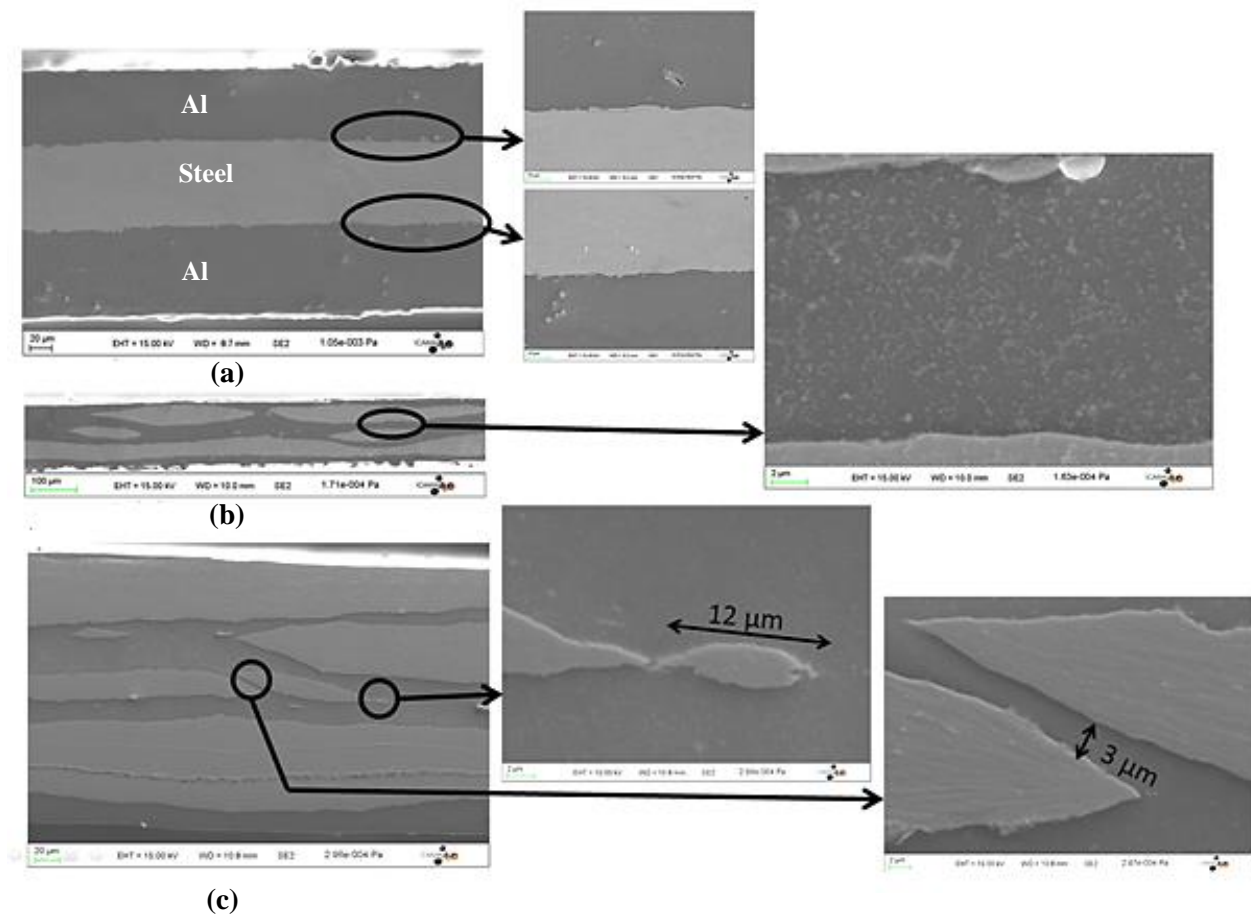


Fig. 4 Optical micrographs of ARB-processed Al/steel/Al composites (thickness of 200  $\mu\text{m}$ ) after : (a) zero (primary sandwich), (b) one, (c) two, (d) three and (e) four cycles.

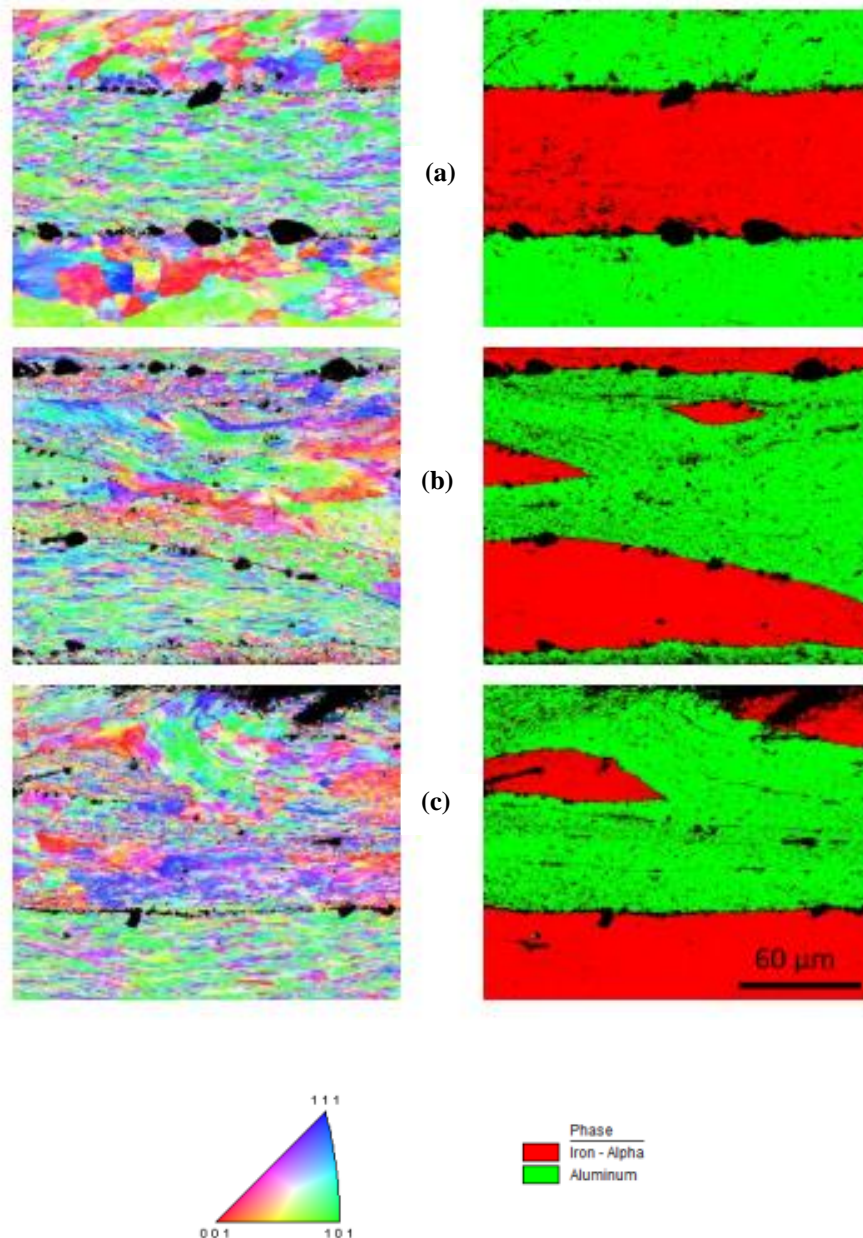


Fig. 5 shows the SEM micrographs of the interface of Al/steel/Al composites taken after 0, 2 and 4 ARB cycles. It is clearly observed in Fig. 5a that the Al and steel layers were well bonded after primary sandwich preparation. These observations are the same showing in optical microscopy (Fig. 4a). As the ARB cycle increases, the layer dislocates and became refine without showing any significant interface degradation. Moreover, both fragmentation and refinement of the layers continue with increasing the ARB cycle up to 4 and small parts of steel with the length of about 12  $\mu\text{m}$  were observed in some points of the Al matrix (Fig. 5c). Similar observations were reported for multilayered Al/Ni composites processed up to 2 ARB cycles at room temperature [16].



**Fig. 5** SEM images of ARB-processed Al/steel/Al interfaces after: (a) zero, (b) two, and (c) four cycles.

Fig. 6 exhibits the EBSD micrographs of Al/steel/Al multilayered composite in 0, 2, and 4 cycles together with phase mapping. Without ARB processing, the microstructure is composed of large elongated grains in steel layer and a clear interface between Al and steel phases were observed with medium adhesion (Fig. 6a) due to the fact that the processing was conducted at room temperature and the apparition of porosities resulting from the defects generated by brushing. As illustrated in (Fig. 6b), the steel reinforcement has been formed in Al matrix up to two ARB cycles. Further, Al/Al interfaces are clearly visible on the phase mapping in some areas (Fig. 6c).

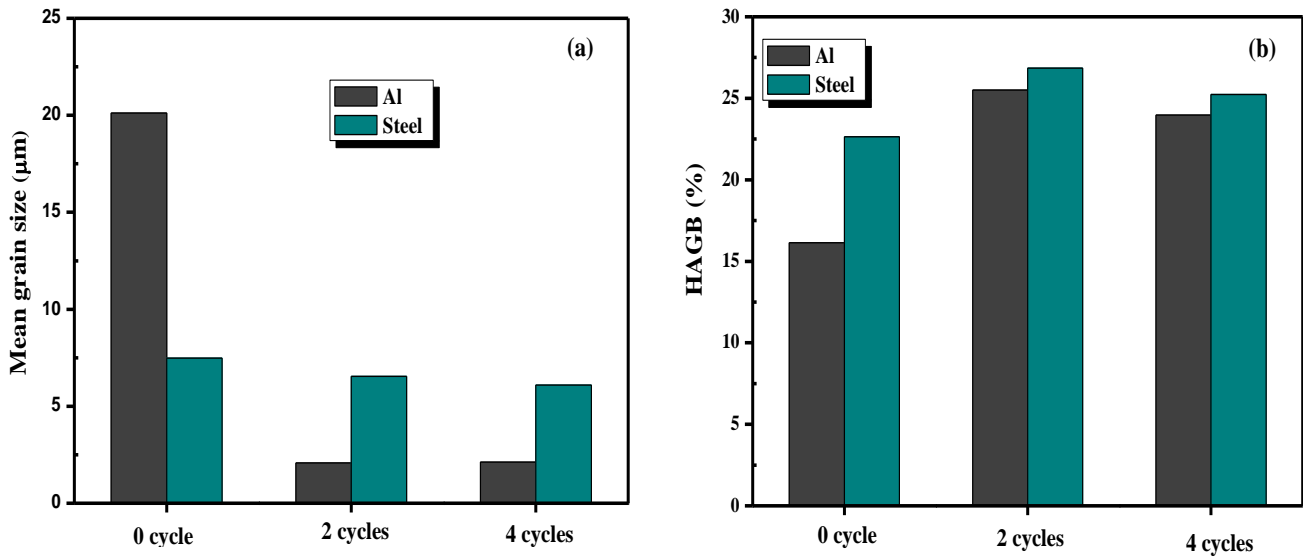


**Fig. 6** EBSD images of the RD-ND plane showing the microstructure of ARB-processed Al/steel/Al composites after :(a) zero, (b) two, and (c) four cycles. The images in the right present the phase mapping (green for Al and red for steel)

Variations of the average grain size and high angle grain boundaries (HAGB) fraction, having disorientation greater than  $15^\circ$ , of Al and steel sheets as function of number of ARB cycles were measured and the plotted curve is illustrated in Fig.7. A significant decrease in grain size of Al sheet from  $20\ \mu\text{m}$  (for the primary sandwich) to  $\sim 2\ \mu\text{m}$  (after 2 cycles) is observed. The size remains then constant up to 4 cycles (Fig. 7a). This may be due to the fact that between each cycle, the composite was annealed at  $400^\circ\text{C}$  for 10 min, allowing a recovery of the Al phase, preventing the grain size decrease by cold-rolling. For Al alloy, the grain size decreases between 0 and 2 cycles is accompanied with an increase of HAGB as expected (Fig. 7b). For the hard phase, the microstructure (main grain size and HAGB) is approximately the same during ARB processing since the steel mechanical strength is higher than the Al one. For both alloys, a very weak change in HAGB fraction is observed between 2 and 4 cycles, probably due to the fact that the an annealing is



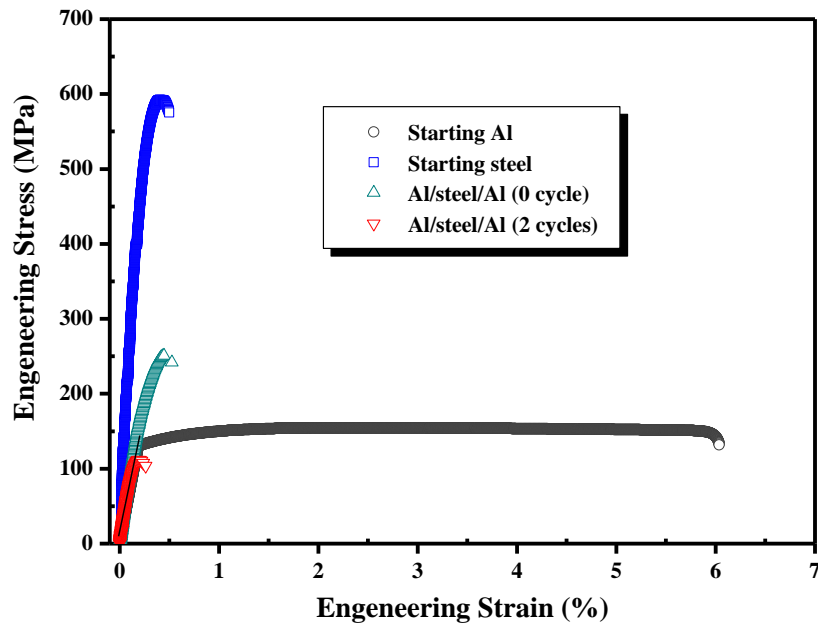
performed at each cycle, which prevents the creation of a very fine microstructure with a large fraction of HAGB. The microstructure has reached a saturate state after 2 ARB cycles.



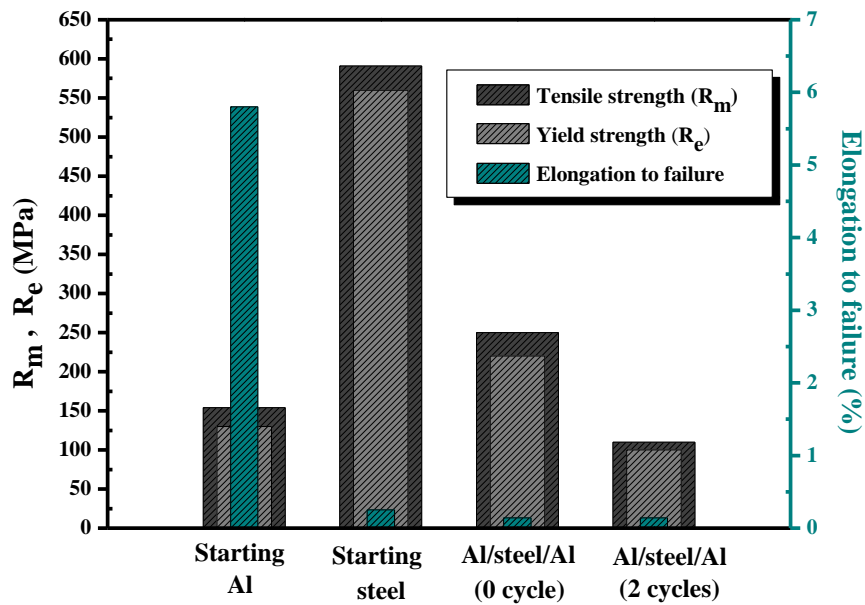
**Fig. 7** (a) Average grain size and (b) HAGB fraction vs. ARB cycle number of Al and steel sheets

### 3.2 Effect of ARB process on mechanical properties

The mechanical properties such as tensile strength ( $R_m$ ), yield strength ( $R_e$ ) and elongation to failure of Al/steel/Al multilayered composites were evaluated before and after two ARB cycles and the engineering stress-strain curves are displayed in Fig. 8. The calculated tensile properties extracted from the stress-strain curves of samples are summarized in Fig. 9. It can be seen that the elongation to failure of the primary sandwich (zero cycle) is similar to the less ductile constituent material: the steel alloy. Although its low elongation to fracture (0.14%), the primary sandwich exhibits a good mechanical resistance ( $R_e = 220$  MPa and  $R_m = 250$  MPa), greater than Al alloy ( $R_e = 130$  MPa and  $R_m = 154$  MPa). After the second cycle of the ARB process, mechanical properties showed a decrease with respect to the primary sandwich. It is noteworthy that, the yield strength of the composite reached 100 MPa after the second cycle, which is quite the same as the starting Al (130 MPa) and almost 6 times lower than that of steel (560 MPa). This loss of strength between zero and 2 cycles may be due to steel fragmentation. Despite the low values of mechanical properties obtained when ARB is conducted up to 2 cycles, it is interesting to measure the associated magnetic performances considering the steel fragmentation could help the magnetic shielding [14].



**Fig. 8** Engineering stress–strain curves of the starting materials and ARBed Al/steel/Al composites

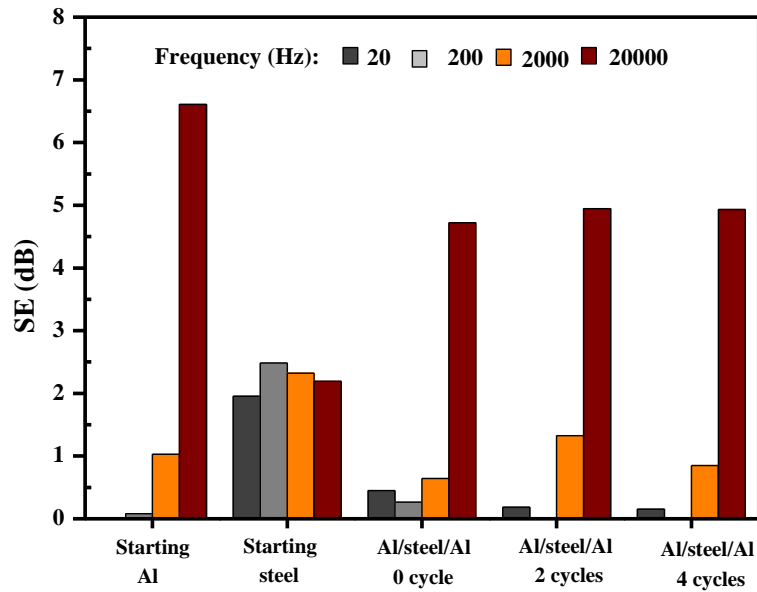


**Fig. 9** Tensile property summarization of the starting materials and ARBed Al/steel/Al composites (0 and 2 cycles).

### 3.3 Effect of ARB process on magnetic shielding

The effect of ARB cycle number on the magnetic shielding was investigated by estimating the shielding effectiveness of the Al/steel/Al sandwich for up to 4 ARB cycles. The experiments were repeated several times to ensure the reproducibility of data. The data obtained are plotted versus frequencies (20 Hz -20 KHz) in Fig. 10. The Al sheet starts to shield at 200 Hz and SE increases gradually with frequency due to its higher electrical conductivity. In fact, the steel sheet shields at low frequency (~1.98dB) due to its higher magnetic permeability. The magnetic shielding of the primary and ARB sandwiches is a compromise between the steel and Al properties. The

sandwiches are able to shield for low frequencies (but less efficiently than steel itself) and their SE increases with increasing frequency, such as the Al alloy.



**Fig. 10** Change of SE with respect to the frequency for starting steel and Al/steel/Al composites processed at different number of ARB cycles

#### 4. Discussion

According to the literature, the strengthening of the severely deformed composites, composed of hard and soft phases together) is not only affected by strain hardening (in the initial cycles) and grain refinement (in the subsequent cycles) but also by hard layers reinforcing the matrix [7, 16-19]. Nevertheless, several reports find that the necking and fracture of the hard layers inside the matrix have an undesirable effect on the composite strengthening [6, 14, 20]. The reason of necking and fracture in hard layer is due to the difference in mechanical properties of dissimilar metal composites which leads to plastic instabilities [12, 13, 22, 23]. In this research, after 2 ARB cycles necking and steel fragments are observed (Fig. 5b) with an abrupt decrease of tensile properties of the Al/steel/Al multilayered composite (Fig. 9). Besides, the ARB process has only a pronounce effect on the grain size of Al layers whereas the misorientation of both dissimilar layers showed a weak increase with respect to primary sandwich. As mentioned in the experimental procedure, an intermediate annealing for 10 min at 400°C is performed for ARBed composites, conducting to a significant decrease in dislocation density and residual stresses which are important for the subgrain nucleation surrounded by HAGBs (i.e recovery process). Our results are in align with previous literature where, the tensile properties of Al/steel composite were dramatically decreased after 2 ARB cycles [20]. This was attributed to the steel layers rupture inside the Al matrix. The mechanical strength after 2 cycles is similar to the Al one, since the steel is fragmented and is no longer useful to support the tensile strength. Besides, the loss of elongation to fracture compared to the Al sheet may be due to the imperfect interfaces created between Al layers. This lack of bounding can generate cracks that will propagate and lead to an early failure. The ARB process at higher temperature (300°C for example) could be benefit to the bounding and thus to the sandwich ductility. More, an annealing in a controlled Ar-H<sub>2</sub> atmosphere between each cycle,

instead of air, could prevent corrosion at the Al/steel interfaces in the ARB sandwiches and thus may improve the mechanical properties. It is worth mentioning that during ARB cycles the outer Al layers tend to disappear and be replaced by steel layers as it is clearly apparent in the SEM image (Fig. 5c) and more conspicuous in EBSD phase mapping image after 4 cycles (Fig. 6c). This is probably as a result of the increase in steel strength and the increase in ductility of the soft layers (Al) after annealing. In addition, the recovery process is slow in the steel layers because of a lower stacking fault energy of steel. Consequently, in this study, a sudden decrease of strength and elongation to failure of the Al/steel/Al multilayered composite after the second ARB cycle is attributed to the necking and rupture which takes place in the hard phase.

It has been reported that the composite thickness as well as the hard phase fragmentation in the matrix influenced the shielding effectiveness [14, 21]. The decrease in thickness led to the decrease in SE [14, 21] because the EMW absorption loss of the shielding material is proportional to its thickness [15]. Recently, Clerico et al. [21] showed that the steel fragmentation in Al matrix of Al/Steel/Al processed via cold roll bonding (CRB) led to the decrease in shielding effectiveness and a more negative impact of steel fragmentation is often observed at higher frequency (10 kHz). On the contrary, in the work of Verstraete et al. [14] after the third ARB cycle of Al/Steel/Al, fragments of the steel in the Al matrix led to an improve in shielding which may be probably due to the difference in elaboration processes. In the present study, it can be observed that SE is improved from 0 to 2 cycles as suggested by Verstraete et al. associated to steel fragmentation. As mentioned above, the microstructure of the ARB sandwiches is stable after 2 cycles. As a consequence, the magnetic properties remain constant between 2 and 4 cycles.

## 5. Conclusion

The tri-layered Al/steel/Al composites with 0.2 mm in thickness have been successfully fabricated by ARB up to 4 cycles at room temperature. An intermediate annealing between each cycle is performed at 400°C for 10 min in the air. The influence of the cycle number on the microstructural, mechanical, magnetic shielding properties of the prepared sandwiches was studied. The conclusions drawn from the results obtained can be summarized in the following points:

1. The microstructure of the Al/steel/Al composite showed a necking and fragmentation of steel in Al matrix during ARB process. Further, the outer of Al layers tends to disappear and be replaced by steel layers in the composite proceed for 4 cycles.
2. The grain size of Al layers gradually decreased from 20  $\mu\text{m}$  in the primary sandwich to  $\sim 2 \mu\text{m}$  after 2 cycles and remains constant as ARB cycle increases up to 4 cycles. Steel grain size is not greatly impacted by the ARB process up to 4 cycles.
3. After 2 ARB cycles, the microstructure of the sandwiches remains stable.
4. The tensile properties for the sandwich reduced after 2 cycles due to the fragmentation of steel inside the Al matrix.
5. The optimal ARB cycle number is 2 for these thin sandwiches. Increasing the cycle number does not permit to improve nor the mechanical nor the magnetic properties.
6. The 2 cycles ARB processed sandwich is able to shield at low frequency and a gradually increase in SE with increased frequency is achieved. It combines the advantages of steel and aluminum magnetic abilities.

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