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Ten Years of Severe Plastic Deformation (SPD) in Iran, Part II: Accumulative Roll Bonding (ARB)

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Abstract: The present paper is the second part of a previously published overview entitled “ten years of severe plastic deformation (SPD) in Iran”. Part I concentrates on the equal channel angular pressing (ECAP). In this part, the focus is on the accumulative roll bonding (ARB) because, currently, Iran is ranked the first in the world by the total number of publications in this field. In the present section, the emphasis is not on the microstructure and ultrafine-grained materials produced by ARB. Instead, its focus is on several aspects of ARB to which small attention has been paid so far. The impact and contribution of Iran to each category is evaluated in comparison to researchers from other countries. The main interest of Iranian researchers in the field of ARB is to fabricate the composite materials, particularly metal matrix composites (MMCs). The Iranian researchers were the first who introduced ARB as an effective method to produce particulate MMCs.

Keywords: Severe plastic deformation, Accumulative roll bonding (ARB), Ultrafine-grained materials, Properties.

Contents

1. Introduction

From the invention of severe plastic deformation (SPD) as an effective method to produce ultrafine-grained materials, several new techniques (more than 100) have been introduced. Equal channel angular pressing (ECAP), high-pressure torsion (HPT) and accumulative roll bonding (ARB) are three basic techniques that are known as the conventional SPD methods. Among three conventional methods, ARB has attracted more considerably by Iranian researchers. Several factors can be attributed to this. First, unlike ECAP and HPT, ARB process does not need the die construction and it can be carried out by the use of conventional rolling mill. Second, the processing by ARB is easier than that of ECAP and HPT.

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Third, the samples used in ARB are in the form of sheet and there is no need to any additional processing for sample preparation.

ARB, first invented by Saito et al [1], is one kind of severe plastic deformation (SPD) in which two layers of metal strips are stacked and joined together by a roll-bonding process. Then, the length of rolled strip (typically by 50% reduction in thickness) is sectioned into two halves. The sectioned strips are surface-treated, stacked and roll-bonded again and the process is repeated up to several cycles. Similar to other SPD methods, the main goal in ARB is to fabricate the ultra-fine grained materials but in the form of sheets with excellent mechanical properties.

The history of ARB in Iran started from 2008 when Iranian scientist used ARB to produce ultrafine-grained Mg [2], Cu [3], Al [4-7] and IF steel [8], concurrently. The first attempt of Iranian researchers to fabricate metallic multilayers of Al/Cu [9] and Al/IF steel [10] were also published in the same year. The analysis of the records extracted from the Web of Science (WoS) indicates that in the last decade (from 2008 to 2017), the rate of the number of publications from the top ranked countries remains more or less constant. In contrast, the number of published papers by Iranian researchers increases remarkably in that period. Presently, Iran is ranked the first in the world based on the total number of publications during the period of ten years, which is more than 247 publications out of ~780 records, in the field of ARB processing. Japan with 202 publications has occupied the second place after Iran, though the ARB process was first introduced by Japanese scientists in year 1998 [1]. Among many countries, Iran is an appealing case to study in the field of ARB due to its impact and contribution in this field. The ultrafine-grained characteristics of ARB processed materials have been widely investigated by various scientists around the world. Therefore, this review deals primarily with those aspects of ARB to which small attention has been given with emphasis on the impact of Iranian researchers. The topics includes the composite materials fabricated by ARB, processing routes, corrosion behavior, wear characteristics, weldability and simulation of ARB processed materials.

2. ARB Processed Materials in Iran

Initial works on the deformation bonding in Iran started by Danesh manesh and his co-workers [11,12]. In 2003, they investigated the bond strength and formability of an aluminum-clad steel sheet [11]. Lately, in 2008, the effect of the amount of deformation and the rolling temperature on the bond strength and the threshold deformation of the roll-bonded Al strips was evaluated [12]. These preliminary investigations opened the field of research on the ARB. To date, numerous works have been published in the field of ARB that focus on the UFG materials and their characteristics. Accordingly, in the present section various materials other than UFG ones that are produced by ARB are highlighted with an emphasis on Iran's achievements. The ARB processing attracted the attention of Iranian researchers first in 2008 in the course of several articles in various journals. At this year, Fatemi-Varzaneh et al.[2] produced an AZ31 Mg alloy with an ultrafine grained (UFG) structure by using the ARB process. At the same time, the ARB was utilized by Pirgazi et al. [4-6] and Talachi et al. [7] to form UFG structure in Al. Besides, the UFG Cu and IF steel were also produced by Shaarbaf et al. [3] and Tamimi et al. [8], respectively through ARB. This method has been utilized to fabricate various UFG metal and alloys through since the following years until now.

Among all works published on ARB in 2008, one utilized ARB with a different approach. Instead of using a single metal and other than producing a UFG structure, Izadjou et al. [9] used ARB method to produce an Al-Cu multilayer. They used a sandwich of Al and Cu as the starting material and observed that Cu layers necked and fractured during ARB. After five ARB cycles, a multilayered Al/Cu composite with a homogeneous distribution of Cu fragments in Al matrix was reported. The idea of using ARB to fabricate a metallic multilayer goes back to the Tsuji et al. (2005) [13] where they severely deformed a multilayer of Cu-Zr up to an equivalent strain of about 14 by ARB at ambient temperature. During the early ARB cycles, they found many shear bands formed by a kind of plastic instability during rolling due to significant difference in the flow behaviors between Cu and Zr. The shear banding retarded the steady decrease of the microstructural dimension. It was clarified that the amorphous phase formed within the shear bands, where plastic strain was greatly localized in the ARB processed [14]. This approach was then utilized by other Iranians to fabricate composite materials containing two metallic phases including Cu/Ag [15], Al/Ni [16,17], Al/Zn [18], Al/Cu [19-21], Cu/Ni [22], Cu/Zn [23], Cu/Ti [24], Ni/Ti [25], Al/Sn [26] and Al/Steel [27]. Hybrid metallic composites of the type Cu/Zn/Al [28,29], Al/Cu/Mn[30,31], Al/Ti/Mg [32], Al/Cu/Sn [33], and multi-phase composites [34] were also produced by Iranians using this approach. It is noted that the fabrication of metallic composites has also been of interest to other researchers in other countries, but, here, only the Iranians' works are highlighted.

Generally, the microstructure of a metallic multilayer processed by deformation synthesis method consists of two morphological features [35]. In one, the hard layer necks and breaks into several fragments due to the difference in flow properties of metallic phases. At final stages of ARB, the hard phase distributes uniformly in the soft matrix and acts as the reinforcement phase. Figure.1 illustrates the scanning electron microscopy (SEM) images of a multi-phase composite of Al-Cu-Ni-SiC at various cycles of ARB. The necking and fracturing of the hard phase (Cu in this case) at initial cycles and its gradual distribution in the Al matrix at final stages of ARB are clearly obvious.

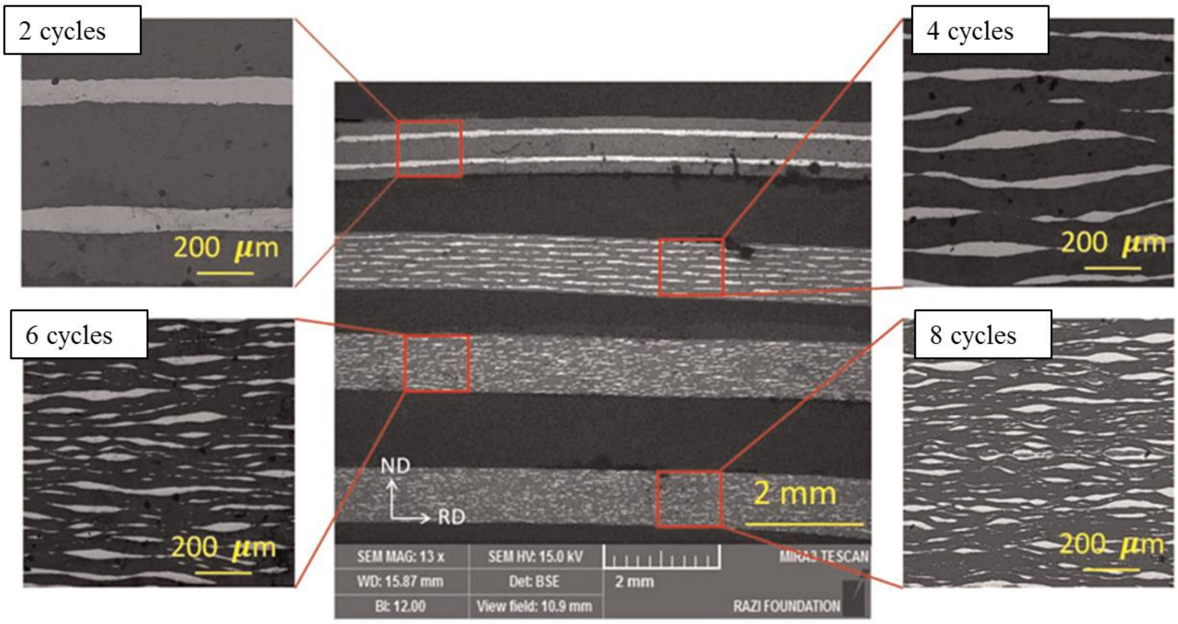

Fig. 1. SEM micrograph of the Al–Cu–Ni composite at low and high magnifications at various ARB cycles [34].

In this case, the thickness ratio and the flow properties of the metal constituents are two key factors for predicting qualitatively the occurrence of necking. The higher the hardness ratio and the lower the thickness ratio, the more easily necking/rupture occurs in the hard layer. In other multilayers, the continuity of layers is maintained up to several ARB cycles though irregularities are formed at the interfaces and thickness variations occur amongst the layers. In these systems, the initial thicknesses of two metal phases are usually considered similar. Figure 2 shows SEM images and the corresponding elemental maps of a Cu/Zn multilayer after five and six ARB cycles. The continuity of layers is maintained at this composite even after six ARB cycles.

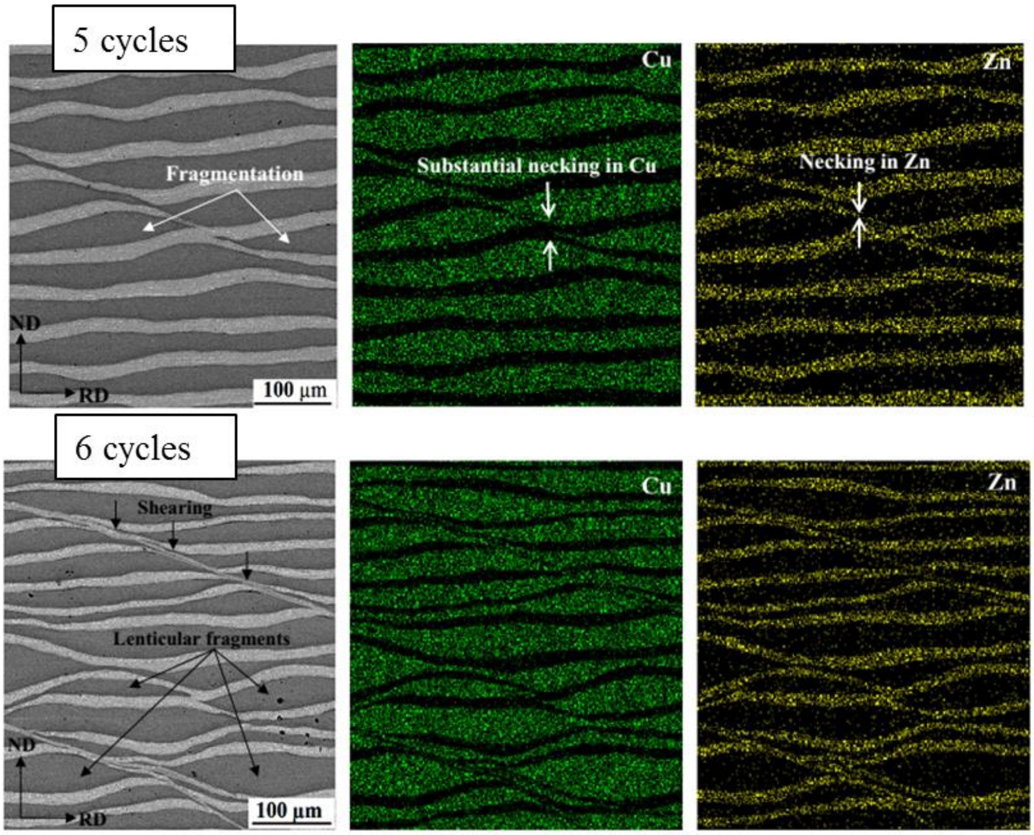

Fig. 2. SEM image of Cu/Zn composite after five and six ARB cycles and the corresponding SEM elemental maps for Cu distribution and Zn distribution [23].

In year 2009, Alizadeh and Paydar [36], introduced a new procedure to fabricate Al/SiC composite by the so-called repeated roll-bonding (RRB) process. The main difference between this technique and the well-known ARB is that in the RRB process the strips are annealed after each cycle and therefore no strain can be accumulated by increasing the number of cycles. Jamaati and Torginejad [37] in 2010 used this method to fabricate an Al/Al_2O_3 composite but with a different name as continual annealing and roll-bonding (CAR). According to this method (RRB and CAR), ceramic particles are added between the metal layers during the initial cycles of ARB. After imposing a critical reduction, a uniform distribution of particles is achieved in the matrix. Since the year 2010, further works can be found in literature by Iranian researchers that consider this technique to fabricate composite materials of the type Al/B_4C [38], Al/SiC [39-41], Al/Al_2O_3 [42-44], Al/TiB_2 [45,46] and Cu/SiC [47]. Furthermore, Al/Al_2O_3/SiC [48], Al/B_4C/SiC [49,50], Al/Al_2O_3/B_4C [51] and Al/WO_3/SiC[52]and Al/SiC-Gr [53] are several hybrid composites that are of interest to and manufactured by Iranians.

The microstructural change of an Al/SiC composite during ARB process is shown in Fig. 3. It is observed that by increasing the number of ARB cycles, SiC particles disperse more and more homogeneously in the Al matrix. The mechanisms that are responsible for particle distribution in the composites are as follows. When two 1 mm thick strips are roll bonded up to eight cycles with a 50% reduction per cycle, the number of layers increases to 256 and their thickness reduces to 3.9 μm, assuming a homogeneous deformation. Therefore, the particles at the layer interfaces share out through the thickness of the strip as the ARB process proceeds. At the same time, the plastic deformation and the extrusion of the Al through the particles lead to the separation and movement of the particles from each other. Another mechanism that is considered for dispersion of the particles is the movement of particles from edges of the particle clusters, which causes the particle clusters to become smaller as the number of ARB cycle increases [40,54].

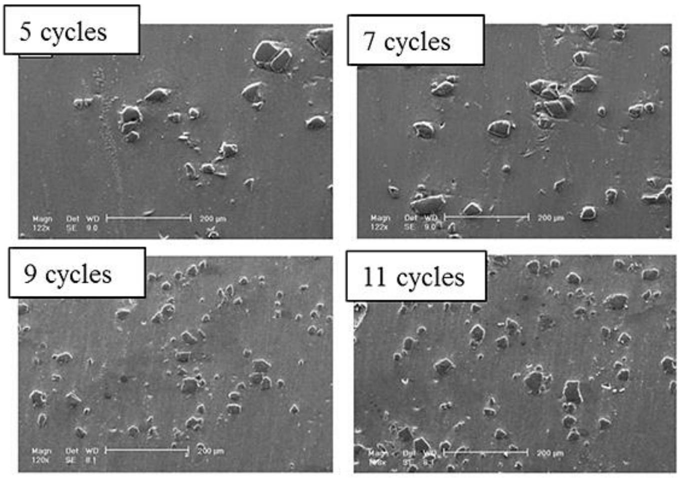

Fig.3. SEM micrographs of the Al/SiC composite microstructures produced by various cycles of the ARB process [55].

To date, as discussed above, the distribution of particles in MMCs processed by ARB has been examined experimentally by several researchers. However, only a few reports consider specifically the effect of particles on the microstructure evolution of the matrix metals during ARB and these investigations are limited almost only to the particle-matrix interfaces. Bagherpour et al. [56] in 2016 considered the role of particle distribution in the microstructure evolution during SPD method. They considered the Al/SiC composite produced by ARB as a case and examined the grain refinement in the Al matrix by transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) at various zones: particle free zone, single particle zone and cluster zone (Fig. 4). Their results showed that the lowest grain size was obtained in the cluster zone between two nearly neighboring particles.

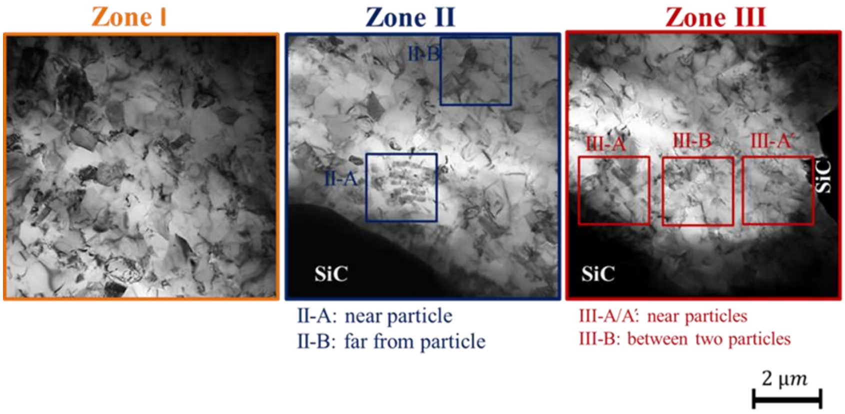

Fig. 4. Typical TEM images of Al/SiC composite produced by ARB, taken from different microstructural zones [56].

In 2010, Jamaati and Toroghinejad [57] and Jamaati et al. [58] introduced a new method to fabricate Al/Al_2O_3 composites, which was based on a combination of ARB and anodizing. During this method, the anodized strip is placed between the uncoated metal strips. As the ARB proceeds, the anodized layer necks, fractures and distributes uniformly within the metal matrix due to the difference in flow properties of the anodized layer and the matrix. In 2012, Shabani et al. [59] used electroplating as an alternative to anodizing and produced a multi component Al/Ni/Cu composite. Instead of anodizing or electroplating, Reihanian et al. (2015) [60], used plasma electrolytic oxidation (PEO) to generate an alumina oxide layer and placed the coated strip in length between two uncoated Al strips. They showed that a uniform distribution of Al_2O_3 fragments was achieved within the Al matrix after six ARB cycles. The combined method of ARB and anodizing/electroplating was utilized by various Iranian teams to produce hybrid composites of the type Al/Al_2O_3-TiC [61], Al/Al_2O_3-SiC [62], Al/Cu-Al_2O_3 [63], Al/Al_2O_3-B4C [64] and Al/Al_2O_3–ZrC [65]. Based on this approach, Ahmadi Ana et al. (2015) [34] produced a multi-component Al-based metal matrix composite by ARB of the composite coated strips. They generated a Ni/SiC composite layer with three different thicknesses on the Cu substrate by electroplating. The coated strips were placed between two Al strips and processed by ARB up to eight cycles to fabricate the multi-component Al-Cu-Ni/SiC composites.

Besides UFG metals and MMCs, metallic foams are considered as another material that can be formed by ARB process. However, compared to other materials, metal foam has attracted the least attention. Up to the beginning of 2017, 10 records can be found in this field; all are published only by Japanese (with 7 records) and Iranian (with 3 records). Metal foams were produced by ARB for the first time in Japan by Kitazono et al. in 2004 [66]. They produced Al foam through ARB and used TiH_2 particles as the foaming agent. They obtained foamed Al plates of about 40% porosity by heating the pre-form sheets under controlled temperature conditions. Kitazono and his co-workers used this method to produce other metallic foams such as Al-Si alloy foam [67] and Al-Mg alloy foam [68]. Kamimura et al. in 2005 [69] proposed a new application of superplasticity to manufacture metal foams. The preform sheets were manufactured using superplastic 5083 Al alloy sheets through ARB process. They produced microcellular Al foam plates with 50% porosity through solid-state foaming under the superplastic condition. The idea of producing metal foams was attracted the attention of Iranians in year 2015 by publishing three articles. Hosseini et al. investigated the effect of nano-SiCp on the microstructure and formability of Al/TiH_2 foam precursor produced by ARB [70,71]. In addition, Zeidabady et al., produced a closed cell Cu foams through ARB using $CaCO_3$ as the blowing agent [72]. Figure 5 shows SEM images of the early pore formation and its evolution in Al/TiH_2 and $Al/TiH_2/SiC$ strips after various dwell times in the preheated furnace at 750 °C (air atmosphere).

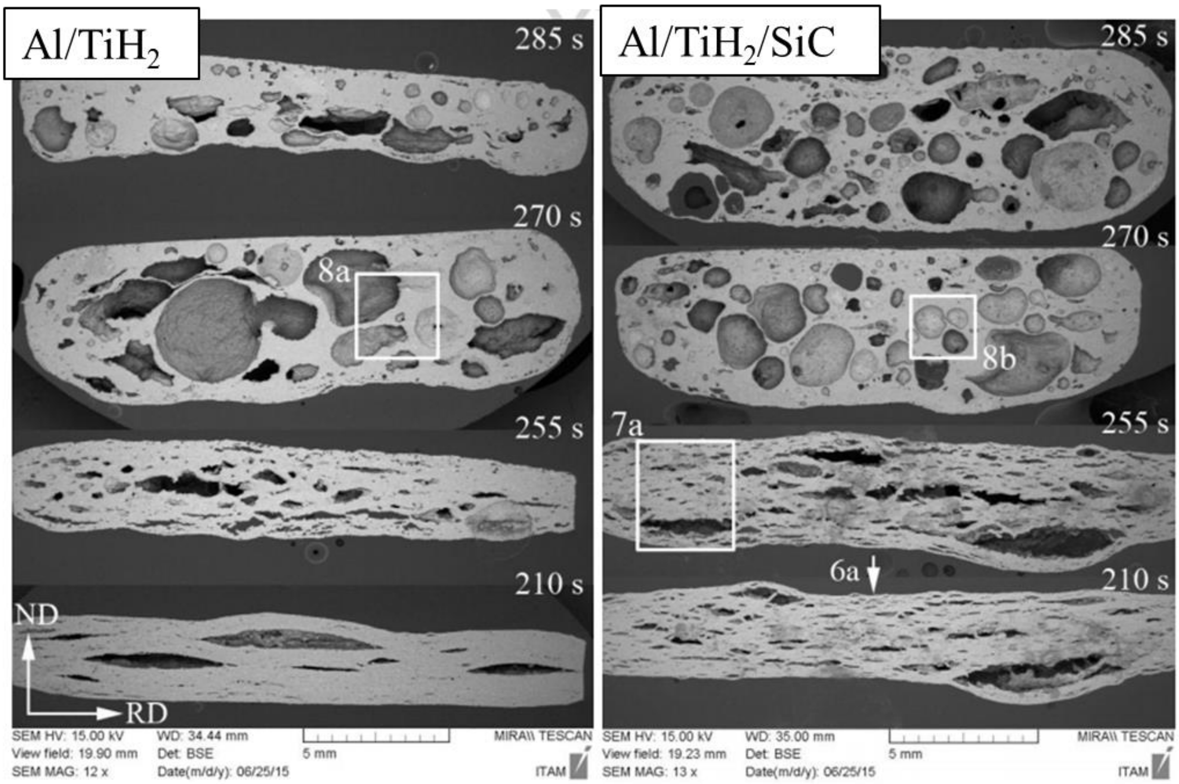

Fig.5. SEM images showing the early pore formation and its evolution in Al/TiH_2 and $Al/TiH_2/SiC$ strips after various dwell times in the preheated furnace at 750 °C (air atmosphere) [71].

3. Processing Routes

Cross-accumulative roll bonding (CARB) is a rolling technique similar to ARB. The main difference between ARB and CARB is that during CARB the strain path is changed by a 90° rotation around the normal direction (ND) of the sheets after each cycle. Kaneko et al. (2003) [73] were the first researchers who introduced CARB and concluded that the ARB with cross rolling is more effective in ultra- grain refinement and high strengthening than conventional ARB. The method was then utilized by Kim et al. (2006) [74,75] to show the effectiveness of the method on the grain refinement and ductility enhancement in commercially 1050 Al alloy. In Iran, Alizadeh (2010) [76] was the first who used CARB to produce an Al/B_4C composite. To date, CARB has been conducted on several materials including commercially pure Al [77,78], AA 6014 [79], Al/Al_2O_3 [80,81], Al/SiC composite [82], Fe-Ni alloy [83], AA5754/AA6061 composite [84,85], commercially pure Ti [86], Al/B_4C/SiC hybrid composite [87] and Cu/Ta nanolamellar multilayer [88]. Figure 6 shows the electron backscattered diffraction (EBSD) maps of Al after eight cycles of conventional ARB and CARB. The EBSD map of the annealed Al is also indicated. The effectiveness of the CARB in grain refinement is evident from this figure.

In a collaboration between Monash University (Australia) and University of Erlangen-Nürnberg (Germany), Ng et al. (2013) [89] fabricated Al/Ti composite sheets through a new route named asymmetric accumulative roll bonding (AARB), which capitalized on additional shear to enhance plastic deformation. They found that not only AARB led to a more refined grain size of the Al matrix but also it promoted the development of a nanostructured surface layer on Ti. They also showed that AARB-processed sheets exhibited a larger thickness of the interdiffusion layers at the Al/Ti interfaces compared with the symmetric ARB route.

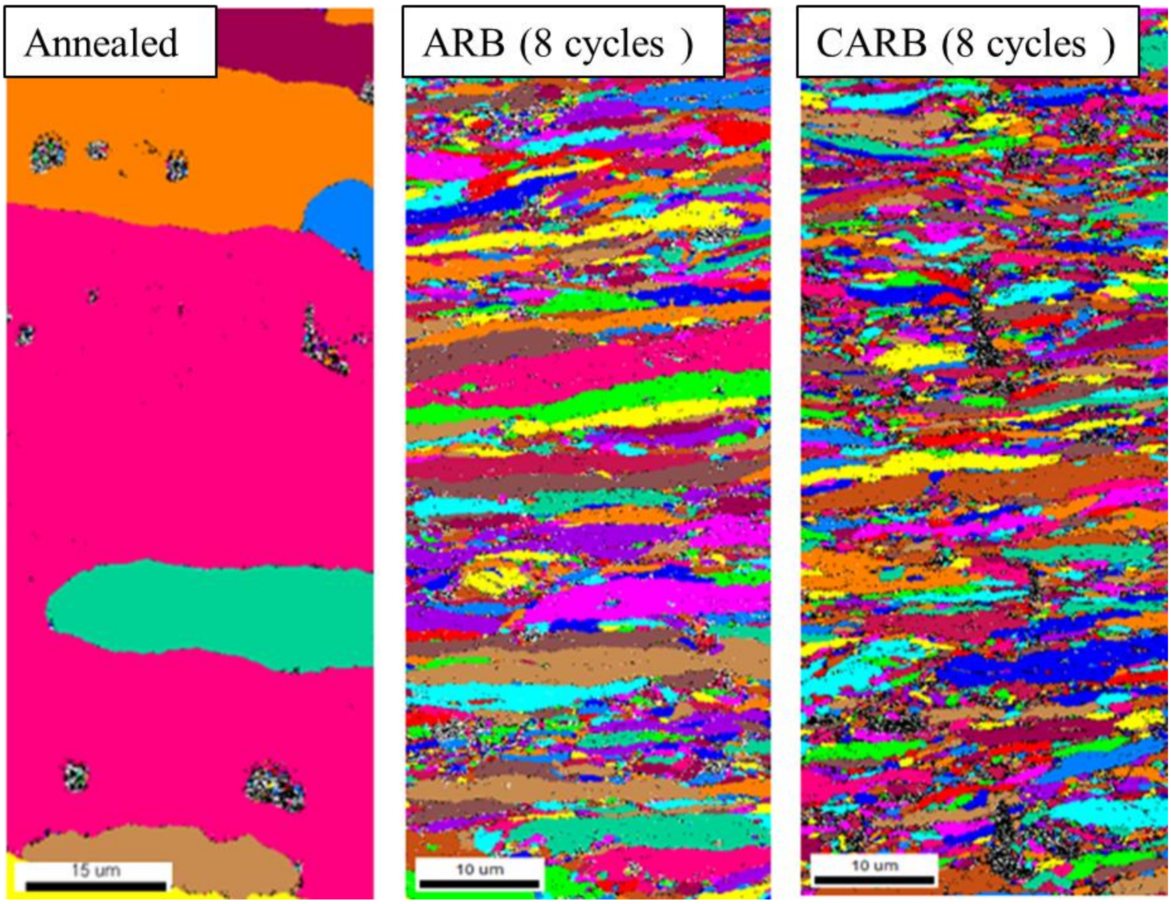

Fig. 6. Orientation color maps of the annealed, ARB and CARB Al specimens processed to eight cycles [78].

In 2013 [90] a new route for ARB was introduced by Yazdani et al. in order to impose a distribution of different accumulated strain and hardness across the thickness of the strips, entitled strain composite strips (SCS). During the initial stage of this procedure, one pass of ARB technique is performed on annealed strips of AA5083. A strip of this product (on half) is again roll-bonded to another annealed strip. Similarly, a strip of this new sample is again roll-bonded with another annealed strip. The sequences of roll bonding with an annealed sample are continued up to a number of cycles (Fig. 7). Such stacking sequence of strips provides a monotonic and gradual increase in the accumulated strain through the thickness. They called the produced strip a strain strip composite (SCS). Comparison of SCS and ARB processed strips shows an improvement in the ductility of SCS at the cost of a small decrease in strength.

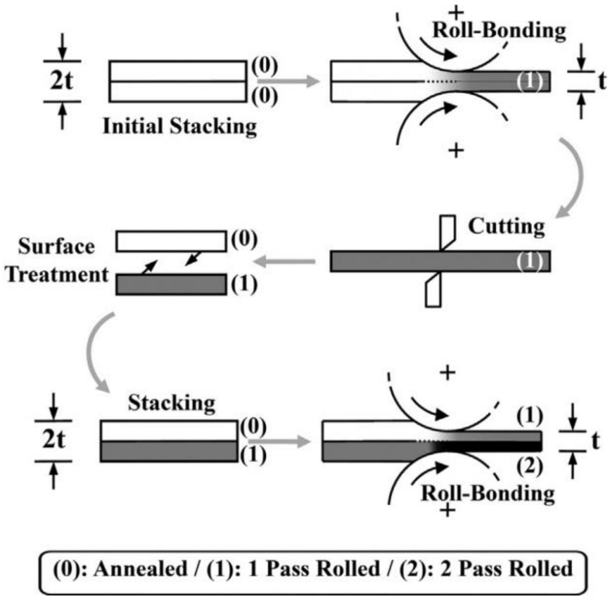

Fig. 7. Schematic illustration of the proposed method for producing strain composite strips (SCS) [90].

Naseri et al. (2016) [91] used a similar procedure in ARB with this difference that they used an annealed strip of AA2024 Al alloy between the previously roll-bonded strips of the same material after each cycles. The process involves two steps. In the first step, two annealed AA2024 strips are stacked over each other and roll-bonded to 50% reduction in thickness. In the second step, the roll-bonded strips were cut into two pieces and another annealed AA2024 strip is sandwiched between the two pieces of previously roll-bonded strips. The stacked strips were roll-bonded again. This procedure is repeated up to four cycles. The stress-strain curves of the materials processed by these new routs indicate that these routes have the capability of producing ARB processed materials with an improvement in ductility with a small sacrifice the strength of the material (Fig. 8).

The effect of shear strain distribution due to frictional effects between rolls and sheet materials in the conventional ARB on grain refinement was first investigated by Lee et al. in 2002 [92]. They stated that in ARB process without lubrication, a large amount of shear strain must be introduced in the surface regions of the Al sheet in every roll bonding. Accordingly, they quantified the shear strain distribution in the ARB processed Al sheets by embedding cylindrical pin of the same material in the initial strip and their results are presented in Fig. 9. Based on this investigation, Kamikawa et al. [93] studied the effect of redundant shear strain on microstructure and texture evolution during ARB of IF steel. They concluded that the redundant shear strain caused the through-thickness microstructural heterogeneity at early stages of ARB. However, the repetition of cutting, stacking and rolling in the ARB, generated a complex distribution of strain through the sheet thickness so that a rather uniform UFG structure at a high number of ARB cycle was achieved.

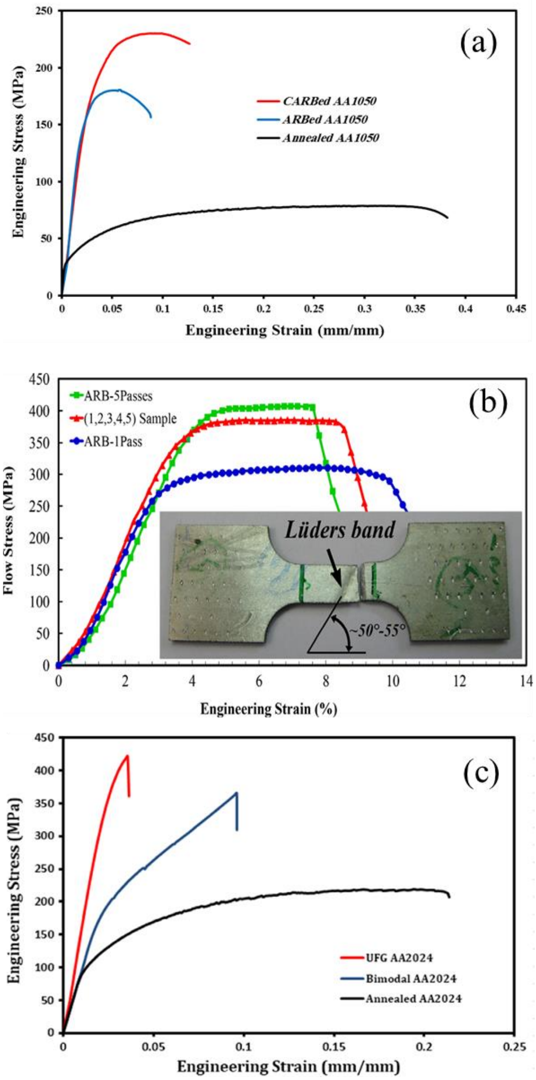

Fig. 8. Comparison of the stress-strain curves of the samples after various ARB routes with the conventional ARB; a) CARB [78], b) strain composite strips [90] and c) bimodal strip [91].

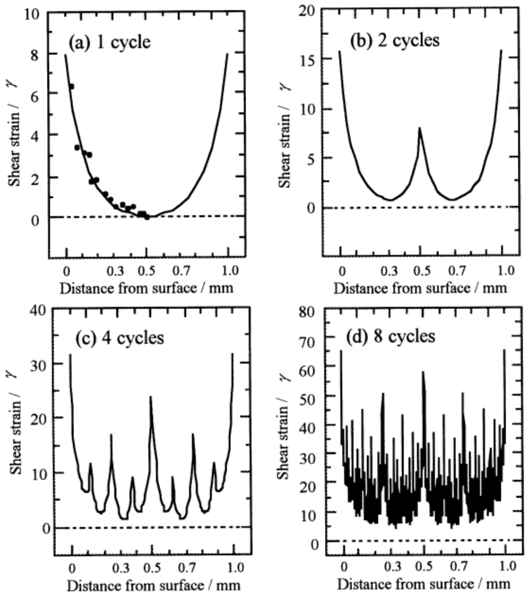

Fig. 9. Distribution of shear strain through thickness of ARB processed Al after different number of ARB cycles [92].

4. Special Characterization

The microstructure, mechanical behavior and deformation texture of ARB processed materials have been investigated widely in literatures. This section focuses on various features of ARB processed materials that have attracted relatively small attention in the research community. These features include corrosion, wear, welding, physical properties and the modeling of ARB processed materials. The authors try to review the most important publications in these fields until the beginning of 2017.

4.1. Corrosion behavior

Similar to other SPD methods, the corrosion behavior of ARB processed materials has attracted considerable attention in the research community. The literature survey extracted from Web of Science indicates that Iranian researchers have the most contribution in the field of corrosion behavior (more than 60%) after ARB. The corrosion of UFG materials produced by SPD has been well reviewed by Miyamoto [94]. He reported that while enhancing mechanical properties, grain refinement by SPD did not compromise the overall corrosion resistance and in many cases, SPD could improve it in comparison with coarse-grained counterparts. However, he found that there were some contradictory results within the same materials and same environment.

According to the literature, the first investigation on corrosion behavior of ultra-fine grained materials produced by ARB was reported by Fujimoto et al. (2004) [95]. They considered Al and Al-2%Cu alloy as the starting materials and examined the pitting behavior with and without the heat treatment. Their results showed that the defects generated during ARB caused the higher probability of initiating pitting corrosion. Moreover, both ARB processed and full annealed Al-2%Cu alloy exhibited noble pitting potential compared with that of pure Al. The corrosion behavior of Al-Mn alloy and AA 5754 processed by ARB materials was then explored by Wei et al. (2007) [96] and Haosul et al. (2010) [97], respectively. The details of the corrosion behavior of materials processed by ARB are not the goal of the present review. The critical achievements attributed to Iranian researchers are highlighted. The first Iranian's work on the corrosion behavior of ARB processed materials can be found in the work of Jamaati et al. (2011) [98] where they investigated the tribocorrosion behavior of Al/Al2O3 composite strips manufactured by anodizing and ARB. They found that the non-homogeneous, lower quantity, fine, and acicular-shape of alumina particles caused serious materials loss in the tribocorrosion process. The most major contribution in this field arises from Fattah-Alhosseini and his co-workers who have several publications on the corrosion behavior of Al 1050 [99-101], Cu [102-106] and Al/B_4C/SiC composite [50] among the other. Other Iranian researchers have also published numerous works on the corrosion behavior of Al/SiC [107-109], Cu [110,111], Al/Al_2O_3 [112] and lead based composites [113] processed by ARB.

4.2. Wear

Wear behavior is an important material property for UFG materials because they may be used in a range of structural applications. Gao et al. (2012) [114] have published a review paper to examine the recent reports related to the wear resistance of materials processed by SPD with particular emphasis on ECAP, HPT and ARB. They reported that only limited reports are available to date on the wear behavior of SPD-processed materials and, furthermore, many of these results appear to be conflicting. Among all countries, South Korea and Iran have the biggest role in the wear behavior of the ARB processed materials. The first report on the wear behavior of ARB processed metals can be found in the work of Korean researchers, Kim et al. (2002) [115], where they examined dry sliding wear behavior of ultrafine grained commercial purity Al processed ARB. Their results showed that, in spite of the increased hardness and strength, wear resistance of the ultrafine-grained materials was lower than that of the coarse-grained as-received one. Between the years 2004 to 2005 Kim and his coworkers extended their studies on the wear of ARB processed 6061 Al [116], 5052 Al and 5083 Al [117,118] and 1100 Al [119]. In Iran, the wear of ARB processed materials was studied first by Talachi et al. [7] in 2008 and they found that the wear resistance of the ARB processd Al alloy was less than that of the non-processed Al alloy. Talachi et al. in 2011 [120] characterized the wear behavior of Al sheet after ARB using a pin on disc wear test under different conditions. They found that wear rates of the ARB processed Al sheets increased by increasing wear load and rotation speed, while, immersion lubrication decreased the wear rate significantly. They also proposed a model for the wear of the ARB processed Al based on their experimental observations. Sliding wear behavior of ARB processed 6061 Al alloy sheets subjected to dry sliding wear at different loading and sliding velocities was also investigated by Izadjou et al. (2011) [121] using a pin on disc wear machine. To the end of 2016, five published works have considered the wear properties of the composite materials produced by ARB. Four of the five works have been published in Iran, and they consider the wear characteristic of Al_2O_3 [98,122], Al/SiC [108]and Cu/Zn [123] composites produced by ARB. Among these works, one is related to Liu et al. [124] in which they evaluated the wear of Al/WC composite manufactured through warm ARB.

4.3. Welding

According to literatures, a few records can be found on the field of welding and weldability of the ARB processed materials. Among all, Iran and Japan with seven and six records, respectively, are located as the first and the second rank. Generally, the conventional fusion welding of UFG materials produced by SPD causes the mechanical properties deterioration of these materials because of the remarkable grain growth of the ultrafine grains during welding at high temperatures [125]. Therefore, friction stir welding (FSW) as a solid-state joining process with lower heat-input than that of fusion welding processes, enabling the formation of a fine grain structure in the stir zone, has been considered as an effective method to prevent the deterioration of the mechanical properties of the ultrafine-grained materials. Friction stir welding (FSW) was first applied by Sato et al. (2004) [126] to an ARB processed Al alloy 1100 and resulted in reproduction of fine grains in the stir zone and small growth of the ultrafine grains in the ARB processed material just outside the stir zone. Therefore, FSW effectively prevented the softening in the Al alloy processed by ARB. Fuji et al. (2005) [127] reported that, after ARB processing, high strength joints were obtained for the ultrafine grained steel and Al under the optimum welding conditions while the strength of the ultrafine grained copper joints significantly decreased in comparison to that of the base metal due to grain growth in the heat affected zone (HAZ). FSW processing was conducted by other researchers on various materials including IF steel [128] and Al alloys [129-131]. In Iran, Hosseini and Danesh Manesh (2010) [132] proposed a technique to reduce the deterioration of mechanical properties of the joint. They joined the ARB processed strips by FSW in immersed (underwater) and conventional (in-air) conditions to investigate the effect of the immersion method on the microstructure and mechanical properties of the joint. Their results showed that the hardness and tensile properties of the immersed friction stir welded sample and ARB processed base metal were both similar in two materials, and better than those of the conventionally friction stir welded sample. This was attributed to the smaller grains in the stir zone of the immersed FSW condition with respect to the conventional FSW method. It is interesting to note that, except this work, the attention of other Iranian researchers has been directed toward FSW of the composite materials including Al/Al_2O_3 [133], Al/Cu [20] and $Al/Al_2O_3/B_4C$ [134] produced by ARB. In addition, Fattahi et al. used ARB as an effective method to fabricate composite filler metals of the type nanoparticle/Al composite [135] and TiC/Al composite [136] for tungsten inert gas (TIG) welding. They showed that the composite filler could serve as suitable filler for GTA welding of aluminum and its alloys.

4.4. Electrical and magnetic properties

Among many characteristics of ARB processed materials, the electrical and particularly the magnetic properties of these materials have attracted the least attention. Along with thirteen records on the electrical properties of ARB processed samples, only two correspond to Iranian researchers. Similar to the corrosion and wear behaviors, the results are somewhat conflicting. The first study on the electrical property of ultra-fine-grained Cu-Cr-Zr alloy sheet was produced by ARB conducted in Japan by the work of Kitagawa et al. [137] in year 2008. They showed that the aging treatment after ARB process enhanced not only the mechanical properties but also the electrical conductivity in the Cu-Cr-Zr alloys. Hosseini et al. (2009) [138], from Iran, explained that the electrical conductivity of Cu decreased with increasing the number of ARB cycle up to six cycles and then increasing up to eight cycles. Takata et al. (2009) [139] claimed that UFG Cu alloys with sub-micometer grain sizes could achieve both superior mechanical properties and high electric conductivity. Ghalandari and Moshksar (2010) [15], other Iranian researchers, measured the electrical conductivity of Cu-Ag multilayer after ARB, and concluded that the electrical resistivity of the samples increased slightly by increasing the number of cycles. The investigation on electrical conductivity was continued by other researchers on the ARB processed Al [140,141], Cu-Ni-P-Zr alloys [142], Al-Cu alloy and composite [143,144], Al/W composite [145], Cu-Ni-Si-Zr Alloy [146], Cu alloy [147] and Al/AlMg$_3$ [148].

The magnetic properties of the ARB processed materials have been of interest only to Iranian researchers. Eslami et al. (2013) [149] evaluated the magnetic properties of Cu/Ni multilayer composite fabricated by ARB as the first group. They reported that the magnetic properties such as retentivity, coercivity and magnetic saturation of the multilayer composite, were significantly influenced by the changes in the microstructure and grain size. Deneshvar et al. (2016) [150] used ARB to fabricate Al/Ni (with two initial Ni thicknesses) and Al/Ni/Fe$_3$O$_4$ composites. Their results showed that after eight cycles, an Al-based composite with a satisfactorily magnetic behavior was produced (Fig. 10). The Al/Ni composite with larger Ni thickness exhibited the highest tensile strength with the highest value of saturation magnetization. The relative permeability decreased with increasing the frequency for a given number of ARB cycles. The Fe$_3$O$_4$ particles caused the saturation magnetization to decrease and the critical frequency to increase due to the eddy current effects.

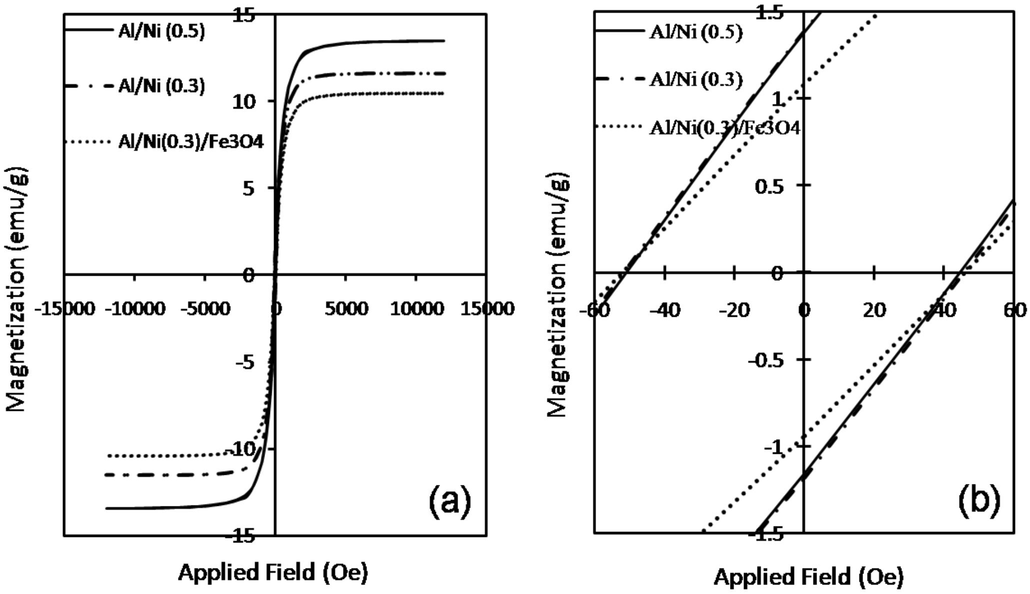

Fig. 10. (a) Hysteresis curves of Al/Ni composites (with two initial thicknesses of Ni) and Al/Ni/Fe3O4 composites and (b) an enlarged view of M–H curves extracted from [150].

5. Modeling and Simulation

The first report on the simulation of ARB can be found in the work of Hesieh et al [151] in 2006. They applied ARB process on the multilayered Zr and Ni foils and mixed them with nanocrystalline and amorphous bulk materials. By using high-resolution transmission electron microscopy and molecular dynamics simulation, they examined the latest stage of the transformation from nanocrystalline elemental phase to the amorphous alloying phase. At the same time, Ikeda et al. [152] used the same approach (molecular dynamics simulation) to study the grain boundary structure in ARB processed Cu. They concluded that the grain boundary structure in the ARB-Cu was not very different from the normal equilibrium grain boundary and this could be explained by conventional dislocation and structural unit model. The first work in which ARB is modeled by finite element analysis has been published by Inoue and Tsuji in year 2009 [153]. They quantified the strain components and equivalent strain in the rolled material using finite element analysis and concluded that the equivalent strain at the surface in the 1100 Al processed by one ARB cycle without lubricant corresponded to the equivalent strain in the material processed by five ARB cycles with lubricant. Modeling and simulation of ARB have attracted a slight attention from Iranian researchers. Roostaei et al. (2010) [154] are the first and only Iranian researchers that used the finite element method to analyze the plastic deformation behavior of an AZ31 alloy during ARB process. Their results indicated that an increase in the friction coefficient led to an increase in the equivalent plastic strain and strain gradient. Furthermore, they found that accumulated strain decreased with increasing the temperature, causing a more homogeneous deformation throughout the thickness.

In contrast to the least contribution of Iran in simulation of ARB processing, Iran has a major role in analytical modeling of the composite materials processed by ARB. Rezayat and Akbarzadeh (2012) [155] proposed a theoretical model to predict the threshold reduction in warm roll bonding of commercially pure Al sheets to get bonding in the presence of ceramic particles. Their model considers the rolling parameters and the effect of the amount and size of the particles. They showed that the measured values of the threshold reduction were well predicted by the modeling results. Reihanian et al. [156], in 2012, proposed an analytical model to predict the critical strain to get a uniform distribution of hard particles in MMCs produced by ARB. The model considered composites containing both single and bimodal sized particles (including micro-and nanometre particles). The effect of the particle size, particle volume fraction and initial thickness of the layers is considered by the model. Their results showed that among all parameters, particle size has the most significant effect on the critical strain.

Soon after, in the year 2013, Reihanian et al. [157] modified the model by considering three cubic arrangements for the distribution of particles in the matrix including simple, face-centered and body-centered cubic models. They concluded that among all considered particle distributions, the simple cubic model was the most effective to predict the critical reduction. Based on the simple cubic model the critical reduction in bi-modal (single type particle) and tri-modal (tow-type particles) composites can be obtained by [157]:

$$R_{cr} = 1 - \left[\frac{\sqrt{3}\pi}{8f}\right]^{1/3} \left(\frac{d}{t_{\circ}}\right) \tag{1}$$

$$R_{cr} = 1 - \left[\frac{\pi}{6\left(f_A d_B^3 + f_B d_A^3\right)}\right]^{1/3} \left(\frac{d_A d_B}{t_{\circ}}\right) \tag{2}$$

where *d* is the particle size, *f* is the volume fraction and $t_{\circ}$ is the initial thickness of the layers. The subscripts A and B stand for particles A and B, respectively. Results showed that the critical reduction to get a uniform distribution of particles rises with increasing volume fraction, decreasing particle size and raising initial layer thickness. Figure. 11 shows the variation of the critical strain with volume fraction for SC, BCC and FCC models.

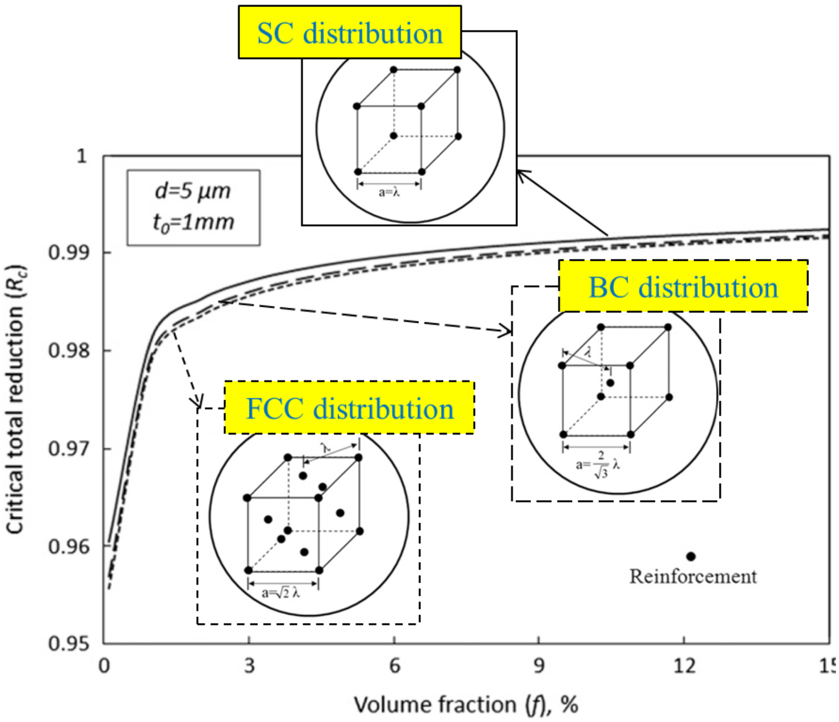

Fig. 11. Variation in critical reduction with particle volume fraction for SC, FCC and BCC model [157].

In the year 2016, Reihanian and Naseri [158] also developed a model to predict the critical strain (based on an instability criterion) for the onset of necking in the hard layer during the ARB of the metallic multilayer. Their model was an extension to the plastic instability during sandwich sheet rolling proposed by Hwang et al. They showed that the critical strain for necking during ARB of metallic multilayer obeys an equation similar to that of sandwich sheet rolling. In addition, they proposed an analytical model to predict the critical strain for fracture based on the Cockcroft and Latham criterion. According to this model, the critical strain for necking (and fracture) increased with increasing the thickness ratio, strength coefficient ratio and the work-hardening exponent of the hard phase while it decreased with increasing the work-hardening exponent of the soft phase. Until that time, modeling the plastic instability in the hard layer during ARB had received only a limited attention, which was directed toward finite element methods [159,160].

6. Summery and conclusions

During the last decade, the attention of Iranian scientists to the ARB process make Iran rank the first among many countries in year 2017 and make it the single-handed country that has an increasing rate in the number of publications. The first published paper on ARB in Iran goes back to year 2008. The main contribution of Iran in the field of ARB does not focus on the production of UFG materials, which is conventionally the main goal of the ARB process. Instead, the attention has been paid to the production of composite materials, particularly metal matrix composites, by using the ARB process. The Iranian researchers were the first who introduced ARB as an effective method to fabricate particulate MMCs. The lesser attention to UFG characteristic of ARB processed materials in Iran may be attributed to two main factors: i) inaccessibility of Iranian researchers to advanced characterization techniques such as TEM and EBSD and ii) low collaboration with scientists in other countries owing to the difficulty of Visa preparation and less amount of funds.

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7. References

[1] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai, R.G. Hong, Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process, *Scripta Materialia* 39(9) (1998) 1221-1227.

[2] S.M. Fatemi-Varzaneh, A. Zarei-Hanzaki, M. Haghshenas, Accumulative roll bonding of AZ31 magnesium alloy, *International Journal of Modern Physics B* 22(18-19) (2008) 2833-2839.

[3] M. Shaarbaf, M.R. Toroghinejad, Nano-grained copper strip produced by accumulative roll bonding process, *Materials Science and Engineering A* 473(1-2) (2008) 28-33.

[4] H. Pirgazi, A. Akbarzadeh, Characterization of nanostructured aluminum sheets processed by accumulative roll bonding, *International Journal of Modern Physics B* 22(18-19) (2008) 2840-2847.

[5] H. Pirgazi, A. Akbarzadeh, R. Petrov, L. Kestens, Microstructure evolution and mechanical properties of AA1100 aluminum sheet processed by accumulative roll bonding, *Materials Science and Engineering A* 497(1-2) (2008) 132-138.

[6] H. Pirgazi, A. Akbarzadeh, R. Petrov, J. Sidor, L. Kestens, Texture evolution of AA3003 aluminum alloy sheet produced by accumulative roll bonding, *Materials Science and Engineering A* 492(1-2) (2008) 110-117.

[7] A.K. Talachi, M. Eizadjou, H.D. Manesh, K. Janghorban, Wear properties of 1100 Al alloy produced by accumulative roll bonding, *International Journal of Modern Physics B* 22(18-19) (2008) 2848-2857.

[8] S. Tamimi, M. Ketabchi, N. Parvin, The effects of accumulative roll bonding process on microstructure and mechanical properties of if steel, *International Journal of Modern Physics B* 22(18-19) (2008) 2866-2873.

[9] M. Eizadjou, A. Kazemi Talachi, H. Danesh Manesh, H. Shakur Shahabi, K. Janghorban, Investigation of structure and mechanical properties of multi-layered Al/Cu composite produced by accumulative roll bonding (ARB) process, *Composites Science and Technology* 68(9) (2008) 2003-2009.

[10] S. Tamimi, M. Ketabchi, N. Parvin, Mechanical properties of ultra fine grained aluminum and iron produced by Accumulative roll bonding method, 1 (2008), pp 193-202.

[11] H.D. Manesh, A.K. Taheri, Bond strength and formability of an aluminum-clad steel sheet, *Journal of Alloys and Compounds* 361(1) (2003) 138-143.

[12] M. Eizadjou, H.D. Manesh, K. Janghorban, Investigation of roll bonding between aluminum alloy strips, *Materials & Design* 29(4) (2008) 909-913.

[13] N. Tsuji, S. Kato, S. Ohsaki, K. Hono, Y. Minamino, Bulk mechanical alloying of Zr-Cu system by accumulative roll bonding (ARB), Metastable, Mechanically Alloyed and Nanocrystalline Materials, A. Inoue, Ed., 2005, pp 643-646.

[14] S. Ohsaki, S. Kato, N. Tsuji, T. Ohkubo, K. Hono, Bulk mechanical alloying of Cu–Ag and Cu/Zr two-phase microstructures by accumulative roll-bonding process, *Acta Materialia* 55(8) (2007) 2885-2895.

[15] L. Ghalandari, M.M. Moshksar, High-strength and high-conductive Cu/Ag multilayer produced by ARB, *Journal of Alloys and Compounds* 506(1) (2010) 172-178.

[16] A. Mozaffari, H.D. Manesh, K. Janghorban, Evaluation of mechanical properties and structure of multilayered Al/Ni composites produced by accumulative roll bonding (ARB) process, *Journal of Alloys and Compounds* 489(1) (2010) 103-109.

[17] A. Mozaffari, M. Hosseini, H.D. Manesh, Al/Ni metal intermetallic composite produced by accumulative roll bonding and reaction annealing, *Journal of Alloys and Compounds* 509(41) (2011) 9938-9945.

[18] R.N. Dehsorkhi, F. Qods, M. Tajally, Investigation on microstructure and mechanical properties of Al-Zn composite during accumulative roll bonding (ARB) process, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 530 (2011) 63-72.

[19] V.Y. Mehr, M.R. Toroghinejad, A. Rezaeian, Mechanical properties and microstructure evolutions of multilayered Al-Cu composites produced by accumulative roll bonding process and subsequent annealing, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 601 (2014) 40-47.

[20] M. Shiraly, M. Shamanian, M.R. Toroghinejad, M.A. Jazani, Effect of Tool Rotation Rate on Microstructure and Mechanical Behavior of Friction Stir Spot-Welded Al/Cu Composite, *Journal of Materials Engineering and Performance* 23(2) (2014) 413-420.

[21] S. Khademzadeh, M.R. Toroghinejad, F. Ashrafizadeh, Structural evolution and interdiffusion in Al/Cu nanocomposites produced by a novel manufacturing process, *Metals and Materials International* 18(6) (2012) 1049-1054.

[22] M. Tayyebi, B. Eghbali, Study on the microstructure and mechanical properties of multilayer Cu/Ni composite processed by accumulative roll bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 559 (2013) 759-764.

[23] L. Ghalandari, M.M. Mandavian, M. Reihanian, Microstructure evolution and mechanical properties of Cu/Zn multilayer processed by accumulative roll bonding (ARB), *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 593 (2014) 145-152.

[24] M. Hosseini, N. Pardis, H. Danesh Manesh, M. Abbasi, D.-I. Kim, Structural characteristics of Cu/Ti bimetal composite produced by accumulative roll-bonding (ARB), *Materials & Design* 113 (2017) 128-136.

[25] O. Emadinia, S. Simoes, F. Viana, M.F. Vieira, A.J. Cavaleiro, A.S. Ramos, M.T. Vieira, Cold rolled versus sputtered Ni/Ti multilayers for reaction-assisted diffusion bonding, *Welding in the World* 60(2) (2016) 337-344.

[26] L. Ghalandari, M.M. Mahdavian, M. Reihanian, M. Mahmoudiniya, Production of Al/Sn multilayer composite by accumulative roll bonding (ARB): A study of microstructure and mechanical properties, *Materials Science and Engineering: A* 661 (2016) 179-186.

[27] M. Talebian, M. Alizadeh, Manufacturing Al/steel multilayered composite by accumulative roll bonding and the effects of subsequent annealing on the microstructural and mechanical characteristics, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 590 (2014) 186-193.

[28] M.M. Mahdavian, L. Ghalandari, M. Reihanian, Accumulative roll bonding of multilayered Cu/Zn/Al: An evaluation of microstructure and mechanical properties, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 579 (2013) 99-107.

[29] M.M.M. M. Reihanian, L. Ghalandari, A. Obeidavi, Formation of a Solid Solution Through Accumulative Roll Bonding (ARB) and Post-Heat Treatment of Multilayered Cu/Zn/Al, *Iranian Journal of Materials Forming* 1(1) (2014) 24-31.

[30] M. Alizadeh, M. Samiei, Fabrication of nanostructured Al/Cu/Mn metallic multilayer composites by accumulative roll bonding process and investigation of their mechanical properties, *Materials & Design* 56 (2014) 680-684.

[31] A.O. Moghaddam, M. Ketabchi, Y. Afrasiabi, Accumulative Roll Bonding and Post-Deformation Annealing of Cu-Al-Mn Shape Memory Alloy, *Journal of Materials Engineering and Performance* 23(12) (2014) 4429-4435.

[32] P.D. Motevalli, B. Eghbali, Microstructure and mechanical properties of Tr-metal Al/Ti/Mg laminated composite processed by accumulative roll bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 628 (2015) 135-142.

[33] M.M. Mahdavian, H. Khatami-Hamedani, H.R. Abedi, Macrostructure evolution and mechanical properties of accumulative roll bonded Al/Cu/Sn multilayer composite, *Journal of Alloys and Compounds* 703 (2017) 605-613.

[34] S.V.A. Ana, M. Reihanian, B. Lotfi, Accumulative roll bonding (ARS) of the composite coated strips to fabricate multi-component Al-based metal matrix composites, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 647 (2015) 303-312.

[35] J.-M. Lee, B.-R. Lee, S.-B. Kang, Control of layer continuity in metallic multilayers produced by deformation synthesis method, *Materials Science and Engineering: A* 406(1–2) (2005) 95-101.

[36] M. Alizadeh, M.H. Paydar, Fabrication of Al/SiCP composite strips by repeated roll-bonding (RRB) process, *Journal of Alloys and Compounds* 477(1–2) (2009) 811-816.

[37] R. Jamaati, M.R. Toroghinejad, A. Najafizadeh, An alternative method of processing MMCs by CAR process, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 527(10-11) (2010) 2720-2724.

[38] A. Yazdani, E. Salahinejad, Evolution of reinforcement distribution in Al-B4C composites during accumulative roll bonding, *Materials & Design* 32(6) (2011) 3137-3142.

[39] R. Jamaati, M.R. Toroghinejad, H. Edris, Effect of SiC nanoparticles on the mechanical properties of steel-based nanocomposite produced by accumulative roll bonding process, *Materials & Design* 54(0) (2014) 168-173.

[40] M. Rezayat, A. Akbarzadeh, A. Owhadi, Fabrication of High-Strength Al/SiC p Nanocomposite Sheets by Accumulative Roll Bonding, *Metallurgical and Materials Transactions A* 43(6) (2012) 2085-2093. (in English).

[41] M. Alizadeh, M.H. Paydar, D. Terada, N. Tsuji, Effect of SiC particles on the microstructure evolution and mechanical properties of aluminum during ARB process, *Materials Science and Engineering: A* 540(0) (2012) 13-23.

[42] M. Rezayat, A. Akbarzadeh, A. Owhadi, Production of high strength Al–Al2O3 composite by accumulative roll bonding, *Composites Part A: Applied Science and Manufacturing* 43(2) (2012) 261-267.

[43] R. Jamaati, M.R. Toroghinejad, J. Dutkiewicz, J.A. Szpunar, Investigation of nanostructured Al/Al2O3 composite produced by accumulative roll bonding process, *Materials & Design* 35(0) (2012) 37-42.

[44] M.N. M. Reihanian, M. Jalili Shahmansouri, Effect of the particle size on the deformation and fracture behavior of Al/4vol.%Al2O3 composite produced by accumulative roll bonding (ARB), *Iranian Journal of Materials Forming* 2(2) (2015) 14-26.

[45] M. Karbalaei Akbari, H.R. Baharvandi, K. Shirvanimoghaddam, Tensile and fracture behavior of nano/micro TiB2 particle reinforced casting A356 aluminum alloy composites, *Materials & Design* 66, Part A (2015) 150-161.

[46] M. Askarpour, Z. Sadeghian, M. Reihanian, Role of powder preparation route on microstructure and mechanical properties of Al-TiB2 composites fabricated by accumulative roll bonding (ARB), *Materials Science and Engineering: A* 677 (2016) 400-410.

[47] O. Ghaderi, M.R. Toroghinejad, A. Najafizadeh, Investigation of microstructure and mechanical properties of Cu–SiCP composite produced by continual annealing and roll-bonding process, *Materials Science and Engineering: A* 565(0) (2013) 243-249.

[48] M. Reihanian, F.K. Hadadian, M.H. Paydar, Fabrication of Al–2 vol% Al2O3/SiC hybrid composite via accumulative roll bonding (ARB): An investigation of the microstructure and mechanical properties, *Materials Science and Engineering: A* 607(0) (2014) 188-196.

[49] M. Naseri, A. Hassani, M. Tajally, Fabrication and characterization of hybrid composite strips with homogeneously dispersed ceramic particles by severe plastic deformation, *Ceramics International* 41(3) (2015) 3952-3960.

[50] A. Fattah-alhosseini, M. Naseri, M.H. Alemi, Corrosion behavior assessment of finely dispersed and highly uniform Al/B4C/SiC hybrid composite fabricated via accumulative roll bonding process, *Journal of Manufacturing Processes* 22 (2016) 120-126.

[51] M. Alizadeh, H.A. beni, Strength prediction of the ARBed Al/Al2O3/B4C nano-composites using Orowan model, *Materials Research Bulletin* 59 (2014) 290-294.

[52] S. Baazamat, M. Tajally, E. Borhani, Fabrication and characteristic of Al-based hybrid nanocomposite reinforced with WO3 and SiC by accumulative roll bonding process, *Journal of Alloys and Compounds* 653 (2015) 39-46.

[53] M. Reihanian, S. Fayezipour, S.M. Lari Baghal, Nanostructured Al/SiC-Graphite Composites Produced by Accumulative Roll Bonding: Role of Graphite on Microstructure, Wear and Tensile Behavior, *Journal of Materials Engineering and Performance* 26(4) (2017) 1908-1919.

[54] A. Yazdani, E. Salahinejad, J. Moradgholi, M. Hosseini, A new consideration on reinforcement distribution in the different planes of nanostructured metal matrix composite sheets prepared by accumulative roll bonding (ARB), *Journal of Alloys and Compounds* 509(39) (2011) 9562-9564.

[55] R. Jamaati, S. Amirkhanlou, M.R. Toroghinejad, B. Niroumand, Effect of particle size on microstructure and mechanical properties of composites produced by ARB process, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 528(4-5) (2011) 2143-2148.

[56] E. Bagherpour, M. Reihanian, H. Miyamoto, Tailoring particle distribution non-uniformity and grain refinement in nanostructured metal matrix composites fabricated by severe plastic deformation (SPD): a correlation with flow stress, *Journal of Materials Science* 52(6) (2017) 3436-3446.

[57] R. Jamaati, M.R. Toroghinejad, High-strength and highly-uniform composite produced by anodizing and accumulative roll bonding processes, *Materials & Design* 31(10) (2010) 4816-4822.

[58] R. Jamaati, M.R. Toroghinejad, A. Najafizadeh, Application of anodizing and CAR processes for manufacturing Al/Al2O3 composite, *Materials Science and Engineering: A* 527(16–17) (2010) 3857-3863.

[59] A. Shabani, M.R. Toroghinejad, A. Shafyei, Fabrication of Al/Ni/Cu composite by accumulative roll bonding and electroplating processes and investigation of its microstructure and mechanical properties, *Materials Science and Engineering: A* 558(0) (2012) 386-393.

[60] M. Reihanian, M. Jalili Shahmansouri, M. Khorasanian, High strength Al with uniformly distributed Al2O3 fragments fabricated by accumulative roll bonding and plasma electrolytic oxidation, *Materials Science and Engineering: A* 640 (2015) 195-199.

[61] H. Farajzadeh Dehkordi, M.R. Toroghinejad, K. Raeissi, Fabrication of Al/Al2O3/TiC hybrid composite by anodizing and accumulative roll bonding processes and investigation of its microstructure and mechanical properties, *Materials Science and Engineering: A* 585(0) (2013) 460-467.

[62] A. Ahmadi, M.R. Toroghinejad, A. Najafizadeh, Evaluation of microstructure and mechanical properties of Al/Al2O3/SiC hybrid composite fabricated by accumulative roll bonding process, *Materials & Design* 53(0) (2014) 13-19.

[63] V. Yousefi Mehr, A. Rezaeian, M.R. Toroghinejad, Application of accumulative roll bonding and anodizing process to produce Al–Cu–Al2O3 composite, *Materials & Design* 70(0) (2015) 53-59.

[64] M.R. Toroghinejad, R. Jamaati, A. Nooryan, H. Edris, Hybrid composites produced by anodizing and accumulative roll bonding (ARB) processes, *Ceramics International* 40(7) (2014) 10027-10035.

[65] M. Shamanian, M. Mohammadnezhad, H. Asgari, J. Szpunar, Fabrication and characterization of Al-Al2O3-ZrC composite produced by accumulative roll bonding (ARB) process, *Journal of Alloys and Compounds* 618 (2015) 19-26.

[66] K. Kitazono, E. Sato, K. Kuribayashi, Novel manufacturing process of closed-cell aluminum foam by accumulative roll-bonding, *Scripta Materialia* 50(4) (2004) 495-498.

[67] K. Kitazono, S. Nishizawa, E. Sato, T. Motegi, Effect of ARB cycle number on cell morphology of closed-cell Al-Si alloy foam, *Materials Transactions* 45(7) (2004) 2389-2394.

[68] K. Kitazono, Y. Kikuchi, E. Sato, K. Kuribayashi, Anisotropic compressive behavior of Al-Mg alloy foams manufactured through accumulative roll-bonding process, *Materials Letters* 61(8-9) (2007) 1771-1774.

[69] S. Kamimura, K. Kitazono, E. Sato, K. Kuribayashi, Application of superplastic flow to manufacturing of microcellular aluminum foams, Pricm 5: The Fifth Pacific Rim International Conference on Advanced Materials and Processing, Pts 1-5, Z.Y. Zhong, H. Saka, T.H. Kim, E.A. Holm, Y.F. Han, X.S. Xie, Eds., 2005, pp 3021-3024.

[70] S.M. Hosseini, A. Habibolahzadeh, Investigation of nano-SiCp effect on microstructure and mechanical properties of Al/TiH2 foam precursor produced via ARB process, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 639 (2015) 80-88.

[71] S.M. Hosseini, A. Habibolahzadeh, V. Petráňová, J. Němeček, Influence of nano-SiCp on the foamability and microstructure of Al/TiH2 foam sheet manufactured by continual annealing and roll-bonding process, *Materials & Design* 97 (2016) 483-491.

[72] M.A. Zeidabady, M. Tajally, E. Emadoddin, Manufacturing of copper foams through accumulative roll bonding (ARB) process: structure and damping capacity behavior, *Canadian Metallurgical Quarterly* 54(2) (2015) 198-204.

[73] S. Kaneko, K. Fukuda, H. Utsunomiya, T. Sakai, Y. Saito, N. Furushiro, Ultra grain refinement of aluminium 1100 by ARB with cross rolling, Thermec'2003, Pts 1-5, T. Chandra, J.M. Torralba, T. Sakai, Eds., 2003, pp 2649-2653.

[74] Y.S. Kim, S.H. Kang, D.H. Shin, Effect of rolling direction on the microstructure and mechanical properties of accumulative roll bonding (ARB) processed commercially pure 1050 aluminum alloy, Nanomaterials by Severe Plastic Deformation, Z. Horita, Ed., 2006, pp 681-686.

[75] Y.S. Kim, S.H. Kang, D.H. Shin, Ductility enhancement of ultrafine grained commercially pure 1050 aluminum alloy by cross accumulative roll-bonding (C-ARB), 2006

[76] M. Alizadeh, Processing of Al/B4C composites by cross-roll accumulative roll bonding, *Materials Letters* 64(23) (2010) 2641-2643.

[77] M. Alizadeh, E. Salahinejad, Processing of ultrafine-grained aluminum by cross accumulative roll-bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 595 (2014) 131-134.

[78] M. Naseri, M. Reihanian, E. Borhani, Effect of strain path on microstructure, deformation texture and mechanical properties of nano/ultrafine grained AA1050 processed by accumulative roll bonding (ARB), *Materials Science and Engineering: A* 673 (2016) 288-298.

[79] M. Ruppert, H.W. Hoppel, M. Goken, Influence of cross-rolling on the mechanical properties of an accumulative roll bonded aluminum alloy AA6014, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 597 (2014) 122-127.

[80] M.R.K. Ardakani, S. Amirkhanlou, S. Khorsand, Cross accumulative roll bonding A novel mechanical technique for significant improvement of stir-cast Al/Al2O3 nanocomposite properties, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 591 (2014) 144-149.

[81] M. Alizadeh, E. Salahinejad, A comparative study on metal-matrix composites fabricated by conventional and cross accumulative roll-bonding processes, *Journal of Alloys and Compounds* 620 (2015) 180-184.

[82] M.R.K. Ardakani, S. Khorsand, S. Amirkhanlou, M.J. Nayyeri, Application of compocasting and cross accumulative roll bonding processes for manufacturing high-strength, highly uniform and ultra-fine structured Al/SiCp nanocomposite, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 592 (2014) 121-127.

[83] H. Azzeddine, K. Tirsatine, T. Baudin, A.L. Helbert, F. Brisset, D. Bradai, Texture evolution of an Fe-Ni alloy sheet produced by cross accumulative roll bonding, *Materials Characterization* 97 (2014) 140-149.

[84] K. Verstraete, A.L. Helbert, F. Brisset, T. Baudin, Comparison between ARB and CARB processes on an AA5754/AA6061 composite, 6th International Conference on Nanomaterials by Severe Plastic Deformation, B. Beausir, O. Bouaziz, E. Bouzy, T. Grosdidier, L.S. Toth, Eds., 2014

[85] K. Verstraete, A.L. Helbert, F. Brisset, A. Benoit, P. Poniard, T. Baudin, Microstructure, mechanical properties and texture of an AA6061/AA5754 composite fabricated by cross accumulative roll bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 640 (2015) 235-242.

[86] S. Sahoo, S. Panda, R.K. Sabat, G. Kumar, S.C. Mishra, U.K. Mohanty, S. Suwas, Effect of pre-annealing strains on annealing texture developments in commercially pure (CP) titanium, *Philosophical Magazine* 95(10) (2015) 1105-1124.

[87] M. Naseri, A. Hassani, M. Tajally, An alternative method for manufacturing Al/B4C/SiC hybrid composite strips by cross accumulative roll bonding (CARB) process, *Ceramics International* 41(10) (2015) 13461-13469.

[88] L.F. Zeng, R. Gao, Q.F. Fang, X.P. Wang, Z.M. Xie, S. Miao, T. Hao, T. Zhang, High strength and thermal stability of bulk Cu/Ta nanolamellar multilayers fabricated by cross accumulative roll bonding, *Acta Materialia* 110 (2016) 341-351.

[89] H.P. Ng, T. Przybilla, C. Schmidt, R. Lapovok, D. Orlov, H.W. Hoppel, M. Goken, Asymmetric accumulative roll bonding of aluminium-titanium composite sheets, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 576 (2013) 306-315.

[90] A. Yazdani, N. Pardis, R. Hosseini, R. Ebrahimi, Strain composite strips produced by accumulative roll bonding technique, *Materials Science and Engineering: A* 577 (2013) 158-160.

[91] M. Naseri, M. Reihanian, E. Borhani, A new strategy to simultaneous increase in the strength and ductility of AA2024 alloy via accumulative roll bonding (ARB), *Materials Science and Engineering: A* 656 (2016) 12-20.

[92] S.H. Lee, Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai, Role of shear strain in ultragrain refinement by accumulative roll-bonding (ARB) process, *Scripta Materialia* 46(4) (2002) 281-285.

[93] N. Kamikawa, T. Sakai, N. Tsuji, Effect of redundant shear strain on microstructure and texture evolution during accumulative roll-bonding in ultralow carbon IF steel, *Acta Materialia* 55(17) (2007) 5873-5888.

[94] H. Miyamoto, Corrosion of Ultrafine Grained Materials by Severe Plastic Deformation, an Overview, *Materials Transactions* 57(5) (2016) 559-572.

[95] S. Fujimoto, T. Iwata, N. Tsuji, Y. Minamino, Corrosion behavior of ultra-fine grained Al and Al-2%Cu alloy produced by accumulative roll-bonding (ARB) process, 2004

[96] W. Wei, K.X. Wei, Q.B. Du, Corrosion and tensile behaviors of ultra-fine grained Al-Mn alloy produced by accumulative roll bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 454 (2007) 536-541.

[97] T. Hausol, H.W. Hoppel, M. Goken, Tailoring materials properties of UFG aluminium alloys by accumulative roll bonded sandwich-like sheets, *Journal of Materials Science* 45(17) (2010) 4733-4738.

[98] R. Jamaati, M.R. Toroghinejad, J.A. Szpunar, D.J. Li, Tribocorrosion Behavior of Aluminum/Alumina Composite Manufactured by Anodizing and ARB Processes, *Journal of Materials Engineering and Performance* 20(9) (2011) 1600-1605.

[99] A. Fattah-Alhosseini, S.O. Gashti, Corrosion Behavior of Ultra-fine Grained 1050 Aluminum Alloy Fabricated by ARB Process in a Buffer Borate Solution, *Journal of Materials Engineering and Performance* 24(9) (2015) 3386-3393.

[100] A. Fattah-alhosseini, S.O. Gashti, Passive Behavior of Ultra-Fine-Grained 1050 Aluminum Alloy Produced by Accumulative Roll Bonding in a Borate Buffer Solution, *Acta Metallurgica Sinica-English Letters* 28(10) (2015) 1222-1229.

[101] A. Fattah-alhosseini, S.O. Gashti, M.K. Keshavarz, Effect of Film Formation Potential on Passive Behavior of Ultra-Fine-Grained 1050 Al Alloy Fabricated via ARB Process, *Journal of Materials Engineering and Performance* 25(4) (2016) 1683-1689.

[102] A. Fattah-alhosseini, O. Imantalab, Effect of accumulative roll bonding process on the electrochemical behavior of pure copper, *Journal of Alloys and Compounds* 632 (2015) 48-52.

[103] A. Fattah-Alhosseini, O. Imantalab, Passivation Behavior of Ultrafine-Grained Pure Copper Fabricated by Accumulative Roll Bonding (ARB) Process, *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science* 47A(1) (2016) 572-580.

[104] A. Fattah-alhosseini, O. Imantalab, Y. Mazaheri, M.K. Keshavarz, Microstructural evolution, mechanical properties, and strain hardening behavior of ultrafine grained commercial pure copper during the accumulative roll bonding process, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 650 (2016) 8-14.

[105] O. Imantalab, A. Fattah-alhosseini, Electrochemical and Passive Behaviors of Pure Copper Fabricated by Accumulative Roll-Bonding (ARB) Process, *Journal of Materials Engineering and Performance* 24(7) (2015) 2579-2585.

[106] O. Imantalab, A. Fattah-Alhosseini, M.K. Keshavarz, Y. Mazaheri, Electrochemical Behavior of Pure Copper in Phosphate Buffer Solutions: A Comparison Between Micro- and Nano-Grained Copper, *Journal of Materials Engineering and Performance* 25(2) (2016) 697-703.

[107] E. Darmiani, I. Danaee, M.A. Golozar, M.R. Toroghinejad, Corrosion investigation of Al-SiC nano-composite fabricated by accumulative roll bonding (ARB) process, *Journal of Alloys and Compounds* 552 (2013) 31-39.

[108] E. Darmiani, I. Danaee, M.A. Golozar, M.R. Toroghinejad, A. Ashrafi, A. Ahmadi, Reciprocating wear resistance of Al-SiC nano-composite fabricated by accumulative roll bonding process, *Materials & Design* 50 (2013) 497-502.

[109] M. Kadkhodaee, M. Babaiee, H.D. Manesh, M. Pakshir, B. Hashemi, Evaluation of corrosion properties of Al/nanosilica nanocomposite sheets produced by accumulative roll bonding (ARB) process, *Journal of Alloys and Compounds* 576 (2013) 66-71.

[110] A. Nikfahm, I. Danaee, A. Ashrafi, M.R. Toroghinejad, Effect of Grain Size Changes on Corrosion Behavior of Copper Produced by Accumulative Roll Bonding Process, *Materials Research-Ibero-American Journal of Materials* 16(6) (2013) 1379-1386.

[111] A. Nikfahm, I. Danaee, A. Ashrafi, M.R. Toroghinejad, Corrosion Behavior of Ultra Fine Grain Copper Produced by Accumulative Roll Bonding Process, *Transactions of the Indian Institute of Metals* 67(1) (2014) 115-121.

[112] S.M.L.B. M. Reihanian, F. Keshavarz Haddadian, M.H. Paydar, A Comparative Corrosion Study of Al/Al2O3-SiC Hybrid Composite Fabricated by Accumulative Roll Bonding (ARB), *Journal of Ultrafine Grained and Nanostructured Materials* 49(1) (2016) 29-35.

[113] M. Karbasi, E.K. Alamdari, Electrochemical Evaluation of Lead Base Composite Anodes Fabricated by Accumulative Roll Bonding Technique, *Metallurgical and Materials Transactions B-Process Metallurgy and Materials Processing Science* 46(2) (2015) 688-699.

[114] N. Gao, C.T. Wang, R.J.K. Wood, T.G. Langdon, Tribological properties of ultrafine-grained materials processed by severe plastic deformation, *Journal of Materials Science* 47(12) (2012) 4779-4797.

[115] Y.S. Kim, T. Lee, K.T. Park, W.J. Kim, D.H. Shin, Dry sliding wear behavior of ultrafine grained commercial purity aluminum and low carbon steel produced by severe plastic deformation techniques, 2002

[116] Y.S. Kim, J.S. Ha, W.J. Kim, Dry sliding wear characteristics of severely deformed 6061 aluminum and AZ61 magnesium alloys, Designing, Processing and Properties of Advanced Engineering Materials, Pts 1 and 2, S.G. Kang, T. Kobayashi, Eds., 2004, pp 597-600.

[117] Y.S. Kim, J.S. Ha, D.H. Shin, The effect of microstructure on the sliding wear performance of ultrafine-grained aluminum alloys by ARB, 2004

[118] Y.S. Kim, J.S. Ha, D.H. Shin, Sliding wear characteristics of ultrafine-grained non-strain-hardening aluminum-magnesium alloys, Pricm 5: The Fifth Pacific Rim International Conference on Advanced Materials and Processing, Pts 1-5, Z.Y. Zhong, H. Saka, T.H. Kim, E.A. Holm, Y.F. Han, X.S. Xie, Eds., 2005, pp 401-404.

[119] Y.S. Kim, T.O. Lee, D.H. Shin, Microstructural evolution and mechanical properties of ultrafine grained commercially pure 1100 aluminum alloy processed by accumulative roll-bonding (ARB), Designing, Processing and Properties of Advanced Engineering Materials, Pts 1 and 2, S.G. Kang, T. Kobayashi, Eds., 2004, pp 625-628.

[120] A.K. Talachi, M. Eizadjou, H.D. Manesh, K. Janghorban, Wear characteristics of severely deformed aluminum sheets by accumulative roll bonding (ARB) process, *Materials Characterization* 62(1) (2011) 12-21.

[121] M. Eizadjou, A.K. Talachi, H.D. Manesh, K. Janghorban, Sliding Wear behavior of Severely Deformed 6061 Aluminum Alloy by Accumulative Roll Bonding (ARB) Process, Nanomaterials by Severe Plastic Deformation: Nanospd5, Pts 1 and 2, J.T. Wang, R.B. Figueiredo, T.G. Langdon, Eds., 2011, pp 1107-1112.

[122] R. Jamaati, M. Naseri, M.R. Toroghinejad, Wear behavior of nanostructured Al/Al2O3 composite fabricated via accumulative roll bonding (ARB) process, *Materials & Design* 59 (2014) 540-549.

[123] M.M.M. M. Reihanian, L.Ghalandari, Fabrication of the Cu-Zn Multilayer and Cu-Zn Alloy by Accumulative Roll Bonding (ARB) with an Emphasis on the Wear Behavior, *Iranian Journal of Materials Forming* 1(2) (2014) 52-62.

[124] C.Y. Liu, Q. Wang, Y.Z. Jia, B. Zhang, R. Jing, M.Z. Ma, Q. Jing, R.P. Liu, Evaluation of mechanical properties of 1060-Al reinforced with WC particles via warm accumulative roll bonding process, *Materials & Design* 43(0) (2013) 367-372.

[125] Y.S. Sato, M. Urata, Y. Kurihara, S.H.C. Park, H. Kokawa, K. Ikeda, N. Tsuji, Microstructural evolution during friction stir welding of ultrafine grained Al alloys, Nanomaterials by Severe Plastic Deformation, Z. Horita, Ed., 2006, pp 169-174.

[126] Y.S. Sato, Y. Kurihara, S.H.C. Park, H. Kokawa, N. Tsuji, Friction stir welding of ultrafine grained Al alloy 1100 produced by accumulative roll-bonding, *Scripta Materialia* 50(1) (2004) 57-60.

[127] H. Fujii, L. Cui, N. Tsuji, R. Ueji, K. Nakata, K. Nogi, Isope, Mechanical properties of friction stir welds of ultrafine grained steel and other materials, Proceedings of the Fifteenth, 2005, pp 22-26.

[128] H. Fuji, R. Ueji, Y. Takada, H. Kitahara, N. Tsuji, K. Nakata, K. Nogi, Friction stir welding of ultrafine grained interstitial free steels, *Materials Transactions* 47(1) (2006) 239-242.

[129] I. Topic, H.W. Hoppel, M. Goken, Deformation behaviour of accumulative roll bonded and friction stir welded aluminium alloys, Nanomaterials by Severe Plastic Deformation Iv, Pts 1 and 2, Y. Estrin, H.J. Maier, Eds., 2008, pp 833-839.

[130] Y.F. Sun, H. Fujii, Y. Takada, N. Tsuji, K. Nakata, K. Nogi, Effect of initial grain size on the joint properties of friction stir welded aluminum, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 527(1-2) (2009) 317-321.

[131] G. Buffa, L. Fratini, S. Pellegrino, F. Micari, On the field variables influence on bonding phenomena during FSW processes: experimental and numerical study, Sheet Metal 2013, R.B. Clarke, A.G. Leacock, J.R. Duflou, M. Merklein, F. Micari, Eds., 2013, pp 484-491.

[132] M. Hosseini, H.D. Manesh, Immersed friction stir welding of ultrafine grained accumulative roll-bonded Al alloy, *Materials & Design* 31(10) (2010) 4786-4791.

[133] M. Shamanian, M. Mohammadnezhad, J. Szpunar, Texture analysis of a friction stir welded ultrafine grained Al-Al2O3 composite produced by accumulative roll-bonding, *Journal of Alloys and Compounds* 615 (2014) 651-656.

[134] M. Mohammadnezhad, M. Shamanian, A. Zabolian, M. Taheri, V. Javaheri, A.H. Navidpour, M. Nezakat, J.A. Szpunar, Microstructure and Crystallographic Texture Variations in the Friction-Stir-Welded Al-Al2O3-B4C Metal Matrix Composite Produced by Accumulative Roll Bonding, *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science* 46A(12) (2015) 5747-5755.

[135] M. Fattahi, V.N. Aghaei, A.R. Dabiri, S. Amirkhanlou, S. Akhavan, Y. Fattahi, Novel manufacturing process of nanoparticle/Al composite filler metals of tungsten inert gas welding by accumulative roll bonding, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 648 (2015) 47-50.

[136] M. Fattahi, M. Mohammady, N. Sajjadi, M. Honarmand, Y. Fattahi, S. Akhayan, Effect of TiC nanoparticles on the microstructure and mechanical properties of gas tungsten arc welded aluminum joints, *Journal of Materials Processing Technology* 217 (2015) 21-29.

[137] K. Kitagawa, T. Akita, K. Kita, M. Gotoh, N. Takata, N. Tsuji, Structure and mechanical properties of severely deformed Cu-Cr-Zr alloys produced by accumulative roll-bonding process, Nanomaterials by Severe Plastic Deformation Iv, Pts 1 and 2, Y. Estrin, H.J. Maier, Eds., 2008, pp 791-796.

[138] S.A. Hosseini, H.D. Manesh, High-strength, high-conductivity ultra-fine grains commercial pure copper produced by ARB process, *Materials & Design* 30(8) (2009) 2911-2918.

[139] N. Takata, S.H. Lee, N. Tsuji, Ultrafine grained copper alloy sheets having both high strength and high electric conductivity, *Materials Letters* 63(21) (2009) 1757-1760.

[140] Y. Miyajima, S.Y. Komatsu, M. Mitsuhara, S. Hata, H. Nakashima, N. Tsuji, Change in electrical resistivity of commercial purity aluminium severely plastic deformed, *Philosophical Magazine* 90(34) (2010) 4475-4488. Pii 926814101,

[141] Y. Miyajima, S. Komatsu, M. Mitsuhara, S. Hata, H. Nakashima, N. Tsuji, Microstructural change due to isochronal annealing in severely plastic-deformed commercial purity aluminium, *Philosophical Magazine* 95(11) (2015) 1139-1149.

[142] K. Nomura, Y. Miwa, Y. Takagawa, C. Watanabe, R. Monzen, D. Terada, N. Tsuji, Influence of Accumulative Roll Bonding and Cold Rolling Processes on the Precipitation Strengthening Properties for Cu-Ni-P Alloy, *Journal of the Japan Institute of Metals* 75(9) (2011) 509-515.

[143] C.W. Schmidt, P. Knodler, H.W. Hoppel, M. Goken, Particle Based Alloying by Accumulative Roll Bonding in the System Al-Cu, *Metals* 1(1) (2011) 65-78.

[144] C.W. Schmidt, M. Ruppert, H.W. Hoppel, F. Nachtrab, A. Dietrich, R. Hanke, M. Goken, Design of Graded Materials by Particle Reinforcement During Accumulative Roll Bonding, *Advanced Engineering Materials* 14(11) (2012) 1009-1017.

[145] C.Y. Liu, Q. Wang, Y.Z. Jia, B. Zhang, R. Jing, M.Z. Ma, Q. Jing, R.P. Liu, Effect of W particles on the properties of accumulatively roll-bonded Al/W composites, *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 547 (2012) 120-124.

[146] Y. Takagawa, Y. Tsujiuchi, C. Watanabe, R. Monzen, N. Tsuji, Improvement in Mechanical Properties of a Cu-2.0mass%Ni-0.5mass%Si-0.1mass%Zr Alloy by Combining Both Accumulative Roll-Bonding and Cryo-Rolling with Aging, *Materials Transactions* 54(1) (2013) 1-8.

[147] I. Altenberger, H.A. Kuhn, M. Gholami, M. Mhaede, L. Wagner, Ultrafine-Grained Precipitation Hardened Copper Alloys by Swaging or Accumulative Roll Bonding, *Metals* 5(2) (2015) 763-776.

[148] M. Cieslar, M. Pokova, M. Zimina, J. Vesely, J. Bajer, Recrystallization in Multilayer Al99.99/AlMg3 Laminates Prepared by Accumulative Roll-Bonding, *Acta Physica Polonica A* 128(4) (2015) 487-490.

[149] A.H. Eslami, S.M. Zebarjad, M.M. Moshksar, Study on mechanical and magnetic properties of Cu/Ni multilayer composite fabricated by accumulative roll bonding process, *Materials Science and Technology* 29(8) (2013) 1000-1005.

[150] F. Daneshvar, M. Reihanian, K. Gheisari, Al-based magnetic composites produced by accumulative roll bonding (ARB), *Materials Science and Engineering B-Advanced Functional Solid-State Materials* 206 (2016) 45-54.

[151] M.C. Chen, H.C. Hsieh, W.T. Wu, The evolution of microstructures and mechanical properties during accumulative roll bonding of Al/Mg composite, *Journal of Alloys and Compounds* 416(1-2) (2006) 169-172.

[152] K. Ikeda, N. Takata, K. Yamada, F. Yoshida, H. Nakashima, N. Tsuji, Grain boundary structure in ARB processed copper, Nanomaterials by Severe Plastic Deformation, Z. Horita, Ed., 2006, pp 925-930.

[153] K. Ikeda, K. Yamada, N. Takata, F. Yoshida, H. Nakashima, N. Tsuji, Grain boundary structure of ultrafine grained pure copper fabricated by accumulative roll bonding, *Materials Transactions* 49(1) (2008) 24-30.

[154] A.A. Roostaei, A. Zarei-Hanzaki, M.H. Parsa, S.M. Fatemi-Varzaneh, An analysis to plastic deformation behavior of AZ31 alloys during accumulative roll bonding process, *Journal of Materials Science* 45(16) (2010) 4494-4500.

[155] M. Rezayat, A. Akbarzadeh, Theoretical model for evaluating the threshold reduction in roll bonding of Al/Al2O3/Al laminations, *Metals and Materials International* 18(5) (2012) 827-832.

[156] M. Reihanian, E. Bagherpour, M.H. Paydar, Particle distribution in metal matrix composites fabricated by accumulative roll bonding, *Materials Science and Technology* 28(1) (2012) 103-108.

[157] M. Reihanian, E. Bagherpour, M.H. Paydar, On the achievement of uniform particle distribution in metal matrix composites fabricated by accumulative roll bonding, *Materials Letters* 91 (2013) 59-62.

[158] M. Reihanian, M. Naseri, An analytical approach for necking and fracture of hard layer during accumulative roll bonding (ARB) of metallic multilayer, *Materials & Design* 89 (2016) 1213-1222.

[159] N.V. Govindaraj, J.G. Frydendahl, B. Holmedal, Layer continuity in accumulative roll bonding of dissimilar material combinations, *Materials & Design* 52 (2013) 905-915.

[160] H.L. Yu, A.K. Tieu, C. Lu, X. Liu, A. Godbole, H.J. Li, C. Kong, Q.H. Qin, A deformation mechanism of hard metal surrounded by soft metal during roll forming, *Scientific Reports* 4 (2014), 5017.

ده سال تغییر شکل پلاستیک شدید در ایران، بخش دوم: پیوند نوردی انباشتی

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چکیده: پژوهش پیش رو، بخش دوم یک مقاله ی مروری است که پیشتر با عنوان " ده سال تغییر شکل پلاستیک شدید در ایران" در همین مجله به چاپ رسیده است. بخش نخست مربوط به فشردن در کانالهای هم مقطع زاویه دار (ECAP) بوده است. در بخش دوم، به دلیل اینکه ایران بعنوان نخستین کشور با بیشترین تعداد مقالات چاپ شده در این زمینه مطرح است، تمرکز بر روش پیوند نوردی انباشتی (ARB) است. در این مقاله بجای تاکید بر ریز ساختار و مواد فوق ریز دانه تولید شده به روش ARB، جنبه های جدیدی از فرایند ARB گزارش شده است که کمتر مورد توجه قرار گرفته اند. در بخشهای مختلف این پژوهش، نقش و سهم ایران در زمینه فرایند ARB با پژوهشگران دیگر کشورها مقایسه شده است. نتیجه گزارش نشان می دهد که علاقه اصلی پژوهشگران ایرانی در زمینه ARB ، تولید مواد ترکیبی (کامپوزیتی) با این روش است. در واقع، پژوهشگران ایرانی نخستین پژوهشگرانی هستند که فرایند ARB را بعنوان یک روش کارساز برای تولید مواد کامپوزیتی تقویت شده با پودر های سرامیکی معرفی کردند.

واژه های کلیدی: تغییر شکل پلاستیک شدید، پیوند نوردی انباشتی، مواد فوق ریز دانه، خواص ماده.