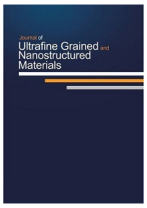

Journal of Ultrafine Grained and Nanostructured Materials
https://jufgnsm.ut.ac.ir
Vol. 50, No.1, June 2017, pp. 1-5
Print ISSN: 2423-6845 Online ISSN: 2423-6837
DOI: 10.7508/jufgnsm.2017.01.01

Accumulative Roll Bonding of Aluminum/Stainless Steel Sheets

Navid Mohammad Nejad Fard[1], Hamed Mirzadeh*[,1], Mohammad Rezayat[1], Jose-Maria Cabrera[2]

[1]School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, P.O.Box 11155-4563, Tehran, Iran.

[2]Department of Materials Science and Metallurgical Engineering, Universidad Plitecnica de Catalunya, EEBE-c/Eduard Maristany 10-14, 08019 Barcelona, Spain.

Recieved: 8 December 2016; Accepted: 8 Janaury 2017
** Corresponding author email: hmirzadeh@ut.ac.ir*

ABSTRACT

An Al/Stainless Steel/Al lamellar composite was produced by roll bonding of the starting sheets at 400 °C. Afterward, the roll bonded sheet was cut in half and the accumulative roll bonding (ARB) process at room temperature was applied seven times. As a result, the central steel layer fractured and distributed in the Al matrix among different layers introduced by the repetition of roll bonding process. The tensile results showed that the roll bonded sheet has much higher strength and strength to weight ratio compared with the initial aluminum sheet as a result of the presence of continuous steel core. However, poor ductility properties were observed during tensile test, which were ascribed to the increasing deformation resistance and localized thinning of the central stainless steel sheet during the roll bonding process. The ARBed sample exhibited lower strength compared with the roll bonded sheet due to the breakup of stainless steel layer into many small segments. Anyway, an ultrafine grained microstructure with average grain size of 400 nm in the aluminum matrix and 71% strain-induced martensite in the steel segments were detected by the electron backscattered diffraction (EBSD) technique, which were found to be responsible for the enhancement of mechanical properties compared with the initial aluminum sheet.

Keywords: *Ultrafine Grained Materials; Accumulative Roll Bonding; Mechanical Properties; EBSD.*

How to cite this article:
Mohammad Nejad Fard N, Mirzadeh H, Rezayat M, Cabrera JM. Accumulative Roll Bonding of Aluminum/Stainless Steel Sheets. J Ultrafine Grained Nanostruct Mater, 2017; 50(1):1-5.
DOI: 10.7508/jufgnsm.2017.01.01

1. Introduction

Roll bonding is one of the most recognized processes for manufacturing composite sheets from metallic sheets, as well as to produce clad sheets [1-3]. Based on the repetition of roll bonding on the same sheet, the accumulative roll bonding (ARB) process [4] has been introduced as one of the most successful severe plastic deformation (SPD) processing techniques competing with the equal channel angular pressing (ECAP) and high pressure torsion (HPT) [5]. Many Al alloys and composites (by introducing powder between the sheets) have been processed by ARB in recent years with magnificent mechanical properties due to the development of ultrafine grained (UFG) structures [6-9]. However, it might be advantageous to apply ARB on the roll bonded sheet produced from different materials and study the evolution of the components during this process.

Stainless steel alloys have relatively high strength and can be further hardened by mechanical working due to strain-induced martensitic transformation

[10] while the aluminum alloys have relatively high thermal/electrical conductivity and lower density. Generally, both mentioned classes of materials have good corrosion resistance and high ductility. Therefore, their combination can be used to produce clad sheets with unique properties. These clad sheets are supposed to exhibit a combination of high strength, good corrosion resistance, high thermal and electrical conductivity, and cost-competitiveness, which can find applications in automotive industry, cookware, electronics, aerospace, ship building, cryogenic and chemical applications [11,12].

The roll bonding of three-layered Al/AISI 304L stainless steel/Al sheet has been studied so far [3], where the thickness of Al and 304L alloy was 1 and 1.2 mm, respectively. However, subjecting it to ARB process was unsuccessful due to the intense cracking of the sheet [3]. To solve this problem, Tayyebi and Eghbali [13] proposed a new technique, named as mesh reinforcing by roll bonding, in which the 304 stainless steel alloy was considered as a mesh (with 250 meshes per inch and 40 mm wire diameter) and successfully ARbed it to manufacture the desired metal matrix composite. However, there is no report in the literature on ARB of roll bonded aluminum/stainless steel in the sheet form.

It should be noted that by consideration of Al and St-12 steel with thickness of 1.2 and 0.6 mm, producing three-layered Al/St-12/Al sheet and its ARB up to 3 passes has been reported by Talebian and Alizadeh [14]. While the elongation to failure values of St-12 and 304L are nearly the same (~ 50%), the strength of 304L is ~ 2.7 times that of St-12. Moreover, the 304L stainless steel experience strain-induced martensitic transformation [10] during roll bonding and ARB process, which needs to be taken into account.

Based on the above facts, the present work aims to deal with the ARB of Al/stainless steel composite sheets and to evaluate the evolution of microstructure and mechanical properties.

2. Experimental details

2.1. Processing

Commercial pure aluminum (AA1050) and AISI 304 stainless steel sheets with chemical compositions shown in Table 1 were used as raw materials. Two initial aluminum sheets with dimensions of 30×100×0.5 mm and one steel sheet as core material with dimensions of 30×100×0.2 mm were considered. Degreasing and wire brushing operations were performed on four contacting surfaces of Al/304/Al. Wire brushing was carried out using a stainless steel circumferential brush operating at rotation speed of 2400 rpm. Afterward, the roll bonding process with reduction in thickness of 50% under unlubricated condition at 400 °C was performed using a rolling machine. Fig.1 shows a schematic representation of this process. The resulted sheet was cut in half and wire brushing operation and cold roll bonding were done on these sheets at room temperature repetitively to produce a sample corresponding to the 7 passes of the ARB process.

2.2. Characterization

Tensile test samples according to ASTM E-8 standard with gauge length of 25 mm were prepared and tested at room temperature with a crosshead speed of 1 mm/min using a SANTAM STM-20 machine. The electron backscattered technique (EBSD) was used for microstructural analysis. The samples were ground with SiC papers, mechanically polished with diamond slurries and then were finely polished with 0.04 μm colloidal

Table 1- Chemical compositions of the sheets used in the present research

AA1050									
Element	Al	Si	Fe	Cu	Mn	Mg	V	Ti	Zn
Wt.%	99.64	0.074	0.185	0.012	0.021	0.008	0.015	0.012	0.016
AISI 304 Stainless Steel									
Element	C	Mn	Ni	Cr	Mo	Si	P	S	Fe
Wt.%	0.050	1.11	8.5	18.27	0.257	0.237	0.038	0.0002	Balance

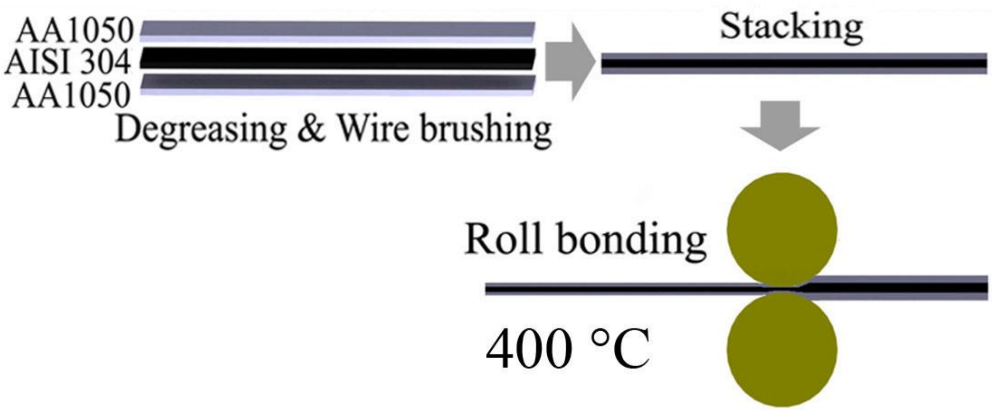

Fig. 1- Schematic representation of the roll bonding process.

silica solution for one hour. A Zeiss UltraPlus analytical field emission gun scanning electron microscope (FEG-SEM) equipped with an EBSD detector, provided by HKL Technology, was used for EBSD studies. The Channel 5 software was used to analyze and display the data. The high angle boundaries (misorientations greater than 15°) and low angle boundaries (misorientations less than 15°) were shown as black and white lines, respectively.

3. Results and discussions

3.1. The initial and roll-bonded sheets

Fig. 2 shows the tensile flow curves of the initial and roll-bonded sheets. As it can be seen, the stainless steel sheet exhibits much higher strength and elongation to failure compared with the aluminum sheet. While both materials have FCC crystalline structure before tensile test, the stainless steel material undergoes strain-induced martensitic transformation known as TRIP effect

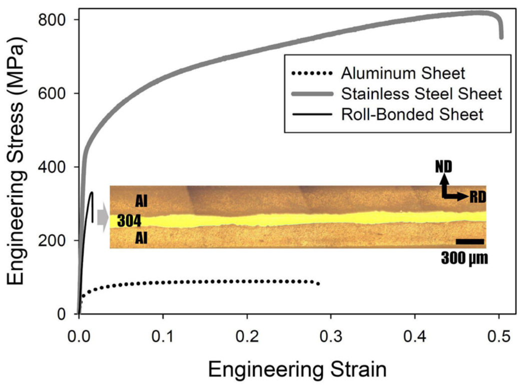

Fig. 2: Tensile flow curves of initial sheets and the roll-bonded sheet along with the microstructure of the roll-bonded sheet.

[15,16], which might be partly responsible for the obtained high elongation to failure value. The obtained value of strength to weight ratio (UTS/Density) is ~ 105 and 32 MPa.cm^3/g for stainless steel and aluminum, respectively. Therefore, if small amount of stainless steel is added to the aluminum sheet, it can enhance the strength to weight ratio of the composite sheet, significantly.

From the tensile flow curves of the roll-bonded sheet, it can be deduced that the roll bonded sheet has much higher strength compared with the initial aluminum sheet. Since the roll bonding process has been conducted at the nominal temperature of 400 °C, which is a high homologous temperature for Al, this increase can be largely attributed to the presence of stainless steel layer. Moreover, the resultant strength to weight ratio is ~ 94 MPa.cm^3/g, which is much higher than that of the aluminum sheet and approaches to that of stainless steel sheet. This can span the applicability of these composite sheets in diverse fields of industrial applications [11-14].

However, while both stainless steel and aluminum show appreciable ductility, the roll-bonded sheet shows poor ductility properties. This can be ascribed to the increasing deformation resistance in Al (due to work-hardening) and in stainless steels (due to work-hardening and martensitic transformation) and localized thinning of the central stainless steel sheet during roll bonding process, which might be responsible for the premature failure of the composite sheet during subsequent tensile straining. An optical micrograph of the roll-bonded sheet is shown in Fig. 2, which displays the necked regions along the rolling direction. The significant decrease in ductility in the roll-bonded sheet is in sharp contrast to the observation of Kim and Hong [17] in Cu/Al/Cu clad composite, where the authors stated that the detrimental effect of less ductile layer on the overall ductility is not applicable to the tri-layered Cu/Al/Cu clad composite. This was also the case for the Ti/439 stainless steel clad composite [18], where the enhancement of ductility in the clad composite is caused by the suppression of the localized necking and the promotion of homogeneous deformation driven by the mutual constraint imposed by an adjacent layer. However, this detrimental effect has been acknowledged by Lesuer et al. [19], where the low tensile ductility was attributed to the susceptibility of the less ductile layer to early cracking. Akramifard et al. [3] studied the roll bonding of Al/stainless steel system by using a much thicker stainless steel as middle sheet and obtained a much higher elongation to failure value, which supports the effect of thin stainless steel sheet as described above.

3.2. The ARBed sheet

Fig. 3 shows the tensile flow curves of initial aluminum, the roll-bonded and 7 pass ARBed sheets. On the one hand, the ARBed sample exhibits lower strength compared with the roll-bonded sheet. This can be partly related to the break up of stainless steel into many small segments as can be seen in the microstructures, and As a result, the continuous steel layer is no longer present. Therefore, the steel no longer experiences direct loading during tensile testing, and by consideration of the fact that the strength of stainless steel is much higher than that of aluminum (Fig. 2), the lower strength of ARBed sheets seems reasonable. Moreover, the ARBed sheet is composed of several layers due to the nature of the ARB process, which can introduce many interfacial defects that might be responsible for the deterioration of mechanical properties.

On the other hand, the ARBed sample exhibits much higher strength compared with the initial aluminum sheet. The resultant strength to weight ratio is ~ 50 MPa.cm^3/g, which is higher than that of the aluminum sheet (32 MPa.cm^3/g). This enhancement in the strength can be attributed to the following factors: (1) The presence of stainless steel segments and load transfer effect, (2) The work-hardening of aluminum matrix as a result of cold rolling associated with the ARB process, (3) The strain-induced martensitic transformation of the steel counterpart, and (4) The development of ultrafine grained microstructure as a result of accumulative severe plastic deformation. To studying these effects, microstructural investigations based on EBSD maps was conducted as described below.

The EBSD maps of the ARBed sheet taken from the matrix and steel segments are shown in Fig. 4. The EBSD map of the matrix reveals that an ultrafine grained microstructure with average grain size of 400 nm has been produced. It should be noted that the average grain size of the initial aluminum sheet was ~ 15.6 μm. Moreover, the fine aluminum grains are also elongated along RD, which provides an evidence for the work-hardening of aluminum

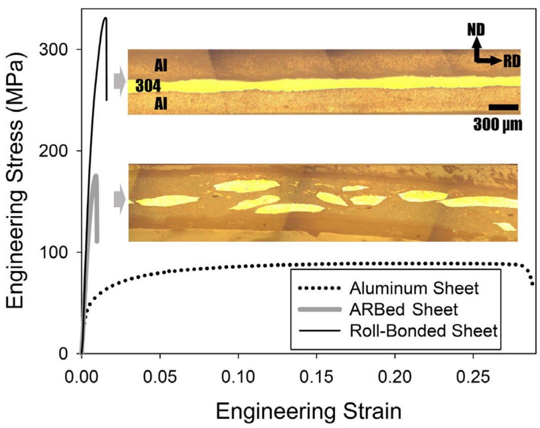

Fig. 3: Tensile flow curves of different sheets along with the corresponding microstructures.

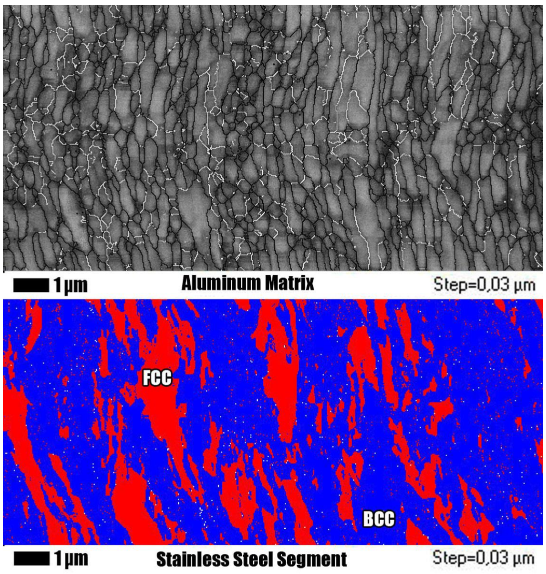

Fig. 4: EBSD maps of the ARBed sheet taken from the matrix and steel segments. The black and white lines show high and low angle boundaries, respectively. The red and blue areas imply FCC and BCC phases, respectively.

matrix. Finally, the EBSD map of the steel segments reveal that ~ 71% BCC phase (strain-induced martensite) is present in these segments, which are produced during ARB. All of these observations are consistent with the observed high strength of this material.

4. Conclusions

The Al/Stainless Steel/Al lamellar composite was produced by roll bonding of the starting sheets at 400 °C. Afterward, the roll bonded sheet was cut in half and the accumulative roll bonding (ARB) process at room temperature was applied seven times. The mechanical properties of the resultant sheets were investigated. The following conclusions can be drawn from this study:

(1) The tensile results showed that the roll bonded sheet has much higher strength and strength to weight ratio compared with the initial aluminum sheet as a result of the presence of continuous steel core. However, poor ductility properties was observed in this sample, which was ascribed to the increased deformation resistance of components and localized thinning of the central stainless steel sheet during roll bonding process.

(2) As a result of ARB process, the central steel layer fractured and distributed in the Al matrix among different layers. This sample exhibited lower strength compared with the roll bonded sheet due to the break up of stainless steel layer into many small segments and introduction of interfacial defects associated with the layered materials. Anyway, an ultrafine grained microstructure with average grain size of 400 nm in the aluminum matrix and 71% strain-induced martensite in the steel segments were detected by the EBSD technique, which were found to be responsible for the enhancement of mechanical properties compared with the initial aluminum sheet.

References:

1. Jin JY, Hong SI. Effect of heat treatment on tensile deformation characteristics and properties of Al3003/STS439 clad composite. Materials Science and Engineering: A. 2014;596:1-8.
2. Kim IK, Hong SI. Effect of component layer thickness on the bending behaviors of roll-bonded tri-layered Mg/Al/STS clad composites. Materials & Design. 2013;49:935-44.
3. Akramifard HR, Mirzadeh H, Parsa MH. Cladding of aluminum on AISI 304L stainless steel by cold roll bonding: Mechanism, microstructure, and mechanical properties. Materials Science and Engineering: A. 2014;613:232-9.
4. Tsuji N, Saito Y, Lee SH, Minamino Y. ARB (Accumulative Roll-Bonding) and other new techniques to produce bulk ultrafine grained materials. Advanced Engineering Materials. 2003;5(5):338-44.
5. Valiev RZ, Langdon TG. Principles of equal-channel angular pressing as a processing tool for grain refinement. Progress in materials science. 2006;51(7):881-981.
6. Jamaati R, Toroghinejad MR. Manufacturing of high-strength aluminum/alumina composite by accumulative roll bonding. Materials Science and Engineering: A. 2010;527(16):4146-51.
7. Alizadeh M, Paydar MH. High-strength nanostructured Al/B 4 C composite processed by cross-roll accumulative roll bonding. Materials Science and Engineering: A. 2012;538:14-9.
8. Salimi S, Izadi H, Gerlich AP. Fabrication of an aluminum–carbon nanotube metal matrix composite by accumulative roll-bonding. Journal of materials science. 2011;46(2):409-15.
9. Gashti SO, Fattah-alhosseini A, Mazaheri Y, Keshavarz MK. Microstructure, mechanical properties and electrochemical behavior of AA1050 processed by accumulative roll bonding (ARB). Journal of Alloys and Compounds. 2016;688:44-55.
10. Naghizadeh M, Mirzadeh H. Microstructural evolutions during annealing of plastically deformed AISI 304 austenitic stainless steel: martensite reversion, grain refinement, recrystallization, and grain growth. Metallurgical and Materials Transactions A. 2016;47(8):4210-6.
11. Kang HG, Kim JK, Huh MY, Engler O. A combined texture and FEM study of strain states during roll-cladding of five-ply stainless steel/aluminum composites. Materials Science and Engineering: A. 2007;452:347-58.
12. Masahashi N, Komatsu K, Watanabe S, Hanada S. Microstructure and properties of iron aluminum alloy/CrMo steel composite prepared by clad rolling. Journal of alloys and compounds. 2004;379(1):272-9.
13. Tayyebi M, Eghbali B. Processing of Al/304 stainless steel composite by roll bonding. Materials Science and Technology. 2012;28(12):1414-9.
14. Talebian M, Alizadeh M. 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. 2014;590:186-93.
15. Shen YF, Li XX, Sun X, Wang YD, Zuo L. Twinning and martensite in a 304 austenitic stainless steel. Materials Science and Engineering: A. 2012;552:514-22.
16. Shirdel M, Mirzadeh H, Parsa MH. Nano/ultrafine grained austenitic stainless steel through the formation and reversion of deformation-induced martensite: Mechanisms, microstructures, mechanical properties, and TRIP effect. Materials Characterization. 2015;103:150-61.
17. Kim WN, Hong SI. Interactive deformation and enhanced ductility of tri-layered Cu/Al/Cu clad composite. Materials Science and Engineering: A. 2016;651:976-86.
18. Ha JS, Hong SI. Deformation and fracture of Ti/439 stainless steel clad composite at intermediate temperatures. Materials Science and Engineering: A. 2016;651:805-9.
19. Lesuer DR, Syn CK, Sherby OD, Wadsworth J, Lewandowski JJ, Hunt WH. Mechanical behaviour of laminated metal composites. International Materials Reviews. 1996;41(5):169-97.