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Bonding Characteristics of Al and Al-Alloy Strips: Processed by Severe Plastic Deformation

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Abstract— In this paper, the study of efficient bonding characteristics of AA6014 and AA1050 metal strips is carried out for Accumulative Roll Bonding (ARB) process. Among various Severe Plastic Deformation (SPD) techniques, ARB process is widely used due to its ability to produce ultra-fine grained (UFG) or nanostructured bulk material. It has been observed that, if the experimental pressure and corresponding temperature achieve their respective threshold values, then the bonding can be successfully joined as compared to the solid state welding.

Keywords- Composite Metal Sheet, Ultra-Fine Grained (UFG), Nano-Structured Material, Severe Plastic Deformation, Accumulative Roll Bonding

I. INTRODUCTION

Accumulative Roll Bonding (ARB) is the solid-state bonding process applied to joining similar or dissimilar metal strips by rolling. These are easy and low-cost fabrication methods for mass production of sheet metals. It is possible to fabricate ultra-fine grained (UFG) or nano-structured material products by applying the accumulative roll bonding process. Other SPD process such as Equal Channel Angular Pressing (ECAP) [1], High Pressure Torsion (HTP) [2], Cyclic Extrusion Compression (CEC) [3], Twist Extrusion (TE) [4], Continuous Confined Strip Shearing [5], and Mechanical Milling processes[6], have the following drawbacks. Firstly, the above pointed out processes are found to be improper to produce bulk materials. Secondly, the required forming dies are quite expensive, and also the required forces are very high. As compared to the above processes, ARB has no such inadequacies. In order to produce ultrafine grained bulk aluminum sheets, the ARB process was at first suggested by Saito et al. [7] then it was modified successfully by Tsuji et al. [8] by producing UFG bulk sheet of interstitial free (IF) steel, which had the average grain size less than 1µm. Hongzhi et al. [9], [16] stated the development of efficient joining of Al 6111 alloy which reveals high shear strength compared to the parent alloy. The four fundamental controlling factors of the roll bonding process were annelid temperature, inlet temperature, rolling speed and the percentage of reduction. Among the above four factors, the rolling temperature was found to be the important element influencing accumulative roll bonding. Saito et al. [10] have carried out the same research with AA5083, IF steel and AA1100. The outcome shows that the strength of AA1100, increased after eight cycles, from 84 MPa to 304 MPa, but the elongation decreased from 42 % to 8 %. The strength of AA5083 rose from 318 MPa to 550 MPa after seven cycles and elongation decreased from 25 % to 6 %, but for IF steel the strength increased to 751 MPa from 274 MPa after five cycles, whereas the elongation decreased from 56 % to 6 %. Tsuji et al. [11], [17] suggested that the true strain reaches 4.0 at 200°C, and average grain size decreases up to 280 nm. Eizadjou et al. [12] experimentally examined the bond strength by peeling of AA1100. Also, AA1100 strips were enhanced its strength with an increase of overall reduction in thickness and temperature. Ultimately the peel strength achieved the value of base metal strength. The bond strength was increasing by increasing the rolling temperature having the constant reduction in the percentage of the thickness of bi-layered strips of two Al1100 and Al1100. The application of significant plastic deformation on two types of metals like aluminum and steel to produce the cold roll joining has used by Manesh et al. [13]. The sheet was work hardened and then annealed to attain higher ductility. It has suggested that the heat treatment of the sheets were difficult because of the growth of a brittle intermetallic compound in between Al and iron. The inter-metallic phase thickness strength has increased by increasing the annealing temperature having the constant duration of time. It has established by Movahedi et al. [14], [18] that better controlled anneals temperature up to 400°C can improve the joining strength. As a result, the above-discussed studies have concluded the experiments on grain refinement shear strength enhancement, peel strength improvement, essential controlling factors of accumulative roll bonding and increases in ductility as well as formability by annealing, but there is a need for research which has been identified on minimum bonding criteria for ARB. Therefore, the current study gave priority to find out threshold considerations for accumulative roll bonding

II. EXPERIMENTAL PROCEDURE

In order to address the facts as mentioned earlier, a comprehensive experimental study is conducted with two core points, essential bonding criteria, and grain refinement with strengthening sheet metals. Annealing, the commercially pure aluminum i.e. AA1050 is soft, ductile and has the property of excellent workability and for this reason, AA1050 has selected for the present study. The aluminum-alloy i.e. AA6014 has chosen for its better structural properties from the other aluminum alloys. The chemical composition of AA1050 and AA6014 has been shown in Table 1, [15], 19].

TABLE 1. Chemical composition of Aluminiumalloys

Al alloys	Si	Fe	Cu	Mn	Mg	Ti	Ga	V	Others	Al
AA6014	0.773	0.321	0.137	0.031	0.586	0.011	0.008	0.012	0.121	Balance
AA1050	0.168	0.287	0.014	0.013	0.010	0.012	0.005	0.007	0.084	Balance

The experiment is carried out at the temperatures 150°C and 500°C. The minimum and maximum temperatures were below and upper to the re-crystallization temperature for both types of aluminum metal strips respectively. First of all, the samples of metal strips have prepared for annealing at a temperature of 400°C; they have held for the duration of half an hour in the furnace. Then the heated samples of metal strips were cooled in the controlled furnace for 24 hours.

In the present work, roll bonding (RB) process was used for the temperature range of 200ºC to 400ºC with AA6014 and AA1050 sheet metals with starting thickness of 0.3 mm and 0.5 mm, respectively. In order to perform the successful bonding of joining, the metal samples were preheated above as well as below the re-crystallization temperature, for separate cases. The cleaning, degreasing, and wire-brushing operations were done to those surfaces of sheets to prepare them for rolling. Following the surface preparation, two metal strips having AA6014 and AA1050 have used for stacking one upon another. Then the rolling process was done.

1) Thickness reduction for fixed temperature: The underlying measurements were 20 mm width and 150 mm length for every specimen of aluminum sheets. The roll bonding analysis has begun from 200ºC with the rate of thickness reduction starting from 1% to 20%. The two metals join at the thickness reduction of 20%. Again the rolling was conducted at a temperature of 250ºC with the rate of thickness reduction between 1% and 15%. Likewise, for 300ºC, 350ºC, and 400ºC the rate of thickness reduction started every time from 1% and ended at 15%, 10% and 5% individually, for their adequate bonding. Also, for temperatures 200ºC, 250ºC, 300ºC, 350ºC and 400ºC with corresponding thickness reductions below of 20%, 15%, 10% and 5% the bonding was not done productively.

2) Accumulative Roll Bonding: In the second part of the investigation, the functional reductions have taken just like 20%, 15% and 5% for their comparing preheat temperatures. After the first pass has ended, the rolled samples have cut into two equivalent parts for subsequent passes. At that point, the operations of cleaning, degreasing and wire-brushing were performed before stacking and pre-heating. The sheets have rolled with specified rate of thickness reduction. Again, the rolled sheets have cut by 50% of its length. This procedure has repeated. In the second part of this experiment, the used reductions have 20%, 15% and 5% for their corresponding preheat temperatures. When the first pass was successful, the rolled specimens have cut into two halves for subsequent passes. After this the operations of cleaning, degreasing, and wire-brushing were done before stacking and pre-heating in the furnace. The sheets have rolled considering the mentioned percentage of thickness reductions. Again, the rolled sheets have cut by 50% of its length. This process has repeated up to the third cycle of its rotation.

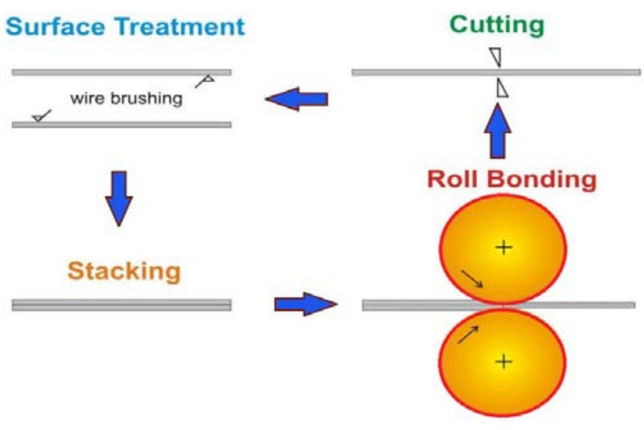

Fig. 1. Schematic diagram of various steps of Accumulative Roll-Bonding

The schematic representation of ARB procedure has illustrated in Fig. 1, [7]. The alloy steel roller having 320 mm diameter, 300 mm length has used for this investigation and the linear surface velocity of the roll was 10 m/minute, in dry condition.

3) Microstructure and Strength: The metallographic tests were set up for optical microscopy by cutting, cold mounting, grinding, cleaning and etching processes. The help of an optical magnifying instrument Leica DM6000M setup has taken for finding the macrostructural image. The mean grain size has measured with intercept technique taking after the quantity of convergences of an altered test line with the grain limits taking after standard ASTM methodology. The bending test has completed in 100kN electro-mechanical controlled Universal Testing Machine (INSTRON 8862). The sample was set up according to ASTM particulars and loaded at a crosshead speed of 0.1 mm/minute. The samples have eventually fizzled after necking and break creating; then the heap versus removal was recorded for rigidity and rate of extensions were assessed.

III. RESULT AND DISCUSSION

It has observed that, for annealed AA6014 the ultimate strength and percentage of elongation are 172MPa and 20%, and for annealed AA1050 these values are 85 MPa and 22% respectively. Consequently, the strength is increasing with increasing number of cycles of ARB for the three sets of temperature with thickness reduction. The results are presented in Table 2. In Fig.4, individual parent metal strengths are indicated by AA6014 and AA1050 and then these have combined into 215 MPa, for the first cycle single pass in roll bonded condition for preheating temperature as 200°C with 20% reduction of thickness. After the third pass, the strength becomes as the maximum value of 272 MPa for 200°C in multilayered AA6014/AA1050 composite. The values of average strengths are 205 MPa, 230 MPa, and 245 MPa for first, second and third cycle respectively for the temperature of 300°C and 15% thickness reduction combination is indicated by the marked line.

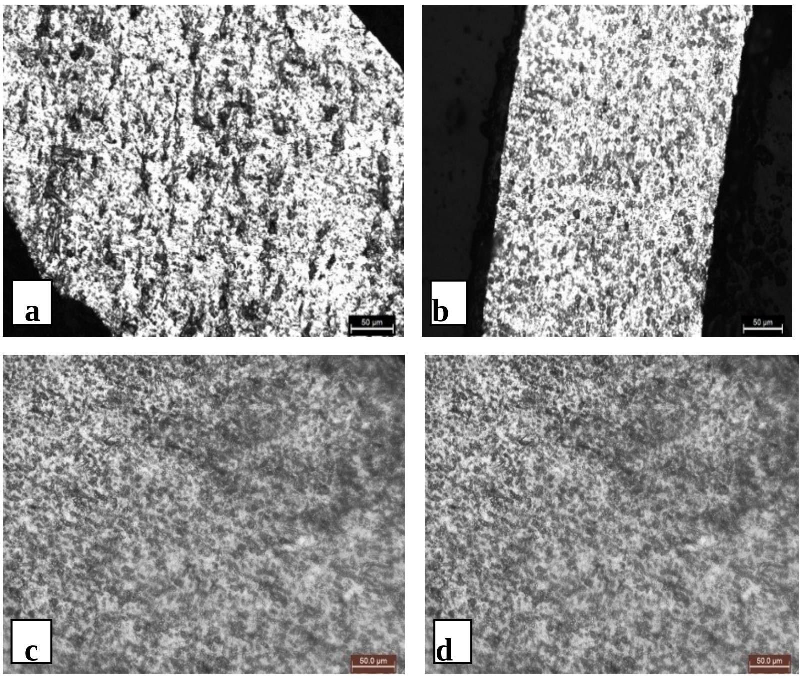

Fig. 2 Optical micrograph of parent and ARB metals for 20% reduction and 200°C preheat temperature(a) Fully annealed parent metal AA1050, (b) Fully annealed parent metal AA6014, (c) AA1050 after 3rd cycle and (d) AA6014 after 3rd cycle.

It has apparently been observed and shown in Fig.2 and Fig. Three that successful bonding between two metal strips can be achieved with the parametric combination of reduction of thickness in the average elongation of parent metals are designated with AA1050, AA6014 and are transformed to 12%, 10% and 9% elongation for the first, second and third cycle of ARB, respectively, as shown in Fig. 5.

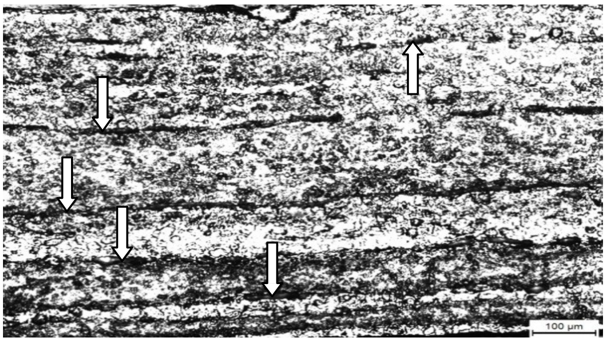

Fig. 3. Optical micrograph of roll bonded sheet after the third pass

The percentage of elongation is decreasing with cycle by cycle, which has identified with other two temperatures, in the same figure. But it is increasing with increasing preheat temperature for a fixed number of cycle.

TABLE 2. Average strength and average percentage of elongation after ARB of multi-layered AA6014/AA1050 composite

	1_{st} Cycle		2_{nd} Cycle		3_{rd} Cycle	
	UTS (MPa)	Elongation in %	UTS (MPa)	Elongation in %	UTS (MPa)	Elongation in %
200^0 C & 20% reduction	215	10	260	9	272	8
300^0 C & 15% reduction	205	11	230	10	245	9
400^0 C & 5% reduction	200	16	220	14	235	11

The lowest average strength is 200 MPa for the last combination of temperature 400°C and 5% of reduction, but it increases with increasing number of cycles, as 200 MPa for the second cycle and 235 MPa for the third cycle, can be identified with the marked line as shown in Fig.4. Consequently, the strength is increasing with increasing number of cycles of ARB for each pass and preheats temperature of five restrictive conditions.

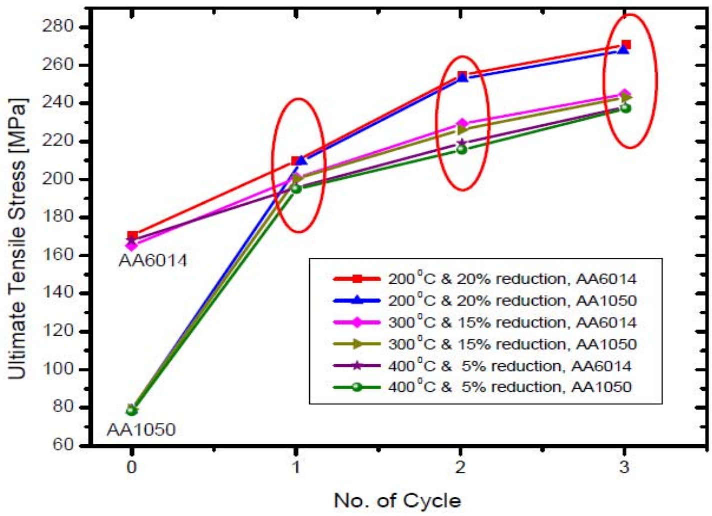

Fig.4. The average tensile strength of parent metals before rolling and after ARB, versus no of cycles

The threshold parameters of bonded samples have accordingly indicated in Table 3. The dot marks having such parameters canton join the AA6014 and AA1050 metallic strip successfully, while the left side of dot marks, the strong bond has not achieved. The outcome reveals that low preheat temperature with high reduction rate and high preheat temperature with low reduction rate combinations can create sufficient bonding. It is also established that the combination of low preheat temperature with a low percentage of thickness reduction is not capable of resulting in successful bonding. To fabricate successful bonding, minimum energy is essential to overcome the initial energy obstruction. This minimum necessary energy can be supplied by rising rolling temperature or by external force followed by general conventional mechanical processes like pressing, hammering, rolling or forging. The percentage of thickness reduction is similar to that of the applied forces, in rolling. The combination of applied force and the preheat temperature contribute the required energy for the successful bonding. In this study, the key factors like pre-heat temperature and threshold percentage of thickness reduction govern the successful bonding.

TABLE 3. Marks sufficient preheat temperature for Bonding on rolling

Limiting thickness reduction	Preheat temperature				
	200°C	250°C	300°C	350°C	400°C
20%	•	•	•	•	•
15%		•	•	•	•
10%					•
5%					•

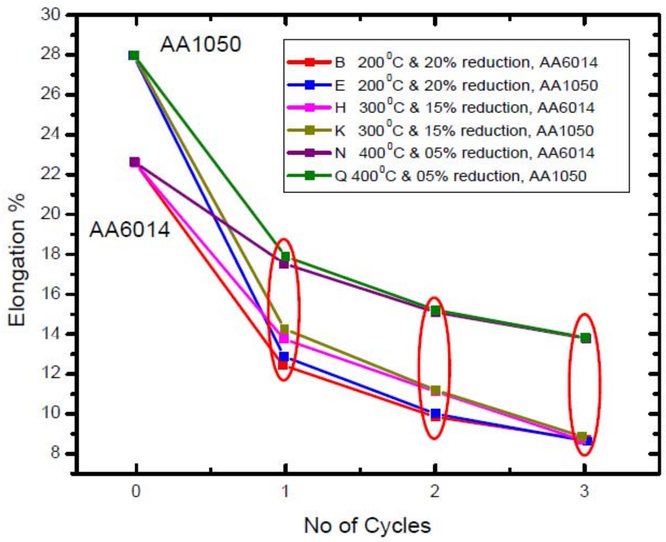

Fig.5. The average elongation in % of parent metals before rolling and after ARB, versus no of cycles

III. CONCLUSION

In the current study, it has been seen that after the third cycle at 200°C preheat temperature with 20% thickness reduction, the average grain size transforms to 8 μ m and 10 μ m for AA6014 and AA1050, respectively; whereas, the mean grain size of fully annealed parent metals are 20 μ m and 30 μ m, respectively. For that reason, it should illustrate the repercussion that grain refinement takes place in ARB process. By the grain refinement, the strength attains the greatest value as 272 MPa which is 1.6 and 3.4 times better than the strength of parent metals AA6014 and AA1050, respectively. In the same way, ductility reduces with increasing of cycle numbers. The current study also investigates the best parameters of minimum joining. For that reason, the preheat temperature and equivalent thickness reduction have created a substantial effect on solid-state bonding in the area of hot rolling which contributes the threshold parameters for bonding of AA6014 and AA1050 strips.

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