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High Strength of Aluminium-Based Composites by Different Methods of Severe Plastic Deformation (SPD)

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Abstract. Composite materials were applied to meet the demands of product efficiency on industrial because they offered the superior properties both of aspects on mechanical and physical properties were constantly being refined and developed with several methods. Composite technology with aluminum as a matrix as well as ceramic materials as reinforcement was very dependent on a result of the perfection of the manufacturing process on the matrix material and reinforcement was used. Aluminum currently still dominates as a matrix because of ductility, while reinforcing materials that are widely used are ceramic elements such as silicon carbide (SiC) and alumina (Al_2O_3). Using of SiC/Al_2O_3 has been widely studied because of the remarkable improvement of the mechanical properties it produces. The addition of number of SiC particles to Al_2O_3 was able to significantly increase the hardness properties. In this study, a number of composite manufacturing methods were compared from the results of properties by accumulative press bonding (APB), accumulative roll bonding (ARB), and repetitive press roll forming (RPRF). The mechanical properties of RPRF results are known to produced better properties, especially mechanical properties. Mechanical properties were observed from tensile and hardness tests. The finer grain size is produced by increasing the compression cycle and increasing the mechanical properties when adding double reinforcement of the SiC/Al_2O_3, which causes the strength and hardness of the RPRF results to increase. Whereas other methods such as APB and ARB it is not compatible for composite materials, this proves that the RPRF method was very suitable for processing composite materials compared to APB and ARB methods.

1. Introduction

Composite is a combination of two different types of material to get better and unique properties of it is constituent material [1]. Composites consist of matrix and reinforcement if the matrix or reinforced are composed of more than one, namely of hybrid composites [2]. One of the successes of composite mechanical properties is determined by the reinforcing material to improve the properties of the matrix in making the reinforcement arrangement which will transmit the load to be distributed evenly. The reinforcement on the composite can produce a mechanical performance that is superior to the matrix material [3]. Functional application of composite materials has been widely used in a variety of products, such as; spacecraft and aircraft components, submarines, sporting goods, sensors/actuators, catalysts and pollution processing materials, biomedical materials, and most recently military equipment [4]. Properties of composites have emerged as the main structural element because the material is lightweight, flexible, and also has high corrosion resistance, impact strength, fatigue strength, composite features is the technique of properties required for the final product can be achieved by selecting matrices and reinforcement [5].

The development of accumulative roll bonding (ARB), accumulative press bonding (APB), and repetitive press roll forming (RPRF) technologies are part of the severe plastic deformation (SPD) technology. ARB was developed to roll sheet load metal processes, while the APB method was developed for sheet plate objects using compressive forces [6-7]. Research conducted by Saito [8] using aluminium processed ARB, after pressing the 8^{th} cycle, there was a significant increase in hardness and tensile strength accompanied by refining grain size, but for composite materials, to achieve a significant increase in mechanical properties requires a pressure cycles up to 12 [9]. While the research conducted by Amirkhanlou [10]. using the APB method, the mechanical properties of composites will increase in a cycle of 14. RPRF method is a combination of roll compression style with compressive stress to obtain increased mechanical properties, it is expected by combining roll and press loads will summarize the ARB or APB process cycle [11]. The processing of composite materials is expected to be less than 12/14 of cycles to obtain fine grains with high mechanical properties. Several investigations on RPRF method were developed on alloy materials and composites, aluminium alloys, and composites based on SiC/Al_2O_3 as a reinforced. While aluminium is the only metal that is suitable for use as a matrix material in ceramic-reinforced composites. The use of alumina as a reinforcement is able to improve mechanical properties, which only reached 48 VH and the tensile strength of 140 MPa was obtained [12-17]. While the development of composites reinforced with SiC hardness increased but also not too significant, namely hardness of 88 VH and tensile strength of 160 MPa [2]. The focus of this research is the use of SiC and Al_2O_3 as reinforcement combined in aluminium-based composites by using pressure cycle of variations at 2, 3, and 6 times. The results will be compared with other SPD methods, namely ARB and APB. This is done to determine the appropriate SPD method and is suitable for processing composite materials.

2. Materials and Experiment Methods

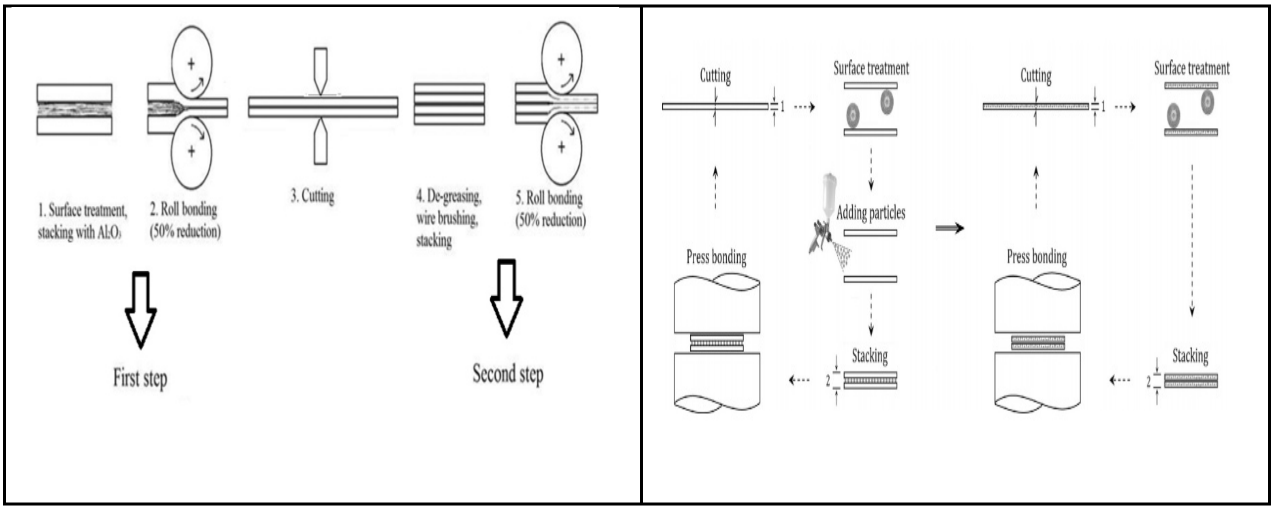
Table 1 shown the chemical composition of the investigated aluminium AA1100 in wt.% as received materials with dimensions of 25 x 100 and 3 mm, while the reinforcement used SiC powders form and Al_2O_3 fibers. The initial characterization of the sample was conducted of the as-received samples. Then, subsequently, the SiC/Al_2O_3 was added to the surface of aluminum and rolled in varying cycles. Pre-heating at 350^0C during 60 minutes, then repetitive pressing loading of 350 - 500 MPa, after that it is pre-heated again with the same temperature then rolling with the 50% size reduction. The methodology of aluminium-based RPRF process based on composites with SiC/Al_2O_3 as reinforcement has been shown in Figure 1.

Table 1. The element composition of AA1100 (wt.%)

Elements	Al	Fe	Cu	Si	Ti	Mg	Mn	Ni	Zn
Composition	99.7	0.57	0.12	0.13	0.03	0.02	0.013	0.017	0.01

2.1. Accumulative roll bonding (ARB) VS Accumulative press bonding (APB)

The ARB process was carried out using only a roll loading without initial pressing, the material was used the same, whereas for APB the load used is only compressing without rolling. A picture of the ARB and APB processes is presented below in figure 1a and b. Each material used AA1100 as a matrix with Al_2O_3/SiC as reinforcement. The ARB and APB were directly carried out in the sixth cycle, to facilitate the efficiency of the process. The reinforced material was used of Al_2O_3 typed gamma aluminium oxide, with the initial stage form is a bundle in harmony, with a diameter of 7 nm and has a length of about 20-50 mm. while SiC material has an initial size of 200 mesh smoothed with ball miles reaching 10-50 µm. Strips with a thickness of about 1 mm are cut from the block and placed parallel to the direction of rotation on the brushed surface and cleaned in the preparation of ARB and APB materials. The reinforcing content in each sample is 0.4-0.8% by weight.



a b

Figure 1. Illustration of procedure to fabricate through a) accumulative roll bonding (ARB) on Aluminum based composites [2]. b) accumulative press bonding (APB) process on the composite strip [10].

2.2. Repetitive press roll forming (RPRF)

AA1100 plate with dimensions of 25 mm x 100 mm has a thickness of 3 mm, reinforcement was added, namely SiC and Al_2O_3. Part of the matrix stack and tied with rivet then preheated in the furnace for 60 minutes at 350°C. The powder of SiC and Al_2O_3 which had been powdered on the surface of the AA1100 plate is 0.4% with a variation of the weight ratio of 25% SiC: 75% Al_2O_3 between the aluminium matrix AA1100. The plates were stacked on the surface of the sample that had been sprinkled with SiC/Al_2O_3. Then the samples were reheated for 15 minutes at 350°C in the furnace and then processed according to the method used, as had been done by the RPRF process. The method of RPRF, ARB, and APB to be compared.

The mechanical and physical properties of composite material by RPRF methods were investigated, then compared to the ARB and APB methods as well. Hardness testing uses Vickers microhardness 10 using a Future Tech Microhardness Tester FM-800 type testing machine, while tensile testing uses the standard ASTM A370-16 using the Universal Testing Machine 250 kN AG-250 kN X-Plus Shimadzu. Microstructure's analysis behaviour used microscope optic was traced to determine the grain morphology and deployment precipitates on grain. Image-J software was used for quantitative microstructure analysis calculation of the grain size.

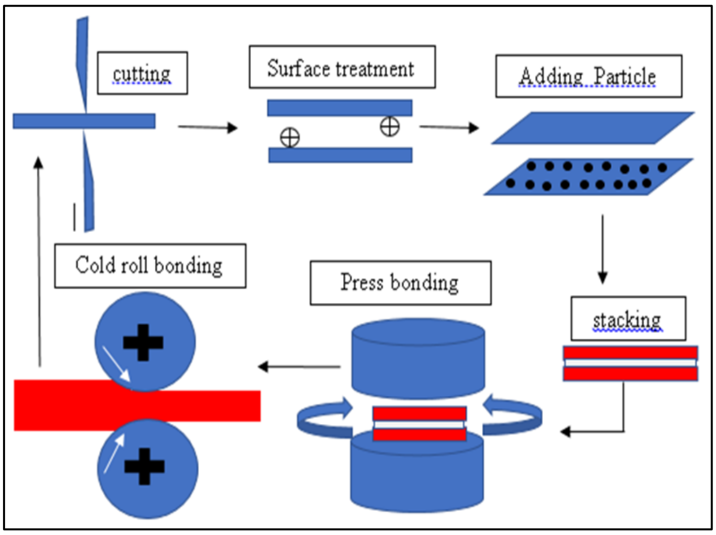


Figure 2. Schematic of repetitive press-roll forming (RPRF) Process for aluminum-based composites [7].

3. Result and Discussion

The results of AA1100/SiC/Al_2O_3 based composites were compared by properties of the ARB/APB method, RPRF as well. Mechanical properties are compared mainly to hardness, tensile strength, and elasticity. To determine the strength of boundary layer bonds, morphological differences in grains are considered. By using mechanical and physical characterization, the resulting properties are analyzed for comparison of the selection of the SPD method that is suitable for fabricating composite materials.

4. Comparison of Mechanical Properties

Table 2 shows the mechanical properties of AA1100/SiC/Al_2O_3 based composites processed by RPRF, ARB, and APB with variations of cycles including as-received materials. The result showed that the hardness and tensile strength of the base material are still too small. The hardness value generated from the RPRF process was observed in different cycle variations, including cycles 2, 4, and 6. Using a ratio of weight 25% SiC and 75% Al_2O_3, presented in table 2, there was a significant increase in the value of hardness compared to AA1100 before the RPRF.

Table 2. Mechanical properties of AA1100/SiC/Al_2O_3 based composites

Mechanical Properties	**AA1100** ***As-Received***	**RPRF 2-Cycles**	**RPRF 4-Cycles**	**RPRF 6-Cycles**	**ARB 6-Cycles**	**APB 6-Cycles**
Hardness (HV10)	43.99	65	81	106	79	85
Tensile Strength (MPa)	100.80	161	173	197	143	167
Elongation (%)	8.28	13.5	6.7	4.8	7	5

The mechanical properties of the RPRF process in 2-4-6 Cycles conditions, each cycle experienced a significant increase, shown in Table 2. In the 6th cycle the results of RPRF process produce a hardness of 106 HV, a tensile strength of 197 MPa, and an elongation of 4.8%. In the SPD theory written by Ruslan Z. Valiev [16] that an increase in compression cycles will significantly increase the mechanical properties. This has been proven by Argentero [9] conducting an ARB experiment using a stable temperature of 350°C, 6-10 cycles, the resulting hardness increased from 84 to 106 HV and tensile strength of 170 MPa, with elongation of 11%. In this study, ARB experiments were carried out using 6 cycles, but the mechanical properties produced were still below the mechanical properties of RPRF. RPRF hardness of 6 cycles is 106 VH, Cycle 79 ARB hardness. Pull strength 197 MPa, for RPRF with elongation 4.8% and ARB process results of 167 MPa with elongation of 5%. Another RPRF competitor is the APB, examined by Amirkhanlou [10,18] cycles usage reaches 14 optimums, resulting in tensile strength of 180 MPa, while the APB, in the 6th cycle reaches 155 MPa. For mechanical properties of hardness on the APB, it was not traced, but the authors tried to test the hardness until in the 6^{th} cycle, it was reached 85 HV as the result. When compared between the technology of SPD such as; RPRF, ARB, and APB methods. The RPRF produces the best mechanical properties, compared to the two methods. The results of the mechanical properties of tensile strength and elongation are presented in Figure 3.

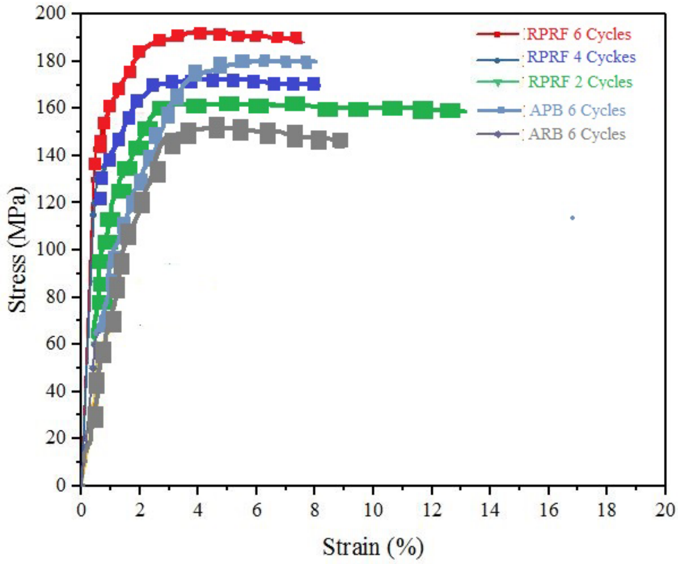


Figure 3. Stress Strains of Aluminium-based composite by Various SPD technology

5. Comparison of Microstructures

Metallographic observations were carried out on aluminium based composite samples from the RPRF process. Before observing using an optical microscope, a sample was carried out. Figure 4a comparison of the microstructure of SPD was presented, namely, RPRF which was carried out using 2-4-6 cycles, and the others were ARB and APB used for 6 cycles of pressing. Figure 4a is a microstructure of aluminium as received material, where aluminium is in as received condition. The beads in the microstructure are still smooth and shaped as nodules. Observation on Al non-treatment grain is still in a regular condition and has morphological similarities. In the second cycle the results of the RPRF process, there is a boundary line, increased by 4 cycles the boundary line starts to decrease in figure 4c. Increased by 6 cycles on figure 4d, there is no boundary line at all, this proves that the bond between the composite results of the RPRF process is perfect so that the mechanical properties increase. The bond found in the RPRF process is the result of delamination between grains which get a force from the direction of parallel rolling loads. Produces increased mechanical properties. Comparable to figure 4, the results of the ARB process show that some grains experience delamination between boundaries, even though the bonding line is not visible but grain peeling due to high roller loads reaches 6 cycles resulting in grains appearing to cross the boundary, according to this is caused by high dislocation mobility in aluminium metal with deformation conditions involving the use of temperature. The movement of grain occurs due to the incorrect energy of high-alloying aluminium. The movement of the grain to slip due to dislocation movement. Compared to the APB process, there is some porosity in the composite cluster formed by the layer between aluminium as a matrix against reinforcement of ceramic materials. The air trapped in agglomerated particles, coupled with blocked metal flow by the particles mentioned, contributes to the formation of porosity. After the next cycle, the laminate structure including aluminium and the reinforcement layer completely disappeared and turned into a particle reinforced composite [19]. When compared with RPRF, to produce 197 MPa of power in 6 cycles, the APB in the 6th cycle produces 167 MPa, and ARB in the 6th cycle produces 143 MPa. In the RPRF process consists of two stages of the deformation process of rolling pressure and compression, while the APB consists of compressive force and ARB is the application of rolling compression force. The APB process shown in figure 4f, the clusters and particle-free zone of the reinforcing ceramic material almost disappear, and the composite contains a truly uniform ceramic reinforcement particle distribution. If there is a change in the morphology of the grain, it will affect the increase in mechanical properties, but the volume fraction of the reinforcing particles will tend to decrease [20-22]. Increasing the number of cycles in all processes will cause reinforcing particles to spread from the interface to all parts of the aluminium matrix so that the distribution of the reinforcing particles will increase.

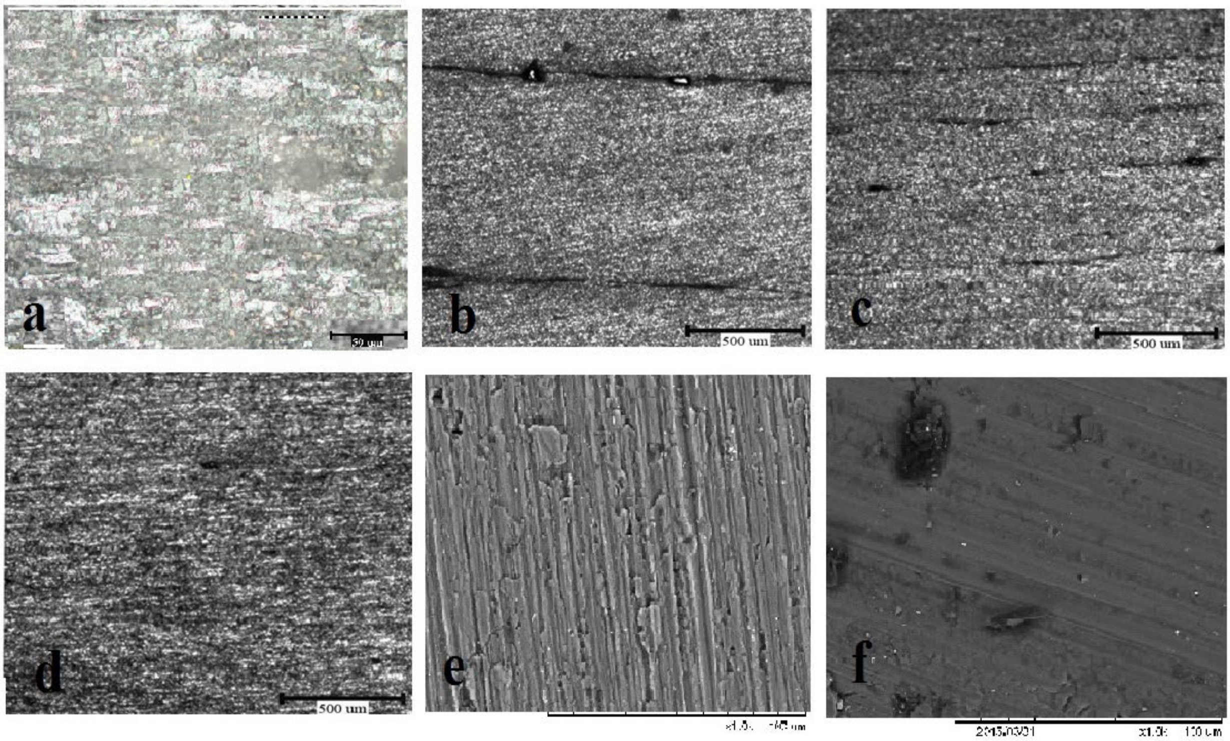


Figure 4. Comparison of microstructures results of various methods of SPD: a). AA1100 by RPRF b). Al based composites by RPRF 2-cycles c). Al-based composites by RPRF 4-cycles d). Al-based composites by RPRF 6-cycles e). Al-based composites by ARB 6-cycles f). Al-based composites by APB 6-cycles.

6. Conclusion

Comparison of mechanical properties, the hardness and tensile strength of the base material (AA1100) were too small, there was a significant increase in the value of hardness result by RPRF 2-4-6 Cycles, AA1100 as a matrix, and SiC/Al_2O_3 as a reinforcement.

Observation on AA1100 non-treatment on grain is still in a regular condition and has morphological similarities. In the second cycle the results of the RPRF process, there is a boundary line, increased by 4 cycles the boundary line starts to decrease. The 6th cycle was able to eliminate the boundary line between interfaces, proving that there is a bond between the material processed by ARB, APB, and RPRF. On Increasing by 6 cycles, there was no boundary line at all, this proves that the bond between the results of the composites of the RPRF process is perfect, so that the mechanical properties increase.

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