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Characteristics of aluminum-based composites reinforced of Al_2O_3/B_4C by accumulative roll bonding (ARB)

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ABSTRACT

Metalworking technology is currently developing rapidly, especially the processing of metal composite materials. The metalworking process in which ultra-large plastic strains are introduced into the device to create ultrafine grained (UFG) metal is a new method for producing high-strength metals. This method is called accumulative roll bonding (ARB). The ideal operating temperature used in the ARB process is the use of dynamic recrystallization temperatures. Roll compression in ARB affects the microstructure and mechanical properties of the composite material, where rolling compression can produce the application of simple forces sequentially evenly on the compressed workpiece. With the addition of Al_2O_3 and B_4C reinforcement in the ARB process, it is expected that the mechanical properties will increase significantly. Composite AA1070 or Al_2O_3 produces an average hardness: 43.36 BHN, using B_4C reinforcement increased 53.50 BHN with AA17075 with Al_2O_3 reinforcement the hardness was 87.20, with B_4C increased significantly by 105.2 BHN. This study compares Al_2O_3 and B_4C as reinforcement on an application in metal matrix composites (MMC). Characteristics compared and comparison of types of AA1070 or AA7075 matrix in their suitability between the use of matrix and reinforcement processed by ARB.

ABSTRAK

Teknologi pengerjaan logam saat ini berkembang pesat, terutama pengolahan bahan-bahan komposit logam. Proses terjadi di mana strain plastik ultra-besar dimasukkan ke dalam perangkat untuk menciptakan logam yang berbutir ultra halus merupakan metode terbaru untuk menghasilkan logam dengan kekuatan tinggi, metode ini dinamakan dengan *accumulative roll bonding* (ARB). Temperatur operasional yang ideal yang digunakan pada proses ARB adalah penggunaan temperatur dinamik rekristaslisasi, kompresi *roll* pada ARB memiliki efek pada struktur mikro dan sifat mekanik dari bahan komposit yang mana kompresi bergulir mampu menghasilkan penerapan gaya-gaya sederhana secara berurutan secara merata pada benda kerja yang mengalami kompresi. Penambahan penguat Al_2O_3 dan B_4C pada proses ARB, terjadi peningkatan secara signifikan. Komposit AA1070/Al_2O_3 menghasilkan kekerasan rata-rata 43.36 BHN, menggunakan penguat B_4C meningkat 53.50 BHN dengan AA7075 berpenguat Al_2O_3 kekerasan sebesar 87.20, dengan B_4C meningkat signifikan sebesar 105.2 BHN. Penelitian ini membandingkan penggunaan Al_2O_3 dan B_4C sebagai penguat dalam penerapanya sebagai penguat dalam kompoisit bermatrik logam. Karakteristik dibandingkan serta pembanding jenis matriks AA1070/AA7075 dalam kesesuaiannya antara penggunaan matriks terhadap penguat yang diproses oleh ARB.

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1. Introduction

Metalworking technology is currently developing rapidly, especially the processing of metal composite materials. A metalworking process in which ultra-large plastic strains are introduced into the device to create an ultrafine grained (UFG) metal is a new method for producing high-strength metals. This technology is called accumulative roll bonding (ARB) [1-3]. Currently, ARB is growing rapidly as a metal and alloy processing, especially for the development of composite materials. Long cycles of pressure are required to produce high strength, as research conducted in [4] in his research requires ten cycles of rolling compression to produce a hardness of 113 HV with tensile strength > 100 MPa.

Improvement of the mechanical properties of the composite has also been carried out in [5] using a new method of accumulative press bonding (APB) to produce fine grains with a tensile strength of 180 MPa from 88 MPa; it takes 14 cycles. The APB process was developed based on the principle of the accumulative roll bonding (ARB) process. The APB process can be applied to sheet and billet materials with relative scale dimensions, while the ARB process can only be applied to sheet materials [5, 6]. In an experiment that focuses more on the hot and cold zones due to aluminum-based composites [7], it is found that temperature affects the formation of bonds between the combined plates. The hot area is a contact area where bonding occurs between plates and reinforcement so that the missing line, which is the interface between plates, can be lost and is evidence of bonding between plates [7, 8]. In industrial applications, the ARB-based rolling process has not been widely applied because it requires parameters and a long cycle, so in this case, additional treatments are needed to prolong the process.

The parameters and variables of the use of rolling are not yet known ideally in the working process, both temperature, and compression. The ideal operating temperature used in the ARB process is the dynamic recrystallization temperature, but the specific temperature value is not stated. For this reason, using the finite element method shows what the ideal temperature value is to produce a flawless ARB product sample to produce high mechanical properties. This research experiment applies the finite element method, which aims to determine the temperature limit applied to aluminum-based composite products resulting from the ARB process with the addition of operational stress. The finite element method (FEM) traces the heat distribution area received by the sample so that it can be determined in which area the heat is received by the aluminum-based composite sample [9, 10]. This study discusses aluminum-based metal composites using Al_2O_3 reinforcement compared to B_4C reinforcement.

The finite element method (FEM) is used to trace the temperature distribution area received by the plate, where the contact area is sprinkled with Al_2O_3 reinforcement compared to B_4C, so that it can be determined in which area the heat is received by the aluminum-based composite sample. Accumulative roll bonding (ARB) is used to make UFG materials. Where sub-micrometer or nano-grain UFG materials are expected to improve mechanical properties much higher than conventional rolling products, further mechanical properties can be improved by strengthening the UFG material using two different types of reinforcement. The material's microstructure was investigated using an optical microscope, as well as scanning electrons accompanied by quantitative microstructure analysis. The plastic deformation of ARB results in the first cycle was observed, and the reinforcing condition of Al_2O_3 was observed along with B_4C.

2. Research Methodology

2.1. Accumulative roll bonding (ARB)

The ARB working process in a lab-scale experiment is 1070 series aluminum sheet with annealed dimensions: 50 x 400 mm with a thickness of 3 mm. The aluminum surface is cleaned using a steel brush until it is completely clean to avoid sticking dirt to the contact area, then apply acetone liquid so that dirt or plates or things that hinder the process can be avoided. The schematic of the ARB process for manufacturing composites involving the hot zone to the cold zone is presented in Figure 1.

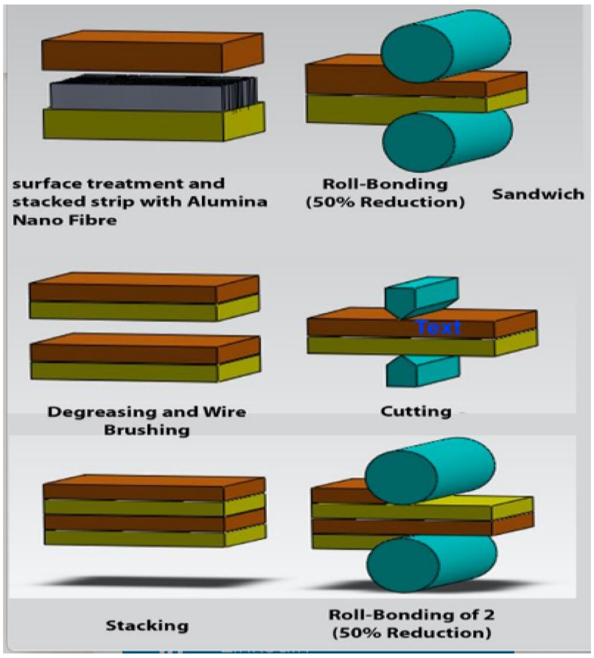

Figure 1. Schematic of accumulative roll bonding (ARB) process stages.

Aluminum oxide nanofibers have a diameter of ±7 nm with a length specification of about 50 mm [7]. On the brushed and cleaned surface, the reinforcement in the form of Al_2O_3 is placed parallel to the rolling motion, and B_4C powder is also used to compare other parts. The reinforcing content of both Al_2O_3 and B_4C in each sample was 0.4% by weight fraction.

To study the role of the bond between the aluminum metal matrix and the reinforcement, Al_2O_3 nanofibers in the form of 7 nm fibers were mixed with B_4C reinforcing powder by ball mill milling. A tumbling ball mill is used to mix the nanofibers and reinforcing powder. The materials specified as aluminum composites were rolled bonded without using lubrication according to reference [11], using a laboratory rolling mill with a roll diameter of 150 mm and a roll length of 180 mm with a loading capacity of 50 tons.

2.2. Characterization of Al_2O_3 or B_4C-reinforced aluminum-based composites

Tests were carried out to determine the composite characteristics of the ARB process. The mechanical properties tested were hardness using the Brinnel indentation method. Measurement of brinnel hardness reveals mechanical properties in resisting indentation loads, so that resistance to loading can be measured which states its strength [12]. Hardness is the ability of a metal to withstand plastic deformation loads [13]. Comparison of hardness is accompanied by measurements of physical properties, such as density and porosity, because metal composites must be able to have light properties and minimal porosity [13, 14]. The Brinell test of specimens uses a spherical indenter made of hardened steel or tungsten carbide. Steel ball indenters are used for materials having a Brinell hardness of up to 450 BHN.

A tungsten carbide ball indenter should be used when the material being tested has a Brinell hardness between 451-650 BHN. Standard tests are carried out using a 10 mm diameter steel ball or tungsten carbide with a load of 3000 kgf for hard metals, 1500 kgf for intermediate metals, and loads of 500 kgf and lower for soft materials. The ARB process using Al/Al_2O_3 materials produces an average hardness of: 43.36;87.20 BHN, while the average hardness using Al/B_4C increases by 53.50; 105.2 BHN. This is in line with the increase in density, namely: 2.66; 2.81 gr/mm^2 on the Al_2O_3 amplifier, with the use of B_4C amplifier it was relatively increased by 2.76; 2.88 gr/mm^2. The value of mechanical properties and physical properties are presented in Table 1.

Table 1. The value of mechanical and physical properties of aluminum-based composites reinforced with Al_2O_3/B_4C.

Process / Material	**Hardness (*BHN*)**	**Density (*gr/mm^2*)**	**Porosity (%)**
ARB-AA7075/no-reinforcement	43.60	2.79	0.9
ARB-AA1070/no-reinforcement	30.12	2.63	0.7
ARB-AA7075/Al_2O_3	87.20	2.81	1.2
ARB-AA7075/B_4C	105.02	2.88	2.8
ARB-AA1070/Al_2O_3	43.36	2.66	1.1
ARB-AA1070/B_4C	53.50	2.76	2.4

The development of ARB-based composite materials is an effective alternative method for manufacturing materials with improved mechanical characteristics. This process was developed based on the accumulative roll bonding (ARB) principle but can be easily installed in laboratory and industrial environments [12-13]. Roll compression in ARB affects the microstructure and mechanical properties of the composite material, where rolling compression can produce a uniform application of simple forces on the compressed workpiece. The addition of Al_2O_3 and B_4C reinforcement in the ARB process has improved the mechanical properties significantly.

For further analysis, microstructure testing is needed to assist in morphological analysis or the role of microstructure in composite materials. Process aluminum-based composites as a matrix and Al_2O_3/B_4C to achieve a uniform distribution of each reinforcement's precipitate in the matrix. Mechanical property changes were found in the composition of the microstructure of the composite material following the procedure, with a weight fraction of 0.4 percent Al_2O_3/B_4C reinforcement for each reinforcement. The heating temperature uses a temperature of 350^{o}C. This temperature was chosen because, based on previous experiments [8] is the ideal heating temperature because this temperature does not cause grain growth that can cancel strain, reinforced by the basis [11] that the operational temperature of ARB must be below the dynamic recrystallization temperature, namely between 350-450^{o}C.

3. Results and Analysis

3.1. Analysis of mechanical properties of aluminum composites reinforced with Al_2O_3 or B_4C

The mechanical properties of the hardness of the composite samples AA1070/AA7075/Al_2O_3/B_4C are presented in Table 1. Each hardness sample is compared with hardness values which have different reinforcement and the type of aluminum series used. The highest hardness value for all variations is 105.02 BHN. The value is because the basic matrix metal AA7075 has a hardness range of 80-90 BHN, whereas the composite sample with the AA1070/Al_2O_3 matrix has a hardness range of 43.36 BHN. This value is comparable to the density value of AA7075/B_4C, which is 2.88 gr/mm^2. The increasing value of hardness is also supported by increasing density, but the porosity value does not affect the mechanical properties.

The increase was due to the porosity having a size of up to m scale, while the hardness was measured based on macro size. The greater the hardness value is directly proportional to the density but not to the porosity [15]. Because carbon has a substantial influence on enhancing mechanical qualities, B_4C plays a function in hardness. The hardness values produced in each variation, both variations in the type of reinforcement and variations in the number of layers, are not too significant. The value happens because of the influence of the number of rolling rounds. In one rolling round, the reinforcement does not significantly affect the resulting hardness value, and there is still porosity between the matrix and the reinforcement [16]. In the ARB process, the first emphasis cycle influences the structure of the composite sample.

In the microstructure of Figure 2, there are four zones of analysis. Figure 2(a) above is copper (Cu) bonding to the rolled sample. The role of copper, in addition to binding the unified plates, also maintains stability so that the roll compression stress is evenly distributed. In Figure 2(b), then the stack of plates processed by rolling undergoes bonding between plates to one another, but the binding still does not result in a diffusion process because there is still an interface line which is a form of adhesive bonding bond, based on previous experiments [7-8] Diffusion bonds are indicated by the loss of the interface line or called the missing line.

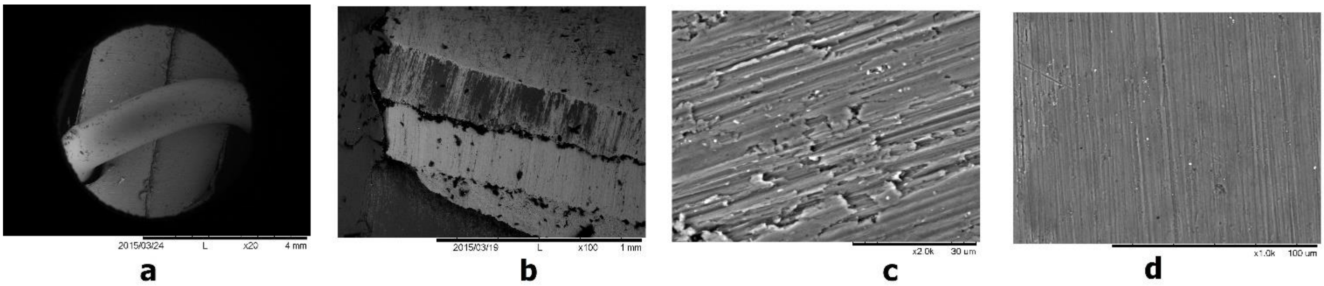

Figure 2. (a) Copper (Cu) wire as a binder for Al plate; (b) Compressed plate piles; (c) Structure of AA1070 as a result ARB compression result; (d) Structure of AA7075 as a result of ARB compression.

The structure of the AA1070 is presented in Figure 2(c). It can be seen that the delaminated structure undergoes morphological changes. The change happens because AA1070 is a pure aluminum series that does not have dominating by-products, so compression loads easily displace the structure [17]. The process can change the characteristics of the material to be harder due to changes in grain morphology. Figure 2(d) is the grain structure of AA7075, based on the literature review [9]. The microstructure of deposits such as the element $MgZn_2$, which functions as a precipitate, frequently constrains the working process on the AA7075 series material. If the stress distribution is not uniform, it will form microsegregation, which causes cracks when the material is processed [18].

Based on [19], the sample creation procedure failed because of insufficient ductility in AA7075 due to fracture microsegregation. The experiment showed that the ability to bond between grains was very weak due to the precipitate of MgZn. The internal cracking factor in the experiment [20] requires process accuracy related to several parameters used in the process, one of which is a heat treatment that causes sample overaging through the formation of relatively coarse and stable particles. The AA7075-O alloy, after overaging treatment, shows granules and lengthwise and leveled parallel to the rolling direction.

Precipitation hardening during thermal treatment is a solution to the limitations of the AA7075 series. Additional improvements can homogenize the microstructure to improve mechanical properties at room temperature and obtain superplastics that form quickly at relatively low temperatures, provided that the UFG granules are developed stably. At this temperature [21]. During gradual freezing, the formation of $MgZn_2$ microsegregation will not occur during rapid cooling, and Micro-segregation can be removed by rapid freezing and proper heat treatment of the process. The microsegregation of $MgZn_2$ in the aluminum matrix shows that the fine grains of the $MgZn_2$ phase are evenly distributed in the aluminum matrix, so microsegregation that can cause cracking can be avoided [22].

3.2. Morphological analysis of the microstructure of the ARB process

The scanning electron microscope (SEM) used the JEOL JSM-6510LA type, which was used to determine the grain morphology and distribution of the precipitate. SEM was used for quantitative microstructure analysis. The microstructure of the SEM resulting from the ARB process is presented in Figure 3. Figure 3(a) is the result of pure unalloyed AA1070 series aluminum-based material, and figure 3(b) is the base material for AA7075. While Figure 3(c) is the result of the Al_2O_3-reinforced ARB process, where it is seen that the jagged grain shift is due to the compression of the roll force, which makes the grains seem like they are peeling off. Compared with the B_4C amplifier, as shown in Figure 3(d), the morphology is more serrated. Based on previous experiments [7] that B_4C powder will cause sliding, which makes grain shifts because the compression on the rolling force cannot immerse the powder grains.

Therefore, three more pressing cycles are required. Another phenomenon is different from the AA7075-based composite with Al_2O_3 reinforcement due to the ARB Process as shown in Figure 3(e). By using Al_2O_3 reinforcement, the distribution of Al_2O_3 reinforcement in the form of fiber can be evenly distributed. In the ARB process using AA7075 with B_4C reinforcement, the sliding that is too strong causes initial macro cracks in the stress concentration field. Although this based material produces high mechanical properties, the possibility of stress concentration is very large, this causes the grains to be evenly distributed, but the sediment morphology is not the same.

The research experiment results showed that Al_2O_3 was able to minimize particle size particles as a result of shear load-deformation in the ARB process. However, grain growth on heating was restrained by the oxide reinforcement, and recrystallization resulted in nano-granules. Alumina and oxide particles are formed on the surface, forming inclusions that are spread more evenly, acting as barriers to grain growth [2,7]. Different conditions occur in B_4C-reinforced particles, where the precipitated powder will cause inter-locking between grains. Contact between the two particles is connected as the matrix, and grain reinforcement adhere to the precipitation. The reinforcing particles in the matrix decrease the density and increase the porosity, as presented in Table 1. According to [13], an increase in dislocation density might result in matrix strengthening at the interface to compensate for the strain imbalance between the two phases. Compared to Al_2O_3, B_4C has a more significant effect on improving mechanical and physical properties, but the resulting interface bond Al_2O_3 produces a uniform grain morphology.

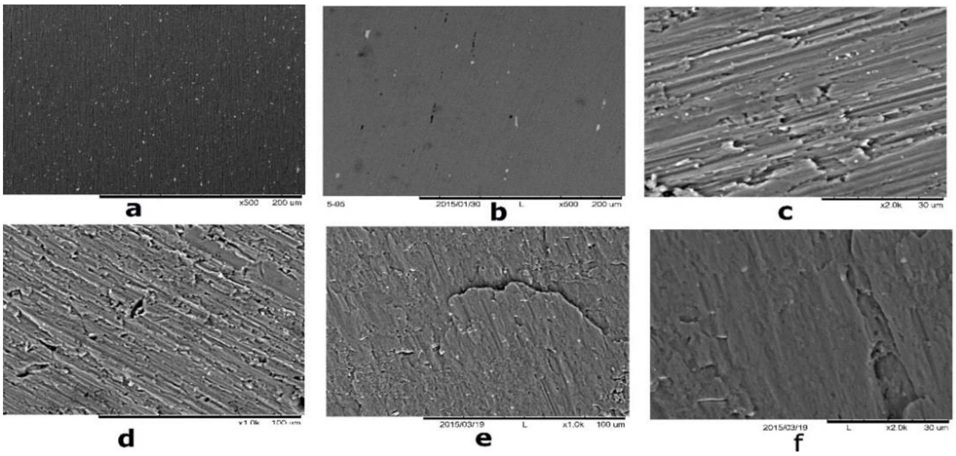

Figure 3. ARB results (a) AA1070 (b) AA7075 (c) AA1070/Al_2O_3 (d) AA1070/B_4C (e)AA7075/Al_2O_3 (f) AA7075/B_4C.

4. Conclusion

Comparing the mechanical properties and physical properties of aluminum-based composites using the ARB process resulted in an average hardness of 43.36;87.20 BHN for the Al_2O_3 reinforced composite, while the hardness used B_4C increased by 53.50;105.2 BHN. In addition, there was an increase in density, namely 2.66; 2.81 gr/mm^2 on the Al_2O_3 reinforcement, and the use of B_4C as reinforcement was also relatively increased, namely 2.76; 2.88 gr/mm^2. The rolling process in ARB occurs between plates binding to each other if the binding process still does not produce a diffusion bond. The bond occurs because there is still an interface line which is a form of adhesive bonding bond between the two connected plates. The diffusion bond is indicated to be successful, with the condition that the interface line on the plate being joined is lost, or it can be called a missing line.

The Al_2O_3 reinforcement has been able to minimize the particle size of the grains, but the grain growth during heating is restrained by the oxide reinforcement and recrystallization, which produces nano-granules. The B_4C reinforcing particles create inter-locking between grains, resulting in more equally distributed inclusions that function as a barrier to grain expansion. If the granules stick to the precipitation, then the interface of the two particles forms a bond resulting from the matrix and its reinforcement, decreasing the density and increasing the porosity. The development of this ARB-based composite material is an effective alternative method for manufacturing aluminum-based composites with Al_2O_3/B_4C reinforcement. Through improving the characteristics of the mechanical and physical properties, this process was developed based on the principle of the accumulative roll bonding (ARB) process, which can be applied to laboratory scale and industrial environments in general.

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