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# Accumulative press bonding; a novel manufacturing process of nanostructured metal matrix composites

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## ABSTRACT

A new manufacturing process for metal matrix composites has been invented, namely accumulative press bonding (APB). The APB process provided an effective method to produce bulk Al/10 vol.% $WC_p$ composite using tungsten carbide (WC) powder and AA1050 aluminum sheets as the raw materials. The microstructural evolutions and mechanical properties of the monolithic aluminum and Al/$WC_p$ composite during various APB cycles were examined by scanning electron microscopy, X-ray diffractometry, X'pert HighScore software, and tensile test equipment. The results revealed that by increasing the number of APB cycles (a) the uniformity of WC particles in aluminum matrix improved, (b) the porosity of the composite eliminated, (c) the particle free zones decreased and (d) the cluster characteristics improved. Hence, the final Al/$WC_p$ composite processed by 14 APB cycles showed a uniform distribution of $WC_p$ throughout the aluminum matrix, strong bonding between particles and matrix, and a microstructure without any porosity and undesirable phases. The X-ray diffraction results also showed that nanostructured Al/$WC_p$ composite with the average crystallite size of 58.4 nm was successfully achieved by employing 14 cycles of APB technique. The tensile strength of the composites enhanced by increasing the number of APB cycles, and reached to a maximum value of 216 MPa at the end of 14th cycle, which is 2.45 and 1.2 times higher than obtained values for annealed (raw material, 88 MPa) and 14 cycles APBed monolithic aluminum (180 MPa), respectively. Though the elongation of Al/$WC_p$ composite lessened during the initial cycles of APB process, it increased at the final cycles of the mentioned process by 78%. Role of WC particles, uniformity of reinforcement, porosity, bonding quality of the reinforcement and matrix, grain refinement, and strain hardening were considered as the strengthening mechanisms in the manufactured composites.

## 1. Introduction

Metal matrix composites (MMCs) are widely used in aerospace, military, and automotive industries due to their excellent properties such as high ratio of strength/density, improved elastic modulus and high wear resistance [1,2]. There are several traditional processing routes to prepare MMCs such as casting, powder metallurgy and spray forming [3,4]. Each of these processes has its own drawbacks such as non-uniform distribution of the reinforcement, poor adhesion between the matrix and the reinforcement, and undesirable chemical reaction [5–7]. Recently, accumulative roll bonding (ARB) has been introduced as a new solid state method to produce particle reinforced MMCs without the above mentioned problems [8,9]. Up to now, several MMCs including Al/$Al_2O_3$ [2], Al/SiC [10,11], Al/$B_4C$ [12], Cu/$Al_2O_3$ [8], Al/CNT [13], Al/$Cu_p$ [14], Mg/CNT [15] and Al/$W_p$ [16] have been fabricated by ARB process.

Many potential applications of MMCs prompted the present authors to invent and propose another solid state process named accumulative press bonding (APB) for manufacturing MMCs. Up to now, tungsten carbide (WC) is the only particle dispersed in the surface layer of metals such as aluminum and, consequently, the resultant hard coatings improves the wear properties of matrix [17–19]. The conventional processes are rarely used for producing bulk Al/$WC_p$ composites because the density and melting point of WC (15.63 g/cm$^3$, 3143 K) is significantly higher than those of aluminum (2.70 g/cm$^3$, 930 K) [19]. The objective of the present study is to produce bulk nanostructured Al/10 vol.% WC particulate composite using APB process. Furthermore, the effect of number of APB cycles on the microstructure and mechanical properties of monolithic aluminum and Al/$WC_p$ composite were examined.

## 2. Experimental procedure

### 2.1. Materials

As-received commercial AA1050 aluminum strips with the dimensions of 100 mm × 50 mm × 1.5 mm were annealed at

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623 K in ambient atmosphere for 1 h, and WC powder with average particle size of about 10 μm, were used as raw materials. The chemical composition of aluminum strips and the micrograph of $WC_p$ powder used in present study are demonstrated in Table 1 and Fig. 1, respectively.

### 2.2. Surface preparation

To create a satisfactory metallurgical bond by press bonding, it is essential to remove any contamination that may be present on the surface of the aluminum strips. The aluminum surfaces usually contains humidity, dust particles, greases, adsorbed ions, and alumina oxide. Several authors [20–22] have noted that the best method for achieving high mechanical bonding quality between strips is degreasing surface followed by scratch brushing. Along these lines, the strips were degreased with acetone bath and, subsequently, scratch brushed by a steel crimped wire wheel brush attachment (with 0.4 mm wire diameter) mounted in the drill machine (AEG SBE 600R) with peripheral speed of 2800 rpm. The initial surface roughness of the specimens was 0.6 μm, which after scratch brushing rose to about 5.5 μm. Surface roughness was measured by the SM7 roughness profile meter apparatus and according to ASTM D7127 – 05 standard. To avoid contamination and thick alumina layers formation, the press bonding process must be carried out immediately after degreasing and scratch brushing.

### 2.3. Manufacturing of Al/$WC_p$ composite by APB process

Fig. 2 illustrates the schematic of APB process for producing Al/10 vol.% $WC_p$ composite. This process was performed in two steps. To achieve a good dispersion of WC particles between strips, an acetone-base suspension was prepared and put under ultrasonic waves with frequency of 48 kHz for 30 min. After surface preparation, ultrasonicated WC powder in acetone was sprayed between the two aluminum strips with an atomizer. Then, WC particles deposited and acetone evaporated in air, so that the brushed surface of one strip uniformly covered with WC particles. The amount of $WC_p$ powder, dispersed on the surface, was 2 vol.% per cycle. Then, the two strips were put on each other and stacked. The stack strips were carefully handled to avoid renewed contamination. The cold press bonding process was performed on the stacked strips with no lubrication, employing a laboratory hydraulic press machine (Toni Technik Baustoffprüf systeme GmbH), with a loading capacity of 200 tons. The press bonding process was carried out with a specific amount of reduction equal to 50%. Then, the press bonded strips were cut in half. The same procedure was repeated up to five cycles in the first step (Fig. 2a). First step of APB process was designed for adding reinforcement into metal matrix and thereby producing MMC. In the second step (Fig. 2b), the mentioned procedure was repeated again up to 14 cycles without adding $WC_p$ powder. Second step was designed for dispersing reinforcement particles in all part of the matrix. The same process was employed for the production of the monolithic aluminum, while the aluminum strips were APBed without adding $WC_p$ powder in any steps of APB process.

**Table 1**
Chemical composition of the used AA1050 aluminum strip.

| Element | Al | Si | Fe | Mn | Cu | Mg | Zn | Ti | Other |
|---|---|---|---|---|---|---|---|---|---|
| wt.% | 99.50 | 0.20 | 0.22 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |

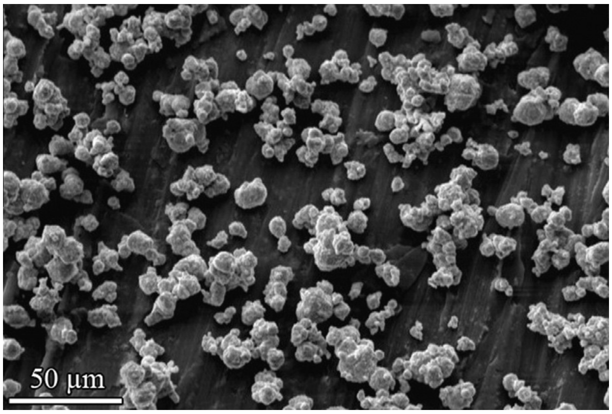

**Fig. 1.** Typical SEM image of the used $WC_p$ powder.

### 2.4. Microstructural evaluations

Scanning electron microscopy (SEM, Philips XL30) was employed to examine the distribution of WC particles through the different cycles of APB process. The X-ray pattern of the manufactured Al/$WC_p$ composite was recorded with an X-ray diffractometer (XRD). The result was used for the microstructural characterization. The XRD experiment was conducted on the specimen with dimensions of 10 mm × 10 mm × 1.5 mm by a Philips X'PERT MPD X-ray diffractometer with Cu Kα radiation in the range of $2\theta = 25-95^\circ$ using a step size of 0.05° and a counting time of 1 s per step. Consequently, XRD pattern was analyzed by using X'PertHighScore software, and microstructural phases of the composite were characterized. The crystallite size of the specimen was calculated from the XRD patterns applying the Williamson–Hall method [23].

$$\beta \cos\theta = \frac{k\lambda}{d} + 2A\varepsilon \sin\theta \quad (1)$$

where $\theta$ is the Bragg diffraction angle, $d$ is the crystallite size, $\varepsilon$ is the average internal strain, $\lambda$ is the wavelength of X-ray (0.154056 nm for Cu Kα radiation), $\beta$ is the diffraction peak width at half maximum intensity, $k$ is the Sherrer constant (0.91), and $A$ is a coefficient, depending on the distribution of strain, which is near to unity for dislocations. In this method, $\beta \cos\theta$ is plotted versus $\sin\theta$ and the intercept of the linear extrapolation yields to the crystallite size.

### 2.5. Mechanical properties

The tensile test specimens were machined from the APBed strips, according to the ASTM E8/E8M standard. The gauge width and length of the tensile test specimens were 6 ± 0.1 and 25 ± 0.1 mm, respectively. The tensile test was carried out at a nominal strain rate of $1.6 \times 10^{-1}\ s^{-1}$ by a Houndsfield H50KS machine. The total elongation of specimens was measured from the difference in the gauge length before and after testing. To have accurate results, three tensile experiments were conducted on each specimen and subsequently averaged.

## 3. Results and discussion

### 3.1. SEM observation

The microstructure variations of Al/$WC_p$ composites produced by different cycles of APB process in two different magnifications are shown in Fig. 3. It can be seen from Fig. 3a that in the primary