A New Approach for Fabrication of Bulk Mmcs Using Accumulative Channel-Die Compression Bonding (ACCB)

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ABSTRACT

A new severe plastic deformation (SPD) based technique entitled accumulative channel-die compression bonding (ACCB) is proposed for fabrication of high strength multi-layered Al/Cu composites for the first time. In order to primarily demonstrate the capabilities of ACCB in fabrication of metal matrix composites (MMCs), AA 1050 and pure Cu strips were processed. The primary Al/Cu sandwich was prepared and subsequently 50% thickness reduction was applied per cycle. The experimental results reveal that thickness of Al and Cu layers decreased by increasing ACCB cycles up to the point of the Cu layers starting to neck and eventually rupture. An Al/Cu bulk composite was processed with homogeneous distribution of fragmented Cu layers in the aluminum matrix after 6 ACCB cycles (corresponding to the effective plastic strain of 5.6). The microstructure evolution and mechanical properties of the processed specimens were evaluated at different ACCB cycles. The results show that with increase in the number of cycles, microhardness, strength, and elongation of the ACCB processed composites increase,too. The capability of ACCB in processing bulk multilayered MMCs was confirmed.

1. Introduction

Severe plastic deformation (SPD) is a promising strategy for the production of bulk nanostructured metals. To date, many different SPD processes such as equal-channel angular pressing (ECAP) [1], high-pressure torsion(HPT)[2], accumulative roll-bonding (ARB) [3], parallel tubular channel angular pressing (PTCAP) [4-6], repetitive forging(RF) [7], accumulative torsion back (ATB) [8] and accumulative channel-die compression bonding (ACCB) [9]have been developed. Fabrication of bulk ultrafine grained (UFG) materials using SPD processes is one of the interesting areas in the field of nanomaterials [10-12]. Recently, metal matrix composites (MMCs) have received considerable attention due to their striking mechanical, electrical, and magnetic characteristics [13]. Metal matrix composites are widely used in aerospace, military, and automotive industries because of their excellent properties such as high ratio of

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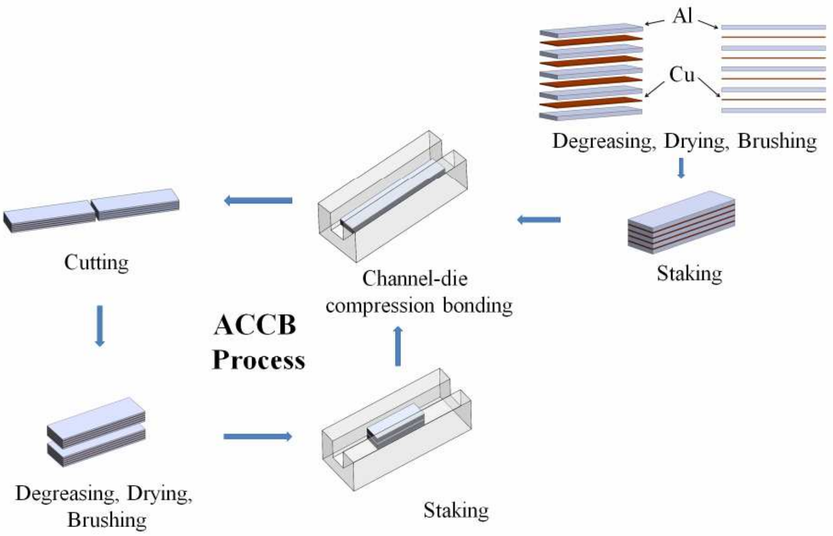

Fig. 1. Schematic presentation of ACCB process in fabrication of layered composites.

strength/density, improved elastic modulus, and high wear resistance [14].

Thin-film metallic multi-layered composites are produced by coating processes like ion sputtering and evaporation [15], or by diffusion bonding of thin strips of different materials. Each of these processes has its own drawbacks, namely non-uniform distribution of the reinforcement, poor adhesion between the matrix and the reinforcement, and undesirable chemical reactions [16].

Severe plastic deformation methods result in grain refinement by formation of incidental dislocation boundaries (IDBs) and geometrically necessary boundaries (GNBs) which finally lead to an ultrafine- grained structure and equilibrium grain boundaries [17]. Recently, numerous investigations have been carried out on ARB process which were widely used to produce several multi-layered composites with different materials, such as Al-Ni [18] and Cu-Ni [19].

Appreciating the ACCB process which was firstly introduced as a new SPD method by Kamikawa and Furuhara [9], the authors propose this process as a fabrication method for producing bulk multi-layered composites of relatively large-scale dimensions. This process was developed based on the principles of ARB, but it can be installed into a laboratory easier than ARB. For instance, in ACCB method a high-capacity rolling mill is not necessary; in fact, a conventional pressing machine equipped with a channel die is the only apparatus which is required. In addition, producing large scale multi-layered composites by this method is an industrial advantage. The production speed of this method is higher than that of ARB process, and ACCB process is capable of producing bulk multi-layered composite samples. It is worth mentioning that to our knowledge, this research is the first of its kind that focuses on the Al/Cu multi-layered composite fabricated by ACCB process.

Accumulative channel-die compression bonding (ACCB) was introduced by Kamikawa and Furuhara [9] as a new severe plastic deformation process. As illustrated in Fig. 1, processing of the material by ACCB in the first cycle includes compression of a billet sample in a channel die. The compression in a channel die results in thickness reduction and elongation in the length of the sample with no lateral spreading. This is a plane strain deformation just like what happens in an ideal rolling process. The second cycle of ACCB includes cutting the compressed sample into half in length, stacking the two billets to the initial thickness, and finally compressing it in the channel die again. As it was explained, ACCB is quite similar to ARB process. ACCB requires a simple apparatus, and consequently the control of strain and strain rate can be performed precisely. Moreover, the ACCB

Table 1. Specifications of Al and Cu sheets

Materials	Strip dimensions (mm×mm×mm)	Hardness (VHN)	Elongation %	Tensile strength (Mpa)
Pure Cu	15×50×0.1	52	15	120
Pure Al 1050	15×50×0.5	25	40	40

process is capable of producing bulk samples with relatively large dimensions. The ACCB process can be repeated as many times as required to achieve high plastic strains. It must be noted that degreasing and wire-brushing of surfaces prior to compression are necessary for achieving good bonding in the produced bulk samples.

2. Experimental procedure

In this study, all experimental works were carried out on the annealed Al 1050 and pure Cu as primary materials of the layered structure. Specifications and mechanical properties of the research materials are listed in Table 1. Layers with dimensions of 15mm × 50mm were cut from stock sheets, degreased in the acetone bath and then scratch brushed by a steel brush. Primary sandwich composite was fabricated using 25 aluminium layers with 0.5 mm thickness and 24 pure copper layers with 0.1 mm thickness. The layers were stacked alternatively to form a multi-layered initial specimen with an overall thickness of about 15 mm and volume fraction composition of 84%Al and 16%Cu.

A channel die with a channel width of 15 mm was fabricated from tool steel and hardened to 55 HRC. The prepared stack was compressed in the ACCB die at ambient temperature to produce primary sandwich with a 50% thickness reduction from 15 mm to 7.5 mm. Then, six cycles of ACCB process were applied at ambient temperature on the prepared primary sandwich. Each cycle of ACCB includes two stages; in the first stage, the compressed billet from the previous cycle was cut into half in length and surface treatments including degreasing of outer layers, air drying, and scratch brushing are carried out. Then they are stacked to the initial thickness. The second stage of the ACCB process is plane strain compression bonding of stacked billet from the first stage in the channel die. Principles of the applied ACCB process for producing Al/Cu composite can be observed in Fig. 1. Time interval between two stages of ACCB (surface treatments and a compression binding) was kept less than 90 s so as to minimize formation of oxide layers on the outer surfaces of the billet. The experiments were performed at constant strain rate with ram speed of 5 mm/min. In this process, the Al/Cu composites with layered structure were subjected to 6 cycles of ACCB corresponding to accumulative plastic strain of 5.6. Microstructural investigations of ACCB processed Al/Cu composites were conducted using scanning electron microscopy (SEM) after specimen preparation by standard polishing methods. Microhardness of the processed composites was measured under a load of 15 g for 15 s using a Vickers microhardness testing machine. All measurements were performed on the cross-section of the processed composites perpendicular to direction of the material flow (length of the billet) during ACCB. Tensile tests were carried out at ambient temperature with strain rate of 1e-3S^{-1} provided by constant speed of the press crosshead.

3. Results and discussion

3. 1. Evaluation of microstructure

Fig. 2 shows the microstructure evolution of Al/Cu composite samples processed by different ACCB cycles. Fig. 2(a) refers to sandwich production named zero cycle corresponding to an equivalent strain of 0.8. As can be seen in Fig. 2(a), uniform and coherent deformation of Al and Cu layers occurred only in sandwich preparation. Fig. 2(b and c) illustrate the microstructure evolution of Al/Cu composite after the first and 6th deformation cycles of ACCB process, respectively. As the ACCB cycles increased, the thickness of Cu layers decreased and the layers were deformed non-uniformly due to the heterogeneous distribution of the strains. As can be seen from these figures, in the subsequent cycles of ACCB process, the Cu layers initiate

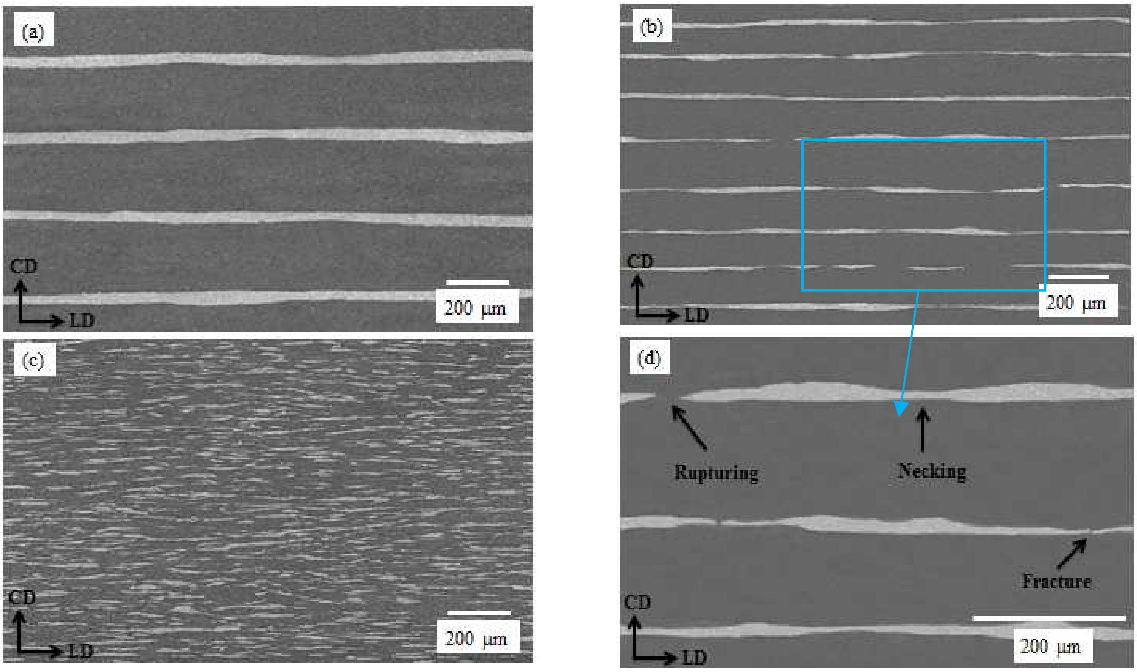

Fig. 2. SEM micrographs of the processed Al/Cu multilayer composites in the (a) primary sandwich, (b) first cycle ACCB, (c) sixth cycle ACCB and (d) Rupturing, necking and fracture of Cu layers during ACCB.

elongating, necking and fracturing locally in the Al/Cu composites. Finally, after 6 ACCB cycles a homogeneous dispersion of Cu fragments in the Al matrix is observed (Fig. 2(c)).

During deformation of dissimilar metals, the softer matrix metal (Al) acts as a transfer media for imposing the forming load to the harder metal (Cu) layers and fills up all the spaces between the Cu layers. On the other hand, by increasing deformation, instabilities originate due to differences in the flow properties of these layers. This results in the commencement of necking, fracture, and finally rupture of harder layers (Fig. 2 d) [20, 21]. According to Fig. 2(b), the fragmentation of Cu layers inside the Al matrix is heterogeneous in the first cycle. The imposed forming load causes different deformation behaviour in Al and Cu layers due to the difference between their strength and work hardening exponent ($n_{Al} = 0.22$, $n_{Cu} = 0.44$). The SEM micrographs of Al/Cu composite in the subsequent ACCB cycles demonstrate non-uniform structural variations in the interface of the Al matrix and Cu layers which originate from inhomogeneous interaction of matrix and reinforcement layers. These are due to different flow stresses of phases, the friction between Al matrix and Cu layers, and the friction between die set and sample surfaces.

The accumulation of strains due to the increase in the ACCB cycles causes continuous fragmentation of harder Cu layers and results in smaller fragments in Al matrix and more uniform distribution for reinforcement. Also, the accumulated strains and shear bands [21] will result in grain refinement in the Al and Cu layers. As it was reported by Kamikawa and Furuhara [9], the original coarse grains of Al and Cu in the starting structure were transformed into a finer grain structure by deformation-induced high-angle boundaries as the number of the ACCB cycles increased. Fig. 3 illustrates the rapid decrease in the thickness of Cu layers during the initial ACCB cycles, and it can be seen that after the second cycle, the thickness of the Cu layers approaches to a saturated value. This phenomenon is due to the fracture of Cu layers. Variations in the thickness of the Cu layers versus the number of the ACCB cycles were measured and shown in Fig. 3. In the sixth cycle of the ACCB process like the ARB process, as reported in [19], very thin layers (less than 1 μm) were observed in various points of the Al matrix.

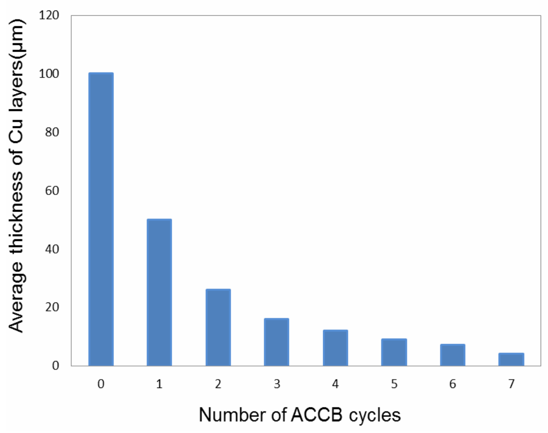

Fig. 3. Thickness variations for copper layers during different cycles of ACCB processed Al/Cu composite.

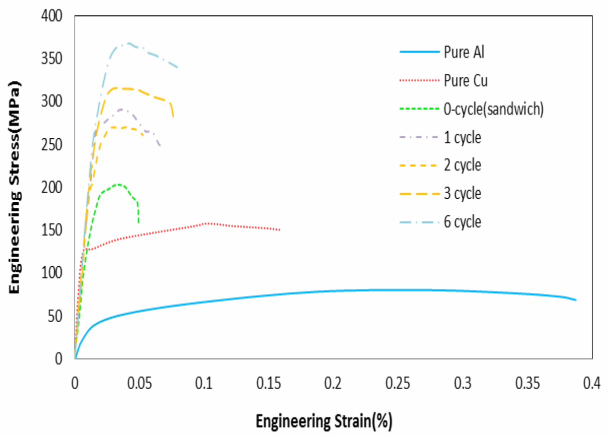

Fig. 4. Stress–strain curves of Al/Cu composites for different ACCB cycles.

3. 2. mechanical properties

Fig. 4 shows the engineering stress-strain curves of Al/Cu composite processed by different ACCB cycles. It can be seen from this figure that the yield and tensile strengths of the composites significantly increased after the sandwich preparation and the first cycle of ACCB, but decreased after the second cycle, and then again for the next cycles showed a rising trend reaching a peak at the sixth ACCB cycle. The total elongation of the Al/Cu composite considerably decreased in the initial sandwich, and then enhanced by increasing the number of the ACCB cycles. As the ACCB process proceeded, elongation of composite increased and reached the amount of 8.4% after the sixth cycle.

As it is shown in Fig.4, after six cycles of the ACCB process, an abrupt increase in the tensile and yield strength can be observed. Therefore, the maximum yield and ultimate tensile strengths reached 310 MPa and 373 MPa, respectively, which could be due to increase of the bond strength and grain refinement in the Al and Cu layers. Mechanical properties of the primary sandwich and the Al/Cu multi-layered composite are depicted in Fig. 5(a, b) as a function of the number of ACCB cycles extracted from the stress-strain curves of the samples at different ACCB cycles presented in Fig. 4.

As it is reported in [22, 23], the increase of strength in the severely deformed composites is due to work hardening and grain refinement. In the early stages of the ACCB process, the strengthening is mainly because of work hardening since the dislocations form the sub-grain structures with low angle boundaries inside the initial coarse grains [24]. It is worth mentioning that, formation of large fragments at the beginning does not act as reinforcement in the Al matrix (Fig. 2.a, b). Also, the bonding strength among the Cu and Al layers is not high, and distribution of Cu fragments is not uniform in the matrix. After the second cycle, disorientation between the sub-grains and the main grain boundaries increases and grain fragmentation occurs. As the number of the ACCB cycles increases, formation of ultrafine grained microstructure plays the main role in strengthening. This trend has also been observed in ACCB processed materials [9] and multi-layer composites [25, 26]. As the number of ACCB cycles increases, Cu fragments inside the Al matrix become smaller, and the bonding strength increases because of the greater punch pressureand the uniform distribution of Cu fragments in the Al matrix. These mechanisms result in increasing material strengths by reinforcing role of the harder layers (Cu) in composites [27].

3. 3. Hardness

Fig.6 illustrates microhardness variations of the Al and Cu layers at different ACCB cycles. It is clear from this figure that microhardness of the Al and Cu layers increases as a function of the ACCB cycles. The abrupt increase was

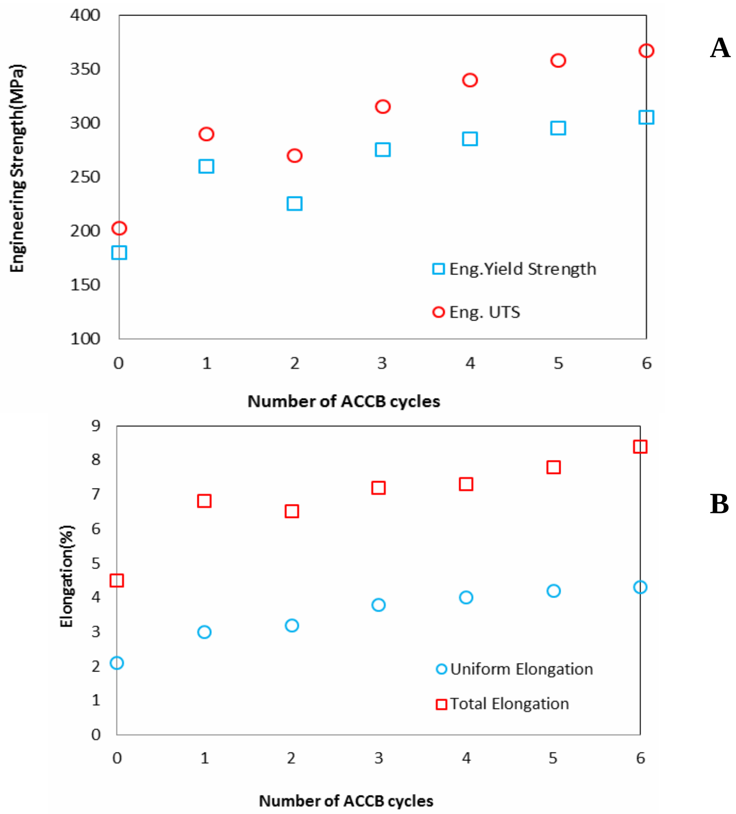

Fig. 5. Variation of (a) strength and (b) elongation with number of ACCB cycles.

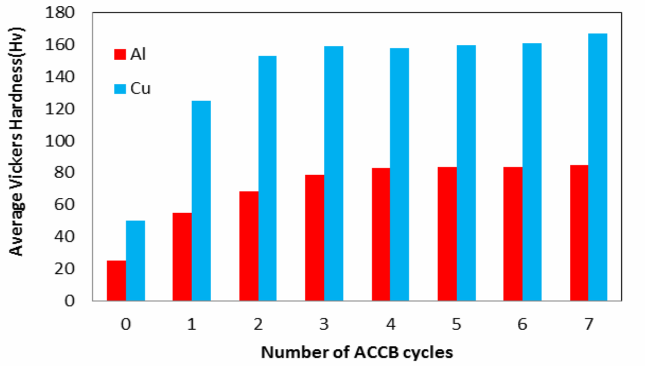

Fig. 6. Microhardness variation for individual copper and aluminum layers for ACCB processed Al/Cu composite.

observed in microhardness of the Al and Cu layers just after sandwich preparation, while the increasing rate for the other ACCB cycles is lower. Thus, microhardness curves follow a trend which reaches stable conditions in the last cycles. As it is reported in [28, 29], work hardening mechanism in the early cycles of ACCB has the main contribution on the microhardness increase which has been attributed mainly to the increase of dislocation density inside the initial coarse grains of Al and Cu. In the latter cycles of ACCB, the grain refinements occur and play the main role in the increase of microhardness.

4. Conclusions

A new SPD based technique entitled accumulative channel-die compression bonding (ACCB) is proposed for the fabrication of high strength multi-layered MMCs for the first time.

The bulk Al/Cu composite was processed by this new method. Mechanical properties and microstructure of the ACCB processed samples were investigated. Experimental results reveal that increase of the number of ACCB cycles causes elongation, necking, fracture, and local rupture of the Cu layers in the Al/Cu composites, and a homogeneous dispersion of Cu fragments in the Al matrix is obtained after six ACCB cycles. Because of heterogeneous distribution of the strain originated from friction between the die set and the sample surface and the friction between the copper and aluminum layers, the deformation of Cu layers is not uniform. The thickness of Cu layers decreased from 100 µm in primary stages to 4 µm after six ACCB cycles. The data extracted from stress-strain curves show a notable increase in yield and ultimate strength of composite, while amounts of elongation decreased with respect to the original values after production of the primary sandwich. Microhardness measurements documented increase in the microhardness of Al and Cu layers with respect to the initial annealed aluminum and copper strips.

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