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EFFECT OF DEFORMATION TEMPERATURE AND STRAIN RATE ON COMPRESSIVE BEHAVIOR OF LAMINATED ALUMINUM BRONZE-INTERMETALLIC COMPOSITES

Laminated composites were produced by reactive bonding using CuAl10Fe3Mn2 bronze and titanium foils with thicknesses of 0.6 and 0.1 mm, respectively. To obtain the composite sample five foils of bronze and four of titanium were used. During fabrication, the titanium layers reacted completely and formed intermetallics (Ti_2Cu, TiCuAl and $TiCu_2Al$). In order to investigate the compressive behavior of the laminated CuAl10Fe3Mn2-intermetallic composites, isothermal compression tests were conducted at the temperatures of 20, 600 and 800°C with two different strain rates of $1\cdot10^{-3}$ s^{-1} and $2.9\cdot10^{-3}$ s^{-1}. The thickness of all the specimens was reduced by 50%. During the compression tests delamination of the layers of the composites was not observed. With an increase in the investigation temperature the yield strength of the composites decreased significantly. The results showed that the deformation temperature and the strain rate were equally responsible for the evolution of deformation during isothermal compression. The most favorable compressive deformation conditions necessary to shape the laminated CuAl10Fe3Mn2-intermetallic phases composites without damaging their layers were determined experimentally.

Keywords: laminated composites, aluminum bronze, intermetallics, compression

WPŁYW TEMPERATURY I SZYBKOŚCI ODKSZTAŁCANIA NA MECHANIZM DEFORMACJI PODCZAS ŚCISKANIA WARSTWOWEGO KOMPOZYTU BRĄZ ALUMINIOWY-FAZY MIĘDZYMETALICZNE

Wytworzono kompozyty warstwowe z foli z brązu aluminiowego CuAl10Fe3Mn2 o grubości 0,6 mm oraz z foli tytanowej o grubości 0,1 mm. W celu uzyskania kompozytu zastosowano pięć folii z brązu i cztery z tytanu. Podczas reakcji syntezy warstwy tytanu całkowicie przereagowały i powstały fazy międzymetaliczne (Ti_2Cu, TiCuAl i $TiCu_2Al$). W celu przeanalizowania mechanizmu deformacji podczas ściskania kompozytów przeprowadzono testy w temperaturze 20, 600 i 800°C, stosując dwie różne prędkości odkształcania: $1\cdot10^{-3}$ s^{-1} oraz $2,9\cdot10^{-3}$ s^{-1}. Próby prowadzono do uzyskania 50% redukcji grubości. Podczas prób ściskania nie zaobserwowano delaminacji warstw kompozytu. Stwierdzono znaczny spadek granicy plastyczności kompozytów wraz ze wzrostem temperatury badania. Wyniki pokazały, że zarówno temperatura, jak i prędkość odkształcania miały wpływ na mechanizm deformacji. Eksperymentalnie określono optymalne parametry procesu odkształcania kompozytu CuAl10Fe3Mn2-fazy międzymetaliczne pozwalające na jego kształtowanie bez niszczenia warstw.

Słowa kluczowe: kompozyty warstwowe, brąz aluminiowy, fazy międzymetaliczne, ściskanie

INTRODUCTION

Metal-intermetallic laminated (MIL) composites are interesting materials that inosculate the high ductility of metals or alloys with the higher strength and elastic modulus of intermetallics [1-15]. They can also fulfil various functions, e.g. ballistic protection, vibration damping, heat exchange, blast mitigation, and thermal management [4]. The lamination ameliorates fracture toughness, fatigue behavior, corrosion, wear, and damping capacity. It can also provide enhanced formability for generally brittle intermetallics [6]. It is very beneficial that the laminated structure of the composites permits variations in the layer thickness and phase volume fractions of the components. A great number of MIL composites have been produced using Al and Ti [1-7], Mg [8, 9], Ni [10, 11], or Nb [12] foils. Many works also have shown that copper-intermetallic composites could be produced by a reaction that occurs at the interface of Cu and Ti [13-15]. Aluminum bronzes are commonly used corrosion-resistant alloys of copper. They normally contain between 4 and 15 wt.% aluminum and small amounts of other metals. Alloys containing from 9 to 12 wt.% aluminum are often fabricated by sand casting and gravity diecasting into strong objects, including many machine parts or tools and ship propellers [16]. Above 565°C, the microstructure of alloys with 9.4 to 11.8 wt.% aluminum consist of two phases with different proportions of α and β grains (Fig. 1).

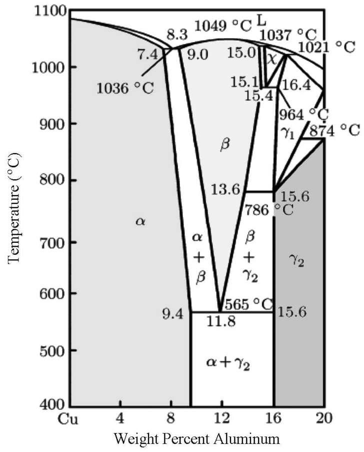

Fig. 1. Part of Cu-Al binary phase diagram [17]

Rys. 1. Część układu równowagi fazowej Cu-Al [17]

At temperatures below 565°C, the β phase decomposes into a eutectoid consisting of α and γ_2 phases, but this pearlite-like structure forms only when the cooling rates are less than 1°C/min [18]. At very high cooling rates these alloys undergo diffusionless transformation, as a result producing the β' phase - a supersaturated disordered solid solution. It is described as martensite and has a face centered cubic structure [19]. Composites with an aluminum bronze matrix and intermetallic layers could be considered for structural applications because of their lower density than monolithic bronze. Previous investigations showed that it is possible to fabricate these kinds of laminated composites using bronze and titanium foils [20]. Moreover, the influence of heat treatment on the microstructure, mechanical properties and fracture behavior was analyzed [21]. The aim of this work is to study the influence of the deformation temperature and strain rate on the compressive behavior of these laminated composites and to define the most favorable compressive conditions necessary to shape the alloy-intermetallic phases composites without damaging their layers.

EXPERIMENTAL PROCEDURE

Titanium foils (containing 99.51 Ti, 0.09 Fe, 0.08 C, 0.07 Al, 0.18 O, 0.05 V and 0.02 N) of 0.1 mm thickness and CuAl10Fe3Mn2 foils (containing 83.36 Cu, 2.78 Fe, 10.75 Al, 1.98 Mn, 0.76 Ni, 0.29 Zn and 0.08 Sn) of 0.6 mm thickness were used to produce the bronze-intermetallic laminated composites. All the foils were cut into 50 x 12 mm rectangular pieces and any contamination was removed in a bath of 5 % HF in water. After rinsing in water, the foils were stacked into laminates in an alternating sequence (four foils of titanium between five foils of aluminum bronze). A pressure of 5 MPa was applied at room temperature in a specially constructed vacuum furnace to ensure good contact between the foils. After a series of attempts, was found [20] that a temperature of at least 870°C was necessary for the start and rapid development of structural processes at the interface between aluminum bronze and titanium. The temperature was increased from 20 to 800°C and the samples were heated in vacuum of 0.01 Pa for 1 h under the applied 5 MPa pressure to allow diffusion bonding of the layers. After that the temperature was increased to 875°C and the samples were held at this temperature for 1 h. The pressure was removed during this processing sequence with the purpose of eliminating the possible expulsion of liquid phases. After that, the temperature was decreased slowly to 700°C and the pressure of 5 MPa was applied again to reduce possible porosity. Finally, the samples were furnace-cooled to ambient temperature. The microstructure of the formed composite is shown in Figures 2 and 3.

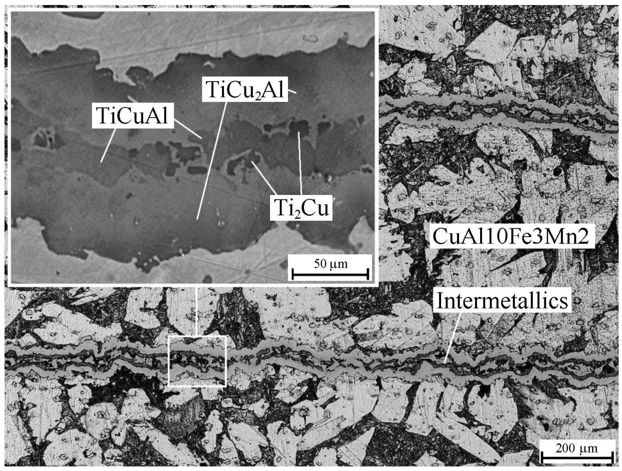

Fig. 2. Microstructure of as-fabricated laminated CuAl10Fe3Mn2--intermetallic composite

Rys. 2. Mikrostruktura uformowanego kompozytu warstwowego CuAl10Fe3Mn2-fazy międzymetaliczne

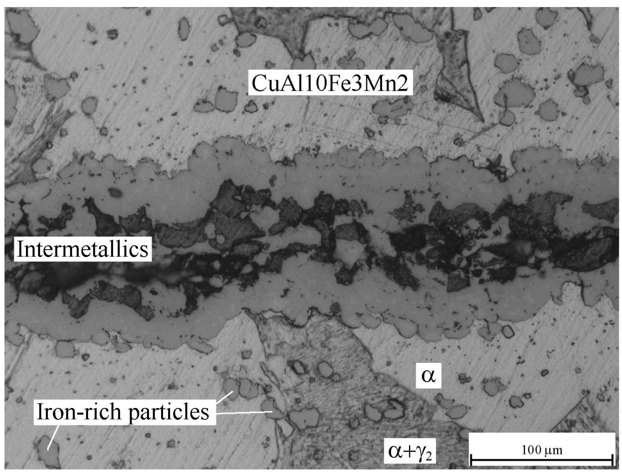

Fig. 3. Microstructure of single intermetallic layer in laminated CuAl10Fe3Mn2-intermetallic composite

Rys. 3. Mikrostruktura pojedynczej warstwy faz międzymetalicznych w kompozycie CuAl10Fe3Mn2-fazy międzymetaliczne

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The samples for metallographic investigations were cut using diamond blade and polished applying standard techniques. The microstructural observations were performed using a JEOL JMS 5400 scanning electron microscope and a Nikon ECLIPSE MA 200 light microscope. The chemical composition of the phases was previously determined and reported [20]. Before the samples were examined with the light microscope, they had been etched to reveal the grain boundaries and the microstructure of the intermetallic layers. Etching was performed with a solution of 40 g CrO_3, 7.5 g NH_4Cl, 8 ml H_2SO_4, 50 ml HNO_3 and 1900 ml H_2O. Compression tests were carried out in air at ambient (20°C) and at elevated temperatures (600 and 800°C) using an Amsler testing machine fitted with a vertical split tube furnace. Square samples with dimensions of 10 x 10 x 3.4 mm were deformed at strain rates of $1\cdot10^{-3}$ s^{-1} and $2.9\cdot10^{-3}$ s^{-1}. All the samples were loaded perpendicular to the layer direction and deformed to achieve a 50% thickness reduction.

RESULTS AND DISCUSSION

The mechanical behavior and deformation mode of the laminated composites were strongly dependent on the deformation temperature and strain rate. Two different deformation mechanisms were found (Fig. 4).

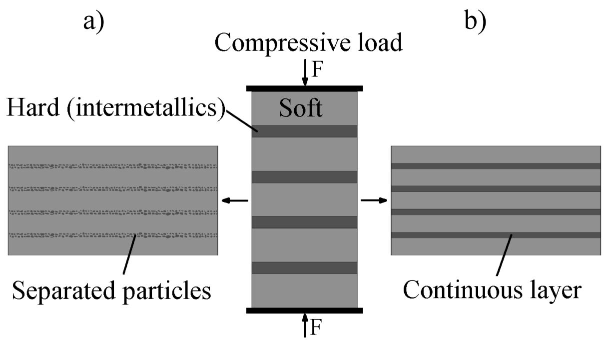

Fig. 4. Deformation response of laminated composites during compressive deformation: a) fragmentation of intermetallic layers and b) isostrain behavior of all layers

Rys. 4. Sposób deformacji kompozytów warstwowych podczas ściskania: a) fragmentacja warstw faz międzymetalicznych i b) wspólne odkształcanie się wszystkich warstw

Observing the nature of the compression deformation of laminated materials, Mola et al. [22] realized that the bonding of the layers prevented each layer from freely moving laterally. During compression, the layers of composites are compressed but they are also subjected to tensile deformation in the direction that is perpendicular to the global load of the specimen. Therefore intermetallic layers can be fragmented and converted into separated particles arranged in bands (Fig. 4a). On the other hand, isostrain behavior is approached when individual component layers are able to deform uniformly (Fig. 4b). The ideal strain rate and temperature can be chosen for deformation so that the layers of the composite have comparable flow stresses, which limits the extent to which one component can preferentially extrude from the laminated composite during compression. These considerations are important in shaping laminated composites by open die forging or by rolling. Figure 5 shows the load-displacement curves as received from the compression tests at the strain rate of $1\cdot10^{-3}$ s^{-1}. The yield strength corresponding to the deformation temperatures 20, 600 and 800°C, were 380, 130 and 44 MPa, respectively.

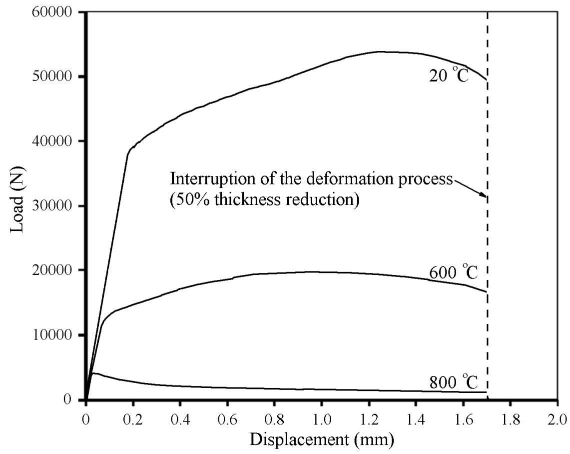

Fig. 5. Load-displacement curves for laminated composites compressed at 20, 600 and 800°C until 50% thickness reduction

Rys. 5. Krzywe obciążenie-przemieszczenie dla kompozytów warstwowych odkształcanych w temperaturze 20, 600 i 800°C do 50% redukcji początkowej grubości

Figure 6 shows the sample after compressive deformation at 20°C at the strain rate of $1\cdot10^{-3}$ s^{-1}. Similar results were also obtained for the strain rate of $2.9\cdot10^{-3}$ s^{-1}.

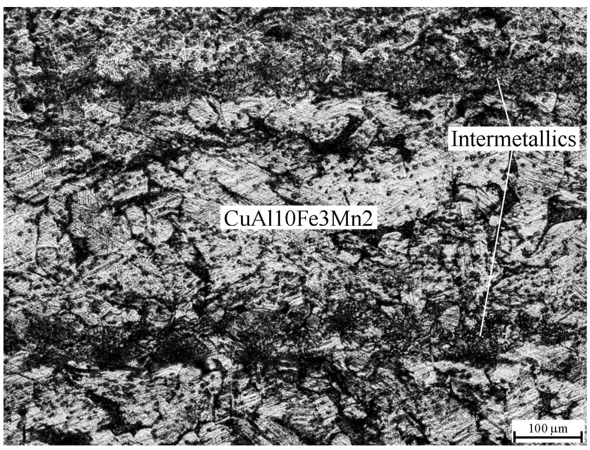

Fig. 6. Micrograph of sample compressed at 20°C

Rys. 6. Mikrofotografia próbki ściskanej w temperaturze 20°C

The layers of intermetallics were fragmented and converted into separated particles arranged in bands. As a result, the layers of CuAl10Fe3Mn2 bronze gradually underwent external stress, and strain hardening of the specimen that was produced due to plastic deformation of the bronze layers was observed (Fig. 5). Cracking that indicated the beginning of the deformation process in the intermetallic layers created stress concentration points at the bronze-intermetallic interfaces, which formed shear bands that propagated from the crack tip through the bronze layers into the next intermetallic layer (Fig. 6).

Deformation due to shear band formation was reported also in earlier papers [12, 14, 15]. This failure mechanism has been shown in the literature to be typical of laminated composites. The damage mechanisms of dissimilar laminated composites during testing are alike because various intermetallics formed from the different constituent metals behave very similarly. They are ordinarily brittle at room temperature due to the limited mobility of dislocations and have an insufficient number of slip or twinning systems. Alman et al. [10] investigated the mechanical behavior of Ni-Ni_2Al_3 composites at elevated temperatures and found that the properties decreased rapidly at the temperature of 650°C. Bloyer et al. [12] obtained remarkably similar results during an investigation of Nb-Nb_3Al laminates and found the brittle-to-ductile transition temperature at about 800°C. Furthermore, analogous results were reported by Konieczny [15] for Cu-intermetallic laminated composites deformed at 700°C. At 600°C the deformation mode of the bronze-intermetallic composite was different. The layers of intermetallics still cracked brittle and were fragmented but the deformed bronze recrystallized dynamically. The structure evolution was characterized by the development of newly formed grains in the bronze layers and bands of separated particles of intermetallics (Fig. 7). The deformation mechanism at 600°C did not depend on the strain rate.

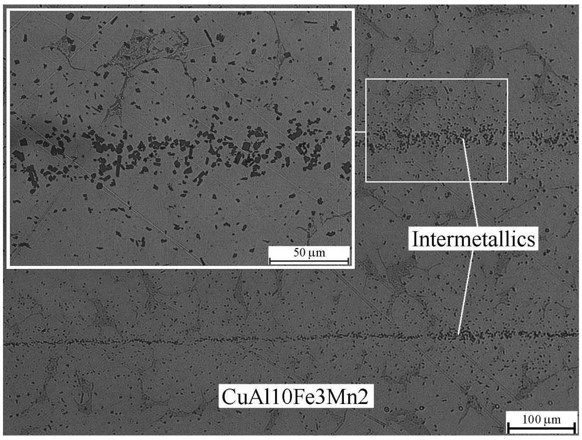

Fig. 7. Micrograph of sample compressed at 600°C

Rys. 7. Mikrofotografia próbki ściskanej w temperaturze 600 °C

The temperature of 800°C was above the brittle-to-ductile transition temperature for intermetallics and they were able to deform plastically together with the layers of bronze. Figures 8 and 9 show samples after compressive deformation at 800°C at the strain rates of $2.9 \cdot 10^{-3}$ s^{-1} and $1 \cdot 10^{-3}$ s^{-1}. It can be seen that for the highest temperature of the compressive tests, the deformation mode of the bronze-intermetallic composite depends on the applied strain rate. At the strain rate of $2.9 \cdot 10^{-3}$ s^{-1} some layers of intermetallics cracked longitudinally and cavities appeared inside them. It should be mentioned that there were no transverse cracks in the intermetallic layers, which was proof that the layers were able to deform plastically. On the other hand, at the strain rate of $1 \cdot 10^{-3}$ s^{-1} all the layers deformed together and there was no evidence of any cracks or large cavities in the intermetallic layers.

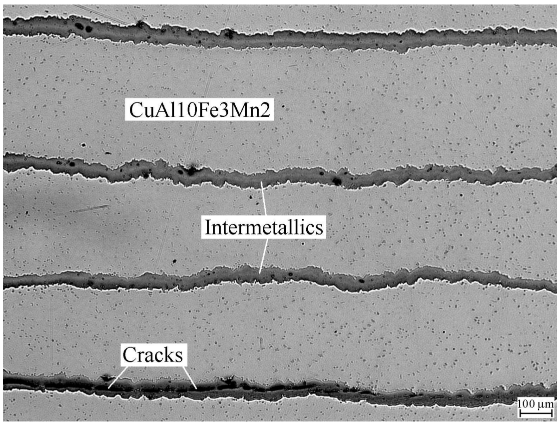

Fig. 8. Micrograph of sample compressed at 800°C at strain rate of $2.9 \cdot 10^{-3}$ s^{-1}

Rys. 8. Mikrofotografia próbki ściskanej w temperaturze 800°C z prędkością $2.9 \cdot 10^{-3}$ s^{-1}

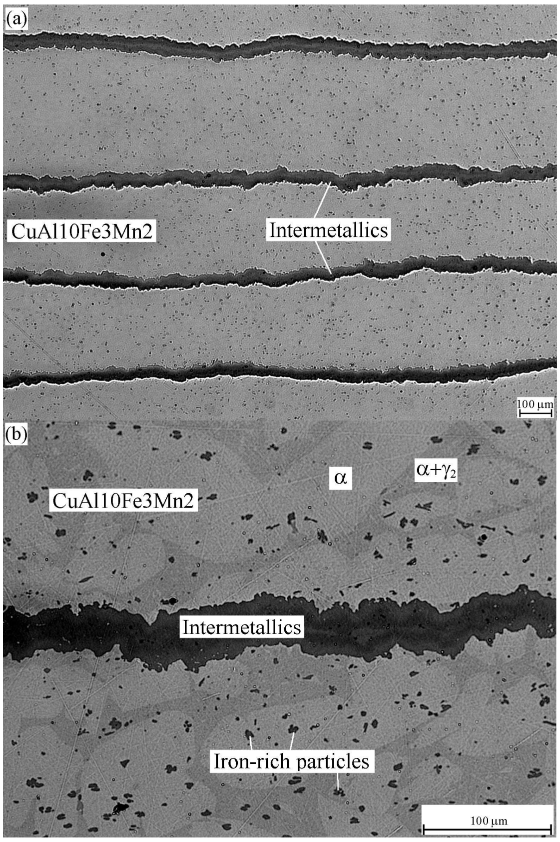

Fig. 9. Micrograph of sample compressed at 800°C at strain rate of $1 \cdot 10^{-3}$ s^{-1} (a) and microstructure of single intermetallic layer (b)

Rys. 9. Mikrofotografia próbki ściskanej w temperaturze 800 °C z prędkością $1 \cdot 10^{-3}$ s^{-1} (a) oraz mikrostruktura pojedynczej warstwy faz międzymetalicznych

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The deformation response of the laminated composite was in accordance with the model presented in Figure 4b. In practice, isostrain behavior is approached when individual component layers are thin, bonding between layers enforces uniform deformation and a strain rate is low enough [23]. The used deformation temperature (800°C) was the transition temperature where the α+β-duplex microstructure of aluminum bronze changes into one phase β microstructure (Fig. 1). Previous studies have shown that aluminum bronze at 800°C is very ductile and even may be superplastic when its grains are small enough [24]. Greenwood and Johnson [25] proposed a widely accepted model of transformation superplasticity which has no grain-size requirement because it relies on the biasing of internal stresses produced by cyclical phase transformation. 800°C (to be precise in the temperature range of 795 and 805°C, because the measured temperature changed in time) was the transformation temperature $\alpha \rightarrow \beta$.

CONCLUSIONS

The results showed that the deformation temperature and strain rate are responsible for the evolution of deformation during the isothermal compression of laminated CuAl10Fe3Mn2-intermetallic composites.

1. At 20°C the composites, regardless of the strain rate, fail due to cracking and fragmentation of the intermetallic layers, which is followed by extensive shear banding in the bronze layers.
2. At 600°C composites, also irrespective of the strain rate, deform due to fragmentation of the intermetallic layers but the layers of bronze deform and recrystallize dynamically. During deformation the intermetallic layers convert into bands of separated particles.
3. At 800°C the deformation mode of the bronze-intermetallic composite depends on the strain rate. The strain rate of $2.9{\cdot}10^{-3}$ s^{-1} is too high and some layers of intermetallics crack longitudinally and also cavities appear inside them. At the strain rate of $1{\cdot}10^{-3}$ s^{-1} the composite shows isostrain behavior and all the layers deform together without evidence of any cracks or large cavities in the intermetallic layers.

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