Deformation mechanisms in copper-intermetallic layered composite at elevated temperatures

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Abstract

This article is mainly devoted to examination of the structure evolution in the course of straining of the copper-intermetallic phases layered composite at temperatures of 20–700 °C. Investigations of the slip lines distribution obtained in a tensile test specimen revealed that shear banding was the essential feature of the composite deformation up to 300 °C. Microstructural observations of specimens tested in the range 400–600 °C revealed that intermetallic layers of the composite still cracked brittly but copper recrystallized dynamically, especially between opposite cracks. No cracks in intermetallics were observed after deformation at 700 °C. Mechanical tests showed that up to 600 °C the yield strength for layered copper-intermetallics composites changes inconsiderably (only about 10 %).

K e y w o r d s: copper, layered composite, intermetallic phases

1. Introduction

Intermetallics are phases formed from constituent metals and their crystal structures and their properties are different from individual metals. As a distinct class of materials, intermetallics have high stiffness, high resistance to oxidation and corrosion, high melting point and relatively low density [1]. Metal-intermetallic composites are very attractive for structural applications and many techniques have been proposed to process them [1, 2]. A number of diverse brittle intermetallics-ductile metal laminates have been produced in the way of intermetallic compounds synthesis at the interface between foils: Ni and Al, Fe and Al [3], Ti and Al [3, 4] or Ti3Al2.5V and Al [5, 6]. This technique has been also recently used to produce a copper-intermetallic layered composite [7]. The composite consisting of copper layers partitioned by layers of polyphase structure, containing mainly Cu_4Ti intermetallic compound, offers very attractive combination of electrical conductivity and wear resistance [8, 9]. Many researchers have focused on the deformation mechanisms and the fracture behaviour of the metal-intermetallic laminates concerns mainly the Ti-intermetallic composites [3, 4, 10–12] and Nb-intermetallics composites [13–15]. Unfortunately, most intermetallics exhibit brittle fracture and low tensile ductility, because of limited dislocation mobility and insufficient number of slip systems. On the other hand, intermetallics have a good high-temperature strength and creep resistance [16–18]. Previous works [19] have investigated the strain behaviour of the copper-intermetallic layered composite deformed at room temperature, and elucidated its mechanism of damage evolution. This contribution is mainly concerned with investigations of strain behaviour during tensile tests at elevated temperatures.

2. Experimental procedure

For a composite fabrication titanium foils (containing 99.1 % Ti) 0.1 mm thick were alternatively stacked between copper (99.99 % Cu) sheets of 0.7 mm thickness. The "sandwich" was placed in a vacuum furnace. Pressure of 5 MPa that was used to ensure a good bonding between copper and titanium layers was released at temperature of 850 °C. After

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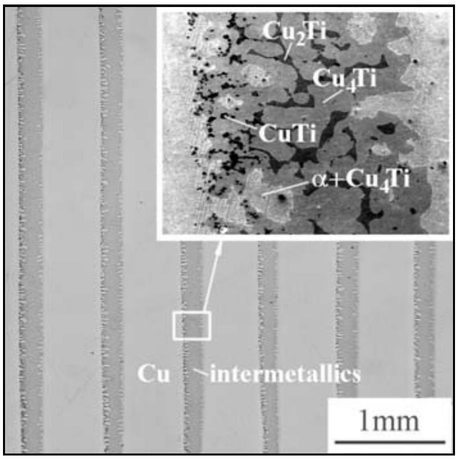

Fig. 1. Microstructure of the Cu-intermetallic phases layered composite.

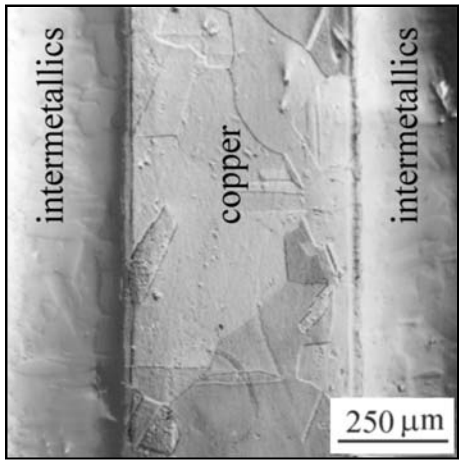

Fig. 2. Lateral wall of a copper-intermetallic phases composite as-prepared and polished.

holding at temperature of 890 ℃ for 10 minutes the samples – sandwiches were furnace-cooled till room temperature. As a result of reaction with the liquid phase contribution all titanium has been fully consumed and transformed together with part of copper sheets into a structure composed of several intermetallic phases, analysed formerly [8], mainly: Cu_4Ti and also Cu_2Ti, CuTi and solid solution titanium in copper (α). Products of high temperature reactions assumed shape of the layers (Fig. 1). Detailed information concerning the synthesis of copper-intermetallic layered composite has been published previously [7].

The tension tests were conducted at temperatures of 20, 100, 200, 300, 400, 500, 600, and 700 ℃ on an INSTRON screw machine with a mounted pipe furnace at the strain rate of 2.77×10^{-3} s^{-1}. Samples 3 mm × 8 mm × 50 mm were made from fabricated composite and from copper (for comparison). Deformation of the composite includes strain processes that take place in the metallurgically bonded layers of opposite properties: ductile copper and brittle intermetallics. Therefore a special attention has been paid to the study of the stress/strain transmission across copper--intermetallic interface. Optical microscopy was used to investigate the topography of the lateral walls of specimens (perpendicular to composite layers). Specimens tested at temperatures of 20, 100 and 200 ℃ before straining were carefully mechanically polished initially with a grade 800 abrasive paper and finally using Struers polishing machine, and subsequently etched. Etching was performed with solution of 40 g CrO_3 – 7.5 g NH_4Cl – 8 ml H_2SO_4 – 50 ml HNO_3 – 19 ml H_2O to reveal the copper grain boundaries. Slip traces produced during deformation were observed using Nomarski contrast. Since specimens tested at temperatures of 300–700 ℃ oxidized, they were polished and etched after testing.

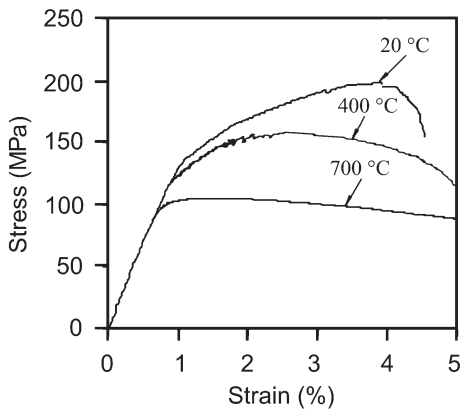

Fig. 3. The stress-strain curves for composites tested at temperatures of 20, 400 and 700 ℃.

3. Results and discussion

Figure 2 shows a picture of the lateral wall of a specimen prepared for the study of the deformation process during the tensile test of a composite. Etching was performed carefully to reveal only copper grain boundary, remaining layers of intermetallics.

The quasi-static stress-strain curves for the composites tested at temperatures of 20, 400 and 700 ℃ are shown in Fig. 3, whereas the results of all specimens (composites and comparatively copper) are depicted in Figs. 4 and 5.

Results of tensile tests at elevated temperatures show that up to 600 ℃ the yield strength for layered composite changes inconsiderably (less than 10 %) while tensile strength decreases gradually with an increase of the test temperature. Just at the temperature of 700 ℃ the yield strength decreases rapidly. This demeanour is typical of many previously investigated layered composites [4, 20–24]. In one of the

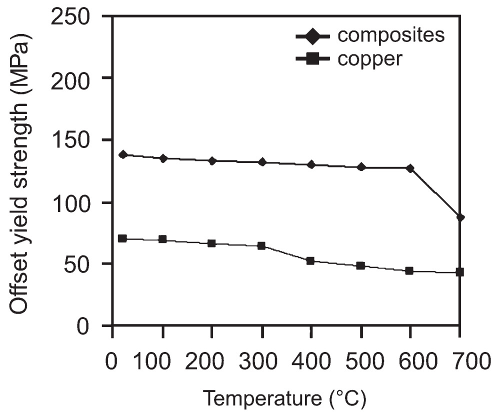

Fig. 4. Offset yield strength vs. temperature for composites and copper.

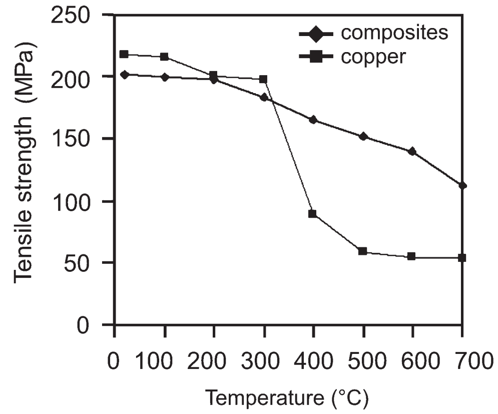

Fig. 5. Tensile strength vs. temperature for composites and copper.

few published studies, Alman et al. [20] examined a tensile behaviour of Ni-Ni_2Al_3 composites at elevated temperatures. They found that the tensile properties of Ni-Ni_2Al_3 layered composites decreased rapidly at temperature of 650 ℃. Jacob et al. [4], Li et al. [12] and Venkateswara Rao et al. [23] obtained remarkably similar results during an investigation of Ti-Al-based metal-intermetallic laminates and found the brittle-to--ductile transition temperature at about 800 ℃. Similar results were reported by Van Heerden et al. [21]

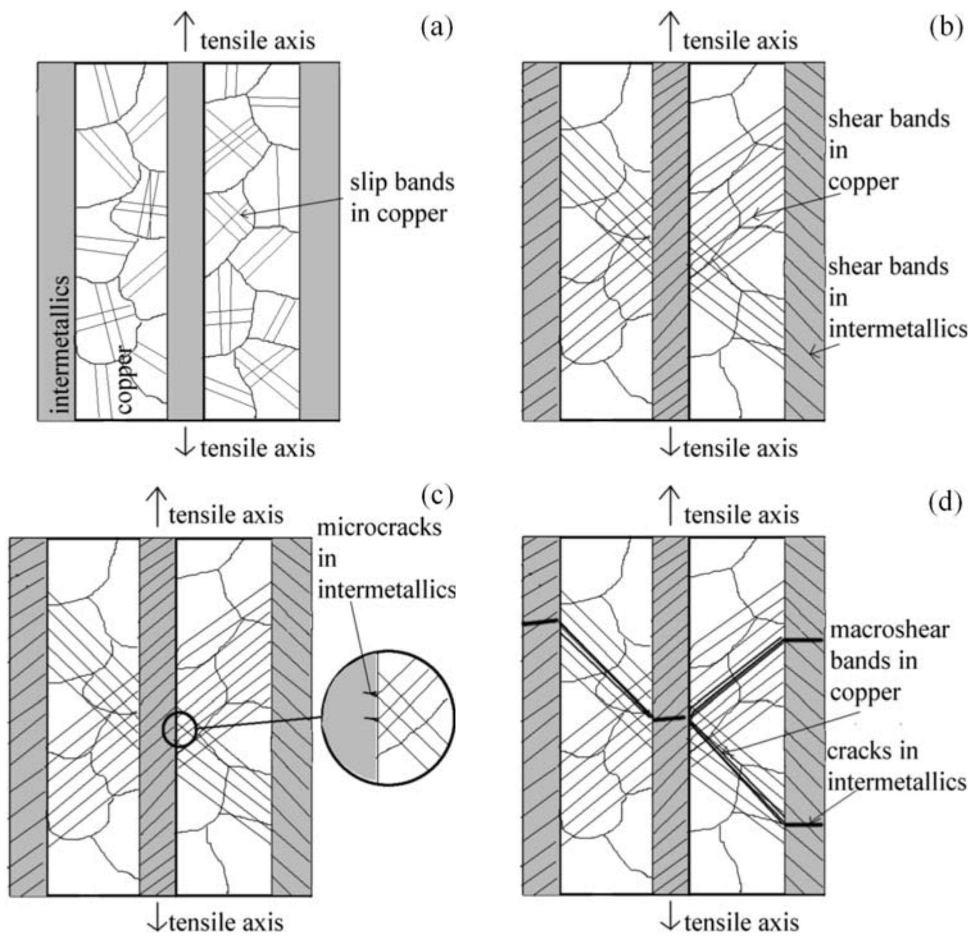

Fig. 6. The diagram of composite deformation stages (a), (b), (c) and (d) during tensile test in the range 20–300 ℃.

(Nb/Nb_5Si_3 laminates), Yang [22] (NiAl-Cr composites) and Rudnitskii [24] (Ti-Nb-based layered composites).

Copper samples deformed in the range of 20–700 ℃ have a different behaviour. At temperatures above 0.4 of the melting point the dynamic recrystallization occurs [25]. Therefore the yield strength and tensile strength of copper at temperatures above 300 ℃ decrease very rapidly.

The structure evolution in the course of straining of the copper-intermetallic phases layered composite at elevated temperatures has been investigated. Up to 300 ℃ examination of the slip lines distribution obtained in a tensile tested specimen revealed that the shear banding was the essential feature of the composite deformation. At the early stage of the plastic strain, copper grains of composite were deformed by the multiple slip (Fig. 6a). With increase of the load, bands of localized deformation in the copper and in the intermetallic phases layers were observed (Fig. 6b). Subsequently cracks appeared in the layers of intermetallic phases of the composite (Fig. 6c). Cracking of intermetallic layers in turn involves a shear deformation of the copper layers that is localized in the spacing between opposite cracks (Fig. 6d). Localized deformation of the copper layers was prolonged till the composite's failure. Alman et al. [20] obtained similar results and found that the fracture behaviour of the Ni-Ni_2Al_3 layered composites was similar from room temperature to 600 ℃, with the Ni layers rupturing in a ductile manner after bridging many cracks in the Ni_2Al_3 layers. Deformation of the metal layer of the metal-intermetallic phase composites due to shear band formation was reported by Rohatki et al. [11], Bloyer et al. [14] and Pickard et al. [15] in earlier papers. The authors stated that shear deformation was initiated by cracking in the brittle layers of the composites. It should be added that the copper-intermetallics composite exhibits a good cohesion between copper layers and layers of intermetallic phases during tensile test (Fig. 7).

In the temperature range 400–600 ℃ strain behaviour of the composite was different. Layers of intermetallics still cracked brittly but deformed copper recrystallized dynamically. The structure evolution is characterized by the formation of deformation-induced dislocation boundaries followed by new grain development in copper at high strains, especially in regions between opposite cracks in the neighbouring layers of intermetallic phases (Fig. 8). Belyakow et al. [25], Mori et al. [26] and Nakayama et al. [27] have clarified the mechanisms of structure evolution in deformed copper.

For the highest temperature of tensile tests (700 ℃) a failure of the tested sample was not followed by cracking of intermetallics layers, whereas elongation increased about two times in comparison to the

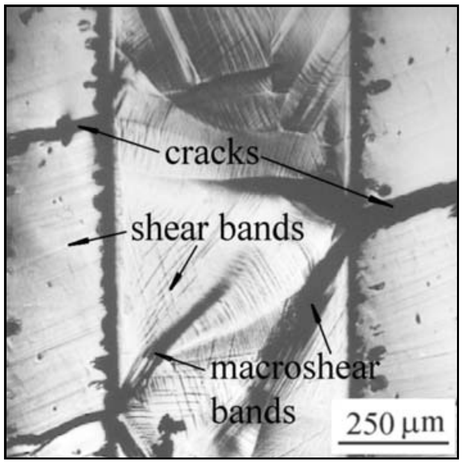

Fig. 7. Typical structure of the composite after deformation at temperatures up to 300 ℃.

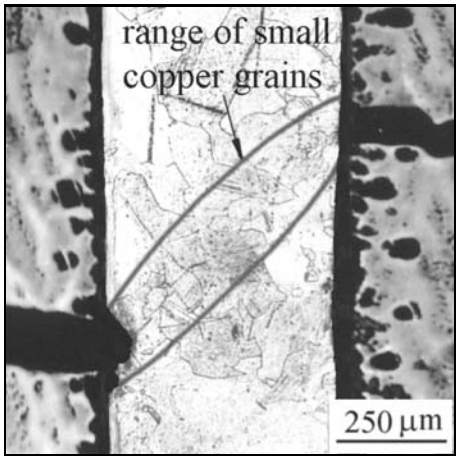

Fig. 8. Microstructure of the Cu-intermetallic phases composite after deformation at 500 ℃.

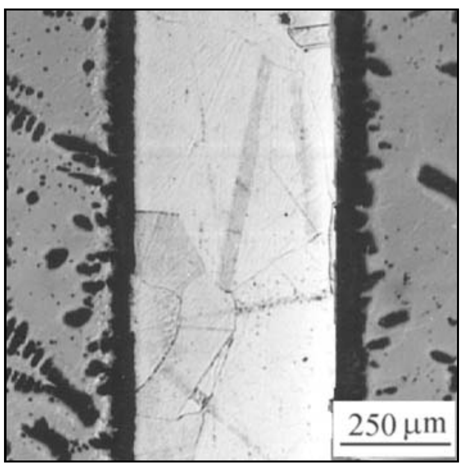

Fig. 9. Microstructure of the composite after deformation at 700 ℃.

samples tested at room temperature (Fig. 9). It was caused by plasticization of intermetallic phases. Also copper grains grew considerably in the process of grain coarsening.

4. Conclusions

The principal results of this study can be summarized as follows:

1. Examinations of the slip lines distribution obtained at temperatures up to 300 ℃ in a tensile test specimen reveal that shear bending is the essential feature of the composite deformation.

2. In the temperature range of 400–600 ℃ intermetallic layers of the composite crack brittly but copper recrystallizes dynamically, especially between opposite cracks.

3. Up to 600 ℃, the yield strength for layered composite changes inconsiderably while tensile strength decreases gradually with increase of temperature.

4. At temperature of 700 ℃, the yield strength for layered composite decreases rapidly what is caused by plasticization of intermetallic phases.

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