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Bending Strength and Fracture Investigations of Cu Based Composite Materials Strengthened with δ-Alumina Fibres

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Abstract

Bending strength, thermal and electric conductivity and microstructure examinations of Cu based composite materials reinforced with Saffil alumina fibres are presented. Materials were produced by squeeze casting method applying the designed device and specially elaborated production parameters. Applying infiltration pressure of 90MPa and suitable temperature parameters provided manufacturing of copper based composite materials strengthened with Saffil alumina fibres characterized by the low rest porosity and good fibre-matrix interface. Three point bending tests at temperatures of 25, 100 and 300ºC were performed on specimens reinforced with 10, 15 and 20% of Saffil fibres. Introduced reinforcement effected on the relatively high bending strengths at elevated temperatures. In relation to unreinforced Cu casting strength of composite material Cu – 15vol.% Saffil fibres increase by about 25%, whereas at the highest applied test temperature of 300^{o}C the improvement was almost 100%. Fibres by strengthening of the copper matrix and by transferring loads from the matrix reduce its plastic deformation and hinder the micro-crack developed during bending tests. Decreasing of thermal and electrical conductivity of Cu after incorporating fibres in the matrix are relatively small and these properties can be acceptable for electric and thermal applications.

Keywords: Metal matrix composites, Copper, δ-alumina fibres, Squeeze casting, Bending strength.

1. Introduction

Metal matrix composite materials MMC are commonly applied in automotive and aerospace industries as the light weight materials characterized by the good mechanical properties, high stiffness and good wear resistance [1-4]. Manufacturing involving powder metallurgy or casting methods is constantly developed providing new materials with unique properties. Usually light alloys (Al, Mg) are reinforced with ceramic particles or fibre preforms. Recently pressure infiltration as a low cost, efficient and fast method are frequently used for reinforcing castings in the most loaded regions. Among them squeeze casting as industry method can be easy adopted for production of composite materials characterised with low porosity, fine microstructure and good mechanical properties [5-7]. Though to infiltrate porous preform with Cu alloys new process parameters and construction of the mould should be elaborated to overcome problems with high temperature and rapid solidification of metal.

Copper based composite materials can be very interesting for the practical applications due to their high thermal and electrical conductivity, good corrosion resistance good wear resistance at reasonable costs. Therefore potential applications can be found in production of electrical components such as sliding electrical contacts, pantograph linings, transfer switches etc. [8,9]. Furthermore, some automotive parts like brake disc can utilize copper based composite materials to reduce temperature of sliding contact and stabilize friction coefficient.

In this work squeeze casting as a novel method for Cu based composite materials production was elaborated and new process parameters and design of mould applied. Produced composite materials exhibited low porosity, homogeneous structure and good bonding at the fibre-matrix interface. Reinforcing of plastic Cu improve bending strength in the wide temperature range and simultaneously slightly reduce thermal and electrical conductivity.

2. Experimental methods

Manufacturing of composite materials includes preparation of porous ceramic preforms and next their infiltration with molten copper. Preforms were produced from Saffil ceramic fibres (3-5μm diameter) containing of 96 - 97% Al_2O_3 - δ and 3-4% of SiO_2. Silica constrains aluminium oxide grain growth at higher temperatures. Fibres were mixed in aqueous solution of the silica binder, next formed, dried and fired at 950°C to create strong joints between fibres and durability for pressure infiltration. Preforms exhibit a skeleton structure, with a randomly arranged fibres in layers. Preforms of 80, 85 and 90% of porosity were infiltrated under the pressure of 90MPa by means of direct squeeze casting.

Rectangular specimens of 55x10x10 mm from manufactured composite materials were examined at 20, 100 and 300°C temperatures applying the three point bending tester at Tinius Olsen H25KT testing machine.

3. Results and discussion

3.1. Microstructure

The microstructure of the bended specimens in the vicinity of fracture at the both opposite sides subjected to tensile and compressive stresses was investigated. Crack development at ambient temperature passes through unreinforced Cu and depending on the orientation of reinforcement along the fibre-matrix interface. Before the crack appears at the side which is subjected to tensile stresses, (opposite to that where point load was applied), fibres subjected to tensile stress break into small segments, see Fig.1a. In such state they transfer small loads and mainly prevent from the plastic deformation of the matrix. There was no pulling out of fibres fragments from the matrix what may indicate that they effectively inhibit development of cracks and improve the bending strength, see Fig.1b.

With increase of testing temperature copper matrix was plastically deformed and cracking of fibres were more visible. In vicinity of the fracture the fibres were arranged along direction of the stresses or at a slight angle break most often in areas where eutectic oxides segregated, see Fig. 2 with places marked by arrows. It can be ascertained that the eutectic is characterized by a low yield and in strongly deformed matrix fibres are subjected to the largest loads. In research of oxide layers [8], it was found that the strength of Cu/Al_2O_3 interface is higher than Cu_2O/Cu. Moreover at higher oxygen concentration Cu_2O oxide is reduced and released O_2 gas which segregates at the interface what finally resulted in microporosity, effecting on the lower load transfer from the matrix to ceramic fibres.

a)

b)

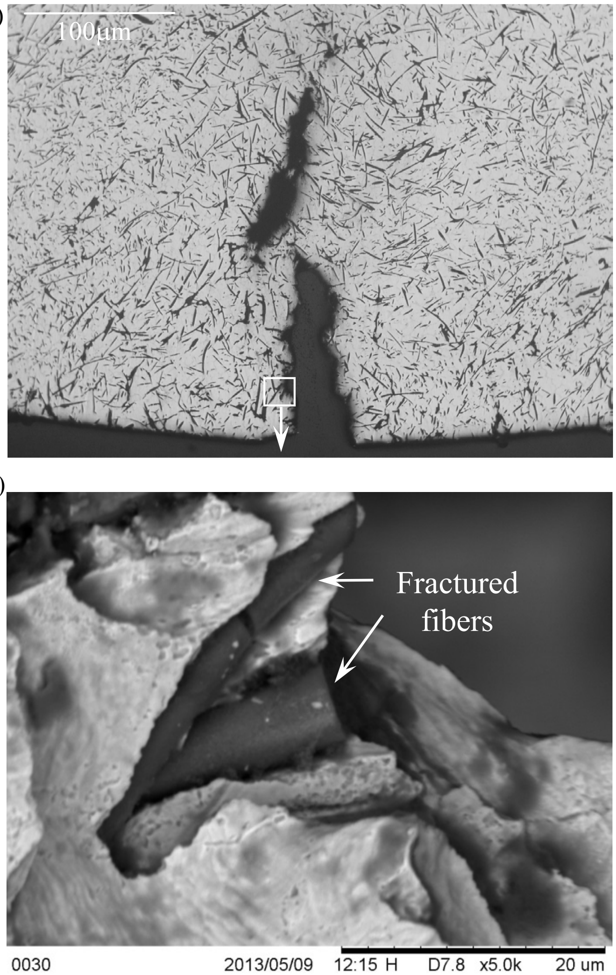

Fig.1 Microstructure of composite materials Cu-10vol. % Saffil fibres after bending test at 20°C. Crack propagated at the side where tension stresses were created (a), fracture with broken fibers in area marked in a subsection (b)

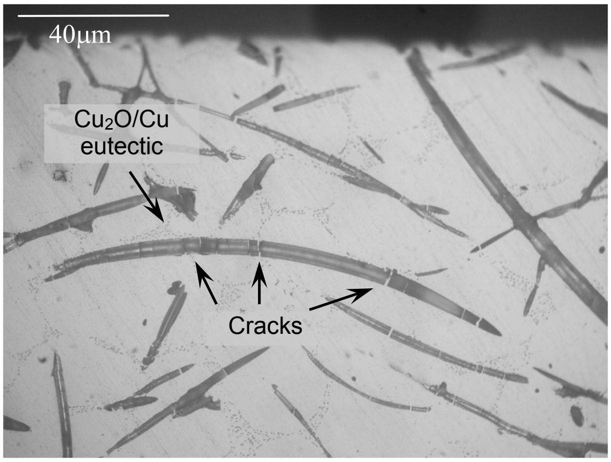

Fig.2. Microstructure of Cu-10 vol.% Saffil fibres composite materials examined at 300°C with fragmented fibres subjected to tension stresses.

It can be confirmed, especially in specimens bended at 300°C, that the smooth, rounded fracture surface is formed, mainly according to the outline of the dendrite arms. Crack propagates through eutectic and under stresses destroyed fibres, see Fig. 3.

It can be concluded that beside local structure defects occurred in the vicinity of the interface and imperfectly wetted fibres, poor oxide eutectic is the major factor weakening the structure and inefficient stress transfer to the fibres.

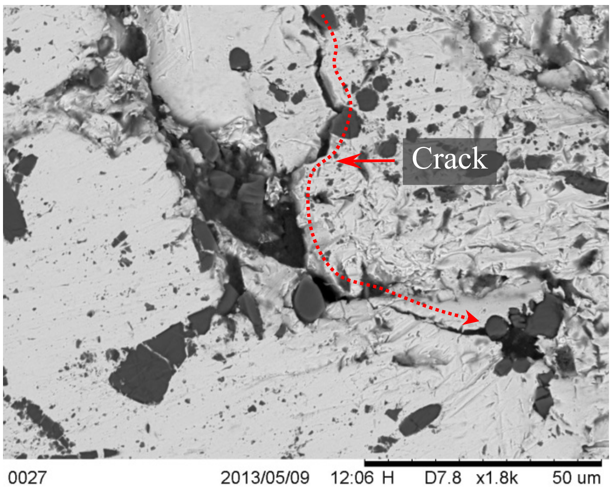

Fig.3. Microstructure of composite material Cu-10 vol.% Saffil after bending in fractured region with propagation of crack thorough Cu matrix between Al_2O_3 fibres.

In this work for production of ceramic preforms silica based binder was used. Therefore fibres, which contain about 4% of silica as a protection against grains coarsening at high temperatures, are covered with thin, 50-100nm, layer of SiO_2, see Fig.4. Binder forming small bridges between separate fibres after firing produces strong preform required for pressure infiltration. Properties of manufactured preforms were investigated and for the preforms from Saffil fibres with 85% of open porosity the hardness T_c = 93, mean bending strength R_g = 3.6 MPa, and tensile strength R_m = 5.1 MPa were achieved. Investigations of preform strength have shown that fracture develop rather with crack of fibres than of binder joints. Thus quantity of binder can be reduced to necessary small volume, because it tends to react with Cu at the interface.

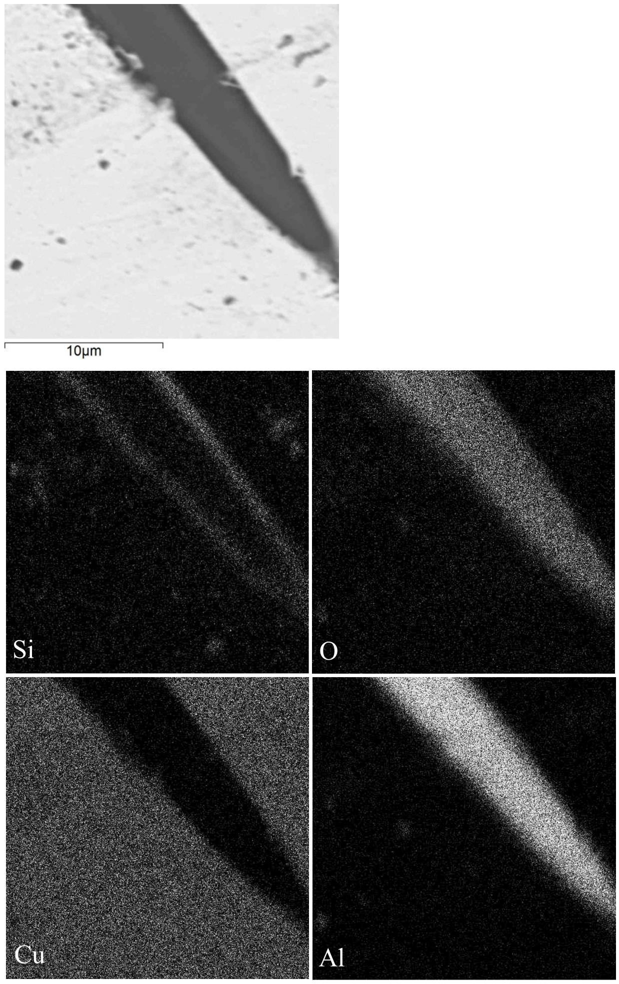

Fig. 4. Alumina fiber embedded in Cu matrix with mapping of Si, O, Cu and Al and elements

During infiltration binder layer can be decomposed and released oxygen react with Cu forming Cu_2O. Therefore at the fibre-matrix interface layer of SiO_2 and CuO_2 with amorphous Si can be found, see Fig.5b. Occasionally on fibre surface higher concentration of Na and O as line analysis indicates, can be found, see Fig.5c. This indicates formation of compound Na_2CO_3, which originates from reaction of binder with carbon dioxide during firing of preform.

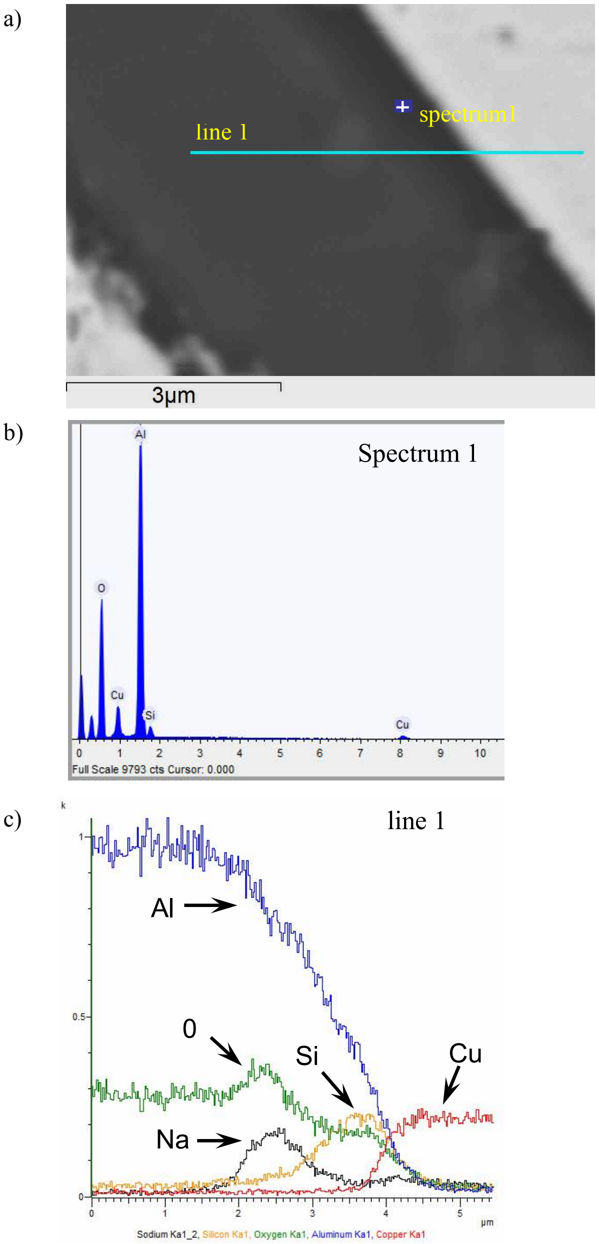

Fig. 5. Fiber-matrix area with marked point and line of EDS analysis (a), point analysis of the interface (b), line distribution of Al, O, Si, Na and Cu elements (c)

3.1. Bending strength

Strength of unreinforced copper (squeeze cast at the same conditions) decreased from about 280 to 160 MPa in 25-300°C temperature range, see Fig.6. Reinforcing with fibres significantly inhibits this drop and improve bending strength even at high temperature of 300°C. Composite materials with 10-15vol.% of fibres exhibit higher bending strength, comparing to unreinforced copper, by ca. 25% at ambient temperature and almost 100% at 300°C. Composite material reinforced with 20 vol.% of Saffil fibres shows worse bending strength than materials strengthened with 10 vol.% and 15 vol.% of fibres, however, improvement is comparing to unreinforced copper is clear although taking into account the good wear resistance of this material [10] its practical application id forseen. Probably higher volume of reinforcement causes larger number of microstructure defect and increase the composite brittleness. During bending tests at the side of the specimen with prevalent tension stresses, fibres are strongly loaded and cracked mainly in region under point probe of tester. Next fracture develops rapidly thorough entire specimen destroying almost untouched fibres. Therefore at the beginning only small number of fibres located in those areas, oriented perpendicularly to thevfracture, transferred stresses and restrained damage of composite materials.

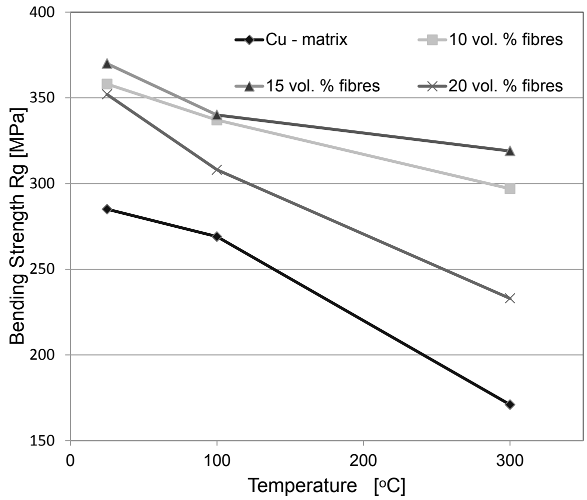

Fig. 6. Bending strength of unreinforced and copper based composite materials strengthened with 10, 15 and 20% of alumina fibers.

Produced Cu based composite materials exhibited also good hardness and relatively sufficient electrical and thermal conductivity, see Table 2. It is very important for potential application in electric devices, contacts, switches etc. With increase of fibre content to 10 and 20 vol.% electrical conductivity is reduced to 78 and 68 IACS (International Annealed Copper Standard).

Table 2.
Hardness, electrical and thermal conductivity of composite copper based materials [11]

Material	Hardness [HB]	Electrical Cond. IACS [%]	Thermal Cond. [W/m*K]
Cu - matrix	65	99	384
Cu+10 %	102	78	342
Cu+15 %	108	72	321
Cu+20 %	112	68	279

Regardless of this reduction in electrical conductivity these materials are still appropriate for electric application, when according to standards it should be higher than 50% IACS. Average values for aluminum alloys are of 25-35% whereas for copper alloys like bronze of 5-15% and brass of 30-60% IACS.

Summary

1. Cu based composite materials strengthened with Saffil fibres manufactured by squeeze casting exhibit uniform distribution of reinforcements, low porosity and good adhesion at the fibre-matrix interface. Silica binder used for preform production covers fires and during infiltration can be decomposed releasing oxygen to form Cu_2O.
2. Alumina Saffil fibres transfer tension stresses in bended specimen but at high plastic deformations of composite samples are fragmented. Fracture starts at weakened fibres, interface or local defects and develop in similar way in all specimens examined at different temperatures.
3. No pull-out effect of fibres at the fracture surface was observed what confirmed good bonding at the interface matrix-reinforcement. At the interfaces formation of Cu_2O-SiO_2 oxides can be ascertained.
4. With increase of test temperature bending strength of unreinforced Cu drops from 280 to 160 MPa. Reinforcement significantly inhibits this reduction of bending strength at elevated temperatures.
5. The largest bending strength was measured for a composite material containing 15% vol. of alumina Saffil fibres. At ambient temperature improvement was about 25% and at temperature of 300°C almost 100%.
6. Reinforcing Cu with Al_2O_3 fibres reduces thermal and electrical conductivity. Decreasing is relatively small (for Cu-15vol.% of Al_2O_3 Saffil fibres composite electrical conductivity is 72% IACS) and this conductivity is acceptable for potential applications.

Acknowledgment

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