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Building metallurgical bonding interfaces in an immiscible Mo/Cu system by irradiation damage alloying (IDA)

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ABSTRACT

For the immiscible Mo/Cu system with a positive heat of mixing ($\Delta H_m > 0$), building metallurgical bonding interfaces directly between immiscible Mo and Cu and preparing Mo/Cu laminar metal matrix composites (LMMCs) are very difficult. To solve the problem, a new alloying method for immiscible systems, which is named as irradiation damage alloying (IDA), is presented in this paper. The IDA primarily consists of three steps. Firstly, Mo is damaged by irradiation with multi-energy (186, 62 keV) Cu ion beams at a dose of 2×10^{17} ions/cm². Secondly, Cu layers are superimposed on the surfaces of the irradiation-damaged Mo to obtain Mo/Cu laminated specimens. Thirdly, the irradiation damage induces the diffusion alloying between Mo and Cu when the laminated specimens are annealed at 950 °C in a protective atmosphere. Through IDA, Mo/Cu LMMC are prepared in this paper. The tensile tests carried out for the Mo/Cu LMMC specimens show that the Mo/Cu interfaces constructed via IDA have high normal and shear strengths. Additionally, the microstructure of the Mo/Cu interface is characterized by High Resolution Transmission Electron Microscopy (HRTEM), X-ray diffraction (XRD) and Energy Dispersive X-ray (EDX) attached in HRTEM. The microscopic characterization results show that the expectant diffusion between Mo and Cu occurs through the irradiation damage during the process of IDA. Thus a Mo/Cu metallurgical bonding interface successfully forms. Moreover, the microscopic test results show that the Mo/Cu metallurgical interface is mainly constituted of crystalline phases with twisted and tangled lattices, and amorphous phase is not observed. Finally, based on the positron annihilation spectroscopy (PAS) and HRTEM results, the diffusion mechanism of IDA is discussed and determined to be vacancy assisted diffusion.

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1. Introduction

Mo/Cu laminated metal matrix composites (LMMCs) can be used in many fields due to their excellent properties including high thermal conductivity, low coefficient of thermal expansion and high temp-resistance. For example, the Mo/Cu composites are used in electronics industry and nuclear reactor, which include heat sink material in high power semiconductor, ceramic sealing material, high current-carrying contacts and the diverter for fusion reactors [1–3]. However, Mo and Cu are essentially immiscible with each other in liquid or solid states, and there is also no intermediate phase according to the equilibrium phase diagram [4]. Besides, both metals Mo and Cu have extremely different melting points (2620 °C and 1084 °C, respectively), so it is very difficult to realize the alloying directly between them via the conventional techniques.

Many alloying processes, such as rapid solidification [5], ion beam mixing (IBM) [6–8] and mechanical alloying (MA) [9,10], have been used for creating alloys in immiscible alloy systems over the past few decades. In more recent years, mechanical alloying (MA) by severe plastic deformation (SPD), such as accumulative roll bonding (ARB) or high-pressure torsion (HPT) [11–13] has also gained wide acceptance as a versatile means for processing non-equilibrium materials. It needs to be pointed out that these methods mentioned above are more applicable to prepare metal matrix composites made up of immiscible powders and nanoscale thin films.

At present, the Mo/Cu LMMC can be prepared using a metal interlayer [14,15], which will undermine the consistency of the composition and bring some unnecessary performances. For example, the nickel interlayer will bring ferromagnetism [16,17]. The processes suitable to construct directly metallurgical interface and prepare the LMMC based on immiscible metals have not appeared as yet.

To solve the above-mentioned problem, a new alloying method via the irradiation damage caused by ion implantation technology

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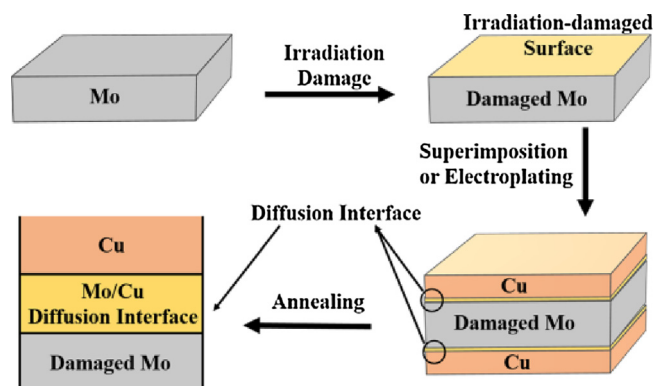


Fig. 1. Schematic chart of the IDA for Mo/Cu LMMCs.

has been used to prepare the Mo/Cu LMMCs in this study. The reasons for the idea can be expressed as follows. Ion implantation can lead to a non-thermal equilibrium status which occurs after high energy ion beam irradiation on the surface of matrix metals [18,19]. For example, severe irradiation damages, which mainly include off-site atoms, lattice distortion, vacancies and dislocations [20], are produced in a crystalline target when a moving ion transfers sufficient energy to a target atom to displace it from its lattice site. So the metal elements on the surface layer may diffuse into the matrix metal through the irradiation damage to form a metallurgical bonding interface between Mo and Cu. The final results in this paper prove the feasibility of this new alloying method. Since irradiation damage plays a prominent part in the alloying, the new alloying method is named as IDA.

2. Experimental

The whole process of the IDA, as mentioned previously, was shown in Fig. 1. According to the schematic chart of the IDA presented in Fig. 1, two kinds of Mo/Cu LMMCs specimens were prepared, including plate and bar specimens. The bar specimens of Mo/Cu LMMCs are essentially a kind of Mo/Cu joints. The alloying mechanisms of the Mo/Cu interfaces in the two kinds of specimens were identical. The bar and plate specimens were used for the tensile tests of the normal and shear strengths of the Mo/Cu interfaces constructed through IDA, respectively.

The base materials for the IDA were commercially pure Mo (99.97%) and commercially pure Cu (99.5%). The sizes of the Mo plate, the Mo bar, the Cu plate and the Cu bar were 180 mm × 100 mm × 0.8 mm, ϕ 10 mm × 20 mm, 180 mm × 100 mm × 0.012 mm and ϕ 10 mm × 20 mm, respectively.

Firstly, the surface-pretreatment was carried out for the Mo matrix metals, including chemical cleaning oil, chemical etching and ultrasonic cleaning, successively. Secondly, irradiation-damage in Mo was caused by the ion implantation technique with a metal vapor vacuum arc (MEVVA) implanter, during which multi-energy (186, 62 keV) Cu ions were implanted into the surfaces of Mo plates and the end surfaces of Mo bars. The implanting doses of the Cu ions at energies of 186 and 62 keV were both 2×10^{17} ions/cm². Thirdly, the Cu plates or bars cleaned by ultrasonic were superimposed on the two surfaces of the irradiation-damaged Mo plates or two end faces of the irradiation-damaged Mo bars through the fixtures shown in Fig. 2. It needs to be pointed out that, when the thickness of the Cu plate is very thin, the superimposition of Cu plates on the Mo for the plate specimens can also be replaced by copper electroplating. Lastly, the assembled Mo/Cu laminated specimens were annealed at 950 °C in hydrogen atmosphere for 8 h, during which, the damages (mainly vacancies) induced the diffu-

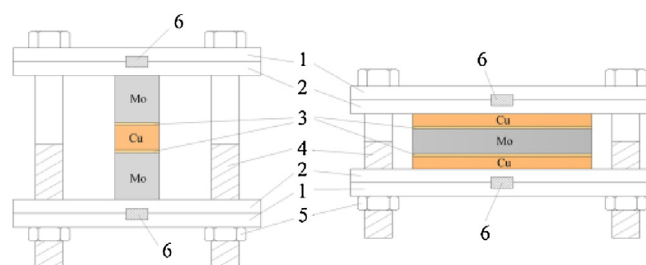


Fig. 2. Schematic diagram of fixtures for the Mo/Cu specimens: (a) fixture for the bar specimen, (b) fixture for the plate specimen. 1-molybdenum plate; 2-quartz plate; 3-damaged surface of Mo; 4-bolt; 5-nut; 6-pressure transducer.

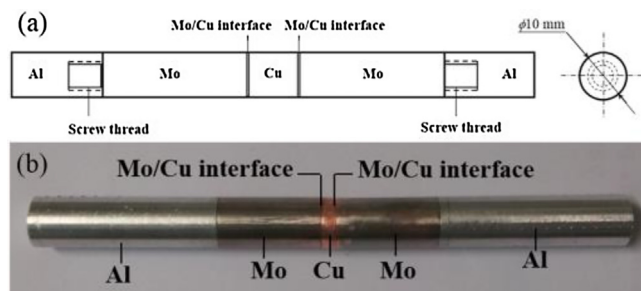


Fig. 3. Tensile specimen for interfacial normal strength test: (a) structure schematic drawing of the bar specimen, (b) digital photo of the bar specimen.

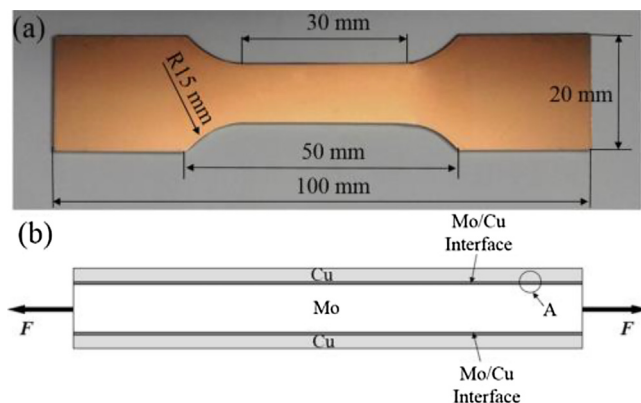


Fig. 4. Tensile specimen for the shear strength test: (a) dumbbell-shaped plate specimen of Mo/Cu LMMCs, (b) section structure of the dumbbell-shaped specimen.

sion between Mo and Cu. When the annealing process finished, the bar and plate specimens of Mo/Cu LMMCs were obtained.

The normal strength tests of the Mo/Cu interfaces constructed via IDA were carried out on the as-obtained bar specimens of Mo/Cu LMMCs with a tensile test equipment (CSS-44100). Since aluminum was relatively soft and cannot slip in the fixtures of tension machine during the tension process, the bar specimens of Mo/Cu LMMCs were connected with aluminum bars through the internal screw threads machined in the Mo bars and the external screw threads in the Al bars. This design could ensure the smooth progress of the tensile tests of interfacial normal strength. The corresponding structure schematic drawing and the finally obtained tensile specimen were shown in Fig. 3(a) and (b), respectively. Tensile tests were implemented at room temperature, during which the tension rate was 5.0 mm/min. The tensile tests were repeated on the three same specimens and the average interfacial strength was calculated.

The shear strength of the Mo/Cu interfaces constructed via IDA was investigated using tensile tests on the dumbbell-shaped plate specimens of Mo/Cu LMMCs shown in Fig. 4. The tests were carried

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