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Effects of ternary additions on the microstructure and thermal stability of directionally-solidified $MoSi_2/Mo_5Si_3$ eutectic composites

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ABSTRACT

Effects of ternary additions on the microstructure and thermal stability of directionally-solidified $MoSi_2/Mo_5Si_3$ eutectic composites have been studied for twelve different elements (Ti, V, Cr, Fe, Co, Ni, Nb, Ta, W, Ir, B and C) paying special attention to the variation of lattice misfits and interface segregation behavior with ternary additions. Among six elements (type-1: Ti, V, Cr, Nb, Ta and W) with a relatively high solubility in $MoSi_2$ and Mo_5Si_3, Ta and W are found to be beneficial to microstructure refinement. All other six ternary elements (type-2: Fe, Co, Ni, Ir, B and C) with a negligibly low solubility in $MoSi_2$ and Mo_5Si_3 exhibit a strong tendency to segregate on $MoSi_2/Mo_5Si_3$ interfaces, resulting in both microstructure refinement and the modification of the interface morphology.

1. Introduction

In recent years, there is a very strong demand for efficiency improvement of combustion systems for power plants and aircraft engines in order to reduce the consumption of fossil fuels and emission of greenhouse gases. One of the most effective ways to achieve this is to increase the operating temperature of gas turbine combustion systems, which currently achieve thermal efficiency about 40% as stand-alone units and over 60% when combining with steam turbine systems [1,2]. In the latest gas turbine systems with air-cooled turbine blades of Ni-based superalloys, the highest gas inlet temperature reaches to 1600 °C, which is more than 200 °C higher than the melting temperature of the superalloy used [1]. As far as the combustion system relies on the air-cooling of turbine blades, any drastic increase in the operating temperature (and therefore in the thermal efficiency) may not be expected. From this perspective, it is evident that a new class of ultra-high-temperature structural materials that can be used in the severe oxidizing atmosphere at temperatures beyond the maximum operating temperatures of Ni-based superalloys has to be developed. Transition-metal silicides have been considered as promising candidates for replacing Ni-based superalloys mainly because of their high melting temperature mostly more than 2000 °C and expected good oxidation resistance at high temperatures [3–5]. Among various transition-metal silicides, a considerable amount of attention has been paid to $MoSi_2$ with the tetragonal $C11_b$ structure because of its high melting point (2020 °C), excellent high-temperature oxidation resistance and relatively low density [3–9]. Mechanical properties of $MoSi_2$, such as yield strength, fracture toughness and creep properties have been studied with the use of single crystals [7–11] and polycrystals [5,6]. Of particular interest is that in single crystals, plastic flow is possible by dislocation motion even at and below room temperature depending on crystal orientation [7,9,10]. Nevertheless, poor fracture toughness of monolithic $MoSi_2$ around 3 MPa $m^{1/2}$ at room temperature has remained as one of the drawbacks, together with insufficient strength of polycrystals at high temperatures [3–5,9]. Extensive studies have been made to improve these drawbacks in mechanical properties by forming composites with hard ceramics such as SiC, TiC, ZrO_2, TiB_2, Si_3N_4 through powder processing routes [3–5,9,12–14]. Although modest improvement in fracture toughness is reported to achieve by these composites, some of them are reported to suffer from pesting, which is catastrophic oxidation that occurs

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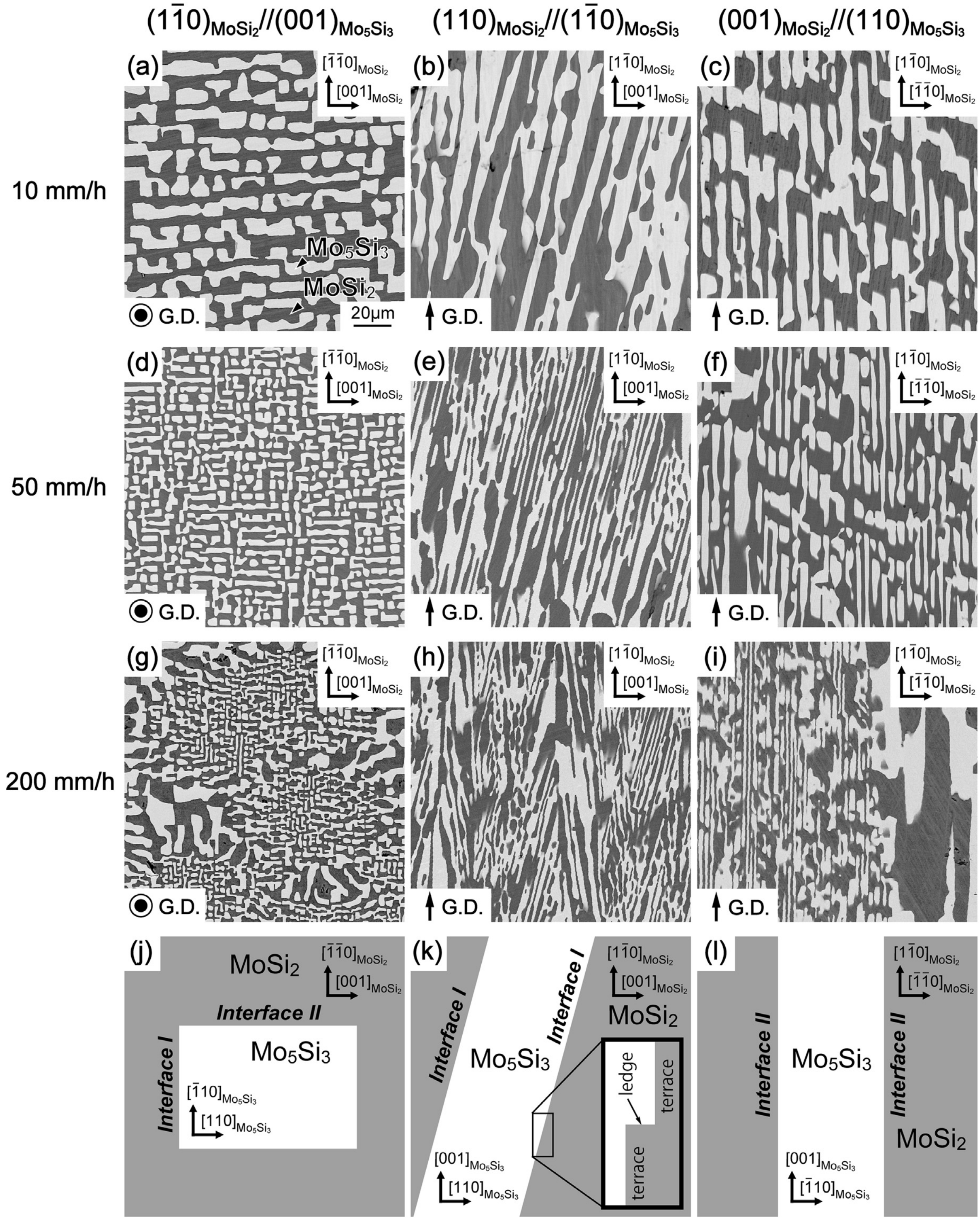

Fig. 1. (a–i) SEM backscattered electron images of three mutually orthogonal sections of DS ingots of binary $MoSi_2/Mo_5Si_3$ eutectic composites grown at growth rates of (a–c) 10 mm/h, (d–f) 50 mm/h and (g–i) 200 mm/h. (j–l) Schematic illustration of two types of interfaces between $MoSi_2$ and Mo_5Si_3 phases in the eutectic composites.

in the temperature range of 400–600 °C especially when they are less dense [3–5,15–18]. Since pesting is known to be suppressed to occur in single crystals of $MoSi_2$ [15,16,18], $MoSi_2$-based single crystalline composites produced by ingot metallurgy routes are considered to have great advantages over polycrystalline composites produced by powder metallurgy routes.

$MoSi_2/Mo_5Si_3$ eutectic composites may be one of the promising candidates because of their high eutectic temperature (1900 °C for the binary alloy) and fine microstructures of the so-called script lamellar type formed simply by directional solidification (DS) [9,13,18–26]. Previous studies on $MoSi_2/Mo_5Si_3$ eutectic composites have revealed that the creep properties are much superior to those of other $MoSi_2$-based composites [21], while fracture toughness at room temperature for DS ingots of binary $MoSi_2/Mo_5Si_3$ eutectic composites is still insufficient [9,13]. In the eutectic script lamellar structure in binary DS ingots, an orientation