Study of the Interaction Between Tensile Properties and Thermal Conductivity of Al-X (X=Si, Mn, Mg) Alloys

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Abstract: In this study, the Al-1-5wt.% X (X=Si, Mn, Mg) alloys were prepared by permanent mold casting, in order to study the relationship between the mechanical properties and thermal conductivity of the alloys. The micro-structures and the phases compositions of the alloys were characterized by OM, SEM, EDS, and XRD. In addition, the density of electronic states (DOS), elastic constants, and other parameters of several alloys were deeply analyzed by first-principles, which assisted in analyzing the relationship between the mechanical properties of the alloys and their thermal conductivity. The results showed that the microstructure of the alloy was changed with the increase of the content of Si, Mn and Mg elements, producing the effects on the mechanical properties and thermal conductivity of the alloy. Al-Mn alloys showed better mechanical properties than Al-Si and Al-Mg alloys. The thermal conductivity is Al-Mg > Al-Si > Al-Mn. This study reveals an inverse relationship between the reinforcing elements on the mechanical and thermal conductivity of aluminum. It provides a theoretical foundation and experimental basis for the development of aluminum alloy materials with both excellent mechanical and thermal conductivity properties.

Keywords: Aluminum, Alloying elements, Mechanical properties, Thermal conductivity

Introduction

Aluminum alloys have the advantages of low density, high specific strength, and good electrical and thermal conductivity [1, 2]. In recent years, they have gradually replaced copper in power transmission lines and electric vehicle manufacturing. With the continuous advancement of technology and increasing industrial demands, the requirements for the performance of aluminum alloys have become increasingly diverse and stringent [3]. In-depth research into the interaction between the mechanical and thermal conductive properties of aluminum alloys, especially through the regulation of their properties by doping elements, has become a significant topic in the field of materials science.

Existing studies have shown that the impact of solute atoms on the thermal conductivity of aluminum alloys is higher than that of element concentration or secondary phases by one to two orders of magnitude [4]. The fundamental reason is that the addition of solute atoms causes lattice distortion in the aluminum matrix, leading to increased free electron scattering, with different alloying elements causing varying degrees of scattering.

However, the mechanisms by which these doping elements affect the thermal conductivity of aluminum alloys are quite complex, and there has not yet been a systematic study that comprehensively reveals the relationship between mechanical and thermal conductive properties of the alloys. Therefore, this study will utilize a combination of experimental methods and first-principles calculations to investigate the relationship between the thermal conductivity and mechanical properties of aluminum alloys in detail.

Experimental procedure

Al-Si, Al-Mn and Al-Mg alloys were prepared by permanent mold casting. The pure Al and Al-10X (X=Si, Mn, Mg) master alloys are initially placed in a resistance furnace and melted at 790 °C. Once completely melted, the melt was stirred using a graphite rod, and a 1 wt.% covering agent (0.5 wt.% NaCl + 0.5 wt.% KCl) was evenly dispersed over the melt surface. The melt temperature is then adjusted to 760 °C and maintained for 30 min. After insulation, the melt is poured into a preheated metal-type mold at 250 °C to obtain an alloy test bar of Φ18 mm×150 mm. The Al-1-5 wt.% X (X=Si, Mn, Mg) alloys were obtained respectively.

The DK7–725 EDM CNC cutting machine was used to sample the center of the alloy test bar (12.5 mm×12.5 mm× 3mm) for microstructure observation and thermal conductivity testing. The mechanical properties were tested on a WDW-100D electronic universal material testing machine with a tensile rate of 0.5 mm/min and a measurement length of 20 mm. three specimens for each experimental parameter are selected, and the average value is calculated as the final result data. Calculation of material properties by using Materials studio 2023.

Result and discussion

Fig. 1 employs a three-dimensional stress tensor representation to analyze the anisotropy of Al alloys with different doping elements and concentrations. The colors in the figure indicate stress values (GPa), with red

representing high-stress areas and blue representing low-stress areas. The study found that anisotropy significantly increases with the concentration of doped elements. The impact of different doping elements on the mechanical properties of the alloys varies: Si and Mn doping results in high-stress areas mainly concentrated in the Z direction, whereas Mg doping makes the anisotropy more complex, with high-stress areas distributed in multiple directions.

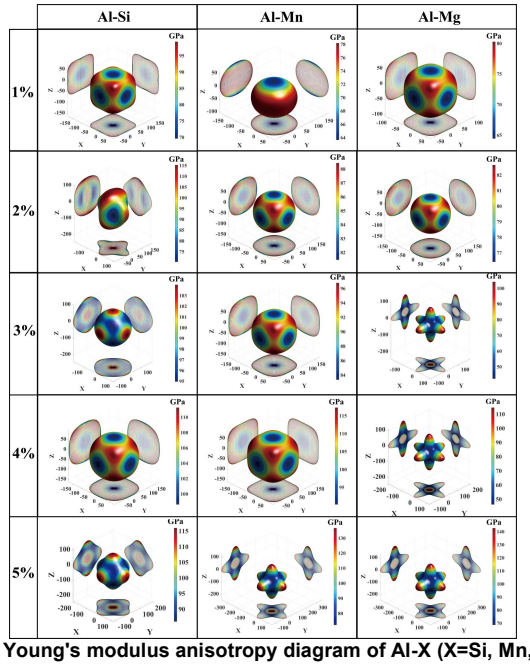

Fig.1 Young's modulus anisotropy diagram of Al-X (X=Si, Mn, Mg)

For the thermal conductivity of alloys, the influence of doping elements is minor at low concentrations, but at high concentrations, due to lattice distortion, formation of secondary phases, and increased phonon scattering, the thermal conductivity significantly decreases. The doping mechanisms of different elements vary, but the main influencing factors include changes in lattice structure, increased phonon scattering centers, and formation of precipitates. In Al-Si alloys, Si phases mainly exist in the form of eutectic Si, while high concentrations of Mn promote the formation of Al_6Mn phases. These second-phase particles not only affect the mechanical properties of the alloy but also significantly reduce the thermal conductivity through interface scattering. Under high Mg doping concentrations, precipitates such as Mg_2Si form within the alloy, reducing its thermal conductivity.

Conclusion

(1)The three elements have varying degrees of impact on the thermal conductivity and mechanical properties of the alloy.

(2)In terms of mechanical properties, Al-Mn alloy exhibits higher mechanical performance than Al-Si alloy, while Al-Mg alloy performs the worst. This experimental result preliminarily demonstrates the inverse relationship between the alloying elements' effect on aluminum's thermal conductivity and mechanical properties.

Acknowledgments

This research is supported by Gansu Provincial Basic Research Program-Natural Science Fund, PR China [Project number: 22JR5RA251].

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