Study on Strength and Toughness Regulation of SiCp/Al Composite for Aerospace Vehicles

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Abstract： Aerospace vehicles face harsh environments such as extreme temperature changes and various load coupling effects during their service in space, which puts forward more stringent requirements for the dimensional stability, strength, plasticity and toughness of their key structural components. Improving the strength and toughness of Aluminum Matrix Composite, breaking the contradiction between strength, plasticity, toughness, and thermal properties, is a key scientific problem in the development of composite. This work focuses on the preparation of medium high volume fraction SiCp/Al composite by powder metallurgy method, and focuses on the strength and toughness regulation strategies of Aluminum Matrix Composite. The regulation methods and influencing laws of factors such as reinforcement types and sizes, aluminum alloy matrix, interface bonding, and heat treatment process are explored, and the interface structure characteristics, matrix microstructure, and second phase evolution law of composite are revealed. The strength and toughness mechanism of composite under the synergistic effect of interface effects and multi-scale second phases is elucidated. The research provides theoretical basis and technical support for the engineering application of lightweight, low expansion, and high-strength Aluminum Matrix Composite.

Keywords: Aluminum Matrix Composite, Interface Bonding, Strength and Toughness Regulation

1 Introduction

In order to meet the special requirements of key structural components of aerospace vehicles in terms of dimensional stability, strength, and plasticity and toughness. Medium to high volume fraction SiCp/Al composite are expected to become substitutes due to their integrated structural and functional properties. However, the addition of SiC improves strength while sacrificing plasticity, which limits its wider application. Finding the optimal balance of strength and plasticity inversion has been a challenging problem in the development of SiCp/Al composites. By optimizing composite components, composite processes, and heat treatment techniques to achieve multi-scale second phase and interface structure control, lightweight, high-strength, and low expansion SiCp/Al composite materials can be developed to meet national needs.

2 Experimental procedure

The composite used in this paper are all prepared by powder metallurgy method. Spherical aluminum alloy powders and irregular 6H–SiC powders were used as raw materials. Pretreated SiC particles (SiCp) were mixed with aluminum alloy powders at different fraction ratio. The mixed powders were ball milled and sintered by vacuum hot pressing sintering furnace. The phase compositions, micro-morphology and elemental distribution were analyzed by XRD, SEM, HAADF-STEM snd EDS. The tensile and compressive properties were tested using a universal testing machine.

The CASTEP quantum mechanics program in Material Studio software was used for all of the first-principles calculations conducted in this study. Different interfacial configurations of $MgAl_2O_4$/Al and $MgAl_2O_4$/SiC low index interface models were constructed. The adhesion properties of the interface were predicted by calculating the interfacial spacing, adhesion work, and interfacial energy for different $MgAl_2O_4$/Al and $MgAl_2O_4$/SiC interface models. The uniaxial tensile tests were conducted on eight different 6H-SiC/Al interface models through the molecular dynamics method(LAMMPS). The deformation of the interface was monitored to obtain the main mechanical property parameters and to explore the dynamic process of atomic migration, stress-strain characteristics, and dislocation interactions.

3 Result and discussion

3.1 Effect of preparation process on the microstructure and properties of composite

For SiC/Al-Si composites, by controlling the sintering temperature, extrusion temperature, and solid solution temperature, the Si phase size can be controlled. Adopting a suitable heat treatment process (500 ℃ solid solution and 180 ℃ aging for 6 hours) can achieve synergistic improvement of strength and plasticity.

3.2 Effect of adding rare earth elements on the microstructure and properties of composite

For SiC/Al-Si composites,the appropriate addition of CeO_2 can achieve a synergistic improvement in strength and plasticity. The addition of rare earth elements inhibits the dissolution, precipitation and growth of Si element, refines the precipitated phase, and forms a rare earth compound strengthening phase.

3.3 Interface characteristics of composite

The SiC/Al-Si and SiC/Al composite prepared by powder metallurgy method have good interfacial bonding. The interfaces of SiC/Al, Si/Al, and SiC/Si are clear, with no obvious interface reactants or defects. The SiC/Al interface is mainly a clean interface, and the interface atoms formed between Si/Al and SiC/Si are matched as a semi coherent interface.

3.4 Effect of interface reaction layer regulation on the microstructure and properties of composite

Moderate interface reaction(Generating $MgAl_2O_4$ phase) is beneficial for improving interface bonding strength. By controlling SiC oxidation and the content of Mg in the matrix, the thickness and coating effect of the $MgAl_2O_4$ layer can be effectively adjusted to change the fracture mode during deformation and achieved a comprehensive improvement in strength and ductility.

3.5 Intrinsic computational simulation and in-situ experimental research on interface properties of composite

First principles calculations indicate that the interfacial bonding strength between SiC and Al is higher than that between atomic layers within the Al matrix. Molecular dynamics calculations indicate that the tensile fracture position at the SiC/Al interface is more likely to occur within the Al matrix near the interface. The TEM in-situ tensile test of the SiC/Al interface micro zone shows that fracture first occurs in the aluminum matrix, and the bonding strength of the SiC/Al interface is higher than that of the aluminum matrix.

4 Conclusion

（1）By regulating the multiple scales second phase, the synergistic improvement strength and plasticity of composite can be achieved. The control technical parameters vary depending on the aluminum alloy matrix.

（2）Moderate interface reaction is beneficial for improving interface bonding strength and enhancing load transfer effect; The combination of SiC oxidation pretreatment and appropriate control of Mg element in the matrix is an effective method for enhancing toughness.

（3）Using the concept of material genetic engineering to carry out material research and development, using first principles, molecular dynamics and other methods, the intrinsic characteristics of composite can be studied in depth at the atomic scale, which plays an important role in the development of composite.

5 Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (51371077, 51771070, 52171138) .

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