Fabrication of Al-W Functionally Graded Impact Material via Vacuum Hot-Pressing Sintering Method

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Abstract Dense graded material as a type of functionally graded material (FGM) changes its wave impedance gradually along the thickness direction. In this investigation, Al-W functionally graded material was fabricated via vacuum hot-pressing sintering method (VHPS). The results showed that densified Al-W composite was fabricated at 550°C-300MPa-120min which the relative density was higher than 98.5% without intermetallic compounds. The density graded material of Al-W FGM was attained at the optimized parameters which the component of Al was from 10% to 100%. The microstructure of Al-W FGM composite indicated that W particles in single-layer composite were distributed homogeneously. The density of each layer in Al-W FGM composite was consistent with the design value.

1. Introduction

Functionally Graded Material is a kind of inhomogeneous composite, and its properties change gradually with structure and components which varies continually or quasi-continually [1-2]. Composites with graded wave impedance can be regarded as a special kind of functionally graded materials (FGMs), which create quasi-isentropic loading to target materials, and have come to show great potential for the application in dynamic high-pressure technology [3-6]. So the composites with graded wave impedance have attracted many attentions of researchers in the world.

Researchers have fabricated the simple binary functionally graded materials by decreasing components of the composites to control concisely the constituent and graded wave impedance variations [6-10]. F. H. Streitz and H. Nguyen [11] et al. have prepared Al-W functionally graded materials by powder metallurgy. The components of Al-W composites changed graded layer by layer and the polymer was added as binder in the composites. However, it was still not binary system because polymer was the third phase in the composites, and there was not research on the mechanism of densification. L. P. Martin [12] et al. have made Mg-W graded file-plates by type-casting to achieve the density quasi-continuous variations which varied from 1.74 g·cm⁻³ to 8.90 g·cm⁻³. By this method, the wave front could be controlled and the correlation between density and acoustic wave impedance was monotonous nearly linear which was consistent with the simulation. Therefore, the composites of Mg-W have achieved quasi-continuous variation for the wave impedance.

In this paper, we aimed to fabricate high densification Al-W composites with different components and Al-W functionally graded material which meets the design requirement. The hot-pressing sintering has been used to prepare Al-W composites with different components. The effects of W contents and processing parameters on the densification of Al-W composites have been
studied to acquire the optimum processing parameters. Al-W functionally graded materials with density gradient have been fabricated successfully, and the structure and constituent of Al-W functionally graded materials have been characterized.

2. Experimental

In the present work, the starting W powders (particle size of 5 μm, purity > 99.9%) were provided by Beijing Nonferrous Metal Research Institute, Al powders (particle size of 6 μm, purity > 99.9%) were provided by Xiamen Golden Egret Special Alloy Co. Ltd. The process was as follows: Al and W powders were weighed, and mixed in air in a shaker-mixer for 12h to produce Al-W powder blend. The long hours milling was to make distribution of the different powders more uniform. After the milling completed, the mixture was cold pressed into 10-mm-diameter and 3-mm-thick green compacts at a pressure of 400 MPa without any lubricant. The compacts were heated up in vacuum hot-pressing sintering furnace.

The density of sintered compacts was measured by the Archimedes principle. The theoretical density of the samples was calculated according to the rule of mixtures. Scanning electron microscopy (SEM, JSM-S3400N) was used to evaluate the microstructure and EDS of Al-W samples. X-ray diffraction (XRD, Ultima III) for phase analysis was collected.

3. Results and discussion

3.1 Effect of sintering temperature on the phase of Al-W composites

Fig. 1 The XRD patterns of Al-W composites sintered at different temperatures and with different W contents

Fig. 1 displays the X-ray patterns of Al-W composites at different sintering temperatures and with different W contents. As shown in Fig. 1 (a), there is only Al and W phase in the Al-W composites without any intermetallic compounds during 400 °C and 550 °C. There are also no obviously changes for the intensity, position and peak width of XRD patterns with sintering temperature increasing. However, when the temperature is excess 560 °C, it appears the intermetallic compounds of Al12W and Al3W diffraction peaks besides Al and W peaks in XRD patterns. And the diffraction peak intensity of Al12W and Al3W increase gradually in contrast to the intensity decreasing of Al and W diffraction peaks with increasing temperature. There is almost no Al phase diffraction peak at 600 °C. So Al is melted from 560 °C from which it forms intermetallic compounds. Because of the brittle of intermetallic compounds, the sintering temperature should be lower than 550 °C to avoid the formation of intermetallic compounds.

Fig. 1 (b) shows the XRD patterns of Al-W composites with different W contents at 550 °C. As it is shown, there is only Al and W phase diffraction peaks in the Al-W composites without any intermetallic compounds. With increasing W contents, the intensity of Al diffraction peak weaken, in
contrast to that, the intensity of W diffraction peak makes stronger. And there is no position shifting or width variation for Al and W phase. It indicates that there is no obviously solid solution or formation of intermetallic compounds between Al and W at 550 °C for different W contents in the Al-W composites.

Therefore, in order to achieve high densified Al-W composites and ensure no formation of intermetallic compounds, the sintering temperature should be below 560 °C. And when the sintering temperature is 550 °C, there is only Al and W phase in the Al-W composites. So the sintering temperature is chosen to 550 °C to acquire densified Al-W composites.

3.2 Fabrication of Al-W functionally graded materials

For the Al-W functionally graded material, the front interface density of $\rho_0$ is the density of Al which is 2.70 g·cm$^{-3}$, the back interface density is 8.652 g·cm$^{-3}$. In this work, the total thickness for Al-W functionally graded material is designed as 3.5 mm, which the single layer thickness is 0.5mm. The processing parameter is 550°C-300MPa-120min.

3.2.1 The microstructure of Al-W functionally graded material

![Fig. 2](image)

**Fig. 2** the microstructures of the Al-W FGMs for each graded layer: (a) 100Al (b) 88.5Al-12.5W (c) 66Al-34.0W (d) 48.6Al-51.4W (e) 36.9Al-63.1W (f) 28.5Al-72.5W (g) 20.0Al-80.0W

Fig. 2 is the microstructure of each layer of Al-W functionally graded material. It can be shown that every layer of Al-W functionally graded material is densified, and Al and W are distributed homogeneously. With layers increasing, the W content increases while the Al content decreases. The first layer is pure Al. The W particles are almost distributed homogeneously in the Al matrix from the second to fourth layers. In the fifth and sixth layers Al and W are both distributed homogeneously, and in the seventh layer W particles are connected tightly and Al is filled into the pores between W particles.

3.2.2 EDS of Al-W density functionally graded material

![Fig. 3](image)

**Fig. 3** the SEM image: (a) and EDS (b) of the Al-W FGMs
Fig. 3 shows the microstructure of Al-W functionally graded material with density gradient and EDS along the gradient direction. From Fig. 3 (a), it can be seen that the Al-W functionally graded material is nearly full-density; there is no obviously pores or any other defects in the composite. What’s more, the transition layer interface is clear and the parallelism is good, which indicate that there is no fracture or dislocation for every layer during the sintering process. From Fig. 3 (b), it can be clearly seen that it appears good gradient variation along the thickness.

4. Conclusion
In this work, Al-W functionally graded material with density gradient is designed and the optimum processing parameters are acquired. And the Al-W functionally graded material which the constituent varies continually is fabricated under the optimum parameters.

1. The relative density of Al-W composites increases with temperature. When sintering temperature is below 550 ºC, only Al and W phase can be detected, however, when sintering temperature exceeds to 550 ºC, there is Al-W intermetallic compounds.

2. The transition layer interface of Al-W functionally graded material is clear and the parallelism is good. The components of Al and W exhibit well gradient distribution. Al-W functionally graded material is near full-density and Al and W particles are distributed homogeneously.

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