The Application of Ti/Al$_2$O$_3$ Composite in W-Mo-Al System Wave Impedance Graded Flier-plate

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Abstract: Ti/Al$_2$O$_3$ composite of different components were prepared by Spark Plasma Sintering technique, mechanical and acoustical properties of Ti/Al$_2$O$_3$ composite were analyzed, weldability of Ti/Al$_2$O$_3$ composite with Mo and Al was also studied. The results indicate that 38.5vol% Ti/Al$_2$O$_3$ composite has good mechanical performance with relative density >99.20%, bending strength 897MPa, fracture toughness 17.38 MPa·m$^{1/2}$ and microhardness 17.13GPa. The wave impedance of the composite was between which of Mo and Al, and the 38.5vol% Ti/Al$_2$O$_3$ welded well with Mo and Ti. These demonstrate that 38.5vol% Ti/Al$_2$O$_3$ composite could serve as one of interlayer materials in W-Mo-Al system graded flier-plate.

1 Introduction

In research fields of astrophysics, geophysics, solid-state physics and inertial confinement nuclear fusion etc, it is necessary to study the dynamic behavior and response characteristics of materials at extremely high pressure (1-2TPa)[1,2]. An important technique, in which a flier-plate is driven to a high velocity to impact on a flat-plate target by two-stage light gas gun[3,4], is widely used for research on dynamic high-pressure physics. So, it is important to design the structure of the flier-plate besides optimizing the super high-speed launch devices. The study shows that wave impedance graded flier-plate, compared with traditional homogeneous flier-plate, can load a nearly isentropic compression to target at a lower temperature when the target is impacted on[5]. Various systems of graded flier-plate were reported recently years[6-10]. However, the study on W-Mo-Ti-Al system flier-plate is difficult because of the bad welding property and dramatic reactions between titanium and aluminum [11], which affect quasi-isentropic compression effect and structure stability of composite both during the impact time and high-speed flying time. So, one proper substituted interlayer material is very important. Ti/Al$_2$O$_3$ composite is considered one of candidates of graded flier-plate interlayer materials due to good mechanical performance and intermediate density between Mo and Al. This article will demonstrate the feasibility of the Ti/Al$_2$O$_3$ composite as the interlayer material of W-Mo-Ti/Al$_2$O$_3$-Al system wave impedance graded flier-plate. In this experiment, Ti/Al$_2$O$_3$ composites were prepared by Spark Plasma Sintering (SPS) technique.
2 Experimental

2.1 Preparation of samples
High purity alumina, titanium and niobium powders were raw materials. The mean particle sizes of the three powders were 1.5µm, 7.76µm and 5.7µm respectively. Different proportions of powders were mixed uniformly as design in Table 1, and then poured them into a graphite mold. The sintering was performed in a spark plasma sintering device (SPS-1050, Sumitomo Coal Mining Co. Ltd. Japan) at 1300°C for 10min with heating rate of 200 °C/min, the applied mechanical pressure was 30MPa. The sizes of samples were Ø32 × 5mm.

| Sample NO. | Ti   | Nb | Al₂O₃ |
|------------|------|----|-------|
| T2         | 18.5 | 1.5| 80    |
| T4         | 38.5 | 1.5| 60    |
| T6         | 58.5 | 2.0| 40    |
| T8         | 78.5 | 2.0| 20    |

2.2 Mechanical property testing
After being polished using 120µm, 80µm, 20µm SiC abrasive and 10µm, 1.5µm diamond paste in turn, samples were incised bars of 26mm × 3mm × 4mm and 26mm × 2mm × 4mm (with incision of 0.2mm width and 1.8mm length). The final densities of samples were determined by the Archimedes method using distilled water. Three-point bending strength and fracture toughness were measured at room temperature using a universal testing machine (INSTRON 5569, USA) with the pressure head down speed of 0.5mm/min and 0.05mm/min, and the supporting span is 20mm. The micro-hardness was measured using a digital micro-hardness tester (HDX-1000) at a load of 1Kg and indentation time of 20s. The Scanning Electron Microscope (SEM, HITACHI S-2500) with Energy Disperse Spectroscopy (EDS, LINKISIS-300) was used to observe the micro structures of sample sections.

2.3 Acoustical properties testing and welding experiment
Ultrasonic pulse-echo method was adopted to measure the shear wave velocity and vertical wave velocity of the composite, the instrument used in this method were Ultrasonic Signal Receiver (Panametrics5072PR) and Oscilloscope (TDS2022). Wave impedance and elasticity mechanical were calculated from shear wave velocity and vertical wave velocity using the equations followed[12]:

\[ C_b^2 = C_i^2 - \frac{4}{3} C_i^2 \]
\[ Z = \rho \cdot C_b \]
\[ K = \rho C_b^2 \]
\[ G = \rho C_i^2 \]
\[ E = \rho C_i^2 \frac{3C_i^2 - 4C_i^2}{C_i^2 - C_b^2} \]
\[ \nu = \frac{C_l^2 - 2C_t^2}{2(C_l^2 - C_t^2)} \]  

(6)

Where \( K \) is bulk modulus, \( G \) is shear modulus, \( E \) is Young modulus and \( \nu \) is Poisson’s ratio.

Diffusion welding method was adopted to test the weldability of Ti/Al\(_2\)O\(_3\) composite with Mo and Al as technological parameters listed in Table 2. And SEM was used to observe the microstructure of weld joints.

### Table 2. Parameters for diffusion welding

| Welding joint | Temperature/°C | pressure/MPa | t/min |
|---------------|----------------|--------------|-------|
| Mo-T4         | 1300           | 5            | 30    |
| Al-T4         | 600            | 5            | 30    |

3 Results and discussion

#### 3.1 Mechanical Properties of Ti/Al\(_2\)O\(_3\) Composite

Table 3 shows that with Ti content increasing, relative densities of Ti/Al\(_2\)O\(_3\) composite increase firstly, then decline slightly, but are all larger than 99.10%; bending stress, fracture toughness and micro-hardness also show trend of rise firstly then decrease with Ti content increasing. This due to that with the metal phase increasing, the combination way of metal phase and ceramic phase and the modification mechanism of second phase to matrix performance change.

### Table 3. Mechanical properties of Samples

| Sample NO. | Relative density/% | Bending stress/MPa | Fracture toughness/MPa\(\cdot\)m\(^{1/2}\) | Micro hardness/GPa |
|------------|--------------------|--------------------|---------------------------------------------|-------------------|
| T2         | >99.10             | 893±60.74          | 10.94±0.80                                  | 19.85±1.64       |
| T4         | >99.20             | 897±49.32          | 17.38±1.07                                  | 17.13±0.82       |
| T6         | >99.20             | 429±37.11          | 9.62±0.68                                   | 12.02±0.77       |
| T8         | >99.15             | 274±22.06          | 5.89±0.54                                   | 11.14±0.79       |

When the Ti content is much higher, it is metal matrix composite. The dispersed Al\(_2\)O\(_3\) particles change the flow stress behavior and limit the deformation of matrix, which make the cracks formation around alumina grain boundaries. These cracks reduce fracture toughness and bending stress of composite. When the Al\(_2\)O\(_3\) phase is major phase, Al\(_2\)O\(_3\) particles are coated by metal thin layer and the interface reaction also improves interfacial energy [13], these make alumina particles connected tightly and transgranular fracture failure appear. Figure 1 shows cross section SEM photos of T2 and T4, where the light part is Al\(_2\)O\(_3\) and the grey is titanium. The photos show that grains grow finely and combine compactly. And from the grain fracture and draw traces on the cross section, the mixed intergranular and transgranular fracture mode can be determined. The transformation of load phase from ceramic to metal with the Ti content increase leads the micro-hardness decline.

#### 3.2 Acoustical and welding Properties of Ti/Al\(_2\)O\(_3\) Composite

Shear wave velocity and vertical wave velocity tested by ultrasonic pulse-echo method and parameters of acoustics and elasticity mechanics calculated are all listed in Table 4.

The data demonstrates that not only the wave impedance value of Ti/Al\(_2\)O\(_3\) composite is in between the higher value of Mo and the lower value of Al, but the mechanical performance of composite is good enough to keep the stability of flier-plate.

From the analysis above, T4 sample is selected to weld with Mo and Al because its good properties and proper wave impedance value. The SEM photo in Fig. 1 shows the welding interface of Mo-T4 is smooth, and the corresponding EDS photos show one thick transition layer in interface area.
Table 4. Parameters of acoustics and elasticity mechanics

|         | Mo[10] | T2    | T4    | T6    | T8    | Al[14] |
|---------|--------|-------|-------|-------|-------|--------|
| ρ/g·cm⁻³ | —      | 4.074 | 4.086 | 4.278 | 4.423 | —      |
| Cₜ/m·s⁻¹ | —      | 5670  | 5203  | 4740  | 4384  | 3133   |
| C₁/m·s⁻¹ | —      | 9856  | 9480  | 8421  | 7767  | 6500   |
| Cb/m·s⁻¹ | 5160   | 7367  | 7333  | 6400  | 5891  | 5400   |
| Z/10⁶kg·m⁻²s⁻¹ | 52.74 | 30.22 | 30.90 | 27.65 | 26.08 | 14.58 |
| E/GPa   | 325    | 330   | 293   | 246   | 216   | 71     |
| G/GPa   | 260    | 132   | 114   | 97    | 85    | 27     |
| K/GPa   | 261    | 223   | 227   | 177   | 154   | 79     |
| ν       | 0.293  | 0.253 | 0.285 | 0.268 | 0.266 | 0.348  |

SEM and EDS photos of T4-Al are shown in Figure 3. The interface is also flat, but the T4 and Al cannot distinguish obviously from SEM photo. The result from two reasons: one is alumina brightener insert in the surface, the other is a few aluminum is oxidized to alumina during polishing; the latter reason is also certified from corresponding EDS photo where aluminum area is detected higher oxygen concentration.

Figure 1. Cross section SEM photos of T2 (a) and T4 (b)

Figure 2. Microstructure of Mo-T4 welding joint and the corresponding line distributions of elements Mo, Al, Ti and O
4 Conclusion
38.5vol%Ti/Al$_2$O$_3$ composite has good performance with relative density 99.23%, bending strength 897MPa, fracture toughness 17.38 MPa·m$^{1/2}$ and micro-hardness 17.13GPa and its wave impedance value is in between which of Mo and Al. The Ti/Al$_2$O$_3$ composite satisfies the requested properties of mechanics and wave impedance.

This component composite can be bonded well with Mo and Al. The welded Mo-T4-Al laminate material has good parallelism and the interfaces of Mo-T4 and Al-T4 are fine. So the 38.5vol%Ti/Al$_2$O$_3$ composite is suitable to W-Mo-Al system wave impedance graded flier-plate as interlayer material.

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