Strength and Modulus of a Molybdenum-Coated Ti-25Al-10Nb-3V-1Mo Intermetallic

R.U. Vaidya, A.K. Zurek, A. Wolfenden, and M.W. Cantu

The three-point bend strength, Young's modulus, and vibrational damping of a plasma-sprayed molybdenum-coated Ti-25Al-10Nb-3V-1Mo intermetallic were measured. The bend strength of the intermetallic samples was significantly reduced as a result of the molybdenum coating. This decrease in the strength was attributed to cracks formed in the molybdenum coating during the plasma spraying process. Experimental measurements done using the piezoelectric ultrasonic composite technique (PUCOT) indicated that the modulus and vibrational damping of the coated samples were significantly higher than for the uncoated substrates. Thermal cycling of the molybdenum-coated intermetallic between 600 °C and room temperature revealed a saturation increase in the modulus with a corresponding decrease in the mechanical damping. This behavior was attributed to crack healing occurring in the molybdenum coating during the thermal cycling process.

Keywords
coatings, intermetallic compounds, modulus, strength, Ti-Al intermetallics

1. Introduction

Ti3Al-BASED INTERMETALLICS show tremendous promise in high-temperature structural applications. These intermetallics have the potential to serve in a variety of environments, depending on the type of application, including jet turbines and internal combustion engine components. These materials have been found to maintain good strength at temperatures up to 1000 °C (Ref 1-4).

Oxidation of these intermetallic materials at temperatures in excess of 500 °C is an important limitation. Since most of the high-temperature environments have an abundance of oxygen, it is necessary to address the oxidation problems in these materials. The resistance of a material to oxidation at higher temperatures is dependent on the potential of the material to form and maintain a protective oxide scale on the surface. Previous studies have shown (Ref 5, 6) that the oxide scale formed on the surface of Ti3Al-based intermetallics does not adhere well to the surface of the substrate and tends to spall off. The oxide layer formed on the surface of the intermetallic develops discontinuities and does not prevent oxygen from diffusing into the substrate.

The use of plasma-sprayed coatings is a common method of protecting substrates from corrosive environments and high-temperature oxidation. The successful use of a 0.1 mm thick Al2O3 coating as an oxidation barrier for these intermetallics has been shown (Ref 7, 8). However, the major disadvantage of Al2O3 as a coating material is its inability to withstand large thermal cycles. The Al2O3 coatings were observed to spall off after repeated thermal cycling between 600 °C and room temperature. Thermal shock resistance is an important requirement in most of the applications these intermetallics are intended for.

In our present study we have investigated the use of molybdenum as a coating material for Ti-25Al-10Nb-3V-1Mo intermetallic substrates. We envisage the use of such coated intermetallics in applications demanding moderate temperatures (up to 600 °C) and low friction characteristics, including a number of internal combustion engine applications. The bending strength, elastic modulus, and mechanical damping of the molybdenum-coated Ti-25Al-10Nb-3V-1Mo were measured. The effect of thermal cycling on the modulus and mechanical damping was documented through ultrasonic measurements.

2. Experimental Procedure

2.1 Materials and Coating Procedure

The Ti-25Al-10Nb-3V-3Mo intermetallic substrates used in this study were obtained in the form of cast plates from Howmet. The chemical composition of the plates is given in Table 1. The molybdenum coating was applied to the substrate by plasma spraying. The intermetallic plates were sand blasted prior to spraying. A Plasmadyne gun was used for spraying the molybdenum onto the intermetallic substrates. Trace amounts of iron and aluminum (less than 0.02%) were present in the molybdenum powder. Plasma spraying parameters used in the process are given in Table 2. The molybdenum coating had an average thickness of 0.112 mm (standard deviation 0.043 mm). The sprayed plates were cut into smaller samples using a slow-speed diamond saw.

Table 1 Chemical composition of the intermetallic substrate

<table>
<thead>
<tr>
<th>Element</th>
<th>Measurement</th>
<th>Ti</th>
<th>Al</th>
<th>Nb</th>
<th>V</th>
<th>Mo</th>
<th>Cu</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>56.3</td>
<td>14</td>
<td>23</td>
<td>4</td>
<td>3.87</td>
<td>2.07</td>
<td>0.15</td>
<td>0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>at%</td>
<td>60.8</td>
<td>25</td>
<td>20</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>(a)</td>
<td>(a)</td>
<td>(a)</td>
</tr>
</tbody>
</table>

(a) Trace concentrations
2.2 Determination of Bend Strength

The strength of the coated intermetallic samples was measured in three-point bending. The samples were positioned in a hardened steel fixture and loaded by a central pin on a span of 19 mm. The ratio of loading span to specimen thickness for all the samples tested was 5.8, while the ratio of loading span to specimen width was 7.6. The samples were loaded in an Instron machine with a 5 kN load cell and tested at a crosshead speed of 0.1 mm/min. Eight coated samples were tested.

2.3 Thermal Cycling

Three individual samples of similar dimensions were thermally cycled at 600 °C. This temperature was chosen based on proposed use temperatures for such materials. The samples were heated in a box furnace to these temperatures, then were soaked in air for 1 h prior to air cooling to room temperature. Six thermal cycles were applied to each sample. This number was chosen based on our earlier studies (Ref 8), which showed spallation of the Al2O3 coating after six thermal cycles. Furthermore, changes in the Young's modulus and mechanical damping saturated after two thermal cycles.

2.4 Measurement of Elastic Modulus and Damping

The elastic modulus and vibration damping of the coated samples were measured at room temperature using the piezoelectric ultrasonic composite oscillator technique (PUCOT). Details of the technique are provided elsewhere (Ref 9-13). From the measurement of the mass density and length of the specimen, the resonant period of the drive and gage crystals, the resonant period of the system, and the drive and gage voltages, the values of the Young's modulus, strain amplitude, and vibrational damping were determined.

3. Results and Discussion

The results of a two-parameter Weibull analysis on the strength values of the molybdenum-coated intermetallic and uncoated intermetallic samples are presented in Table 3. The Weibull analysis was carried out using a simplified two-parameter Weibull equation:

\[ P(\sigma_f) = 1 - \exp\left[-\alpha \sigma_f^\beta\right] \]  

(Eq 1)

where \( P \) is the probability of failure at Weibull mean stress \( \sigma_f \), \( \beta \) is the Weibull modulus, and \( \alpha \) is the modified scale parameter.

Equation 1 was rearranged as:

\[ \ln \ln \left[ \frac{1}{1 - P} \right] = \ln \alpha + \beta \ln \sigma_f \]  

(Eq 2)

The probability of failure \( P \) was obtained by arranging the strength values of the samples in ascending order, then assigning a probability of failure to each strength value using the estimator

\[ P(\sigma_f) = i/(1 + N) \]  

(Eq 3)

where \( P(\sigma_f) \) is the probability of failure corresponding to the \( i \)th strength value and \( N \) is the total number of samples tested.

The Weibull mean strength (\( \sigma_f \)), standard deviation (sd), and coefficient of variation (CV) were calculated as:

\[ \sigma_f = \alpha^{-1/\beta} \Gamma \left[ 1 + 1/\beta \right] \]  

(Eq 4)

\[ \text{sd} = \alpha^{-1/\beta} \left[ \Gamma \left( 1 + 2/\beta \right) - \Gamma^2 \left( 1 + 1/\beta \right) \right]^{1/2} \]  

(Eq 5)

\[ \text{CV} = 100 \frac{\text{sd}}{\sigma_f} \]  

(Eq 6)

where

\[ \Gamma(n) = \int_0^{\infty} e^{-t} t^{n-1} \, dt \]

The Weibull parameters for the uncoated intermetallic substrates were obtained from a previous study (Ref 8). From the results it is evident that the molybdenum coating decreased the strength of the intermetallic samples significantly. These results were not in agreement with the results of a study on a 0.1 mm Al2O3 coating. In that study (Ref 8) it was found that a 0.1 mm Al2O3 coating had no effect on the strength of the intermetallic substrate.

Scanning electron microscopy (SEM) carried out on the fractured surfaces of molybdenum-coated intermetallics revealed the cause for the decreased strength of the coated sam-

### Table 2 Plasma spraying parameters used in the coating process

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma gun voltage, V</td>
<td>25</td>
</tr>
<tr>
<td>Plasma gun current, A</td>
<td>300</td>
</tr>
<tr>
<td>Gun to specimen distance, cm</td>
<td>7.5</td>
</tr>
<tr>
<td>Arc and powder gas</td>
<td>Argon</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Air</td>
</tr>
</tbody>
</table>

### Table 3 Weibull parameters of the uncoated and molybdenum-coated intermetallic samples

<table>
<thead>
<tr>
<th>Sample condition</th>
<th>Weibull parameter</th>
<th>Value</th>
<th>Standard deviation, MPa</th>
<th>Coefficient of variation, %</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull mean strength, MPa</td>
<td>( \sigma_f )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncoated</td>
<td>( 7 \times 10^{-26} )</td>
<td>7.59</td>
<td>1751</td>
<td>291</td>
<td>16.6</td>
</tr>
<tr>
<td>Molybdenum-coated</td>
<td>( 3.3 \times 10^{-20} )</td>
<td>6.21</td>
<td>1213</td>
<td>226</td>
<td>18.6</td>
</tr>
</tbody>
</table>