Original Article

Fabrication of Al–TiC composites by hot consolidation technique: its microstructure and mechanical properties

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ARTICLE INFO

Article history:
Received 26 January 2015
Accepted 6 July 2015
Available online 14 August 2015

Keywords:
Hot consolidation
Composites
Vickers hardness
Elemental mapping
Young’s modulus

ABSTRACT

Al-based metal matrix composites reinforced with different volume fraction of TiC particles as reinforcement was synthesized by the hot consolidation process. The titanium carbide used in this study was synthesized directly from the titanium ore (ilmenite, FeTiO3) by carbothermic reduction process through thermal plasma technique. The field emission scanning electron micrographs (FESEM) reveals the homogeneous distribution of TiC particles in the Al-matrix. Enhanced Young’s modulus and mechanical properties with appreciable ductility were observed in the composite samples. The significant increases in the mechanical properties of the composites demonstrate the effectiveness of the low-density TiC reinforcement.

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1. Introduction

Metal matrix composites (MMCs) are engineering materials in which a hard ceramic component is dispersed in a ductile metal matrix. These materials have the characteristics that are superior to those of the conventional monolithic metallic alloys, required for aerospace and automobile industries [3–11]. In most of the MMCs, aluminium is the most frequently used metal matrix material due to its low density and excellent castability. Aluminium matrix composites (AMCs) reinforced with ceramic particles exhibit high strength, high elastic modulus and improved resistance to wear, creep and fatigue compared to unreinforced metals that make them promising structural materials for aerospace and automobile industries [3,12–16]. However, TiC is
particularly attractive due to high hardness, elastic modulus, low density, excellent wettability with molten aluminium and low chemical reactivity. Hence, Al–TiC composites occupy a unique position in the family of metal matrix composites due to their excellent wear resistance, high strength-to-weight ratio and good mechanical properties. The improvement of such properties in Al–TiC composites completely depends on the amount and uniform distribution of TiC particles [17–19].

There are several techniques available for making particle-reinforced MMCs ranging from powder metallurgy (PM) methods to casting. The segregation of reinforcement to form inhomogeneous distributions during solidification processing limits the performance of the cast-route composites in different application areas. It has been widely reported that inhomogeneous distributions of the reinforcement deteriorate the mechanical properties in particular, the fatigue and fracture performance [3]. The powder metallurgy route is largely used for the manufacturing of metal matrix composite system because it offers several advantages compared to cast-route. The main benefits of this process are the decreased possibility of chemical reaction between the matrix and reinforcement phases as synthesis is occurred at lower temperatures. This increases the chance to incorporate many types of matrices and reinforcement phases in the same composite system. It is also advantageous to include a higher fraction of support particles in the composite when compared with the rheological limitations of casting process. Hence, the materials synthesized by powder metallurgy technology can be targeted to use as structural components and can also considered as replacements for conventional materials for wear resistant applications [20].

In the present investigation, metal matrix bulk composites samples are prepared by the hot consolidation of Al and TiC powders. The reinforcement TiC particles used for composite preparation was synthesized by carbothermic reduction of ilmenite ore by high-temperature thermal plasma technique. An appreciable bulk density has been observed for 20 vol.% TiC-Al composites in comparison to Al with the enhancement of hardness and Young’s modulus.

2. Experimental

The commercial available Al powder (~325 mesh size, SRL Pvt. Ltd, India) and plasma synthesized TiC powder (average size 10 μm) from the ilmenite concentrate was taken as reinforcement for the synthesis of Al–TiC composites. The ilmenite concentrate was obtained from IREL, Chhatrapur, India, which contains approximately 50.5% of TiO₂ and 34.2% of FeO. For the synthesis of fine size with high purity TiC particles, the ilmenite concentrate was reduced carbo thermally by direct current extended thermal plasma reactor for 20 min in an argon atmosphere. The thermal plasma treated product is a composition of TiC and Fe. Hence, chemical leaching procedure is adopted to free the matrix from iron and other impurities. The detail synthesis process of the TiC powder is explicitly discussed elsewhere [21]. The composites were prepared by varying TiC volume fraction from 5% to 20% in Al-matrix. For hot pressing (Make: WEBER PWV 30 EDS electrohydraulic universal axial pressing machine) approximately 2–3 g of powder was placed in a 10 mm diameter die. The hot pressing was carried out at a temperature of 400 °C with an applied pressure of 400 MPa for 5 min under a vacuum of 10⁻⁶ mbar. After the completion of the heating cycle, the chamber was left in vacuum to cool down, and argon was purged to remove the sample from the chamber. Then the composite samples were sectioned and polished for characterization. The bulk density of the composites was measured by Archimedes principle. The structural characterization and phase identification were performed by X-ray diffractometer (XRD Model: X'Pert PRO PANalytical) technique using CuKα radiation. The morphology and compositional mapping of Al–TiC composites have been carried out using an field emission scanning electron microscope (Model: JEOL-JEM 2100 UHR). The Young’s modulus and hardness of the composites have been measured by nanoindentation system (Fisher Cripps, Australia).

3. Results and discussion

The XRD patterns of Al–TiC composites with different volume fractions of the reinforcement are shown in Fig. 1. The XRD pattern of the TiC powder synthesized by thermal plasma treatment of ilmenite ore shows crystalline peaks of TiC without any other impurity peaks. The XRD of the composite with V = 5 indicates the presence of fcc Al along with the cubic TiC phase. For the sample with 10 vol% reinforcement, similar results can be observed where the intensity of the TiC phase increases with respect to the composite with V = 5 due to higher volume fraction of TiC reinforcement. A similar pattern has been observed at V = 20 except the increase in the intensity of TiC peak. The detection of only two phases in the XRD patterns of the composites with V = 5, 10 and 20 indicates that no reaction between matrix and reinforcement to form additional phases has occurred in the current consolidation conditions (hot pressed at 673 K and 400 MPa).

The microstructure of the composites was investigated by FESEM and the corresponding micrographs taken from the cross-section of the consolidated specimens are shown in
Fig. 2. The micrographs clearly display the distribution of TiC particles in the Al matrix. The sample with V = 5 (Fig. 2b) shows the TiC particles (dark areas) homogeneously distributed within the Al matrix (bright areas). As the reinforcement content increases to 10 and 20 vol%, the TiC particles tend to agglomerate to form clusters, though the overall distribution of these particles in the matrix remains relatively uniform (Fig. 2c and d). The microstructure of the composite does not show any porosity, corroborating the high density of the samples (as shown in Table 1). Fig. 3 displays the SEM micrographs and the corresponding Al, Ti and C composition maps obtained by EDX analysis of the composites reinforced with 5 vol.% of TiC particles hot pressed at 673 K and 400 MPa. The elemental distribution map clearly reveals the homogeneous distribution of TiC particle in Al matrix.

The room temperature compression test data of the composites and unreinforced pure Al-matrix are shown in Table 2. The composite with 10 and 20 vol.% of the reinforcement displays a significant increase in strength level with respect to the unreinforced Al-matrix, which indicates that the TiC particles synthesized by plasma route has strong strengthening effect in Al matrix. The yield strength and the ultimate tensile strength increase almost linearly from 107 and 320 MPa for the sample with 5 vol.% TiC particles to 205 and 360 MPa for the composite with 20 vol.% reinforcement. On the other hand, the strain decreases from 47.5% to 27% respectively.

Besides the enhancement of the mechanical properties, the addition of the TiC particles has a positive effect on the Young’s modulus of the composites. The nanoindentation test was performed to measure the elastic modulus and Vickers hardness of these composites, and the result is shown in Fig. 4. The elastic moduli of the Al–TiC composites have been improved dramatically. For instance, the elastic modulus was enhanced from 70 GPa to 88.78 GPa by increasing the volume content of TiC from 0% to 20%. The increase in Young’s modulus indicates that load transfer is more efficient in the Al–TiC system.

<table>
<thead>
<tr>
<th>Table 1 – Measurement of density and porosity of the composite samples with different volume fraction of the reinforcement.</th>
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<tr>
<td>Composition</td>
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<tr>
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<tr>
<td>Al + 5 vol.% TiC</td>
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<tr>
<td>Al + 10 vol.% TiC</td>
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<tr>
<td>Al + 20 vol.% TiC</td>
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Improvement in load transfer is most likely due to strong interfacial bonding encouraged by the direct nucleation of solid Al on the TiC particle surfaces [18].

The hardness measurement is known to be one of the most informative and rapid methods to determine the mechanical behaviour of composites. Hardness results of the matrix and composites with 5, 10, and 20 vol.% of TiC are shown in Fig. 4. The composite shows higher hardness than the base metal. The matrix of composites contains higher dislocation density that generates due to the large difference in thermal expansion coefficient between the matrix and reinforcement [17]. This higher dislocation density leads to higher hardness in the composites. The increase in the hard phase (TiC) results in greater hardness with a concomitant decrease in ductility phase. However, the presence of TiC particle refines the grain size. Finer grain size in composites and lowering of porosity leads to higher hardness [17]. TiC particulate reinforced MMCs are very interesting because TiC is thermodynamically stable and enhances the hardness and lightness of the composite. TiC when dispersed in Al matrix, increases the hardness to weight ratio. Moreover, it imparts thermodynamic stability to the composites [20,22]. The improvement in the bulk hardness of composites is only due to the increased particle volume fraction of TiC in Al. The attribution of increase in hardness is due to the distribution of TiC uniformly throughout the matrix of Al and increased specific surface of the reinforcement for a given volume fraction [23,24]. It can be concluded that the rise in the hardness of the composites containing hard ceramic

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Reinforcement content (vol.%)</th>
<th>Yield strength (MPa)</th>
<th>Compressive strength (MPa)</th>
<th>% strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>42</td>
<td>85</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>107</td>
<td>320</td>
<td>47.5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>180</td>
<td>340</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>205</td>
<td>360</td>
<td>27</td>
</tr>
</tbody>
</table>
particles not only depends on the size of reinforcement but also on the structure of the composite and good interface bonding [24]. The load versus displacement curve for the composites has been shown in Fig. 5. A maximum load of 80 mN was applied, and the indentation depth stays within 2–2.25 nm. The figure clearly shows a decrease in displacement from 5% to 20% TiC containing composite. The depth of indentation decreases with increase in hardness that agrees with the fact that hardness has been increased with increase in vol% TiC.

4. Conclusions

TiC particles used as reinforcement in the Al matrix in the present investigation have been synthesized from ilmenite concentrate by thermal plasma processing within a very short period. The Al-based MMCs have been produced by powder metallurgy method. Microstructural examination showed a uniform distribution of TiC particulates in the matrix and the presence of minimal microporosity. The composite sample shows encouraging room temperature mechanical properties with improved Young modulus over that of the matrix. Vickers hardness values have been increased from the matrix to the composites. The compressive strength increases from 85 MPa for pure Al to about 320 and 360 MPa with 5 and 20 vol.% of reinforcement, respectively. Similarly, the Young’s modulus also increases with addition of the TiC reinforcement of about 70 GPa for pure Al to 78 and 89 GPa for the composites with 5 and 20 vol.% of reinforcement, respectively. Hence, Al–TiC composites prepared by this method are suitable for structural and industrial applications, like other Al based MMCs.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgement

Authors are thankful to CSIR, New Delhi, India for providing financial support to carry out the work.

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