LASER SURFACE ALLOYING (LSA) OF ALUMINIUM (AA 1200) WITH TiB₂ FOR HARDNESS IMPROVEMENT

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Abstract

The present work deals with the development of Aluminium metal matrix composite (MMC) using TiB₂ reinforcement. The aim is to improve the microhardness property of the substrate. The surface of the aluminium was sand blasted to improve its laser energy absorption and simultaneous deposition of the ceramic powder onto the surface of the substrate was carried out using a Rofin Nd: YAG laser with an Argon shield environment to prevent oxidation. The laser processing parameters were varied. The characterization of the alloyed surfaces MMC was carried out by Optical Microscopy (OPM), Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). The microstructure of the alloyed layer shows that the ceramic powder was well dispersed within the Al-matrix. Good metallurgical bonds were evident. Microhardness measurements were carried out. The maximum depth attained was 1.17 mm. There was a microhardness increase from that of substrate which is 24±0.4 HV to that of the MMC layer 58.0±0.2 HV.

Introduction

Aluminium and its alloys are remarkable for their excellent mechanical strength, low specific weight, and relatively low cost, and thus are widely used in industrial applications. The high strength to weight ratio of light metals and their alloys makes them widely used in various machinery and transportation systems [1,2]. Aluminium alloys are not hard enough to be used in many engineering applications especially where wear resistance and high loading conditions are compulsory material property requirements [1,3]. The hardening effects by conventional heat treatments through phase transformation are very limited since Aluminium is not one of the allotropic metals.

Laser surface alloying can be utilized for modification of the surface properties of metallic alloys. This method has been applied for producing metal matrix composite MMC by many researchers [1,2,4]. MMC produced by LSA is achieved by the application of a laser beam on the surface of the substrate material to form a melt pool and then the injection of a powder material into the melt pool. The properties of laser surface alloyed layer depend on microstructure that evolves during melting, cooling and solidification, however, the application and efficiency of laser surface treatments depend on laser processing parameters [1,3].

Titanium diboride (TiB₂) is a refractory material; it exhibits high elastic modulus and hardness, high melting point (2970°C) and electrical conductivity as well as good thermal stability and chemical inertness. TiB₂ has a good thermodynamic stability in Aluminium, hence the reason for its choice as alloying material in this work.

In this investigation, the effects of TiB₂ reinforcement on the microhardness property of Al will be studied, an accurate characterization of the alloyed layer MMC in terms resultant microstructures and phases will be carried out.

Experimental approach

Materials

The base material used in the current investigation is Aluminium AA 1200. The aluminium plates were cut and machined to dimensions 100 x 100 x 6 mm. The chemical composition of the substrate is shown in Table 1. The pure Al -plates were sand blasted prior to laser surface alloying to achieve a uniform rough surface which in turn enhances laser energy absorption at the surface of the Al –plates and also the removal of the oxide scale. The alloying powder used was TiB₂ (99.5%). The powder particle sizes ranges from -100 to 45 μm.
Table 1 Composition of AA 1200 alloy

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition by wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.59</td>
</tr>
<tr>
<td>Cu</td>
<td>0.12</td>
</tr>
<tr>
<td>Si</td>
<td>0.13</td>
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<td>Al</td>
<td>balance</td>
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</table>

A Rofin Sinar continuous wave Nd: YAG solid-state laser fitted with off-axes nozzle used for powder feeding was used for laser surface alloying experiment. A Kuka robot was used to deliver the laser beam through a 600 μm optical fiber to the target surface. The shielding gas used was Argon; this prevents oxidation of metal through reaction with oxygen and also avoids formation of pores that occurs during the alloying process. The processing parameters were optimized by variation and careful selection of the laser processing parameters. The laser parameters used are shown in Table 2. The laser power was held constant while the scan speed was varied during these experimental investigations. Single laser tracks were made on the substrate’s surface.

Table 2 Laser processing parameters and sample composition

<table>
<thead>
<tr>
<th>Sample label</th>
<th>C</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td>System composition</td>
<td>Al-TiB₂</td>
<td>Al-TiB₂</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Beam diameter (mm)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Scan speed (m/min)</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Powder feed rate (rpm)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>Argon</td>
<td>Argon</td>
</tr>
<tr>
<td>Shielding gas flow (L/min)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Materials Characterisation

A Philips PW 1713 X-ray diffractometer fitted with a monochromatic Cu Kα radiation set at 40 kV and 20 mA was used to determine the phase composition of powder. The scan was taken between 10° and 80° two theta (2θ) with a step size of 0.02 degree. Phase identification was done using Philips Analytical X’Pert HighScore® software with an in-built International Centre for Diffraction Data (ICSD) database. The powder particle morphology and size distribution were analyzed using a scanning electron microscope SEM equipped with energy dispersive spectrometer and Malvern Mastersizer 2000 image analyser for particle size.

Cross-sections of the alloyed layers were cut for metallographic analysis. The polished surfaces were etched using Keller’s reagent. The chemical reaction between molten aluminium and the TiB₂ alloying powder led to the formation new phases in the matrix. The new phases formed were studied; the microstructures of the new phases were characterized by optical and scanning electron microscopes. The characteristics of the phases were studied by means of X-ray diffraction. An optical microscope was also used for microstructural analysis.

Microhardness Test

The Vickers hardness of the alloyed cross sections was determined using a Matsuzawa Seiki microhardness tester. A through-thickness hardness profile was determined with a load of 100 g. A minimum of five indents were made to obtain a good representation of the values obtained. The average microhardness value was calculated for the samples.

Results and Discussion

Powder Characterisation

Figure 1 shows the particle size distribution of the TiB₂ powder used for alloying. The average particle size was found to be -100 to 45 μm.

Figure 1: Particle size and distribution of TiB₂ powder

Figure 2 shows the XRD diffractograph of the powder. This shows that the powder used was pure and free from any contaminant. The peaks shown were that of Ti and TiB₂. Figure 3 shows a SEM micrograph of the as received TiB₂ powder particles. The morphologies of the TiB₂ particles were irregular in shape and clustered together.
Figure 2: X-ray spectrum of TiB₂ powder

Figure 3: Scanning electron micrograph showing the microstructure of TiB₂ powder

The X-ray diffractograph of the cross section of the AA 1200 can be seen in Figure 4. This shows the identified phases present in the Al; only aluminium peaks can be seen, an evidence of the purity of the substrate. The microhardness value of the AA 1200 is 24.0 ± 0.4.

Figure 4: X-ray spectrum of AA 1200

Microstructure of MMC

A typical stereo micrograph of the alloyed layer is shown in Figure 5.

Figure 5: A typical stereo micrograph of an Al surface alloyed with TiB₂

Uniform alloying (alloyed layer filled with powder) was achieved, evidence of good metallurgical bond between substrate and powder. The maximum depth of alloyed layer achieved was 1.17 mm representing approximately 20% of aluminium substrate thickness. The width of the single track is approximately equal to that of the laser beam of 3 mm for both samples.

Figures 6-7 shows the scanning electron micrographs of the cross section of the polished sample C laser alloyed. From these SEM results, micrographs consisted of the TiB₂ powder well dispersed in the Al-matrix. The distribution of the TiB₂ particles in the melt is by convection flow. The gray phases are TiB₂ in the solidified Al-matrix. The metallurgical bonding existing between the substrate and the powder can be seen from the SEM micrograph. The same can be said for Sample D, Figures 8-9 also shows the SEM micrographs of these samples, bonding within the matrix are good. The EDS analysis for both samples C and D shows the presence of Al, Ti, B and O. The optical micrographs of the MMC layer for both samples confirmed that TiB₂ particles are well dispersed in the Al-matrix.
The particles of TiB$_2$ can be seen to be fairly homogeneously distributed within the Al-matrix except for sample D where clustering of the powder can be seen from the SEM micrograph. A close comparison between the SEM micrographs of the samples revealed that the volume fraction of the TiB$_2$ particles in the Al-matrix decreases with increase in the scan speed. It can be concluded that the laser processing parameters used actually controlled the width of the melt pool, the quantity of powder deposited into it and hence the properties so modified. Sample D can be seen to have the lowest volume fraction of TiB$_2$ while sample C has the highest volume fraction of powder corresponding to 0.6 m/min scan speed which is the lowest.
Figure 8: Scanning electron micrograph of sample D a laser formed composite surface of Al with TiB$_2$ particles treated with 4 kW laser power, 1.0 m/min scan speed and 4 rpm powder feed rate at different magnification.

Figure 9: EDS analysis and the optical micrograph of sample D laser formed composite surface of Al with TiB$_2$ particles treated with 4 kW laser power, 1.0 m/min scan speed and 4 rpm powder feed rate.

Figure 10 shows the XRD profiles for the samples C and D, from these profiles secondary phases were identified, phases present in the alloyed layer are: TiB$_2$, AlTi, AlB$_2$, Al, Ti, B. The Al and Ti belong to the same crystal system and the same space group, and as such their peaks are overlapping. The same for TiB$_2$ and AlB$_2$ – they belong to the same space group and peaks are overlapping. However, the XRD result of sample D also showed the presence of Al$_3$Ti, this is an intermetallic phase that exhibits high hardness, high melting and also very brittle. This phase may be responsible for the higher hardness value exhibited by sample D.
Figure 10: X-ray spectrum for the laser alloyed surfaces of Al with TiB₂: sample C

Figure 11: X-ray diffraction spectrums for the laser alloyed surfaces of Al with TiB₂: sample D
Microhardness Results

From Figure 12, laser alloying aluminium AA 1200 with TiB₂ powder resulted in microhardness increase from 24.0 ± 0.4 HV for base aluminium AA 1200 to approximately 58.0 ± 0.2 HV for the alloyed layers. The microhardness profile data for all the samples shows significant fluctuation. The average microhardness values for all the samples were calculated, sample C has the highest value of microhardness, this is because of the Al₃Ti phase that was exhibited by this sample. This improvement in hardness (over double the microhardness of substrate) was attributed to the formation of MMC phases during alloying. The optimum laser processing parameter for the highest average microhardness is laser power 4 kW, scan speed 1.0 m/min, powder feed rate 4 rpm. It can be concluded that the hardening using TiB₂ powder is due to formation MMC as a result of the dispersion of the hard particles and that there exist an optimum volume fraction that will give the best microhardness property and also the presence of the Al₃Ti phase in the matrix is very vital.

Table 3 Properties of the alloyed layer

<table>
<thead>
<tr>
<th>Sample label</th>
<th>C</th>
<th>D</th>
</tr>
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<tbody>
<tr>
<td>Average microhardness value displayed by MMC (HV)</td>
<td>46.50</td>
<td>48.70</td>
</tr>
<tr>
<td>Depth of alloyed layer (mm)</td>
<td>1.17</td>
<td>1.09</td>
</tr>
<tr>
<td>Scan speed (m/min)</td>
<td>0.60</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Conclusions

Laser surface alloying of AA 1200 pure aluminium with TiB₂ reinforcement using a 4.4 kW Sinar continuous wave Nd: YAG solid-state laser was successfully carried out. The resultant phases and hardness were investigated:

- A relationship exist between the laser processing parameters and volume fraction of powder deposited into the melt pool, the depth of alloyed layer and finally the microstructure and properties of the MMC formed.
- The increase in hardness from that of Al-substrate 24±0.4 to that of the alloy formed 58.0±0.2 is about twice that of substrate.
References


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Meet the Author

Patricia is a Metallurgist; she is a Lecturer and Section Head of the Department of Chemical and Metallurgical Engineering in Tshwane University of Technology, Pretoria, South Africa.