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Three body abrasion of laser surface alloyed aluminium AA1200

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ABSTRACT

Laser surface alloying of aluminium AA1200 was performed with a 4 kW Nd:YAG laser to improve the abrasion wear resistance. Aluminium surfaces reinforced with metal matrix composites and intermetallic phases were achieved. The phases present depended on the composition of the alloying powder mixture. The wear performance of the alloyed surfaces was characterised using an ASTM G65 three body dry abrasion apparatus. A maximum 82% improvement in the wear resistance of the pure aluminium was achieved with a 40 wt% Ni+20 wt% Ti+40 wt% SiC composition. The three alloys which had the best wear resistance were all produced with a composition of 40 wt% SiC and Ti and Ni powders ranging from 20 to 40 wt%. No direct correlation was observed between hardness and wear resistance. Microstructural examination showed that the main wear mechanisms were intense plastic deformation with micro-fracture of the SiC particles and intermetallic phases. The wear behaviour is mainly determined by the response of the different alloy phases, either independently or in combination, to the action of the abrasive particles and the precise nature of this response is complex and requires further study.

1. Introduction

Aluminium is widely used in industry due to its attractive attributes such as low density, high strength to weight ratio, high thermal conductivity and good formability [1]. Its drawback is the poor surface properties such as hardness and wear resistance. These surface properties can be improved by depositing hard reinforcement materials on its surface in an attempt to provide a composite material which has a tough matrix reinforced with hard particles which should lead to improved wear resistance. This can be achieved by a laser alloying process. Alloying materials are deposited as powders into a melt pool generated on the material surface by a focused laser beam. The beam is scanned over the part and the deposited material resolidifies resulting in good bonding between the substrate and the alloyed layer. The surface of the material is modified by changing the composition and microstructure without affecting the bulk properties of the material. Process parameters such as laser power, laser beam spot size, laser scanning speed and powder feed rate have to be controlled to achieve the desired metallurgical bonding and alloyed surface properties.

Research on the wear properties of aluminium alloys reinforced with either ceramic or metallic materials has been done by several authors [1–22]. Staia et al. [8] alloyed aluminium A356 with 96 wt% WC, 2 wt% Ti and 2 wt% Mg. The wear behaviour of the alloyed material against AISI52100 steel balls under a load of 5 N was investigated. For high laser scanning speeds, large WC particles were formed which served as the load carrying particles and severely abraded the steel. For low laser scanning speeds, the WC particle size decreased and the wear mechanisms changed as the aluminium matrix participated in the transference process. The wear mechanisms of the aluminium A356 was adhesive with high quantities of aluminium transferred to the steel counterface. Almeida et al. [9] studied the dry sliding wear mechanisms of Al–Mo deposited on an aluminium substrate by laser surface alloying. The wear mechanisms were predominantly adhesion followed by material detachment and transfer, oxidation and some abrasion, mainly by hard intermetallic compound particles on the steel counterbody. Elleuch et al. [10] studied the abrasive wear of aluminium alloys rubbed against sand. The author reported that the wear rate increased by three times as the incident angle of sand was increased from 0° to 45°.

Şahin [11] studied the abrasive wear of aluminium AA2014 reinforced with SiC particles of different sizes (9 μm, 14 μm and 33 μm). The authors observed that the wear rate decreased with increasing hardness of the MMC while it increased with increasing abrasive particle size of the counter surface, applied load and sliding distance (up to a maximum value, then either decreased or remained constant). Miyajima and Iwai [12] reported that SiC and Al_2O_3 reinforcement caused severe wear of a steel counter surface

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during sliding wear of the aluminium matrix composite on a pin-on-disc wear tester. Metal matrix composites with low volume fractions of embedded ceramics produced severe wear characterised by plastic deformation and large grooves. MMCs with high volume fractions of embedded ceramics did not wear severely and the surfaces were smooth and flat without large grooves. The embedded ceramic acted as inhibitors against plastic flow and adhesion of the matrix metal to the steel counter surface.

Majumdar et al. [13] laser alloyed Ti with Si, Ti with Al, and Ti with Si+Al and studied the wear behaviour on a ball-on-disc wear testing machine. Surfaces alloyed with Al suffered extensive amounts of abrasive and adhesive wear while surfaces alloyed with Si+Al suffered abrasive wear. No significant amount of adhesive or abrasive wear was observed in samples alloyed only with Si. This decrease in the wear rates was associated with the formation of the Ti_5Si_3 phase which was found in higher volume fractions in the surfaces alloyed only with Si.

Anandkumar et al. [15] conducted three body abrasion wear tests on Al–Si/SiC composite coatings using SiC as the abrasive. The coatings were produced using two different specific energies, namely 26 MJ/m^2 and 58 MJ/m^2 which yielded hardness values of 120 and 250 VH respectively. The higher hardness was attributed to the larger proportions of Al_4SiC_4 and Si precipitates. However the harder coating had the highest wear rate. The authors concluded that this was due to the significant difference between the SiC abrasive and the composite hardness. The lower wear rate achieved by the softer coating was attributed to the presence of SiC particles, which although do not provide an improvement in hardness, do resist scratching by the abrasive. The friction and wear behaviour of aluminium laser surface alloyed with SiC and SiC+Al was also studied by Majumdar et al. [21,22]. It was found that some the SiC dissociated to form Al_4C_3 which led to an increase in the aluminium hardness from 25 VHN to 200–250 VHN. The resulting wear resistance was improved up to three times and was attributed to the dispersion strengthening effect provided by the Al_4C_3 phase.

Shipway et al. [14] studied the sliding wear mechanisms of aluminium reinforced with TiC particles against a carbon-manganese steel (BS 080A15) counterface and found that the wear rates increased as the applied load increased and delamination cracks were observed in the MMC layer. The addition of the TiC particles resulted in counter surface wear as hard particles acted as abrasives in the sliding process. The wear rates of the steel counter surfaces increased as the volume fraction of the TiC particles increased. These TiC particles resulted in ploughing and cutting of the steel counter surfaces in the sliding direction.

In dry sliding wear tests of Al–12Si/TiB_2 laser clads with an AISI 440C tool steel counterbody by Anandkumar et al. [17] the laser clads displayed ultra mild wear. The addition of TiB_2 led to an improvement in the hardness and wear resistance of the Al–12Si alloy. The authors attributed this to the role played by the reinforcement phase in protecting the Al-based alloy against severe plastic deformation. Similar results were found by Majumdar et al. [20] who studied the abrasion wear resistance of aluminium reinforced with TiB and TiB_2 particles where the volume fractions were varied between 7 and 18%. The addition of the TiB improved the hardness threefold using a laser power of 1.2 kW and a scan speed of 500 mm/min. The wear resistance was improved and decreased with an increase in applied load. This was attributed to the increased hardness provided by the TiB particles.

Molybdenum has been shown to improve the mechanical properties of aluminium. In a study done by Almeida et al. [9] on a range of Al–Mo alloys (14.8–19.1 wt% Mo) the hardness was shown to increase from 85 to 160 VH while Young's Modulus increased from 84 to 92 GPa. These increases were attributed to increasing volume fractions of the intermetallic compounds. The wear resistance of the alloys were tested under dry sliding wear conditions using applied loads of 0.15 and 1 N respectively. The wear resistance was found to increase with an increase in the volume fraction of the intermetallic compounds. However higher wear rates were observed at the lower load. This result was attributed to the resulting wear mechanisms which included adhesion, oxidation as well as detachment and transfer of the surface material. Almeida et al. [18] reported that the addition of niobium to aluminium provided a good combination of a very high hardness and moderate toughness which was attributed to the volume fraction and dendritic spacing of the Al_3Nb phase.

Several authors have attempted to model the wear behaviour of metal matrix composites and general multiphase materials as some of the prevailing wear theories do not provide adequate insight into multiphase material behaviour under abrasive wear conditions [16,23–28]. Recently Colaco and Vilar [16] developed a mathematical model to provide understanding of the functional dependence of wear resistance on the properties of the reinforcement phases in metal matrix composites. The model was based on the Rabinowicz approach [29] on defining abrasive wear mechanisms of multiphase materials and also considered the mechanisms proposed by Hutchings [28] and Zum-Ghar [24] which reported that material loss occurs by wear of the matrix, wear of the reinforcement particles and extraction of the reinforcement particles from the matrix. The model was tested against experimental data based on three body abrasion wear of Fe-0.25%C-15%Cr coatings reinforced with different volume fractions of Nb. The authors reported a good correlation between the model and experimental data and provided detailed understanding of the functional dependence of the wear resistance on the proportion of reinforcement particles. The main conclusions showed that while the average hardness increases as the volume fraction of reinforcement increases, increased wear rates are possible when the volume fraction of reinforcement is increased where cracking and extraction of the particles may increase due to interaction with the abrasive.

Published work is generally limited to higher aluminium alloys (i.e. 2*xxx* to 7*xxx* series). To the authors knowledge no published work is available on the abrasive wear of Aluminium AA1200 which has been laser alloyed with ceramic and metallic materials simultaneously. Therefore the aim of this work was to investigate the abrasive wear resistance of Aluminium AA1200 by laser surface alloying with mixed Ni, Ti and SiC powders. Intermetallic phases are formed when aluminium is laser alloyed with metallic materials (e.g. Ni and Ti) while metal matrix composites are formed when alloying with ceramics (e.g. SiC).

2. Material and methods

Laser alloying of the aluminium AA1200 surface was performed with a Nd:YAG laser. Aluminium AA1200 plates were initially sand blasted to enhance the absorption of laser energy by the aluminium substrate. The chemical composition of the aluminium plates was 0.12 wt% Cu, 0.13 wt% Si, 0.59 wt% Fe and the balance was Al. The laser parameters used were 4 kW of power, a beam diameter of 4 mm and a scanning speed of 10 mm/s. These parameters ensured that sufficient laser energy was supplied for the dissolution of the powders. The alloying powder mixture consisted of different compositions of Ni, Ti and SiC powder mixtures as listed in Table 1. The powder feed rate was 2.5–3 g/min (depending on the powder composition) which ensured sufficient supply of powder during the alloying experiments. Argon was used as the carrier and shielding gas to prevent oxidation during the alloying process. Ten overlapping tracks with a track overlap of 50% were made.