Applied Surface Science 313 (2014) 720–729

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Tribological characteristics of an A356 aluminium alloy laser surface alloyed with nickel and Ni–Ti–C

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ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 30 April 2014
Accepted 9 June 2014
Available online 17 June 2014

Keywords:
Laser surface alloying
Aluminium
Ceramics
Intermetallics
Sliding wear

ABSTRACT

Laser surface alloying of an A356 aluminium alloy was performed in order to improve the tribological behaviour of its surface using nickel and Ni–Ti–C powders to provide a reinformcement of intermetallics and ceramic phases. Alloying with nickel resulted in the formation of Al–Ni intermetallics whilst alloying with Ni–Ti–C led to the formation of Al–Ni and Al–Si–Ti intermetallics together with TiC particles produced by an in-situ reaction within the melt. The surfaces achieved hardness values of up to 3.5 times that of the untreated material, and these values were related to the overall content of alloying elements in the alloyed surface. The sliding wear resistance of surfaces alloyed with nickel and Ni–Ti–C was highly improved when using powder flow rates of more than 0.04 g/s, attaining mass loss due to wear at least 15 times less than that of the untreated material. A reduction of plastic deformation and adhesive wear with increasing alloying addition was the main reason for this improvement.

1. Introduction

The use of aluminium alloys in high performance applications is of interest when considering the possibility of a reduction in component weight. These alloys have poor tribological properties [1,2], surface processing of such alloys is therefore of great interest since it allows the enhancement of tribological properties while maintaining the bulk properties. Laser surface modification offers the added advantage of localised processing, and only regions on the surface that require protection against wear need to be processed. This furthermore offers the advantage of creating improved surfaces having a high strength metallurgical bond to the substrate. This high strength bond is an asset when considering the tribological properties of the modified surfaces since defects at the interface between a wear-resistant coating and its substrate are known to lead to failure of the coating and to reduced tribological performance [2].

Laser modification was used by many authors in order to improve the wear resistance of various substrates [3–7]. With respect to modification of aluminium surfaces, various authors have studied the effects of nickel addition by means of laser alloying [8,9]. A microstructure composed of hard aluminium-nickel intermetallics in a soft aluminium-silicon matrix was reported most frequently. Tomlinson and Bransden [10] report various wear rates depending on the various additions of alloying elements. Most coatings improved wear resistance and load-bearing capabilities with the lowest wear rate being achieved by alloying with nickel and copper [10]. Man et al. [11] stated that the hard intermetallics in a soft matrix contribute to form a wear resistant surface which is able to suppress crack growth [11].

Additions of ceramics such as SiC often lead to the dissolution of the carbides resulting in aluminium carbides that are unwanted due to their negative effect on mechanical and corrosion properties [12,13]. In order to avoid the formation of these carbides, titanium can be added to the alloying powder to react with the carbon in solution forming TiC [14,15]. Addition of TiC particles to aluminium was in fact used by various authors in order to improve the surface properties [16,17]. Hornbogen et al. [18] also state that homogenous structures that combine intermediate hardness and fracture toughness are better than having large particles of a hard but brittle phase. The introduction of TiC particles together with other additional alloying elements was in fact also reported. Viswanathan [19] laser alloyed aluminium with both nickel and TiC and obtained a microstructure made up of Al–Ni intermetallics and TiC particles in an Al–Si matrix. In the work by Tomida et al. [20] it was also noted that the addition of TiC together with the copper resulted in better wear resistance than when copper was the only addition to the alloyed surface [20].

Mabhali et al. [15,21] have carried out alloying of aluminium using Ni–Ti–SiC powder mixtures. The microstructure of their alloyed surface was mainly composed of Al–Ni and Al–Ti

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http://dx.doi.org/10.1016/j.apsusc.2014.06.061
0169-4332/

intermetallics, SiC and TiC, the latter forming by the reaction from the titanium and the free carbon resulting from the partial dissociation of the SiC [15]. Wear testing on surfaces alloyed with Ni, Ti and SiC with various ratios showed that the greatest improvement in wear resistance (of approximately 1.6 times over the wear resistance of the base material) was achieved with the highest SiC content (50 wt%) [21]. An interesting variation of this processing involves the formation of TiC by the direct reaction of titanium and carbon without the need of the dissociation of the SiC. Nonetheless this technique during laser processing was seldom reported, and the few researches found were only on substrates other than aluminium [3,22].

In this work, alloying using Ni–Ti–C powder was investigated as a novel method of introducing TiC particles within a structure of Al–Ni intermetallics in an A356 aluminium matrix. Using this method, the TiC forms by an in-situ reaction and a more uniform dispersion of the TiC particles is achieved in the alloyed layer compared to when solid particles are injected in the melt. The uniform distribution of TiC particles could aid in strengthening the structure and enhance the tribological characteristics. In order to determine the effects of these additional carbides, a comparison of microstructure, alloying content, hardness and sliding wear resistance of surfaces alloyed with this technique with respect to surfaces alloyed using nickel was also performed. The authors have published the effects of such alloying on the corrosion resistance of the surfaces [23] but no other similar work was identified in the literature where such alloying on aluminium was reported and where such direct comparisons were made.

2. Experimental procedure

2.1. Materials used

Surface processing was performed on an A356 continuously cast aluminium alloy supplied by Norsk Hydro ASA (Norway) containing 6.97 wt% Si, 0.29 wt% Mg, 0.1 wt% Fe, 0.1 wt% Ti and 0.1 wt% of other trace elements with a balance of aluminium. The bars were machined into 10 mm thick plates that were grit-blasted (to a roughness of 4.3 ± 0.5 μm Ra) and graphite-sprayed prior to laser processing. Laser alloying was performed by simultaneously irradiating the surface and supplying alloying elements through a powder stream co-axial to the laser beam. Two powder mixtures were used in this study; one composed of 100% Ni powder while the other composed of 75 wt% Ni, 20 wt% Ti and 5 wt% C. The latter mixture was created by mixing 20 wt% Ni-Graphite, 60 wt% Ni and 20 wt% Ti. The raw powders used were 10–45 μm nickel powder from Praxair, 22–90 μm titanium powder from Sulzer Metco and 20–90 μm Ni-Graphite powder from Sulzer Metco (containing 75% nickel and 25% graphite).

2.2. Laser processing

The laser processing was performed using a Rofin Sinar Wegmann Baasel fast axial flow CO_2 laser operating in continuous wave mode, equipped with a co-axial powder delivery head supplied by a Sulzer Metco Twin 10-C powder feeder. The laser beam was focused using a ZnSe lens with a focal length of 190.5 mm. The incident laser power applied at the surface was 2.7 kW (measured with a Primes PMT 120icu power meter), and a beam diameter of 2 mm was used. The traverse rate was 1000 mm/min and argon was used as both co-axial and carrier gas at rates of 20 l/min and 8 l/min respectively. The powder mass flow rate was set to 0.02, 0.03, 0.04 and 0.05 g/s for subsequent experiments, and an overlap of 25% between each track was used to create a number of surfaces. It is to be noted that each respective surfaces was created in a single continuous process using a rectangular spiral track for surfaces intended to be cross sectioned for characterisation and using a circular spiral path for surfaces intended for wear testing; the direction of travel was always inwards. For comparative purposes, laser remelting was also conducted using similar laser parameters but without the powder addition.

2.3. Metallography and characterisation

Laser alloyed samples were sectioned and polished using appropriate metallographic techniques to permit optical and Scanning Electron Microscopy (SEM) to be performed. A Nikon Optiphot-100 was used for optical microscopy and SEM analysis was performed using a Carl Zeiss Merlin field emission scanning electron microscope while Energy Dispersive X-Ray Spectroscopy (EDS) was done using an Ametek EDAX trident system fitted with the SEM. X-Ray Diffraction (XRD) analysis was performed using a Bruker D8 X-Ray diffractometer with a Cu-source ($\lambda = 0.15406$ nm) using a Bragg-Bentano configuration. This analysis was performed on portions of the alloyed surfaces ground flat up to a 4000 grit finish.

Hardness measurements were performed on the cross-sections of the alloyed surfaces using a Mitutoyo MVK-H1 micro hardness tester. Readings were taken approximately 0.25 mm below the surface at intervals of 1 mm parallel to the surface. The load used was set to 500 g and the loading time was 10 s. A minimum of 10 readings for each sample were taken.

2.4. Tribological testing

Wear testing was performed on surfaces laser alloyed using a circular laser track, the surfaces being ground flat and polished up to a 3 μm finish. Prior to wear testing the surfaces were cleaned in an ultrasonic bath of isopropyl alcohol for 5 min and then left to dry in a stream of air. The samples were then weighed on a Precisa 404A microbalance with an accuracy of ±0.1 mg. Pin-on-disc wear testing was then conducted following the ASTM standard *G99 'Standard test method for wear testing with a pin-on-disk apparatus'*. The counter-body used was a pin having an AISI 52100 chrome steel ball ($878 \pm 4\,HV_1$) of 6 mm diameter fitted to a holder. The ball was cleaned in acetone and weighed on the microbalance prior to being attached to the holder. A load of 15 N was used in all experiments and testing was performed on 32 mm and 22 mm wear tracks using rotational speeds of 60 rpm and 87 rpm respectively. The linear speed was therefore always kept at 0.1 m/s and the total sliding distance was 500 m. During testing the frictional force on the pin was recorded. After the test, the sample disc and ball were removed from the test setup, cleaned and weighed again to determine any mass loss/gain. SEM analysis was also performed on the wear scars and on cross sections of the wear tracks.

3. Results and discussion

3.1. Microstructural analysis

Uniform and repeatable alloyed surfaces of approximately 1 mm in depth were created using the parameters described in Section 2.2. Fig. 1 shows typical macrostructures of the cross-sections of the surfaces alloyed with nickel and those alloyed with Ni–Ti–C. Mixing of the alloying elements was uniform and the majority of the alloying elements completely melted and mixed into the melt pool. For the case of the surfaces alloyed with Ni–Ti–C, only some small graphite particles survived the alloying process, and some of these can be seen in Fig. 1b as small black particles.

Fig. 2 shows the typical microstructures for the surfaces alloyed with 0.05 g/s of nickel powder, whilst Fig. 3 presents a typical microstructure for the surfaces alloyed with Ni–Ti–C using 0.05 g/s