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# Laser surface alloying of an A356 aluminium alloy using nickel and Ni-Ti-C: A corrosion study

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ABSTRACT

An A356 aluminium alloy was laser surface alloyed with nickel and Ni-Ti-C. A microstructure composed of aluminium–nickel intermetallics in an aluminium silicon matrix was produced when the surfaces were alloyed using nickel. Alloying using Ni-Ti-C resulted in an additional Al-Si-Ti intermetallic and TiC particles that formed by an in situ reaction directly in the melt pool. Corrosion testing was performed to determine any effects on the corrosion resistance due to the alloying process. The testing showed that the alloyed surfaces had reduced corrosion resistance compared to the untreated material. The presence of the intermetallics weakened the protective oxide and resulted in interdenritic corrosion. The surfaces alloyed with a low alloying content of Ni-Ti-C showed better resistance to localised corrosion extending deeply into the material as compared to the surfaces alloyed with nickel. On the other hand, the surfaces alloyed with nickel proved to resist better generalised widespread corrosion.

## 1. Introduction

Aluminium alloys are renowned for their low density and ease of fabrication, and for this reason, they found a wide range of applications especially in the transport industry [1]. However, these alloys have poor tribological characteristics that hinder their use in many other applications; the surface processing of these alloys is thus of great interest such that to overcome this limitation. The laser surface alloying of aluminium is a useful surface processing technique since it offers the advantage of localised processing and results in homogenous surfaces firmly bonded to the substrate. In fact, there are various reports confirming that the laser surface alloying of aluminium does improve considerably the tribological characteristics at the surface [2–4]. Such processing, however, can also affect other important properties like the corrosion resistance; therefore, investigating the effects of laser alloying on the corrosion resistance of aluminium would be of great interest.

Other work that targeted corrosion characteristics of laser alloyed aluminium resulted in improved corrosion performance [5]. Work by Watkins et al. [6] showed that alloying a 2014 aluminium alloy with various additions increased the pitting potential of the surface, the best improvement being achieved when alloying with Ni-Ti [6].

Anodic polarisation tests in 3.5% NaCl solution on laser alloyed surfaces with nickel performed by Gordani et al. [7] showed that the corrosion potential for the alloyed layers was higher than that of the 356 aluminium alloy. Lower corrosion currents and higher pitting potentials were also reported; still, a reduced passivation region was also noticed. This improvement in corrosion resistance was attributed to the fine Al-Ni intermetallics which were uniformly dispersed and to the Ni-rich aluminium solid solution [7]. Similar tests were carried out on surfaces alloyed with Ni-Cr-Si-B by Man et al. [8] with similar results being obtained. The lack of passivation in this case was explained by the presence of different phases that create local galvanic cells [8]. Corrosion testing on surfaces produced by the introduction of ceramics by Man et al. [9] showed that corrosion resistance was reduced due to the fact that the matrix–ceramic interfaces were ideal pit initiation sites due to the impurities present and also because the passive film was highly weakened in these areas [9].

In this study, an A356 aluminium alloy was laser surface alloyed using nickel and a mixture of Ni-Ti-C powders, the latter being a novel method that enables the production of TiC particles in the alloyed surface by means of an in situ reaction. Alloying using this technique is beneficial since it enables the introduction of a fine dispersion of carbides that could additionally reinforce the intermetallic structure obtained by the addition of nickel, resulting in surfaces that could resist tribological degradation to a higher extent. The in situ formation of the TiC particles is also beneficial since a better dispersion of alloying additions is obtained in the liquid state compared to when direct injection of particles is used. This in turn results in a better distribution of carbides upon solidification. Many studies can been found concerning laser alloying with nickel [7,10,11] as well as a few other reports of alloying using Ni-Ti-SiC [3,12]. No reports could however be found on alloying with Ni-Ti-C on aluminium. Moreover, only few studies concerning laser alloying with nickel focused on the effects on the corrosion behaviour

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of the alloyed surfaces [7,11], while no studies could be found which are related to the corrosion behaviour of surfaces alloyed with nickel with incorporation of TiC particles. Despite the fact that laser alloying in this study is intended more as a means to improve the tribological behaviour of the surfaces, such surfaces can nonetheless be exposed to corrosive environments during their application, and corrosion studies would thus be of interest.

The aim of this work was therefore to investigate the corrosion behaviour of aluminium surfaces laser alloyed with nickel and Ni-Ti-C. The microstructure of both alloying system was studied in order to understand better the mechanisms leading to the corrosion of the surfaces. Potentiodynamic and salt-spray testing were conducted in order to compare the corrosion behaviour of the surfaces created using different parameters and different alloying additions in comparison with the untreated material.

## 2. Experimental procedure

### 2.1. Materials used

Surface processing was performed on an A356 continuously cast aluminium alloy supplied by Norsk Hydro ASA (Norway). The composition of the alloy according to the material certificate is given in Table 1. 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 in the form of 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 was 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 and their specifications are given in Table 2.

### 2.2. Laser processing

Laser processing was performed using a Rofin Sinar (Germany) continuous wave $CO_2$ laser equipped with a co-axial powder delivery head supplied by a 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, and a beam diameter of 2 mm (±0.1 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 lit/min ($3.3 \times 10^{-4}$ $m^3/s$) and 8 lit/min ($1.3 \times 10^{-4}$ $m^3/s$) respectively. The powder mass flow rate was set to 0.02, 0.03 and 0.04 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 surface was created in a single continuous alloying process with no interruption to powder flow or to the laser beam.

### 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. 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 (λ = 0.15406 nm) using a Bragg–Bentano configuration. The analysis was performed on portions of the alloyed surfaces ground flat up to a 4000 grit finish.

### 2.4. Corrosion testing

For potentiodynamic corrosion testing, the alloyed layers were ground flat and polished to a mirror finish using 3 μm diamond paste. Tests were carried out using a Gamry Reference 600 computer controlled potentiostat and a three-electrode corrosion cell with a saturated calomel reference electrode (SCE) and platinum counter electrode. In order to take readings as close as possible to the sample, the reference electrode was placed inside a Luggin capillary tube filled with the test solution, and the tip of the Luggin probe was positioned close to the sample. The area to be tested was masked using porthole electrochemical sample masks from Gamry such that only a circular area of 1 $cm^2$

**Table 1**
A356 alloy composition.

| Composition wt%[*] | | | | | | | |
|---|---|---|---|---|---|---|---|
| Si | Mg | Fe | Cu | Mn | Zn | Ti | Other |
| 6.7–7.3 | 0.27–0.33 | 0.12 | 0.012 | 0.02 | 0.012 | 0.12 | 0.2 |

[*] Single values represent a maximum limit.

**Table 2**
Powders used for alloying.

| Powder | Size/μm | Purity | Supplier | Product name |
|---|---|---|---|---|
| Ni | 10–45 | 99% min | Praxair | NI-101 |
| Ti | 22–90 | 99.5% | Sulzer Metco | Sulzer Metco 4010 |
| Ni-Graphite | 20–90 | Ni 25% C | Sulzer Metco | Metco 307NS-2 |

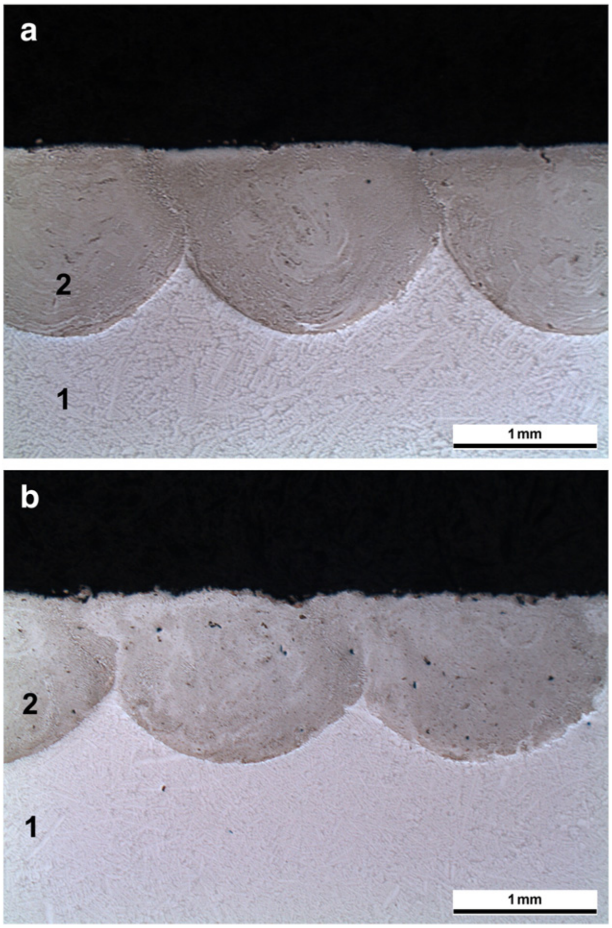

**Fig. 1.** Alloyed surfaces created with 0.03 g/s powder flow rate using (a) nickel and (b) Ni Ti C, where the area marked '1' is the base material and that marked '2' is the laser alloyed region.