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The role of microstructural characteristics in the cavitation erosion behaviour of laser melted and laser processed Nickel–Aluminium Bronze

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ABSTRACT

In this study two types of laser surface treatment, laser surface melting and laser processing, were used to treat the surface of as cast Nickel–Aluminium Bronze. The two treatments were then subjected to cavitation erosion testing and were compared against as-cast Nickel–Aluminium Bronze. While the cavitation performance of the two types of laser surface treatment was equivalent, the morphology of the eroded surfaces was different. Several materials characterisation techniques including neutron diffraction for residual stress measurements and SEM were used to explain why the two eroded surfaces were different. It was found that the tensile residual stresses in the laser melted sample weakened the sample, which negated its superior strength when compared with the laser processed sample. It was also observed that the erosion and pitting in the laser melted sample were deeper and they were attributed to the tensile residual stresses accelerating the attack at grain boundaries.

1. Introduction

Cavitation erosion is a common problem for metallic components that are exposed to high speed fluid flow environments, such as ship propellers and valves. The cavitation process involves the collapse of a bubble in a fluid close to the surface of a component. The collapsed bubble sends a shock wave through the liquid and onto the surface of the component. This occurs repeatedly and creates a fatigue type loading on the surface [1]. The surface accumulates damage and eventually minute flakes are eroded off the sample, creating the characteristic pitted structure. The rate at which this process occurs is dependent on several factors including the properties of the materials such as strength, and strain hardening rate, second phase particles and the presence of grain boundaries, which are weaknesses in the materials structure. The frequency and veracity of the cavitation process also play a role and as such comparisons of cavitation testing can be difficult.

Being a surface based phenomenon, several groups around the world have been tackling the problem by enhancing the surface characteristics of the base material with various surface coatings and treatment techniques. This has included laser plasma hybrid spraying of NiTi alloy [2], boronizing heat treatments of stainless steel [3], laser surface alloying of Aluminium to a hard intermetallic layer [4], laser melting of stainless steel [5,6], laser surface alloy of Ni–Cr–Si–B on brass [7], and the laser surface alloying of steel with Aluminium [8]. The consistent aspect of all these different treatments is that the new layer is harder and more wear resistant than the substrate and in all cases the cavitation erosion behaviour was improved.

The alloy that is the subject of this investigation is Nickel–Aluminium Bronze (NAB). NAB is a copper based alloy with additions of Aluminium, Nickel and iron. It is used extensively in marine environments due to its excellent combination of strength and corrosion resistance. Its two most common applications are valves and ship propellers. Both of these applications involve exposing the alloy to flowing fluids and as such cavitation erosion is an issue. There has been an attempt to improve the cavitation behaviour of NAB through laser cladding of NAB on NAB [9]. The hardness of the coating was improved and as such the cavitation erosion performance was also improved. However for laser

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cladding the Widmanstatten microstructure formed, which is known to have poor stagnant sea water corrosion resistance and as such is not applicable to valves and propellers that spend significant amount of time stationary [9].

Along similar lines the laser melting and alloying of Manganese–Aluminium Bronze (MAB) which is a similar alloy to NAB have been investigated by Tang et al. [10,11]. Both techniques improved the cavitation corrosion behaviour of MAB in fact the alloying of Aluminium with MAB produced cavitation erosion rates 30 times higher than MAB. While these results are substantial the Widmanstatten microstructure still prevailed and as such the stagnant sea water corrosion may be poor. Therefore a laser processing technique that can both improve the cavitation erosion behaviour of as cast NAB, as well as improve the stagnant sea water behaviour is desirable for the applications of valves and propellers.

A technique that has not been explored with NAB is laser processing [12]. This technique heats the material up to just below the melting point for a long enough duration that a phase transformation can occur. An example of this is the surface hardening of steels with a laser, where the heating from the laser transforms pearlite colonies into austenite and the subsequent fast cooling forms hard martensite. The phase transformation utilised in NAB is the reverse eutectoid reaction $\alpha+\kappa_{III}\rightarrow\beta$. Then with the right processing parameters the Widmanstatten microstructure is avoided.

The role of residual stress on the cavitation performance of materials has received very little attention. A lot of the interest in relation to this area is the use of the cavitation process to impart compressive residuals stresses for improved fatigue performance [13]. However the role of residual stress on the rate of cavitation is not well understood. Mathias et al. [14] have measured the residual stress and shown that initially during cavitation exposure a compressive residual stress is formed followed by no change in the stress levels and then the formation of tensile residual stresses. Preece and Draper [15] concluded that tensile residual stresses formed during laser surface melting are detrimental to the cavitation performance of the two steels that were under investigation.

This paper seeks to evaluate the new laser processing technique in relation to cavitation erosion performance and compares it against laser surface melting. Residual stress analysis using neutron diffraction was used to evaluate the differences in residual stress to understand the role of residual stress on the cavitation erosion performance of laser treated NAB.

2. Experimental procedures

2.1. Laser treatments

Laser processing of as-cast NAB with nominal composition Cu-8.5Al-5Ni-4.5Fe (wt%) was carried out with a fibre coupled, 2.5 kW Rofin-Sinar Nd:YAG laser. The beam was delivered via a 1 mm diameter optic fibre terminated with a 200 mm collimating and focussing optic attached to an ANCAR CNC table. The surface of the NAB was grit blasted to increase absorption of the laser. Laser melting was conducted with a laser power of 1000 W with a Gaussian spot size of 3 mm diameter and a laser traversing speed of 1500 mm/min. No shielding gas was used and was found not to be detrimental to the properties of the treated material. Each track was 30 mm in length and an inter-track spacing of 0.5 mm was used to produce 30 mm^2 regions of melted material. The plate treated was 6 mm thick. The laser processing technique used a laser power of 780 W with an 8 mm diameter Gaussian spot using a traversing speed of 6 mm/min. Again each track was 30 mm in length with an inter-track pacing of 2 mm to produce a treated region of 30 mm^2.

2.2. Neutron diffraction

Residual strain through-sample-thickness scanning was carried out by a neutron diffractometer KOWARI. Details about this particular diffractometer can be found in [16]. The details of how neutron diffraction is carried out for residual stress measurement can be found in [17]. The specifics of how the instrument was set up for this particular set of experiments are given in the following. The neutron beam had a wavelength range of 1.20–2.85 Å with peak intensity at 1.5 Å. The {311} lattice plane for NAB was selected because it was found to have a peak at $2\theta=90^\circ$ and an adequately high intensity to conduct the experiment. An average in the d-spacing for each of the *x*-direction 25 points was taken over 11 points along the *y*-direction. Neutron diffraction data was collected for three perpendicular directions (two perpendicular in-plane direction and one normal) enabling the resolution of in-plane stresses and the unstrained lattice parameter d_0 to be determined. In order to calculate stresses from strains, Hooke's law used with elastic constants on the {311} family of planes was 115 GPa and Poisson's ratio, ν, in the {311} family of planes was 0.328.

2.3. Cavitation erosion testing

Cavitation erosion testing was performed using an ultrasonic horn (Sonic VCX) with a replaceable tip made from Ti–6Al–4V, which had a diameter of 13 mm. Testing was conducted in 3.5 wt% NaCl solution, with the specimen held at a depth of 10 mm. The horn was operated at a frequency of 20 kHz and amplitude 50 μm, and the horn tip was 1 mm above the specimen. The temperature was controlled using a coil to 25 ± 2 °C. Disc-shaped specimens (12.8 mm diameter) were machined from NAB coupons. These were polished to 1200 grit with SiC paper prior to testing. Each specimen was cleaned with ethanol, dried, and weighed before and after testing. The duration of each test was 6 h, and weight loss was measured by interrupting testing at regular intervals (1, 3 and 6 h). The results are an average of three individual specimens. All testes were done in accordance with ASTM G32

2.4. Sample characterisation

For optical microscopy samples were etched using a solution of 5 g $FeCl_3$, 15 ml HCl and 60 ml ethanol for 3 s. The grain size was measured using the linear intercept method where five fields of the microstructure were taken at a magnification where there was more than 100 grains in the image. Hardness traverses of the laser processed and as-cast substrate were conducted using a Buehler micro-hardness tester with a load of 300 g, using a Vickers indenter. Samples for SEM were mounted in Bakelite, ground and polished down to a colloidal silica and then coated with a 20 nm layer of carbon for improved conduction in the SEM.

2.5. Finite element modelling

The finite element code ANSYS version 14.0 was used to simulate both types of laser treatment. The code solved the heat conduction equation

$$\rho C_p\left(\frac{\partial T}{\partial t}\right)=\nabla(k\Delta T) \qquad (1)$$

where ρ is density, C_p is the specific heat, T is temperature and k is Boltzmann's constant. A subroutine was created to mimic the heat distribution of the laser as well as its movement across the sample.