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Erosion damage of laser alloyed stainless steel in mercury

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Abstract

The effect of laser surface alloying of type 316 stainless steel on the erosion resistance in mercury has been investigated. The alloying was produced by melting predeposited Al–Si powder and a portion of underlying substrate with a pulsed Nd:YAG laser beam. The microhardness of the modified layer was found to be 2.5 times higher than that of untreated steel. The erosion test of laser alloyed surface and steel in mercury was carried out by using the electromagnetic impact testing machine. The laser alloyed surface was found to be less damaged after 10^5 cycles of impacts compared to untreated stainless steel. However, after 10^6 cycles the erosion resistance of the modified layer is much lower than that of untreated steel. Liquid metal embrittlement in contact with mercury and residual stresses were considered as factors impairing the erosion resistance of the laser alloyed surface.

Keywords: Laser surface alloying; Cavitation erosion damage; 316 stainless steel; Aluminum; Silicon; Mercury

1. Introduction

The spallation neutron source (SNS) is an accelerator-based neutron scattering facility that provides pulsed beams of spallation neutron by bombarding a mercury target with 1 GeV protons. Structural materials in the SNS mercury target container have to bear great loads in terms of radiation dose and contact with high velocity flowing mercury [1]. The pulsing proton beams also create pressure waves by rapid heating in the mercury, which both causes stress transients in the target container and induce cavitation in the mercury [1–5]. Collapse of the cavitation babbles in turn induces violent erosion of the target container wall. Commonly, cavitation erosion is defined as a progressive loss of material from a solid due to the impact action of the collapsing bubbles or cavities in the liquid near the material surface.

Consequently, three materials issues are currently being addressed related to the mercury target container module: cavitation erosion, radiation effects, and compatibility with mercury. After extensive investigations, type 316 stainless steel (316SS) was found to be the best material for target modules with respect to radiation effects and compatibility with mercury [1–3]. However, cavitation erosion has the potential to seriously limit the service lifetime of a target container made of 316SS, owing to its relatively low cavitation erosion resistance [5], which is mainly attributable to a low hardness (about 200 Hv) [6].

Potentially, the cavitation–erosion resistance of annealed 316SS may be improved by hardening the material via surface treatments or cold-work [7]. Laser surface alloying is an attractive method of surface hardening due to formation of a small heat-affected zone leaving the bulk properties unchanged and the possibility of forming novel surface alloys unattainable by other methods. The relatively high rate of processing, ease of automation, and possible operation at atmospheric pressure are other advantages of laser alloying over conventional surface modification techniques [6,8–11].

It has been shown [6,8] that laser alloying of the type 316SS with Al–Si powders significantly improved both microhardness and cavitation erosion resistance in a 3.5% NaCl solution (with an improvement of 3.75 and 11.1 times respectively compared to the as-received steel specimen). In view of that it would be interesting to investigate the feasibility of laser surface

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modification of the type 316SS by alloying with Al–Si against cavitation–erosion damage in mercury.

Therefore, the aim of the present work is to investigate the effect of laser surface modification of the type 316SS by alloying with Al–Si on the erosion resistance in mercury. The erosion tests in the mercury environment of the modified layer and untreated substrate were carried out using the electroMagnetic IMpact Testing Machine (MIMTM).

2. Experimental

2.1. Laser surface alloying

Austenitic stainless steel 316SS, with a chemical composition of 16.79 Cr, 10.3 Ni, 2.16 Mo, 0.06 C, 0.68 Si, 0.027 P, 0.001 S and balance Fe in wt.%, in a form of a plate specimen of $60 \times 60 \times 2.5$ mm^3 was used as the substrate material.

The powder placed as slurry on the surface of the specimen consists of reagent grade Si and Al in the weight ratio of 2:3. The use of this proportion allows producing modified layer with very high microhardness and cavitation erosion resistance in a 3.5% NaCl solution at room temperature [6]. The specimen was painted with the mixture of powder and an organic binder and then dried on a hot plate for 4 h at 250 °C. Finally, the painted surface was polished with a 1000 grit silicon carbide paper to achieve a uniform layer of about 0.27 ± 0.01 mm thick [12].

The laser treatment was carried out using a pulsed Nd:YAG laser (wavelength of 1.06 μm) with a spot size of 0.36 mm in diameter. The flow of argon was used as a shielding gas.

During solidification, the area molten by the laser beam undergoes inevitable shrinkage. Tensile stress of the order of or more than yield strength is generated due to constraints imposed by the surrounding material [13]. Such tensile stress can induce cracking of the laser alloyed surface (LAS). It has been found earlier [12] that the relation to cracking of the Al–Si LAS can be suppressed by controlling the substrate temperature during laser alloying. Therefore, in the present investigation, the temperature of the substrate during laser alloying was maintained as high as 350 °C in order to attain a crack-free homogenous modified layer. Laser alloying of an 8×35 mm^2 area was carried out by melting the painted surface (Fig. 1B). The processing parameters of the laser treatment are shown in Table 1.

Table 1
Parameters of laser alloying

Frequency of pulsing, Hz	100
Pulse voltage, V	220
Pulse duration, ms	2.5
Output energy, W	0.88
Laser beam scanning speed, mm/min	200
Energy density, W/mm^2	0.76
Overlapping ratio, %	45
Thickness of placed powder, mm	0.27
Substrate temperature during alloying, °C	350

2.2. Erosion test

Before the erosion test the surface of the specimen was polished to a 1 μm diamond finish. The erosion test of the modified layer and untreated substrate was carried out in mercury using the MIMTM (Fig. 1A) [14]. The inner diameter and height of the mercury chamber in the MIMTM are ϕ100 mm and 15 mm, respectively. Vapor pressure of mercury was 0.28 Pa at 300 K. The temperature of mercury during the test did not exceed 40 °C that was controlled by air cooling system. The impulsive pressure was imposed on the mercury through the plate specimen driven by the striker which is controlled by the electromagnetic force. Compressive or tensile stresses are created in the chamber, depending on the striker moving direction. The maximum magnitude of pressure in the chamber was about of 0.3 MPa. The frequency of pulses was 25 Hz which is the same as that in Japan SNS. The changing pressure in the chamber exerts cavitation in mercury, which in turn leads to cavitation erosion of surfaces contacting with mercury [14].

The MIMTM was developed to examine the pitting damage at over 1 million cycles that is necessary to extrapolate the lifetime of the candidate target to 7×10^7 of beam pulses [2,14] This number of value set (7×10^7 of beam pulses that corresponds to 2 weeks of working at 1 MW beam power at 60 Hz) is minimum to estimate if the material can be used in the SNS at the present conditions. Using a mask, two parts of the plate

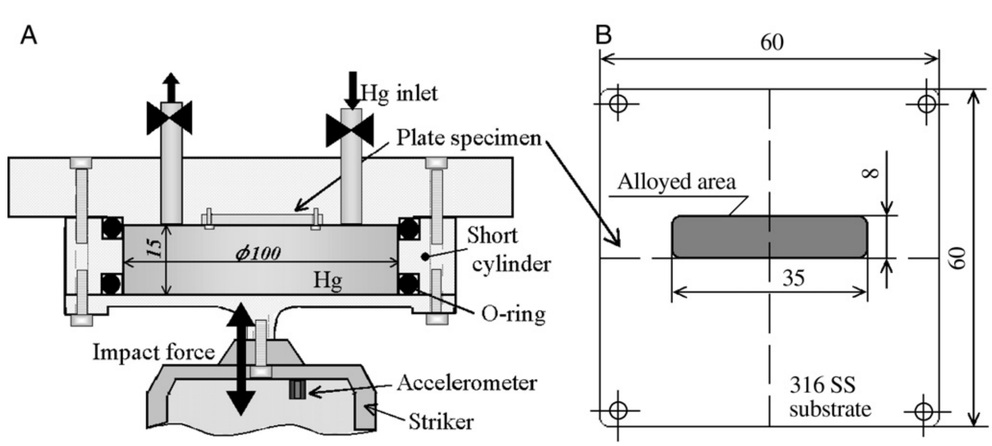

Fig. 1. Schemes of electroMagnetic IMpact Testing Machine (MIMTM) (A) and specimen for cavitation erosion test with laser alloyed area (B).