Erosion Damage of Laser Alloyed Stainless Steel in Mercury

Sergey ZHEREBTSOV, Takashi NAOE, Masatoshi FUTAKAWA, Katsuhiko MAEKAWA

1 Satellite Venture Business Laboratory, Ibaraki University 4-12-1, Nakanarusawa-cho, Hitachi-shi, Ibaraki, 316-8511, Japan
2 The Research Center for Superplasticity, Faculty of Engineering, Ibaraki University, 4-12-1, Nakanarusawa-cho, Hitachi-shi, Ibaraki, 316-8511, Japan
3 Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki, 319-1112, Japan

Effect of laser surface alloying of type 316 stainless steel on the erosion resistance in mercury was investigated. The alloying was produced by melting Al-Si powder predeposited on 316 SS substrate with a pulsed Nd:YAG laser beam. Microhardness of modified layer is higher than that of untreated 316SS. It was found during erosion test that laser alloyed surface is hardly damaged after 10^5 cycles. However after 10^6 cycles the erosion resistance becomes much lower than that of untreated steel. Mercury attack, e.g. liquid metal embrittlement, on modified layer has been revealed.

Key words: laser surface alloying, cavitation erosion damage, mercury, liquid metal embrittlement

1. Introduction

Type 316 stainless steel was found to be the suitable material for future use of the Spallation Neutron Source target module with respect to radiation effects and compatibility with mercury. However, owing to the relatively low cavitation erosion resistance its application is limited in environments where cavitation is present [1].

There are many techniques to enhance surface resistance against cavitation erosion. An attractive method among them is laser alloying (LA), because of the formation of a small heat-affected zone leaving the bulk properties unchanged and the possibility of forming novel surface alloys unattainable by other methods. Relatively high rate of processing, ease of automation, possible operation at atmospheric pressure are other advantages of this technique [2].

It has been found [2], that LA of the 316SS with Al-Si powders appropriately improved both microhardness and cavitation erosion resistance in NaCl solution. It would be interesting to investigate an efficiency of such laser treatment against cavitation erosion in mercury.

The aim of the present work is to investigate an effect of laser surface modification of the 316SS by alloying with Al-Si on the erosion resistance in mercury.

2. Experimental

Austenitic stainless steel type SS 316 (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 plate specimens of 60×60×2.5 mm^3 was used as the substrate material. Powder placed as slurry on the surface of the sample consists of reagent grade Si and Al in the weight ratio of 2:3 [6]. The specimens painted with the slurry were dried on a hot plate for 4 hours at 250°C. Then the painted specimens were polished to achieve a uniform layer of about 0.27±0.01 mm thick.

Laser treatment was carried out using a pulsed Nd:YAG laser. The flow of argon was used as a shielding gas. Temperature of the substrate during LA was maintained at 350°C approximately, in order to attain crack-free homogenous modified layer.

The erosion test was carried out in mercury using the electroMagnetic Impact Testing Machine [3]. The frequency of pulses was 25 Hz. Using a mask, two parts of the plate sample were subject to 10^5 and 10^6 cycles impact.

In order to estimate the effect on mercury attack laser alloyed surface (LAS), two samples were exposed in mercury for 100 h at 25 and 150°C respectively. The size of the samples was 10×10×2 mm^3 and the laser alloyed area 7×7 mm^2. A part of the LAS of each sample was protected from contact with mercury by masking with a polyamide tape.

3. Results

Laser alloyed layer has a lamella-type microstructure (Fig. 1) whose microhardness is about 3 times higher than that of the untreated substrate (Hv 1100 approximately). Distribution of chemical elements (Fe, Al, Si, Ni and Cr) through the LAS was quite homogeneous. Microstructure of the modified layer consists of two phases with a little bit different hardness and chemical composition. Content of Si and Al in the light phase is 38.6% and 19.1% respectively. Dark phase consist of 20.3% of Si and 39.4% of Al. Light phase (probably γ-FeAlSi) alloy is harder by about 10% than dark phase (probably FeAl3 alloy).

![Fig. 1 Microstructure of LAS](image)

Results of erosion tests of the LAS and 316SS after 10^5 and 10^6 pulses are presented in Fig. 2. It is seen that the number of pits in the LAS after 10^5 pulses is smaller than that in 316SS substrate (Fig. 2, left). Total area of pits observed in laser treated surface is 9% while that in untreated steel surface is 20%.

However the LAS was destroyed completely after 10^6 pulses, while about 15% of initial surface is still observed in the untreated area of the sample (Fig. 2, right). Depth profiles of each area after erosion test are illustrated in Fig. 3.

It is seen on the LAS tested up to 10^5 cycles that the dark (soft) phase is eroded more readily than light (hard) (Fig. 4a). Small cracks were formed in the eroded areas. Extension of the cracks leads to consequent fracture of the LAS. The fracture seems to be brittle without any sign of a plastic zone (Fig. 4b).
Immersion of sample in mercury at 150°C for 100h does not change noticeably microhardness of LAS. At the same time it seems that indentation in immersed areas produces more cracks than that in masked area (Fig. 5). Microstructure of LAS did not change visibly after immersion test, however tested surface was found to be brighter than masked one.

![Fig. 2 Images of LAS (top) and 316SS surfaces (bottom) after erosion test in mercury.](image)

![Fig. 3 Profile of eroded surfaces after 10^5 and 10^6 cycles](image)

![Fig. 4 Pit initiation (a) and brittle fracture (b) in LAS](image)

### 4. Discussion

The resulting localized pressures might be negative, and induce cavitation on the interface. The collapse of cavitation bubbles impose high impulsive pressures on small areas of the surface and cause localized cumulative damage by a fatigue-like process [4]. Increase in surface hardness seems to be one of methods to resist erosion damage. Indeed, the positive correlation between erosion resistance and the Vickers hardness have been found in some papers [2, 5].

In our case LAS has a high hardness (around Hv 1100) that was supposed to be enough to guarantee an excellent erosion resistance. However it is true only for the number of cycles of 10^5. Increase in the period of test leads to a drastic decrease in erosion resistance.

Process of erosion evolution in the LAS could be described as follows. The cavitation erosion resistance of a dual-phase system is primarily determined by the resistance of the weaker phase, which is preferentially eroded away. In our case the softer matrix was eroded faster than the harder lamellae (Fig. 4a). Increase number of cycles leads to cracks appearance, which initially form in matrix, but further branch cracks propagate through the lamellar phase. With further impact material disengage from the surface by propagation of cracks to be almost parallel to initial surface (Fig. 4b). Finally a large size area of material removal appears on the eroded surface of the LAS (Figs. 2 and 3).

Meanwhile mercury environment can also be a reason of a surface degradation due to LME. Change in color and more intensive cracking of LAS after immersion test compared to masked part (Fig. 5) imply that contact with mercury apparently changes properties of the LAS. Besides, degradation of surface due to LME is known to be typical for some Al alloys [4]. It noted, that damage initially is localized in the dark grey phase with high content of Al. Faster damage of the Al rich phase hence can also be associated with LME of this phase.

![Fig. 5 Cracks around indents after immersion test in mercury in masking (a) and unmasking (b) area](image)

### 5. Conclusions

Effect of laser surface alloying with Al-Si powder of type 316 stainless steel on the erosion resistance in mercury has been investigated. Microhardness of modified layer is sufficiently higher than that of untreated 316SS. The erosion test in mercury environment has revealed that after 10^5 cycles of impacts laser alloyed surface has better erosion resistance than that of 316 steel. However for 10^6 cycles erosion resistance of modified layer much lower compared to that of untreated steel. A liquid metal embrittlement effect on modified layer has been found after immersion test in mercury.

### 6. References