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Degradation of AlMg2 aluminium alloy caused by cavitation — An effect of cavitation intensity

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ABSTRACT

Investigations of an influence of various cavitation intensity on the cavitation erosion of AlMg2 alloy is presented. In order to learn an effect of low- and high-amplitude pulses on material degradation, long- and short-lasting tests were performed. Linear correlation between the cavitation load and mean depth of penetration rate of AlMg2 alloy in the long-lasting test occurs. Presence of particles of intermetallic precipitations in AlMg2 alloy accelerate the erosion. Changes of hardness during the short-lasting test are correlated with cavitation intensity. The exposition of AlMg2 alloy to cavitation of $J = 26\ \mathrm{kW/m^2}$ causes an increase of hardness that started with the beginning of the short-lasting test and was continued over the whole test. A decrease of cavitation intensity caused a delay in the beginning of the hardness increase, a decrease of rate of surface work-hardening and a decrease of hardness during the last minute of the short-lasting test. The dislocation investigations showed that the dense dislocation network, low-angle boundaries developed in the top layer of AlMg2 alloy, which was exposed to cavitation intensity $J = 11$ and $5\ \mathrm{kW/m^2}$, but in deeper layers the dislocation structure of dynamic recovery was observed. In the case of exposition of AlMg2 alloy to cavitation intensity $J = 0.03\ \mathrm{kW/m^2}$, the structure of dynamic recovery is observed in the top layer. With an increase of cavitation intensity increases density of dislocations in the top layer and the depth, at which the dynamic recovery structure occurs.

1. Introduction

Cavitation erosion is a complex phenomenon, in which imploding cavitation bubbles interact with a solid surface causing its gradual degradation. Therefore, it is often taken that mass loss of exposed material reflects intensity of cavitation load. The intensity of cavitation load is understood as a total number of cavitation micro-jets and shock waves that are generated during implosion of cavitation bubbles and impact materials surface. Attempts of measurement of aggressiveness of a simple cavitation bubble or a whole cloud of cavitation bubbles have been performed for many years. In 1955, Knapp investigated cavitation and cavitation erosion phenomena, and found that increase in a flow rate was associated with an increase in the length of a cavitation cloud and the number of cavities [1]. Moreover, he noticed that only few imploding cavitation bubbles from all traveling ones are able to cause damage (pit) in soft aluminium and the pitting rate increases logarithmically with flow velocity. In 1966, Benjamin and Ellis observed asymmetrical deformation of vapour bubbles in the presence of a nearby solid boundary, which resulted in formation of a micro-jet, which penetrates the bubble [2]. Later on, experimental investigations and fluid calculations proved that the micro-jet may reach velocity of approximately 600 m/s [3,4]. Investigation of the collapse of a single laser-generated cavitation bubble in respect to the distance from the centre of bubble to a solid surface showed that only bubbles imploding in direct contact with the solid surface produce most aggressive jets that hit the solid surface with maximum speed [5]. With an increase of the distance between the centre of bubble and the solid surface, the impact velocity of the jet falls down rapidly due to a damping effect of a water layer. This was likely the reason that Knapp observed only few pits on soft aluminium generated by the whole cavitation cloud [1].

Simultaneously with study of cavitation bubble implosion there were performed investigations of cavitation erosion of materials [6–9], correlations between materials properties and their cavitation resistance [7–9], and attempts to assess aggressiveness of the cavitation load and its correlations with material degradation [10–13].

Hammitt proposed to measure energy of individual pressure pulse generated by cavitation bubble collapse as the acoustic energy, in which the energy flux E of individual bubble collapse is equal $E = \frac{1}{\rho c}\int p^2 dt$ (p is a pressure wave, t is duration of pressure wave, ρc is the acoustic impedance of the liquid) [10]. Taking the summation of the energy fluxes (ΣE) for all cavitation pulses as the measure of cavitation power, the linear correlation between cavitation power and mean depth of penetration rate (MDPR) was found [11]. The results of Hattori et al.'s investigations [11] had an impact on further research in this

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direction, and affected mostly methods of measurement of cavitation pulses and cavitation intensity, and its correlation with cavitation damage [12–15]. Okada et al. [12] using piezoelectric ceramic discs for pressure detectors found several correlations: between number of pulses and their impact load, between cumulative impact load and cumulative area of indents, and between cumulative impact energy e, $e = \Sigma P_i^2$, where P_i is the impact load, and volume loss of tested materials: aluminium and copper. Furthermore, authors have found a lineal relation between the diameter and depth of indents [12]. Momma and Lichtarowicz [13] using transducers made from piezoelectric polyvinylidene fluoride (PVDF) films found out that the size of pressure transducers has an influence on the distribution of detected pulses: with an increase in the transducer size more pulses are measured (an increase in number and pulse height). Using similar method of calculations of cavitation energy to Okada et al. [12], Momma and Lichtarowicz obtained results showing excellent correlation of pulses energy with the peak (maximum) erosion rate (PER) [13].

Fortes-Patella and Reboud [15] have exploited the results of Okada et al. [12] and Momma and Lichtarowicz [13], and proposed a new idea to measure cavitation intensity, following their analysis of pit shape, jet impact or pressure shock wave emission and numerical calculation of plastic deformation of materials subjected to dynamic loading. As a pulses transducer the whole surface of exposed material was taken, and the pit size distribution was used for calculations of cavitation impact energy. Later on, Fortes-Patella and Reboud using 3D laser profilometry for a geometry analysis of pits generated in the short-lasting pitting tests [16] and based on dynamic elasto-plastic behaviour of a material and fatigue criteria, they assessed cavitation load and the erosion rate of a material in a long-lasting cavitation test [17].

Although cavitation load assessment with use of pit test provide good results, it should be noted, that not all cavitation pulses can form a pit, even in soft aluminium, as it was noticed by Knapp [1]. The analysis of the pulses distribution [12,14,18], the geometry of pits [16] and work-hardening of surface layer of exposed material [18,19] led author to distinguishing three kinds of cavitation pulses, depending on the results of their activity and fatigue criteria [20]. According to Ref. [20], pulses of Fraction 1 are high-amplitude loads, which act with the highest velocity and cause the highest strain rate. That is the least numerous group of pulses. Degradation caused by these pulses can be compared to low-cycle fatigue fracture. Degradation made by pulses of Friction 2 is compared to high-cycle fatigue fracture. These pulses are assumed to be responsible for gradual degradation and work-hardening of surface layer. Fraction 3 contains most numerous, low-amplitude pulses. Based on this division, the degradation process of a PVD coating-substrate system caused by cavitation was proposed [20]. Depending on the impact velocity, which is determined by pulse amplitude, a deformation mode of a coating changes from isothermal to adiabatic. The adiabatic process is induced by action of fraction 1 pulses, which cause the strain rate of about $10^4\ s^{-1}$ [21], while the isothermal process — by action of fraction 3 pulses. Due to high toughness of a PVD coating, its deformation is controlled by creep process, sliding and/or shearing along the column grains boundaries. However, due to low thermal conductivity of a PVD coating, no thermal effect affected the deformation mechanism of a substrate, which underwent isothermal elastic or elastic-plastic deformation [20].

This paper refers to the previous paper, in which the relative impact of each kind of cavitation pulses on the material degradation was analyzed [20]. It also covers the area of current direction of investigations of cavitation erosion [16,17,21–25]. However, in opposition to the previous analysis of degradation of a PVD coating – substrate system [20], the degradation process of a bulk aluminium alloy AlM2g is investigated in detail. Due to direct action of cavitation pulses on a soft AlMg2 material, the present paper concerns an effect of cavitation pulses and cavitation intensity on the degradation rate and the degradation mechanism that is different from that presented in Ref. [20]. In order to learn an effect of low- and high-amplitude pulses on material degradation, the dislocation investigations have been performed.

2. Methodology/Materials and Methods

The cavitation tests were performed using a cavitation chamber with a system of barricades (Fig. 1). The description of the cavitation chamber is presented in Ref. [18]. Measurements of cavitation pulses were performed using 113A72 PCB Piezotronics pressure transducers of 0–35 MPa measurement range, 0.148 mV/kPa sensitivity, 450 kHz resonance frequency and 4.5 mm effective membrane diameter, inlaid in a dummy specimen surface. Measurement duration was 2 s with 500 kHz sampling frequency at the inlet pressure $p_1 = 1000$, 1100 and 1200 kPa, outlet pressure $p_2 = 120$, 125 and 130 kPa, respectively,[1] and slot width $\delta = 5$ mm. Sensors were situated at five different distances from the slot: 8, 24, 40, 56 and 72 mm. Detailed description of pulses measurements is presented in Ref. [19]. Next, cavitation load, J, was calculated using following expression [18]:

$$J = \frac{1}{T}\frac{1}{\rho c}\sum_{k=1}^{M} n_k p_k^2 \qquad (1)$$

where T is the sampling period duration, ρ is the liquid density, c is the sound celerity of liquid, M is the number of pressure intervals, n_k is the number of pulses measured by means of a pressure sensor in a single interval, p_k is the value of pressure amplitude corresponding to each single interval midpoint and k is the consecutive number of the interval. This measure of cavitation intensity corresponds to the proposition of Hammitt [10] and Hattori [11], but it refers to a unit of time.

In order to investigate an influence of cavitation intensity on degradation of AlMg2 alloy following tests have been performed: long-lasting tests to obtain cavitation curves and short-lasting tests to analyse an impact of cavitation intensity on work-hardening and on dislocation development. The duration of the long-lasting erosion tests was 11 h, while the short-lasting tests lasted 5 min. The long-lasting tests were performed at $p_1 = 1000$ and 1200 kPa, $p_2 = 120$ and 125 kPa, respectively, and slot width $\delta = 5$ mm, while the short-lasting tests were performed at $p_1 = 1000$ kPa, $p_2 = 120$ kPa and slot width $\delta = 5$ mm. In each test 5 specimens (exposure surface area of one specimen is 16 × 45 mm) were examined, the position of each specimen corresponded to position of pressure sensors for cavitation load measurement. However, in a test for examination of dislocation structure, one specimen with exposure surface of 80 × 45 mm was used. AlMg2 aluminium alloy (5052 aluminium alloy) was chosen as a tested material. Chemical composition taken from the material's certificate and mechanical properties of tested material received from a standard tensile test are shown in Table 1. AlMg2 aluminium alloy was investigated in as-received condition. Mass losses of the specimens were measured using an analytical balance with 0.1 mg accuracy. Before the test and after each test exposure the specimens were cleaned, dried and reweighed. After 2 h of the exposure, when the specimens were not significantly eroded, the surfaces of the specimens were examined by means of the Philips XL-30 scanning electron microscope.

In order to investigate an influence of cavitation intensity on work-hardening, the microhardness was measured after every 1 min of test using an LMT-3 N-61530 tester with load of 0.005 N and loading time of 15 s. The measurements of the hardness were performed on each specimen on the side wall of specimens, 0.02 mm underneath the exposed surface. The mean value of hardness was taken from three measurements.

The dislocation structure was investigated using the Jeol JEM 3010 transmission electron microscopes at the Warsaw University of Technology. The dislocation foils were taken from the places of the pressure transducers locations: 8 mm (position 1), 24 mm (position 2) and 40 mm (position 3). With an increase in depth from the outer

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[1] Pressures are given in absolute units.