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The ability of using the cavitation phenomenon as a tool to modify the surface characteristics in micro- and in nano-level

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ABSTRACT

The aim of this paper is to investigate the possible application of the cavitation phenomenon as efficient method to modify the surface properties (e.g. the surface roughness) in the nano- and micro-levels. Aluminum alloy (AlSiMg) specimens were subjected to high speed submerged cavitating jets under various working conditions, for short time periods between 15 and 30 s. The force generated by the cavitating jet is employed to modify the surface roughness of the specimen. The target surface was analyzed with optical microscopy, white light interferometry, atomic force microscopy (AFM) and also with electrostatic force microscopy (EFM). The results show the possibility to use the cavitation bubbles as a nanofabrication method e.g. for shotless surface peening. With AFM, the deformation mechanism and the formation of planar or wavy slip were also investigated. EFM shows that the changes in the surface roughness also have a strong influence on the electrostatic field above a biased sample.

1. Introduction

The phenomenon of cavitation damage is complex since it includes both hydrodynamic and material aspects. Hydro-dynamically, cavitation is characterized by the appearance of vapor bubbles in a liquid subjected to a sudden decrease in pressure below the vapor pressure, in correspondence with the liquid temperature. Collapse of vapor bubbles in the sub-cooled environment creates liquid micro-jets which can cause damage to solid surfaces [1–4].

Cavitation causes different effects that are in general avoided or at least controlled in any hydraulic facility. It is well-known that cavitation can severely damage solid walls by removing material from the surface. On the other hand, cavitation is used in many diverse scientific and industrial applications (jet cutting, underwater cleaning, and improvement of fatigue strength of materials, etc.) with cavitation clouds produced by cavitating jets. It is also well known, that the impingement of cavitating jet leads to serious erosion in valves and associated hydraulic equipment [1–3,5–7].

The cavitation damage starts as a consequence of the contact between the specimen and the liquid microjet, following the collapse of the cavitation bubble (liquid–solid interaction in a micro-scale). The bubbles themselves are created when the pressure in the liquid falls below its vapor pressure. Collapse is followed by the subsequent vapor pressure increase [8]. The mechanical performance of a material is largely depending on its ability to absorb the shock waves without sustaining microscopic fractures on its surface [9,10].

As well known, the purpose of most laboratory tests regarding the cavitation erosion is to predict the material performance under cavitation attack in a full-scale hydraulic machine or structure. As the course of erosion is generally known to depend essentially on the distribution of the cavitation impacts, the reproduction of this distribution in a laboratory environment may be considered as a condition of reliable quantitative assessments [11].

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In order to provide a greater understanding of the cavitation damage phenomenon, a number of different testing techniques have been used by researchers to investigate the different cavitation damage stages. Still, this subject is in the focus of investigation, especially, when new technologies are used such as the pit-count technique, the 2D optical method, the 3D measurements by roughness meter, and the 3D laser profilometry technique [12]. Surface roughness is an important factor when dealing with issues such as friction, lubrication, and wear. It also has a major impact on applications involving thermal or electrical resistance, fluid dynamics, noise and vibration control, dimensional tolerance, and abrasive processes, etc. [13]. Surface roughness of metals which are used in the medical field as implants fixed to the bone is an important factor in the recovery process of the patient, because it affects osseointegration. It is reported that increased micro/submicron roughness could enhance the bone cell function [14]. The micro-roughness of the solids plays the main role for the heat transfer in a cross interface, which is important in a wide range of applications, such as microelectronics cooling, spacecraft structures, satellite bolted joints, nuclear engineering, ball bearings, and heat exchangers. The heat transfer mode at the micro-contact is conduction, which leads to a high temperature drop across the interface [15]. Changes in the surface roughness also influence the electrostatic field above a biased sample. In electrostatics the intensity of the electric near field is higher above structures with small geometrical curvature (e.g. sharp features). Such perturbed and intensive near fields could be desirable for some applications [16]. Surface roughness could exert a profound effect on the performance of radio-frequency (RF) cavities or slow wave structures [17–19]. Surface roughness may lead to excessive local electric field enhancement that could trigger RF breakdown [20,21]. Surface roughness may also cause local magnetic field enhancement which can lead to abrupt quenching i.e. loss of superconductivity [17,22].

Considering all points mentioned above surfaces with nano and micro scale roughness with regular or irregular shape, wavy or stripped shape etc. assumed to be important targets for research. Modifying the surface properties with cavitation has several advantages compared to common machining methods used for the same purpose (such as for example abrasive blasting, including shot peening or sandblasting) [42,43]: 1) Compared to shot peening it does not require balls (or other abrasive media besides water), so it is cheaper and cleaner. 2) The cavitation damage can be localized with the jet and the attacked surface area can be very small and/or narrow which can be advantageous for hard to reach areas. 3) The cavitation intensity can be easily controlled by the hydraulic and geometrical parameters. 4) There is no thermal effect to the target surface (compared for example to laser polishing methods). 5) The cavitating jet can be used to selectively pattern the target surface. Such controlled patterning with the jet is possible by selecting an appropriate nozzle (in simpler cases) or by applying a scanning jet and optional thin layers of temporary mask (e.g. a hard coating) to protect local areas.

Therefore the aim of this research is 1) to investigate the effect of cavitation on the surface of the tested AlSiMg alloy during the incubation time period, which refers to the time while only plastic deformation occurs on the surface of the target; and 2) by the characterization of the surface properties prove, that it would be possible to use cavitation as a tool to modify the roughness of surfaces in the sub-micron range in a controlled fashion. White light interferometry and atomic force microscopy (AFM) were used in this work, which – besides the quantitative characterization of surface roughness – can provide additional insight to the deformation process. To investigate the effect of the increased surface roughness on the electrostatic properties of the sample electrostatic force microscopy (EFM) was used.

2. Facility, cavitation characteristics

2.1. Facility setup

The experimental setup for the investigation of the damage resistance is a closed hydraulic loop. A high-speed submerged cavitating jet was produced in the test chamber by the adjustment of appropriate hydrodynamic conditions and the final outflow to the test chamber through the nozzle. The specimen was prepared and then mounted in the holder in the chamber in front of the nozzle. The chamber was filled with water and then the water was pressurized by a plunger pump. A shortcut line with a pressure gauge functioned as a pressure regulator in the system. The regulation of the water temperature with ±1 °C precision during the cavitation damage tests was achieved by a cooling circuit with a heat exchanger. The details of the chamber are shown in Fig. 1(a), the details of the test rig are published in a previous work [4].

The cavitating jet impinged on the specimen at 90° to its surface, as shown in Fig. 1(b). After a certain exposure time the facility was turned off, the chamber was evacuated and the specimen was removed. The specimens were dried, investigated and then the procedure was repeated with other specimens. The intensity of the cavitating jet was controlled via the upstream pressure (P_1) and downstream pressure (P_2), which were measured precisely by transducers and controlled using the needle valves (regulation valves). Filters were employed to remove particles from the circulating water. A temperature regulator and temperature sensors were used to control the water temperature. The nozzle could be mounted in the holder in two ways regarding the inlet and outlet diameters: divergent and/or convergent conicity. The apparatus in the facility (cavitating jet generator) was calibrated in order to obtain results with a high accuracy. The cavitation number was calculated based on the average exit jet velocity assuming one phase flow (the definition of cavitation number proposed by Thema in 1925 is more accurate compared to the ASTM definition, but still not enough). The cavitation number here is assumed to be an average because of the pressure fluctuation, the velocity decays and the compressibility change along the jet coordinates (R, X), thus the cavitation number varies with the points in the jet trajectory on the coordinates (R, X) [10,23]. In the experiments the convergent nozzle was used with inlet and outlet diameters of 1 and 0.45 mm respectively.

2.2. Cavitation mechanism and characteristics created by cavitating jet generator

As the high speed liquid jet from the nozzle enters the test chamber filled with liquid, shear stress occurs between the moving and the stagnating liquid as a result of the differences in their velocities. Thus vortices will occur and as a consequence the pressure inside these vortices will decrease to the level of saturation pressure at the working temperature. A number of small spherical bubbles are initially generated in a starting vortex formed at the jet tip and often connected circumferentially with each other in the form similar to a vortex ring (the bubbles are generated when the pressure in the center of the vortex reaches the saturation pressure of the working fluid temperature-conditions of cavitation). The rings of bubbles are connected tighter thus a cone of bubbles is formed around the jet in the shear region (Fig. 2) which decreases the momentum exchange between the jet and the ambient fluid. The effectiveness of the cavitation cone depends on the quantity and radii of the cavitation bubbles. The thickness of the cavitation cone layer is not constant over the full length of the cone (see Fig. 2). The jet is divided into many regions according to the cone state (cavitation state). In the cone development region both the number of bubbles per unit length