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Plastic deformation and modification of surface characteristics in nano- and micro-levels and enhancement of electric field of FCC materials using cavitation phenomenon

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ABSTRACT

The aim of this paper is to demonstrate and establish a possible application of the cavitation phenomenon as an efficient method to modify surface properties. Three FCC (Face Centered Cubic) materials were subjected to high speed submerged cavitating jets under certain working conditions, for time periods between 15 and 1800 s. The force generated by cavitation is employed to modify the surface roughness in nano- and micro-scales. The target surface was investigated with digital optical microscopy, atomic force and electrostatic force microscopy (AFM and EFM) and also with a white light interferometer. These different observation techniques indicate that at short exposure times, the observed characteristic features in the microstructure – hills, holes and wavy configuration – can be related to the start of the plastic deformation of the specimen surface. Longer exposure times inevitably result in a greater number of jet specimen interactions leading to specimen erosion and fracture. The results demonstrate the possibility to use cavitation bubbles as a micro-nanofabrication method for the surface preparation/modification or shoot-less surface peening. EFM results present a possibility of using cavitation as tool to enhance the electrostatic properties of a metal surface by modifying its roughness. The degree of enhancement depends on the material properties.

1. Introduction

Cavitation is generally considered to be an undesired, sometimes even harmful phenomenon in hydraulic systems. It was first discovered and investigated theoretically as a physical phenomenon, by Reynolds O. in 1873. Inertial cavitation was first studied by Lord Rayleigh in the late 19th century (Rayleigh, 1917).

Cavitation phenomenon is a process, which is characterized by small bubbles or large "cavities", which appear and grow when and where the pressure drops below the vapor pressure of the liquid at a given temperature. Pressure recovery causes these bubbles to implode in a few microseconds. These implosions or collapses generate pressure shockwaves, micro-liquid jets and noise. These implosions can be so violent that they produce local permanent deformation and rupture of the materials in its vicinity. Moreover, if cavitation replaces a large volume of the liquid in a machine, a drop in efficiency could be the result. These side effects (noise, vibration, erosion and performance drop), explain why this research field is important for hydraulic systems (Christopher, 1995, Soyama et al., 2002, Soyama, 2007, Abdolreza and Ahmad, 2005, Knapp et al., 1970). On the other hand, cavitation can widely be used in many areas such as

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industrial cleaning applications, since cavitation has sufficient power to overcome the particle-to-substrate adhesion forces to loosen contaminants. It also plays an important role in the chemical engineering industry (homogenization, mixing and breaking down processes). In the biomedical field cavitation is used for the destruction of kidney stone and there are also numerous attempts to apply it for the non-thermal and non-invasive fractionation of tissue for the treatment of a variety of diseases. It may also be used in High-Intensity Focused Ultrasound (HIFU) to locally heat and destroy diseased or damaged tissue through ablation. In the engineering industry cavitation impact is also utilized to modify surfaces in the same way as shot peening, for example, it could be used to improve the fatigue strength. Soyama H, et al. (Soyama et al., 2002) have already demonstrated the enhancement of compressive residual stress, the improvement of the fatigue strength of metallic materials, and an improvement in corrosion resistance by using a normal cavitating jet in water. He also reported in another work that the fatigue strength of a specimen peened by a cavitating jet is considerably improved compared to a shot peened specimen by using a rotational bending fatigue test (Soyama, 2007). Therefore the possibility of using cavitation phenomenon as tool to modify the surface and to improve the material properties sheds a positive light onto this phenomenon which explains the increased investigation activity in this area too.

In order to provide a greater understanding of the cavitation-solid interaction 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 active investigation, especially, when new technologies are used. Examples of available techniques are the pit-count technique, the 2D optical method, the 3D measurements by roughness meter, and the 3D laser profilometry technique (Regiane et al., 2000). As well known, the surface roughness is an important factor when dealing with issues such as cavitation collapse on the surface, 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. (Thomas, 1998). 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 (Jakson and Ahmed, 2007). The micro-roughness of the solids plays the main role for the heat transfer in a cross interface, which is an important phenomenon existing 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 high temperature drop across the interface (Bahrami et al., 2004). Changes in the surface roughness also influence the electrostatic field above a biased sample. In electrostatics the intensity of the electric near filed is higher above structures with small geometrical curvature (e.g. sharp features). Such perturbed and intensive near fields could be desirable for some applications (Lazić and Persson, 2010). Surface roughness could exert a profound effect on the performance of radio-frequency (RF) cavities or slow wave structures (John, 2008, Pandit et al., 2005, Peng et al., 2009). Surface roughness may lead to excessive local electric field enhancement that could trigger RF breakdown (Caughman et al., 2007, Kevin, 2008). Surface roughness may also cause local magnetic field enhancement which can lead to abrupt quenching i.e. loss of superconductivity (John, 2008, Vasil'ev, 2005).

Considering the above mentioned points, the surfaces with nano and micro-scales of roughness, with regular or irregular shape, wavy or stripped shape etc. are assumed to be important targets for research. Therefore, the primary aim of this work was to experimentally determine the initiating mechanism at the start of the cavitation damage and the erosion process in FCC materials (namely Al-alloy, Cu and SS316 as a tested materials, or targets); and then secondly, to investigate the behavior of the target material during and after the incubation time period by using nanometrology tools (such as AFM) in order to demonstrate the possibility of using the cavitation phenomenon as tool to test and modify the surface properties in a micro- and nano-level (roughness and/or waviness). The white light interferometric surface analyzer was used in this work as an experimental tool which provided additional insight into the deformation process. To investigate the effect of the surface roughness on the electrostatic properties of the sample electrostatic force microscopy (EFM) was used.

2. Methodology and experimental procedure

Series of tests were carried out involving repeated exposure of the tested specimens of FCC materials to the action of a cavitating water jet for given time periods. Fig. 1 shows the schematic diagram of the test chamber and a photo of how the cavitating jet impacts the specimen. The working fluid used in the experiments was tap water. It was not degassed; hence it is expected to be saturated with dissolved air. This gas content has not been measured.

In order to have a good control over the cavitation intensity, the upstream pressure (P_1) and downstream pressure (P_2) were measured at the inlet and outlet of the test chamber, respectively, as shown in Fig. 1. The pressure transducers were calibrated by the manufacturer and accuracy certificates were issued for a maximum error of +0.2/−0.21 % FS (Full Scale). The flow rate (exit jet velocity) was determined by using P_1 and P_2 values from the previous nozzle calibration, the uncertainty of its determination is also in the range of +/− 0.3 % FS.

The exposure times were chosen in a way that the level of damage on each specimen would not exceed the plastic deformation level – i.e the exposure time is less than or equal to the incubation time of the target materials. The surface roughness and surface characteristic of the specimen before and after the cavitation damage test was investigated. Before the tests, specimens were prepared by polishing, in order to provide a smooth surface for the examination of cavitation damage in detail. Before the analysis of a tested sample, it was cleaned, dried and placed in the desiccator at ambient conditions. More information regarding the sample preparation and the control of cavitating jet parameters can be found in our previous works (Hutli et al., 2008, Hutli et al., 2012, Hutli et al., 2013b).