Macro, Micro, and Nano Level Analysis of Cavitation Damage Mechanism in FCC Materials

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Abstract. The aim of this paper is to demonstrate the analysis of cavitation damage mechanism in FCC (Face Centered Cubic) materials, and to establish a possible application of the cavitation phenomenon as an efficient method to modify surface properties. Three FCC materials (copper, AlMg-alloy and stainless steel (St.St.316)) were subjected to high speed submerged cavitating jets under certain working conditions, for different time periods. The force generated by cavitation is employed to deform and to damage the surface in scales ranging from nano to micro and macro. The target surfaces were investigated with various techniques. Results 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. By increasing the exposure time, the surfaces became eroded, the damaged area is characterized by many rings, with different degrees of surface roughness. The results related to the early stage of cavitation damage demonstrate the possibility to use cavitation bubbles as a micro/nano fabrication method for the surface preparation/modification or for example shoot-less surface peening.

1. Introduction

The phenomenon of cavitation damage is complex, since it includes both hydrodynamic and material aspects. The cavitation damage starts as a consequence of the contact between the specimen and the liquid microjet, followed by the collapse of the cavitation bubbles (fluid-solid interaction in a micro scale). The velocity of nano and micro jets is a function of the position of the bubble collapse. Some literature claim maximum jet velocities between 50 and 100 m/s, while others claim that the velocity can reach even 950 m/s [1]. The impact velocity of the micro jet is much less than the micro jet velocity, which is related to the momentum and energy exchange with the surroundings during its trajectory. But still, the jet impact velocity onto the boundary generates a water hammer pressure in most cases, which is higher than the ultimate tensile strength (UTS) of target material [2]. The mechanical performance of a material is largely depending on its ability to absorb the shock waves and impact loads without sustaining microscopic fractures on its surface. Plastic deformation in the target materials is the early stage of cavitation damage. It happens when the maximum stress applied on the material target is close to the threshold value, i.e., yield stress of the target material. The time which a material can sustain under this stage is called the incubation time. This time is a function of the mechanical properties of the material subjected to this stress (cavitation), working conditions, and the properties of the cavitation generator or source. After the plastic deformation stage, erosion takes place only at local areas (hence the surface roughness will increase), so the ability of the material in absorbing impact working through local coordination deformation appears to be important [3]. The modification of the surface on the nano/micro level and the examination of material resistance to cavitation should be done in this stage (plastic stage).

In nano/micro levels, the cavitation phenomenon is very important for future applications in nanoscience and engineering, considering that surfaces with nano- and micro scale roughness with regular or irregular shape, wavy or stripped shape etc. are important targets for research. Therefore the aim of this paper is to investigate the behavior FCC materials under cavitation attack during the incubation time period, which refers to the time while only plastic deformation occurs on the surface of the target. While copper and AlMg-alloy samples were also investigated, stainless steel (St.St.316) will be used for the discussion as a primary example. White light interferometry and atomic force microscopy (AFM) were used in this work, which – besides the quantitative characterization of surface roughness with the latter – can provide additional insight to the deformation process.

2. Experimental setup and Procedure

Series of tests were carried out including repeated exposure of the tested specimens of FCC materials to the action of a cavitating water jet for given time periods, by using a cavitating jet generator. The surface roughness of the specimen before and after the cavitation damage test was investigated with various surface characterization techniques (digital microscopy, white light interferometry and atomic force microscopy (AFM)). More information regarding the sample preparation and the control of cavitating jet parameters can be found in our previous works [4,5,6,7].

3. Influence of the material properties on the cavitation damage process

Long term tests. For long term investigations, a series of tests were carried out involving repeated exposure of the specimens of pure copper, AlMg-alloy, and St.St.316 to the action of cavitating jets for periods of 1 hour to 5 hours. The exposure times were chosen in a way that the level of damage on each specimen could be easily evaluated. As it is presented in Fig. 2, the long term exposure (1-5 h) leads to macroscopic cavitation damage "erosion". The macro investigation of the damaged surfaces shows that, the damage on the specimen surface is concentrated within the ring formed by the cavitation bubbles "ring of bubbles". This feature is regulated by the nozzle geometry. The observed lesser cavitation damage within the ring as well as away from it is due to the much lower density of collapsing bubbles, i.e. in these areas the damage process is shifted to much longer times. At the beginning of the cavitation attack, the untouched specimen is assumed to have a smooth surface (in our case the scratches are shallower than 0.5 µm for macroscopic damage evaluation).

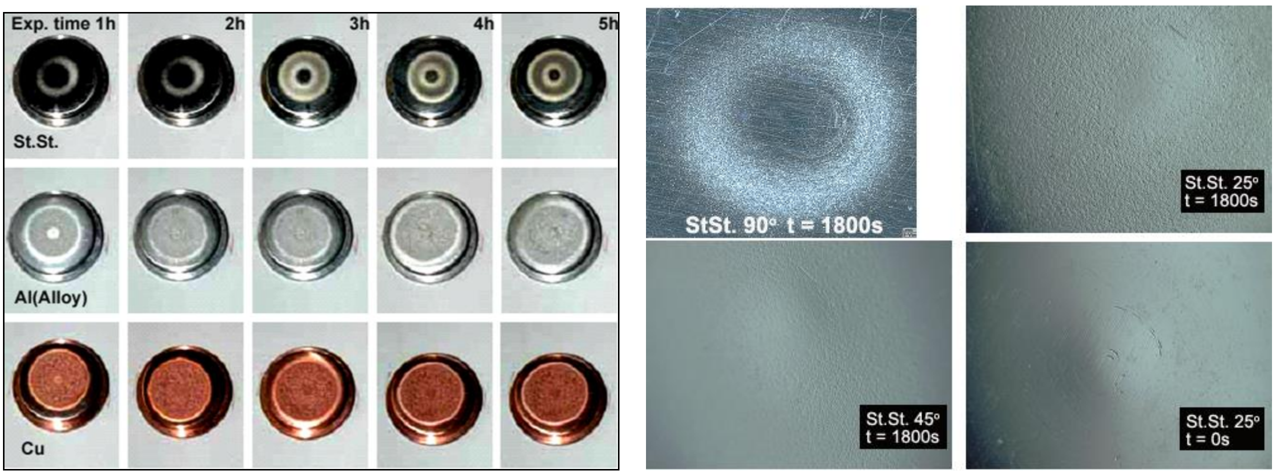

Fig. 2 Left: Erosion pattern in different tested materials. Top row: St.St316, middle row: AlMg-alloy, bottom row: copper. Exposure times were ranging from 1 h to 5 h. Conditions P_1 = 145±1 bar, P_2 = 2.1±0.1 bar, V_J = 113.6±0.5 m/s, σ = 0.017±0.001, T = 20 °C, x/d = 57, convergent nozzle. **Right:** Erosion pattern in St.St.316.

For Cu and Al-Mg-alloy, it is assumed that the roughness is increasing with increasing exposure times during the whole test, enabling the induction of high stresses at the surface, which leads to plastic deformation and rupture at the specimen surface.

As it can be noticed in Fig. 2, many rings could be seen in Cu and AlMg-specimens. These rings have different degrees of damage. In some cases it could clearly be seen, that the ring with the highest damage is surrounded by low damage rings: this feature of the damage indicates the cavity bubble distribution along the jet diameter according to their strength, their density as number and to the pressure distribution near the target specimen. In addition, the difference between the rings may be related to the position of the collapse process.

In the case of St.St. these different rings appeared on surface after 2 h exposure time. This is due to the fact, that there was no erosion in St.St: the surface was only plastically damaged, and in this phase it is harder to observe visible differences in the level of deformation between various areas with these investigation techniques.

By using a special digital microscope (Hirox-Digital Microscope KH-7700), the images were captured with a high optical resolution and a wide field of view. As we can see in Fig. 2, the resolution is good enough to see the damage in the case of St.St (1800 s). The damaged area in St.St. appears as a homogenous roughened area, the difference between damaged and non-damaged areas is clear. The same could be seen clearer in the cases of Cu and Al-alloy (1800 s).

Regarding the images of Cu-and AlMg-alloy, it can be seen that the damage pattern is shaped as groups of rings with nearly circular geometry with different degrees of roughness. These rings are not symmetric, which means that the intensity (strength) of bubbles varies along the jet diameter as mentioned earlier. So, it may be concluded that the cavitation intensity varies from non-damaging values outside the eroded area to the strongest attack at the location of maximum depth in the material. Comparing the pictures of Cu, AlMg-alloy and the pictures of St.St.316, the differences in the features may be noticed, and also in the number and the depth of the holes (in Cu and AlMg-alloy specimens fatigue features can be observed, with deep holes and cracks in Cu) while for St.St. the samples are free of such holes and cracks, as can be seen in the images of Fig. 2/right.

Tests with short incubation times. In order to understand the influence of material properties on the behavior of the samples during cavitation attack in the time period before erosion appears, in these investigations the exposure time was chosen to be less than the time needed to create erosion or crack or fracture in the attacked surface. Therefore in this test, the exposure times were chosen in a way that the level of damage on each specimen would not exceed the plastic deformation level. Both Cu and AlMg-alloy was tested for short time starting from 15 s to 600 s and the results were published elsewhere [5, 6].

In general, the tested materials Cu, AlMg-alloy and St.St. showed that they are able to absorb a large part of the impact energy due to good ductility, but of course there are differences in their capabilities. Let us assume, that the energy which caused the plastic deformation of the whole specimen is localized in the ring as mentioned earlier. The cavitation ring collapses at the moment of its impact on the surface of the specimen and micro-jets are produced. Due to the varying size of the bubbles, the formed “micro-jets” will hit the specimen at an angle other than 90^o, introducing the shear stress component on the surface. Reported values of the micro-jets induced local material stress are between 100 MPa up to over 1000 MPa [8]. This shear component seems to be sufficient to start plastic deformation on the surface of the specimen, leading to more or less pronounced roughness after a certain exposure time which is depending on the working conditions and material type. It is predicted that, after this initial step, further micro jets hit the roughened surface (instead of the smooth and polished one), which leads to the rupture and erosion of the surface. For precise investigation of the cavitation damage, the possible influence of temperature, which increases during the cavitation bubble collapse, should also be considered [9,10].

The AFM results illustrates that the damage in the surface could be in the nano- and micro levels. As it can be seen in the images of Fig. 3, the shapes of the pits are irregular and the slip directions are varying from pit to pit which indicates, that the angle of attack is not 90°, therefore it confirms, that shear forces play an important role in the cavitation damage process. This fact can by proved by analyzing crater boundaries. As we can see the AFM measurements alone are not enough to properly investigate the distribution of the roughness on the surface. In order to investigate a larger area on the damaged surface white light interferometry was also used. Five points along the diameter of the damaged area were chosen to be measured. Each point has an area of 0.0266 mm^2, their locations are 0, 1.5, 3, -1.5, and -3 mm away from the center of the cavitating jet impact.

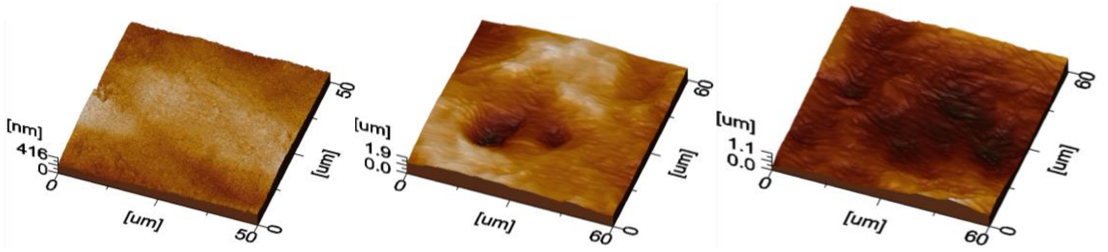

Fig 3 3D topography AFM images from the St.St.316 sample which presents the state of the surface before (left, 0 s) and after the tests (1800 s).

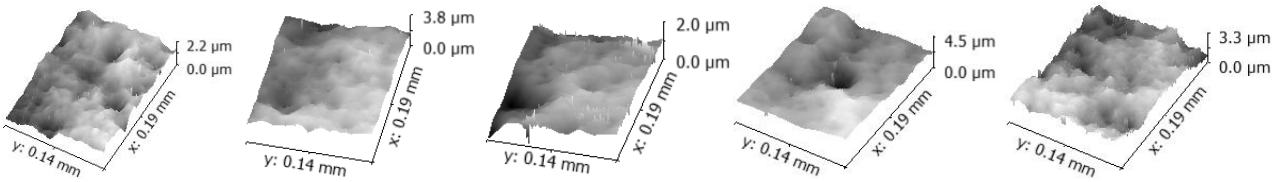

Fig. 4 Surface topography of the St.St. sample after short time exposure (1800 s) measured with a white light interferometer along the diameter of the damaged sample at 0, 1.5 ,3, -1.5, -3 mm away from the center of jet impact (50x magnification).

The obtained images are presented in Fig. 4. It can be noted that, there is a difference in the surface topography of the investigated points, the lowest damage was measured at the center, the damage increases until reaching 1.5 mm from the center, and then it starts to decrease. This characteristic ring shape is the feature of the cavitation damage created by a cavitating jet with a circular nozzle.

During the plastic deformation stage, multiple impacts on the same area could be possible without any erosion or crack. After the formation of the first pit, further pits can be formed by subsequent impacts which results in deformation bands associated with localized strain, characterized by wavy markings frequently detected on the wall of the pits, as can be seen in Figs. 3 and 4. These are the results of a wavy slip or serpentine glide [9,10], confirming a significant deformation, which can precede a possible rupture (Fig. 4). Further erosion could be created by the wave-guide model for the acceleration of surface damage (Cu and AlMg-alloy) [9]. In all figures (both AFM and interferometry) the damage (plastic-deformation) is pronounced, pits and holes with different width and depth.

Based on the obtained surface topography presented in Figs. 3 and 4 the following observations can be made: 1) compared to the polished surface (reference in Fig.3 left), the increase in the surface roughness due to plastic deformation is significant (increase in S_a is around 25x compared to the reference at the point of highest damage) 2) the deformation damage is most pronounced in a ring, 1-2 mm away from the center of jet impact.

The characteristic damages on the surface during the plastic deformation stage are holes and pits, as can be seen on the presented interferometric topography result (Fig. 4). These pits have conical shape with different inclinations, which is related to the angle of attack between the micro jet and the target surface. Due to the high frequency of bubble collapse on the surface, even after short exposure times, the pit volume and shape cannot be directly related to single impacts.

The irregular shape and asymmetric features of the hollows indicate that subsequent rebounds can implode over or near a crater which was previously produced by an earlier collapse and extend the impingement damage [11]. So these features are caused by collective collapses and are common in the materials-cavitation resistance tests using cavitating jets [12]. Collective collapses are typically characterized by cascades of implosions. Also the angle of impact between the wall surface and the micro-jets is not 90^o in most of time. The existence of collective collapses is an evidence for the existence of different angles of attack.

4. Conclusions

The investigation of cavitation damage using a high speed submerged jet has been done using FCC materials. Different observation techniques indicate that after short exposure times, the observed characteristic features in the microstructure – hills, holes and wavy configuration – could be related to the plastic deformation of the specimen surface. The characteristic features of the damage in the incubation time confirm the possibility of modifying the surface structure of metals in a controllable fashion by cavitation. Also this tool can be an efficient technique to investigate the mechanical properties of the materials in the micro and nano level (tested area). This tool “cavitation” is more convenient, easy to use, easy to control, safer and cheaper compared to other techniques.

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