

The effect of cavitation erosion on austenitic-ferritic steel

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Abstract

Cavitation is a one of many wear mechanisms which are related to the flow of liquid. It is one of the most destructive wear methods for stainless materials. The local changes in the pressure of the liquid stream related to the flow across the metal component cause straightening of the surface area, as well as its erosion and the formation of pits on the surface layer. The erosion value of cavitation is related to the material's microstructure, the geometry of the element, the phase composition of the material and the surface roughness. In this paper the investigation of the cavitation process for duplex stainless steel has been performed. Samples examined in the first stages of the experiments were not significantly changed, but after a long time the hardness increase was very visible. The result of the cavitation was also cracking along the interphase boundaries, which resulted in the chipping of the material. One of the most important results was a description of the change in the wear mechanisms and its intensity during the cavitation exposure time. At first plastic micro deformation of the material's surface occurred, then the plastic deformation increased significantly and after some time this resulted in erosion of the material and interfacial boundary decohesion; these two effects increased simultaneously. The last of the mechanisms was mechanical destabilization of the austenite, but the clear result of the mechanical destabilization of the austenite was only observed in the last sample. Martensitic transformation of the material changed the material's mechanical properties, but for the stainless steels this resulted in electrochemical corrosion of the material, especially through the formation of an electrochemical potential between austenite and martensite.

Introduction

Carbon steels are characterized by a lower cavitation erosion resistance than, for example, copper, nickel and aluminium alloys (Farzam, 2008). Duplex stainless steels (DSS), due to their greater cavitation erosion resistance, have been highly investigated (Rede & Grilec, 2009; Escobar et al., 2013; Micu et al., 2015b; 2015c). It was shown that the cavitation erosion value was related to the material's microstructure, and the geometry of the interphase boundaries (Al-Hashem & Shalaby, 1996; Al-Hashem et al., 1997; Kwok, Man & Cheng, 1998a; Escobar et al., 2013; Micu et al., 2015b; 2015c). The cavitation erosion intensity is related to the material's surface roughness (Micu et al., 2015c; Lin et al., 2018).

Micro-scaled plastic deformation of the surface, indicating cavitation, resulted in the mechanical destabilization of the austenite phase (Kwok, Man & Cheng, 1998b; Wang et al., 2016). The spinodal decomposition of ferrite and the precipitation of secondary phases were also observed (Mitelea et al., 2016). The degree of erosion due to cavitation could be reduced by the use of protective layers. In general, cavitation erosion could be decreased by the increase of the DSS's surface hardness. (Mochizuki et al., 2008; Szkodo, M., 2008; Micu et al., 2015a)

The aim of this research was a description of the correlation between mechanically indicated martensitic transformation and the cavitation time. Plastic deformation of the material's surface is related to the changes in the material's surface roughness and the

weight loss of the samples. The research presented here has allowed for the proposal of a theory about the changes in the wear mechanism related to the cavitation time.

Methodology and material

The material used for the investigation was duplex stainless steel; the chemical composition of the investigated material has been presented in Table 1. The chemical composition analysis was performed by the use of an optical emission spectrometer – from Foundry Master (WAS). The material was delivered as a 2 cm diameter rod. The samples were cut perpendicular to the rod's axis. Each of the samples was 1 cm high. For the investigation the surfaces were ground and polished to obtain the same roughness for all of the investigated samples and to avoid the cutting having an effect on the results. Cavitation erosion was investigated using a jet – striking device. The diagram of the investigation device has been shown in Figure 1. Samples were placed in the device's jibs; they were then rotated at a high angular speed and impacted by the stream of the liquid. During the impacts the material's surfaces were exposed to cavitation erosion impulses.

Table 1. Chemical composition of the investigated steel (mass %)

| C | Mn | Si | P | S | Cr | Ni | Mo | Cu | V | Fe |
|------|------|------|-------|-------|------|------|------|------|------|------|
| 0.04 | 1.46 | 0.51 | 0.038 | 0.024 | 24.9 | 5.61 | 1.43 | 0.23 | 0.09 | Bal. |

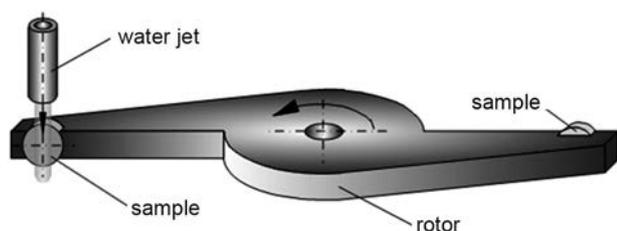


Figure 1. Diagram of the jet-striking device used during the investigation (Jasionowski, Zasada & Polkowski, 2016)

The samples were exposed to the water stream which was influent parallel to the sample's surface. The water pressure that was used during the experiment was 0.06 MPa. The water jet had a 10 mm diameter and was at a distance from the samples' edges of about 1.6 mm. The flow rate of the water was constant and was equal to 1.55 m³/h. The experiments were run for: 5, 15, 30, 60, 120, and 300 min. After each test, the sample was subjected to ultrasonic cleaning for 5 min at 30°C, and dried at 120°C for 5 min.

The weight loss of each sample was determined after the test by the use of laboratory scales with an accuracy of 0.1 mg. An examination of the changes in the surfaces of the materials was performed using a light microscope (LM) and a scanning electron microscope (SEM). The surface roughness was determined by the use of an optic profilometer WYKO NT930. The changes in the volume fraction of austenite was determined by the use of X-Ray diffraction, throughout the investigation a cobalt source ($\lambda = 0.179 \text{ \AA}$) was used. The diffractometry tests were performed with an asymmetric constant angle of incidence ($\alpha = 3^\circ$). Measurements were carried out with an angular step of $\Delta 2\theta = 0.04$ in the range of 2θ from 48° to 93° . The measurement time was $t = 15 \text{ s}$ per angular step. Hardness tests were performed by the use of a Vickers hardness tester with a load of 49 N (HV5).

Results and discussion

An increase of the cavitation exposure time resulted in increased degradation of the sample's surface caused by cavitation erosion. At the material's surface some dimming could be observed in the area of the stream's influence. The shape of the stream's area of influence was constant throughout the experiment. Therefore it can be stated that the area of cavitation wear was not changed throughout the experiment. The shape of the cavitation exposure area has been presented in Figure 2. The average values for each investigated parameters for the areas D and C were the values that were referenced in the further analysis.

When the cavitation exposure time was increased beyond 30 min, there was an increase in the weight loss of the investigated materials (Figure 3). For the tests that lasted less than 30 min it was not possible

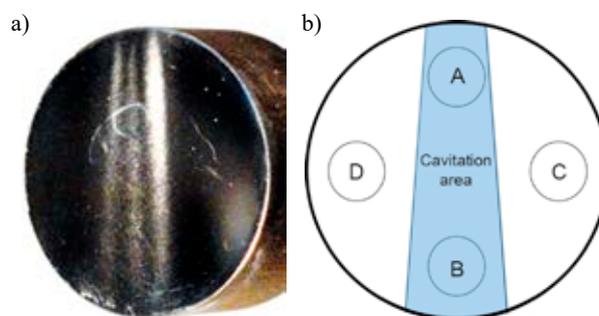


Figure 2. Area of the cavitation wear: a) sample after 300 min test, b) Sample diagram; A – location of the beginning of the test – the beginning of the stream's influence, B – location of the end of the stream's influence, C, D – areas outside the stream

to determine the weight loss of the sample. In this stage of the cavitation erosion the whole energy reacted with the material's surface and the wear was accumulated in the subsurface area. Thirty minutes was the possible threshold above which the formation of microcracks and chipping of the surface material occurred. These mechanisms of wear resulted in a non-negligible weight loss. This stage is usually called the stage of increased damage. The constant area of the stream influenced and increased the weight loss, which created the possibility that the whole cavitation wear accumulated in a precisely defined top layer of the material.

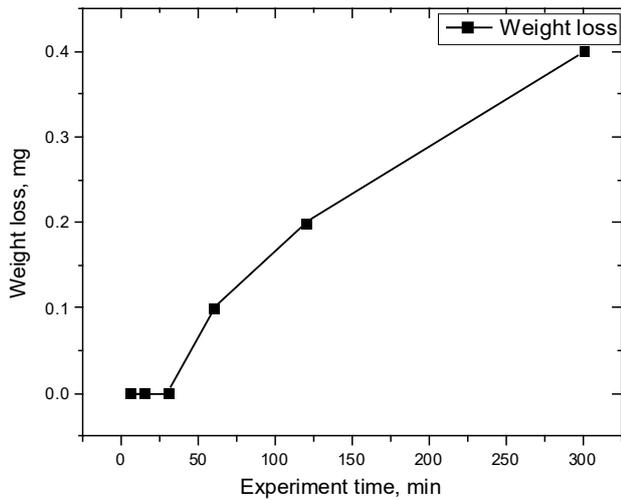


Figure 3. Influence of the cavitation exposure time on the weight loss of the investigated samples

The changes in the subsurface layer's morphology as a result of the cavitation have been presented in Figure 4. Despite the lack of etching, the dual phase microstructure, characteristic of duplex steels, was visible. By the use of the microscopy analysis it could be seen that after the first 5 minutes the first micropits on the material's surface had formed. This effect increased as the time increased. In the case of longer exposures, decohesion of the interphase boundaries were observed. This phenomenon was visible for times longer than 30 minutes. Simultaneously, an increase in the intensity of the plastic deformation of the surface was observed.

The results of the roughness measurements in relation to the exposure time to cavitation have been presented in Figure 5. The roughness was presented with parameters of R_a , R_q and R_t . The correlation of R_q in nanometers to the exposure time has been presented in Figure 6. A significant increase of the surface roughness occurred between 15 to 30 minutes into the test. It could be assumed that for the first stage of the cavitation test it was

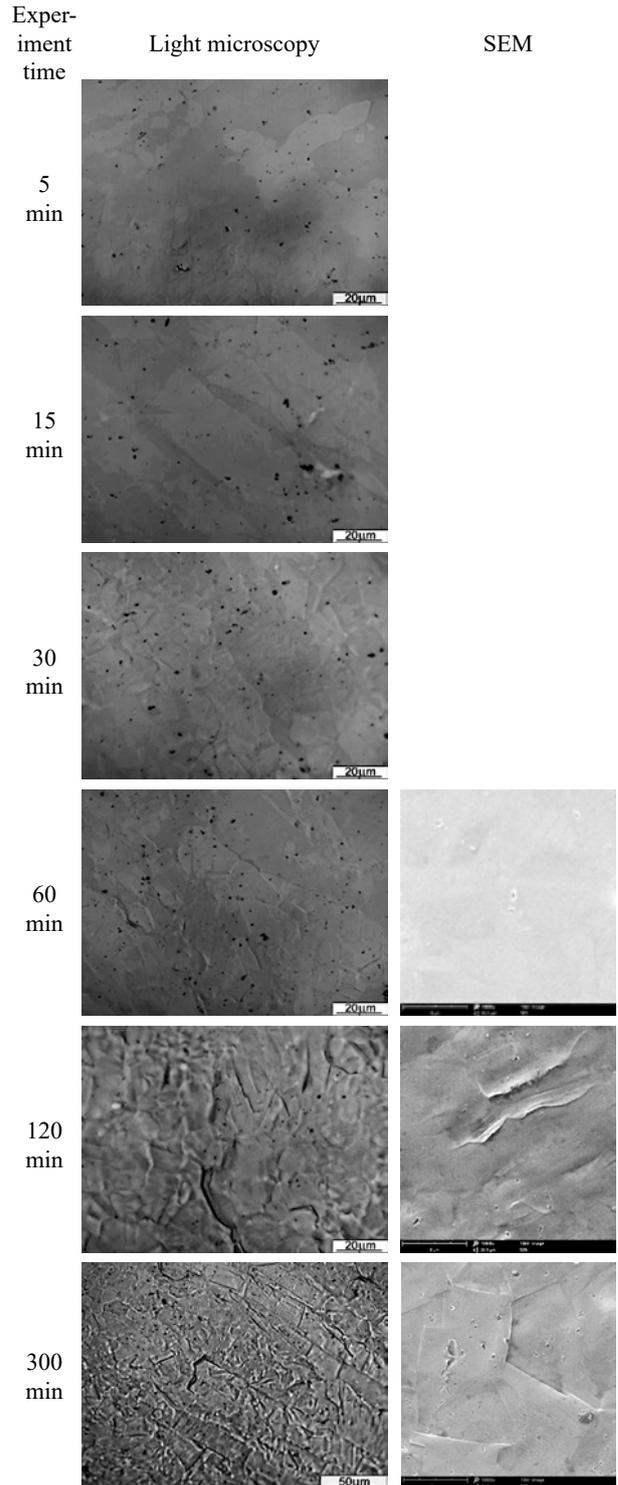


Figure 4. Morphology of the material's surface after the cavitation erosion tests

related to less damage. This was because some zones were formed in the water stream, which were characterized by intense cavitation (Figure 2a). It could be assumed, that the best parameter to describe the most intense cavitation wear area was R_t (Figure 7). It could be seen that up to 30 minutes, the R_t parameter increased, then a sudden reduction was observed, following by a second increase of

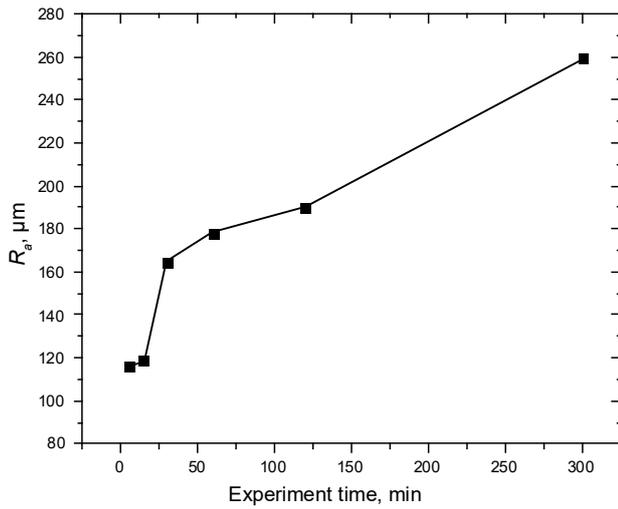


Figure 5. Correlation between the R_a parameter and the cavitation experiment time

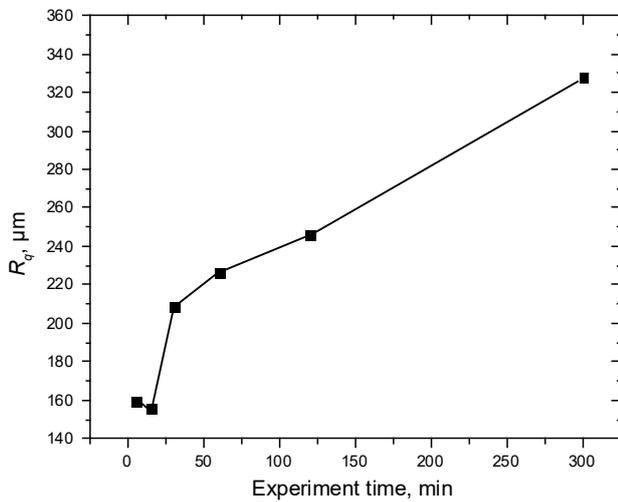


Figure 6. Correlation between the R_q parameter and the cavitation experiment time

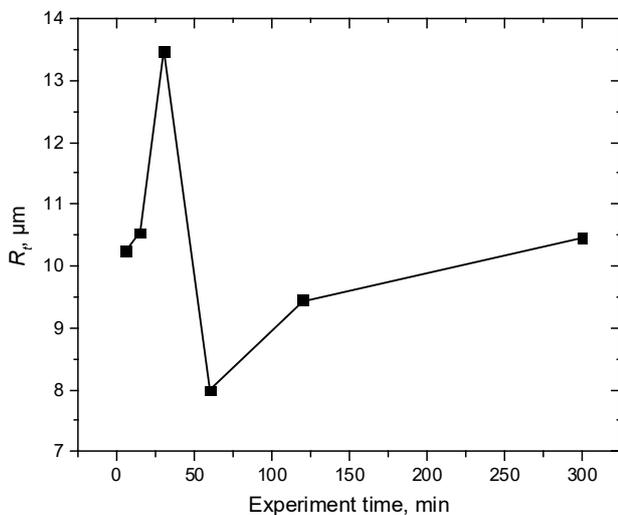


Figure 7. Correlation between the R_t parameter and the cavitation experiment time

the R_t parameter with time. This could be related to the plastic deformation without weight loss in the first 30 min of the test. Then the process of the surface material chipping began and it reduced the surface roughness. However the decrease in the surface roughness did not stop the surface's plastic deformation, but resulted in a lower intensity than before.

X-Ray diffraction analysis was used to determine the volume fraction of each phase in the microstructure. The austenite volume was determined from the diffraction pattern; the ferrite volume was the complement to 100%. The influence of the cavitation on the phase composition of the material was also determined. The influence of the cavitation exposure time on the volume fraction of the austenite has been presented in Figure 8. Up to 60 minutes the austenite volume fraction loss due to cavitation exposure at the surface layer was in the range of the experimental method's standard error. This could explain the negative value of the analyzed parameter for the first samples. Over 300 minutes the effect of the relative loss of the austenite volume fraction became clearly visible. This phenomenon could be associated with the mechanical destabilization of the austenite, and the martensitic transformation. It could be assumed that at the initial stages of cavitation the ferrite volume fraction experienced significant loss due to its lower plasticity. When the mechanical destabilization of the austenite increased, the difference between the austenite to ferrite ratio at the surface became more significant.

The hardness differences in the area exposed to cavitation and the areas not exposed to cavitation have been presented in Figure 9. The differences were

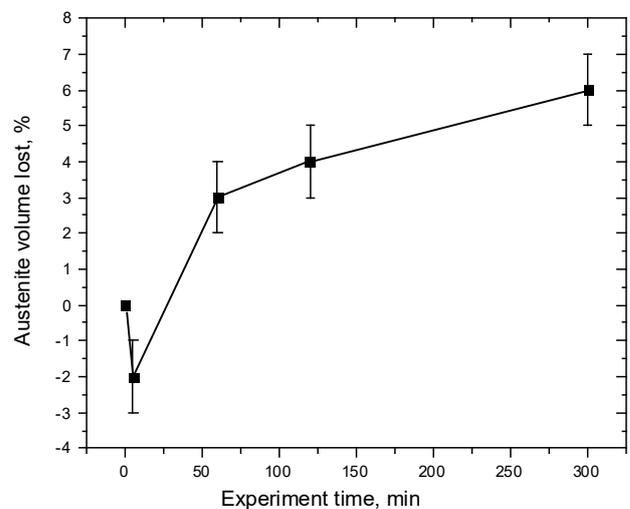


Figure 8. Austenite volume fraction loss with increased cavitation exposure time

not significant and were close to the measurements' standard error. In the first stage of cavitation the hardness increase was a consequence of the strength of the surface layer increasing. When decohesion of the interfacial boundaries had occurred, a decrease of the hardness of the material was observed. Further cavitation exposure time resulted in a small hardness increase. The destabilization of the austenite did not increase the material's hardness significantly due to the small value of the relative loss of austenite volume. In the investigated materials, the volume fraction of austenite was about 60%. A relative decrease of about 6%, in the case of the austenitic – ferritic material did not change the overall hardness of the material. However in the case of the observed volume loss of austenite and the increase in hardness, the proposal of the mechanical destabilization of the austenite can be justified.

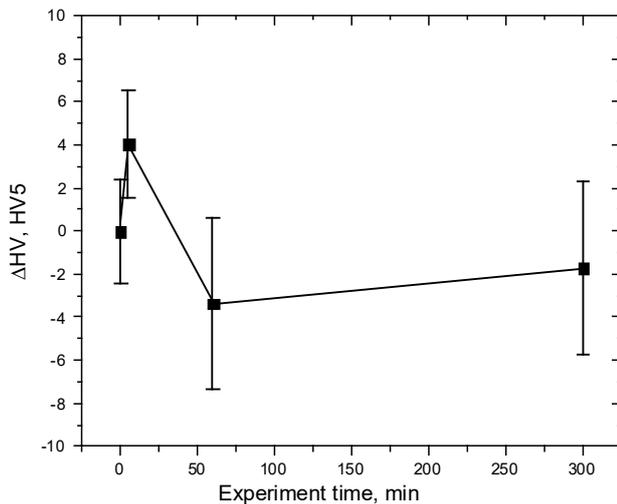


Figure 9. Change in the relative hardness with regard to the experiment time

Conclusions

The results of the research indicated that the cavitation resulted in: plastic deformation of the surface layer, erosion of the material, cracking along the interfacial boundaries and the mechanical destabilization of the austenite. These effects had a varying intensity through the whole time of the cavitation. Each mechanism of the material's surface degradation could simultaneously affect the surface layer. However the most intense plastic deformation of the material occurred in the first stage of cavitation exposure, after that there was a simultaneous increase in the erosion and the interfacial boundary decohesion, and after a further period of time austenite destabilization was observed. The suggested explanation

of the microstructural changes that were related to the cavitation exposure time could be presented as a graph with a qualitative description of the surface degradation mechanisms' intensity as a function of cavitation wear exposure. The plot which describes the difference of the intensity for each mechanism against the cavitation exposure time for a duplex steel has been presented in Figure 10. The plot shape was based on the metallographic and roentgenographic results presented in this paper.

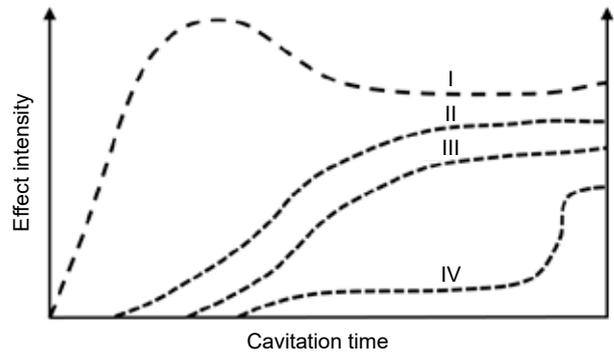


Figure 10. Influence of the cavitation exposure time on the numerous mechanisms of the structural changes in the surface layer of the duplex steel: I – plastic deformation, II – erosion, III – decohesion along the interfacial boundaries, IV – strain indicated destabilization of the austenite

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