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# Comparative cavitation erosion test on steels produced by ESR and AOD refining

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Cavitation erosion studies of steels produced by Electroslag Refining (ESR) and Argon Oxygen Decarburization (AOD refining) have been carried out. The experiments were conducted using the modified ultrasonically induced cavitation test method. Erosion rates were measured and the morphology of damages under cavitation action was studied by scanning electron microscopy and optical microscopy techniques. The present work is aimed at understanding the cavitation erosion behaviour of electroslag refined steel (ESR) compared with the steel produced by Argon Oxygen Decarburization (AOD refining), commonly used in the production of hydraulic machinery parts (Pelton blades). The results exhibited lower cavitation rate of ESR steel compared with AOD steel, as a consequence of its better mechanical properties and homogeneous and fine-grained microstructure.

Keywords: *cavitation, refining, SEM, optical microscopy, microhardness*

## 1. Introduction

Cavitation erosion is a type of wear in hydraulic turbines, on ship propellers, valves and other hydraulic structures in contact with high-velocity water subjected to pressure changes. Cavitation can occur if the pressure on water is reduced sufficiently to cause formation of bubbles or vapor-filled voids. When the water is subsequently subjected to higher hydrostatic pressure, the bubbles can collapse suddenly and cause surface damage through microjet and shock waves [1].

The properties and manufacturing characteristics of ferrous alloys commonly used in the production of hydraulic machinery parts, depend on microstructure. These alloys are adversely affected by the amount of impurities, inclusions and other elements present. It is well known that such elements diffuse to the grain boundaries and decrease the strength of the material, leading to material fracture induced by fatigue. In order to increase the fatigue resistance and so cavitation resistance, impurities and inclusions should be removed from the grain boundaries of the material.

The removal of impurities is known as refining, much of which is done in melting furnaces or ladles, with the addition of various elements. There is an increasing demand for cleaner steel having improved and more uniform properties and consistency of composition. Refining is particularly important in producing high-grade steel and alloys for high-performance and critical application.

The martensitic stainless steels, produced by Argon Oxygen Decarburization (AOD refining) are commonly used in the production of hydraulic machinery parts. AOD refining provides numerous advantages, such as: precise control of carbon to 0.01 % and lower, rapid desulphurization to less than 0.001 % of sulphur, cleaner metal, with low retained oxygen, nitrogen and hydrogen as well as good mechanical properties: high value tensile strength, yield stress, hardness, toughness [2].

Electroslag Refining (ESR) is another refining process. In electroslag processing, the metal to be processed is formed into an electrode and dipped into a chemical slag pool within a water cooled mold. The slag can contain calcium fluoride, lime, magnesia, aluminum, silica, and in smaller quantities, titanium or magnesium fluoride. An electric current flows from the electrode through the slag pool to a base plate which acts as a second electrode. The heat produced by this current melts the tip of the metal electrode, forming molten droplets. These

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Table 1. Chemical composition of the tested steels, wt %.

| Steel | C<br>[%] | Si<br>[%] | Mn<br>[%] | P<br>[%] | S<br>[%] | Cr<br>[%] | Ni<br>[%] | Mo<br>[%] | V<br>[%] |
|---|---|---|---|---|---|---|---|---|---|
| 38HN3MFA | 0.38 | 0.27 | 0.41 | 0.011 | 0.007 | 1.35 | 3.08 | 0.37 | 0.14 |
| CA6NM | 0.026 | 0.65 | 0.62 | 0.023 | 0.001 | 12.3 | 4.31 | 0.48 | – |

Table 2. Mechanical properties of the tested steels.

| Steel | Vickers hardness HV30 | Yield stress [N/mm$^2$] | Tensile strength [N/mm$^2$] | Elongation [%] | Reduction of area [%] |
|---|---|---|---|---|---|
| 38HN3MFA | 321 | 1340 | 1420 | 10.5 | 42 |
| CA6NM | 214 | 685 | 794 | 22 | 72 |

droplets fall into and through the slag pool, where impurities are chemically removed. An underlying mass of molten metal is then formed in a mold at the bottom of the slag pool. This material solidifies by controlled conduction to the cool walls of the mold, producing a homogeneous grain structure. As the mold is withdrawn, a thin slag layer solidifies on the outer surface of the metal, producing a smooth surface finish [3].

Electroslag Refining (ESR) provides a possibility for an improvement of the technical level to obtain the high quality metal and metal products along with the reduction of metal consumption and production costs. The metal obtained in this way has an oriented microstructure, it is homogeneous, and there are no defects in it, while its mechanical properties have high values.

Taking into account all these facts, the cavitation erosion study has been carried out to determine the cavitation resistance of ESR steel compared to that of AOD steel, commonly used in the production of hydraulic machinery parts (Pelton blades), and to understand the influence of the microstructure on the morphology of erosion damages.

# 2. Experimental

## 2.1. Material

In this paper, the cavitation resistances of 38HN3MFA steel produced by electroslag refining (standard GOST4543-71) and CA6NM steel produced by AOD refining (ASTM standard A743) were investigated. Both steels were heat treated by tempering.

Chemical compositions of the tested steels are presented in Table 1.

Mechanical properties of the tested steels (Vickers hardness, yield stress, tensile strength, elongation, contraction, toughness) are presented in Table 2.

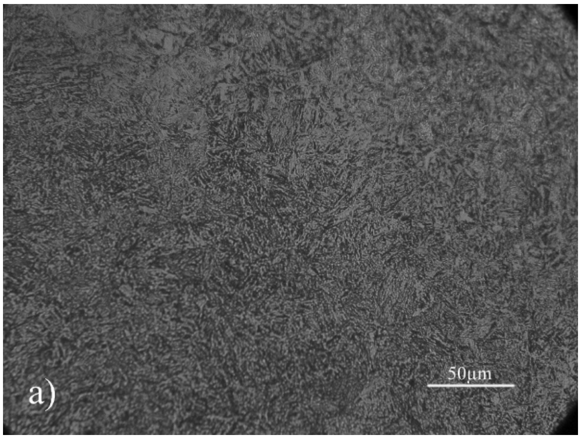
The formed microstructure of 38HN3MFA steel consists of a mixture of ferrite and carbide. It may be regarded as a fine-grained steel.

The microstructure of 38HN3MFA steel is shown in Fig. 1a. The microstructure of CA6NM steel is composed of a coarse-grained tempered martensite with some free ferrite, as shown in Fig. 1b. The presence of retained austenite was demonstrated indirectly.

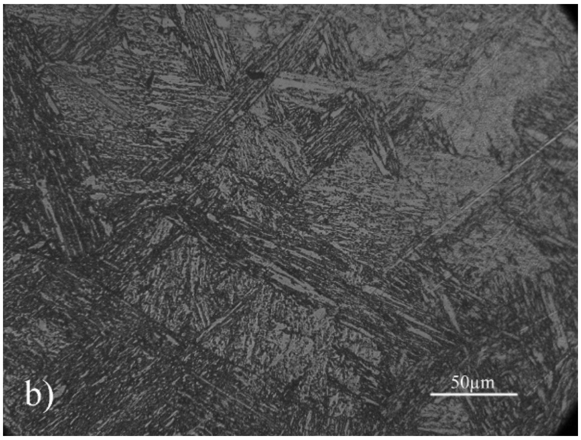
## 2.2. Methods

The modified ultrasonically induced cavitation test method was used for conducting the laboratory testing of cavitation resistance [4, 5]. The test set up consists of a high frequency generator of 360 W, an electrostrictive transducer, a transformer for mechanical vibrations and a water bath containing the test specimen. The cavitation erosion testing has been accomplished by utilizing the recommended standard values [6].

An analytical balance with an accuracy of ±0.1 mg was used to evaluate the mass losses of the test specimens. Prior to the measurements, the test specimens were washed in alcohol and dried in hot air. The measurements were performed after the



(a)



(b)

Fig. 1. Microstructure of the tested steels (500x):
a) 38HN3MFA steel (mixture of a ferrite and a carbide where dark particles represent carbides and white particles represent ferrite);
b) CA6NM steel (martensitic structure – matrix of coarse-grained tempered martensite with some free ferrite represented by white islands).

test specimen had been subjected to cavitation for a duration of 30 minutes.

The obtained results are presented in the coordinate system: mass loss (ordinate) and exposure time (abscissa). The diagram shows the relation between the mass loss and testing time, where the lines were drawn by least-square method and the data can be represented by straight lines. The slope of the straight line represents the cavitation erosion rate. Three test specimens were used for each test and an average value of the measurements was taken as a result. The duration of the tests was 240 minutes.

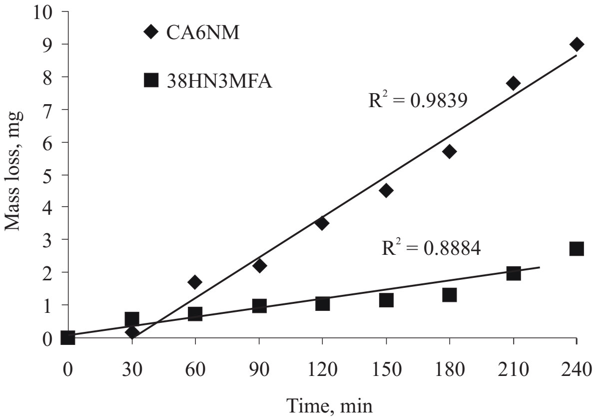


Fig. 2. Cavitation erosion of tested steels (the lines were drawn by least-square method and the slope of the straight line represents the cavitation erosion rate).

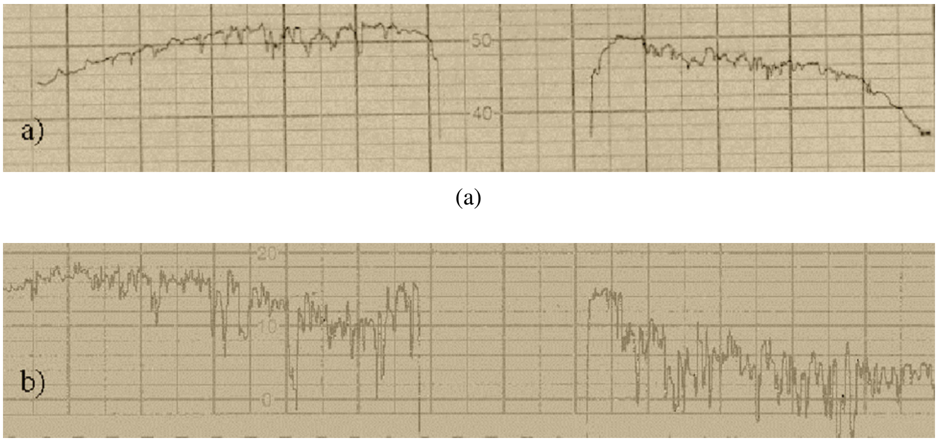
After the cavitation tests, the roughness determination of the damaged surface of the specimens was performed with a profilometer. The measurement was done in direction of the specimen radius. The gap between the left and right side of the diagram represents an aperture in the centre of the test specimen. The magnification of the diagrams of roughness in vertical course amounts to 1000 times. The roughness of all specimens measured before the cavitation action was Ra = 0.03–0.05 μm.

Scanning electron microscopy (SEM) and optical microscopy techniques were used to analyze the mechanism of the erosion and to interpret the results of the cavitation tests.

Cross sections of the test specimens were also prepared. They were chemically plated with a layer of copper to protect the edge of the tested surface during cutting, mounted in epoxy-resin, polished and etched. The Vickers microhardness tests in the cross sections of the test specimens were also performed in order to verify the existence of work-hardening subsurface layers affected by cavitation [7]. The indentations were done at a distance of 40 μm. The applied load was 50 grams.

## 3. Results

The results that indicate mass loss in the test specimens made of 38HN3MFA steel and CA6NM steel are shown in Fig. 2. The calculated slope



(a)

(b)

Fig. 3. Roughness of damaged surfaces after 240 minutes of testing (pictures of original profilometer sheet, where the gap between the left and the right side of the diagram represent an aperture in the centre of the test specimen): a) 38HN3MFA steel b) CA6NM steel.

for the 38HN3MFA and CA6NM steel corresponds to the cavitation rate of 0.0115 mg/min and 0.046 mg/min, respectively.

The roughness of damaged surface of the specimens measured with a profilometer, is shown in the picture of an original profilometer sheet in Fig. 3. The roughness values of 38HN3MFA and CA6NM steels were Ra = 0.8 µm and Ra = 2.4 µm, respectively.

The scanning electron micrographs of the surface features of 38HN3MFA steel and CA6NM steel after the cavitation exposure of 240 minutes are presented in Fig. 4a and Fig. 4b.

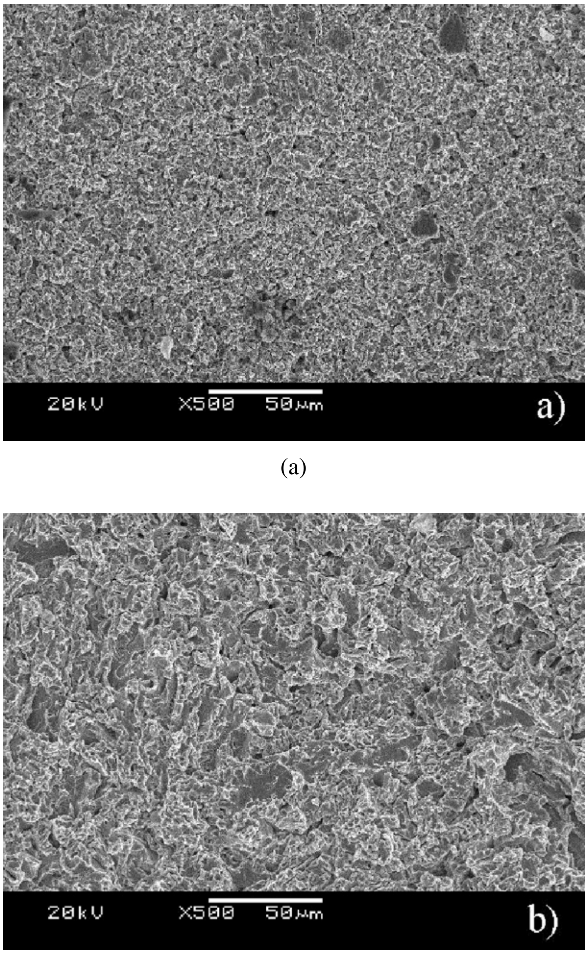
The optical micrographs of cross sections of the surface of 38HN3MFA steel and CA6NM steel after the cavitation exposure of 240 minutes are presented in Fig. 5a and Fig. 5b.

The results of the Vickers microhardness tests performed on the cross sections of the test specimens are shown in Fig. 6.

## 4. Discussion

The steel produced by ESR refining – 38HN3MFA steel has greater hardness and tensile stress compared to CA6MN steel – produced by AOD refining, as given in Table 2. After the refining process, the 38HN3MFA steel has been heat treated by tempering. The refining process involved decreasing the level of inclusions and improved ductility of the steel. By tempering, the martensite and retained austenite were transformed into a mixture of ferrite and carbide, as a result of high rate of tempering. This structure may be regarded as fine grained and homogeneous (Fig. 1a). The values of mechanical properties and the fine grained and homogeneous microstructure are connected with greater cavitation resistance of the 38HN3MN steel. These facts are in accordance to the observation that cavitation resistance of materials increases with greater hardness, tensile strength, yield stress, capabillity of work-hardening and smaller grain size [8].

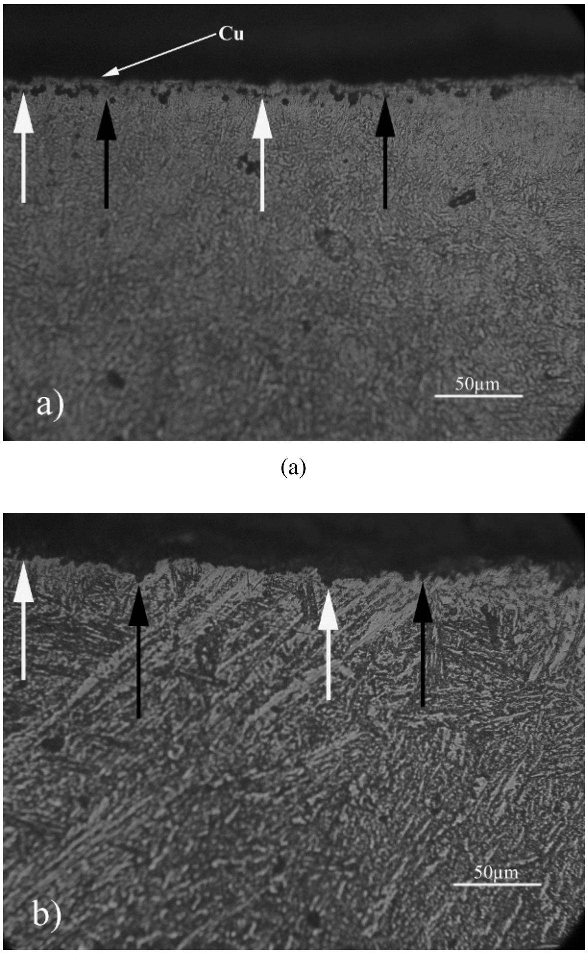
The steel CA6MN has been produced by AOD refining and heat treated by tempering. The AOD refining provided decarburization (carbon content 0.026 %) and desulfurization (sulphur content 0.001 %). This steel was a coarse-grained tempered martensite with some free ferrite (Fig. 1b). As a result of slow cooling from the tempering temperature, retained austenite occurred. The retained austenite caused instability of microstructure such as lower hardness, tensile strength and yield stress of the steel that revealed lower cavitation resistance. A cavitation rate is commonly measured as a mass loss per an unit of time. As a result of



(a)

(b)

Fig. 4. SEM micrographs of the surfaces after 240 minutes of testing: a) 38HN3MFA steel (uniform distribution of pits at the damaged surface which have characteristic honeycombed appearance) b) CA6NM steel (the transgranular fracture path indicates that there is brittle fracture).



(a)

(b)

Fig. 5. Optical micrographs of cross-sections after 240 minutes of testing (500x): a) 38HN3MFA steel (the surface is covered with small pits and fine ductile cracks in deformed layer) b) CA6NM steel (brittle cracks developed in all directions are noticable).

fine-grained and homogeneous microstructure, the cavitation erosion testing of 38HN3MFA steel exhibited low cavitation rate of 0.0115 mg/min. The cavitation erosion test of CA6MN steel exhibited the cavitation rate of 0.046 mg/min. It was shown that the cavitation rate of 38HN3MFA steel was about 4 times lower than that observed for CA6MN steel. The cavitation rates of both the tested steels were compared with the available results of steels having similar chemical composition and mechanical properties and showed almost 6 times lower cavitation rate [9].

In order to assess the damage rate of the surfaces exposed to cavitation action, the roughness measurements were performed. The value of roughness of 38HN3MFA steel after 240 minute exposure to cavitation was Ra = 0.85 µm (Fig. 3a). This steel has a fine grained and homogeneous microstructure and the low roughness is the result of small surface damage during the testing. Compared to 38HN3MFA steel, CA6MN steel has greater value of roughness of Ra = 2.4 µm (Fig. 3b). Such roughness is the result of greater surface damages due to unstable microstructure.

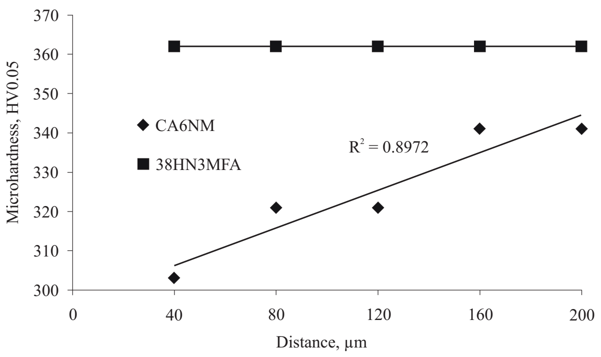


Fig. 6. Microhardnesses in the subsurface layer (increase in microhardness of 38HN3MFA steel was uniform in all parts of the subsurface layer as a result of fine grained and homogeneous microstructure whereas the remarkable increase in the microhardness of CA6MN steel was a result of retained austenite transformation into martensite due to cavitation impacts).

In order to evaluate the morphology of a surface damaged due to cavitation, scanning electron microscopy and optical microscopy techniques were used. The SEM micrograph of 38HN3MFA steel exhibited its capacity to plastic deformation, such as presented in Fig. 4a. There is a uniform distribution of pits at the damaged surface which have honeycombed appearance characteristic of ductile fracture. Although ferrite is soft and carbides are hard, their homogeneous mixture involves uniform distribution of energy released due to cavitation impacts. The ductility was greater because of lower level of inclusions obtained by refining process. The SEM micrograph of the CA6MN steel damaged surface, after 240 minute exposure to cavitation is presented in Fig. 4b. There are no surface undulations typical in case of plastic deformations. The fracture path is transgranular (through the grains) which indicates that there is a brittle fracture. Such behaviour is a result of martensitic structure which does not have many slip systems and decrease the ductility of the steel.

In Figs. 5a and 5b, optical micrographs of the test specimens of 38HN3MFA and CA6MN steel after 240 minute exposure to cavitation are shown. In the subsurface layer of the 38HN3MFA specimen, which is plastically deformed and covered with numerous small pits, cracks may also be seen. There is no plastic deformation in the subsurface layer of the CA6MN specimen, but the roughness resulting from metal particles separation such as cracks developed in all directions is noticable.

Work hardening in the subsurface layer manifesting itself in microhardness increase was registered in case of both tested steels by microhardness measurements (Fig. 6). The increase in the microhardness of CA6MN is especially remarkable. The presence of retained austenite as a result of slow cooling from a tempering temperature made possible its transformation into martensite due to cavitation impacts [10]. The increase in the microhardness was generated by this transformation. The increase in the microhardness of 38HN3MFA is uniform in all parts of the subsurface layer as a result of the fine grained and homogeneous microstructure.

## 5. Conclusions

The following conclusions can be drawn:

1. Cavitation laboratory testing exhibited 4 times lower cavitation rate of ESR steel (38HN3MFA) compared to AOD steel (CA6MN).
2. Better mechanical properties of ESR steel such as high value of yield stress, tensile strength and higher hardness as well as homogeneous and fine-grained microstructure of ESR steel resulted in a better ability to work-harden, a better capacity to absorb energy and more limited range of cavitation erosion. The SEM micrograph exhibited honeycombed appearance of damaged surface typical of ductile fracture.
3. Greater cavitation rate of AOD steel was a consequence of its coarse-grained and unstable microstructure such as transformation of retained austenite in martensite during the cavitation action. The residual stress generated by the martensitic transformation induced damages by fatigue. The SEM micrograph exhibited transgranular fracture path typical in case of brittle fracture as a result of martensite microstructure.

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