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MEETING POINT OF THE SCIENCE AND PRACTICE IN THE FIELDS OF CORROSION, MATERIALS AND ENVIRONMENTAL PROTECTION

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Mechanisms and morphologies of cavitation damage of NN 70 steel

Mehanizmi i morfologije kavitacionog oštećenja čelika Nionikral 70

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Abstract

Broken test tubes for low-cycle fatigue testing of Nionicral 70 (NN-70) parent material (PM) steel and simulated heat-affected zones (SHAZ) were used to produce samples for cavitation resistance testing. Ultrasonic vibrational cavitation method (stationary sample method) was applied for testing in laboratory conditions. The test conditions and procedure, sample preparation and interpretation of results are defined by ASTM G32. The surfaces of the NN-70 PM and SHAZ steel samples were exposed to cavitation and damage monitoring over time. Measuring the weight loss of samples on the analytical balance after a certain time allowed us to determine the cavitation velocity as a measure of the material's resistance to the effect of cavitation. Scanning electron microscopy (SEM) was applied to monitor variations in surface morphology with changing test time. On the basis of the results of the cavitation resistance test, the morphologies of the surface damage for different exposure times of the cavitation of PM and SHAZ steel NN-70 samples were analyzed, as well as the mechanisms that led to the damage of the sample surfaces.
Keywords*: cavitation; steel NN-70; PM; SHAZ; mechanisms and morphologies of damage*

Izvod

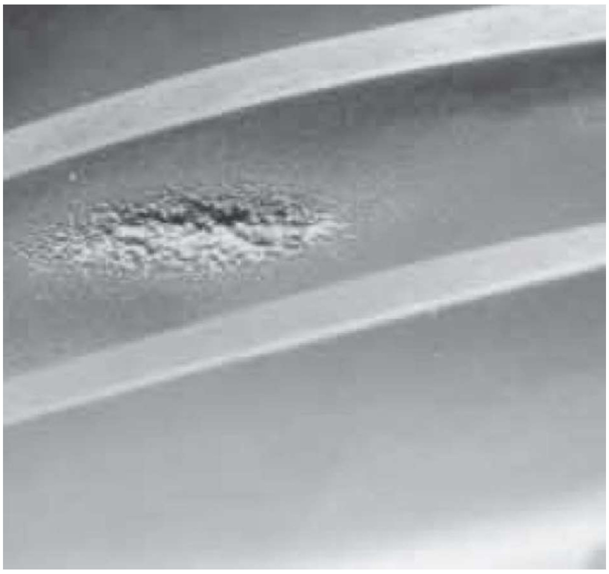
Polomljene epruvete za ispitivanje niskocikličnim zamorom čelika Nionikral 70 (NN-70) osnovnog materijala (OM) i simulirane zone pod uticajem toplote (SZUT) poslužile su nam za izradu uzoraka za ispitivanje otpornosti na kavitaciju. Za ispitivanje u laboratorijskim uslovima primenjena je ultrazvučna vibraciona metoda kavitacije (metoda stacionarnog uzorka). Uslovi i procedura ispitivanja, priprema uzoraka kao i interpretacija rezultata definisani su standardom ASTM G32. Površine uzoraka čelika NN-70 OM i SZUT bile su izložene dejstvu kavitacije i praćenju oštećenja kroz određeno vreme. Merenje gubitka mase uzoraka na analitičkoj vagi posle određenog vremena omogućilo nam je određivanje kavitacione brzine kao mere procene otpornosti materijala na dejstvo kavitacije. Za praćenje varijacija u morfologiji površine s promjenom vremena ispitivanja primijenjena je skenirajuća elektronska mikroskopija (SEM). Na osnovu rezultata ispitivanja otpornosti na kavitaciju u radu su analizirane morfologije oštećenja površina za različita vremena izlaganja dejstvu kavitacije uzoraka OM i SZUT čelika NN-70 kao i mehanizmi koji su doveli do oštećenja površina uzoraka.
Ključne reči: *kavitacija; čelik NN-70; OM; SZUT; mehanizmi i morfologije oštećenja*

Introduction

Cavitation is a phenomenon that involves the formation and implosion of vapor or vapor gas bubbles in a flowing fluid. The implosion of cavitation bubbles results in a number of undesirable phenomena: pressure increase, temperature rise in the vicinity of cavitation bubble implosion, chemical corrosion and electrochemical processes.

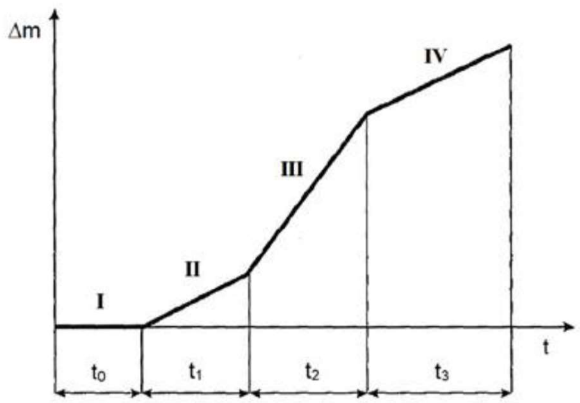
Cavitation is also called cold boiling. Unlike boiling, when heated at which the pressure rises depending on the heat supplied, boiling occurs in cavitation according to changes in pressures in the space surrounding the bladder.
Due to changes in fluid pressure or the influence of rigid boundaries, cavitation bubbles generally deviate from a spherically symmetrical shape. The bubbles implode forming a micrometer that damages the surface to which it is directed, as can be seen in Figs. 1.


a)

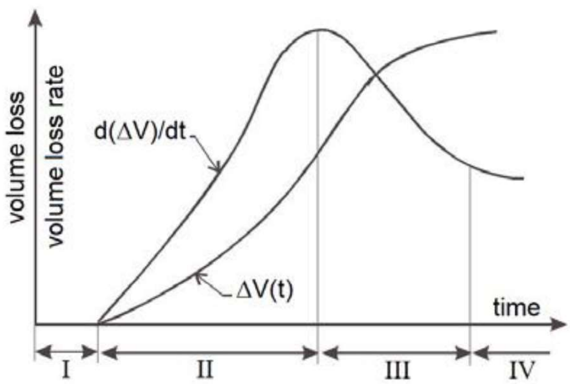

b)

Cavitation material destruction

The destruction of materials under the influence of cavitation is a dynamic phenomenon caused by the repetition of the action of cavitation bubbles that implode and condition the formation of micromlases and shock waves, which leads to the formation of high pressures and temperatures in local microvolumes. In the case of recurrent impulses, cavitation destruction has been shown to have fatigue character. Therefore, plastic deformation, crack initiation and their development depend on the mechanical properties of the material (hardness, modulus of elasticity, tensile strength and dynamic strength), the microstructure of the material (grain size, phase and number of defects in the material), as well as surface roughness.
The four characteristic periods of material cavitation destruction are shown in Figs. 2.



a) Weight loss [3,4,5]



b) Volume loss [6]

Figure 2. *Characteristic cavitation erosion curves*

Under laboratory conditions, the destruction of a cavitation material is evaluated by measuring the loss of mass [5] or volume [6] during the time of material exposure to cavitation.
The curves of Figs. 2a and b, obtained experimentally, provides a link between mass loss, ie volume, and cavitation action time, and shows four characteristic cavitation destruction periods.
The first period (t_0), (I), is the so-called. incubation period, when there is practically no loss of mass or volume due to the effect of cavitation. During this period the material accumulates energy and plastic deformation begins with a noticeable appearance of micro and macro reliefs. During this period, fatigue processes and material reinforcement may occur. During this period, only minor surface damage to the shape of the pits resulting from the loss of microscopic particles from different places on the surface occurs. Determining the duration of this period depends on the accuracy of the measurement of the samples during testing.
The second period (t_1)), (II), is the period of onset of slight destruction of the surface layer followed by minimal mass loss. When the limit of deformation reinforcement is reached, continuous plastic deformation leads to the separation of the material and the formation and propagation of cracks near the surface, resulting in the removal of the material or the appearance of loss of mass of the material. The damaged surface becomes rougher with many small bumps.
The third period (t_2)), (III), is the period of accelerated destruction followed by pronounced mass loss. Small craters formed in the previous period merge to form entire pits on the surface layer exposed to the effect of cavitation. Cavitation velocity can be increased to its maximum value due to deformation of the surface and crack development. The degree of increase in cavitation velocity will depend on the type of material and cavitation conditions. When mass loss begins, surface characteristics change, cracks, deep pits occur, and fatigue becomes more apparent. During this period, the loss of part of the volume reaches its maximum value.
The fourth period (t_3)), (IV), is the period in which slow destruction occurs, but the pits continue to merge and form large craters on the surface exposed to cavitation. The decrease in cavitation velocity during this period depends on many factors such as material properties, the interaction between the fluid flow and the worn surface through the straightening process. Residual air or gas bubbles in deep craters can also act as a cushion and absorb some of the impact energy. This is a period of slow destruction, but the craters still merge and form large cavities and openings on the surface exposed to cavitation. The damaged area corresponding to this period is generally rougher with wider craters. This stage of cavitation only occurs under certain conditions.
In the third period, (III), a decrease in cavitation damage was observed. Volume loss is reduced. This is explained by filling the pits with water.
The last, fourth (IV), period is characterized by almost constant erosion-induced volume loss.

Material resistance to cavitation

The ability of a material to counteract the destruction caused by cavitation is called the resistance of a material to the effect of cavitation. Laboratory tests are used to evaluate the cavitation resistance of materials, so several methods have been developed for the laboratory testing of cavitation resistance of materials such as [7]:

1. High-speed methods (Venturi tube);
2. Jet impact methods using both stationary and rotating samples exposed to high speed jet;
3. High-frequency vibration methods involving magnetostrictive and ultrasonic devices.

To determine the erosion rate and resistance of PM and SHAZ steel NN-70, in this work, a stationary pattern ultrasonic vibration method and the ASTM G32 standard were used [8].
A schematic diagram of a stationary sample ultrasonic vibration test apparatus is shown in Figs. 3.

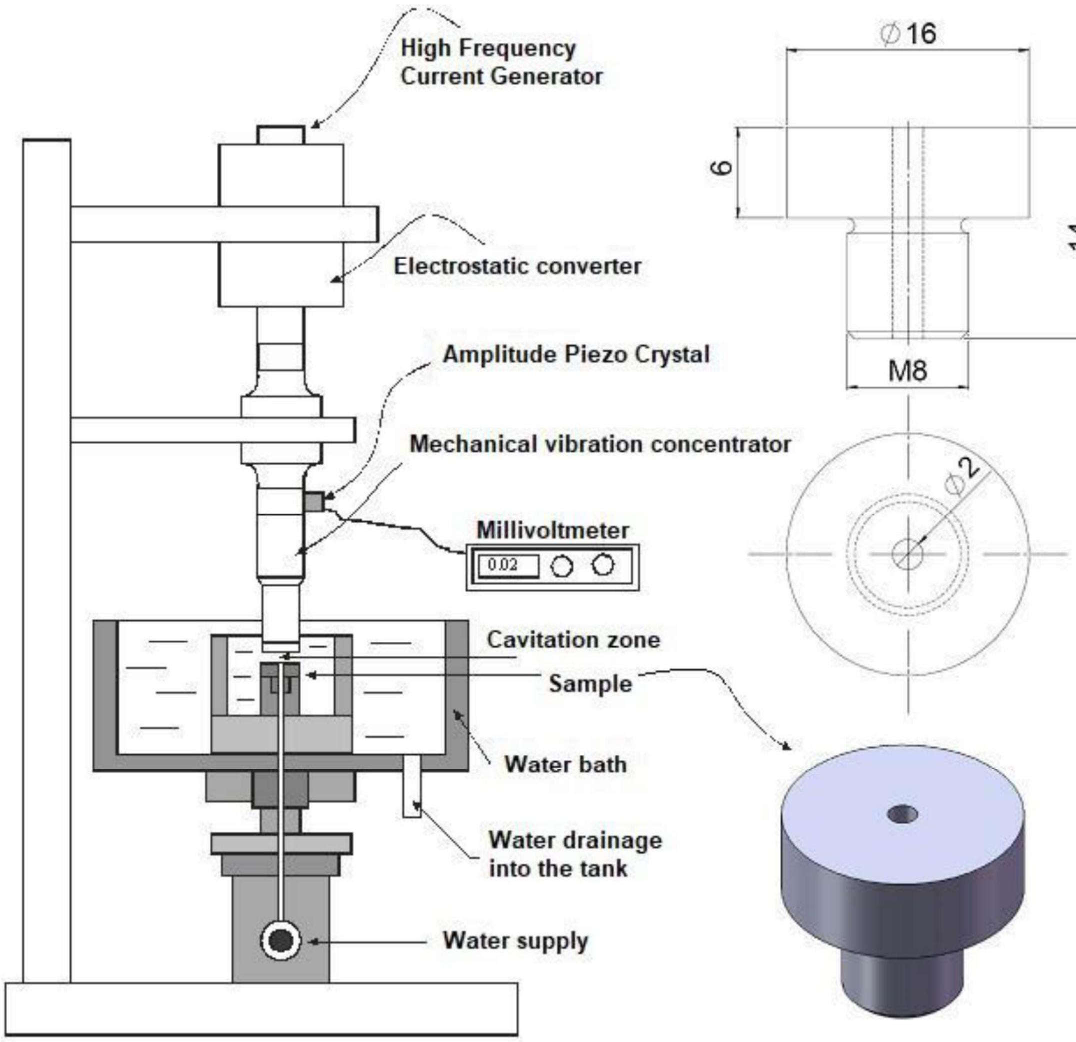


Figure 3. *Scheme of a device for testing the resistance of a material to the effect of cavitation by an ultrasonic vibration method with a stationary sample [3, 4, 8]*

High frequency output current generator 360 W, generates a frequency of 20÷50 kHz that is kept constant throughout the test. A high-frequency current feeds an electrostrictive converter - a convector in which a high-frequency current is converted into mechanical vibrations via a piezoelectric element (zirconium titanate).

In this method, the sample of the material under test has an opening of ϕ2 mm through which fluid flows and the sample is placed below the front surface of the vibration concentrator with a gap. The shape and dimensions of the specimen are prescribed by the standard [8], and fit in Figs. 3.

In this method, the destruction of the material under the action of cavitation depends on the magnitude of the amplitude, the gap between the sample and the concentrator face, the flow of water through the sample opening and the water temperature of the water bath. In order to determine the standard values of the above test parameters, cavitation velocity tests were performed depending on the above parameters. Based on these tests of the influence of individual parameters on the cavitation velocity, standard values of these parameters were adopted, with the aim that the results of the research could be compared:

1. Mechanical vibration frequency are 20±0.2 kHz;
2. Mechanical vibration amplitude at the top of the concentrator is 50 m;
3. Clearance between test sample and concentrator is 0.5 mm;
4. Water flow is 5-10 ml/s;

5. The water temperature in the water bath is 25±1 °C.

4. Testing of the resistance of NN-70 steel to the effect of cavitation

The cavitation resistance was tested on PM and SHAZ samples, NN-70 steel. The chemical composition of NN-70 steels is given in Tab.1, and the mechanical properties of PM and SHAZ, of NN-70 steels are given in Tab.2.

Table 1. Chemical composition of NN-70 steel, % wt [9]

Series	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	As	Sn
PM	0.106	0.209	0.220	0.005	0.0172	1.2575	2.361	0.305	0.052	0.007	0.017	0.014
	Cu	***Ti***	***Nb***	***Ca***	***B***	***Pb***	***W***	***Sb***	***Ta***	***Co***	***N***	-
	0.246	0.002	0.007	0.0003	0	0.0009	0.0109	0.007	0.0009	0.0189	0.0096	-

Table 2. Mechanical properties of the materials tested, [9]

Series	E, GPa	Rm, MPa	Rp0.2, MPa	A5, %	Impact toughness	Hardness, HV30	Hardness, HV10
PM	221.4	853	805	18.4	121	245-269	
SHAZ	225.0	884	830	8.7	79		270-280

After testing the OM and SZUT samples, NN-70 steel, with low-cycle fatigue, non-standard samples were made from the broken SZUT tube, Fig. 4, for testing cavitation resistance by ultrasonic vibration method according to ASTM G 32 standard [8].

The surface of the test specimens was prepared by grinding and polishing so that the same roughness quality Ra = (0.03-0.05) µm was achieved on all specimens.

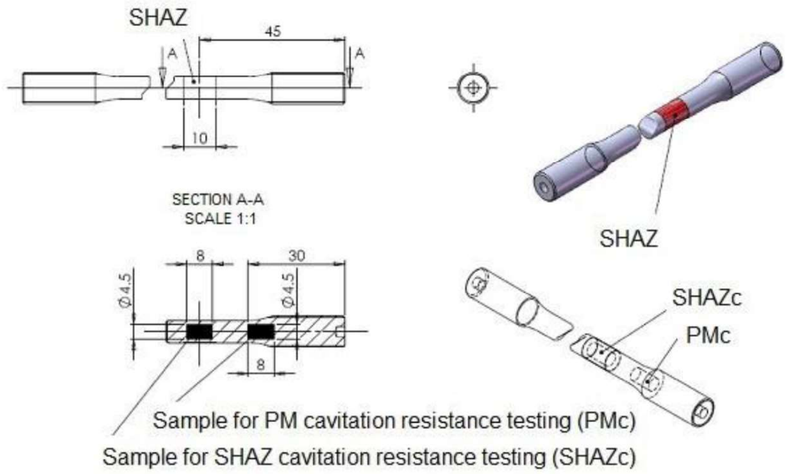
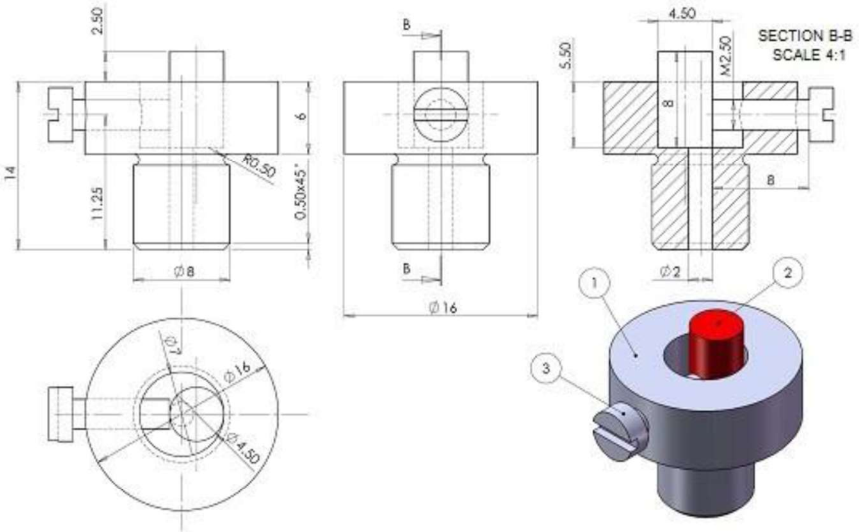


Figure 4. *Cavitation resistance test specimens made from LCF SZUT sample 01 [9]*

A refined standard stationary sample was used as the holder for these samples, as shown in Figs. 5. Samples for metallographic testing were also made from the broken sample of the LCF SHAZ sample, fig. 6, the results of which served as a basis for explaining the morphologies and mechanisms of cavitation erosion of PM and SHAZ steel NN-70.

In order to explain the mechanisms of cavitation erosion, after examination of samples of PM and SHAZ steel NN-70 on the effect of cavitation, as well as the morphology of the surfaces exposed to cavitation erosion, the surface exposed to cavitation was observed by scanning electron microscope (SEM), as was done in [3 , 4 and 9-14].



1 - sample holder, 2 - test specimen, 3 - fixing screw

Figure 5. *Cavitation resistance test sample in sample holder [9]*

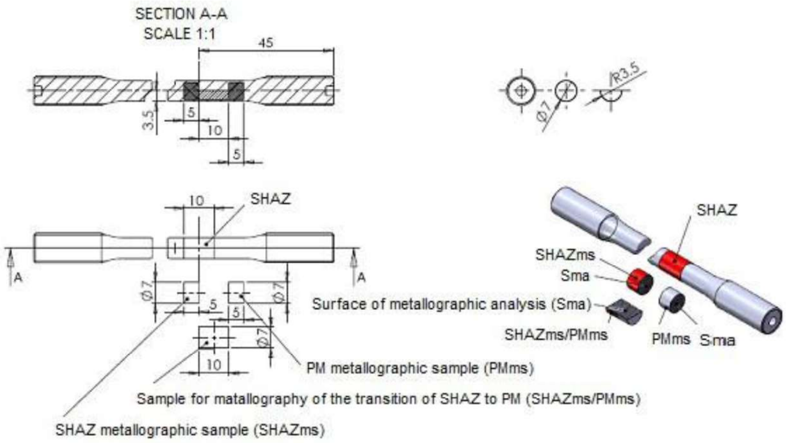
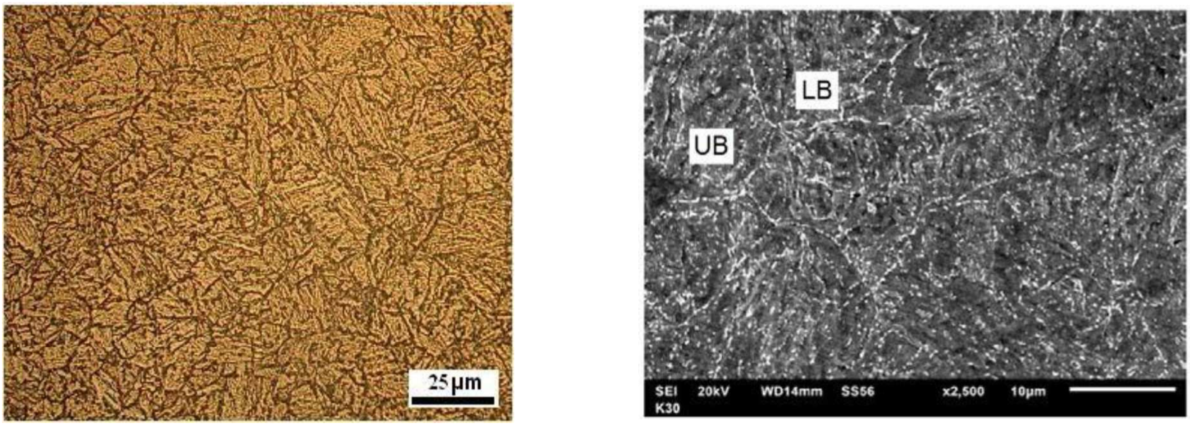


Figure 6. *Metallographic testing specimens made from LCF SZUT sample 07 [9]*

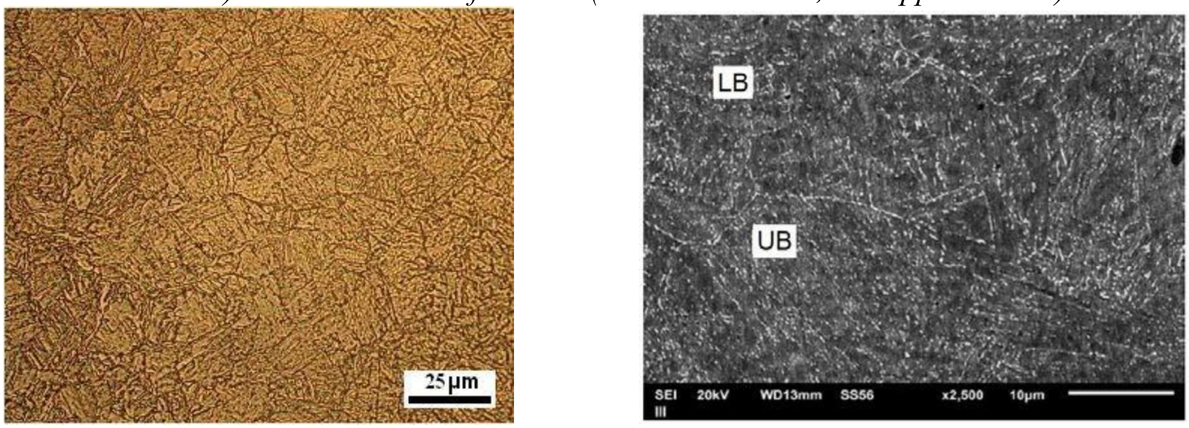
Test results and discussions

The micro structure of PM and SHAZ of NN-70 steel contains martensite and beinite, Figs. 7 [9,14].

Analyzing the microstructures of the fracture surfaces, we can see that the upper beinite is dominated by the SHAZ, and significantly less in the PM. This is why SHAZ has a reduced toughness compared to PM. There is very little difference in grain size and overall structure of PM and SHAZ.



a) Microstructure of the PM (LB-lower bainite, UB-upper bainite)



b) Microstructure of SZUT (LB-lower bainite, UB-upper bainite)

Figure 7. *a) PM (martensite and bainite with carbides), b) SHAZ (martensite, bainite and ferrite with carbides)*

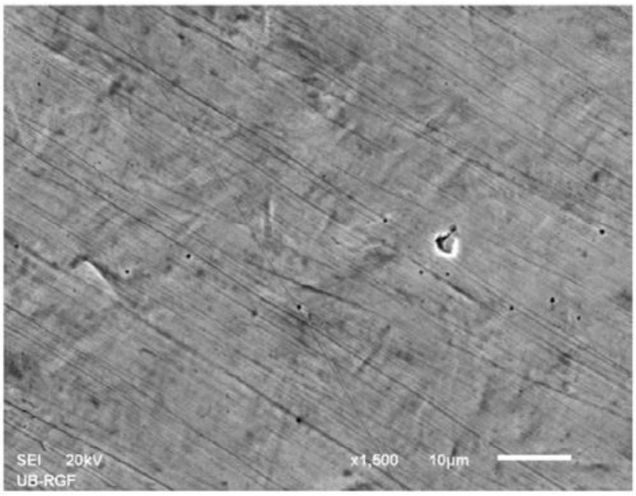
In addition to the above micro constituents, the SHAZ microstructure also includes a small amount of carbide ferrites (Figure 1b). The material was found to be characterized by a high degree of porosity.

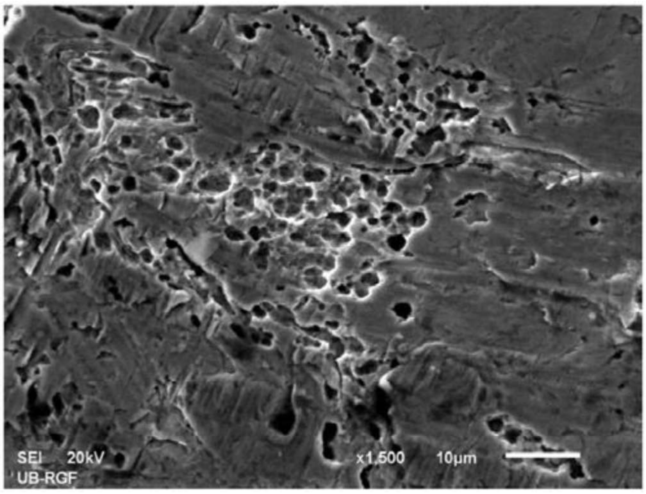
The measured PM hardness was 269 HV1. The SHAZ hardness value was 276 HV1.

After exposure of each sample to the effect of cavitation for 30 min, mass loss was measured. The mass was measured on an analytical balance whose measurement accuracy was 0.0001 g. After each test interval, the sample was dried with warm air and kept in a desiccator for 24 hours to remove residual moisture.

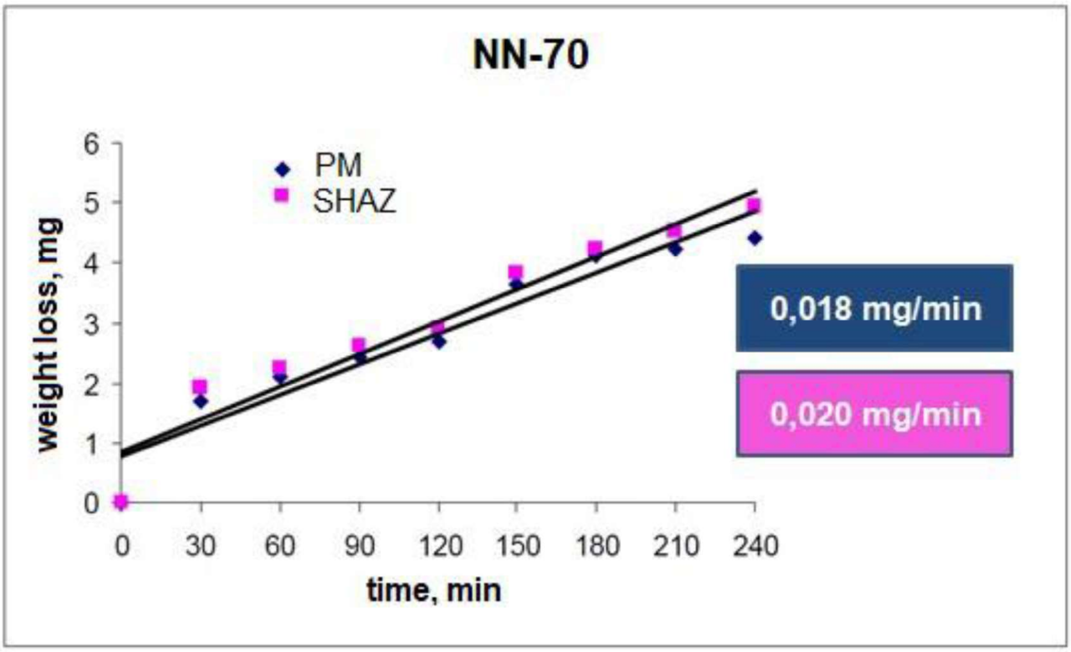
To determine the cavitation velocity, which is used to evaluate the material's resistance to cavitation, diagrams of test time-mass loss were made. The loss of mass caused by cavitation damage is applied to the ordinate, and the abscissa records the time intervals of the test. Using the least squares method, the points of the diagram are approximated by the direction whose tangent of the slope angle represents the loss of mass over the period of cavitation action and represents the cavitation velocity, Fig. 8.

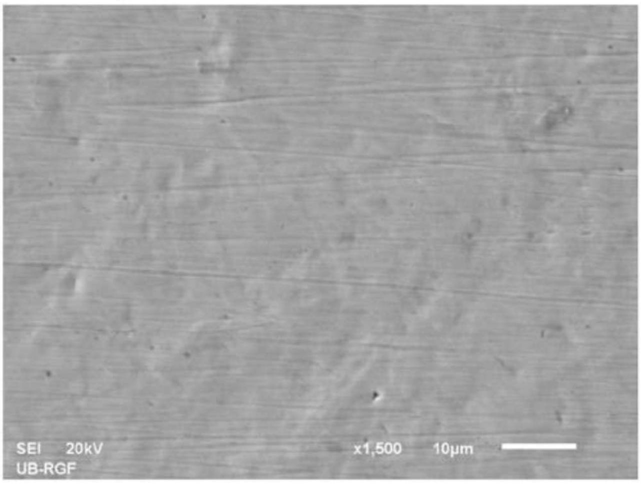
Scan electron microscopy (SEM) of the surface damage of the PM sample exposed to cavitation for 30, 60, 90, 120, 180 and 240 minutes and scan electron microscopy (SEM) of the surface damage of SHAZ samples exposed to cavitation for 30, 60, 90 , 120, 180 and 240 minutes is also shown in Figure 8.

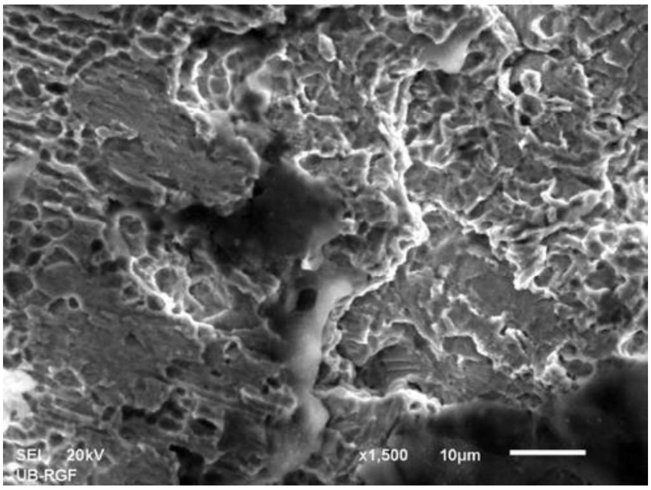




PM-30 min ***PM – 240 min***



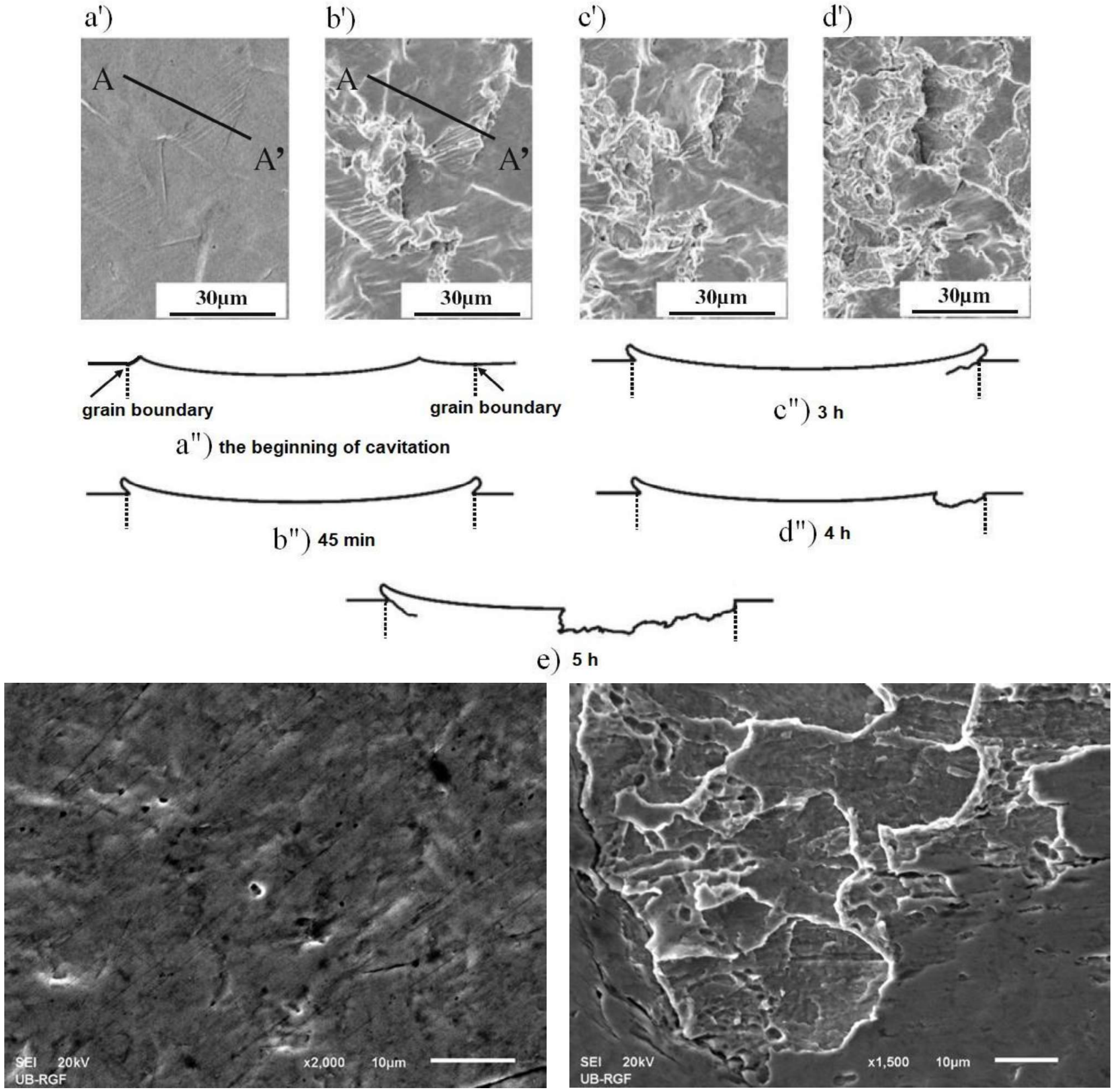




SHAZ-30 min ***SHAZ-240 min***

Figure 8. *Diagram of change in cavitation velocity and SEM of damaged surfaces of tested samples PM and SHAZ of steel NN-70*

The scanning electron microscopy photographs analyzed the surface morphology, Figs. 8, samples of PM and SHAZ of NN-70 steel damaged by cavitation exposure, and on the basis of it, the mechanisms of damage occurrence were determined, fig. 9.
The cavitation rate of the PM sample is 0.018 mg/min, while the cavitation rate of the SHAZ sample is 0.020 mg/min, and this was calculated from the diagram shown in this slide.
After 240 min of exposure of the sample surface PM and SHAZ to the effect of cavitation, numerous wells were observed, most likely due to the porosity of the starting PM.

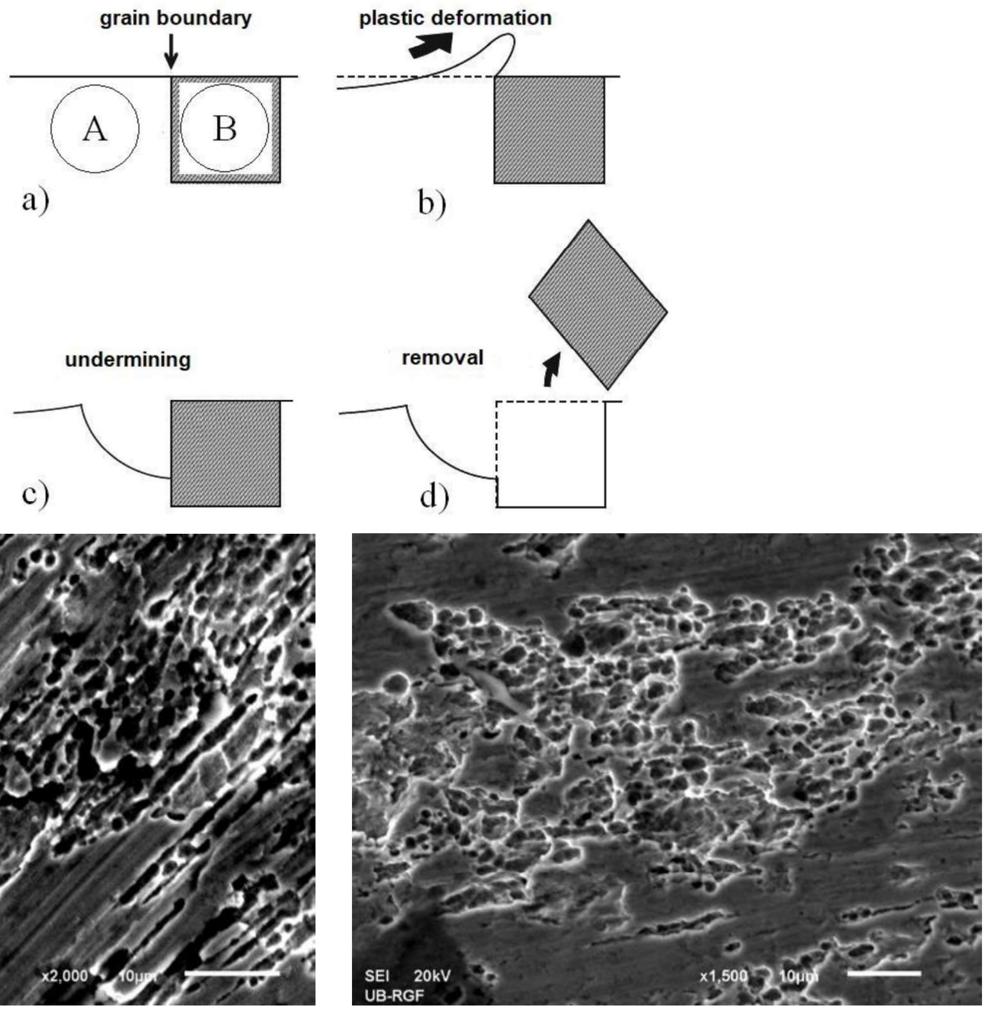


PM-180 min ***SHAZ-90 min***

Figure 9. *Mechanism of surface destruction by cavitation [15, 16]*

The original surface was repeatedly exposed to the destruction of cavitation bubbles, which caused plastic deformation of the surface of the material by shock waves and micro jets generated by the destructive bubbles, a schematic illustration of FIG. 9a ”. Multiple repetition of the action of the destructive bubbles on the deformed surface causes a gradual expansion of the surface and the accumulation of plastic deformation at the boundaries of the crystalline grain as shown schematically in Figs. 9b ”, which corresponds to SEM photography after 45

minutes of cavitation action, Figs. 9b '. At the boundaries of the crystalline grain, extruded parts of the plastically deformed surface material appear. These parts produce an additional load relative to adjacent grains with less plastic deformation and cause a high stress concentration, resulting in a crack as in Figs. 9c ”. Figure 9d ”shows that erosion easily occurred at the site of crack formation. Figure 9c and d correspond to SEM photographs after 3 - 4 h, Figs. 9c 'and d'. The evolution of erosion after 5 hours is shown schematically in Figs. 9e, where we see that cavitation erosion has invaded a wide space within the grain.
For hard constituents, such as carbides, the model of the mechanism of destruction by cavitation erosion is shown in Figs. 10, based on SEM observations [16]. Figure 10a shows the intact surface of an eutectic structure consisting of a metal matrix and a carbide. Figure 10b illustrates that the metal matrix is softer than the carbide, causing plastic deformation to occur in the matrix. In this case, carbides play the role of grain boundary from the mechanism model of Figs. 9. Plastic deformation occurs in the matrix, and the extruded part of the material appears near the carbide. The extruded part near the carbide has a high stress concentration that easily initiates cracking. Figure 10c shows that the erosion takes place at the interface between the matrix and the carbide. Erosion undermines the carbide and then ejects it from the matrix, as shown in Figs. 10d.
This mechanism can explain the cavitation erosion of metals in which other hard constituents, inclusions (slag, gas pores, impurities), porosity, etc. are present.



PM-180 min ***SHAZ-90 min***

A - metal matrix, B - hard constituents or inclusions (slag, gas bubbles, impurities)

Figure 10. *Model of the mechanism of cavitation destruction of metals [15, 16]*

Conclusion

Based on the results related to the experimental considerations of the behavior of low alloy high strength steel, in this case PM and SHAZ of NN-70 steel, under the conditions of cavitation destruction based on the analysis of morphologies and mechanisms of damage, as well as a discussion of the results of experimental tests, the following general conclusions can be drawn:

- The morphology of the PM surface is characterized by marked hardening of the material, but the morphology of the damage in subsequent stages indicates the porosity of the PM and cannot be related to the microstructure of the PM in which beinite is represented;
- During the examination of SHAZ specimens, two types of morphology can be observed: morphology characteristic of martensite and damage morphology resulting from the porosity of the material;
- In the case of SZUT, the presence of beinite is assumed to reduce the negative effect of ferrite having little resistance to the effects of cavitation.

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