J. Serb. Chem. Soc. 71 (8–9) 977–984 (2006) UDC 669.041.3+621.039.548.5+666.9.04:681,723
JSCS-3491 *Original scientific paper*

The morphology of cavitation damage of heat-treated medium carbon steel

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(Received 20 April, revised 29 December 2005)

Abstract: In this paper the morphology of the cavitation damage to heat-treated medium carbon steel was analyzed. The experiments were conducted using a modified vibratory cavitation test set up. The erosion rates were measured by an analytical method. The morphology of the cavitation damage was studied by the scanning electron microscopy and optical microscopy techniques. The present work was aimed at understanding the cavitation erosion behaviour of heat-treated medium carbon steel under laboratory conditions. The results indicate that the heat-treated medium carbon steel is not to be recommended for the production of hydraulic machinery parts exposed to high hydrodynamic intensity.

Keywords: cavitation, heat treated medium carbon steel, optical microscopy, scanning electron microscopy, microhardness.

INTRODUCTION

Cavitation, one of the mechanisms of liquid erosion, involves the formation and subsequent collapse of bubbles within a liquid.[1–3] The pressure waves emitted during the collapse of the bubles interact with neighboring solid surfaces, leading to materijal damage.[4–6] Damaged surfaces of hydraulic machinery parts exposed to cavitation may very rapidly obtain dimensions from a few square milimeteres to a few square meters. The duration of the damage process is from a few minutes to a few thousand working hours.

The purpose of most laboratory tests on cavitation erosion is the production of the performance of a material under cavitation attack in a full-scale hydraulic machine or structure. As the course of erosion is generally known to depend essentially on the distribution of the cavitation impacts, reproduction of this distribution in the laboratory may be considered a prerequisite for reliable quantitative assessments.[7]

The cavitation erosion study presented in this paper was carried out to determine the resistance of a heat–treated medium carbon stell to cavitation erosion.

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doi: 10.2298/JSC0609977D

In order to obtain realastic cavitation erosion predictions in hydraulic machines, a vibratory device was used. The cavitation cloud was generated by a horn vibrating at a high frequency in water. The obvious advantages of the method include: high erosion rate (a test duration of 4 to 6 h is often sufficient), small size of the device and low energy consumption. The vibratory method was standardised by the ASTM Committee on Wear and Erosion in an interlaboratory test carried out in 1969.[8]

EXPERIMENTAL

Material

The main reason for heat treating steels is to modify their mechanical properties. In this case, a heat treatable medium carbon steel was chosen for examination. The heat treatment was performed by quenching (heating at 860 °C and cooling in water) with subsequent tempering (heating at 610 °C and air cooling). The chemical composition and mechanical properties of the heat treated medium carbon steel, standard C35E (EN) or Ck35 (DIN), are listed in Tables I and II, respectively. The chemical composition and mechanical properties are those given by the producer.

TABLE I. Chemical composition of the tested steel/wt %

C/%	Si/%	Mn/%	P/%	S/%
0.34	0.31	0.64	0.018	0.022

TABLE II. Mechanical properties of the tested steel

HV_{30}	R_e N/mm^2	R_m N/mm^2	As %	Z %	KV J + 20°C
187	330	550	24	56	72

The formed microstructure consisted of a ferrite phase and a pearlite phase (ferrite and cementite). The grain size of N° 6 (grain diameter d = 0.044 mm) means that the steel may be regarded as a coarse–grained material. The microstructure of the tested material is shown in Fig. 1.

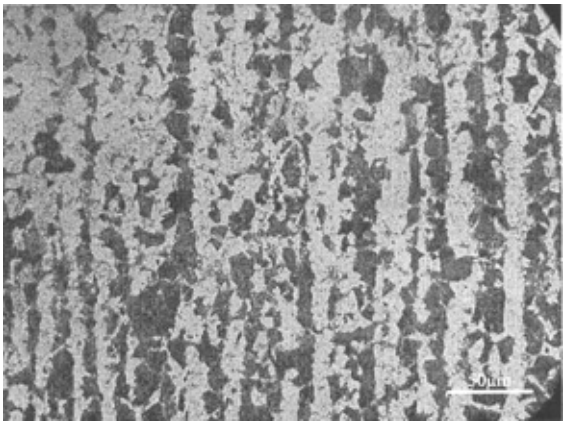


Fig. 1. Microstructure of the heat treated medium carbon steel. Magnification 500x.

Methods

The test equipment for conducting the laboratory testing of the cavitation resistance using the Modified Vibratory Cavitation Test Method is shown in Fig. 2.[9] The equipment consists of: a high frequency generator of 360 W, an electro-strictive transducer, a transformer for the mechanical vibrations and a water bath containing the test specimen.

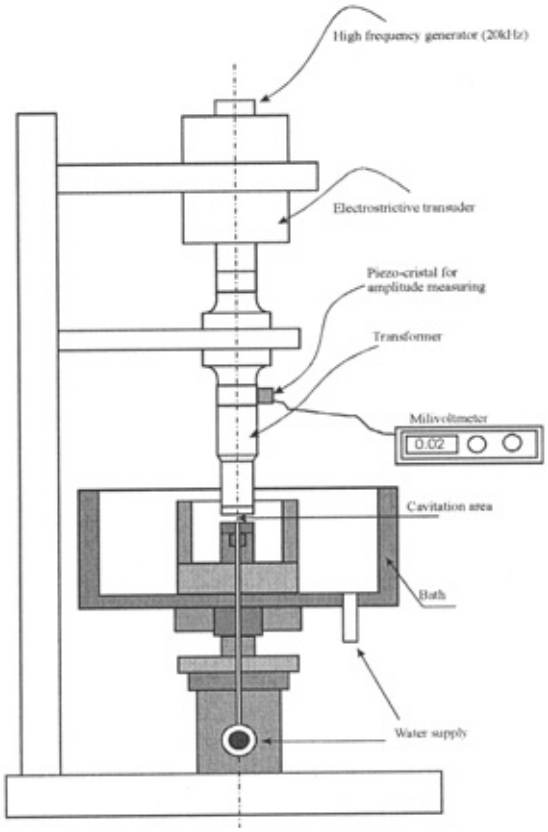


Fig. 2. Schematic overview of cavitation test set up.

Cavitation erosion testing was accomplished utilizing the recommended standard values:

- Frequency of vibration: 20 ± 0.2 kHz
- Amplitude of vibrations at the top of the transformer: 50 μm
- Gap between the test specimen and the transformer: 0.5 mm
- Temperature of the water bath: 25 ± 1 °C
- Water flow 5 – 10 ml/s

These parameters were rigorously controlled throughout the testing process.[10]
The dimensions of the heat-treated test specimen are shown in Fig. 3.

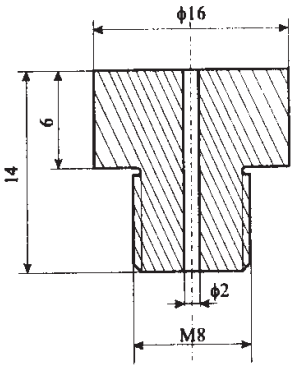


Fig. 3. Dimensions of the test specimen.

The test specimen was placed under the transformer with a gap of 0.5 mm. An analytical balance with an accuracy of 0.0001 grams was used to evaluate the mass losses of the test specimens. Prior to the measurements, the test specimens were dried in hot air. The measurements were performed after each test specimen had been subjected to cavitation for a duration of 30 min. Three test specimens were used for each test.

After the cavitation tests, the roughness of the damaged surface of the specimens were determined by a profilometer.

Scanning electron microscopy (SEM) and optical microscopy were performed 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 cuting, mounted in epoxy-resin, then polished and etched in Nital.

Vickers microhardness tests on the cross sections of the test specimens were also performed in order to verify the existence of work-heardening subsurface layers affected by cavitation. The indentations were done with distance of 40 μm. The applied load was 50 grams.

RESULTS

The results of the cavitation resistance testing of the test specimens are given in Fig. 4, which shows a linear relation between the mass loss and testing time. The slope represents the cavitation erosion velocity and the intercept with the abscissa indicates the induction period, *i.e.*, the elapsed time before destruction of the material commences. The calculated value of the cavitation erosion velocity is 0.064 mg/min.

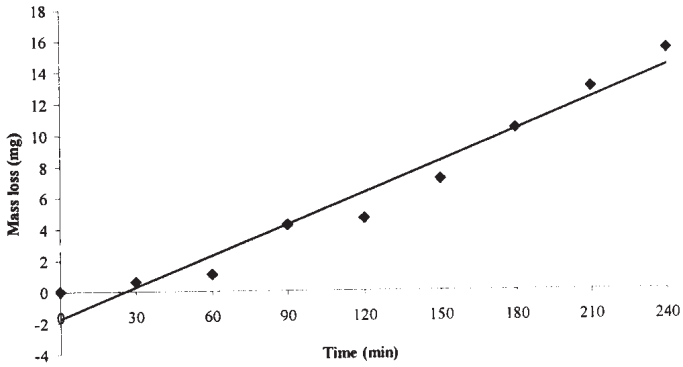
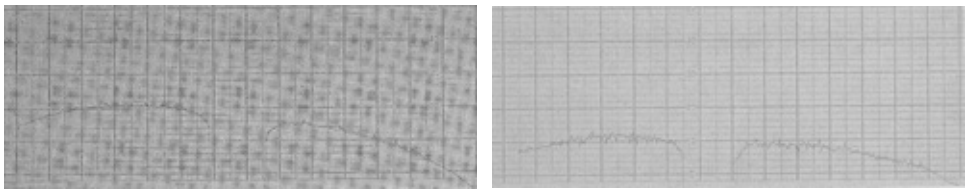


Fig. 4. Cavitation erosion as a function of time.

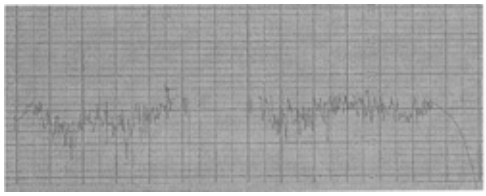
Three significant stages after 60, 120 and 240 min, in the damage development in the vibratory cavitation device are shown in Figs. 5–7.

The roughness of the damaged surfaces of the specimens, obtained by the profilometer, are shown in Fig. 5a, b and c for test durations of 60, 120 and 240 min, respectively.

SEM micrographs of the test specimens after the three stages in the damage development, corresponding to exposure times of 60, 120 and 240 min, are shown in Fig. 6 a–c, respectively.

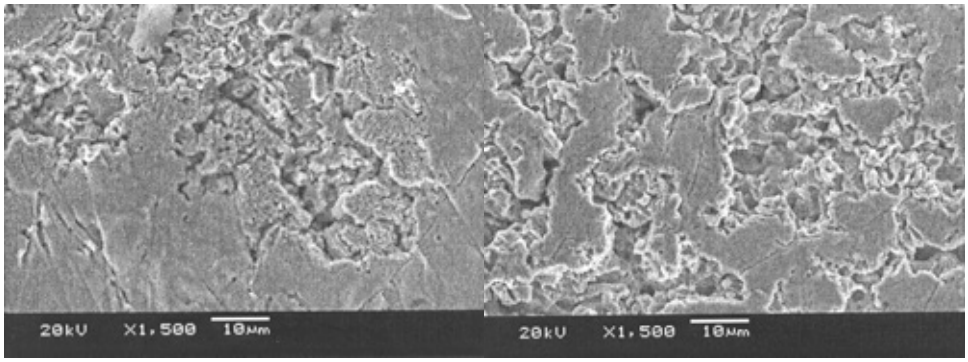


a) b)



c)

Fig. 5. Roughness of the damaged surfaces (pictures of the original profilometer sheets) after an exposure time of a) 60 min b) 120 min c) 240 min.



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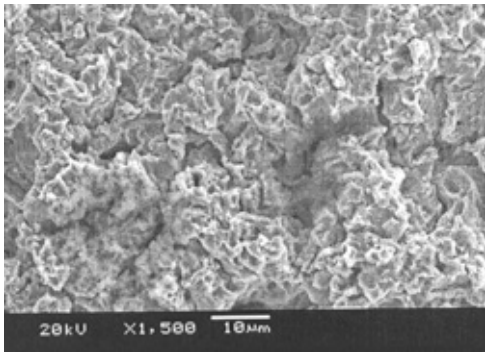


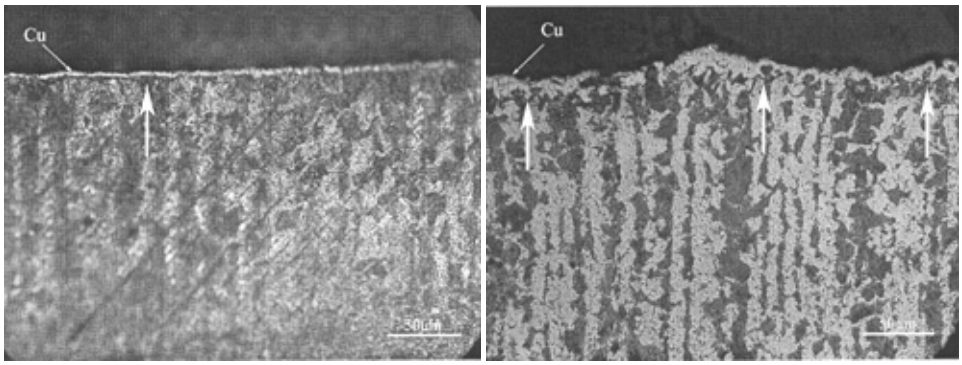
c)

Fig. 6. SEM Micrographs of the surface of specimens exposured for a) 60 min b) 120 min c) 240 min.

Optical micrographs of the cross sections of the test specimens after cavitation testing, for 60, 120 and 240 min are shown in Fig. 7 a–c, respectively.

Typical indentations on the cross section of a test specimen are shown in Fig. 8.

The changes of the microhardness in the subsurface layers as a function of exposure time are shown in Fig. 9.



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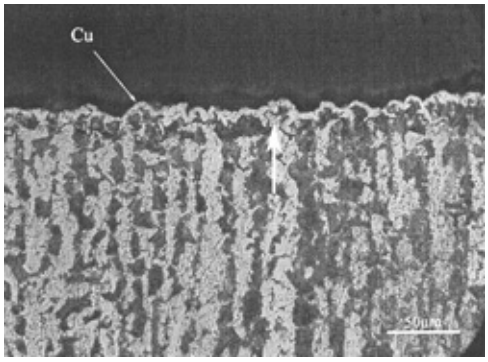

c)

Fig. 7. Optical micrographs of cross sections of specimens exposed for a) 60 min b) 120 min c) 240 min. Magnification 500 x.

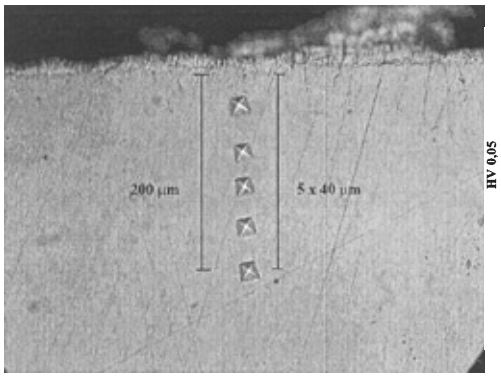

Fig. 8. Microhardnesses indentations on the cross section of a specimen (100 x).

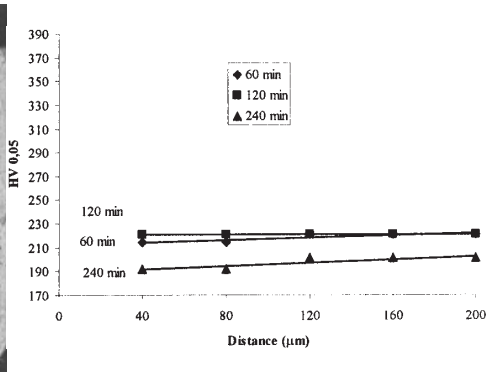

Fig. 9. Microhardnesses in the subsurface layer as a function of exposure time.

DISCUSSION

The heat treated medium carbon steel specimens showed low cavitation resistance because of the high value of the cavitation erosion rate 0.064 mg/min (see Fig. 4). Such a behaviour can be explained by the microstructure (the mixture of perlite and ferrite) and grain size (Nº 6, grain diameter $d = 0.044$ mm) of the steel which can be coupled to the low values of hardness, tensile strength and tensile stress (Table II). This steel contains relatively high concentrations of phosphorus, sulphur and other impurities. It is well known that such elements diffuse to the grain boundaires and decrease the strength of the material, leading to material fracture.

The value of roughness, in the first stage of cavitation damage after 60 min was $R_a = 0.455$ μm (Fig. 5a). The low roughness is the result of the long incubation period (30 min), and it indicates that little surface damage occurred during this period. Increasing the exposure time results in greater cavitation damage of the surface and the value of the roughness after 240 min was $R_a = 2.25$ μm (Fig. 5c). Such a high value of roughness can be explained by the separation of massive particles from the damaged surface.

Fig. 6a shows a SEM micrograph of the surface during the first stage of cavitation damage, *i.e.,* after 60 min. The start of cavitation attack over grain boundaries and surface of grains can be clearly seen. Surface undulations indicate that there is deformation of the grains. This is in accordance with the roughness obtained in this stage of cavitation damage, shown in Fig. 5a. Metal loss was already recorded, but the erosion was mostly confined to the individual areas.

Fig. 6b illustrates the condition of the surface of the specimen after 120 min of testing. The increase in exposure time resulted in a greater loss of metal, characterized by crack propagation and separation of metal particles from the surface.

In the next stage of cavitation damage *i.e.,* after 240 min of testing, the whole surface of the test specimen becomes deformed and uniformly covered with pits, as shown in Fig. 6c.

An optical micrograph of the cross section of the test specimen in the first stage of cavitation damage, *i.e.,* after 60 min, is shown in Fig. 7a. Surface undulations and plastic deformation of the surface layer can be seen (marked with arrow).

An optical micrograph of the cross section of a test specimen after 120 min of cavitation action is presented in Fig. 7b. In the plastically deformed layer covered with numerous small pits, cracks nucleate and develop. The craks, marked with arrows, follow the boundaries of deformed and non-deformed grains.

According to the optical micrograph in Fig. 7c, there are many places where metal particles had been removed. Also, in the subsurface layer of the test specimen the cracks may be seen. These cracks can link, leading to separation of metal particles from the test specimen. A particle which was about to be separated is indicated by an arrow in Fig. 7c.

Using a microhardness measurement technique, some authors evaluated the depth of the hardened layer to be about 200 μm.[3] Microhardness measurements exhibited a decrease of the microhardness of the subsurface layer during cavitation testing (see

Fig. 9). Such a behavior can be explained as follows: imploding bubbles release energy causing heating of the surrounding surface. In our opinion, this heating of the surface caused the decrease of the microhardness of the subsurface layer, because the heat treated medium carbon steel was tempered during this period.[11]

CONCLUSIONS

The experimental results show that the cavitation resistance of the investigated heat-treated medium carbon steel was not satisfactory, mostly because of the high cavitation erosion rate. Also, the microstructure (the mixture of ferrite and pearlite phases) with the coarse-grained size exhibited low cavitation resistance. Therefore, the heat treated medium carbon steel is not to be recommended for the production of hydraulic machinery parts, particularly those that operate in regions of high hydrodynamic intensity.

ИЗВОД

МОРФОЛОГИЈА КАВИТАЦИОНОГ ОШТЕЋЕЊА СРЕДЊЕУГЉЕНИЧНОГ ЧЕЛИКА У ПОБОЉШАНОМ СТАЊУ

МАРИНА ДОЈЧИНОВИЋ и СРЂАН МАРКОВИЋ

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У раду је анализирана морфологија кавитационог оштећења средњеугљеничног челика у побољшаном стању. Експеримент је вођен применом модификиране ултразвучне методе. Степен кавитационог оштећења је мерен класичном аналитичком хемијском методом. Морфологија оштећења насталог дејством кавитације праћена је скенинг електронским микроскопом и светлосним микроскопом. Циљ овог рада је било тумачење кавитационог ерозионог понашања средњеугљеничног челика у побољшаном стању у лабораторијским условима. Добијени резултати показали су да примена средњеугљеничног челика у побољшаном стању није препоручљива у производњи елемената хидрауличних машина изложених екстремним хидрауличним условима.

(Примљено 20. априла, ревидирано 29. децембра 2005)

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