THE QUENCHING - TEMPERING HEAT TREATAMENT AND CAVITATION EROSION RESISTANCE OF NODULAR CAST IRON WITH FERRITE - PEARLITE MICROSTRUCTURE

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Abstract

Samples made of nodular cast iron FGN 400-15 have been heat treated by oil quenching from 850 °C followed by tempering at 450 °C. The objective of the paper aimed the microstructure modification and improvement of the mechanical properties and wear resistance by cavitation. The results showed that the cavitation erosion resistance of heat treated cast iron is 1.8 times higher than that of the thermal stress relieved cast iron.

Examination of surface topography and microstructure of the cross section samples after the cavitation attack showed that the wear of heat-treated samples occurs by fatigue cracking mechanism, while by the thermal stress relieved cast iron a severe plastic deformation and a combined micro-cutting and micro-ploughing of the ferritic matrix appeared.

Improving of the cavitation resistance after the quenching-tempering heat treatment is explained by the fine structure, a relatively high hardness and yield strength, associated with an acceptable toughness.

Keywords: Quenching - tempering, nodular cast iron, cavitation erosion

1. INTRODUCTION

Nodular cast irons represent an important class of engineering materials due to the high mechanical strength characteristics and toughness. In addition, they have excellent cast ability and good cutting machinability, being designed for execution of structural components with complex shape from automotive industry (shafts), metallurgy (rolling cylinders), etc. which are subjected to cyclic stresses [1, 2]. However, these materials have experiencing a severe erosion when are used in cavitational environments [3, 4]. A number of researchers have studied the resistance to cavitation erosion of cast irons with lamellar or spheroidal graphite before and after application of some heat treatments. They found that graphite plays a stress concentrator role and depending on the form it takes (lamellar, vermicular, nodular, flake) reduces more or less the resistance to cavitation erosion [3]. In this paper it is analysed the influence of the quenching - tempering heat treatment on the cavitation behaviour of nodular cast iron with ferrite and pearlite matrix.

2. EXPERIMENTAL PROCEDURE

Cylindrical cast iron bars EN-GJS-400-15 with chemical composition: C = 3.57 %, Si = 2.51 %, Mn = 0.23 %, P = 0.044 %, S = 0.010 % and Fe = balanced were martensitic quenched followed by tempering **(Figure 1).** Subsequently, from these materials, samples were cut for cavitation tests and structural analysis. As a standard material the same cast iron was used, which has been subjected to stress relief annealing.

Cavitation tests were conducted on a vibrating apparatus with standard piezo-ceramic crystals **(Figure 2)** realized in accordance with norms ASTM G32-2010. As a testing medium was used drinking water from the public network. During researches the water temperature was maintained at the value of 22 ± 1 °C. Before cavitation, the tested surface of each sample was polished to r oughness R_a = 0.051÷0.090 µm. The testing duration of each sample was 165 minutes, being divided into 12 periods (one of 5 and 10 minutes, and 10 periods of every 15 minutes).

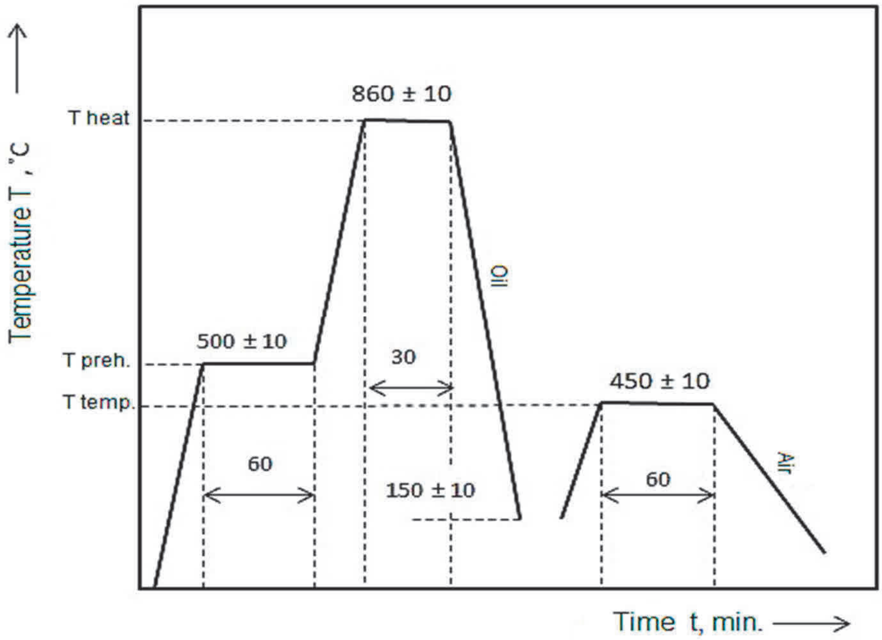


Figure 1 Heat Treatment Cyclogram of Quenching - Tempering

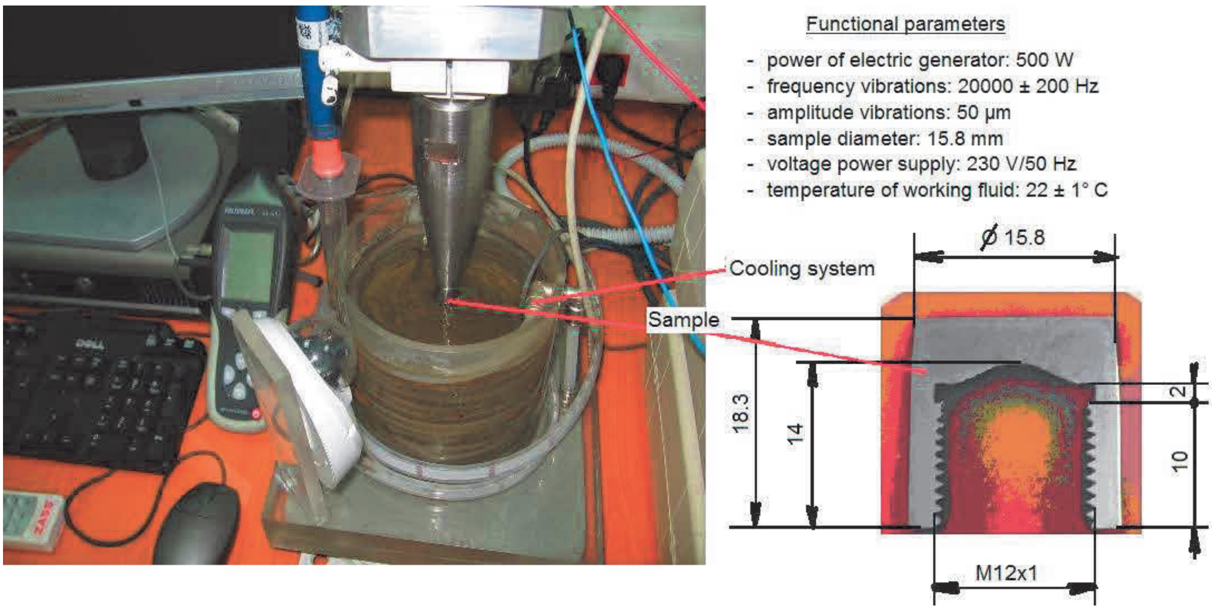


Figure 2 Overview of the vibrating apparatus with piezo-ceramic crystals

As a testing medium was used drinking water from the public network. During researches the water temperature was maintained at the value of 22 ± 1 °C. Before cavitation, the tested surface of each sample was polished to a roughness R_a = 0.051 ÷ 0.090 µm. The testing duration of each sample was 165 minutes, being divided into 12 periods (one of 5 and 10 minutes, and 10 periods of every 15 minutes). At the end of each testing period, it has been determined, by weighing, the material mass lost by cavitation erosion, respective the mean depth of erosion (MDE) and the related mean depth erosion rate (MDER); the cavitation eroded surfaces were examined by optical microscopy and macro photographed. Once the cavitation attack tests (165 minutes) were finished, the eroded surfaces were also examined using scanning electron microscope.

The resistance to cavitation erosion evaluation was done by determining the variation curves of MDE and MDER with the testing time. At different attack periods the mass losses were determined and the eroded surfaces were examined by light and scanning electron microscopy.

3. CAVITATION CURVES

Cavitation tests were conducted on three sets of samples, measuring the cumulative mass losses; based on these the mean depth of erosion (MDE) and the mean depth erosion rate (MDER) were calculated:

- for the cumulative mean depth erosion, after each intermediary period "i"

$$MDE_i = \sum_{i=1}^{12} \Delta MDE_i = \frac{4 \cdot M_i}{\rho \cdot \pi \cdot d_p^2} \text{ [mm]}; \quad (1)$$

- for the mean depth erosion rate, after period "i"

$$MDER_i = \Delta MDE_i / \Delta t_i \text{ [mm / min]} \quad (2)$$

where:

i - represents the testing period,
m_i - is the cumulative mass lost during the period i (grams),
ρ - cast iron density (gram / mm^3),
Δt_i - the cavitation exposure in the period "i" (first period of 5 minutes, second 10 minutes and the rest 15 minutes),
d_p - specimen diameter (d_p = 15.8 mm),
ΔMDE_i - mean depth erosion generated by cavitation in the Δt_i period.

In **(Figure 3)** and **(Figure 4)** are given time evolution of these two parameters that characterize the erosion cavitation behaviour of cast iron heat treated by quenching-tempering compared to the cast state and stress relief annelead.

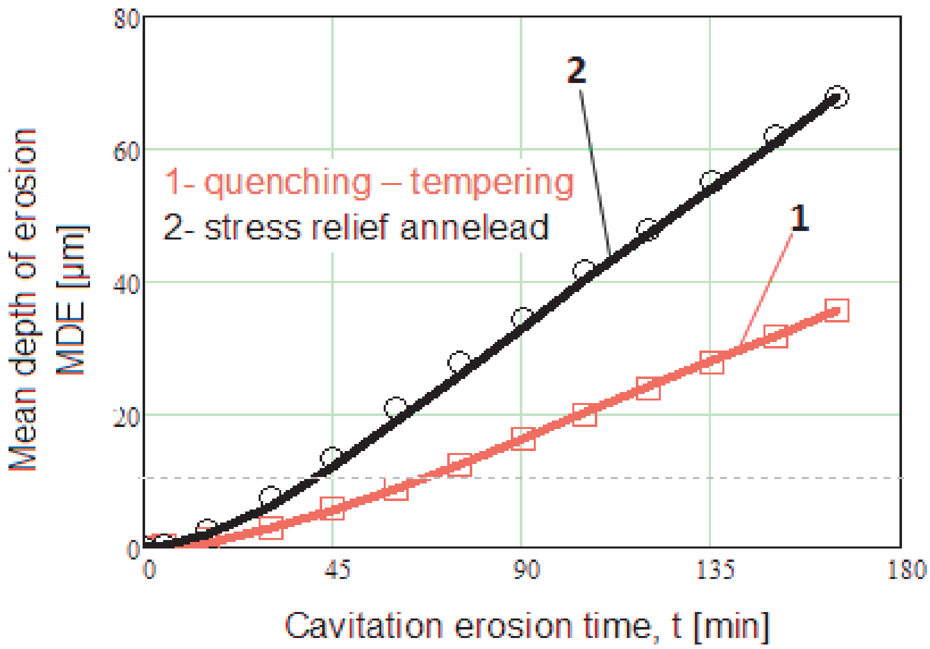


Figure 3 Variation of the mean depth erosion penetration with the attack cavitation duration: 1 - quenching-tempering heat treatment; 2 - stress relief annealing

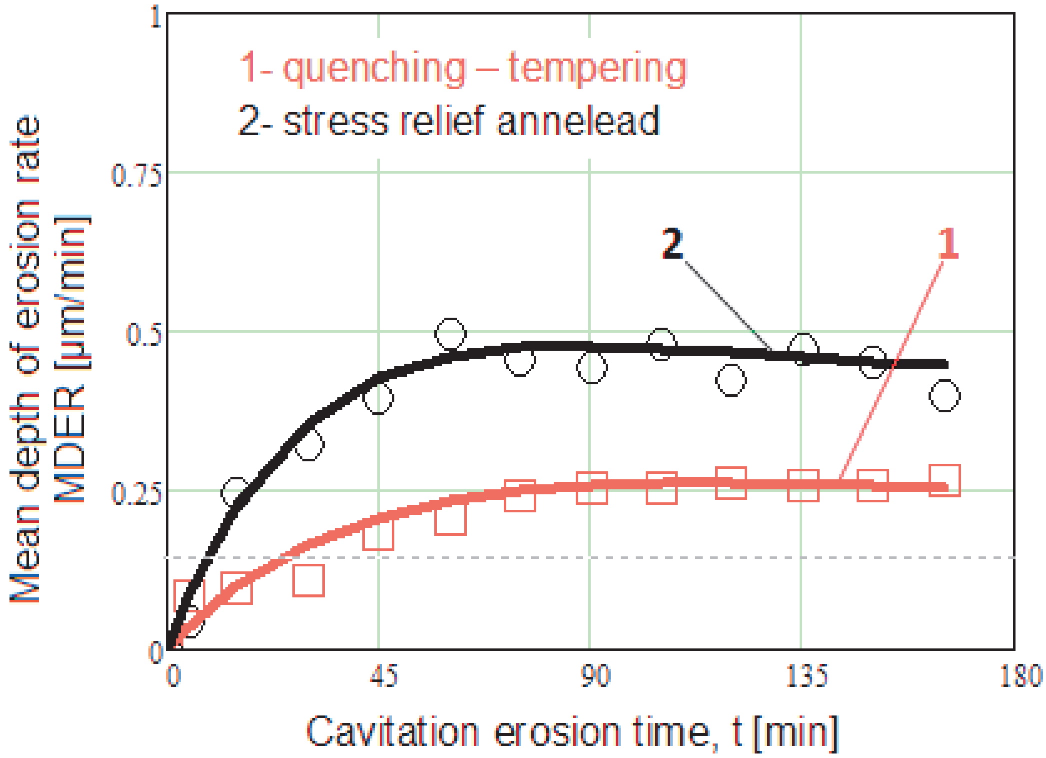


Figure 4 Variation of the mean depth erosion penetration with the attack cavitation duration: 1 - quenching-tempering heat treatment; 2 - stress relief annealing

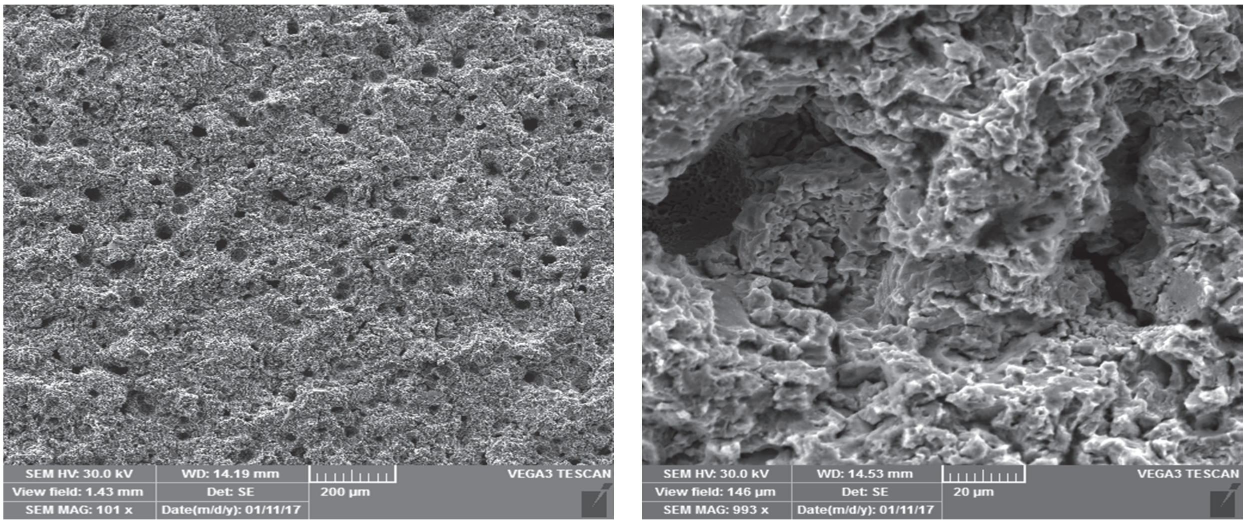
The dispersion of the experimental points versus mediation curves show a good resistance of samples surface during the vibratory cavitation attack. This kind of behaviour is due the graphite shape more or less spherical which prevents crack propagation being created the conditions to obtain satisfactory ductility and toughness characteristics. As a result, structural cracking speed decreases at the impact with the micro-jets generated by the cavitation bubbles implosion. Lower dispersion of the experimental values obtained for the erosion rate, at the quenched and tempered samples, is caused by the microstructure homogeneity and mechanical properties improving by the applied heat treatment.

All these lead to an increase of the cavitation erosion resistance of approx. 80 %, after the stabilization value of the erosion rate MDER. Also, took place a decreasing of the mean depth of erosion, MDE, at the final attack period (165 minutes), of about 90% compared with the structural state obtained after the stress relief annealing.

4. METALOGRAPHIC EXAMINATION

These scanning electron microscopy investigation of surface topography for 165 min cavitation time shows a fragmentation and removal of graphite nodules beside the presence of fatigue fracture cracks at the matrix - graphite interface **(Figure 5 a, b).** The material zones remained after the graphite removal has shape of pinching or micro-craters with high stresses concentrators which favour the development of radial cracks.

If by the sample subjected to stress relief annealing, the ferrite which surrounds the graphite is strongly deformed [4], by applying the quenching - tempering heat treatment, it is obtained an increase of hardness and mechanical strength, so that the surface deformation is reduced.

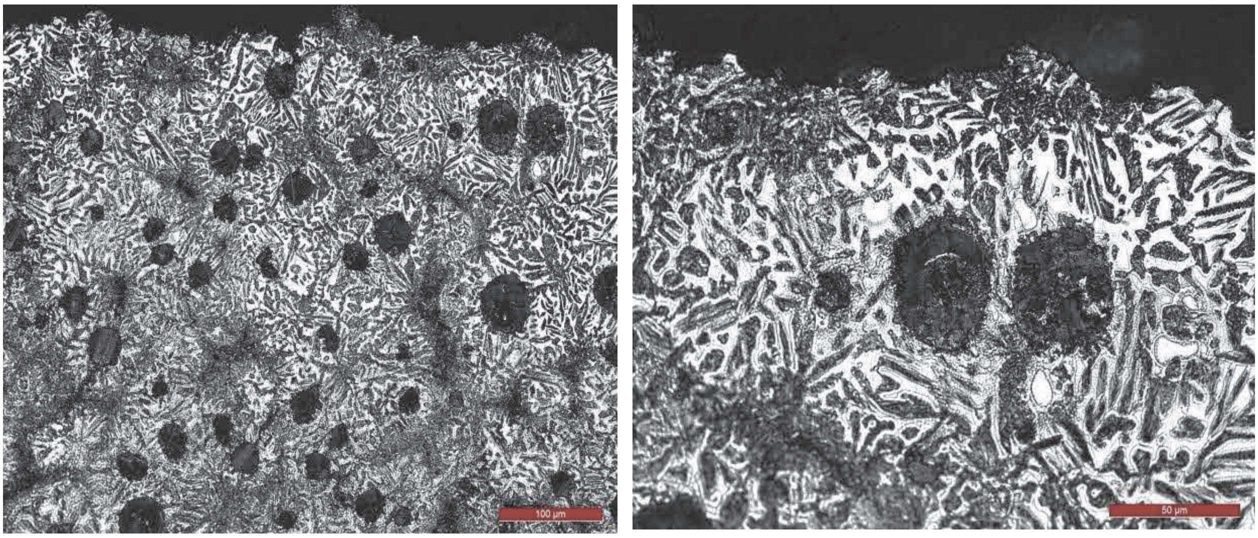


-a- -b-

Figure 5 SEM image of the eroded quenched - tempered surface after 165 minute cavitation time: a - material pinching; b - micro-cracks coalescence and formation of a micro tunnel

Although the number of micro-pinches formed by plastic deformation is significantly lower by quenched samples, the developed cracks suffer the coalescence phenomenon, leading to the appearance of deep craters or even micro-tunnels **(Figure 5b).** The analysis by optical microscopy of the longitudinal section through the cavitation samples tested for 165 min. **(Figure 6)** shows that by both stress relieved annealed and quenched - tempered samples the graphite nodules expulsion favours the metal matrix degradation.

Since the mechanical strength of the tempered martensite microstructure is higher than of the ferrite-pearlite microstructure, it is expected that the erosion penetration depth is higher by the latter.



-a- -b-

Figure 6 Optical image of the longitudinal section through the eroded quenched - tempered samples tested for 165 min

5. ROUGHNESS MESUREMENTS

The comparative analysis of the surface degradation degree after cavitation tests proves again the positive effect of the final applied heat treatment to the cavitation behaviour of investigated cast iron. Even after graphite removal, which is a non-metallic inclusion, those portions of the material surface become rougher; from **(Figure 7)** it can be seen that the base metal mass keeps more favourable values if it was subjected to the quenching-tempering heat treatment

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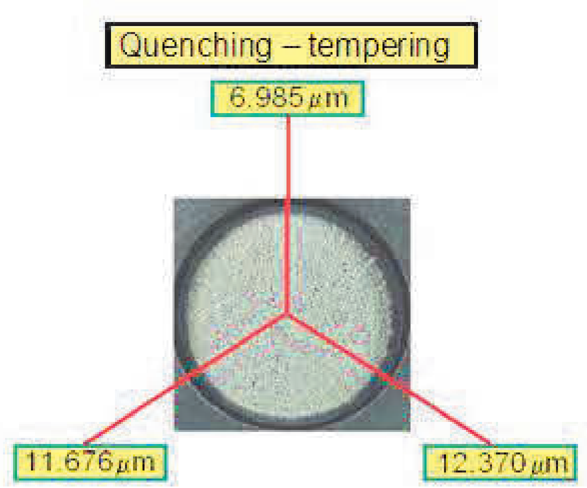

-b-

Figure 7 Roughness values on the three measuring directions for the two structural states: a - stress relief annealing; b - quenching-tempering

6. CONCLUSION

The quenching - tempering heat treatment of nodular cast iron with ferrite - pearlite matrix causes a reduction of the mean depth of erosion of about 1.9 times and of the erosion rate of approx. 1.8 times compared with the structural state obtained after stress relief annealing.

The graphite shape (more or less spherical) beside the tempered martensitic matrix, justify the improving of the erosion cavitation resistance.

The mean roughness of the cavitation tested surface decreases from 16.25 μm (quenched-tempered state) to 10.34 μm (stress relieved annealed state).

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