Roughness Parameters during Cavitation Exposure of Nodular Cast Iron with Ferrite-Pearlite Microstructure

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Abstract. The cavitation erosion resistance of EN-GJS-400-15 nodular cast iron was tested in the laboratory according to ASTM G32-2010 standard. The erosion average penetration depth values, MDE, were correlated with the roughness parameters and the microstructure of the samples subjected to volume heat treatments consisting from stress relieving and for softening, annealing, normalization and quenching followed by tempering. The results obtained showed that the changes in the surface roughness of the samples tested at cavitation can be used to predict the resistance of the material to this wear phenomenon.

1. Introduction

The evaluation of the cavitation erosion resistance of a material is done by standardized tests in order to simulate this process under laboratory conditions. Such tests provide the relevant results that can be used to compare the strength of a material in different structural states or more to test materials under similar conditions [1, 4, 5, 6]. The equipment used allows the assessment of cavitation erosion resistance of a material in terms of erosion rate, thus allowing a classification of materials based on this property [3, 4, 6]. One of the difficulties encountered in such examinations is the multiple unsuccessful or only partially successful attempts to correlate cavitation erosion resistance with one or a combination of metallic properties [7, 8].

This paper aims to find a correlation between the depth of erosion penetration, MDE at the end of the test period and the characteristic parameters of the surface roughness of the EN-GJS-400-15 nodular cast iron surface subjected to volume heat treatments.

2. Investigated material, experimental stand and working procedure

The investigated material is a ferrite-perlite matrix nodular cast iron, EN-GJS-400-15, having the following chemical composition: C = 3.57%, Si = 2.51%, Mn = 0.23%, P = 0.044%, S = 0.010% and Fe = balance. The microstructure of the base metallic mass consists of approximately 60% F si 40% P (Figure 1).
Figure 1. Image of the foundry nodular casting microstructure (x100).

Cast iron bars with the dimensions Φ 25 x 40 mm were subjected to the following volume heat treatments:

- Stress relief annealing (500 ± 10 °C/120 min./oven);
- Softening annealing (710 ±10 °C/30 min./oven);
- Normalizing (860 ±10 °C/60 min./air);
- Martensitic quenching followed by tempering (860 ±10 °C/30 min./oil + 450 ±10 °C/60 min./air).

Subsequently, samples were prepared for cavitation tests [3-6] and for the investigation of surface roughness. Cavitation attempts were conducted on an oscillator with piezoceramic crystals, performed in accordance with the requirements of ASTM G32-2010 [2].

The assessment of the cavitation erosion resistance was done by determining the mean erosion depth, MDE and erosion rate MDER curves with attack time [5].

At various attack times, mass losses were determined, and eroded surfaces were examined by optical and scanning electron microscopy.

The roughness measurements were made in 10 directions, on the surface of each sample using the Mitutoyo apparatus [3,9].

3. Evaluation of experimental results

After each cavitation attack period, images of the surface tested were made using a Canon Power Shot SX200 IS camera. The results obtained are shown in (Figure 2) and they highlight the way in which the surface degradation phenomena extend. Their analysis confirms that in the first 30 - 45 minutes of testing only the surface of the heat-treated samples is sensibly affected by softening annealing (Figure 2b). At samples subjected to other volume heat treatments, degradation of the surface is minimal up to 45 minutes (Figure 2a, 2c, 2d), after which there is a continuous increase in the density of material pinches and their depth with attack time. The phenomenon is explained by low particle expulsion the material (graphite and matrix particles) at the beginning of the wear process. At higher attack times, there are large differences in the degree of degradation of the sample surface depending on the applied treatment. The geometric quality of the surface is significantly improved by the application of heat treatments for normalization (Figure 2c) or quenching followed by tempering (Figure 2d).
Figure 2. The macroscopic aspect of the surface of the tested samples at cavitation variable times depending on the thermal treatment condition: a) – stress relief annealing; b) - softening annealing; c) - normalizing; d) - quenching –tempering.

In (Figure 3a ... 3d), for each type of heat treatment, one significant image of the roughness profiles is displayed, with the corresponding values of the Ra, Rz and Rt parameters measured with the Mitutoyo
equipment. The profiles of these images and the values of the roughness parameters Ra, Rz and Rt were recorded in 10 arbitrarily chosen directions in the cavity surface, from the periphery to the central area. They show the complicated dynamics of surface degradation under the local fatigue demands created by the repeated impact of microjets produced by cavitation bubble implosion.

The substantial differences between the values of these parameters, recorded in different areas, show the intensity of the shock caused by the impact with the hydrodynamic microjet, but also the different structure response of the required material. Smaller values are specific to areas near the center of the cavity, and larger values are recorded to the periphery. The phenomenon is supported by the macroscopic images of Figure 2, where the stellar caverns can be seen from the periphery of the cavity surface.

The difference (percentages) between the lowest and the highest value of the roughness parameters, depending on the structural state of the tested samples, is from 13.13% to 138.27%. The smallest differences (percentages) are for softening annealing, and the highest for the quenching - tempering.

These values prove the complexity of the cavitation mechanism destruction, based on the hydrodynamics of the phenomenon (cavitation bubble formation and implosion) and on the iron response mechanics (deformation, cracks, expulsions after impact with microjets). At the same time, this difference also has an explanation in the formation of gas pockets in the eroded surface caverns (much larger in samples subjected to softening annealing), acting as attenuators of the pressure force developed at impact with microjets and shock waves.

The different shapes of the profiles are caused by different values of the main mechanical characteristics (hardness, breaking strength and flow limit) in the cavity surface, as well as by the graphite dispersion mode, the first structural constituent being destroyed and expelled.
Figure 3. Roughness and profile profiles specific to cavity surfaces 165 min. after volume heat treatments: a) – stress relief annealing; b) – softening annealing; c) - normalization; d) - quenching + tempering.

Table 1 compares the values of roughness parameters and MDE erosion depths obtained at the end of the cavitation test, using as reference the one obtained from stress relief annealing. The data in this table represents the arithmetic mean of roughness measured in three directions. They reflect the resistance to vibration cavity acquired by the exposed surface. It is noted that the best resistance to cavitation erosion after the MDE parameter is obtained by the heat treatment of quenching-tempering (increase of about 160%) and the worst by softening annealing (decrease is about 84%).

Since the ASTM G32-2010 standard recommends cavitation resistance assessment based on the average MDE erosion depth, and the laboratory's practice is to use this parameter, in Table 1 are shown the MDE values for the four heat treated states. The comparison was performed with the mean values of Rz.

| The treatment state of the sample | MDE_{(165minute)} [µm] | Ra [µm] | Rz [µm] | Rt [µm] |
|-----------------------------------|-------------------------|---------|---------|---------|
| Softening annealing               | 125.336                 | 27.746  | 134.848 | 233.917 |
| Stress relief                     | 67.802                  | 14.307  | 74.010  | 101.974 |
| Normalizing                       | 39.619                  | 8.68    | 49.725  | 74.976  |
| Quenching tempering               | 26.054                  | 5.976   | 34.092  | 45.411  |

**Treatment effect (the reference state: stress relief annealing)**

| Treatment effect                  | Softening annealing | Normalizing | Quenching tempering |
|-----------------------------------|---------------------|-------------|---------------------|
| Increase with                     | 84.86%              | 71.13 %     | 160.23%             |
| Increase with                     | 93.93%              | 64.82 %     | 139.40 %            |
| Increase with                     | 82.76 %             | 48.83 %     | 117.08 %            |
| Increase with                     | 129.38 %            | 36.00 %     | 124.55 %            |
Comparison between MDE\textit{(165min)} and Rz

| The treatment state of the sample | MDE\textit{(165 minute)} [µm] | Rz [µm] | Increase Rz | Rz difference between Val_{min} and Val_{max} |
|----------------------------------|-------------------------------|----------|--------------|---------------------------------------------|
| Softening annealing              | 125.336                       | 134.848  | 7.58 %       | 28.03%                                      |
| Stress relief annealing          | 67.802                        | 74.010   | 9.15 %       | 40.08%                                      |
| Normalizing                      | 39.619                        | 49.725   | 25.50 %      | 90.61%                                      |
| Quenching tempering              | 26.054                        | 34.092   | 30.85 %      | 102.03%                                     |

It is found that the differences (from 7.58% to 30.85%) are slightly lower than the minimum and maximum values of Rz (see Figure 4) ranging from 28.03% to 102.3%.

This finding confirms that the Rz parameter is a correct indicator for assessing cavitation resistance. The histogram of (Figure 4) shows that the value of the MDE parameter at the end of the cavitation test is within the range of the Rz roughness parameter, confirming its importance as an important indicator in comparing surface resistance to cavitation erosion.

At the same time, this histogram shows that the volumetric heat treatment and quenching-tempering thermal treatments can be successfully applied to the nodular graphite cast iron, which can substantially increase their resistance to cavitation erosion.

![Figure 4. Comparison of parameter Rz with MDE (165 minutes).](image)

4. Conclusions
1. The average surface roughness, Ra, of the samples tested to cavitation decreases from 14.307 µm (stres relief annealing) to 5.976 µm (quenching-tempering); Rz roughness decreases from 74.01 µm (stress relief annealing), to 34.092 µm (quenching-tempering); the Rt roughness decreases from 101.974 µm (stres relief annealing) to 45.411 µm (the quenching-tempering state);
2. The different shape of the profiles regardless of the type of thermal treatment recorded in various areas of the exposed area and the large differences between the values of the three parameters $R_a$, $R_z$ and $R_t$ express the complexity of degradation of surfaces exposed to cavitation.

3. The comparison of the MDE cavitation resistance (165 minutes) and the roughness $R_z$ parameter shows that the last is a good indicator of cavitation resistance and which, in the future, can be considered for the evaluation of this property.

5. References

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