Correlations between mechanical properties and cavitational erosion resistance for stainless steels with 12% Chromium and variable contents of Nickel

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Abstract. The running time of hydraulic machineries in cavitation conditions, especially blades and runners, depend on both chemical composition and mechanical properties of the used steels. The researches of the present paper have as goal to obtain new materials with improved behavior and reduced costs. There are given cavitation erosion results upon eight cast steels with martensite as principal structural constituent. The chromium content was maintained constant at approximate 12% but the nickel content was largely modified. The change of chemical content resulted in various proportions of austenite, martensite and ferrite and also in different cavitation erosion behavior. From the eight tested steels four have greater carbon content (approximately 0.1%) and the other four less carbon content (approximate 0.036%). All steels were tested separately in two laboratory facilities: T1 with magnetostrictive nickel tube (vibration amplitude 94 μm, vibration frequency 7000 ± 3% Hz, specimen diameter 14 mm and generator power 500 W) and T2 is respecting the ASTM G32-2010 Standard (vibration amplitude 50μm, vibration frequency 20000 ± 1% Hz, specimen diameter 15.8 mm and generator power 500 W). Analyzing the results it can be seen that the cavitation erosion is correlated with the mechanical properties in the way shown in 1960 by Hammitt and Garcia but is influenced by the structural constituents.

1. Introduction
An increased cavitation erosion resistance of materials is determined by high values of mechanical properties correlated with the chemical constitution, the nature and homogeneity of the structural constituents [1], [3], [7]. For hydraulic machinery details, running in industrial accepted cavitation condition, the use of materials with high cavitation erosion resistance is an important economic factor [2].

Significant results for the connection between cavitation erosion resistance and the material mechanical properties were obtained in the past by Garcia and Hammitt [5]. The mentioned relations which correlate one or many properties with the parameter 1/MDER (which define the cavitation erosion resistance) are practical power functions, whose exponent differ from a material to other,
depending also on the nature of the cavitation liquid. For example, Garcia considers that the increase of cavitation erosion resistance (1/MDER) is proportional to \( HB^{1.8} \). The results of our researches obtained with a range of stainless steels having various structures (combinations between martensite, austenite and ferrite) show significant differences between the values of the scale and shape (power exponents) in the relations correlating the parameter 1/MDER with tensile strength \( R_m \), yield point \( R_{p0.2} \), Brinell hardness (HB) and ultimate resilience \( UR = (R_m)^2 / 2E \) in comparison with the value indicated by Garcia and Hammitt [5] which use test facilities similar to T1.

2. Tested materials

The tested materials are stainless cast steels used in manufacturing hydraulic turbines blades or pump impellers. In Tables 1 and 2 are presented the values of mechanical characteristics determined by Strength Materials Laboratories and the structural constituents, before cavitation exposure, obtained by using the Schäffler diagram [3], after computing chromium and nickel equivalents.

Because the tested steels are not standard brands, to simplify their identification it was conceived the notation presented in Table 1, which use the symbol of the principal chemical elements and the numbers showing the content, as follows:

- the chemical symbol of chromium (Cr) followed by the number 12, representing the percentage of this element, equal for all eight used steels;
- the chemical symbol of nickel (Ni) followed by a figure or a group of figures representing in percents, the content of this element;
- the chemical symbol of carbon (C) followed by the figure 1 or the number 036 representing the content of this element (either 0.1% C or 0.036% C).

Table 1 Values of mechanical properties [6]

| Steel            | Carbon content % | Fracture strength \( R_m \) [MPa] | Yielding strength \( R_{p0.2} \) [MPa] | HRC \((\approx HB)\) | Necking, \( Z, \% \) | Elongation \( A_5, \% \) |
|------------------|------------------|----------------------------------|----------------------------------|-------------------|----------------|----------------|
| Cr12Ni0.5C1      | \( \approx 0.1 \) | 1450                             | 1020                             | 44 (411)          | 26.8           | 6.8            |
| Cr12Ni2C1        |                  | 1336                             | 935                              | 40 (369)          | 25.4           | 6.9            |
| Cr12Ni6C1        |                  | 1540                             | 1083                             | 46 (434)          | 24.8           | 6.3            |
| Cr12Ni10C1       |                  | 835                              | 626                              | 25 (254)          | 32.2           | 11             |
| Cr12Ni2C036      | \( \approx 0.036 \) | 968                              | 678                              | 29 (280)          | 29.3           | 8.2            |
| Cr12Ni4C036      |                  | 989                              | 695                              | 30 (287)          | 28.7           | 8              |
| Cr12Ni6C036      |                  | 1035                             | 725                              | 31 (297)          | 30.1           | 8.7            |
| Cr12Ni8C036      |                  | 1002                             | 701                              | 30 (288)          | 31.3           | 8.8            |

The data presented in Table 1 and 2 prove the diversity of the mechanical properties of the analyzed structures. It must be noted that for the steels with 0.1% of carbon, with the exception of Cr12Ni10C1, the mechanical properties \( R_m, R_{p0.2} \) and HB have superior values in comparison to steels with 0.036% carbon.
Table 2 Structural constituents [6]

| Steel       | Chromium Equivalent, Cr_e, [%] | Nickel Equivalent, Ni_e, [%] | Structural constituent               |
|-------------|-------------------------------|-----------------------------|-------------------------------------|
| Cr12Ni0.5C1 | 14.26                         | 4.81                        | 75% Martensite +25% Ferrite         |
| Cr12Ni2C1   | 14.62                         | 6.23                        | 90% Martensite +10% Ferrite         |
| Cr12Ni6C1   | 14.9                          | 10.14                       | 40% Martensite +60% Austenite       |
| Cr12Ni10C1  | 14.66                         | 14.74                       | 100% Austenite                      |
| Cr12Ni2C036 | 13.27                         | 3.15                        | 55% Martensite +45% Ferrite         |
| Cr12Ni4C036 | 13.1                          | 5.25                        | 86% Martensite +14% Ferrite         |
| Cr12Ni6C036 | 13.16                         | 6.69                        | 100% Martensite                     |
| Cr12Ni8C036 | 13.54                         | 9.16                        | 90% Martensite +10% Austenite       |

3. Tested method
For testing the cavitation erosion resistance there were used two vibratory devices, the first T1, of magnetostrictive type with nickel tube (vibration amplitude 94 µm, vibration frequency 7000 Hz, specimen diameter 14 mm, power of the electronic generator 500 W) and the second T2, constructed by taking into account the recommendations of ASTM G32-2010 Standard (vibration amplitude 50 µm, vibration frequency 20,000 Hz, specimen diameter 15.8 mm, power of the electronic generator 500 W). Both devices were realized at the Hydraulic Machinery Laboratory of the Timisoara Polytechic University [3].
The testing liquid was drinking water closer to that use by the field hydraulic turbines and pumps. Total cavitation exposure was 2.75 hours divided in intermediary periods (one of 0.083 h, one of 0.167 h and ten of 0.25 h). The testing procedure respect the ASTM G32-2010 Standard [8].

4. Experimental results and discussions
Figure 1 and 2 present the correlations between the cavitation erosion resistance 1/MDER and the principal mechanical properties of the eight tested steels, for both testing facilities. From the Figures 1 and 2 results that for some steels the dependence of cavitation erosion resistance evolve with the mechanical characteristic values approximate in the form of power functions. This behavior is in accordance with those obtained by Garcia and Hammitt [5]. The steels with 0.036 %C present small scatters from the curve. The best cavitation resistance was obtained for Cr12Ni8 with 10% austenite and the worst for Cr12Ni2 with 45% ferrite. These results confirm the conclusion that ferrite is the weakest structure to cavitation erosion. For the steels with 0.1 % C, the brand Cr12Ni6 (structure 40% M+60%A) present the outmost resistance to cavitation erosion and excellent mechanical properties. The rest of the steels present great scatters from curve. Cr 12Ni8 (structure 100% A) has reduced mechanical characteristics but very good cavitation erosion resistance. The steel Cr 12Ni05 (25% F) has good mechanical characteristics but poor cavitation resistance. The important scatter of the results for the steels with 0.1 % of carbon shows that cavitation erosion tests are imperious necessary.
Figure 1. Correlation between cavitation erosion resistance and the principal mechanical properties (device T1); – tensile strength, b) - yield point, c) - Brinell hardness, d) – ultimate resilience

Figure 2. Correlation between cavitation erosion resistance and the principal mechanical properties (device T2); – tensile strength, b) - yield point, c) - Brinell hardness, d) – ultimate resilience
The principal cause of the scatter is the proportion of unstable austenite which at the stresses created by the bubble implosions is transformed suddenly in martensite exactly in the zone were the erosion take place and determines a local increase at cavitation erosion. Because the steels with 0.1% C show good cavitation erosion resistance, in the future for the steels used for important cavitation attack, the reduction of carbon content must not go to great values under 0.1% C.

The results obtained in the present work show that regardless of the vibratory device used, T1 or T2, there are no great differences in comparing various steels, even if both value of the MDE and MDER present great differences (approximately 1/8).

5. Conclusions
1. The increase of the values for principal mechanical characteristics (R_m, R_p0.2, hardness), in general, reduce the cavitation erosion.
2. The correlations between the parameter 1/MDER and the mechanical characteristics are similar with those established by Garcia and Hammitt, but the values the exponents depend on the tested material.
3. The values of the scale and shape parameters of the curves “mechanical properties against erosion” varies with the cavitation intensity of the test facility.
4. For simultaneously good cavitation erosion and an easy welding, the steels used for the hydraulic turbines blades or pump impellers must have the carbon content under 0.1 but in immediate vicinity of this value.
5. The scatter of the results for the steels with 0.1% C, regardless of the parameters taken into account (R_m, R_p0.2, etc) show that such tests remain necessary also in the future, because for some stainless steels the increase of mechanical parameters are not proportional with the increase of cavitation erosion.
6. The principal cause of the scatter observed is the unstable austenite which at the stresses created by the bubble implosions is transformed suddenly in martensite and determines a local increase at cavitation erosion.

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