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RESEARCHES UPON CAVITATION EROSION RESISTANCE OF THE MARTENSITIC STAINLESS STEEL HEAT TREATED

Ioan PĂDUREAN
"Politehnica" University of Timişoara
P-ta Victoriei no. 2, 0729 351201,
padurean58@yahoo.com, http://www.upt.ro/

Marin TRUŞCULESCU
"Politehnica" University of Timişoara
P-ta Victoriei no. 2, 0256 403737,
astr@mec.utt.ro, http://www.upt.ro/

Dorian NEDELCU
"Eftimie Murgu" University of Reşiţa
P-ta Traian Vuia no. 1-4, 0723 299 050, 0256 219134, d.nedelcu@uem.ro, http://www.uem.ro/

Elvira PĂDUREAN
High School „Tănăsescu" Timişoara
Str.Lorena 53, Timisoara,
elvirapadurean@yahoo.com

Mircea POPOVICIU
"Politehnica" University of Timişoara
P-ta Victoriei no. 2, 0256 403683,
http://www.upt.ro/

Octavian MEGHELEŞ
Hydro Engineering Reşiţa
Str. Calea Caransebesului, nr. 16 A,
0744 642476,omegheles@hydrorom.com,
http://www.hydrorom.com/

***Corresponding author*: Str. Martir Dumitru Jugănaru, nr. 5/A, ap.5, 300765 Timişoara, Romania**
Tel.: (+40) 0729 351201, Email: padurean58@yahoo.com

ABSTRACT

The paper presents the researches carried on upon the cavitation erosion of Martensitic stainless steel GX4CrNi 13-4 (SR EN 10283/99) [16] used for manufacturing Kaplan runner blades. The studied steel was subjected to a heat treatment consisting from a quenching followed by tempering at high temperature, sandblasting and nitriding [14], [15], [12]. The results have been compared with those of the steel 40Cr10 with good but not excellent cavitation erosions and with the Martensitic steels T07CuMoMnNiCr165-Nb and T09CuMoMnNiCr185-Ti used for hydraulic turbines and also with the Austenitic steel GX5CrNi19-10 studied by the authors in a previous work. For comparisons have been used the characteristic cavitation erosion curves [1], [2] and it resulted that the steel GX4CrNi 13-4 has excellent cavitation erosion qualities [10], [11], [12].

KEYWORDS

Cavitation erosion resistance, martensitic steel, heat treated.

INTRODUCTION

Among the negative effects of cavitation, one of greatest importance is the erosion of the solid boundaries guiding the flow [4]. Working out hydraulic machinery with total exclusion of cavitation is not possible for economic reasons. Commonly, the running of hydraulic machinery take place with "industrial allowed cavitation" for which the power characteristics are not at all affected but cavitation erosion is present, in the limits of prescribed material losses of [4], [12]. The material tearing through cavitation erosion represents a permanent challenge for the scientists with interests in the design, construction and maintenance of hydraulic machinery.

The complexity of the involved phenomena and their dependence on numerous factors both from the material used in manufacturing the machine elements and the used fluid, determine the difficulties in understanding this process. That is why the obtaining of materials with good behavior against this stress remains an important desideratum.

In present numerous studies are oriented towards finding new materials with improved resistance to cavitation erosion, inclusively the analysis and the correlation of parameters that influence the tearing caused by the implosion of bubbles. Analyzing the manufacturing procedures and the standards of the stainless steel used for hydraulic turbines, we selected for tests the Martensitic steel GX4CrNi13-4 heat-treated through quenching/tempering followed by nitration. The heat treatment technology was modified in order to obtain a definite structural state, having such dimensions, nature and dispersion of the structural constituents necessary to obtain chemical and physico-mechanical properties with optimum cavitation erosion resistance [10], [11], [12] [14], [15].

After applying the studied heat treatment there have been made macro and microscopic analysis, which partially cleared the mechanism of the cavitation tearing (detachment of micrograins, locally melting, mechanically or thermally stressed zones which create microcrakes and sub layers with phase modifications). The hardness test put also into evidence the good influence of the heat treatment upon the material behavior [12].

In the Timisoara Laboratory for Hydraulic Machinery we have tested specimens manufactured from the chosen steel, the results being compared with the characteristic curves of other steels considered with good resistance against cavitation erosion. The comparison was extended also to the costs involved in the manufacturing of the new runners. The values necessary to draw the charcteristic curves have been obtained using a vibratory test facility with nickel tube [2], [12].

MATERIALS USED FOR CASTING KAPLAN TURBINE BLADES

The materials used for manufacturing turbine elements must fulfill simultaneous numerous structural, chemical, mechanical and physical conditions [1], [2], [6], [12]. A compromise must be found between the hardness and the tenacity. This problem can be solved through structural modifications achieved by various heat treatments [14], [15], [12]. Simultaneously the chosen variants of heat treatment must assure an increase of the resistance to corrosion, erosion and fatigue. In the industrial practice it can be seen a clear trend to use stainless steels with Martensitic or Austenitic-Martensitic structure [1], [2], [3], [6], [12].

In our country, for manufacturing Kaplan turbine blades or Francis impellers, there are used the materials presented in Table 1, [2], [3], [6],[7], [8], [12].

Table 1

Materials used for manufacturing hydraulic turbines		
Steel mark	Manufactured elements	Structure
T07CuMoMnNiCr165-Nb	Runners and blades	40%M+40%A +20%F
T09CuMoMnNiCr185-Ti	Runners and blades	60%A+10%M+ 30%F
GX5CrNi13-4	Runners and blades	M
GX5CrNiMo13-6-1	Runners and blades	M

Note: A- Austenite, M-Martensite, F-Ferrite

The Austenitic and Martensitic stainless steels commonly used for manufacturing hydraulic machinery elements, having good cavitation erosion resistance are presented in Table 2, SR EN 10283/99 [16].

Table 2

Chemical composition (analyses made on liquid steel) (percentage in masses%)						
Symbolization		C Si max %	Mn P max. %	S max. Cr %	Mo %	Ni %
Alpha numerical Structure	Nume-rical					
GX4 CrNi13-4 martensitical	1.4317	0.06 1.00	1.00 0.035	0.025 12.00.. 13.50	max 0,70	3.5.. 5.00
GX4CrNi Mo16-5-1 martensitical	1.4405	0.06 0.80	1.00 0.035	0.025 15.00.. 17.00	0.70.. 1.50	4.0.. 6.0
GX4CrNi Mo16-5-2 martensitical	1.4411	0.06 0.80	1.00 0.035	0.025 15.00.. 17.00	1.50.. 2.00	4.0.. 6.0
GX5 CrNi19-10 Austenitical	1.4308	0.07 1.50	1.50 0.04	0.03 18.00.. 20.00	-	8.00.. 11.00
GX5CrNi Nb19-11 Austenitical	1.4552	0.07 1.50	1.50 0.04	0. 03 18.00.. 20.00	-	9.00.. 12.0
GX5CrNiMo19-11-2	1.4408	0.07 1.50	1.500 0.04	0.03 18.00.. 20.00	2.00.. 2.50	9.00.. 12.00

TESTED MATERIAL

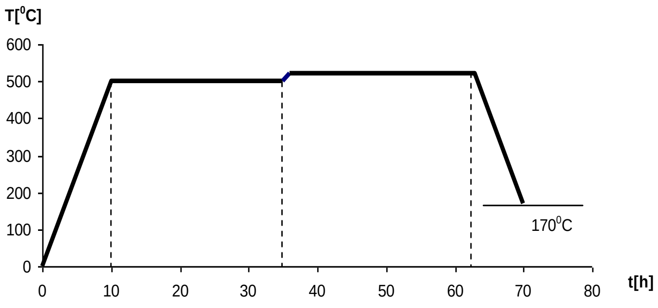
The specimens tested to cavitation erosion are manufactured from the Martensitic stainless steel GX4CrNi13-4 (SR EN 10283/99) [16] after a quenching and tempering treatment. The chemical composition and the mechanical characteristics determined on prismatic samples are presented in table 3.

Table 3

Steel mark: GX4CrNi13-4 1.4317 Status: Q+T- Quenching and Tempering, volume treatments							
Chemical composition %							
C	Si	Mn	P	S	Cr	Ni	Mo
0.02	0.47	0.56	0.010	0.06	13.1	4.4	0.55
Mechanical characteristics at 20ºC							
Rp0,2 MPa		Rm MPa		A5 %	KV J		HB
623		800		20	50		270

HEAT TREATING

Quenching	Temperature T_Q = 1,050 ^{0}C
	Maintaining time at the high temperature t_m = 1 hour
	Agent water
Tempering	Temperature T_T =650ºC
	Maintaining time at the high temperature t_m = 3 hours
	Agent air
Gaseous nitriding	As in the complex cyclograma, Figure 1, with the nitrating temperatures: step I-550 ^{o}C/24 h and step II-570 ^{o}C/25 h nitrating atmosphere, cooling up to 170 ^{o}C and continued in air
Sand-blasting and nitrating	A sand-blasting installation was used. The sand-blasting was done at a pressure of 4-6 bars, for 75 s, at an attack angle of β = 45 degrees and sand granulation of G=50 μm.



Note: Step I 550 ^{o}C α_{NH3}=25-30%; / 24 h
Step II 570 ^{o}C α_{NH3}=25-30%; / 25 h
Figure 1 Nitration Cyclogram

On the specified steel there have been carried out structural analyses samples metallographic prepared according to [17], [18], [19], [20]. For the metallographic examination it was used an optical microscope provided with a camera. In fig. 2 there is presented the microstructure of the heat treated steel. After the heat treatment the steel presents:

- the granulometric indices G=8, according to the ASTM standards [16];
- the structure is tempered Martensite with fine carbides uniform distributed.

Figure 2 - The microstructure of the steel GX4CrNi 13-4; OM 500X – Optical microscop with 500X increase factor

RESEARCHES UPON THE CAVITATION EROSION OF THE SPECIMENS MANUFACTURED FROM GX4CrNi 13-4

In conformity with the ASTM standards [21] the tests were carried out on three probes, in distilled water at the temperature T = 20.00±1ºC.

The cavitation attack was realized at Timişoara Hydraulic Machinery Laboratory in a vibratory magnetostrictive test facility with nickel tube. The results are presented as mean value of three specimens. The facility is characterized by the following parameters:[2], [4], [5], [12]:

- vibration amplitude: A = 94.00 μm;
- frequency: f = 7,000 ± 3 Hz;
- pressure at the liquid surface: $p = p_{at}$;
- power: P = 500.00 W;
- specimen diameter: d = 14.00 mm;
- specimen immersion: h = 3.00 mm.

The total duration of the cavitation attack of 165 minutes was divided in 12 periods, as follows: one of 5 minutes, one of 10 minutes and 10 of 15 minutes. At the beginning and at the end of each period the specimens have been washed successively in current water, distilled water, alcohol, acetone, after that desiccated in a hot air current and finally weighed in an analytical balance with six characteristic figures.

EXPERIMENTAL RESULTS. TESTINGS. MICROSCOPICAL STRUCTURES INTERPRETATIONS

The cavitation erosion velocities " v " have been obtained, for each attack period Δt, from the mass losses Δm_a using the relation:

$$v = \frac{\Delta m_a}{\Delta t} \quad [g/min] \qquad (1)$$

The measured and computed data are presented in "Testing Bulletin" and subsequently the following cavitation erosion characteristic curves have been obtained: variation in time of the cavitation eroded mass $m_a(t)$, Figure 3 and of the cavitation erosion velocity v(t), Figure 4.

Observation: The value m_a in the "Test Bulletin" is obtained averaging the mass losses of the three tested samples.

TESTING BULLETIN

- Magnetostrictive facility with nickel tube
- Material: stainless steel GX4CrNi13-4
- Test liquid: distilled water
- Control amplitude: 94.00µm
- Mean frequency: 7,000 ± 3% Hz
- Temperature of the working liquid: 20 ± 1°C

Using the experimentally obtained values there have been plotted the dependencies $m_a(t)$ şi v(t), Figure 3, 4.

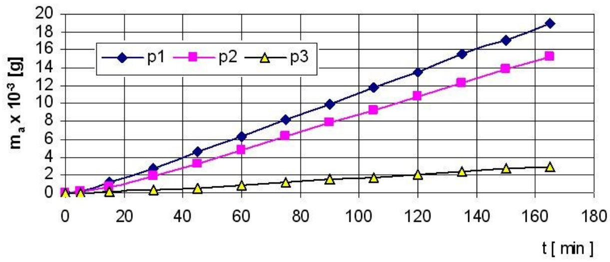


Figure 3 Eroded mass of the three tested samples

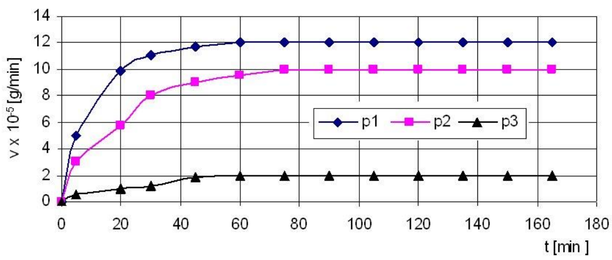


Figure 4 Erosion velocity of the three tested samples

The treatment of the three samples subjected to cavitation leads to the mean values presented in the Table 4 and the Figures 5, 6.

Table 4

Time [min]	Eroded mass x10^3 [g]	Erosion velocityx10^5 [g/min]
0	0,00	0,00
5	0,06	1,26
15	0,34	2,82
30	1,22	5,86
45	2,34	7,50
60	3,46	8,00
75	4,66	8,00
90	5,86	8,00
105	7,06	8,00
120	8,80	8,00
135	10,00	8,00
150	11,20	8,00
165	12,40	8,00

The characteristic curves: time dependence of the eroded mass $m_a(t)$ and erosion velocity v(t) are plotted as mean values in Figure 5, 6.

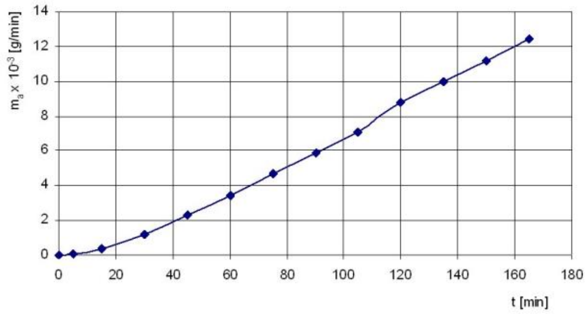


Figure 5 Eroded mass - mean values

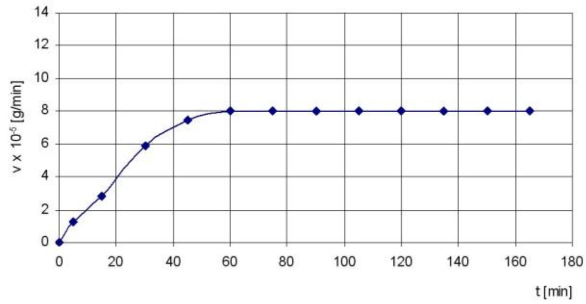
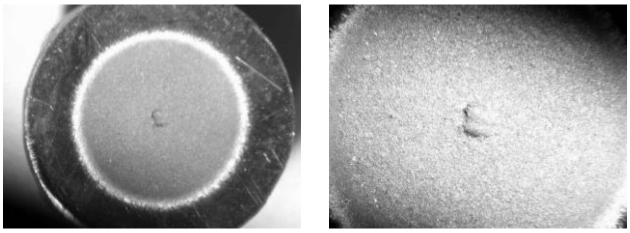


Figure 6 Erosion - mean values

Taking into account the data from table 4 and Figure 5, 6 it results that the martensitic steel GX4CrNi13-4, subjected to the quenching / tempering / nitriding heat treatment, attains after 80 minutes the characteristic cavitation erosion figures: $v_s = 8.00x10^{-5}$ [g/min] and $m_a = 12.40x10^{-3}$ [g] after 165 minutes; the total time of the test was 165 minutes.

THE MACROSCOPIC ANALYSIS OF THE SPECIMENS

The cavitation-tested specimens were analyzed at various aggrandizements using a stereomicroscope.



OM 10X OM 20X

Figure 7 The macrostructure of the probes tested at cavitation (after 165 minutes)

Through macroscopic and microscopic analyses it was put into evidence the manner in which the cavitation erosion take place, inclusively the granulation and structural modifications of the layers subjected by cavitation (Fig. 7)

The macroscopic analyses were realized with a stereomicroscope, at different aggrandizements and the following cavitation eroded area were observed:

- a central zone is heavily eroded and presents crakes and microcrakes;
- a zone adjacent to the central one has only shallow erosions;
- a third zone is also heavily eroded and presents microcrakes;
- a fourth zone has only few erosions.

In some area there has been seen detachments of grains and the occurrence of some porous zones.

THE STRUCTURE OF THE CAVITATION EROSION TESTED SPECIMENS MANUFACTURED FROM THE STEEL GX4CrNi 13-4 AND HEAT TREATED THROUGH QUENCHING/TEMPERING, SANDBLASTING AND GASEOUS NITRATION

The structure of the cavitation tested specimens manufactured from the GX4CrNi13-4 steel, subjected to Q&T, sandblasting and gaseous nitration is presented in Figure 8, 9, 10, 11 and 12. The specimen preparation and the metallographic attack are similar to those presented in [12]. The metallopgraphic analysis put into evidence the following characteristic aspects:

- the sandblasting produces a granulation refinement on a depth of several micrometers without creating microasperities on the specimen surface, Figure 8;
- the nitration after sandblasting create very fine and dispersed structural constituents, composed from intermetallic phases and nitrates of iron and other alloy elements, Figure 9;
- the cavitation destruction take place by microcraks in the sandblasted and nitrated layer and by creation of microasperities as a result of electrochemical corrosion, Figure 10, 11;
- in central part of the eroded area there can be seen structural modifications caused by the cavitation erosion mechanisms;
- there can be seen also phase refinement and very disperse precipitates, Figure 12.

The creation through sandblasting of a hardened microlayer and of some precipitate constituted from iron and alloy element nitrates increases the cavitation erosion resistance.

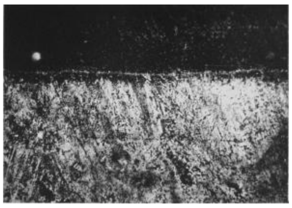


Figure 8 OM 100X

Figure 9 OM 500X

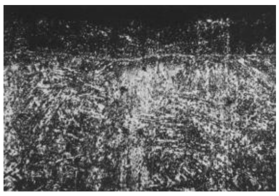


Figure 10 OM 100X

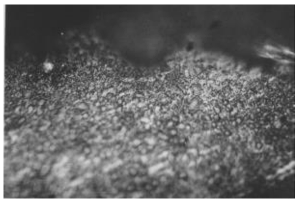


Figure 11 OM 500X

Figure 12 OM 500X

MICRO HARDNESS MEASUREMENTS

The results of the measurements on specimens manufactured from the GX4CrNi 13-4 stainless steel subjected to quenching, tempering, sandblasting and gaseous nitriding and the variation of the hardness HV0.1 is presented in Figure 13, 14, 15.

In the superficial layers, not subjected to cavitation, for depths until 0.1 mm the HV0.1 hardness is 750–1000 (Figure 13) and between 0.1 and 0.4 mm the variation is between 750 and 300.

For depths over 0.4 mm the HV0.1 hardness is 300. For the zones affected by cavitation, Figure 14, 15, at depths until 0.1 mm the measured HV0.1 hardness varies between 300 and 1100. For depths over 0.3 mm the measured HV0.1, hardness has a constant value, namely 300. These hardness variations are in agreement with the structure of the steel.

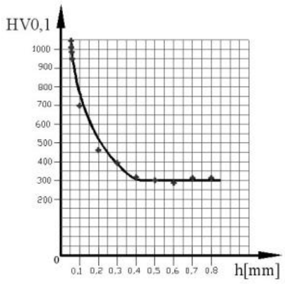


Figure 13

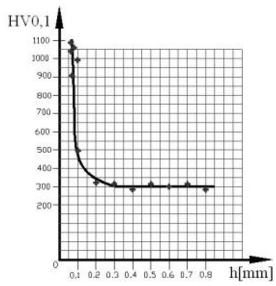


Figure 14

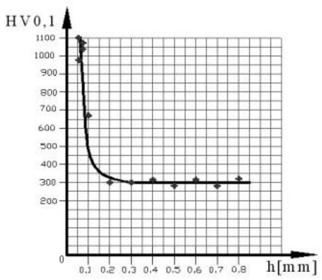


Figure 15

The same conclusion is obtained from the comparison of the steady state velocities v_s or the final eroded masses m_a of some steels with a good behavior at cavitation [2], [3], [5], [7], [9], [10], [11], [12], Table 5.

Table 5

Steel mark	Eroded mass m_a x10^3<g>	Erosion velocity V_s x10^5<g/min>
GX4CrNi13-4 Q+T+Sandblasting +Nitration	12.40	8.00
40Cr10	51.00	35.00
GX5 CrNi Mo13-6-1	33.24	22.00
T07CuMoMn NiCr165-Nb	20.67	13.60
T09CuMoMnNi Cr185-Ti	22.77	15.00
GX5Cr Ni19-10 [ST]	15.50	13.20
GX4 CrNi13-4 [Q+T]	17.63	12.50

CONCLUSIONS

We purpose to obtain new information upon the mechanism of cavitation destruction.

The metallographic and optic analyses, undertaken upon the longitudinal and transversal cross sections of the cavitation tested specimens, together with the micro hardness measurements performed in these zones put into evidence the mechanism of cavitation erosion, which acts through the melting of some micro zones, through thermal and mechanical stresses, which induces microcrakes, detachments of crystalline grains, phase modifications in sub layers and expelling of material particles through the formed craters.

The cavitation erosion has as principal mechanism the modifications of the granulation and microstructure, fact that probably results from a pronounced electrochemical attack, as a consequence of the phenomena connected to the bubble implosions.

The cavitation erosion of the specimens takes place slowly, gradually and without craters having important depth.

After the recommended heat treatment, the carbides were dissolved in the grain boundaries so the homogeneity of Martensite is improved.

The experimental cavitation researches upon the specimens manufactured from the steel GX4CrNi13-4 indicate that this Martensitic stainless steel has a very good resistance at cavitation tearing if it is subjected to well conducted heat treatments of the type quenching / tempering/sandblasting/nitration; in this condition it is recommended with priority for manufacturing the machine elements subjected to cavitation.

The obtained steady-state velocity was v_s=8.00x10^{-5}<g/min> and the eroded mass was m_a=12.40 x10^{-3} <g>, fact that confirms a high cavitation resistance.

The damages through cavitation were achieved through the attack at the boundaries of the crystalline grains, the formation of micro-fissures and by breaking into pieces of some grains. The material in the cavitation zone presents also structural modifications on small depths. It appears also a finishing of the granulation and an agglomeration of complex carbides at the limit of the grains.

Gas nitriding gives to steel the biggest resistance at cavitational erosion.

The sand-blasting and nitrating treatment makes a grained finish on a depth up to a few microns without creating roughness on the tested surface.

As a consequence of the cavitational attack a finished and precipitated phaseappears.

Through the sand-blasting and gassed nitrating treatment is creating a hardened micro level witch enlarges the cavitation resistance of the steel.

The sand-blasting and the gaseous nitriding produce an increase of hardening in the superficial layers.

The cavitation erosion resistance of the steel GX4CrNi13-4, thus treated, became better in comparison with other steels used commonly in manufacturing the hydraulic turbines runners.

The tests carried out with the stainless steel Gx4CrNi13-4 certify a good behavior at cavitation erosion and it is useful to undertake studies for employing it in hydraulic machinery manufacturing.

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