RESEARCHES UPON CAVITATION EROSION RESISTANCE OF MARTENSITIC STAINLESS STEEL USED FOR MOULDING KAPLAN AND FRANCIS TURBINES RUNNER BLADES

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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 and Francis runner blades turbines. The studied steel was subjected to a heat treatment consisting from a quenching and tempering at high temperature followed by gaseous nitration[12], [14], [15]. 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 works. 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].

1. 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], [13], [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].

2. MATERIALS USED FOR CASTING KAPLAN AND FRANCIS 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 [12], [14], [15]. 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 no. 1, [2], [3], [6],[7], [8], [12].

Table no. 1

Materials used for manufacturing hydraulic turbines

No.	Steel mark	Manufactured elements	Structure
1	T07CuMoMnNiCr165-Nb	Runners and blades	40%M+40%A +20%F
2	T09CuMoMnNiCr185-Ti	Runners and blades	60%A+10%M+30%F
3	GX5CrNi13-4	Runners and blades	M
4	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 no. 2, SR EN 10283/99 [16].

Table no. 2

Chemical composition (analyses made on liquid steel) (% in masses)

No.	Symbolization		C max %	Si max. %	Mn max. %	P max. %	S max. %	Cr %	Mo %	Ni %	Structure
	Alpha numerical	Numerical									
1.	GX4CrNi13-4	1.4317	0.06	1.00	1.00	0.035	0.025	12.00.. 13.50	max 0,70	3.5.. 5.00	Martensitical
2.	GX4CrNiMo16-5-1	1.4405	0.06	0.80	1.00	0.035	0.025	15.00.. 17.00	0.70.. 1.50	4.0.. 6.0	
3.	GX4CrNiMo16-5-2	1.4411	0.06	0.80	1.00	0.035	0.025	15.00.. 17.00	1.50.. 2.00	4.0.. 6.0	
4.	GX5CrNi19-10	1.4308	0.07	1.50	1.50	0.04	0.03	18.00.. 20.00	-	8.00.. 11.00	Austenitical
5.	GX5CrNiNb19-11	1.4552	0.07	1.50	1.50	0.04	0. 03	18.00.. 20.00	-	9.00.. 12.0	
6.	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	

3. 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 no. 3.

Table no. 3

Steel mark Q+T	Chemical composition %								Mechanical characteristics at 20ºC				
	C	Si	Mn	P	S	Cr	Ni	Mo	Yield strength Rp0,2 [MPa]	Fracture Strength Rm [MPa]	Linear Extension A5 [%]	Resiliency KV [J]	Brinell Hardness HB [-]
GX4CrNi 13-4 1.4317	0.02	0.47	0.56	0.010	0.06	13.1	4.4	0.55	623	800	20	50	270

Table no. 4

Heat Treating	Quenching	Tempering	Gaseous nitrading
Temperature	T_Q= 1,050.00 ºC	T_T =650.00 ºC	as in the complex cyclograma, figure no. 1, with the nitrating temperatures: Step I 550 ºC α_{NH3} = 25-30 % / 24 h Step II 570 ºC α_{NH3} = 25-30% / 25 h nitrating atmosphere and cooling up to 170 ºC and continued in air.
Maintaining time at the high temperature	t_m = 1 hour	t_m = 3 hours	
Agent	water	air	

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 figure no. 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.

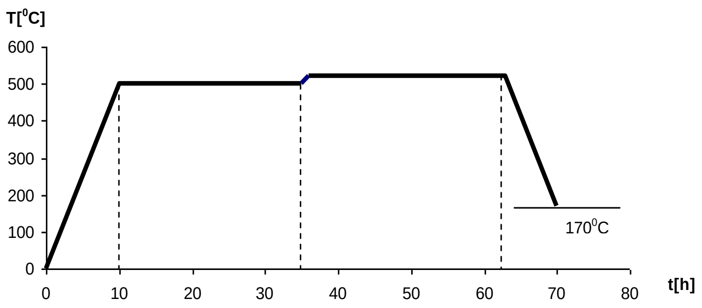


Figure no. 1 Nitration Cyclogram

Figure no. 2 The microstructure of the steel GX4CrNi 13-4 Optical microscop with 500X increase factor

4. 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.

4.1 EXPERIMENTAL RESULTS. TESTINGS. MICROSCOPICAL STRUCTURES INTERPRETATIONS

The cavitation erosion velocities **v** have been obtained, for each attack period **Δt**, from the mass losses $\mathbf{\Delta m_a}$ 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 no. 3;
- variation in time of the cavitation erosion velocity **v(t),** figure no. 4;

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

4.2 TESTING BULLETIN

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

Using the experimentally obtained values there have been plotted the dependencies **m_a(t)** şi **v(t)**, figure no. 3 and 4.

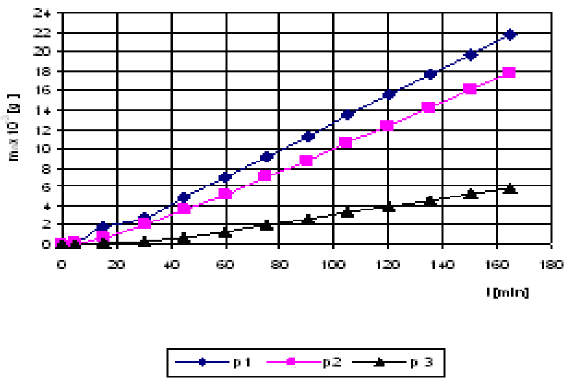


Figure no. 3 Eroded mass of the three tested samples **m_a(t)**

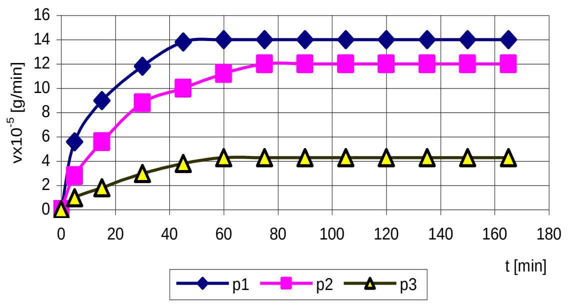


Figure no. 4 Erosion velocity of the three tested samples **v(t)**

The treatment of the three samples subjected to cavitation leads to the mean values presented in the table 5 and the characteristic curves: time dependence of the eroded mass **m_a(t)** and erosion velocity **v(t)** are plotted as mean values in figure no. 5 and 6.

Table no. 5

Testing Bulletin - Mean values of the three tested samples

Time [min]	Mass x 10^3 [g]	Velocity x 10^5 [g/min]
0,00	0,00	0,00
5,00	0,07	1,50
15,00	0,37	3,00
30,00	1,42	7,00
45,00	2,77	9,00
60,00	4,24	9,82
75,00	5,75	10,10
90,00	7,26	10,10
105,00	8,77	10,10
120,00	10,28	10,10
135,00	11,79	10,10
150,00	13,30	10,10
165,00	14,81	10,10

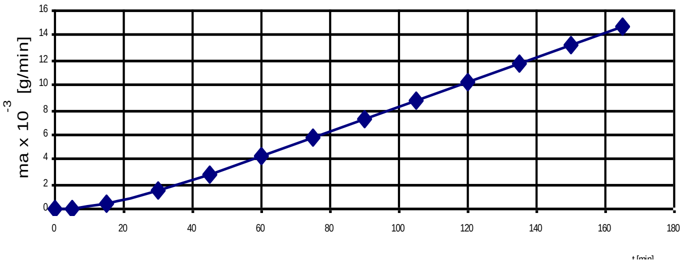


Figure no. 5 Eroded mass (mean values)

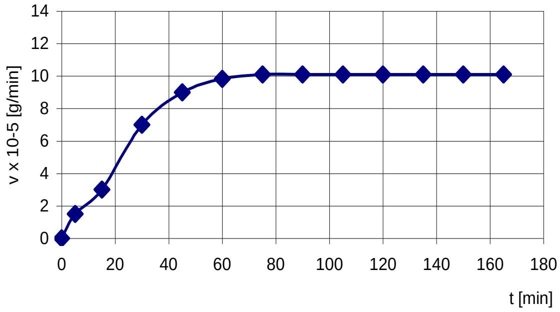


Figure no. 6 Erosion velocity (mean values)

Taking into account the data from table 5 and figure no. 5 and 6 it results that the martensitic steel GX4CrNi 13-4, subjected to the quenching/tempering/nitriding heat treatment, attains, after 80 minutes, the characteristic cavitation erosion figures: $v_s = 10.10 \times 10^{-5}$ [g/min] and $m_a = 14.81 \times 10^{-3}$ [g] after 165 minutes; the total time of the test was 165 minutes.

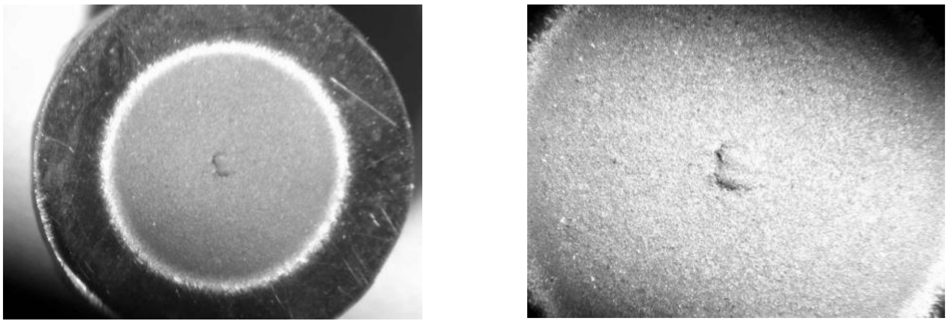
5. THE METALOGRAPHIC ANALISIS OF THE CAVITATION ERODED SPECIMENS

5.1 THE MACROSCOPIC ANALYSIS OF THE SPECIMENS

The cavitation-tested specimens were analyzed at various aggrandizements using a stereomicroscope. 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 (figure no. 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.



Optical microscope with 10X increase factor   Optical microscope with 20X increase factor

Figure no. 7 The macrostructure of the probes tested at cavitation (after 165 minutes)

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

The structure of the cavitation tested specimens manufactured from the GX4CrNi13-4 steel, subjected to Q&T and gaseous nitration is presented in figure no. 8, 9, 10, 11. The specimen preparation and the metallographic attack are similar to those presented in [12]. The structural images reveal the following aspects:

- a nitrated layer with depths under 0.1 mm;
- the thickness of the layer varies from one point to another;

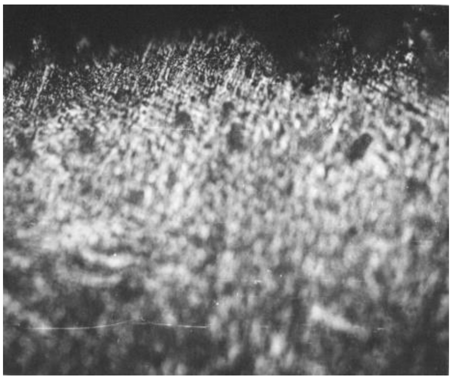
- the existence of a transition zone formed by nitration constituents (nitrates of alloy elements and iron nitrates) and a zone with tempered martensite structure, figure no. 8, 9;

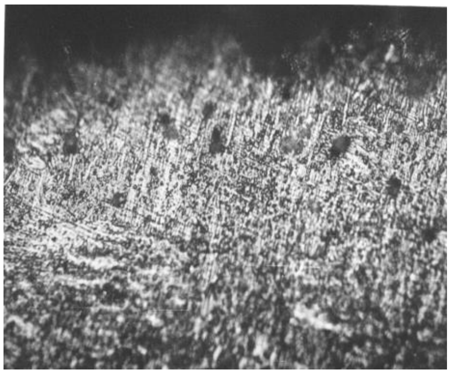
- the destruction by cavitation of the nitrated layer is effected through microcracks and epulsions of crystalline grains, figure no. 10, 11;

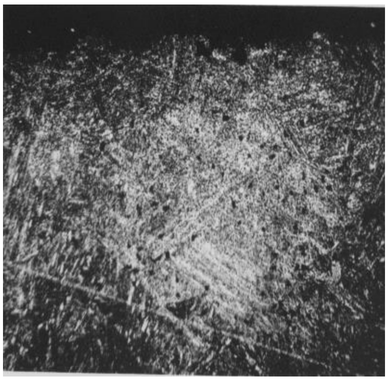
- in the nitrated layer appear microstructural modifications, their nature can be put into evidence by electronic microscopy;

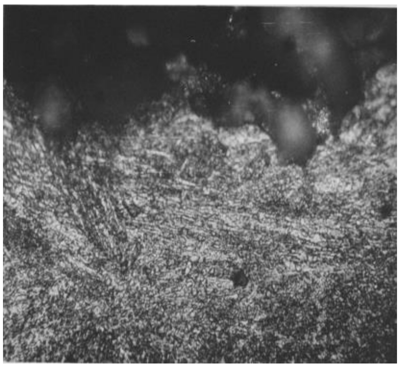
- it is evident that in the central zone of the eroded area there are important microkraks and particle detachments, fig. 11.

The complex phenomena of cavitation erosion determines structural modifications in the nitrated layer (in the present stage, these modification are not evidenced), which justify the good resistance to cavitatoin erosion of the GX4CrNi13-4 martensitic stainless steels subjected to Q&T followed by nitration. Probably inward of those fine grains it is maintained a Martensitic tempered structure situation, which should be confirmed by further research using electronic microscopy. In this situation, the cavitaiton erosion has as principal mechanism the modifications of microstructure and granulation, which leads to a very pronounced electrochemical attack as a result of some phenomena connected to the cavitation process [12]. The separations of the complex carbide at the boundaries of the grains reduce the corrosion resistance of the steel and produce a tension-creaking corrosion that leads to the expulsion of particles. Through the structure fines, the homogeneity of the granulation and the uniform dispersion of carbides, the steel that we talk about presents a good cavitation resistance [12].


Optical microscope with 500X increase factor
Figure no. 8


Optical microscope with 100X increase factor
Figure no. 9


Optical microscope with 500X increase factor
Figure no. 10


Optical microscope with 500X increase factor
Figure no. 11

5.3 MICRO HARDNESS MEASUREMENTS ON SPECIMENS MANUFACTURED FROM THE GX4CRNI 13-4 STAINLESS STEEL SUBJECTED TO QUENCHING, TEMPERING AND GASEOUS NITRADING

In the superficial layers for depths until 0.1 mm the HV0,2 hardness varies between 300 - 600 (figure no. 12). The hardness variation is a result of the nitride precipitations both in the superficial and transitions layers. Those precipitations induce compressive stresses, which justify the increase of both the hardness and the corrosion resistance. In the sub layers under the eroded zone, the hardness has the value HV0,2-240, a normal situation taking into account that the measurements were done in a structure Q&T. (figure no. 13). Evidently, the hardness remains without modifications (HV0,2-240) when the depth is greater than 0.9 mm (figure no. 14).

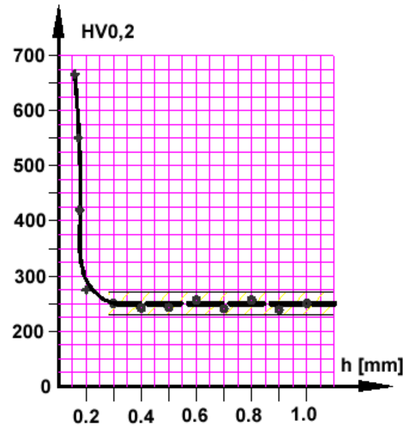


Figure no. 12

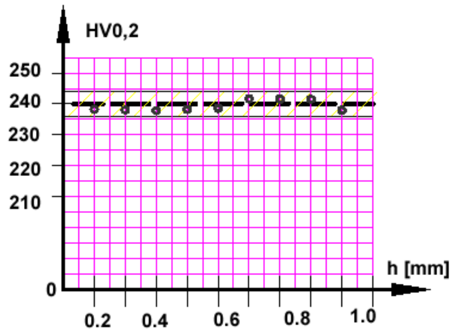


Figure no. 13

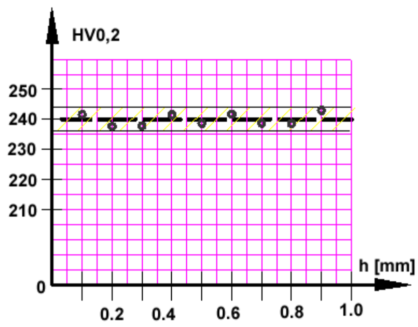


Figure no. 14

The same conclusion is obtained from the comparison of the steady state velocities $\mathbf{v_s}$ or the final eroded masses $\mathbf{m_a}$ of some steels with a good behavior at cavitation [2], [3], [5], [7], [9], [10], [11], [12] (table no. 6):

Table no. 6

Steady state erosion velocity and final eroded masses		
Steel mark	**m_a x 10^3 [g] Eroded mass**	**v_s x 10^5 [g/min] Erosion velocity**
GX4CrNi13-4 {Q+T+Nitration}	**14.81**	**10.10**
40Cr10	51.00	35.00
GX5 CrNiMo13-6-1	33.24	22.00
T07CuMoMnNiCr165-Nb	20.67	13.60
T09CuMoMnNiCr185-Ti	22.77	15.00
GX5CrNi19-10	15.50	13.20

6. CONCLUSIONS

It was applied a special method for the investigation of materials degraded through cavitation, with the 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/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=10.10 x 10^{-5} [g/min] and the eroded mass was m_a=14.81 x 10^{-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.

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

The cavitation erosion resistance of the steel GX4CrNi13-4 became better in comparison with other steels used commonly in manufacturing the hydraulic turbines runners (see table no. 6). 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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