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Departamentul: MMUT

THE CAVITATION EROSION OF STAINLESS STEELS WITH INDIRECT MARTENSITIC TRANSFORMATION

- DOCTORAL THESIS -

= REZUMAT =
(limba engleză)

Scientific advisers: Prof.univ.dr.ing. Ilare BORDEAŞU
Prof.univ.dr.ing. Ion MITELEA

Doctoral student:
Ing. Ştefan-Eusebiu KATONA

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INTRODUCTION

The cavitation erosion is present in nearly all domains where fluids are in movement. This phenomena arises through the transmission of forces generated by repeated implosion of vapor bubbles formed in areas where the fluid pressure drops below a certain critical value. The effects of cavitation erosion manifestation on hydraulic equipments are: loss of performance, noise and vibration, and erosion of the solid borders, which guide the flow [2], [3], [9], [28], [29], [30], [31], [35].

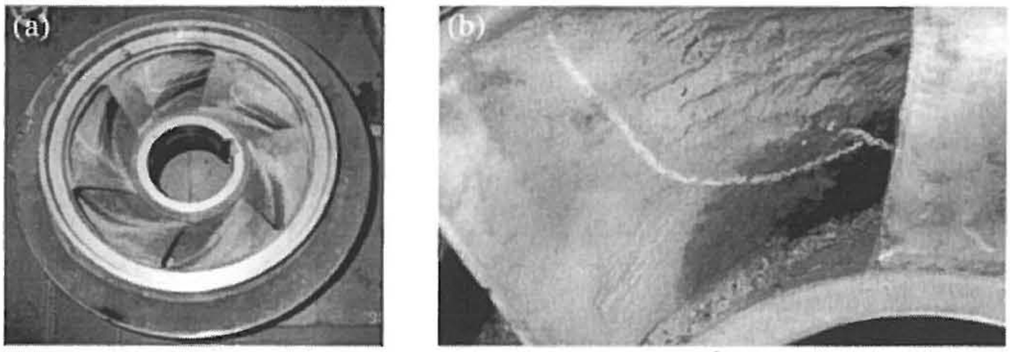
In laboratories, the research of destruction by cavitation erosion is done with ultrasonic vibratory equipments [1], [2], [7], [9], [23], [28], [94], [97], [130], hydrodynamic tunnels or devices with rotating disk. Although the hydrodynamic tunnels best reflect the cavitation flow, due to high costs and long time of study, for the research of the resistance and material behavior at degradation by cavitation, vibratory devices are used, due to, firstly, the short time of erosion, even if the generated phonomenom is completely different from the one from the hydraulic machine.

The paper researches the cavitation of the stainless steel with indirect martensitic transformation, from the 17-4 group, subjected at 3 treatments: heat treatment (8 regimes, from which 4 regimes of quenching for release in solution and 4 regimes of refrigeration), thermochemical laser nitriding treatment (3 regimes) and coating with layers by spraying and remelting with laser (3 regimes). The conducted researches aim at highlighting the effect produced by the change of morphology on the cavitation resistance and the steel behavior during the destructive attack due to the occurred microstructural changes and values of the mechanical characteristics.

1. CURRENT STATUS OF RESEARCHES REGARDING THE CAVITATION EROSION OF STAINLESS STEELS USED AT HYDRO-MECHANICAL EQUIPMENTS

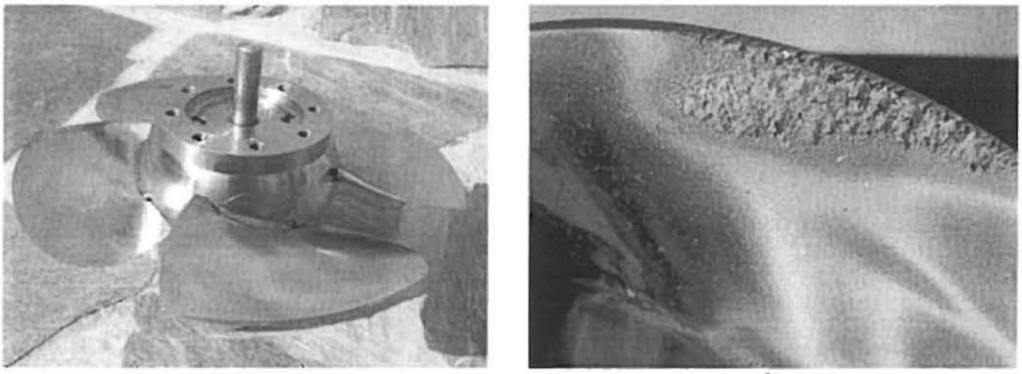
1.1. Fundamental bases

The cavitation is a complex phenomena of interaction of some hydrostatic, mechanic, metallurgical and chemical processes [2], [3], [6], [9], [29], [105]. It is specific to hydraulic machines, of turbine type, pumps, naval propellers, valves or exchangers, Diesel engines, bearings, etc. [5], [6], [9], [29]. In fig. 1.1 a,b the deterioration of a pump rotor blade is exemplified. Such damage leads to diminishment of the ability to pump and finally at the damage of the pump rotor.



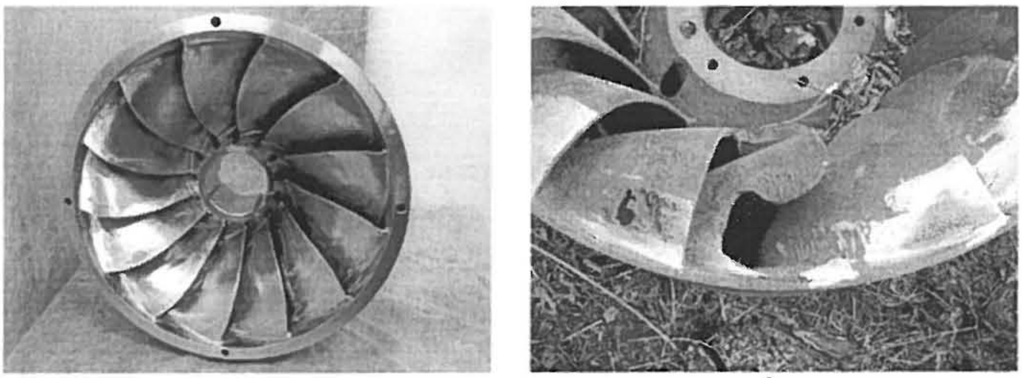
- a -   - b -

Fig. 1.1 Water pump made of austenitic stainless steel AISI 316 [6], [9]:
a – water pump rotor;
b – degradation by cavitation of the rotor blade



- a -   - b -

Fig. 1.2 Kaplan turbine made of stainless steel [6], [9]:
a – turbine rotor before the degradation by cavitation erosion;
b – turbine rotor blade after the degradation by cavitation erosion



- a -   - b -

Fig. 1.3 Francis turbine made of stainless steel [6], [9]:
a – turbine rotor before the degradation by cavitation erosion;
b – turbine rotor blade after the degradation by cavitation erosion

1.5. Objectives of the doctoral thesis

The main objectives are:

- role of the refrigeration treatment in the increase of cavitation resistance of the 17-4 PH stainless steels;
- development of a primary aging treatment, as an alternative solution, for the improvement of the cavitation erosion resistance;
- impact of some surface treatments (nitriding, thermal spraying) in reducing the rate of cavitation erosion;
- morphology and characterization of the surface microstructures of 17-4 PH steels subjected to cavitation erosion.

In the thesis, the researches were conducted on the stainless steel with indirect martensitic transformation, from the 17-4 PH group, because this material is widely used in the execution of some hydraulic equipment components [3], [34], [109].

The novelty of the thesis consists in the opportunity of applying some special techniques of volumic treatment (refrigeration, primary aging) and some modern techniques from the surface engineering (laser nitriding, HVOF spraying) to improve the cavitation erosion resistance of a stainless steel with indirect martensitic transformation, from the 17-4 PH group.

2. GENERAL CONSIDERATIONS REGARDING THE STAINLESS STEELS USED IN THE MANUFACTURING OF PARTS SUBJECTED TO CAVITATION

2.1. Structural classes of stainless steels

The stainless steels show in their chemical composition a concentration of more then 10,5% in Cr and by applying some heat or mechanical treatments, there will be obtained a wide range of chemical, physical and mechanical properties.

2.3. Conclusions

- ➢ it has been shown that through heat treatments, with well correlated process parameters (temperature and duration of heating, cooling medium), a stabile structure can be obtained (of martensite type);
- ➢ it has been evidenced how to achieve the refrigeration treatment, through which a ratio between the drip limit and the tensile strength can be achieved, satisfactory for an increased cavitation erosion resistance;
- ➢ a synthesis of the current research results achieved so far has been made, regarding at the correct proportion of chemical elements: Ni, Cu, Mn, Co, C and N, in the composition of the stainless steel, so as to reduce the ferrite domain (structural component with the lowest resistance to cavitation erosion) and increase the martensite (structural component with the highest resistance to destruction by cavitation).

3. RESEARCHED MATERIAL. EXPERIMENTAL PROCEDURE

3.1. Chemical composition, microstructure and mechanical properties of the researched steel and the method used

The stainless steels with controlled transformation from the 17-4 PH group also called semiaustenitic stainless steels combine the most attractive properties specific to the austenitic steels (weldability and deformability) and martensitic (high mechanical resistance), their modification being possible through a heat treatment applied after the technological processing.

3.2. Experimental stand and the method used for testing the cavitation resistance

The cavitation erosion tests were conducted in the Laboratory of Cavitation of the University Politehnica Timişoara, on a vibratory device with piezoceramic crystals (fig. 3.5), built after the regulatory requirements of ASTM G32-2010 [130], similar device to the model at the University of Michigan.

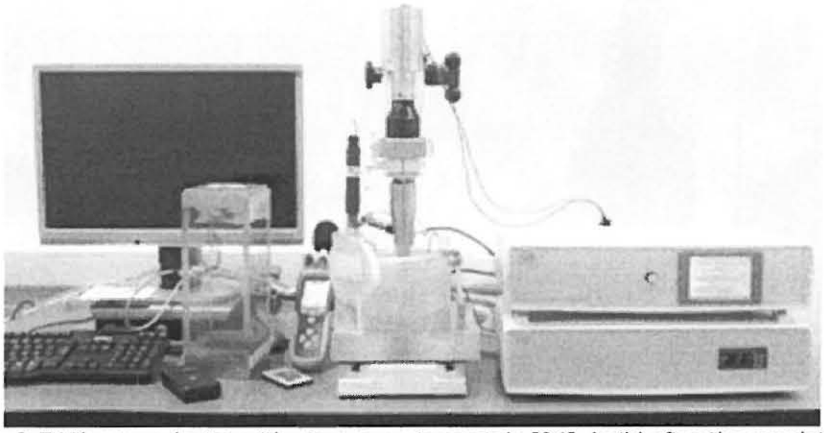


Fig. 3.5 Vibratory device with piezoceramic crystals [94], build after the regulatory requirements of ASTM G32-2010

The functional parameters of the device are:

- Power developed by the electric generator: 500 W;
- Frequency of vibrations: 20.000 ± 200 Hz;
- Amplitude of vibrations: 50 μm;
- Diameter of samples: 15,8 mm;
- Power supply: 220 V / 50 Hz;
- Temperature of the working fluid: 22 ± 1 °C;
- Type of the test sample: vibrating.

As a liquid medium, it was used drinking water from the public network, instead of distilled water, such as the recommended rules of ASTM G32-2010, because tested durations (of the intermediate periods) are short and mass loss through cavitation erosion are not affected by chemical corrosion. During researches the water temperature was maintained at the value of 22 ± 1 °C.

3.3. Conclusions

- The chosen research steel is one used in Romania and other countries at the casting of blades and hydraulic turbine rotors.
- The chemical composition and its structure, established on the basis of Schäffler diagram, are elements which, by heat treatments for release in solution ensures structural changes and increased mechanical properties, which gives him very good behaviors and resistances to various intensities of the cavitational attack.
- The apparatus used in the production of cavitation and for the microscopic investigation is modern, performant, of the latest generation, which offers certainty in performing the experiment, analysis and evaluation at the highest scientific level.

4. INFLUENCE OF THE HEAT TREATMENT ON THE CAVITATION RESISTANCE

4.1. Quenching for release in solution and cavitation erosion resistance

As standard samples, the ones originated from the OH12NDL steel were used at the execution of hydraulic turbine blades from the Hydroelectric Power Plant Porţile de Fier I and II.

The images from fig. 4.2 show that by quenching for release in solution at 1050 °C/air the surface has a superior resistance to the one achieved by quenching for release in solution at 950 °C/air.

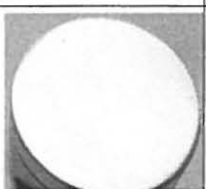
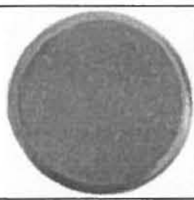
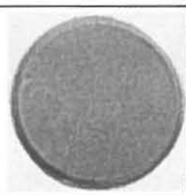
Condition of heat treatment	**Cavitational attack duration, in minutes**			
	0	**60**	**90**	**165**
Quenching at 950 °C/air				
Quenching at 1050 °C/air				

Fig. 4.2 Appearance of the cavitated samples surfaces

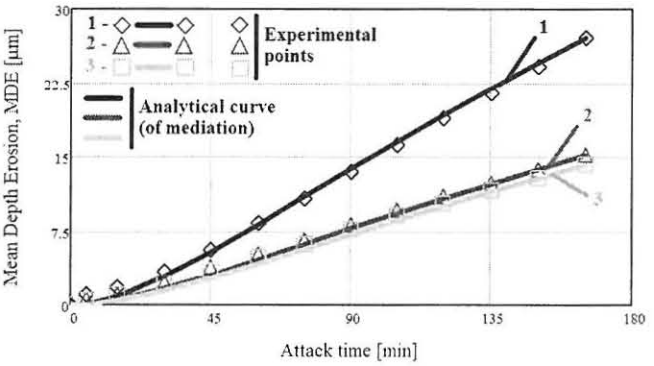


Fig. 4.8 Comparisons of the specific curves between the mean depth of erosion with the cavitational attack duration: 1 - OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/air; 3 - Quenched 17-4 PH steel at 1050 °C/air

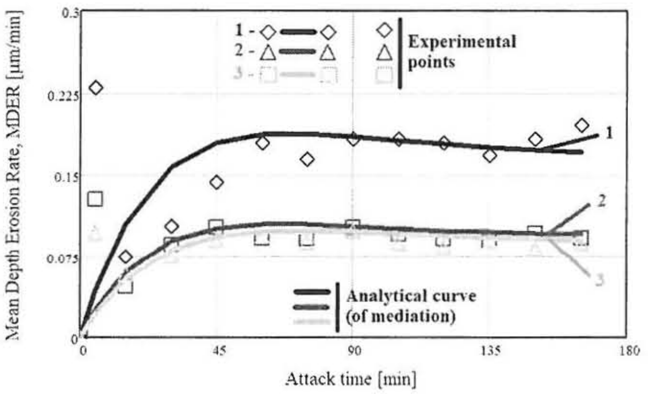


Fig. 4.9 Comparisons of the specific curves between the mean depth of erosion rate with the cavitational attack duration: 1 - OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/air; 3 - Quenched 17-4 PH steel at 1050 °C/air

Therefore, the data demonstrates that the quenching temperature for release in solution at 1050 °C ensures the highest cavitation erosion resistance and both quenching heat treatment states lead to better results in comparison to the standard steel.

4.2. Primary and secondary aging effect on the the cavitation erosion resistance

4.2.1. Heat treatments, microstructure, mechanical properties

The application of primary aging treatment at 700 °C (fig. 4.10), favors the increase of Vickers hardness (328 - 338 HV) only at the samples austenitizated at 1050 °C (fig. 4.11); this fact is due to the transformation of a part of metastabile austenite in martensite; instead, the samples quenched for release in solution at 950 °C and subsequently subjected to primary aging at 700 °C, possess practically hardness values (318 - 323 HV) similar to those specific to quenching for release in solution (fig. 4.12); this fact is a result of a relatively low carbon content of the steel, implicitly of a limited proportion of precipitated carbines and of a similar concentration in carbon and in chromium of the austenite after both release in solution and primary aging treatment.

Fig. 4.13 and 4.14 exemplify the microstructures specific to the tempered steel at 450 °C.

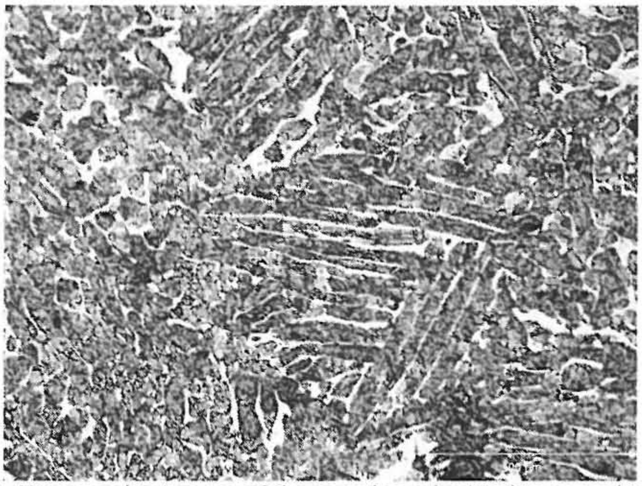


Fig. 4.13 x 200. Micrographic images of the samples submitted to quenching for release in solution at 950 °C/air, followed by primary aging at 700 °C/air and tempering at 450 °C/air

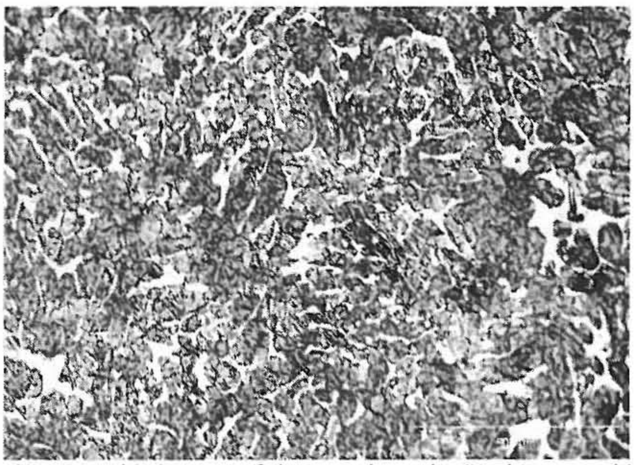


Fig. 4.14 x 200. Micrographic images of the samples submitted to quenching for release in solution at 1050 °C/air, followed by primary aging at 700 °C/air and tempering at 450 °C/air

4.2.2. Cavitation curves

Fig. 4.15 exemplifies the images of the samples before and after the cavitation tests at different moments of time for the two types of heat treatments applied.

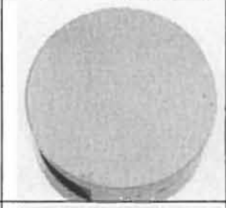
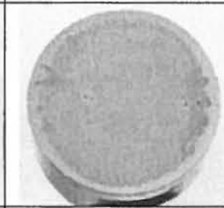
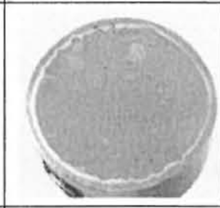
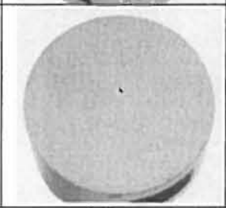
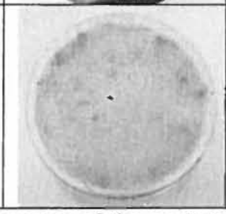
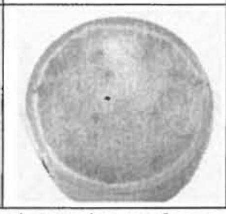
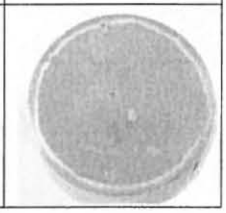
Condition of heat treatment	Cavitational attack duration, in minutes			
	0	60	90	165
950 °C/air + 700 °C/air + 450 °C/air				
1050°C/air + 700 °C/air + 450 °C/air				

Fig. 4.15 Appearance of the cavitated samples surfaces

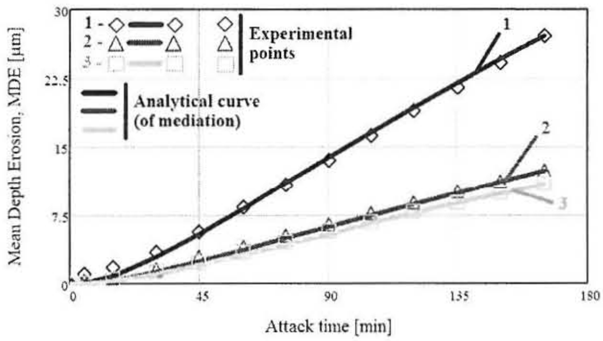


Fig. 4.21 Evolution of mean depth of erosion with the cavitational attack duration: 1 - OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/air + primary aging at 700 °C/air + secondary aging at 450 °C/air; 3 - Quenched 17-4 PH steel at 1050 °C/air + primary aging at 700 °C/air + secondary aging at 450 °C/air

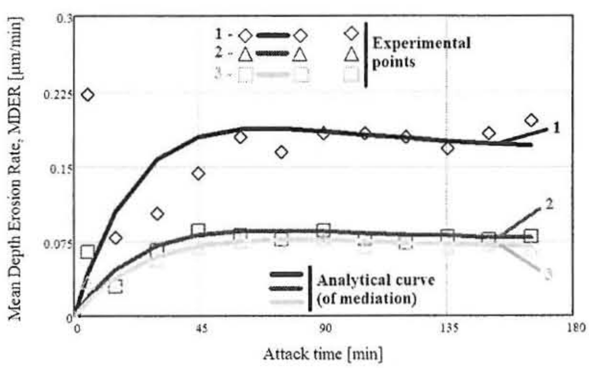


Fig. 4.22 Evolution of mean depth of erosion rate with the cavitational attack duration: 1 - OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/air + primary aging at 700 °C/air + secondary aging at 450 °C/air; 3 - Quenched 17-4 PH steel at 1050 °C/air + primary aging at 700 °C/air + secondary aging at 450 °C/air

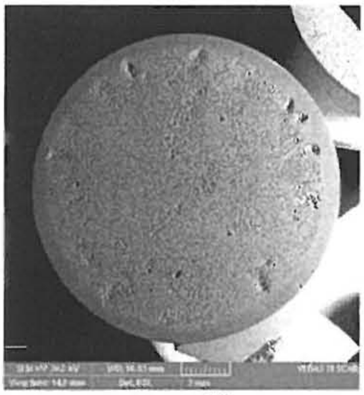
The obtained data demonstrates that both heat treatment regimes ensure a cavitation erosion resistance superior to that of standard steel and the performing of austenitization for quenching at 1050 °C represents the optimal heat treatment solution.

4.2.3. Topography of the eroded surfaces

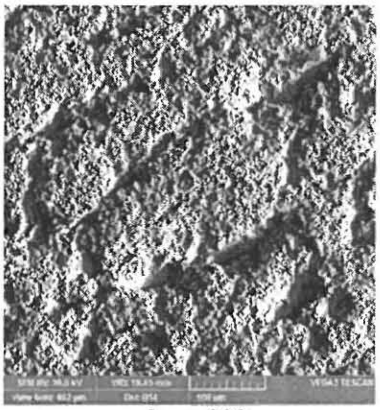
In fig. 4.23 and 4.24 it exemplifies the images with the topography of the surface samples heat treated differently.

The heat treatmant based on a austenitization at 1050 °C, quenching in air and aging leads to a microstructure with higher hardness and implicitly at a more uniform surface degradation through cavitation (fig. 4.24).

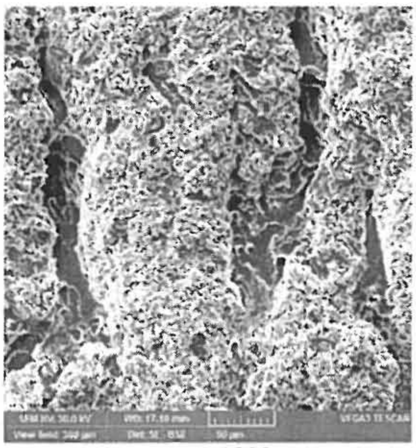
The microstructure of the cross sections through the eroded surfaces (fig. 4.25) confirms that the initiation of the cavitation at both heat treatment regimes occurs in the ferrite islands and on the limits of separation between them and the martensite matrix. At the end of the cavitational attack in the former ferrite areas appear river shapes more or less extended.



- a - x 10

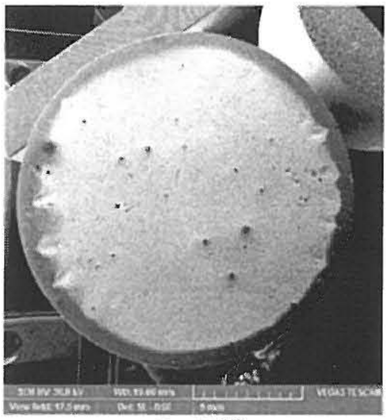


- b - x 300

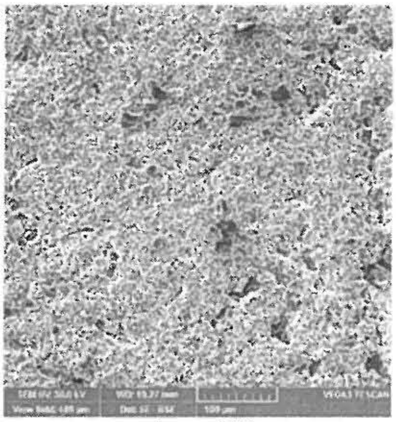


- c - x 1000

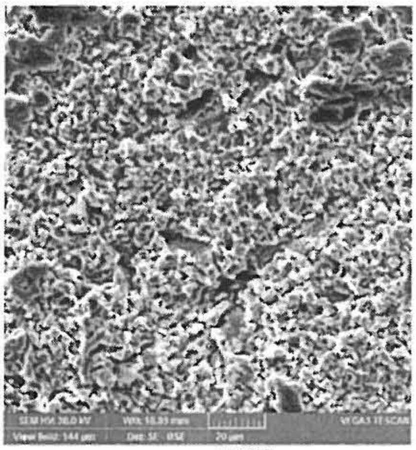
Fig. 4.23 Macrographic image (a) and micrographic (b,c) of the surface samples quenched at 950 °C/air + 700 °C/air + 450 °C/air and tested to cavitation for 165 min



- **a** - x 10



- **b** - x 300



- **c** - x 1000

Fig. 4.24 Macrographic (a) and micrographic (b,c) images of the surface samples quenched at 1050 °C/air + 700 °C/air + 450 °C/air and tested to cavitation for 165 min

4.3. Refrigeration treatment and cavitation erosion resistance

4.3.1. Sclerometrical examinations

From their analysis, the following observations can be drawn:

- the lowest hardness values (225 - 235 HV), are obtained by quenching for release in solution at 1050 °C, following a predominant austenitic microstructure at room temperature;
- a lower heating temperature for release in solution (950 °C), causes the rise of the critical point Ms, therefore the transformation of a considerable part of metastabile austenite in martensite and implicitly an increase of hardness (315 - 325 HV);
- the refrigeration treatment is manifested by a significant increase in hardness, especially at the samples austenitized at 1050 °C; as a result of a

more intense martensitic transformation with those to which the heating for release in solution was conducted at 950 °C;

- regardless of the quenching for release in solution temperature, the performing of tempering at 450 °C leads to a significant hardening of the material (410 - 420 HV).

4.3.2. Cavitation tests

In fig. 4.30 it exemplifies the macrographic images of the sample surfaces before the attack and at significant moments of the cavitation, in fig. 4.35...4.42 are shown the curves which characterize the behavior of the material at this type of degradation, after different versions of compound treatment (heat + refrigeration). As a standard material, the OH12NDL steel was considered.

Condition of heat treatment	**Cavitational attack duration, in minutes**			
	0	**60**	**90**	**165**
950 °C/20 min/air + REFRIGR. 60 min/air				
950 °C/20 min/air + REFRIGR. 60 min/air + Tempering 450 °C/air				
1050°C/20 min/air + REFRIGR. 60 min/air				
1050°C/20 min/air + REFRIGR. 60 min/air + Tempering 450 °C/air				

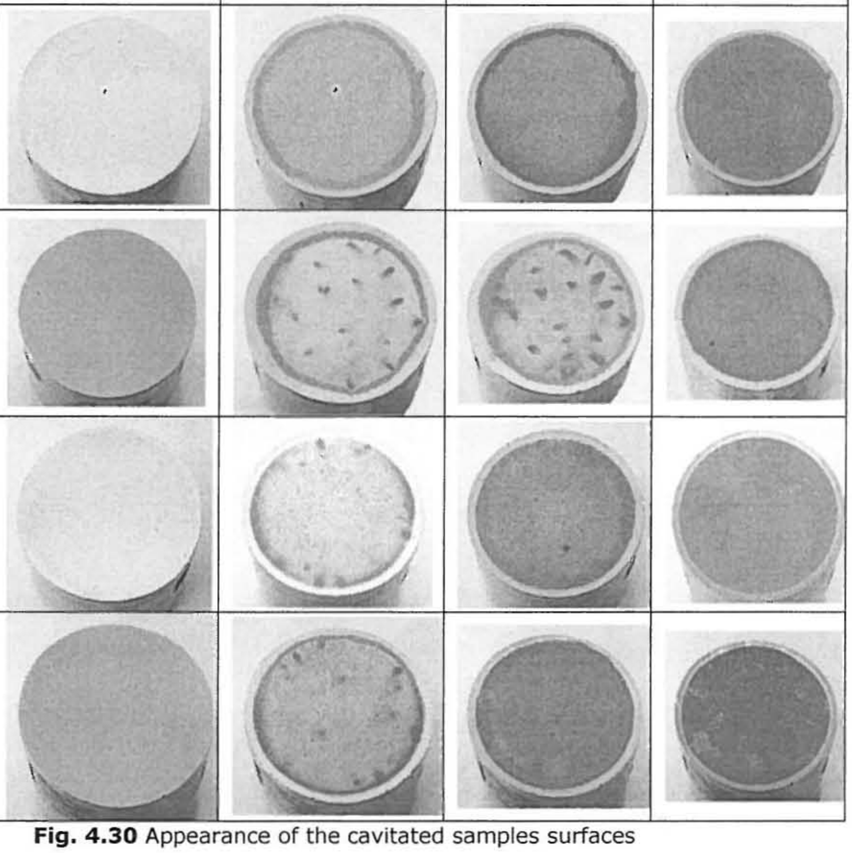


Fig. 4.30 Appearance of the cavitated samples surfaces

Fig. 4.45...4.48 comparatively analyzes the specific cavitation curves of the 17-4 PH steel found in the 4 states of treatment applied and those of the standard steel.

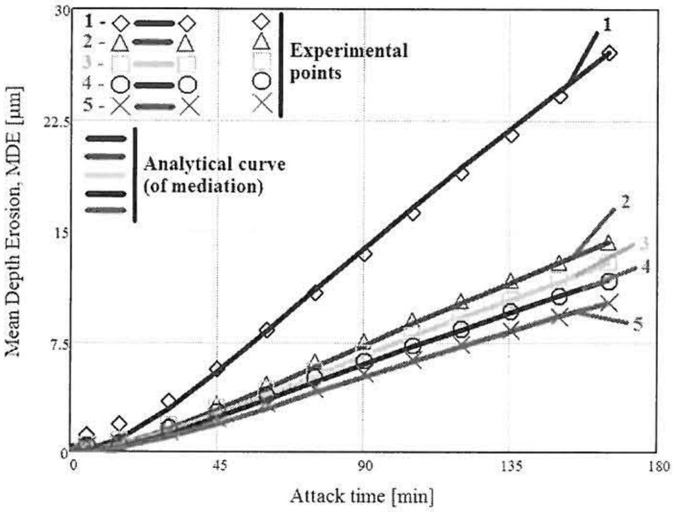


Fig. 4.47 Comparisons of the evolutions of mean depth of erosion with the cavitational attack duration: 1 -OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/20 min/air + refrigeration 60 min/air; 3 - Quenched 17-4 PH steel at 1050 °C/20 min/air + refrigeration 60 min/air; 4 - Quenched 17-4 PH steel at 950 °C/20 min/air + refrigeration 60 min/air + tempering at 450°C/60 min/air; 5 - Quenched 17-4 PH steel at 1050 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air

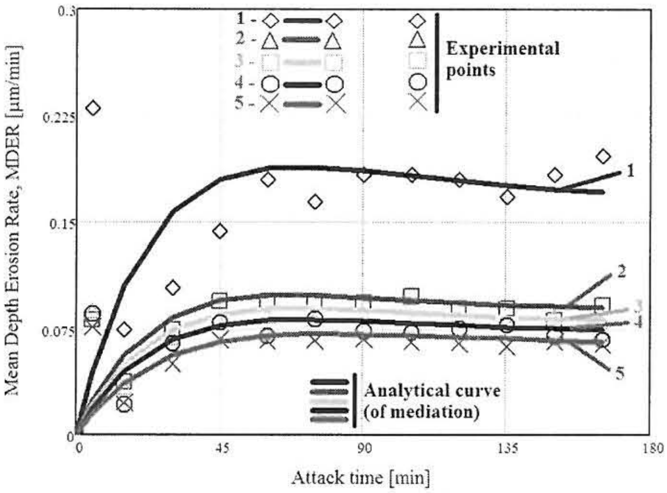
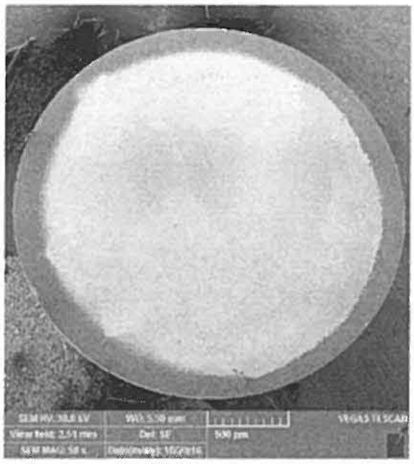


Fig. 4.48 Comparisons of the evolutions of mean depth of erosion rate with the cavitational attack duration: 1 -OH12NDL standard steel; 2 - Quenched 17-4 PH steel at 950 °C/20 min/air + refrigeration 60 min/air; 3 - Quenched 17-4 PH steel at 1050 °C/20 min/air + refrigeration 60 min/air; 4 - Quenched 17-4 PH steel at 950 °C/20 min/air + refrigeration 60 min/air + tempering at 450°C/60 min/air; 5 - Quenched 17-4 PH steel at 1050 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air

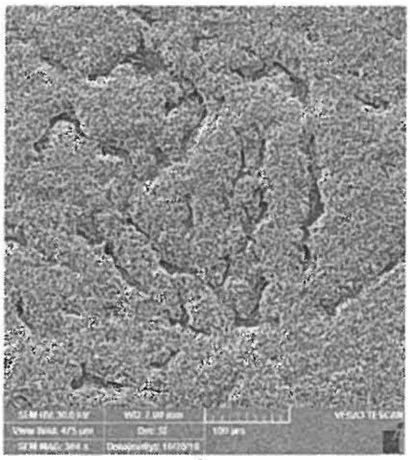
The comparisons from fig. 4.45...4.48 show that the highest resistance is obtained by the heat treatment of quenching at 1050 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air.

4.3.3. Topography of the cavitational tested surfaces

As expected, the degraration mechanism through cavitation erosion at this steel is based on plastic deformation of the surface, the breaking having a ductile character. The SEM images shown in fig. 4.49 and 4.50 attest that the initiation and propagation of cavitation cracks occur primarily in the microzones with δ ferrite, structural constituent with a low resistance to cavitation.



- a -



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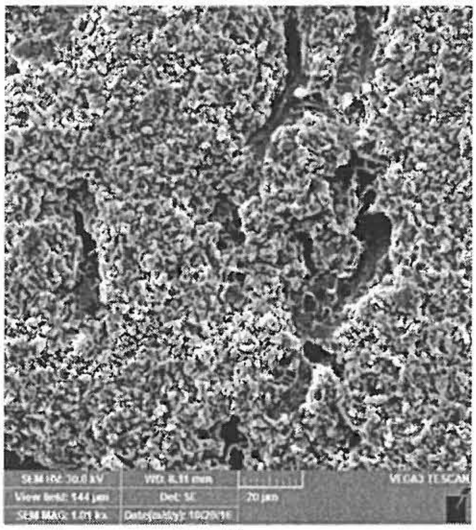
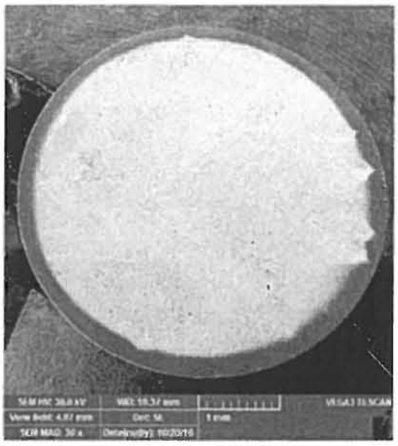
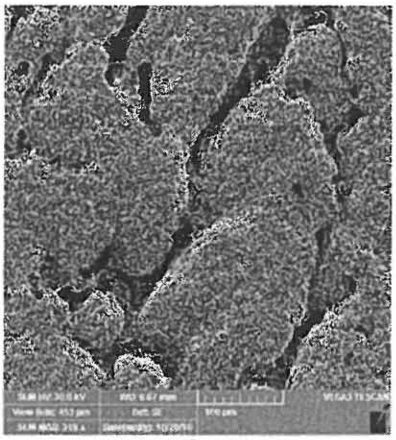


- c -

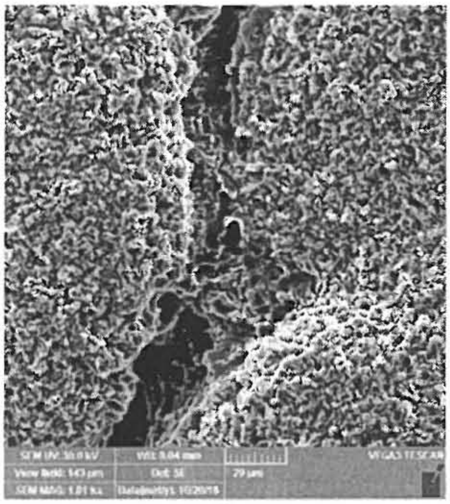
Fig. 4.49 Surface topography of the samples quenched at 950 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air and tested to cavitation for 165 min: a - x 58; b - x 304; c - x 1000



- a -



- b -



- c -

Fig. 4.50 Surface topography of the samples quenched at 1050 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air and tested to cavitation for 165 min: a - x 30; b - x 319; c - x 1000

4.3.4. Microstructural analysis

The obtained results from the micrographic examinations of the longitudinal sections through the samples tested at cavitation for 165 min (fig. 4.51 and 4.52) are in full compliance with the hardness measurements and with the cavitation tests. They demonstrate that the resistance to wear by erosion of the austenitized samples at 1050 °C, refrigerated and tempered at 450 °C is superior to one of the samples refrigerated at 950 C°.

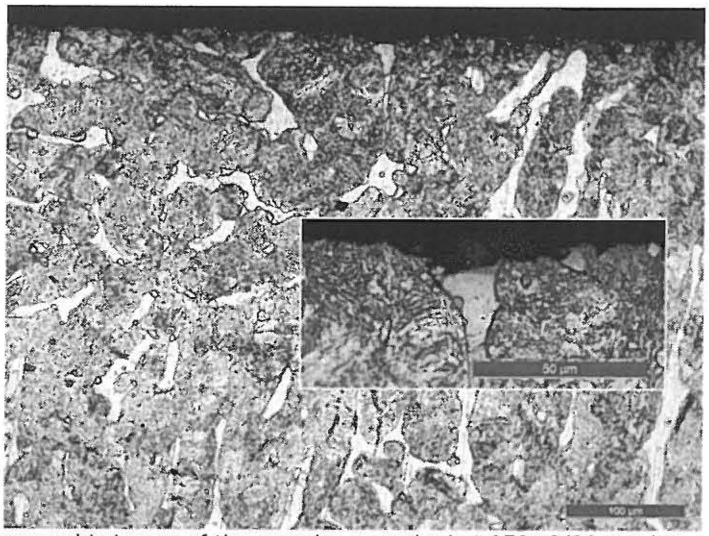


Fig. 4.51 Micrographic image of the samples quenched at 950 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air

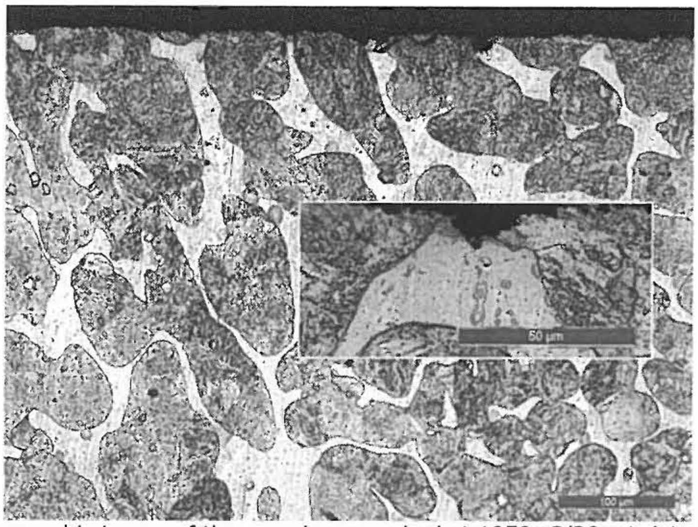


Fig. 4.52 Micrographic image of the samples quenched at 1050 °C/20 min/air + refrigeration 60 min/air + tempering at 450 °C/60 min/air

4.4. Conclusions

- The regimes of quenching for release in solution followed by primary and secondary aging applied to the 17-4 PH steel favors a decrease of the mean depth of erosion after 165 min of testing, and respectively of the the wear rate, of approx. 2,2 - 2,5 times, compared to the OH12NDL standard steel.
- The intercalation of a refrigeration between quenching for release in solution and tempering causes an increase in the cavitation erosion resistance of 2,3 - 2,8 times compared to the standard steel and with approx. 11% with the state of primary aging at 700 °C.

5. ROLE OF THERMOCHEMICAL LASER NITRIDING TREATMENT ON THE INCREASE OF CAVITATION EROSION RESISTANCE

5.1. Introduction

One of the modern technological alloying versions of surfaces with nitrogen is nitriding with laser beam. It is an attractive technological way of improving the tribological properties and different substrates, due to its simplicity and possibility of formation of some functional layers with a high hardness, little affecting the base material.

5.2. Experimental procedure

The surface treatment with laser beam was performed on the experimental stand, Trumpf HL 124 P LCU brand, constituted from a welding - cutting with laser Nd-YAG installation (fig. 5.1), found in the endowment of the National Institute of Research - Development in Welding and material Testing of Timişoara.

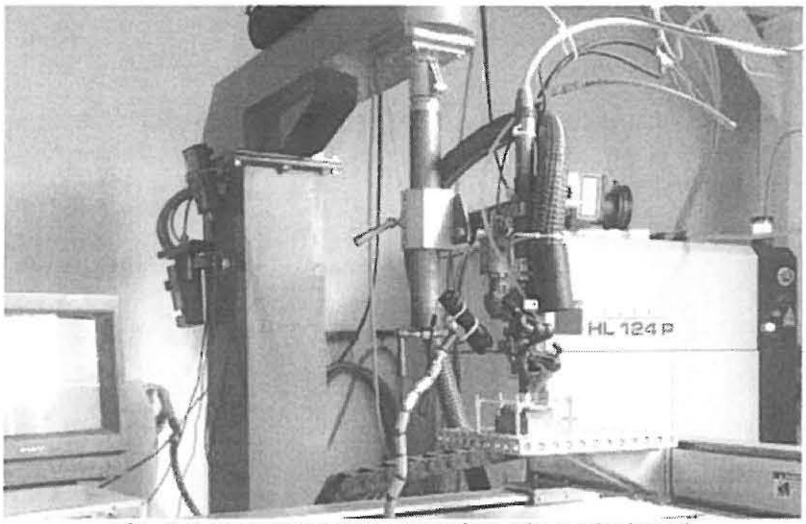


Fig. 5.1 Laser microunit, Trumpf HL 124 P LCU brand

The nitriding process parameters were:

- Power of the installation: 800 W;
- Pulse duration: 10 ms (noted set 4 of samples); 8 ms (noted set 3 of samples); 6 ms (noted set 2 of samples);
- Frequency of the pulse repetition: 10 Hz;
- Atmosphere: pure nitrogen, whose flow was 33 l/min.

5.3. Cavitation curves

The behavior and vibratory cavitation erosion resistance tests, for the three sets of samples, were conducted in the terms described in Chapter 3, in compliance with the standard terms of the laboratory custom.

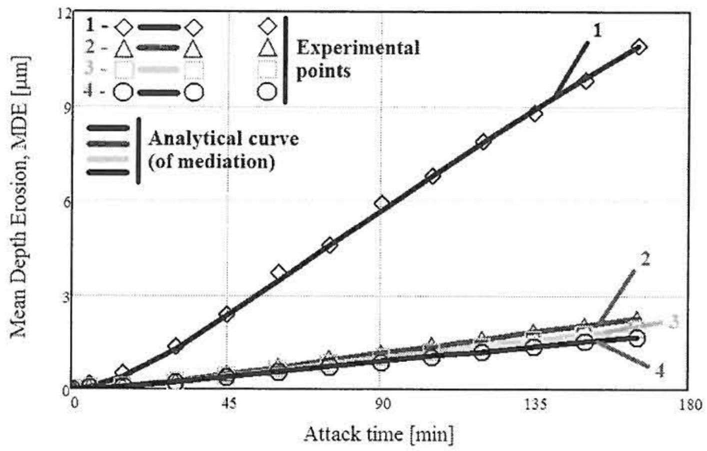


Fig. 5.8 Comparisons of the evolutions of mean depth of erosion with the cavitational attack duration: 1 – Quenched 17-4 PH steel at 1050 °C/air + primary aging 700 °C/air + secondary aging 450 °C/air; 2 – Laser nitrided 17-4 PH steel, pulse duration, 6 ms; 3 – Laser nitrided 17-4 PH steel, pulse duration, 8 ms; 4 – Laser nitrided 17-4 PH steel, pulse duration, 10 ms

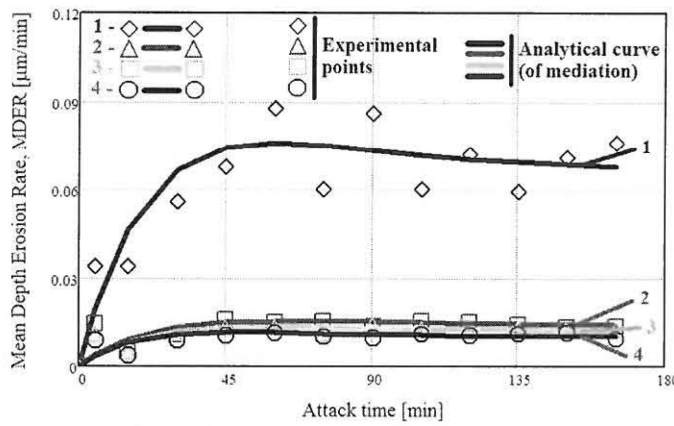


Fig. 5.9 Comparisons of the evolutions of mean depth of erosion rate with the cavitational attack duration: 1 – Quenched 17-4 PH steel at 1050 °C/air + primary aging 700 °C/air + secondary aging 450 °C/air; 2 – Laser nitrided 17-4 PH steel, pulse duration, 6 ms; 3 – Laser nitrided 17-4 PH steel,pulse duration,8ms;4–Laser nitrided 17-4 PH steel,pulse duration,10 ms

The resistance increases of the nitrided surfaces, depeding on the laser pulse duration, compared with quenching for release in solution mentioned, are:

- approx. 4 times for the regime with pulse duration of 6 ms;
- approx. 4,5 times for the regime with pulse duration of 8 ms;
- approx. 6 times for the regime with pulse duration of 10 ms.

5.4. Microstructure, mechanical properties

After each period of cavitational attack, images of the tested surfaces were made using a Canon Power Shot SX200 IS photo camera. The obtained results are shown in fig. 5.10 and highlight the manner in which the degradation phenomenon of the surface extends.

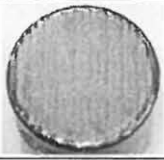
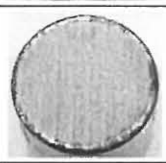
Pulse duration	Cavitational attack duration, in minutes			
	0	60	90	165
6 ms				
8 ms				
10 ms				

Fig. 5.10 Macrographic images of the tested surfaces at different periods of time

5.5. Conclusions

- At a laser beam power of 800 W, through the changing of the pulse duration from 6 to 10 ms, an increase of the nitrided layer's mean depth of erosion from 0,22 to 0,28 mm will be obtained.
- The three regimes of nitriding with laser beam, through the created hardness of the surface layer exposed to cavitation, compared to the structural state of quenching for release in solution followed by primary and secondary aging, lead to an increase of the resistance to the vibratory cavitation of 4 - 6 times, depending on the pulse duration.
- As a result of remelting of a base material part, it ensures a good metallurgical bond and implies a good adhesion to the substrate layer.

6. CAVITATION RESISTANCE OF 17-4 PH STAINLESS STEELS COATED WITH LAYERS OF CERAMIC POWDERS

6.1. Introduction

One of the technological methods to reduce or avoid the loss through cavitation implies the use of performing oxide coatings, carbides and nitrides which can be applied on the base material's substrate [5], [6], [12], [13], [14], [16], [22], [23], [29], [32], [37], [38], [40], [41], [42], [43].

6.2. Basics of spraying process

This process of coating the surface allows the obtaining of microstrates resistant to wear, thermal shocks, corrosion, isolanting from the thermal and electrical point of view, microstrates and artificial strates, supraconductors, biocompatibles, etc.

6.5. Materials, apparatus, process parameters

From a batch of 17-4 PH stainless steel, cavitation samples were executed, which were subjected to quenching for release in solution at 1050 °C with air cooling, and subsequently a part of these were covered at the surface with powders from the cermet group, type Al_2O_3 30(Ni 20Al), through thermal spraying using a METCO SULZER installation, found in the endowment of the National Institute of Research - Development in Welding and material Testing of Timişoara (fig. 6.3).

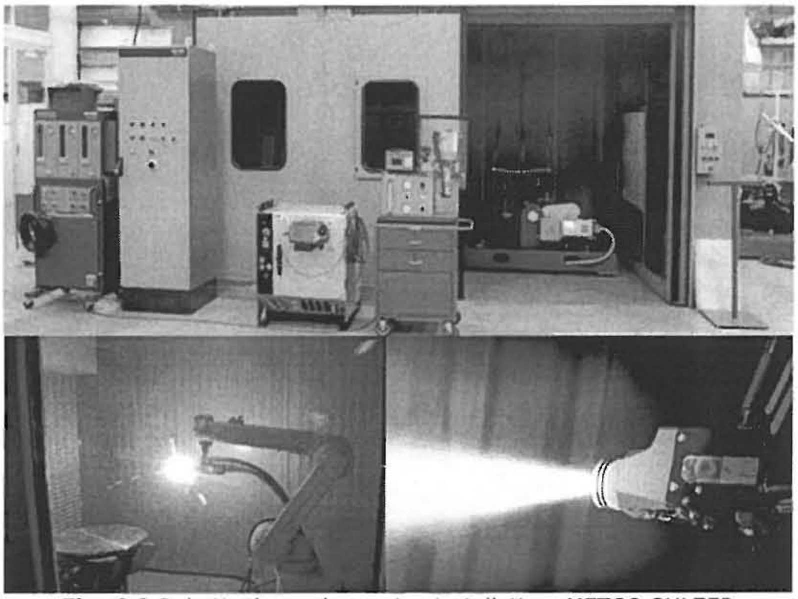


Fig. 6.3 Robotic thermal spraying installation, METCO SULZER

The optimal parameters of the thermal spraying process, established experimentally by preliminary tests, are:

- Plasmagen gas, Ar+6%H, pressure: 9 bar;
- Transport gas, Ar, pressure: 4 bar;
- Compressed air, pressure: 2 bar;
- METCO 410 NS powder debit: 63 gr/min;
- Electric voltage: 80 - 85 V;
- Electric intensity: 550 - 600 A.

6.6. Cavitation tests

The research procedure, regarding the stages, conduction mode and manipulation of samples, macroscopic and microscopic analyzes of the eroded surface, as well as the recording of the experimental results, are presented in Chapter 3.

In fig. 6.4, some representative images of the samples surfaces during the course of cavitation are presented.

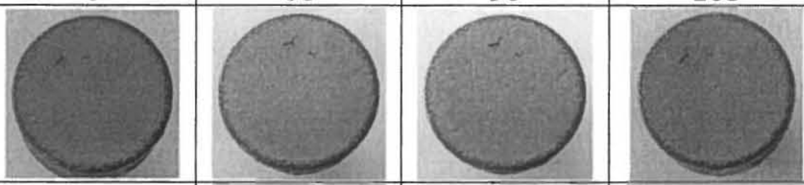
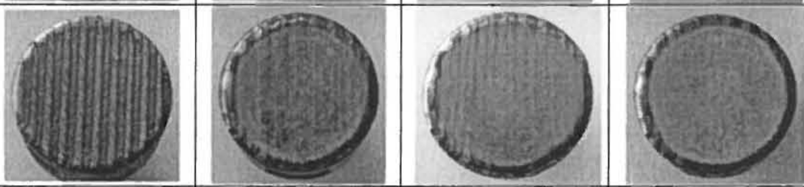
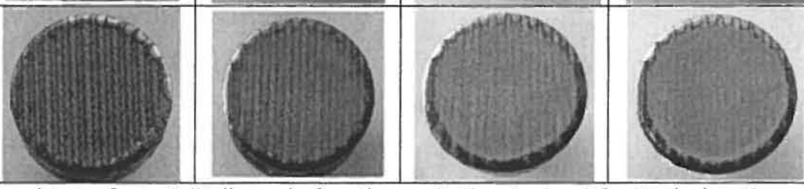
Treatment regimen	Cavitational attack duration, in minutes			
	0	60	90	165
Without laser remelting				
With laser remelting, 8 ms				
With laser remelting, 10 ms				

Fig. 6.4 Macrographic surfaces initially and after the cavitation tests at 3 attack durations

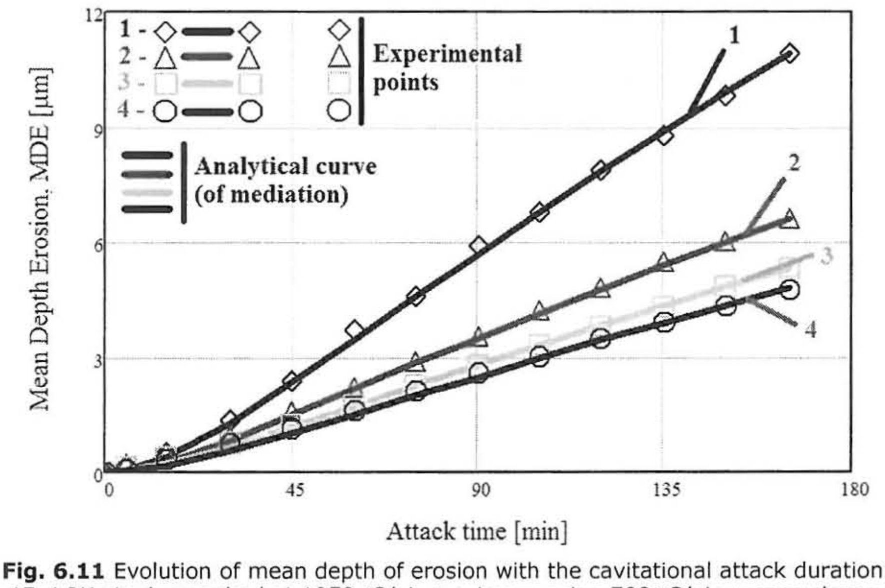


Fig. 6.11 Evolution of mean depth of erosion with the cavitational attack duration: 1 - 17-4 PH steel quenched at 1050 °C/air + primary aging 700 °C/air + secondary aging 450 °C/air; 2 -Thermal sprayed 17-4 PH steel without laser remelting; 3 - Thermal sprayed 17-4 PH steel with laser remelting, pulse duration, 8 ms; 4 - Thermal sprayed 17-4 PH steel with laser remelting, pulse duration,10 ms

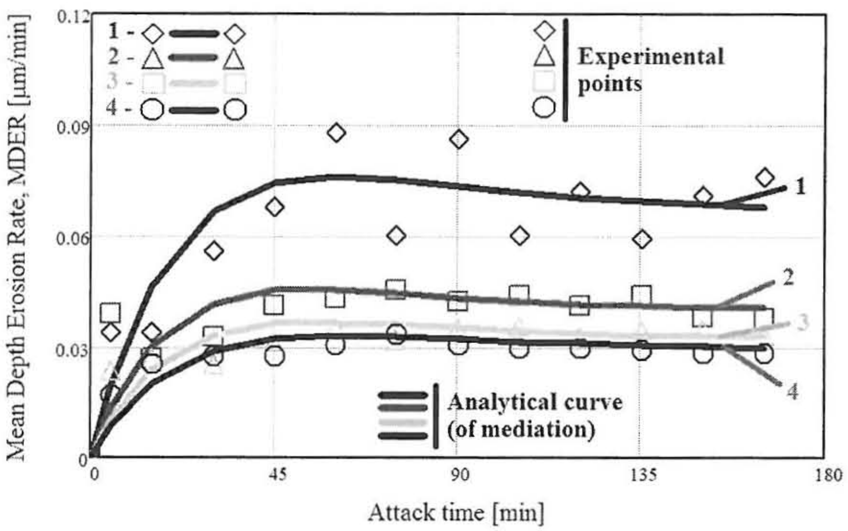


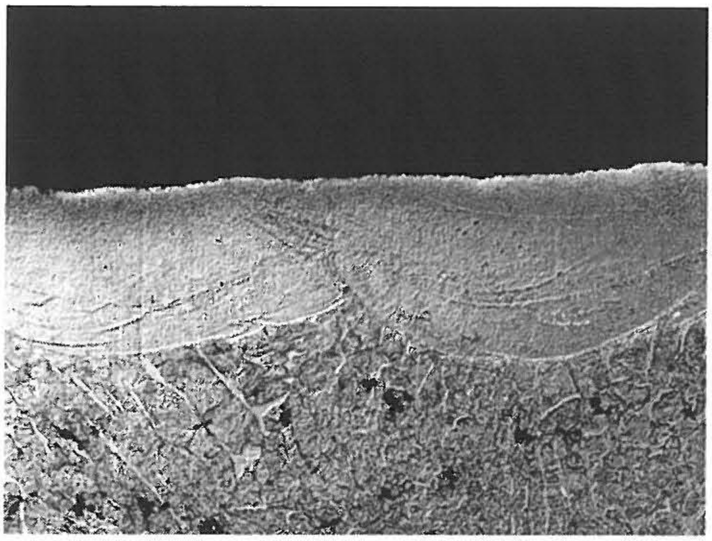
Fig. 6.12 Evolution of mean depth of erosion rate with the cavitational attack duration: 1 - 17-4 PH steel quenched at 1050 °C/air + primary aging 700 °C/air + secondary aging 450 °C/air; 2 -Thermal sprayed 17-4 PH steel without laser remelting; 3 - Thermal sprayed 17-4 PH steel with laser remelting, pulse duration, 8 ms; 4 - Thermal sprayed 17-4 PH steel with laser remelting, pulse duration,10 ms

From the analyse of the showed data in fig. 6.9...6.12, the following is established:

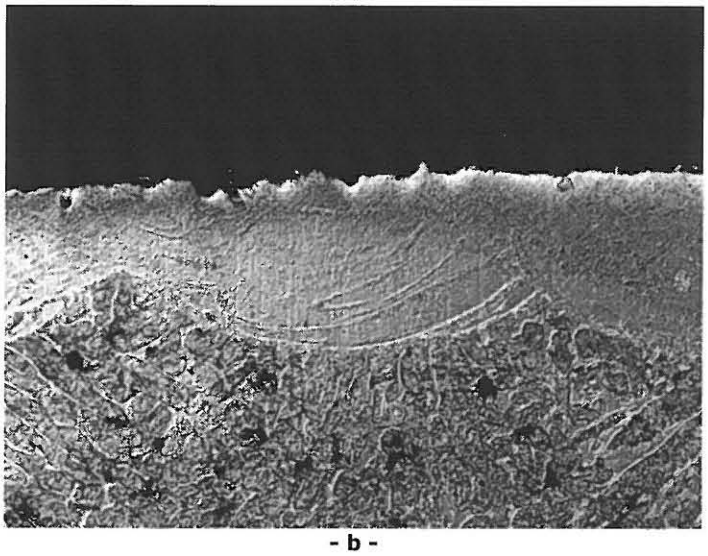
- the coatings produces by thermal spraying in plasma present a mean depth of erosion after 165 min of cavitational attack, reduced by approx. 85% (fig. 6.11) compared to the structural state obtained by quenching + aging and a mean depth of erosion rate (in the stabilization area) reduced by 66% (fig. 6.12);
- the laser beam remelting of the sprayed layer, ensures an important increase of the cavitation resistance, the higher the laser pulse duration was longer, therefore, the MDE values are reduced by (106 - 134)% compared to those specific to heat treatment (fig. 6.11) and with (24 - 44)% compared to those obtained by thermal spraying of the surface (fig. 6.12).

6.7. Microstructural analysis

The image shown in fig. 6.13 outlines the obtaining of a fine microstructure of the remelted layer, with lack of porosities and other flaws of continuity, with a good metallurgical bond at substrate. After the cavitational attack, the same cross section through the remelted layer with the laser beam (fig. 6.13 b) highlights an uniform degradation, with pinches produced mainly on the interface between the structural matrix and the chemical combination particles.



- a -



- b -

Fig. 6.13 Micrographic image of a cross section through the thermal sprayed and remelted layer with laser beams, x 300: a – before the cavitation; b – after the cavitation test

6.8. Conclusions

- The covering of the pieces surfaces, which operate under cavitation regime, with powders from the cermet group, type Al_2O_3 30(Ni 20Al), followed by remelting with a power laser beam, frequencies and durations well defined, favors an increase of cavitation erosion resistance with approx. 134% compared to the structural state of quenching for release in solution at 1050 °C with air cooling followed by primary aging at 700 °C and secondary aging at 450 °C.

7. GENERAL CONCLUSIONS AND ORIGINAL CONTRIBUTIONS. NEW RESEARCH DIRECTIONS

- The evaluation of the behavior and cavitation erosion resistance is indicated to be made based both on curves and charateristic parameters, and micrographic images of the damaged surfaces, taken at different intermediate times and final of the cavitational attack.
- The examination at the scanning electron microscope of the damaged areas and of the cross sections through the cavitated samples, highlight that the initiation of the cavities (at all heat treatment regimes applied) take place in the ferrite inslands and on the limits of separation between them and the structural matrix, and at the end of the cavitational attack in the former ferrite areas appear river shapes more or less extended.
- The examination at the scanning electron microscope of the damaged surface layer by cavitation erosion confirms these statements and shows that the initiations of the cracking phenomenon is produced mainly on the limits of separation between the grain boundries and within the ferrite grains. The wavy appearance of the surface, generated by the laser beam action, keeps itself to some extend, and after the cavitation test.
- The fine microstructure, dense and lacking porosities, with high hardness, obtained by applying the thermal spraying followed by remelting with laser beam technique, explains the pronounced improvement of the resistance to wear by cavitation.
- The examination at the scanning electron microscope of the topography of the tested surfaces by cavitation erosion, highlights the formation of similar shape crusts, wavy and uniformly distributed, at the processing with the laser beam. Also, as expected, a preponderant attack appears, with pinches, which develops in microcraters, at the base of the waves created by the laser beam.

New research directions

- Expansion of the data base with the new methods and technologies of mechanical and thermochemical treatments which can be applied to the 17-4 PH stainless steels, used at manufacturing and reparing of rotors and pump blades and hydraulic turbines,in order to increase resistance to cavitation erosion;
- Research on the influence of the new methods, technologies and applied treatments upon the behavior of stainless steels to cavitation erosion;
- Research on the structural damage of these stainless steels in the early stages of cavitation.

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