

Cavitation Erosion of HVOF Metal-ceramic Composite Coatings Deposited onto Duplex Stainless Steel Substrate

ILARE BORDEASU^{1*}, LAVINIA MADALINA MICU^{2*}, ION MITELEA¹, ION DRAGOS UTU¹, LIVIU DANIEL PIRVULESCU¹, NICUSOR ALIN SIRBU³,

¹University Politehnica Timisoara, 2 Victoriei Sq., 300006, Timisoara, Romania

²Banat University of Agricultural Sciences and Veterinary Medicine, 119 Calea Aradului, 300645 Timisoara, Romania

³National R & D Institute for Welding and Material Testing ISIM Timisoara, 30 Mihai Viteazul Bld, 300222, Timisoara, Romania

The surface of any metallic material, is degradating over time from the repeated impact with the microjets and shock waves generated by the bubbles implosion formed during cavitation. Beside the classical methods of heat or thermochemical treatments, several research institutes and hydromechanical equipments users are oriented to the development of metal-ceramic composite coatings deposited by thermal spraying, to provide good protection from corrosive and erosive action of the liquid medium. The researches from this paper analyse the behavior and resistance to erosion cavitation of a Duplex stainless steel whose surface is coated with WC-9Co-5Cr-1Ni powder, deposited by high velocity oxygen fuel (HVOF) spraying method and followed by laser remelting. These investigations, performed in the Cavitation Laboratory of University Politehnica Timisoara, on the vibratory apparatus with standard piezoceramic crystals, outline the need for remelting the sprayed coating in order to improve its adhesion to the substrate and moreover for growing the mechanical impact resistance with the microjets and shock waves developed during cavitation.

Keywords: cavitation, composite, HVOF spraying, laser

Currently, in many industrial sectors (aerospace, automotive industry, shipbuilding industry, etc.), surfaces protection using composite powders against the destructive action of the working environment, as chemical corrosion, abrasive and cavitation erosion, became indispensable [1,4,5,8,9,15]. The reason is the superior mechanical characteristics which the deposited layer is acquired as a result of using sophisticated coating technologies [5,7,10]. The deficiencies generated by the different temperatures of the base metal and of the deposited coating (cracks, spallation), in case of the thermal spraying deposition, which are unacceptable for parts operated in cavitation regime are removed by laser surface remelting.

The problem of the sprayed coating, and eventually followed by laser remelting, is the ribbed form which, for parts that operate in cavitation conditions (rotors for turbines and hydraulic pumps, ship propellers), reduce the energy transfer efficiency at the component. Another issue is the chemical composition of the coating and the precipitated carbides which are easily expelled during cavitation, leaving gaps, which may constitute primers cracks which, in time, are extending and can increase the surface degradation of the component. However, if the coating thickness allows a machining operation (grinding, polishing, lapping, honing, etc.) these bumps can be eliminated, thus guaranteeing the quality needed for a optimum energy transfer. For this reason, in order that the deposited and laser remelted coating to behave well to cavitation attack, it is necessary that the process parameters of the laser beam (power, repetition frequency and pulse duration, the beam velocity on the surface coating during remelting) to be chosen and rigorously correlated so that the coating to have a reduced unevenness and homogeneous hardness distribution over the entire attacked surface. Therefore, from these laser beam process parameters depend the micro-coatings which bounds the base metal and the deposited material, with the

development of a certain hardness, respectively high resistance to brittle fracture and cavitation erosion solicitation [1,4,5]. The research results presented in the paper, show differences in vibrating cavitation behavior of metal-ceramic composite coatings deposited onto the surface of Duplex stainless steel samples, X2CrNiMoN22-5-3 by the following two techniques: HVOF thermal spraying and HVOF thermal spraying followed by laser remelting beam using two different conditions.

Experimental part

The feedstock powder WC-9Co-5Cr-1Ni, from Thermico company, having a granulation of $-106 + 45 \mu\text{m}$ was deposited by high velocity oxygen fuel (HVOF) spraying method onto the surface of a Duplex stainless steel.

For cavitation three types of coatings were tested. The first was in as-sprayed state and the other two were as-sprayed and further laser remelted using different pulses duration (6 and 10 ms). The other parameters were kept constant: laser power 150 kW, pulse repetition frequency 10 Hz and laser beam speed 2.85 mm/s. Before depositions, the substrates made of a Duplex stainless steel, were prepared according to the demands necessary for the cavitation tests [6-8].

The used HVOF method is suitable for coating deposition, using composite powders, resistant to wear and corrosion [4,5]. In fact, the technique is based on a combination of combustion gases that are injected into the gun combustion chamber at high pressures and further ignited.

The WC-9Co-5Cr-1Ni powder injected into the flame, was heated and accelerated at supersonic speed toward the substrate, leading to the obtaining of dense coatings, with a porosity less than 2 %, presenting low oxidation and a fine aspect.

The main characteristics of this process and of the obtained coatings are:

- sample surface temperature was not exceeded 150°C;
- spraying distance, 220 mm;

*email: ilarica59@gmail.com.; Phone: 0723650248; lavimicu@yahoo.com, Phone: 0744566148

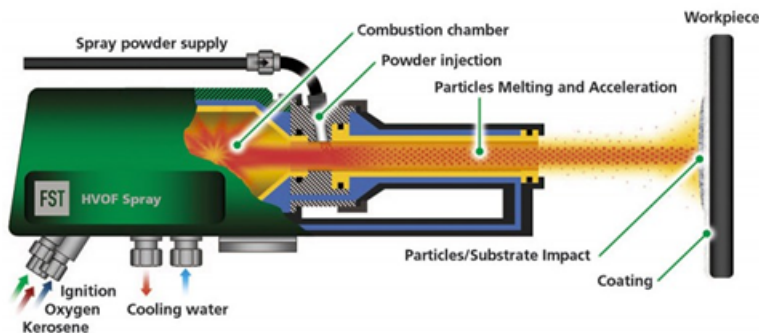


Fig.1. Principle of the HVOF spraying method [14]

- powder rate, 63 g/min;
- coating porosity less than 2%;
- measured hardness: 1100-1350 HV0.3;
- coating thickness about 300 microns.

Table 1 present the flow rate and pressures of the gasses used for the spraying process.

Coating remelting was conducted on a Nd:YAG laser, Trumpf HL 124P LCU, located at the National Research and Development Institute for Welding and Material Testing, ISIM Timisoara. Because of the impact force with the metallic surface of the cavitation samples, the powder particles are transformed from spherical in lamellar shape forming adjacent and overlapping strips, (fig. 2).



Fig.2. The aspect of the sprayed coating

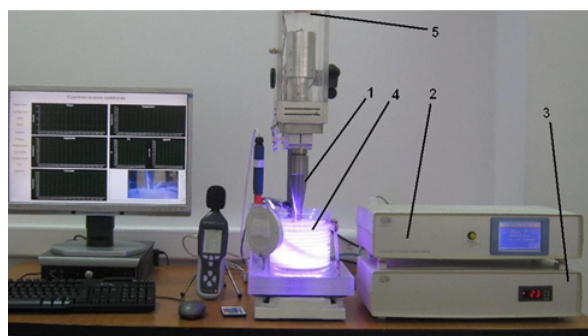


Fig.3. Vibrating apparatus with piezoceramic crystals: 1-sonotrode, 2-electronic system, 3-water temperature regulator, 4-liquid vessel and cooling coil, 5-ventilation system

Equipment and research methods

The study program of the behaviour and resistance to cavitation was conducted in the Cavitation Laboratory from the University Politehnica Timisoara, on a vibrating apparatus with standard piezoceramic crystals, (fig. 3).

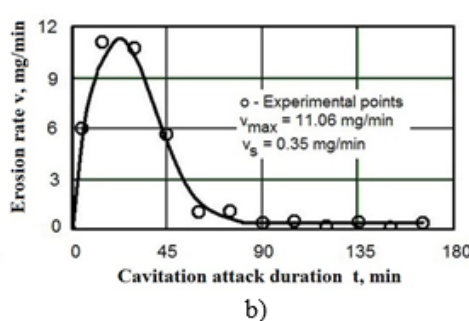
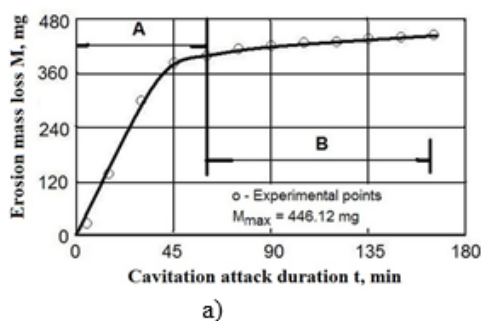


Fig.4 Evolution of the mass loss and erosion rate (as-sprayed coating), a) mass loss, b) erosion rate

Table 1
COMBUSTION GASES AND THE PHYSICAL CHARACTERISTICS OF THE HVOF SPRAYING METHOD

Gas	Q [%]	P [Bar]
Nitrogen	20	3
Propane	35	65
Oxygen	25	12
Aier	40	65

The sample preparation methodology for conducting the experiments, is specific to the laboratory, but in strict compliance with norms ASTM G32-2010 [1-3,6-13]. The laboratory procedure is linked to washing and drying the samples at the beginning and ending of each test stage (cavitation attack) and to determine the material losses from cavitation erosion by using a high precision analytical balance, with an accurate of 10^{-5} g [1-3,6-8]. Also, another feature of the laboratory, resulted from over 60 years of field experience is the total duration of 165 min, corresponding for testing a sample, which is divided into 12 intermediate periods (one of 5 and 10 min and 10 of every 15 min each) [1,2,7]. For each of the processes for obtaining the composite coatings, three samples were tested in double distilled water at a temperature of 21-22°C.

Results and discussions

Based on the mass loss recorded after each intermediate attack period, they were determined mass loss rates related to each period, and the cumulative weight loss, according to the relationships:

$$v = \Delta M_i / \Delta t_i \quad (1)$$

$$M = \sum \Delta M_i \quad (2)$$

where:

i - intermediate testing period;

Δt_i - intermediate testing time period (5, 10 or 15 min);

ΔM_i - material mass lost from the coating by cavitation erosion (mg);

v - is the erosion rate or mass loss rate, corresponding to the „i” period (mg/min);

M - cumulated material loss, realized during the attack cavitation (mg).

In the diagrams from figure 4, 5 and 6 are given mass losses and erosion rates evolutions, showing the behavior and resistance of the coatings obtained by the three technological variants. Data points from the 6 diagrams are the average values obtained on the three samples set of each process variants. In order to make an analysis of the coatings behavior evolution by the microjets and shock waves impact generated from the cavitation bubbles implosion in the diagrams from figure 4, 5 and 6, are built the mediation curves of the experimental points.

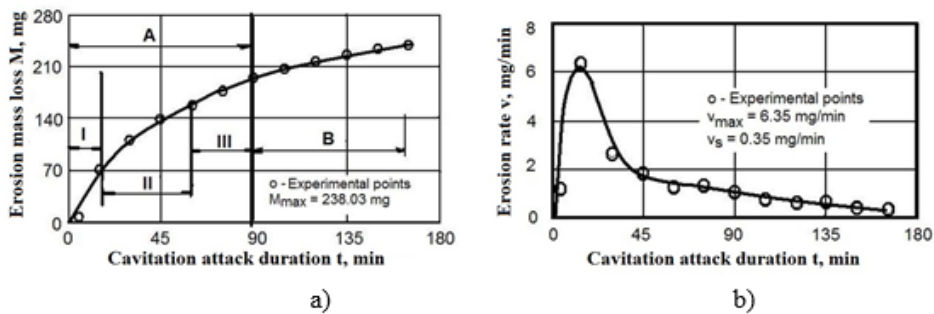


Fig.5 Evolution of the mass loss and erosion rate (as-sprayed and laser remelted with 6 ms pulse duration), a) mass loss, b) erosion rate

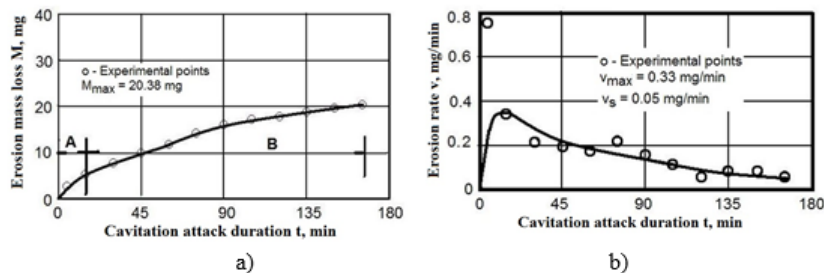


Fig.6 Evolution of the mass loss and erosion rate (as-sprayed and laser remelted coating with 10 ms pulse duration), a) mass loss, b) erosion rate

0 min	5 min	45 min	60 min	105 min	165 min
As-sprayed coating					
As-sprayed and laser remelting coating with 6 ms pulse duration					
As-sprayed and laser remelting coating with 10 ms pulse duration					

Table 2
EVOLUTION IN TIME OF THE METAL-CERAMIC COMPOSITE COATING DEGRADATION

At the end of each intermediate period of the cavitation test, cavity surfaces were photographed, macroscopic and microscopic examined. In table 2 are presented coatings degradation evolutions at the most significant periods of time.

In figures 7, 8 and 9 are given the images of the degradation attacked surfaces localized in central and peripheral areas. These images correlated with the mass loss and erosion rates from figure 4-6, provide the understanding of the behavior and superior resistance to cavitation of the as-sprayed and laser remelted coating whose pulse duration was 10 ms, compared to the remelting regime where the pulse duration was 6 ms. It is also noticed the laser remelting necessity of the HVOF sprayed coating.

Images from table 2 and figure 7 show clearly that the coating in as-sprayed state, is easily destroyed by the

microjets resulted during the cavitation by bubbles implosion. Adherence to the base metal, and the bounding between the lamellar carbide particles is easily destroyed by cavitation, the degradation starting from the moment of the attack, increasing rapidly all over the exposed surface, removing, in short time, the entire coating.

Samples with HVOF deposited coating (diagrams from fig.4)

Images from table 3 and figure 7 show that the cavitation erosion occurs intensely since the first minutes of the attack. After the first 5 min of cavitation attack the exposed coating shows deep caverns. After min. 75 the degradation is just in the base material. As you can see in the images (table 2 and fig. 7) from the very first minutes the deposited layer is removed, proving the weak bounding with the base metal.

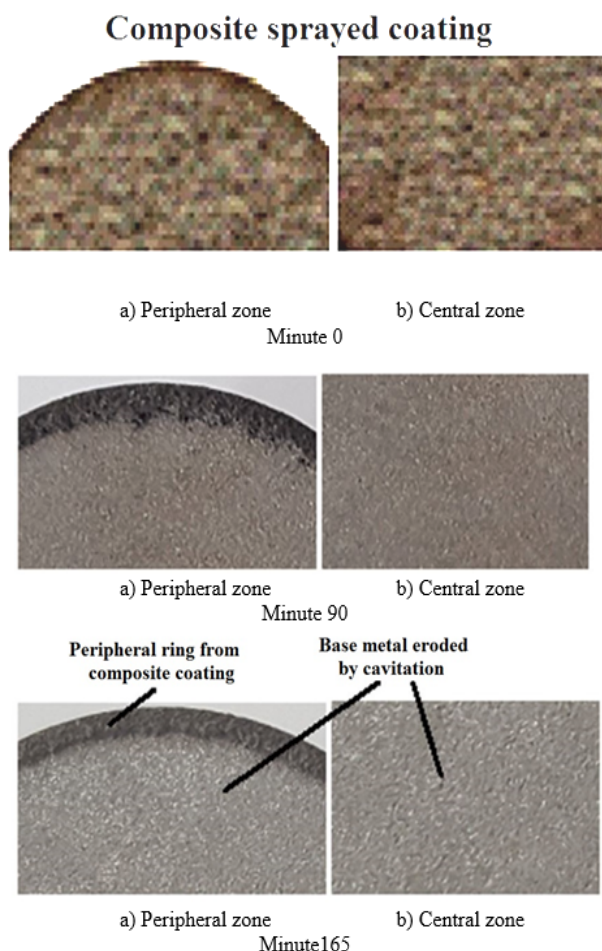


Fig.7 Images of the degradation by vibrating cavitation of the HVOF deposited WC-9Co-5Cr-1Ni composite coating

Discussions from the macroscopic surface examination:

- after the first 5 min of cavitation a strongly coating spallation can be noticed (about 10% of the surface);
- after 30 min of cavitation exposure on more than half of the attacked area the surface coating is expelled;
- after 60 min of cavitation attack the coating is completely removed from the area where the cavitation bubbles cloud is formed, the erosion evolving into the base metal as shown the mass loss evolution, respectively $M(t)$ and $v(t)$ curves after minute 60, (fig. 4). The peripheral ring, is specific to this cavitation form as a result of the bubbles cloud which adhere to the surface during the sample vibration [1].

Therefore, the surface protection with metal-ceramic composite coating, deposited by HVOF spraying technique without to be followed by another method that provides a strong bond between coating and substrate is not a viable solution for increasing the erosion cavitation resistance. The reason is the strong pressure that is developed by the impact with the microjets resulted from implosion, when practically the whole kinetic energy (the microjets having speeds of hundreds of m/s) is converted to potential pressure contact energy which causes the material expulsion from the contact area.

Samples with HVOF deposited coating followed by laser remelting with 6 ms pulse duration (diagrams from fig. 5)

The coating shape obtained by laser remelting with 6 ms pulse duration, consists of strips with sharp carbides edges, pronounced (fig. 8) and lots of gaps between them. For this reason, according to the mass loss and erosion

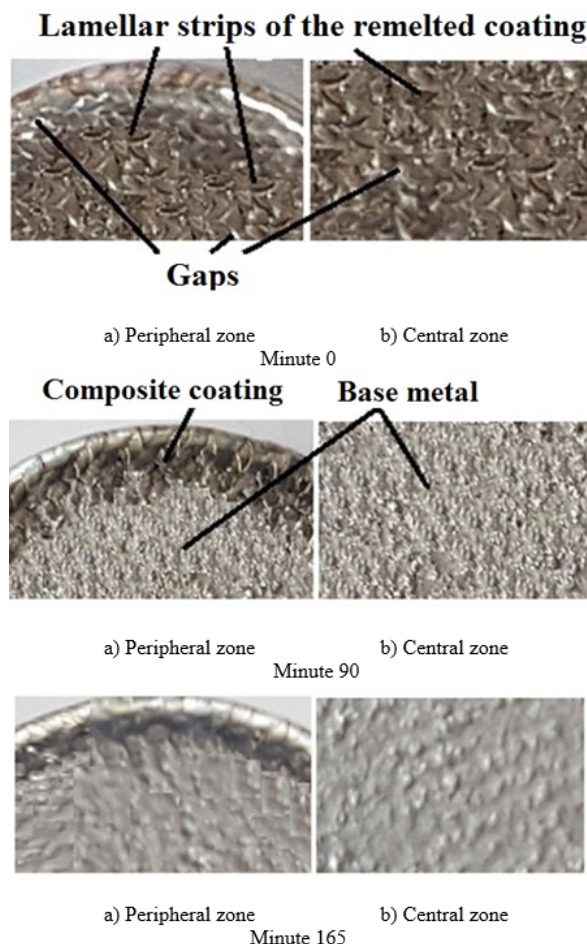


Fig.8 Images of the degradation by vibrating cavitation of the HVOF deposited WC-9Co-5Cr-1Ni composite coating followed by laser remelting with 6 ms pulse duration

rate from figure 5 and also images from table 2, it is found that: until minute 15 (zone I) the destruction took place only in the coating; between 15-60 min (zone II) the degradation continues in the composite coating and the base metal, being stronger in the composite coating; in the range 75-90 min (zone III) the destruction is stronger in the base metal, the deposited coating being present only on the periphery of the attacked surface, in shape of a ring, of small sizes, being basically completely eliminated. In zone B (after 90 min) the erosion is developed only in the base metal.

The images from figure 8 show that due to the short duration of the laser pulse, the melted powder strips have pronounced forms, with noticeable gaps between them, giving the impression that the deposited coating is more blown than melted. It also observed the existence of some very sharp carbides peaks, which under the impact with the high speed microjets are broken since the first minutes of the attack.

Discussions from the macroscopic surface examination:

- After the 5 min of cavitation attack the entire surface is marked by strong pitting on about 30% of the surface, without to be noticed the base metal; these may be associated with breaking of the carbide peaks;
- After 30 minutes of cavitation about 90% of the coating surface is marked by pitting;
- After 60 min of cavitation attack one observes the base material which, according to its wavy form, confirms that it was formed no interface which can provide the bounding between the coating and substrate. An important part of the coating (about 50%) is already expelled;

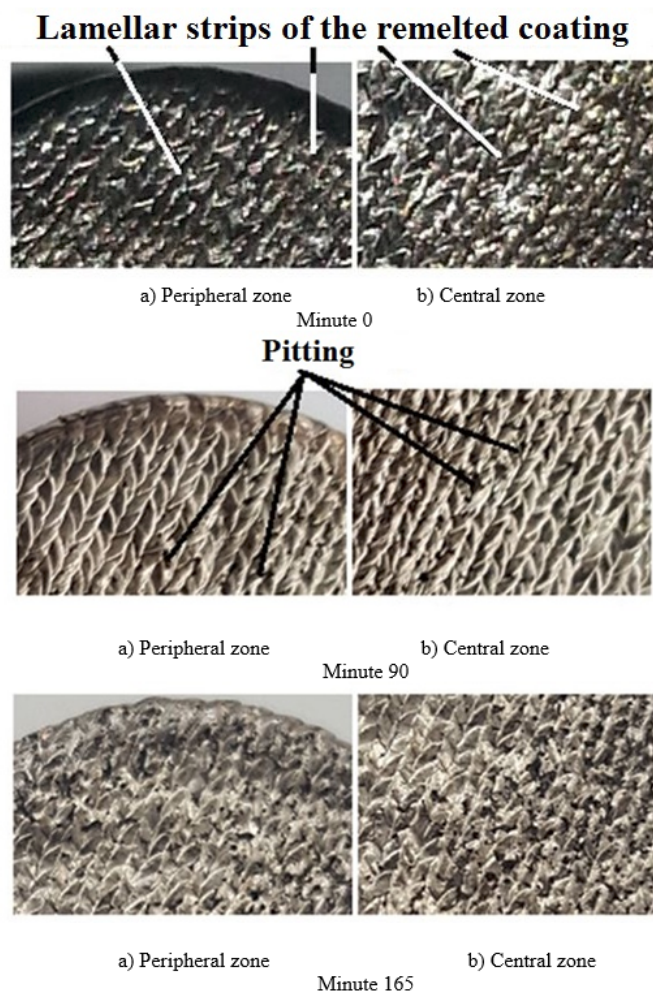


Fig.9 Images of the degradation by vibrating cavitation of the HVOF deposited WC-9Co-5Cr-1Ni composite coating followed by laser remelting with 10 ms pulse duration

- After 120 min of cavitation, practically the whole exposed coating to the bubbles cloud, specific to the vibrating cavitation [1] is removed, the erosion developing in the base material, which explains the linear evolution of $M(t)$ curve, (fig. 5a), after this period and the linear decreasing of the erosion rate $v(t)$ curve, (fig. 5b), toward the stabilization value.

Therefore, this melting regime with 6 ms pulse duration does not contribute to significant improvement of the coating cavitation resistance.

Samples with HVOF deposited coating followed by laser remelting with 10 ms pulse duration (diagrams from fig. 6)

The coating shape obtained by laser remelting with 10 ms pulse duration, is one made up of fine strips, with small gaps and small carbides peaks, (fig. 9a).

Due to the more extensive beam pulse (10 ms) the corrugations and strips form are thinner than in the previous case. Consequently, the behavior and resistance to cavitation of the laser surface remelted coating using these regime parameters is very good.

Analysis of the coating behavior, based on the experimental diagrams from figure 6 and of the photographic images from table 3 and figure 9 shows that: the roughness peaks are dispelled in the first minutes of the attack; the mass loss from zone A (fig. 6a) is determined by the removing of the abrasive dust caught between strips created by the laser flow during melting and the resulted melt burr, easily removed by the microjet

impact force with the coated surface; in zone A (after 15 min of cavitation exposure, as can be seen in the images taken at various attack times, the erosive attack is developed only in deposited coating which opposed an increased resistance, being difficult to be destroyed.

Discussions from the macroscopic surface examination:

- after 15 min of cavitation exposure, the carbides peaks are expelled, the surface begins to become smooth and the pitting generated by the microjets and shock waves are very low, mainly because of the precipitated carbides expulsion after the solidification of the laser molten bath;
- after 30 min, and by the end of the cavitation attack some poor expulsions can be noticed;

Evolution of the $M(t)$ and $v(t)$ curves and also the coating photographic aspect at various attack times (table 2 and fig. 9) show that by using this remelting parameters, it is formed an interface that makes a strong bounding between the base metal and the coating and contributes to increasing of cavitation erosion resistance.

Conclusions

The surfaces coated with the powdered WC-9Co-5Cr-1Ni composite by HVOF thermal spraying method have a relatively low resistance to the pressure forces created by the microjets and shock waves impact developed during the cavitation process, due to poor bounding between the base metal and the sprayed coating.

Increasing the cavitation resistance of WC-9Co-5Cr-1Ni coatings, deposited by HVOF method, can be achieved by applying a laser remelting which, by the correctly chosen process parameters, lead to the creation of coating-substrate interfaces that provides a metallurgical bond between these two components of the system.

The rigorous selection of the mainly laser beam parameters leads to the obtaining, after the remelting, of a surface made of fine strips, without defects (cracks, voids, protruding peaks, burnt material) with a high hardness, which enhances a high erosion cavitation resistance.

The technological variant based on the laser remelting with a 10 ms pulse duration, provides the highest resistance to ultrasonic cavitation generated by the vibrating device used in the Cavitation Laboratory from University Politehnica Timisoara.

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Manuscript received: 14.02.2016