Some aspects over the quality of thin films deposited on special steels used in hydraulic blades

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Abstract. The experimental research involved in this paper consists in the obtaining of superior physical, chemical and mechanical properties of stainless steels used in the construction of hydraulic turbine blades. These properties are obtained by deposition of hard thin films in order to improve the wear resistance, increasing the hardness but maintaining the tenacious core of the material. The chosen methods for deposition are electrospark deposition because it has relatively low costs, are easy to obtain, the layers have a good adherence to support and the thickness can be variable in function of the established conditions and the pulsed laser deposition because high quality films can be obtained at nanometric precision. The samples will be prepared for the analysis of the structure using optical method as well as for the obtaining of the optimal roughness for the deposition. The physical, chemical and mechanical properties will be determined after deposition using SEM and EDX, in order to emphasize the structure film-substrate and repartition of the deposition elements on the surface and in transversal section. The non-destructive testing has emphasized the good adherence between deposited layer and the metallic support, due to double deposition, spallation regions doesn’t appear.

1. Introduction

The destruction of materials due to abrasive erosion is the principal problem in the production of hydro-mechanical devices, due to the changes in the geometry of components in contact with abrasive fluids, having effects over the performances and lifetime of respective parts. Recent studies [1-3] have been focused on analyzing the materials from resistance at abrasive erosion as well as phenomena produced during these attack points of view, in order to find technological solutions for increasing the lifetime of the structures that functions in hydroabrasive environment.

Stainless steels are highly alloyed materials, with minimum 12% Cr content. These alloys have high affinity to oxygen, forming chrome oxide at the surface of material, giving it the stainless steel’s character and resistance to corrosion. The martensite steels have large mechanical resistance and stability at tempering. At temperatures of 950-1000°C, the structure is austenite and due to high hardening at air cooling, the structure becomes martensite. After martensite hardening, the steels are tempered to obtain better resistance to corrosion and an optimal assembly of mechanical and plastic characteristics.

The martensitic stainless steels have good resistance to corrosion but they have low resistance to abrasive wear and hydro-abrasive wear. In this paper we seek to remedy these disadvantages by
deposition of hard thin films in order to improve the wear resistance by increasing the hardness. High hardness is required by the mixer blades to homogenize the mixture that contains abrasive particles and by the hydraulic turbine blades that should support dynamic and mechanic shocks due to the particles in suspensions that leads to hydro-abrasive wear appearance.

To deposit amorphous alloy on a surface or to produce an amorphous surface layer, various technologies have been used; e.g., laser cladding, vacuum plasma spray, high velocity oxygen fuel spray (HVOF), electron beam surface treatment with gas atomized powders and magnetron sputtering [4-8]. One of the most popular methods for production of an amorphous coating is electro-spark deposition (ESD). ESD is less time consuming and more cost-effective than the above-mentioned methods for the preparation of amorphous coatings [9-11].

Electro-spark deposition process is a simple and cost-effective low-energy technique [12-14]. This method produces metallurgical bonding between the coatings and substrates, resulting in a much better coating adhesion compared to other low-energy coating processes such as detonation-gun, plasma-spray and electrochemical plating. The short duration of the electrical pulse leads to an extremely rapid melting and solidification of the electrode materials to form micro- or nano-structured coatings.

This paper study the improvement of the surface quality of X10Cr13, DIN 1.4006, by deposition of single layer and two layers of WZr3 in order to improve the safety in exploitation of blades from hydraulic turbine and mixers by increasing the resistance to hydro-abrasive wear. The WZr3 thin films were deposited by electrospark deposition (ESD) [15] because by this method, thick layers and better adherence to substrate can be obtained [16].

2. Materials and Methods

X10Cr13 martensite stainless steel has been chosen as substrate due its high hardness and resistance to hydroabrasion, promoting them in the use as blades for hydraulic turbines.

2.1. Base material.

Chromium stainless steel grade X10Cr13 after oil quenching has a martensitic-ferritic microstructure with the hardness 420 HV. Tempering of this steel (up to 450°C) changes the hardness and abrasion resistance in a narrow range. X10Cr13, DIN 1.4006 has been used as base materials. This martensitic steel deforms very easy at cold but subsequent treatments are not appropriate. The chemical composition has been determined using Foundry Master Spectrometer from the Department of Technologies and Equipment for Materials Processing in the frame of Faculty of Materials Science and Engineering, Gh. Asachi Technical University Iasi. The concentration for each chemical element is given in percent, in table 1.

To improve the strength and hardenability of the martensitic grades they have higher carbon content compared to other grades, and nitrogen is sometimes added to further improve to strength. These grades contain no or rather small amounts of nickel and molybdenum is seldom added. By adding some nickel and reducing the carbon content the rather poor weldability of martensitic grades can be improved. Sometimes sulphur is added to improve the machinability. Martensitic stainless steels are characterized by high strength in the quenched and tempered condition and are strongly affected by the heat treatment cycle. The steels are therefore usually used in a quenched and tempered condition.

| Table 1. Chemical composition of the base material |
|--------------------------------------------------|
| Element | Fe | C | Si | Mn | P | S | Cr | Mo | Ni |
| %       |    |   |    |    |   |   |    |    |    |
| balance | balance | 0.094 | 1.09 | 0.88 | 0.036 | 0.030 | 13.8 | 0.03 | 0.09 |

The samples from the X10Cr13 were cut on a cutting the following sizes: 25 mm long, 45 mm wide and 2.5 mm height. After cutting these were prepared by successive grinding on metallographic paper to the 1200 grain size.
The polishing is made to obtain better WZr3 deposition. By grinding, the peaks of the surface decreases. If the deposition with electrospark is made on no polished surface, local burning can take place, leading to the apparition of deposition flaws.

2.2. Deposition Material
The thin films deposition has been effectuated in single and two layers by ECD method. WZr3 electrode has been chosen because it has good compatibility with the base material, having closed expansion coefficient, leading to the increasing of the material adherence to substrate.

WZr3 electrodes boasts a fine performance in welding under the condition of AC and has a good anti-corrosiveness. Especially in the case of high load of current, the WZr3 excellent performance is far better than that of other electrodes. When welded, the end of WZr3 electrode remains pellet-shaped, reducing the chance of tungsten oozing. It is suitable for welding magnesium, aluminum and their alloy under alternating current.

2.3. Deposition Method
The Electro-Spark Deposition is a micro-bonding process, in which short duration pulses of current are used to bond the electrode material to a metallic substrate. ESD possesses some unique advantages. The coating material is metallurgical bonded to the substrate. The low net heat input allows the substrate to remain at ambient temperature during the process, and the rapid solidification of the deposits produces a nano-structured or amorphous structured coating. As a result, the most common application of the ESD process is to apply wear resistance coating. However, there are some limitations to the ESD process, such as the low coating efficiency, and the stress relief cracking inherent in some materials [14]. This method are advantages following: metallurgical bonded coating, low heat input, eliminates distortion or metallurgical changes in substrate, nano-structured or amorphous layers possible through rapid solidification, little or no substrate preparation or post-coating surface finishing required, reproducible process, easily automated, operators easily trained, portable equipment and process, applicable to complex shapes, can apply nearly all metals and cermets.

Electro spark Deposition (ESD) is a micro-bonding process that is capable of depositing wear and corrosion resistance coating to repair, to improve and to extend the service life of the components and tools. During the coating process, short duration of electrical pulses ranging from a few microseconds to milliseconds are used to deposit the electrode material to the component’s surface producing a protective layer [4]. The spark is produced through the moving electrode as it is momentarily short-circuited and hence pulse discharged with the base material. ESD is a pulsed-arc micro-welding process that uses short-duration, high-current electrical pulses typically three orders of magnitude shorter than in other pulse welding processes to weld a consumable electrode material to a metallic substrate [17]. Generally, it is used to apply coating for corrosion and wear-resistance [18-20], it also finds more applications in restoration and refurbishment of worm or damaged high valued parts [21], especially those materials ordinarily considered unweldable by other processes.

The ESD process produces an electric arc through the rotating electrode as it is short-circuited momentarily with the substrate. During the generation of arc, small particles of the electrode material are melted, accelerated through the arc, impacted against the substrate, solidified rapidly and build-up incrementally. The device for ESD is presented in figure 1.

Figure 1. The principle scheme of electro spark method.
The material transfer from the electrode to the piece is produced due to polar effect that assures well determined properties to the superficial formed layer, both from physical as well as chemical point of view (this having however different structure and chemical composition).

The material quantity transferred from electrode to piece, during one discharge is very small \((2\div3)\times10^{-6}\, \text{g}\). The processes that take place in the superficial layer deposited by electric spark alloying are: annealing at high speed, carburizing, nitriding, alloying and deposition. Figure 2 presents the samples taken into study.

![Figure 2. Studied sample: a) top view; b) side view](image)

The droplets have average diameter of 20μm. The outward splash around the droplet edge can be regarded as evidence of the speed by which the molten droplets detached from the WZr3 electrode have impacted the X10Cr13 substrate. The molten droplet gains speed as it travels through the magnetic field produced by the spark discharge. The impact force forms a hole at the center of splat and pushes the molten metal to the edge of the hole, so a valley occurs as a result of this phenomenon. The splats do not have a uniform thickness. Because of the variation in thickness of the splats, the cooling rate would vary to some extent at different points. The volume of molten metal in each splat is very small compared to the mass of the cool substrate and that leads to extreme cooling rates. The molten splat freezes instantly without having time for the molten metal waveform produced as the result of impact to damp out and dissipate to form a smooth surface, resulting in an irregular shape.

3. **Morphology of thin films deposited with WZr3 electrode on stainless steel support**

3.1. **Surface Analysis for Single Layer Deposition**

Due to melting in electric arc both of the support and WZr electrode, the deposition with vibrant electrode forms hard layers with superposed droplets on the surface of stainless steel specimen. The electrode used here is W with 0.3%Zr, made by sintering of powders of W with Zr adding.

![Figure 3. Deposition with WZr3 electrode on stainless steel by ESD in a single run: a) SEM image 100μm scale; b) deposition profile.](image)

Tungsten hardens the surface by tempering with remelting and forming outside an amorphous layer with glass structure, due to its high melting temperature. This leads to the formation of hard...
intermetallic compounds like complex carbide formed with iron and with alloying elements as Cr and Mn together with the material from the melting of W electrode.

![Image](a) ![Image](b)

**Figure 4.** Deposition with WZr3 electrode on stainless steel by ESD in a single run: a) SEM image 20µm scale; b) deposition profile

Between the electrode and basis material, a sparkle with temperature between $5 \times 10^3$ - $10^4$ °C is formed, leading to sublimation of W, not to melting, so that over the micro-bath of melt from basis material, W vapors are formed and absorbed by the melt metal.

![Image](a) ![Image](b)

**Figure 5.** 3D image of the surface deposited by ESD in single run with WZ3 electrode on stainless steel surface: a) 100 µm scale; b) 20 µm scale.

The droplets on the material surface are formed cyclical and relatively uniform, following the spiral trajectory of the electrode. At the deposition in single layer, the surface is gently undulating with areas of maximum roughness at the edges of droplets. The droplets formed in the regions with vaporized metal have approximately round shape and concave meniscus in the middle.

### 3.2. Surface Analysis for Two Layers Deposition

In the case of two runs of WZr3, a uniformity of surface take place by melting the peaks formed at the single run deposition, obtaining reduced roughness. The surface analysis presented in figure 6 shows a good compaction of deposited layer.

![Image](a) ![Image](b)

**Figure 6.** Deposition with WZr3 electrode on stainless steel by ESD in two runs: a) SEM image 100µm scale; b) deposition profile
Due to superficial tension of the liquid metal from the droplet, regions with relief and regions relatively smooth appear on the deposited surface. The thermal conductivity of W electrode is 174 W/(m·K) is higher than the one of stainless steel, leading to a very quick cooling of the new formed layer.

![Figure 7](image1.png)

**Figure 7.** Deposition with WZr3 electrode on stainless steel by ESD in two runs: a) SEM image 20µm scale; b) deposition profile

At the deposition of two layers, the peaks become smoother, the microcracks are covered by new melted droplets and the regions without deposition are reduced.

![Figure 8](image2.png)

**Figure 8.** 3 D images of the surface deposited by ESD in two runs with WZ3 electrode on stainless steel surface: a) 100 µm scale; b) 20 µm scale.

Analyzing 3D images and profiles, it can be observed that at single run deposition, the layer has a structure with irregularities, droplets, regions without depositions, micro cracks, overlapping of materials, leading to a roughness surface. The second layer deposition leads to smoother surfaces due to dissolving in metallic bath of irregularities as droplets and partial melted material pull out.

Using electromagnetic nondestructive testing with the electromagnetic sensor with metamaterials, in order to establish the adherence of the thin films to the steel, it has been proved that the double deposition has led to a good adherence between the thin film and the metallic support. The data will be further compared with other methods of nondestructive testing using focused sensors.

### 4. Conclusions

Deposition of W by ESD on stainless steels creates hard thin films, relatively compact, with roughness larger than the one of the raw sample, due to the specific of the deposition (loads) that forms droplets, oxides, embedded gases, microcracks, etc.

In order to obtain smoother and uniformed surface, second layer of WZr3 is deposited, having as effect the remelting of the first layer and decreasing of roughness. W has as first effect the hardening of the surface, in principal due to tempering with remelting and forming of amorphous and glasses surfaces. The deposition of W is made by more by absorption of sublimed W vapor in the sparkle region and less to the melting of electrode. SEM micrographs show that deposition on...
two layers generate a compact surface, the deposition being more uniform that the one in single layer. Profiles analysis show that the roughness at two layer deposition is lower. Roughness and hardness influences the wear resistance, the maximum wear resistance being obtained at high hardness and low roughness. The high wear resistance is obtained by a well-controlled hardness.

References

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