Aspects regarding the influence of the processing regime on the surface quality of thermal sprayed coatings

C Stescu\(^1\), D L Chicet*\(^2\), C Munteanu\(^1\), B Istrate\(^1\), M Benchea\(^1\) and G-N Basescu\(^1\)

\(^1\)Mechanical Engineering, Mechatronics and Robotics Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania
\(^2\)Materials Science and Engineering, Materials Science Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania

E-mail: dchicet@tuiasi.ro

Abstract. Thermal spray coatings are increasingly gaining ground in their use for various applications: protecting the surfaces from stresses, temperatures, corrosive or abrasive environments at various temperatures, repairing surfaces and providing new features, etc. One of the important operations in defining the role that a thermal spray layer will have is finishing the surface after coating by mechanical machining. In this paper the surfaces of five thermal coated samples mechanically finished by two different methods were studied. Surface morphology was observed by electronic microscopy, the appearance being correlated with the micro-hardness and roughness of these surfaces before and after processing. It was observed that the choice of the method of processing depends on the hardness of the surface and its chemical composition.

1. Introduction

Once with the development of thermal spraying methods and the range of materials that can be used, a number of industrial applications of them have been developed. Thus, in addition to improving wear resistance, corrosion properties in various environments and at different temperatures, these coatings must meet dimensional requirements with certain tolerances, but also surface quality requirements, the main aspect of which being their roughness [1]. For these reasons it becomes necessary to develop studies that highlight the influence of the post-processing methods of the thermal spraying coatings.

According to the literature [2, 3], it is recommended to finish the coatings produced by thermal spraying by several types of operations, depending on the type of coating, as follows:

a. machining (turning and milling);

b. grinding;

c. abrasive belt grinding and polishing;

d. super-finishing;

e. other finishing methods: hand stoning, buffing and polishing, tumbling and burnishing.

In current practice however, finishing of the coatings can raise great problems because, due to the lack of experience and experimental data, the parameters and techniques used for the compact materials are used in processing. This is fundamentally incorrect [4] because the structure of the coatings is not compact but layered, the bonds between the deposited particles (splits), respectively, between the layer and the substrate are mostly of a mechanical nature, they have variable porosity and the mechanical processing occurs mainly by removing the splits. For example, many deficiencies in
practice [5] are reported due to the use of inappropriate techniques or parameters: peeling of the layer due to the wrong feed (thermal coatings tend to produce crumble chips), obtaining porous surfaces due to inappropriate feed removal of the particles deposited), the discoloration of the surfaces due to the wrong choice of the abrasive stone which loads very quickly with particles, etc.

Thus emerged the opportunity of this study, in which we analysed the way the surfaces of five types of coatings deposited by thermal spraying are affected by their mechanical processing by several processes.

2. Experimental setup

In the present paper, 5 types of samples were made using the thermal spraying method from different types of powders, using two different techniques: atmospheric plasma spraying (APS) and flame spraying (FS).

The samples were realized as follows:

A. by APS were sprayed the following commercial powders (manufactured by Sulzer Metco), with the SPRAYWIZARD 9MCE plasma spray deposition facility:

- one powder from the tungsten carbide system with the nominal composition WC<sub>10</sub>Co<sub>6</sub>Cr. These materials are especially used for applications where both wear resistance (abrasion, erosion, fretting) and corrosion are required, with a working temperature of up to 500 °C. The particle size ranges from 45 to 11 μm and were obtained by agglomeration and sintering. Samples obtained with this type of powder will be referred to as APS1;

- one powder of the Ni- based alloys: mixture of nickel - aluminium - molybdenum category, with Ni<sub>6</sub>A1<sub>3</sub>Mo nominal composition. The coatings thus obtained are of high density, are resistant to oxidation and corrosion at high temperature. The addition of Mo provides good wear and erosion resistance and a low contraction coefficient [6]. Samples obtained with this type of powder will be referred to as APS2;

- one powder of the ceramics class - aluminium oxide mixed with titanium oxide, with the nominal composition Al<sub>2</sub>O<sub>3</sub> - 13 TiO<sub>2</sub>. These materials are used for coatings subjected to abrasion and slipping wear, they have oxidation resistance at working temperatures of about 550 °C and have good behaviour in alkaline or acidic environments. Samples obtained with this type of powder will be referred to as APS3.

As deposition substrate were used bearing rings from Cr alloyed steel, 100Cr6 grade, with the following chemical composition according to ISO 683-17: 0.93-1.05% C, 0.15-0.35% Si, 0.25-0.45% Mn, 1.35- 1.6% Cr, max. 0.10Mo, max. 0.025% P, max. S 0.015%. In order to increase the adhesion of the deposited layer to the substrate, in the case of APS1 and APS3 samples a thin intermediate layer, called bonding layer, was also deposited using the Ni-Al-Mo powder. Table 1 summarizes the working parameters of the plasma deposition system used to obtain these layers [7].

| Table 1. Atmospheric plasma spraying deposition parameters |
|-----------------------------------|---------------|----------------|----------------|
| Powder                            | Ni<sub>6</sub>A1<sub>3</sub>Mo | WC<sub>10</sub>Co<sub>6</sub>Cr | Al<sub>2</sub>O<sub>3</sub> – 13 TiO<sub>2</sub> |
| Ar flow (l/min)                   | 46            | 46             | 46             |
| H<sub>2</sub> flow (l/min)         | 13.5          | 13.5           | 13.5           |
| Ar flow (carrier gas) (l/min)     | 45            | 45             | 45             |
| Tension (V)                       | 60            | 60             | 60             |
| Intensity (A)                     | 600           | 600            | 600            |
| Spraying distance (mm)            | 120           | 120            | 120            |

B. by FS were sprayed the following commercial powders:

- one nickel-based powder with chromium / boron carbides and addition of molybdenum and copper (manufactured by Hoganas), 1355-20 type according to the manufacturer's code, with the following chemical composition: 15.8% Cr, 4.07 % Si, 3.49% B, 2.72% Fe, 2.95% Cu, 2.96% Mo, 0.54% C, Ni balance. Samples obtained with this type of powder will be referred to as FS1.
- one nickel-based powder with chromium and boron carbides (manufactured by Deloro Stelite), JK 586 type according to the manufacturer's code, with the following chemical composition: 15%Cr, 4.3%Si, 3.1%B, 4%Fe, 0.7% C, Ni balance. Samples obtained with this type of powder will be referred to as FS2.

The alloys used for these coatings, such as NiCrBSi, are the result of adding other elements to traditional Ni-based alloys to improve some of their properties. Chromium is the element that sustains oxidation and corrosion resistance at high temperatures and increases the hardness of the coating by forming very tough precipitates. Boron is the element that lowers the melting temperature and helps to form hard phases, especially with Ni, with Ni₃B formation [6], which determines the increase of coating hardness. Silicon is added to improve the self-fluxing properties of the sprayed alloy. Carbon is the element that determines the formation of very high hardness carbides that improve the wear resistance of the coatings [8].

As substrate was used a carbon steel having the following chemical composition: 0.34% C, 0.22% Si, 0.56% Mn, 0.01% P, 0.02% s, 0.07% Cr , 0.035% Mo, 0.11% Cu, 0.081% Ni, Fe balance. Subsequent to deposition, the coatings were subjected to a heat treatment of remelting, necessary to significantly reduce the porosity of the layers and to achieve metallurgical bonds between the coating and the substrate. The working parameters used for spraying the layers are summarized in Table 2.

| Cleaning the substrate with acetone | yes |
|-----------------------------------|-----|
| Aggressive sanding with electrocorundum F20 to activate the substrate surface | yes |
| Oxygen working pressure | 3 - 4 bar |
| Acetylene working pressure | 0.7 - 1.5 bar |
| Temperature reached during the coating process | 1000°C |
| Distance between the flame tip and the substrate | 20 cm |
| Preheating temperature of the substrate | 50 - 80°C |
| Temperature reached for the remelting postcoating thermal treatment | 800°C |

In order to observe how the processing operations influence the surface quality of the coatings deposited by thermal spraying, the samples were finished by two different methods, as follows:

- the APS samples were sanded with abrasive paper of various grain sizes, respectively polished with abrasive emulsion, using the Metcon sanding machine type FORCIPOL 1V,
- the FS samples were machined in two stages: by turning with cylindrical-front cutter with carbide inserts on a vertical milling machine (with 0.05mm feed) and by subsequent grinding with abrasive wheel.

The samples were analysed with secondary electron images obtained using scanning electron microscopy on the Quanta 200 3D Microscope, working both with the High Vacuum module with the Everhart-Thornley Detector (ETD) and with the Low Vacuum module (for non-conductive samples) at working pressures between 30-60 Pa, using the Large Field Detector (LFD) detector. The acceleration tensions of the electron beam used were 20 or 30 kV, and the working distance ranged from 12 to 19 mm [9, 10].

To observe the effect of finishing operations on surface quality, surface roughness measurements were made using the Form Talysurf Intra system (Taylor Hobson LEICESTER, ENGLAND). The characterization of the coatings was completed with microhardness measurement, made using the 2M-CTR UMTR micro-nano tribometer, with a Rockwell diamond-tipped test setup with a 5 mm radius and a load force of 20N.

3. Results and discussions

The studied coatings obtained by the two methods have different thicknesses due to the differences between the deposition methods. Figures 1a, b, c show the secondary electron images of the APS1,2,3 sample cross-sections, and measurements of the thickness of the deposited layers are made. It can be
seen that the thickness of the coatings ranges from 50 to 90 microns, and it is also justified to choose the surface treatment by sanding and polishing with abrasive paper.

![Image](https://example.com/image1)

**Figure 1.** Secondary electron images of the samples cross-sections: a) APS1, b) APS2, c)APS3.

In Figure 2 are presented the secondary electron images of the cross sections of the samples FS1 and FS2, and also thicknesses of the coated layers. It is noticeable that they have much higher thicknesses than the APS coatings, ranging from 500-900 microns, and in this case it is also justified to choose the method of machining by two methods: turning and grinding.

![Image](https://example.com/image2)

**Figure 2.** Secondary electron images of the samples cross-sections: a) FS1, b) FS2.

For the complete evaluation of the effect of the finishing process on the quality of the surfaces of the studied samples it was considered incomplete the evaluation of the appearance of the samples surface so that measurements of roughness were made both before and after the mechanical processing. In Figures 3a, b, c and 4a, b the graphs resulting from the roughness measurements on each of the five samples are presented.
Figure 3. Roughness measurement graphs for: a) sample APS1 (Ra = 3.97 µm),
b) sample APS2 (Ra = 9.18 µm), c) sample APS3 (Ra = 4.14 µm)

Figure 4. Roughness measurement graphs for:
a) sample FS1 (Ra = 1.77 µm), b) sample FS2 (Ra = 1.219 µm)

It can be observed that the FS samples exhibit a smaller roughness than those deposited by APS, mainly due to the remelting treatment to which the samples were subjected post-deposition, treatment which is specific and necessary for the NiCrBSi-grade self-fluxing alloys.
Comparatively, roughness measurements were made on the surfaces resulted after the mechanical finishing and the resulting graphs are shown in Figures 5a, b, c and 6a, b. It is observed that uniform surfaces with satisfactory roughness have been obtained: Ra = 0.0508 μm for the APS1 sample, Ra = 0.116 μm for the APS2 sample, Ra = 0.709 μm for the APS3 sample, Ra = 0.5098 μm in case of sample FS1, Ra = 0.4197 μm for sample FS2.

It was considered necessary for the interpretation of the results to measure the average microhardness of the surfaces of samples by microindentation, obtaining the following results: APS1 – 6.3 GPa, APS2 – 2.99 GPa, APS3 – 4.5 GPa, FS1 – 5.32 GPa, FS2 - 5.38 GPa.

It is thus observed that the APS2 sample is the least durable, fact reflected also in the degree of roughness obtained after finishing, which has the highest value from all the samples. It is also observed that the FS1 and FS2 samples are characterized by close values of microhardness and have similar values of roughness obtained after mechanical processing.

Additionally, there were made acquisitions of secondary electron images of these surfaces at 1000x and 2500x magnification for APS samples, respectively 200x and 5000x for samples obtained by FS, presented in Figures 7-11.
Figure 7. Secondary electron images of APS1 sample surface after finishing: a)1000x, b)2400x

Figure 8. Secondary electron images of APS2 sample surface after finishing: a)1000x, b)2500x

Figure 9. Secondary electron images of APS3 sample surface after finishing: a)1000x, b)2400x
In the images acquired on the surfaces of the finished samples we can observe how the particles were removed during the mechanical processing. Thus, on the sample with the smallest microhardness - APS2 - it is observed that there remained protruding scratches that could not be removed by subsequent polishing steps and the removal of the excess material was accomplished by pulling off the particles by the abrasive elements of the paper.

In the case of the APS1 sample - with the highest microhardness, a very good behaviour is observed for the chosen finishing method, a very good finishing degree, but also the presence of very small superficial pores.

In the case of medium microhardness sample - APS3, it was observed that the Al₂O₃ metal matrix responded well to the abrasion process, obtaining smooth surfaces, but the TiO₂ particles were pulled off causing a "pinch" appearance, which does not have correspondent in the depth of the layer.

The two samples deposited with FS had the best behaviour at mechanical processing, being noteworthy that they are characterized by homogeneous surfaces, without porosities or material shedding, the layers being removed uniformly.
4. Conclusions

The mechanical finishing of the coatings deposited by thermal spraying can be used to obtain the dimensional tolerances, respectively the roughness required for their industrial applications.

The choice of processing techniques should be considered according to the characteristics of the coatings:
- high hardness layers can only be machined by abrasion, while medium hardness layers can be machined by cutting or abrasive cutting;
- the chemical composition of the coatings: the layers of ceramic material cannot be machined because they are very fragile and can easily destroy or even exfoliate the substrate;
- matrix type: coatings that have soft matrices can be machined both by cutting and abrasion, but the softer the matrix is, the faster the abrasive paper / wheel became loaded, thus is recommended to remove it initially by cutting.

5. References

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