Machining of thermal sprayed coatings – a case study for self-fluxing powder

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Abstract. In this paper we studied the possibility of mechanical processing of a coating produced by atmospheric plasma spray method from nickel-based self-fluxing powder. Two samples were realized from the same alloy type - NiCrBSiFe alloyed with WC, one of which was mechanically processed in the raw state and the other after applying the self-fluxing treatment. Subsequently, their behaviour was observed during the mechanical processing. Both the morphology of the coatings after processing and their mechanical properties (using scratch method) were evaluated.

1. Introduction
The thermal spraying method is a general method by which superficial treatment can be achieved by applying various types of coatings [1 - 5], by combining the various existing techniques: flame spraying, HVOF, electric arc, APS, cold spraying etc. [6, 7] This method is used on industrial scale, both for the protection of parts subjected to wear or corrosion [8], and for the repair of worn or damaged machine parts [9].

In principle, the thermal spraying method requires a feed-stock material (powder, wire or bar) that will be melted by introducing it into a heating zone (flame, plasma, electric arc etc) and accelerated to the surface of the substrate [10 - 12]. At the impact, a rapid cooling of the particles and a deposit build-up of the splats will occur, resulting in a layer with lamellar structure [13]. The quality of the coating is given by the resulted microstructure (porosity, the amount of resulting oxides after deposition, the percentage of semi-melted / unmelted particles), the latter being dictated mainly by the deposition technique [14, 15]. One of the categories of coatings whose microstructure can be modified post-coating is that of Ni-based alloys with addition of B. This is subject to remelting by various methods (direct flame, laser etc.) [16], resulting in an improvement by reduction of porosity, increased cohesion between particles and better adhesion to the substrate due to the formation of metallurgical bonds [17].

The finishing of the thermally sprayed coatings, accordingly to the literature [18, 19], is recommended to be realised using several types of operations: machining (by turning and milling), grinding, polishing, super-finishing, all of them corroborated with the layer microstructure. In the industrial practice, the processing of the coatings raises a number of difficulties because the
microstructure is not homogeneous and compact as in the case of commonly processed materials, but is layered, with porosities and micro-cracks [20-23].

In this paper are presented experimental data resulted from the study of the manner in which two samples of coating produced from Ni-based self-fluxing powder behave in dry mechanic processing, one of which is as-coated and the other after retouching.

2. Materials and methods

2.1. Materials
A NiCrBSiFe powder mechanically alloyed with 60% WC (commercially known as Eutalloy 10112) was used to produce the studied coatings, the elemental chemical composition and appearance of which are presented in Figure 1. A low alloyed steel was chosen as the substrate for the deposition of these layers, which was processed in the form of discs whose overall dimensions are Φ180x40 mm. This geometry was needed because it was the only one that allowed the assembly on the conventional SNA lathe to study the machinability of the layers.

![Figure 1. NiCrBSiFe-WC powder: a) secondary electron image (500x); b) elemental chemical analysis](image)

2.2. Methods
In order to produce the coatings, the atmospheric plasma spraying method was chosen and the SprayWizard 9MCE Facility (Metco - Oerlikon, 2006) was used for this purpose. The discs used as a substrate for the deposition were prepared for spraying by sandblasting to activate the surface and cleaned with isopropyl alcohol. Subsequently, the samples were mounted, in turn, on a rotating table that provided the circular motion with the constant rate of the sample during the spraying process. As seen in Figure 2, the sample was centered on the rotating table, secured with 5 centering supports, and the spray gun was positioned perpendicular to the surface of the specimen so that, by moving it horizontally, it would be obtained a uniform surface as thickness and chemical composition.

After the thermal spraying of the two discs, one of them was kept in the as-sprayed state (S1) and the other was subjected to a heat treatment (remelting) of the coating by heating it up to 1050°C, maintaining until reaching the semi-liquid state and slow air cooling (S2).

The experiments on sample 1 were carried out on a conventional lathe SNA 560x1500 (as presented in Figure 3a) in dry cutting condition, with following cutting parameters:
- cutting speed \( V_c = 100 \) m/min;
- feed rate \( f = 0.05 \) mm/rev.
Machining tests were conducted by using a CBN insert 2NU-CNGA 120408 made by Sumimoto Electric mounted on a left hand toolholder (as presented in Figure 3b) having the following geometric parameters:

- negative rake angle, $\theta < 0^\circ$;
- major cutting angle $K = 85^\circ$;
- minor cutting angle $K' = 5^\circ$;
- nose radius $R = 0.8$ mm.

Due to the high hardness of the surface resulted after the remelting thermal treatment, Sample 2 was processed by grinding with abrasive stone.

The samples were processed in turn (Figure 4a, b), with observations on the behaviour of the cutting on the basis of the chip formation during the machining process. In order to complete the evaluation, microstructural observations of chips collected during the machining process were made, using the Quanta 200 3D electronic microscope (FEI, Holland, 2008) equipped with elemental chemical analysis module EDX (Ametek, Holland, 2008).

For the assessment of abrasion behaviour, the samples were subjected, at different stages, to scratches with progressive loading force (PLST), using the UMTR 2M CTR Microtribometer equipped with a micro-blade with a 5 mm diamond tip Rockwell type.
3. Results and discussions
The first of the studied samples was that in which the coating was processed in as-sprayed state (without being subjected to the heat treatment of the NiCrBSiFe coating) - sample S1. It has been noticed that the machining is done smoothly, without shocks or interruptions, and the resulting chips are of small size and do not stick to the processing knife. In Figure 4 it is presented the appearance of these chips, whose maximum dimensions range from 200 - 850μm (Figure 4a). Figure 4b shows the appearance of one of the chips, showing the fragmentation of the removed material by dry cutting, which favours the choice of a stable and predictable cutting regime. In Figure 5 it is visible the rupture of the splats that form the coating, and the chemical composition of the analysed chips demonstrates the homogeneity of the sprayed layer and the fact that it is not selectively machined.

Figure 4. Aspect of some chips resulted from the machining in dry cutting conditions of S1: a) 50x; b) 2000x.

Figure 5. Morphology (a) and elemental chemical composition (b) of one chip collected as result of S1 machining.

The same observations were made for sample 2, but with visible differences caused by the structural modification induced by the fusion process of the coating, which generally lead to an increase in the hardness of the layer and a decrease in its porosity. In Figure 6 are presented, similar to sample 1, images of the chips resulted from sample 2 processing. It is obvious that the removed
particles have very small dimensions (Figure 6b), being taken more as agglomerates (Figure 6a) and not as independently, separate chips.

![Figure 6. Aspect of some chips resulted from the grinding of S2: a) 100x; b) 1200x.](image)

![Figure 7. Morphology (a) and elemental chemical composition (b) of one chip collected as result of S2 grinding.](image)

![Figure 8. Surfaces morphology after machining a: a) S1 (1000x); b) S2 (1000x).](image)
To evaluate the effect of mechanical processing on surface quality in both cases, these were also morphologically analyzed (Figure 8). It is noticed that the processed surface in the as-sprayed state presents some irregular cracks and irregularities of the deposited material (Figure 8a), while the processed surface in the fused state has a homogeneous appearance, with no major discontinuities (Figure 8b). A possible solution for rectifying the quality of the processed as-sprayed coating is, however, subjecting it to a thermal fusion treatment after processing and bringing to the dimensional dimensions required for various parts.

The abrasion behavior of the coatings has been studied by applying scratch tests with progressive loading force (PLST - progressive loading scratch test) ranging from 0 to 20N. The friction coefficients (COF) and loading forces variation charts over the duration of the tests are shown in figures 9-11 for each of the three trials performed. Figure 9 shows the variation of the coefficient of friction with respect to time for the NiCrBSiFe - WC layer in the as-coated state, with maximum values of 1.6 and with an average value between 0.35 and 0.67. There is a decrease in the COF variation with the increase in the applied loading force being reached at the end a value of about 0.5. Figure 10 shows the COF variation in the sample S1 after its machining by dry cutting, with a smaller variation observed between 0.16 and 0.96 and with a peak at 1.28. As in the previous case, there was a decrease in COF variation as the loading force increased, with a value of about 0.40 at the end of the test.

A different behavior was recorded for sample S2 (Figure 11), where COF varied between 0.08-0.36, the mean value being about 0.24. This behavior can be explained by the fact that the remelting for fusion is accompanied by the compaction of the layer and the formation of metallurgical bonds between the component elements, causing an increase in the hardness of the coating to the raw state.
This phenomenon is also validated by the penetration depth values recorded during the scratch tests, as can be seen from Table 1.

![Figure 11. The friction coefficients (COF) and loading forces variation chart during the scratch test applied on S2.](image)

| Depth/Sample   | S1 "as-sprayed" [mm] | S1 machined [mm] | S2 [mm] |
|----------------|-----------------------|------------------|---------|
| scratch mark 1 | 0.865                 | 0.850            | 0.834   |
| scratch mark 2 | 0.876                 | 0.869            | 0.821   |
| scratch mark 3 | 0.874                 | 0.861            | 0.819   |
| average        | 0.872                 | 0.860            | 0.825   |

It is noted that the biggest depths are recorded for sample S1: 0.872 mm for the "as-sprayed" sample and 0.860 mm for the surface after machining by dry cutting. An explanation of the lower values recorded for the S1 machined sample would be the production of a hardening phenomenon as a result of the dry cutting machining process. The smallest depth of penetration - 0.825 mm - is recorded for sample S2, being explained by the much more compact structure of the coating resulted after the self-fluxing heat treatment.

4. Conclusions

After the tests of the NiCrBSiFe - WC coating in "as-sprayed" state (not subjected to the remelting treatment), it was observed that the layer retained its integrity and resulted in a uniform surface with a few cracks and fine exfoliation of the material. We can consider this aspect specific for the processing by cutting of the thermal spraying coatings, because they have a layered structure obtained by overlapping the molten material splats.

The resulting chips are of small size, have layered appearance and have been removed during the cutting process without affecting the smooth running of the process. As a result of the machining by dry cutting, a slight superficial hardening of the coating occurred, as evidenced by the scratch-type tests.

The obtained results recommend the continuation of the researches regarding the workability of the coatings produced by thermal spraying in two directions: the machining for the execution quotas followed by remelting, respectively the cutting processing of the coatings already subject to the fusion process.

5. References

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