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Inner walls laser cladding of WC reinforced Ni coatings

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Abstract

Thick and hard coatings are widely applied in a substantial number of heavy-duty industrial applications to improve wear and corrosion resistance. The techniques that allow producing depositions of metallic, ceramic or metallic-ceramic mixtures in zones with difficult access, like inner walls of a cylinder, are quite limited. Methods like spin casting, for instance, are successfully applied in parts with cylindrical symmetry. Nevertheless, when parts with more complex geometries have to be coated, new solutions must be applied.
The use of laser cladding as a possible alternative for these applications is studied in the present work. Coatings of a NiCr matrix reinforced with hard tungsten carbide particles were produced in internal walls. Carbides with different shape and size were employed in order to find the most suitable candidate for producing defect free coatings with maximum thickness. In order to achieve this goal, the effect of different processing parameters had to be investigated, and the use of preheating and a soft buffer layer was also considered for minimizing the residual stresses produced during the rapid cooling of the coating, from the melting point to the solid state.
Liquid penetrant tests were used for detecting eventual cracks of the coatings and optical and electron scanning microscopy, as well as microhardness tests were used for characterizing crack-free samples.

Keywords: Laser cladding; Hardfacing; Wear; Metal Matrix Composites; Tungsten carbides

1. Introduction

Improved machinery performance and safety can be achieved by developing protective wear and corrosion resistant coatings with advanced tribological properties. Many different techniques and materials may be employed for producing layers with the desired tribological properties. Among them, the metal matrix composites play an important role when wear resistant thick coatings are needed (Yakovelev et al., 1962).

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So far, numerous researches had been concentrated on the mechanical properties of laser cladded WC/Ni coatings, and showed that the addition of a high-stiffness WC to Ni-based coatings can result in a substantial increase in surface performances, such as wear resistance (Huang et al., 2004), corrosion resistance (Zhang et al., 2005) and fatigue properties (Stewart et al., 2004). The mechanical performances of these reinforced coatings are not only associated with the processing parameters, but also depend on the coating thickness (Nakayima et al., 2000) and the distribution, size and content of the hard particles (Van Acker et al., 2004). Actually, Nakajima et al., 2000 found that the increase in coating thickness was beneficial in improving the rolling contact fatigue life of WC cermet coatings, which could be attributed to the change of subsurface stress distribution by the variation in coating thickness. Van Acker et al., 2005, showed that a higher carbide content enhance the wear resistance of the coating, while their size shows no improvement on wear behaviour.

Even though the benefits of using this kind of coatings are more than demonstrated, methods for producing them on regions with difficult accessibility are quite limited. In this work, the suitability of the laser cladding technique was studied for producing hard and thick coatings of WC reinforced NiCr alloy on the inner walls of a twin screw barrel, adapting the already known laser cladding technique for producing crack-free coatings to this particular geometry.

2. Materials and experimental procedure

A 2.2 kW Nd:YAG laser was used for the cladding process. The laser beam was guided to the working region by means of an optic fibre and through an inner diameter cladding head. This head allows varying the laser spot on the work zone by changing the position of the focusing lens. For this work, the spot size was set at 2 mm. The laser head was fixed into a six-axis robot arm, for generating the linear movement along the axis of a twin-screw barrel. In order to produce the rotary movement, the barrel was fixed in an indexing table, by means of an intermediate adapter that allowed the barrel to rotate independently along each of its two axes.

Two flake burners were used for preheating the barrels, placed at each side of them. These burners produce a long and intense flame and combining two of them was proven to be enough to reach a temperature of 350 ^{o}C in the inner walls of the barrel.

The coatings were produced inside barrels of C60 carbon steel. A powder mixture of a NiCr alloy and tungsten carbide with a proportion of 40% NiCr:60% WC, was used for producing the hard coating inside the twin-screw barrel. In order to minimize the risk of producing cracks in the deposition process, a NiCr alloy with a hardness of approximately 35 HRc was used instead of other harder alternatives available in the market (Amado et al., 2011). The powders were mixed by means of a dual powder feeding system.

The chemical composition of this alloy is shown in Table 1, and its particle size was of +45 -125 µm.

Table 1 – Chemical composition of the C60 steel (substrate) and NiCr alloy (powder)

Wt. %	B	C	Co	Cr	Fe	Mn	Ni	P	Si	Other
C60	-	0.60	-	<0.40	Bal.	0.75	<0.40	<0.03	<0.40	0.10
NiCr	1.30	0.31	0.15	6.48	1.77	-	Bal.	0.06	4.10	0.10

With regard to the carbides, three different alternatives were used with different particle sizes and shapes, as shown in Fig. 1.

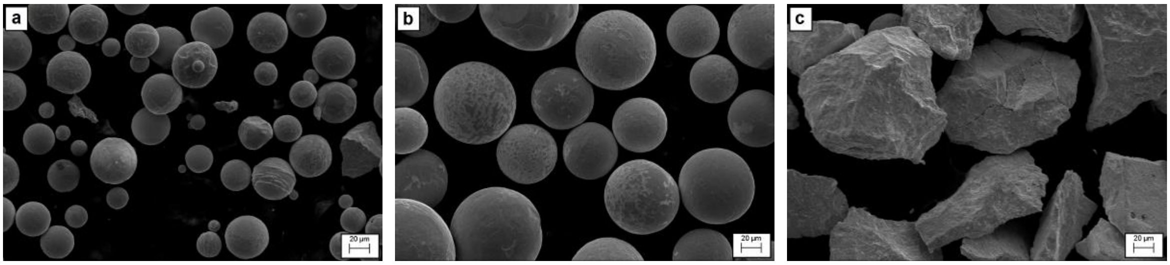

Fig. 1. Different types of tungsten carbide powders: (a) WSC-45 spherical 10-45 µm; (b) WSC-125 spherical 45-125 µm; (c) MWSC polygonal 50-150 µm

The coating samples were first analysed by liquid penetrant analysis and then cross sections were extracted and polished with diamond powder and chemically etched with Nital 4% reagent. Microstructural analyses were carried out by optical and scanning electron microscopy, including EDS (energy dispersive X-ray spectroscopy) semi-quantitative chemical analysis. Microhardness measurements were carried out using a microhardness tester with a load of 0.3 Kg, from the surface of the coating to the core.

3. Results and discussion

3.1. Dilution and carbide melting

In order to produce good quality coatings, the dilution has to be high enough to guarantee a correct adhesion between the coating layer and the base metal, but with values below 5%, in order to avoid an excessive mixture of the coating and base materials, which might worsen the properties of the coating layer (Toyserkani et al., 2004). Furthermore, dilution can be used as an indicator of the energy input of the process. Too high dilution values are associated with high energy inputs (high laser power and low scanning speed). When this is the case and mixed powders are used for producing the coatings, this excess of energy produces temperatures in the surface of the coatings high enough to melt the carbides, which lowers the overall hardness of the overheated region, as it can be observed in Fig. 2. It is thus compulsory to maintain the dilution at minimum for producing coatings with uniform carbide distribution.

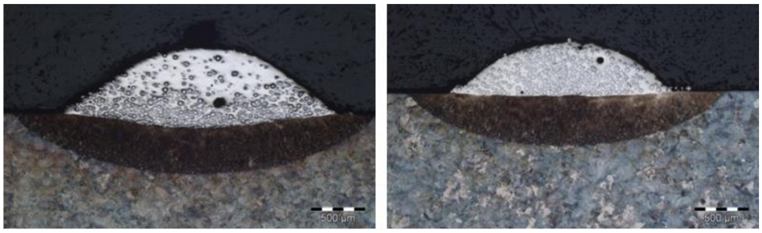

Fig. 2. Individual tracks, produced with the WSC-45 carbides: excessive (Left: P=1800W, V=20mm/s, C=40g/min) and adequate (Right: P=800W, V=10mm/s, C=20g/min) dilution values.

There is one additional dilution-related issue that may arise when overlapped tracks are produced. When the height of the individual tracks is large and/or their width is small, in other words, when the aspect ratio of the individual tracks is too big, regions with lack of coating material may be produced in the boundary between subsequent tracks and the base metal, as it can be observed in Fig. 3. In such hard coatings, these small holes can act as crack initiation sites, so it is essential to avoid this kind of defects.

Fig. 3. Inter-run porosity in a coating with overlapped tracks

A compositional analysis was carried out on the dilution region of coatings produced with WSC-45 carbides, by means of EDS maps for different alloying elements. In particular, the content of iron, nickel and tungsten were mapped in a region of about 500 µm (low resolution) and 100 µm (high resolution), centred in the boundary between the coating layer and the base steel (Fig. 4).

Judging from the EDS maps, the chemical composition changes suddenly, in a region of less than 5 µm, in the interface between the molten material and the base metal, and remains uniform inside both regions. This means that the dilution is low enough to avoid the excessive mixture of both substrate and coating alloys, which would be detrimental for the mechanical properties of the coating.

Additionally, in the case of tungsten, which should only be present within the spherical carbide particles, evidence of migration towards the nickel matrix is observed. This means that the carbides started to dissolve from their surface, which is also observed in the shape of the carbides shown in the micrograph with the highest magnification in Fig. 4. Nevertheless, this fact is not necessarily detrimental, as the carbides remain almost completely unaltered and the little tungsten and carbon that migrated to the metal matrix can produce an improvement of the nickel matrix hardness (Amado et al., 2011).

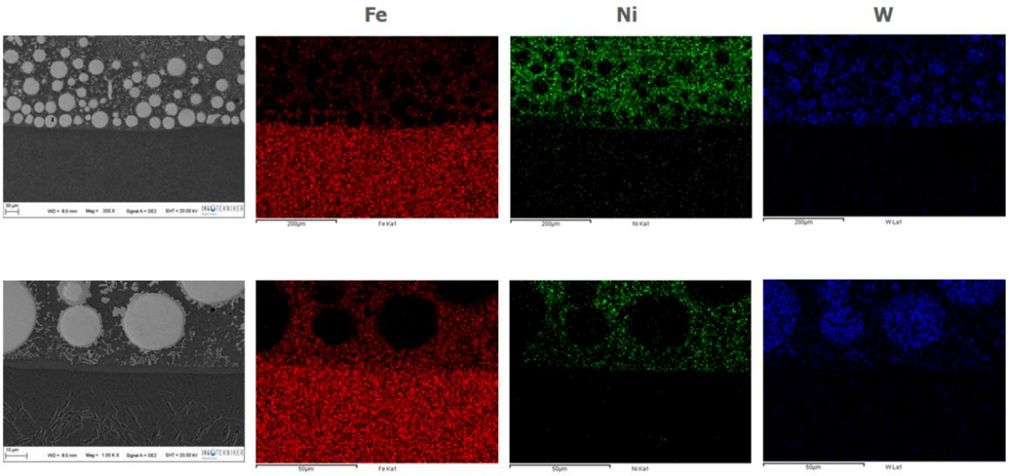

Fig. 4. EDS maps for different alloying elements in the dilution region between the coating and the backing steel at two different magnifications (Top: x200; Bottom: x1000)

Not only the dilution zone between the coating layer and the backing metal was studied, but the dilution between subsequent tracks was also analysed, by means of this EDS mapping method. In some cases, a banded structure was detected within the coating, showing carbide depleted bands exactly matching with the overlap region between each cladding track and the next one. It is clear that in these regions, the process of deposition of each track overheats the surface of the previously deposited region, producing carbide dissolution in a narrow band (Fig. 5). In these bands, the nickel matrix is enriched in tungsten and carbon, which in the one hand will tend to improve the overall hardness of the matrix, but comparing with the hardness of the unaffected spherical carbide particles, the tungsten and carbon enriched metal matrix will present a much lower hardness, so this effect should also be avoided for producing good quality coatings.

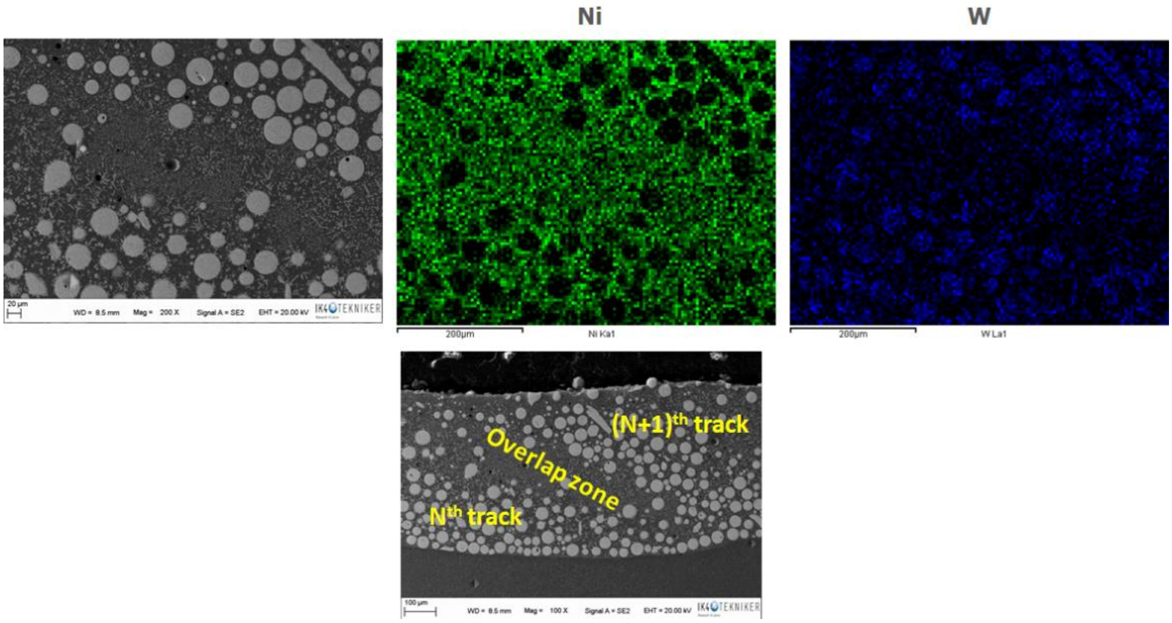

Fig. 5. EDS maps for different alloying elements in the overlap region between the subsequent tracks

3.2. Process optimization

Due to the high hardness of the carbides present in the coating alloy, cracks are usually produced when depositing this kind of coatings. In order to avoid this problem, two methods are usually employed: preheating (Huang et al., 2004) and using a buffer layer between the hard coating and the base metal (Amado et al., 2012).

Preheating was initially considered for this purpose. With regard to the preheating temperature, taking into account the thermo-mechanical properties of the substrate steel, quite high temperatures (700-800 ^{o}C) could be reached without significantly affecting the microstructure of the base metal. On the other hand, it has to be taken into account that the laser head is inserted into the barrel, and must withstand the combined heat produced by the preheating and the laser cladding process itself. Thus, the maximum preheating temperature was limited to 350 ^{o}C in order to avoid damaging the laser head. Nevertheless, that preheating temperature was not high enough to produce crack-free coatings by itself, as it can be observed in Fig. 6. Liquid penetrant tests on (a) preheated sample without buffer layer, (b) non-preheated sample with buffer layer and (c) preheated sample with buffer layerFig. 6a.

The alternative of using a buffer layer was also considered. The same NiCr alloy without carbide particles was deposited between the base metal and the hard coating. Once again, this solution was not suitable for producing crack-free coatings, as the liquid penetrant inspection revealed lots of cracks on the surface of the coating (Fig. 6b).

Even though neither of the two approaches was able to avoid cracks, the combination of both was finally tested, producing crack-free coatings as it can be observed in Fig. 6c.

Fig. 6. Liquid penetrant tests on (a) preheated sample without buffer layer, (b) non-preheated sample with buffer layer and (c) preheated sample with buffer layer

3.3. *Effect of carbide size and shape*

Geometrically similar coatings were achieved with the two spherical carbide powders under the same process parameters, despite the size difference. Nevertheless, some differences could be observed in the cross cuts, as shown in Fig. 7. The coatings produced with the WSC-125 carbides showed a uniform carbide distribution, while the ones corresponding to the WSC-45 powder presented a banded structure like the aforementioned one, alternating regions with high concentration of carbide particles and almost empty zones. Furthermore, a higher degree of porosity was observed in these coatings. Finally, powders with smaller particle size tend to present an inferior flowability, which may eventually produce clogging issues inside the powder carrying pipes or in the powder channels of the cladding head. Thus, the large carbides were selected for producing the final coatings.

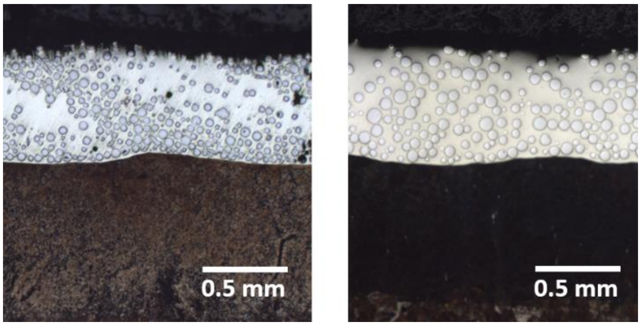

Fig. 7. Cross section of multi-track coatings produced with WSC-45 (left) and WSC-125 (right) powders

On the other hand, in order to compare the effect of the carbide shape on the resulting coatings, the same coating was repeated by using the MWSC polygonal carbides instead of the spherical WSC-125 powder. A remarkable thickness improvement was achieved by the sole fact of using the polygonal carbides, as it can be observed in Fig. 8. Taking into account that the same NiCr alloy was used as the metal matrix in both cases and almost no porosity was present in either case, the thickness difference can only be explained by two possible reasons: either the density of the polygonal carbides is lower than that of the spherical ones, or the powder catchment efficiency increases when using the polygonal powder. The first hypothesis was rejected, as the density of the polygonal carbides (16.3 g/cm^3) is even higher than that of the spherical ones (10.7 g/cm^3). Thus, it seems that the powder catchment efficiency improves with the polygonal powders. The reason for this might be that the spherical powders can be more prone to bounce off out of the melt pool during the process. A similar effect was reported by Huang et al., 2004, who produced clad layers with higher carbide volume fraction, when using crushed (polygonal) powders as compared with the spherical ones, which furthermore improved the wear resistance of the coating.

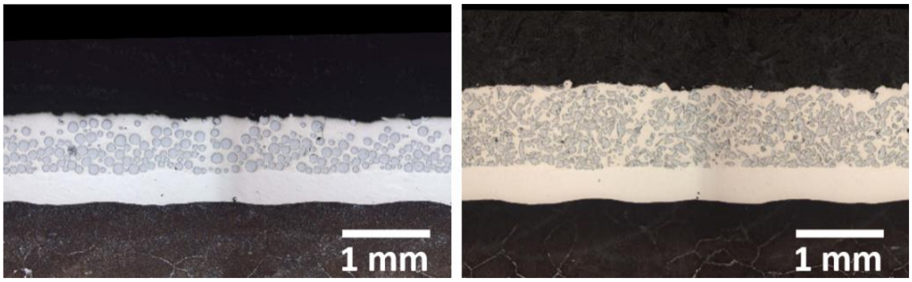

Fig. 8. Cross cuts of multi-track coatings produced inside barrels with WSC-125 (left) and MWSC (right) powders

3.4. Coating inside a twin screw barrel sample

Taking into account the considerations of dilution and carbide distribution discussed in the previous section as well as the crack avoiding method of combining preheating and the use of a buffer layer, the final process parameters were selected, as shown in Table 2. In order to produce coatings as thick as possible, for achieving barrels with longer service life, the polygonal carbides were chosen for the final coating.

Table 2 – Process parameters for producing the final crack free coating

Process Parameters	**Buffer layer**	**Hard layer**
Power (kW)	0.5	0.5
Scanning speed (mm/min)	500	600
Spot diameter (mm)	2.0	2.0
Powder feed rate (g/min)	5	20
Overlap distance (mm)	1.0	1.0
Preheating Temperature (ºC)	350	350
Shielding gas	Ar	Ar
Shielding gas flow (l/min)	20	20

Fig. 9 shows the microhardness profile of this final coating. An average hardness value well above 1000 HV0.3 was measured in the hard layer, across a thickness of roughly 1 mm, with peaks higher than 2000 HV0.3 when the indenter hit a carbide particle.

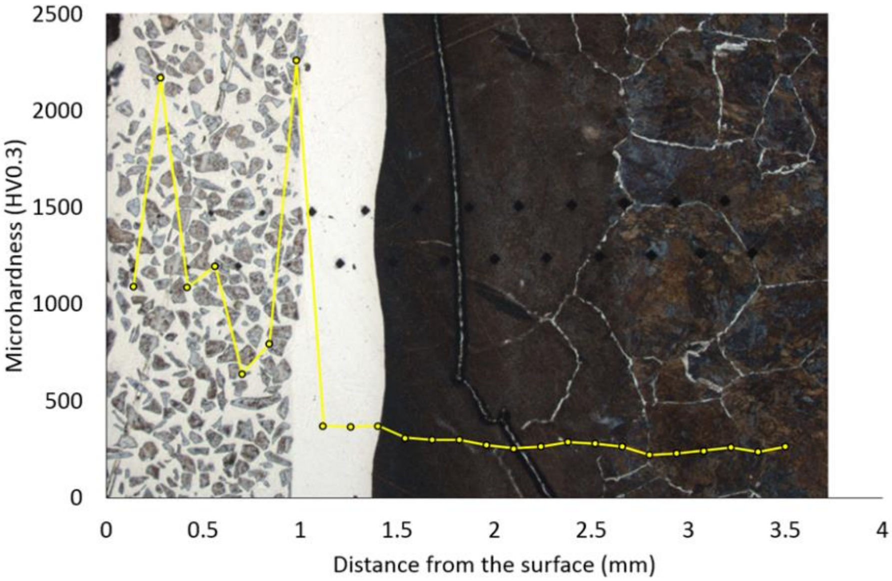

Fig. 9. Microhardness profile of the final coating produced inside a twin-screw barrel

Having optimized the coating process and verified the quality of the produced coatings, a 300 mm long twin screw barrel sample was finally coated by laser cladding. The inner wall of the coated barrel was uniform and smooth, as it can be observed in Fig. 10, with no apparent defects.

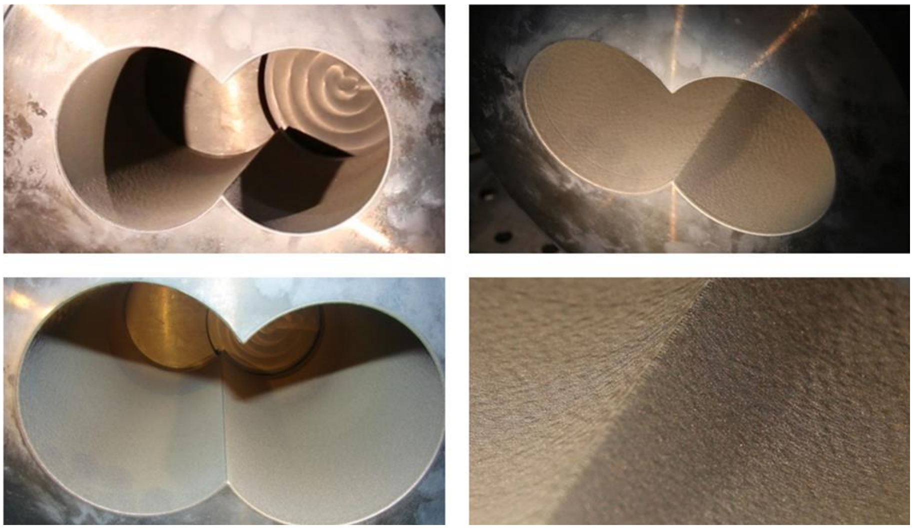

Fig. 10. Different perspectives of the fully coated twin screw barrel sample

4. Conclusions

Hard NiCr-WC coatings were produced inside twin-screw extrusion barrels by means of laser cladding. The deposition process was optimized and the use of different carbide particles was considered. From the results obtained in this work, the following conclusions can be derived:

- Energy input must be controlled in order to prevent the carbide particles to be dissolved, resulting in an inhomogeneous structure. Excessive dilution should also be avoided.
- Carbide melting and higher porosity is observed in the coatings produced with the smallest size spherical carbide particles, as compared with the largest ones.
- Preheating up to 350 ^{o}C is required in order to produce crack-free multitrack coatings on flat samples, and the maximum thickness achievable with spherical carbides is of roughly 0.7 mm.
- Coatings are prone to produce cracks when deposited inside the cylindrical walls of the barrels. The use of a buffer layer is required, as well as preheating, for producing crack-free coatings.
- Thicker coatings are produced with the polygonal carbides, as compared with the spherical ones, probably due to an increase of the powder catchment efficiency.
- 1 mm thick, hard layers with average microhardness of above 1000 HV0.3 were achieved, with peak values higher than 2000 HV0.3 on the carbides.

Acknowledgements

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