An approach to the machining of hard coatings prepared by laser cladding and thermal spraying

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Thermal spraying and laser cladding are widely used in industry for different coating applications. The use of these techniques usually requires a finishing post-process. However, the characteristics of these coatings, such as their high hardness, make difficult to achieve satisfactory results with conventional machining processes. The present study provides a description of the main characteristics of the laser cladding and thermal spraying processes. For machining of these coatings, conventionally, grinding is the first option selected. However, modern industries require gaining flexibility and improving their productivity. Thus, other alternatives such as milling or turning need to be assessed. In this sense, in the last section, several experimental investigations on the machining of WC-Co and Stellite coatings are presented. These studies can bring some insights to face the machining of hard coatings prepared by the laser cladding and thermal spraying techniques. For instance, they can help in the selection of the cutting parameters and provide interesting results on the use of different tool materials and tool geometries.

Keywords: Coatings, Laser cladding, Machining, Stellite, Thermal spraying, Thermal spray, WC-Co

1. Introduction

The need to machine materials with high hardness has become a requisite in a wide variety of industries in the last decades. The demands of the industry encourage the search for new materials with both high strength and heat resistance. However, during the machining processes, these properties lead usually to high cutting forces and cutting temperatures and, thus, to low tool life [1]. When machining hard materials, one of the major concerns is the surface quality because it is responsible for the functional behaviour of the parts [2].

The use of tailored coatings allows the adjustment of properties such as: chemical (biocompatibility, corrosion, permeation, temperature insulation and wettability), electrical (conductivity), mechanical (friction and wear) and optical (absorption, colour, reflection and transmission) [3]. In machining, the need to coat materials is very common. In particular, in the field of cutting tools, coatings have been extensively used in the last decades. To obtain products with the required characteristics, usually the surfaces are modified by different types of methods like carburizing, electroplating, nitriding, and both chemical vapour deposition (CVD) and physical vapour deposition (PVD). Moreover, other techniques such as laser cladding and thermal spraying are receiving more attention in recent times [4].

2. Laser cladding and thermal spraying

2.1. Thermal spraying

Thermal spraying finds a wide range of applications in industries such as aeronautical and space, automobile, chemical, electronics, energy, nuclear, and ship building and naval [5]. The process uses a wide variety of solid feedstock materials: ceramics, hardmetals, metals and alloys, and polymers. The feedstock can be used in form of powders, suspensions and wires [6]. To accelerate the feedstock material is heated, flame, hot gas, or plasma are used [7]. Then, at the time of the impact with the substrate, the coating is formed due to plastic deformation [6]. In Fig. 1, it is presented an image of an equipment use in thermal spraying applications.

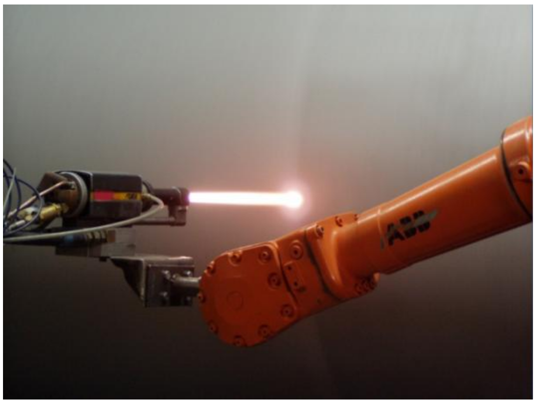

Fig.1 Praxair TAFA JP-5000® HP/HVOF spraying gun (VZU Plzen)
Obr.1 Praxair TAFA JP-5000® HP / HVOF stříkací pistole (Výzkumný a zkušební ústav Plzeň)

There are several types of thermal spraying processes such as plasma spraying, flame, High-Velocity-Oxy-Fuel (HVOF), wire arc spraying and cold spraying. These processes differ in the type of feedstock materials and the heat sources used. Moreover, their outcomes are different in terms of the feedstock velocity or maximum temperature attained [8]. According to Bolelli *et al.* [9], plasma spraying and HVOF-spraying are the most suitable methods for the production of high-quality wear resistant coatings and they are considered to be technologically mature processes. For instance, when considering the production of cermet coatings, a better performance is expected when using the HVOF process. The improvement is due to the much higher gas jet velocity and lower flame temperature resulting in denser coatings with extremely low porosity, low splats oxidation and low carbide decomposition and/or dissolution [9,10].

2.2. Laser cladding

Laser beams are extensively used in a wide range of industrial operations such as cladding, cutting, and welding [11]. Among them, laser cladding is considered to be a good alternative to conventional coating techniques [12]. Moreover, it is claimed that the laser cladding processes are even faster and more precise than the plasma or spraying coating methods [13] causing a minimum alteration inside the bulk material [14]. The use of laser cladding is applied for repairing critical components [15], and also for manufacturing advanced materials by means of micro-manufacturing [16] or rapid manufacturing [17,18].

Laser cladding uses a laser beam with high energy density to fuse a material on a substrate. The material is introduced into the process directly using inert gases such as argon or helium [19,20]. The application of the laser beam on the substrate creates a small melt pool into which the powder particles are injected. Then, the molten material solidifies as the laser beam moves away [21]. Equipment used for laser cladding applications is presented in Fig. 2. Laser cladding shows extraordinarily distinct advantages such as low dilution, minimal distortion of the substrate, narrow heat affected zone, metallurgical bond between the coating and substrate, and fine microstructure [22].

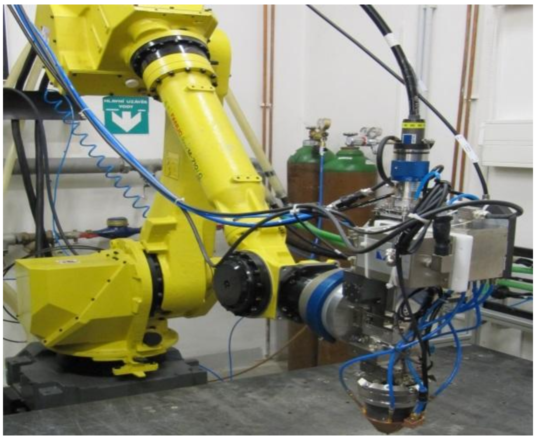

Fig. 2 Precitec YC52© laser cladding head (New Technologies Research Centre, University of West Bohemia)
Obr. 2 Precitec YC52© laserová navařovací hlavice (Nové technologie - výzkumné centrum, Západočeská univerzita v Plzni)

As reported by Mondal *et al.* [13], laser cladding is defined by a wide group of process parameters. Some of the most important are the laser power, laser beam size, laser scanning velocity or specimen motion velocity, and powder feed rate [15,23]. Finally, the coating produced is defined by the characteristics of the clad and the alloying zone formed [19].

3. Machinability of hard coatings

Processes like electro discharge machining (EDM), grinding and lapping are well-established methods for the machining of hard materials [24,25]. Traditionally, grinding has been the most used machining process to finish high-hardness materials. In the case of thermal spraying coatings, there are several investigations that assess the suitability of the grinding process. For instance, Tillmann *et al.* [26] presented a study that combines ball burnishing and grinding for the finishing of finestructured WC-12Co coatings for application to forming tools. The coatings were produced using the HVOF method. The results obtained by using these new forming tools outperformed the ones obtained with conventional cold work steel tools. However, other alternatives such as hard turning are proving their suitability to replace grinding in the machining of materials of high hardness with no reduction in the expected surface quality [27-29].

The problems associated with the machinability of coatings prepared with laser cladding and thermal spraying make difficult to find experimental studies about the topic in the literature. In particular, investigations providing a perspective of the whole process: coating production and finishing process. Thus, as a first approach, this study is mainly focused in the finishing process. Hence, the influence of the production process on the machinability of the coatings is not considered. Moreover, only two coating materials are analysed. These materials are Stellites and WC-Co that are commonly used in laser cladding and thermal spraying applications. Several examples of the machining of these materials are presented in the next sections. Additionally, a summary of the machining conditions used in the experiments is provided.

3.1. Machinability of WC-Co alloys

Among the main important hard materials, the use of WC-Co cermets has a long tradition in thermal spraying applications [30]. Most applications of WC–Co coatings are based on their hot hardness and wear resistance [31,32]. However, cermets have reduced toughness that makes them susceptible to sudden cracks. Besides, during the thermal spraying process the decarburization allows the formation of undesirable phases like W and W_2C, and also causes the dissolution of C and W in the Co binder phase. The decarburization process makes the coating harder and brittle [33].

Belmonte *et al.* [34] evaluated the turning process of sintered WC–27Co (27 wt.% Co) cylindrical forging dies with a medium WC grain size (~4 μm) and an average hardness of 7.5±0.3 GPa. The dimensions of the workpieces were: diameter of 30 mm and length of 12 mm. Moreover, the workpieces had a central hole with a diameter of 5 mm and length of 12 mm. The materials of the tools used were: WC–Co coated with CVD diamond, cubic boron nitride (CBN) and polycrystalline diamond (PCD). Authors recognised the potential of dry facing to reduce the machining time in comparison with the grinding process with diamond grinding wheels. Moreover, no signs of flank wear or chipping were found in the CVD diamond tools, and only crater wear was found in the rake face (distance between the centre of the crater and the edge of 55 μm and depth of 2 μm). When comparing CBN and PCD tools, the main wear mechanism is flank wear, specially, in the case of the PCD tools.

The use of CVD diamond coated cutting tools was also analysed by Belmonte *et al.* [35]. The workpiece material was sintered WC-25Co with a bimodal WC grain size distribution (50% of 6 μm and 50% of 2 μm) and an average hardness of 8.5±0.3 GPa. The form of the workpieces was cylindrical bars (diameter of 17.9 mm and length of 62.2 mm). Two sets of dry turning experiments were conducted. In the first set, the depth of cut and feed rate were fixed, varying the cutting speed and, in the second one, the cutting speed was fixed, varying the depth of cut and feed rate. In the tests, it was possible to identify a clear relation between cutting tool forces, flank wear and workpiece finishing. The adequate selection of the machining parameters allows controlling the cutting forces and, thus, guarantying a satisfactory surface quality. In this sense, authors identified a threshold for the main cutting force (35 N) that corresponds to the cutting conditions: cutting speed of 40 m/min, feed rate of 0.03 mm/rev and depth of cut of 0.1 mm.

A different analysis of the machinability of WC-Co was presented by Almeida *et al.* [36]. In the study, CVD diamond coated cutting tools were used to turn sintered WC–25Co with an average hardness of 8.5 GPa under dry conditions. Three different tool geometries were tested, namely: sharp, chamfer and hone. Due to the higher contact area, the cutting forces measured were higher for the hone tools while the lower values were found for the sharp tools. The geometry was found to be highly related to the flank wear and the film delamination. In particular, the hone tools offered the worst performance in terms of film delamination. Regarding the flank wear, the chamfer tools presented larger flank wear than the sharp ones.

Grinding and turning processes were investigated by Zhong *et al.* [37] for machining both WC-Co and Alloy 625 coatings. The coatings deposited on steel rods (diameter of 63.5 mm and length of 120 mm) were obtained using two thermal spraying processes: arc spraying and HVOF spraying. The processes evaluated for machining WC–Co coatings were diamond grinding, CBN grinding, diamond turning and diamond polishing. Turning was done using PCD tools. Only CBN grinding wheels were used for grinding WC–Co coatings obtained by arc spraying because diamond is not suitable for grinding the steel matrix of the WC-Co coatings. Although, for all the parameters tested, the turning process was faster than the grinding and polishing ones, the surface quality obtained with the diamond tools was poorer with some damaged areas. Moreover, the diamond inserts tended to chip during turning.

The milling process of a WC-Co coating was evaluated by Hintze *et al.* [24] using a 4-axis horizontal machining centre. The coating had a composition of 80WC-20Co. The cutting tool was a PCD with a geometry defined by: corner radius (0.8 mm), edge radius (<10 μm), clearance angle (8º) and rake angle (-8 and -48º). Authors identified significant differences in the microstructure depending on the tool geometry and cutting conditions. In particular, it is stated that the cutting forces have an important influence on the damage of the subsurface. The highest damage was obtained when using the larger negative rake angle (-48º) and depth of cut (~0.15 mm).

Tab. 1 Summary of the machining conditions used in the machining of WC-Co coatings
Tab. 1 Přehled řezných parametrů používaných při obrábění WC-Co povlaků

Author	Material	Process	Cutting speed	Feed rate	Depth of cut
Belmonte *et al.* [34]	WC-27Co	Turning	15 m/min	0.03 mm/rev	0.2 mm
Belmonte *et al.* [35]	WC-25Co	Turning	15-100 m/min	0.03-0.30 mm/rev	0.1-0.2 mm
Almeida *et al.* [36]	WC-25Co	Turning	15 m/min	0.03-0.30 mm/rev	0.1–0.3 mm
Zhong *et al.* [37]	WC-Co	Turning	10-20 m/min	0.071-0.16 mm/rev	0.2-0.35 mm
Hintze *et al.* [24]	80WC-20Co	Milling	14 m/min	-	0-0.15 mm

3.2. Machinability of Stellite alloys

Stellite alloys are cobalt-based materials that offer excellent wear resistance, high heat resistance, and great air corrosion resistance [38]. These properties make them suitable for applications in different sectors such as the aerospace, automotive, chemical and nuclear industries [38,39].

Bagci and Aykut [40] evaluated the face milling of Stellite 6 to assess the surface roughness using PVD TiN coated tools. The Taguchi optimization method performed allowed identifying that the optimum for the surface roughness was obtained when using the lower depth of cut and feed rate, and the higher cutting speed.

The face milling of Stellite 6 was also analysed in the study by Aykut *et al.* [39]. Two different tools: uncoated and coated PVD were used to perform the tests. Authors recognised the influence of the depth of cut and feed rate on the cutting forces, while no effect of the cutting speed was observed. In particular, as these variables are increased, the cutting forces increase.

The machinability of Stellite 12, which typically has a surface hardness of HRC 50±3, was analysed by Shao *et al.* [38]. Authors evaluated the performance of TiAlN coated and uncoated tungsten carbide tools in turning. In the study, it was identified a better performance of the coated tools in terms of tool wear. Moreover, it was observed that the tool life decreased with the increase of the feed rate and cutting speed. The major failure mode of the coated tools was uniform flank wear at low cutting speed, but adhesion, diffusion, chipping and chemical wear were observed at relatively high cutting speed and feed rate. In the case of the uncoated tools, the main failure mode observed was excessive flank wear.

Ozturk [41] evaluated the influence of the cutting speed and feed rate on the surface roughness when turning Stellite 6. Author identified a great influence of the feed rate and a lower influence of the cutting speed. Thus, it is recommended to use low feed rates to attain better surface quality. Two tools were tested: whisker-reinforced ceramic and tungsten carbide. For the tests, higher machining parameters were selected for the ceramic inserts. The surface roughness results showed how ceramic tools outperform tungsten carbide tools because they let attain similar surface roughness but using higher feed rates. However, the obtained surface roughness values, in terms of the average surface roughness, are considered to be high (from 1.8 to 5.1 µm).

Tab. 2 Summary of machining conditions used in the machining of Stellite coatings
Tab. 2 Přehled řezných parametrů používaných při obrábění Stellite povlaků

Author	Material	Process	Cutting speed	Feed rate	Depth of cut
Bagci and Aykut [40]	Stellite 6	Face milling	50-90 m/min	100-180 mm/min	0.25-0.75 mm
Aykut *et al.* [39]	Stellite 6	Face milling	30-40 m/min	60-100 mm/min	0.25-0.75 mm
Shao *et al.* [38]	Stellite 12	Turning	16-43 m/min	0.20-0.25 mm/rev	0.3 mm
Ozturk [41]	Stellite 6	Turning	30-90 m/min	0.10-0.35 mm/rev	0.25 mm

4. Conclusions

The increase of the use of laser cladding and thermal spraying in a wide number of industries requires the assessment of the post-processing operations needed to produce high quality workpieces. In this sense, finishing processes are usually required to produce coatings prepared with these techniques. However, because of the characteristics of these coatings, the machining of the coatings is a difficult task with conventional processes. The present study provides an approach to the machining of hard coatings prepared by laser cladding and thermal spraying. In this sense, several milling and turning experimental investigations focused on the machining of WC-Co and Stellite coatings are reported. Because of the different types of studies presented, it seems to be reasonable to provide general conclusions and ideas to summarise the results presented. In general, the studies suggest that the machining of these coatings can be successfully done by using adequate machining conditions and cutting tools. In particular, milling and turning can even improve the machining times of conventional grinding operations. The machining parameters play an important role in the results expected in the machining. Thus, their selection can help obtaining acceptable results in terms of surface quality and tool wear.

Moreover, the characteristics of the tool regarding geometry and materials are also identified as influential factors for the machining process.

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Abstrakt

Název: **Přístup v obrábění tvrdých povlaků připravených laserovým navařováním a žárovým nástřikem**

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Klíčová slova: Povlaky, Laserové navařování, Obrábění, Stellite, WC-Co, Žárové stříkání, Žárové nástřiky

Žárové nástřiky a laserová navařování jsou široce používané metody nanášení povlaků nacházející uplatnění v mnoha aplikacích v průmyslu. Článek se v první části zabývá základní charakteristikou zmiňovaných metod povlakování. Povlaky se obvykle dále obrábí některými z dokončovacích metod obrábění za účelem zvýšení kvality jejich povrchu. Nicméně, vlastnosti povlaků, jako je např. vysoká tvrdost, omezují dosažení uspokojivých výsledků konvenčním obráběním jako např. soustružením či frézováním. Chceme-li tyto povlaky obrábět konvenčně, jeví se často broušení jako jediná možnost. Nicméně, moderní průmysl vyžaduje vyšší flexibilnost a produktivitu. Z těchto důvodů je vhodné uvažovat i o jiné alternativě jako je například soustruženi či frézování. V tomto smyslu je v druhé části článku uvedeno několik příkladů experimentálního výzkumu obrábění povlaků na bázi WC-CO a Stellite. Výzkum v této oblasti může přinést nové poznatky v obrábění takovýchto tvrdých povlaků.

Zpět