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MACHINABILITY OF THERMAL SPRAY STELLITE 6 WITH CHEMICAL AND MECHANICAL ANALYSIS

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Abstract

This article deals with the machinability of Stellite 6 thermal spray, which is widely represented in many industries today, where it is used as an additive to increase resistance to wear, corrosion and oxidation. The aim of the research was to achieve the same or better quality of the Stellite 6 thermal spray surface with a different technology than grinding technology. The main idea of this change is to shorten production times and thereby increase productivity during thermal spray machining. After the experiment, the chemical analysis of the processed thermal spray is evaluated, during which the microhardness, microstructure, chemical analysis and thickness of the thermal spray were evaluated. Subsequently, an evaluation of the surface roughness and the amount of insert wear was carried out, from which the optimal cutting conditions were determined.

Keywords: Stellite 6; Machinability; Thermal spray; Metallography; Chemical analysis

1. Introduction

Currently, the requirements for materials used in the engineering industry are increasing rapidly. With the development of new materials, emphasis is also placed on surface integrity. In certain cases, it is necessary for the manufactured component to be able to withstand very demanding conditions in operation. This can be achieved in several ways. Among the most well-known variants chemical and heat treatment can be considered, which includes, for example, hardening, tempering, cementation, nitriding, etc. Another possibility that is at the forefront of interest is the use of thermal spraying of very resistant materials. Thermal spraying is practically an irreplaceable technology in many industries. Their biggest advantages are increased resistance to mechanical wear, chemical environment, corrosion and oxidation. They also withstand high temperatures very well. There are many areas in which it is possible to encounter thermal sprays. Take, for example, general engineering, where these sprays are applied to pumping and hydraulic technology to increase resistance to wear and corrosion. It is also used in the printing industry, where sprays are applied to the surfaces of printing cylinders. In the energy industry, they are used as a thermal barrier, protection against cavitation, erosion and hot corrosion. Last but not least, thermal sprays are widely used in the automotive and aerospace industries, where they are applied to internal combustion engine parts to increase resistance to wear and high temperature. We can list here, for example, pistons, valves, cylinder heads, pins, crankshafts or cams. [1] [3] [5]

It is known in the engineering industry that with every machining technology used, residual stresses are introduced into the machined material. These can be divided into tensile and compressive residual stresses. They arise as the machined material tries to return to an equilibrium state. A typical operation for the formation of tensile residual stress is grinding technology. During grinding, a large amount of heat is generated between the grinding wheel and the machined surface, which penetrates into the workpiece, and begins to cool after the process is finished. Tensile residual stresses start to form in the material. Tensile stresses can be considered a negative phenomenon in most cases. When a crack occurs, they help its propagation and thus shortens the lifetime of the component. During grinding, the residual stresses can be partially reduced by using coolant. The second type is compressive residual stresses. These arise during technologies where the surface layer of the machined material is plastically deformed by means of mechanical loading. These are technologies where tool has a defined cutting edge geometry, such as milling, turning, or drilling. In the event of a crack, on the other hand, compressive residual stresses tend to close the crack and thus extend the already mentioned service life even in cases where intensive mechanical wear occurs. [1] [4]

The publication titled "Machinability of Stellite-6 Coatings with Ceramic Inserts and Tungsten Carbide Tools" [2] also dealt with the issue of machinability of thermal sprays. This study focused not only on the cutting conditions but also on the difference in cutting materials and their effect on the resulting surface quality. The Stellite alloy was applied to the base material of austenitic stainless steel with the commercial designation AISI 304. Two types of cutting materials were tested for the thermal spray of Stellite 6. In the first case, it was a ceramic cutting plate fixed to the body of the turning knife. The ceramic plate from Sandvik has the designation RNGN 120700 T01020 and consists of the base material Al_2O_3, which is reinforced with so-called whiskers. According to the authors of the study, this type of insert is suitable for high-speed machining of alloys resistant to high temperatures. The holder was designed in such a way that the inserted plate ensures a negative face angle with a value of -6°. [2]

In the second case, a one-piece turning knife with a brazed cutting edge made of grade K20 tungsten carbide, which was uncoated, was used. Compared to the ceramic plate, the soldered edge has a positive face geometry, the value of which is not stated. The process fluid was used only for the variant with a brazed cutting edge, and it was an oil emulsion. In the case of machining with a ceramic plate, the entire process took place without the use of any process liquid. Cutting conditions took place in combinations of changes in cutting speed and feed per revolution. A detailed elaboration of the entire experiment plan with achieved roughness values are shown in table 1. [2]

Insert type	Cutting speed (m/min)	Feed rate (mm/rev)	Average surface roughness (µm)	Tool type	Cutting speed (m/min)	Feed rate (mm/rev)	Average surface roughness (µm)
	V	*f*	Ra		*V*	*f*	Ra
Whisker-reinforced ceramic CC670	30	0.25	[illegible].48	Tungsten carbide	30	0.1	2.6
		0.3	3.44			0.15	3.8
		0.35	[illegible].74			0.20	5.1
	50	0.25	2.42		40	0.1	2.1
		0.3	3.29			0.15	3.1
		0.35	4.63			0.20	4.7
	70	0.25	2.30		50	0.1	1.8
		0.3	3.19			0.15	2.5
		0.35	4.54			0.20	4.0
	90	0.25	2.21				
		0.3	3.10				
		0.35	4.40				

Table 1. Experiment plan with measured roughness [2]

In the case of machining with a ceramic insert, it can be noted that the best achieved roughness Ra = 2.21 µm was achieved at the highest cutting speed v_c = 90 m/min and at the smallest feed value f = 0.25 mm/rev. When comparing the individual variants in more detail, however, it is evident that the cutting speed does not have such a fundamental effect on the roughness values, in contrast to the displacement values. The measured roughness are very similar at the selected feed values, with the fact that they improve slightly with increasing cutting speed. A similar trend was also observed when machining with a tungsten carbide soldered plate. The best value of the roughness of the machined surface Ra = 1.8 µm was recorded at the highest cutting speed v_c = 50 m/min and the smallest feed f = 0.1 mm/rev. Compared to the previous case, it is clear from the table at first glance that both the feed parameter and the cutting speed value have an effect on the roughness value. However, the overall process is identical to the previous version with a ceramic cutting edge. [2]

In conclusion, it can be said that similar results of surface quality were achieved in both variants, with the fact that the variant with a tungsten carbide solder plate turned out slightly better. This could have been caused both by significantly smaller displacement values and also by the use of an operating fluid in the form of an oil emulsion. This article again confirms the claim that better surface roughness values are achieved at higher cutting speeds and smaller feed values.

2. Description and preparation of the experiment

Stellite 6 alloy contains between 45-55% cobalt (Co) and is referred to as the base. The second most represented element is chromium (Cr), the amount of which ranges from 25 to 35%. Tungsten (W) also has a non-negligible presence in this alloy, from 5 to 25%. Another very important element is carbon (C), which creates individual carbides and is contained here in the range of 0.1 - 1.5%. These alloys also contain other elements in small quantities, such as molybdenum (Mo), nickel (Ni), niobium (Nb), tantalum (Ta), silicon (Si), manganese (Mn) and iron (Fe). According to the given values, it is evident that Stellite alloys can have a very different chemical composition and thus the resulting properties. The exact chemical composition is described in Table 2. The listed contents of individual chemical elements are available from the Deloro and Kennametal catalog. [10] Chromium and tungsten forming carbides with carbon provide the required hardness and strength. The hardness is in the range of 36 – 45 HRC and the tensile strength limit is given in the range of 800 – 1200 MPa. In addition, chromium carbides increase resistance to corrosion and oxidation even at higher temperatures. The melting point is determined by the combination and content of the individual elements and ranges from 1200 to 1400 °C. [7] [8]

Compo-sition in wt %	Co	Cr	W	C	Ni	Fe	Si	Mo	Mn	Other
	45 - 60	27 - 32	4 - 6	0,9 - 1,4	max. 3	max. 3	max. 1,5	max. 1	max. 1	max. 1

Table 2. Chemical composition of Stellite 6 alloy in weight percent [6]

Stellite 6 is popular mainly due to the balanced ratio between hardness and toughness. It contains a large number of hard carbides of chromium and tungsten. Carbides contribute to a very good ability to resist many types of wear, even at elevated temperatures. At room temperature, the hardness value is 410 HV. When the temperature increases, the alloy still retains the appropriate hardness value of 400-300 HV up to 500 °C. As a cutting tool, a curved carving knife made of material marked as 42CrMo4 with a tensile strength of 1000 MPa, which is commonly used for the production of lathe holders, was used. As it is planned to change the angle of the face during the experiment (in the values of -7°, 0°, +7°), it is necessary to produce 3 variants of turning knives. The preparation of the machining knife with IC20 cemented carbide insert can be seen in the picture (Figure 1). [7], [9]

Fig. 1. Machining tool with Iscar IC20 insert

In the experiment, the cutting speed was varied in the range $v_c = 20 – 55$ m/min. Furthermore, the depth of the cut was changed in two variants of 0.1 and 0.3 mm. A cemented carbide insert from the company Iscar marked IC20 is attached to the tool. The chosen technology was a simplified imaging process known as orthogonal free cutting. Steel with dimensions of 400 x 40 mm with a width of 3 mm from material 11 373 according to ČSN was chosen as a semi-finished product. This sheet was treated from the top with Stellite 6 thermal spray produced by the HVOF method with a thickness of 500 µm (Figure 2). High-velocity flame spraying known as HVOF (High-Velocity Oxygen Fuel) belongs to the most modern methods in the field of thermal sprays.

Fig. 2. Manufactured workpieces with Stellite 6 coating

3. Evaluation and result of the experiment

Rockwell, Brinell or Vickers tests are generally used to assess hardness. The main difference between the above tests is the use of different indentors. The Vickers test was chosen to measure the thermal spray. The test according to Vickers consists of perpendicularly pressing a four-sided diamond pyramid into the material being examined. The pyramid has a given wall angle of 136°. According to the magnitude of the load, Vickers is further divided into hardness and microhardness tests. For microhardness testing, the load values are a maximum of 0.2 kg. Vickers is denoted by the abbreviation HV (Vickers Hardness) and a number indicating the value of the load in kilograms, e.g. $HV_{0.2}$. Vickers is used to measure the hardness of both soft and hard materials and is limited only by the surface being measured, which must be flat and polished. The hardness was measured on the workpiece at two distances (Figure 3). The values are around 700 HV. At a distance of 0.5 mm, there is a significant decrease in hardness (Table 3), due to the transition of the thermal spray to the base material, which is steel 11 373 according to ČSN.

Depth [mm]	0,05	0,1	0,15	0,2	0,25	0,3	0,35	0,4	0,45	0,5	0,55	0,6	0,65	0,7
Hardness $HV_{0,1}$	634	793	736	650	623	627	731	680	741	646	284	182	164	148

Table 3. Measured dependence of hardness on the depth of thermal spray

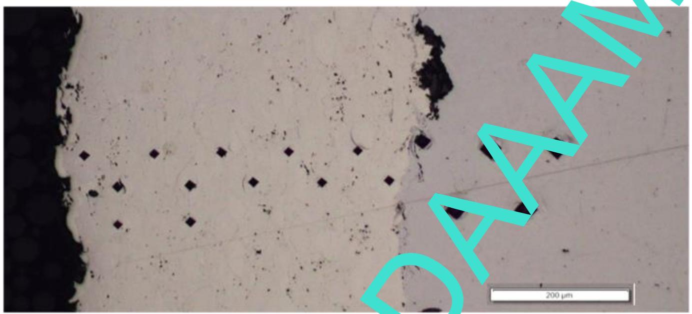


Fig. 3. Vickers hardness test (Olympus BX61, magnification 100x)

Chemical analysis of thermal spray were carried out in order to find out how the chemical composition of the used powder differs from the chemical composition of the already applied coating. This difference is mainly caused by the temperature during the injection process, which causes certain structural changes due to the high temperature. Sometimes there may even be partial or complete evaporation of some elements. Unfortunately, the chemical composition of the applied powder was not known, so it was decided to compare only the measured chemical composition with the table values of the Stellite 6 spray. The measurement was carried out in several places with very similar chemical composition results. When comparing the measured values from Figure 4 with values from Table 2 for the Stellite 6 alloy, it follows that the chemical composition of the measured coating corresponds to the table values in percentage.

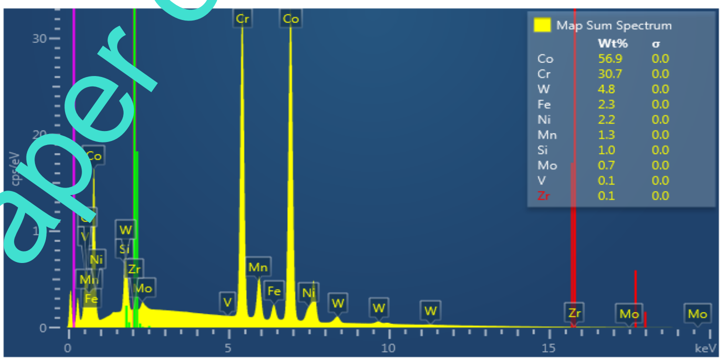


Fig. 4. The measured chemical composition of Stellite 6

The metallographic analysis was carried out from the metallographic specimen. Images are taken with an Olympus BX61 microscope at 50x – 1000x magnification. Light microscopy was performed in the etched and unetched states. 3% Nital was chosen as the etchant. Figure 5 shows the lamellar structure typical pro thermal spraying. There are inclusions and larger impurities at the interface. The coating also contains a certain percentage of pores and probably oxidized parts, which, however, cannot be determined using a light microscope. The thickness of the thermal spray is declared by the manufacturer to be in the range of 0.4 – 0.5 mm. After evaluation, the thickness in the centre of the cross-section is in the range of 0.485 – 0.532 mm.

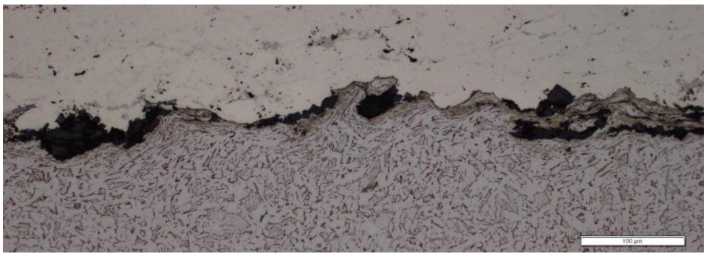
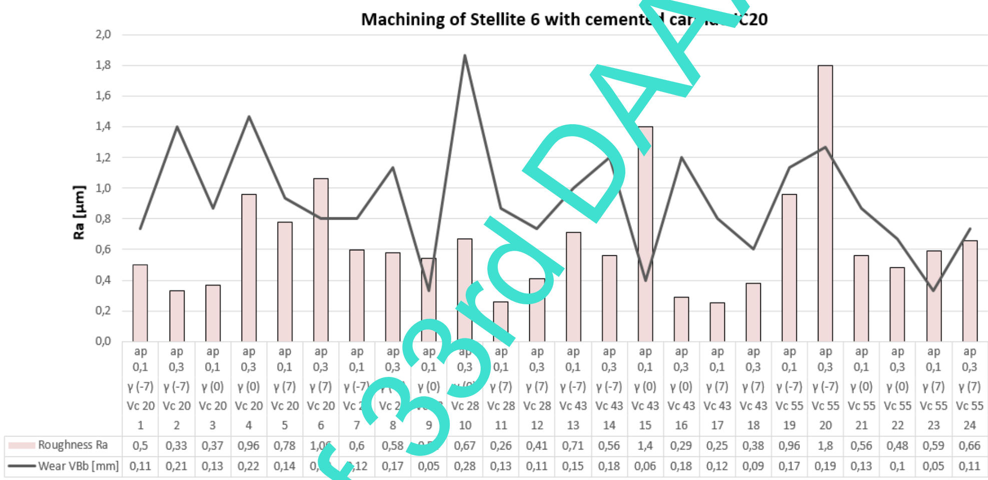


Fig. 5. Light microscopy (Olympus BX61, etched, magnification 200x)

The roughness of the unprocessed thermal spray is given around Ra = 6 µm. This value is influenced by the structure itself, which consists of fused or partially fused deformed particles (splats). For most mechanical applications, the sprayed coating needs to be machined to reduce its surface roughness. In our case, profile roughness was measured on a Hommel Etamic T8000 device. According to the DIN EN ISO 4288:1998 standard, a tip with a size of 2 µm was selected. The measurement took place at 7 places of the semi-finished product with a constant measured length of 4.8 mm. The experimental plan was set so that each cut was made by an insert with an unworn cutting edge. In this way, the effect of the wear of the cutting tool on the quality of the machined coating was eliminated. At the same time, the type and amount of wear was investigated depending on the changed parameters, because the results can be helpful in continuing to solve this issue. After the cut, the plates were marked with the same number as the numbered workpiece. The wear of these plates was measured on a Multicheck PC500 optical microscope, during which the cutting edge, the size of the notch and the increase were examined. The achieved results from the experiment are shown in the following Graph 1.



Graph 1 - Dependence of cutting conditions on the roughness of the machined surface

4. Conclusion

The main objective of this research was to achieve the same or better surface quality of Stellite 6 thermal spray, which was machined with a defined cutting edge geometry when compared to grinding technology. The main idea behind this change is to shorten production times and thereby increase productivity during thermal spray machining. In the theoretical part, the conditions of the experiment are defined, such as the cutting conditions, the machine and the tool.

The experiment is followed by the evaluation section, where in the first part a chemical analysis of the machined thermal spray was carried out, during which the microhardness, metallography, chemical analysis and thickness of the thermal spray were evaluated. The highest measured microhardness was found to be $HV_{0.1} = 623$, which is three times higher than steel 11 523 according to ČSN. When comparing the results of the chemical composition with the table values, we did not notice significant differences. After evaluation, the thickness in the centre of the cross-section is in the range of 0.485 – 0.532 mm. At the interface, there are several inclusions and impurities in the metallographic specimen. The coating also contains a certain percentage of pores and probably oxidized particles, which, however, cannot be clearly determined using a light microscope. These impurities and pores can have a major effect on the service life.

From the obtained machining results, a better surface roughness Ra < 0.4 µm was achieved for several samples. The depth of cut did not depend on the achieved roughness or the amount of wear. For each variant of the cutting speed, the setting of the face angle had the greatest effect and is very different for each variant. The best result appears to be sample 18 with positive face geometry γ = 7°, where the roughness value Ra = 0.38 µm and the size of the back wear $VB_B = 0.09$ mm. From the wear results, it can be seen that uncoated cemented carbide is not suitable for machining these hard coatings. To continue the research, it is necessary to choose harder insert materials and follow up on the results from this experiment.

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