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Grinding of hard-material-coated forming tools on machining centers

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Abstract

In this paper, the grinding of hard-material-coated forming tools on a machining center is presented. The coated materials have to be machined mechanically because of the insufficient surface quality and form errors resulting from the thermal spraying processes. During the fundamental investigations two different tungsten carbide coatings have been machined by applying super abrasive grinding tools consisting of four different bond systems. To identify the suitable grinding tools, the process forces and the surface roughness values have been carried out by a screening design of experiments.

Keywords: Grinding; Super abrasive; Coating; Metal forming; Bonding

1. Introduction

As a consequence of the industrial progress in the automotive industry, the wear resistance of forming tools during the production process has to be improved continuously. To accomplish this, thermally sprayed hard material coatings are one possible solution [1, 2]. However, the surface quality of the coated materials is not sufficient to be used during the production process. In order to achieve high surface qualities and small form errors, the coatings have to be machined mechanically [3, 4]. For this purpose, grinding is a capable and flexible process that can additionally induce compressive stresses into the surface [5]. Due to the complex geometry of forming tools, the presented machining process is conducted on a five-axis machining center while using mounted points [6].

In this paper, an overview of the influence of different bond systems and cutting materials on the surface finish and the process forces during the grinding of thermally sprayed coatings is given. The machined coatings are composed of tungsten carbide in an iron matrix (WC-Fe) in one case and in a cobalt matrix (WC-Co) in the other case. Due to the hardness of the coatings of up to 1,200 HV 0.3, super abrasive cutting materials, in particular diamond and cubic boron nitride (CBN), each with electroplated, vitrified, resin, and metal bonds, were applied. To identify the optimal tool and parameter value combinations for the grinding of the considered coatings, the resulting surface qualities were measured by a confocal three-dimensional microscope *nanoFocus µsurf*. Using an optical measurement, the errors occurring in the surface topography, which results from the influence of the porosity of the thermally sprayed coatings, can be isolated from the actual grinding results. To evaluate the grinding grooves, the chunks and the porosity of the sprayed layer have been examined separately.

2. Materials and methods

2.1. Coatings

To investigate the grinding process behavior of wear-resistant coatings, two different tungsten carbide coatings have been machined. On the one hand, 50 percent by volume of tungsten carbide in an iron matrix (WC-Fe) was applied by an arc spraying process by achieving high deposition rates up to 220 µm per pass and improving the hardness up to 450 HV 0.3. On the

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other hand, a High Velocity Oxy-Fuel (HVOF) flame spraying process was applied to coat the workpieces with 88 percent by volume of ultra-fine tungsten carbide in a cobalt matrix (WC-Co). The deposition rate of 25 µm per pass during the HVOF process is much lower in comparison to the arc spraying process, but the hardness of the surface layer of 1,200 HV 0.3 is much higher. As shown in Fig. 1, the profile heights of both coating systems differ significantly. The porosity of the WC-Fe coating resulting from the arc spaying process is much higher. To achieve the required surface qualities for forming processes, these coating systems have to be machined.

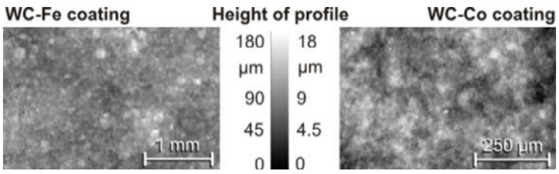

Fig. 1. Surface topographies of tungsten carbide coatings deposited by arc and HVOF spraying processes

2.2. Grinding tools

Due to the high amount of tungsten carbides in the coatings, it is necessary to apply the super abrasive cutting materials cubic boron nitride (CBN) and diamond for grinding the wear resisting layers. In order to reach a smooth surface finish, the grain sizes of 91 µm and 126 µm have been chosen. In addition, electroplated, vitrified, resin, and metal bonds have been applied to the grinding process. The grinding tools were cylindrical shaped and had diameters have been varied between 12 mm and 15 mm. As shown in Fig. 2, the amount of grains on the surfaces of the grinding tools varies extremely regarding different bond systems.

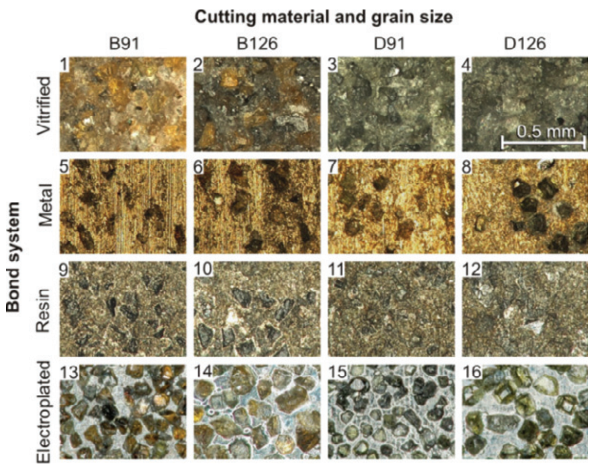

Fig. 2. Images of the applied grinding tools

The varying distribution of the grains influences the process forces and the surface finish during the grinding process directly because of the effective engagements of the cutting grains. A higher amount of cutting grains leads to a reduced single grain chip thickness resulting in lower process forces. Due to the low stiffness of the shank of the grinding tools, low process forces during the grinding process should be achieved.

2.3. Experimental setup

The grinding of hard-material-coated forming tools is conducted on a five-axis machining center Deckel Maho DMU50 eVolution. Due to the design of the machine, the revolution speed of the spindle is limited to 18,000 RPM, which leads to a maximum cutting speed of 14 m/s using grinding tools with a diameter of 15 mm. In order to compare different grinding tools with smaller diameters, the cutting speed was limited to 10 m/s. Due to this limitation of the cutting speed, the thermal stress during the cutting process remains at a low level and the machined workpieces show a good surface quality.

For dressing the grinding tools, a stand-alone dressing device was mounted onto the machine table, as seen in Fig. 3. The revolution speed of the dressing spindle is limited to 16,000 RPM. During the investigations the grinding tools have been dressed after each experiment with a total dressing infeed of aed,ttl = 20 µm in steps of aed = 2 µm per pass and an overlap dressing rate of Ud = 200. A silicon carbide (SiC) grinding wheel was applied to the dressing process.

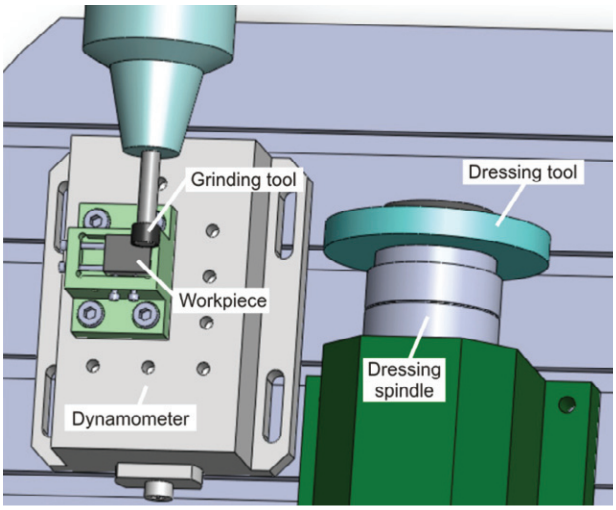

Fig. 3. Experimental setup

The process forces were measured during the grinding processes at a three components dynamometer *Kistler 9257B*. For the evaluation of the surface finish a confocal three-dimensional microscope was used with a measuring length of l = 4.8 mm and a length cut off of L_c = 0.8 mm.

To detect the significant process parameters on the results of the surface finish and the process forces during the grinding process, a screening design was applied for each tungsten carbide coating [7]. The process parameter values for the experimental designs are presented in Table 1.

Table 1. Process parameter values for the screening designs

Coating	WC-Fe	WC-Co
Cutting speed v_c	10 m/s	10 m/s
Feed speed v_f	500…2,000 mm/min	200…800 mm/min
Depth of cut a_e	20…40 µm	10…20 µm
Width of cut a_p	2.4…4.8 mm	2.4 mm
Grinding strategy	Up-/down-grinding	Down-grinding

3. Results and discussion

The experimental investigations have been evaluated by the process forces occurring at the grinding processes and the machined surface finish. The obtained results are subdivided into the grinding of WC-Fe and WC-Co coatings. During this investigation the reduction of the grain protrusion resulting from the dressing process was not taken into account.

3.1. Grinding of WC-Fe coatings

The roughness values of the machined WC-Fe coatings are influenced by its porosity according to the thermal spraying process, as shown in Fig. 4. The selected profile of the surface topography is highlighted in the diagram of the profile heights where the envelope of all profiles is plotted.

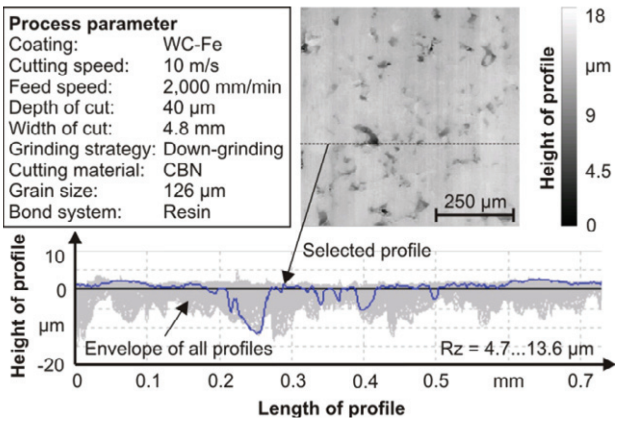

Fig. 4. Surface topography of a grinded WC-Fe coating

The determination of the average maximum height of the profile Rz, measured perpendicular to the grinding direction, strongly depends on the selected profile of the surface topography. Using the example shown in Fig. 4, the roughness values vary between Rz = 4.7 µm and 13.6 µm in consideration of all heights of profile. For further evaluations only the lowest roughness values of all single profiles are taken into account.

The software *Matlab* was used to create the designs of experiments and to analyze the obtained results. Regarding the boxplot distribution of the average maximum heights of profile Rz and the applied grinding tools, as shown in Fig. 5, the roughness values for the vitrified and the metal bonds are almost at the same level. The lowest heights of profile are produced by the resign bonded CBN grinding tool. In contrast to this, the highest roughness values are produced by the electroplated tools caused by its high grain protrusion.

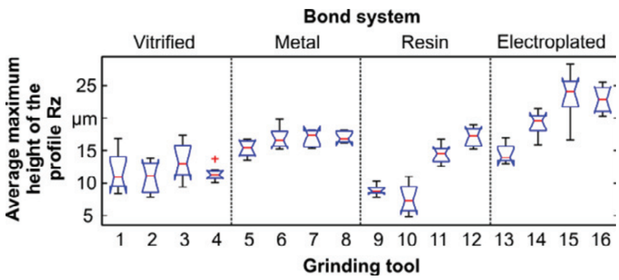

Fig. 5. Boxplot distribution of the roughness values Rz and the used grinding tools, as shown in Fig. 2, for the grinding of WC-Fe coatings

The main effect plots are used to determine the significance of the influencing process parameters out of screening design of experiments. Process parameters that are less important can be disregarded for further investigations. The main effect plots for the average normal forces F_n and the average maximum height of the profile Rz in relation to the varied process parameters are presented in Fig. 6.

Regarding the roughness value Rz, the selection of the cutting material and the bond system influence the values significantly. Due to a low grain protrusion, the application of vitrified and resin bonds result in low roughness values. The lower sharpness of the CBN grains in comparison to the diamond grains result in a reduced height of profile.

The average normal force is strongly influenced by all process parameters, except of the grinding strategy. Increasing the depth of cut, the width of cut and the feed speed lead to higher normal forces because of the high amount of effective cutting edges attended by the increase of the contact area between the grinding tool and the workpiece.

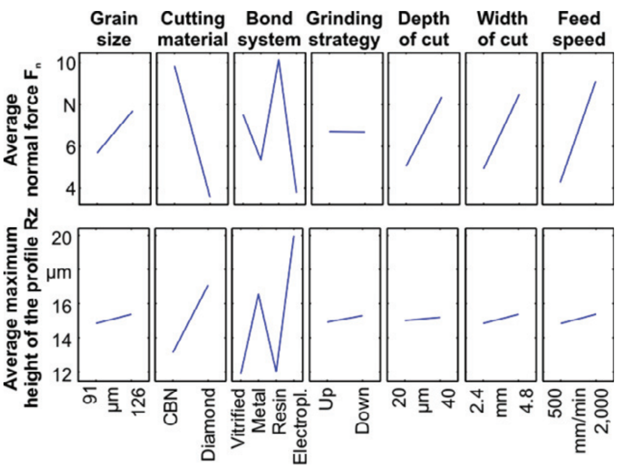

Fig. 6. Main effect plots for the grinded WC-Fe coatings

3.2. Grinding of WC-Co coatings

There are no defects on the surface topography of the grinded WC-Co coatings caused by porosity according to the thermal spraying process, as presented in Fig. 7. The average maximum heights of the profiles are only varying between Rz = 3.6 µm and 4.2 µm. These deviations can be explained by the grinding process and the measuring accuracy of the confocal microscope.

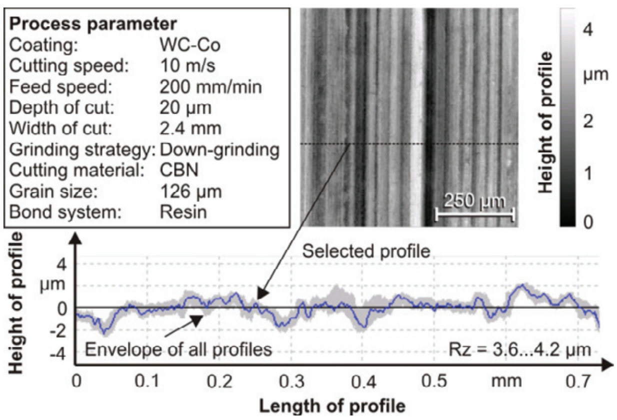

Fig. 7. Surface topography of a grinded WC-Co coating

The variances of the boxplot distribution of the average maximum heights of profiles Rz and the applied grinding tools for the WC-Co coatings, as shown in Fig. 8, are much lower than the roughness values of the grinded WC-Fe coatings. The lowest heights of profile are produced by the resign bonded CBN grinding tool. The smoothest roughness values of metal and vitrified bonds are nearly at the same level of Rz = 6 µm. The grain size variation of both cutting materials shows an inverse influence on the trend of the roughness values Rz. Resulting from the higher sharpness of the diamond grains, the grinding grooves at the surface are more formed.

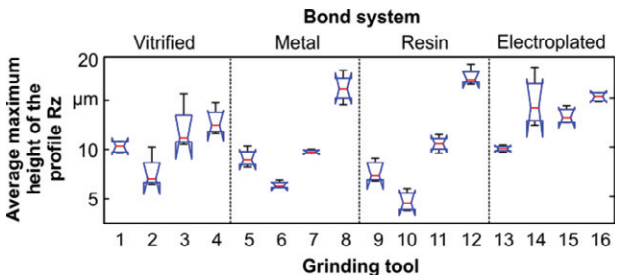

Fig. 8. Boxplot distribution of the roughness values Rz and the used grinding tools for the grinding of WC-Co coatings

The grinding strategy and depth of cut have not been taken into account during the investigations of grinding WC-Co according to previous investigations [3]. The main effect plots of the significant process parameters concerning the average normal force F_n, as shown in Fig. 9, show the same trends as the process forces occurring at the grinding of WC-Fe. In contrast to this, the average maximum height of the profile Rz is influenced by the depth of cut and the feed speed contrarily. The reason for this trend is the small chip thickness for a small depth of cut and for low feed speeds which lead to a higher influence of friction and elastic deformation to the cutting process.

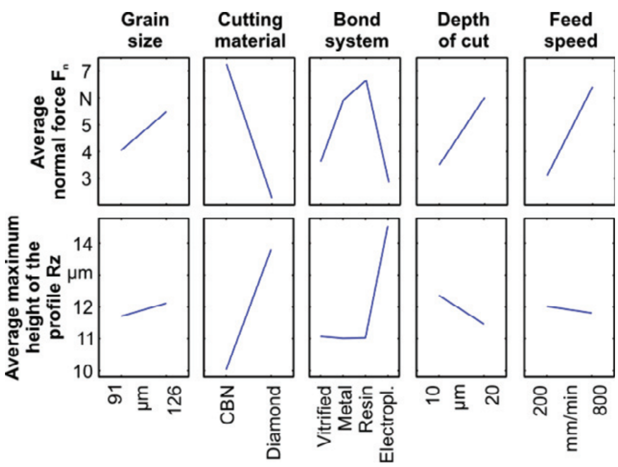

Fig. 9. Main effect plots for the grinded WC-Co coatings

4. Conclusion and outlook

Grinding of thermally sprayed coatings on a machining center by using mounted points is well realizable. The surface qualities of grinded tungsten carbide coatings are strongly influenced by its matrix materials and by the spraying processes. The roughness values Rz of the grinded arc-sprayed WC-Fe coatings are strongly influenced by defects and pores of the surface topography. Defects at the surface topography of the WC-Co coatings could not be detected. The surface finish is directly influenced by the choice of the grinding tool. For both coatings resign bond systems are suggested. The selection of the cutting material depends on the machining task. In contrast to the CBN grinding tools, the process forces are lower but the surface roughness values are higher by using diamond grinding tools.

In current investigations, a more detailed process force model based on the design and analyze of computer experiments (DACE) is developed. In addition to this, the grinding process of free-formed coated molds is analyzed.

Acknowledgements

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