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POSSIBILITIES OF REPLACING GRINDING BY FINISHING MILLING OF NI-CR-B-SI THERMAL SPRAY COATINGS ON SHAPED SURFACES

Marek Babak & Katerina Skovajsa

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Abstract

Thermal spray coatings are often finished by grinding due to their high hardness and difficult machinability. This study investigates the possibility of replacing grinding with finishing milling of a Ni-Cr-B-Si coating deposited by the high-velocity oxy-fuel (HVOF) process on a spherical surface. The cutting speed was kept constant at v_c = 500 m/min, while the feed per tooth f_z and width of cut a_e were varied according to a 3 × 3 factorial design. Surface roughness, deviation of the resulting spherical radius, and insert wear were evaluated. The best overall compromise was achieved at v_c = 500 m/min, f_z = 0.20 mm, and a_e = 0.30 mm, resulting in a measured value of Ra = 0.515 µm, Rz = 4.058 µm, a radius deviation of +0.00338 mm, and average insert wear of 0.145 mm. The measured machining time under these conditions was 514 s, whereas the theoretically calculated grinding time was 1972 s. The results indicate that, with an appropriate selection of cutting conditions, finishing milling can represent a technologically and economically promising alternative to grinding, particularly for geometrically complex surfaces coated by thermal spraying.

Keywords: Thermal spray coatings; HVOF; Ni-Cr-B-Si; finishing milling; spherical surface; surface roughness; tool wear; cutting conditions.

1. Introduction

Thermal spray coatings are used to improve the wear, corrosion, oxidation and thermal resistance of machine components. Their deposition is often followed by machining to obtain the required geometry and surface quality [1], [2], [3]. Ni-Cr-B-Si coatings deposited by high-velocity oxy-fuel (HVOF) spraying are hard and difficult to machine, so grinding is commonly used as a finishing operation. However, the low material-removal rate can make grinding time-consuming [4], [5]. Earlier work on machining Ni-Cr-B-Si thermal-spray coatings investigated the use of a linear cutting edge as an alternative to grinding and showed that surface roughness and insert wear depend on the selected cutting conditions [6], [7], [8]. Research on HVOF-sprayed Stellite 6 has likewise examined the influence of turning parameters on surface roughness and developed predictive relationships for Ra and Rz [9]. More recent work on orthogonal cutting

of HVOF-sprayed Stellite 6 has further evaluated the interaction of cutting parameters, tool wear and surface roughness, identifying the need for more productive finishing approaches for thermally sprayed hard layers [10].

Related studies also show that milling can produce good surface quality when machining difficult-to-cut nickel-based materials. Sommer et al. investigated integrated high-speed milling of additively manufactured Inconel 718 and reported surface roughness values below Ra = 1 µm, although their process concerned laser powder bed fusion rather than thermal spraying [11]. Povolny et al. studied turn-milling of Inconel 718 produced using HVOF and DMLS, showing that the design of a linear-edge tool can significantly affect the resulting Ra and Rz values [12]. These studies support the broader feasibility of machining hard or difficult-to-cut surfaces, but they do not directly establish the performance of conventional finishing milling on a spherical Ni-Cr-B-Si HVOF coating. The present work builds on the author's earlier experimental investigation of the shape and quality parameters of machined Ni-Cr-B-Si thermal-spray coatings [13] and focuses specifically on a spherical surface, where tool engagement and local cutting conditions vary along the tool path.

The aim of this study is to determine the influence of feed per tooth f_z and width of cut a_e, at a constant cutting speed, on dimensional accuracy, surface roughness and indexable-insert wear during finishing milling of a spherical Ni-Cr-B-Si coating deposited by HVOF. The results are used to identify a practical combination of cutting parameters and to assess the potential of finishing milling as an alternative to grinding.

2. Material and Experimental Method

2.1 Workpiece and Coating

The workpiece consisted of a spherical surface manufactured from ČSN 16 343 (34CrNiMo6) steel. The radius of the base material before coating deposition was R = 24.75 mm. After deposition of the Ni-Cr-B-Si coating using the HVOF process, the radius was approximately R = 25.25 mm. The coating thickness was approximately 0.5 mm and the target final radius after machining was R = 25 mm. Metallographic evaluation confirmed a continuous coating with a lamellar structure without local defects that would significantly affect the experiment. According to the experimental study, the coating hardness was approximately 60 HRC. The workpiece and experimental basis follow the author's earlier study of Ni-Cr-B-Si thermal-spray coatings [13]. The prepared workpiece mounted in the five-axis machining centre is shown in Fig. 1.

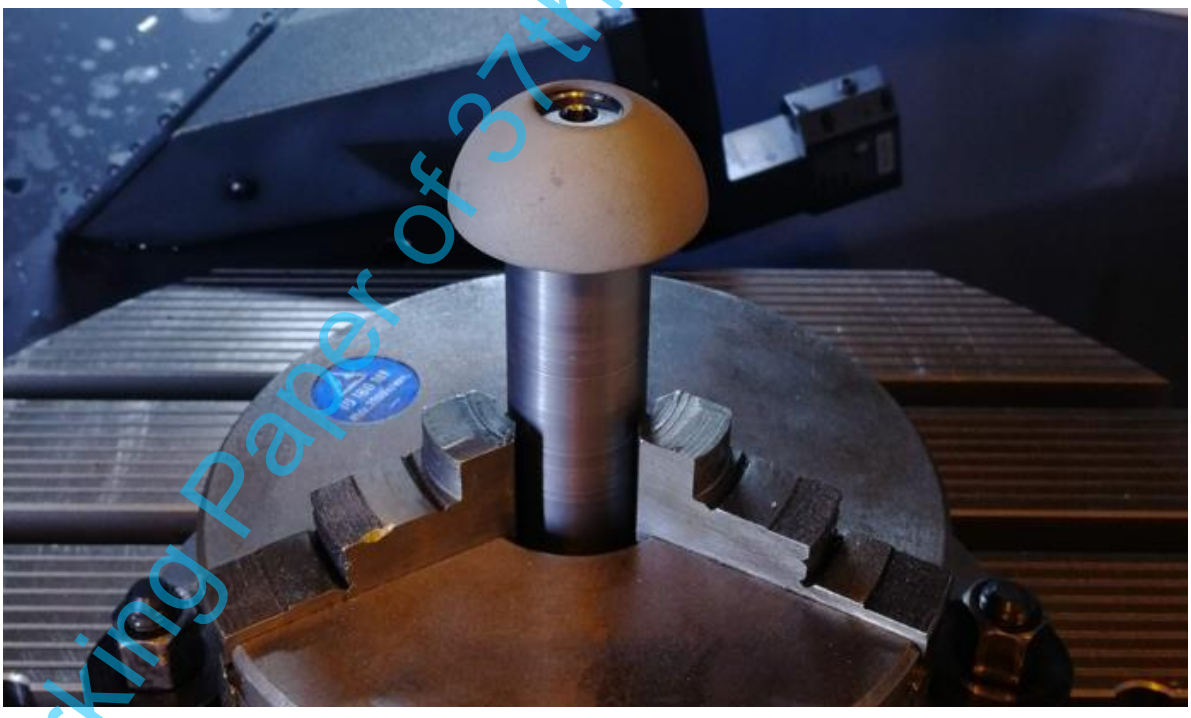

Fig. 1. Prepared workpiece mounted in the machine tool

2.2 Machine Tool, Cutting Tool and Machining Strategy

The machining was performed on a five-axis DMU 40 eVo linear machining centre. Five-axis control was used due to the spherical geometry of the machined surface. A two-flute milling cutter equipped with RNGN 120400 LX11 indexable inserts was used. The round inserts were selected for machining the hard material. The finishing tool path was

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generated using a constant-Z 3D milling strategy. Due to the required material removal, only a finishing operation with a depth of cut a_p= 0.25 mm was used. The use of a linear cutting edge for machining Ni-Cr-B-Si coatings has also been investigated in previous work [6], while turn-milling studies on HVOF-coated Inconel 718 highlight the importance of tool design for surface quality [12].

2.3 Experimental Design

The experiment was divided into a preliminary experiment and a subsequent factorial experiment. The factorial part included all combinations of three feed-per-tooth values and three width-of-cut values. The cutting speed was kept constant. The complete set of experimental conditions is summarized in Table 1.

Parameter	Value
Cutting speed, v_c	500 m/min
Feed per tooth, f_z	0.20; 0.25; 0.30 mm
Width of cut, a_e	0.20; 0.25; 0.30 mm
Depth of cut, a_p	0.25 mm
Target radius	25 mm
Number of factorial combinations	9 (including the repeated centre point)
Workpiece material	ČSN 16 343 (34CrNiMo6)
Coating	Ni-Cr-B-Si, HVOF, approximately 0.5 mm
Tool	Two-flute milling cutter, RNGN 120400 LX11

Table 1. Main experimental conditions

2.4 Measurement and Evaluation

Surface roughness is an important indicator of machined surface quality and reflects several interacting factors, including cutting-edge geometry and vibrations in the tool-workpiece system [14]. The resulting radius of the spherical surface was measured using a Carl Zeiss Prismo 7 Navigator coordinate measuring machine. Surface topography and roughness were evaluated using an Alicona IFM G4 system. Two surface profiles were evaluated and their arithmetic mean was used as the resulting roughness value. The Ra and Rz parameters were evaluated; the material bearing ratio was also assessed using the Abbott curve. Insert wear was measured using a Keyence VHX6000 digital microscope. Four measured wear values of both inserts, including the rake and flank faces, were evaluated using their arithmetic mean.

3. Results and Discussion

3.1. Dimensional Accuracy

The measured radii of the spherical surface are summarized in Table 2. The value closest to the nominal radius was achieved at f_z = 0.25 mm and a_e = 0.20 mm, where a radius of R = 24.99971 mm was measured, corresponding to a deviation of -0.00029 mm. However, in the original experiment, the negative deviation was considered unsuitable with respect to the required dimension. The largest positive deviation was measured at f_z = 0.30 mm and a_e = 0.20 mm (+0.00676 mm), whereas at f_z = 0.30 mm and a_e = 0.30 mm a negative deviation of -0.00338 mm was measured.

Test	f_z [mm]	a_e [mm]	R [mm]	Deviation [mm]
5	0.20	0.20	25.00259	+0.00259
9	0.20	0.25	25.00218	+0.00218
10	0.20	0.30	25.00338	+0.00338
11	0.25	0.20	24.99971	-0.00029
7	0.25	0.25	24.99609	-0.00391
12	0.25	0.30	25.00188	+0.00188
13	0.30	0.20	25.00676	+0.00676
14	0.30	0.25	25.00274	+0.00274
8	0.30	0.30	24.99662	-0.00338

Table 2. Measured radius of the spherical surface for the factorial combinations

The results do not show a simple linear dependence of the radius deviation on f_z or a_e. A repeated center point was included to assess repeatability. Two measurements at f_z = 0.25 mm and a_e = 0.25 mm yielded values of 24.99609 mm and 25.00556 mm. The result confirms that dimensional accuracy cannot be optimized independently of the actual coating geometry and local machining conditions. The individual measured radii and deviations are listed in Table 2.

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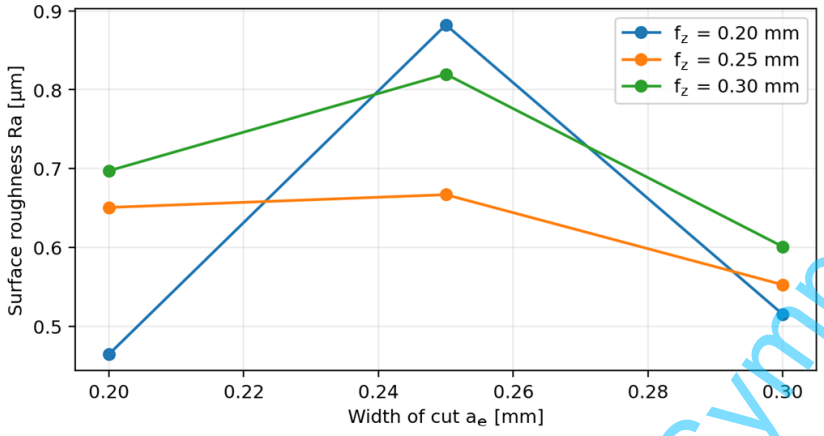
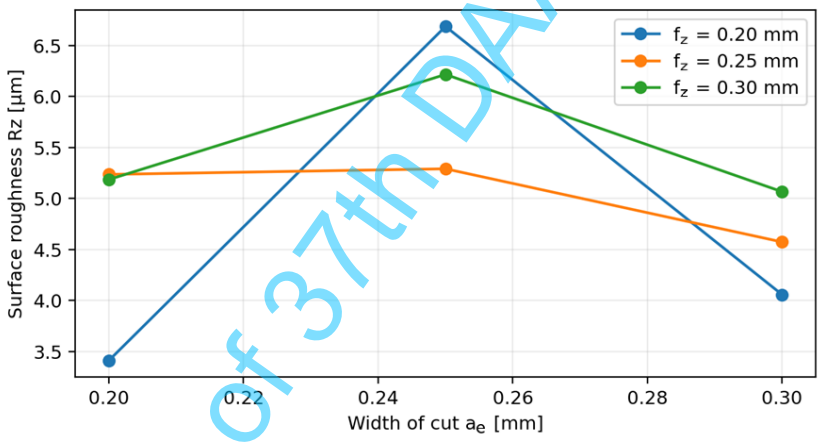
3.2 Surface Roughness



Graph 1. Effect of feed per tooth and width of cut on surface roughness Ra

The lowest Ra value was achieved at f_z = 0.20 mm and a_e = 0.20 mm, where Ra = 0.4645 µm. The dependence of Ra on feed per tooth and width of cut is presented in Graph 1. At f_z = 0.20 mm and a_e = 0.30 mm, the roughness was only slightly higher, with Ra = 0.5150 µm. In contrast, at f_z = 0.20 mm and a_e = 0.25 mm, the roughness increased to 0.8823 µm. At higher feed values, Ra generally remained below 0.82 µm, with the exception of the combination f_z = 0.30 mm and a_e = 0.25 mm, where Ra = 0.8198 µm was measured.



Graph 2. Effect of feed per tooth and width of cut on surface roughness Rz

The Rz results show a similar trend to Ra, as shown in Graph 2. The minimum Rz value was 3.4123 µm at f_z = 0.20 mm and a_e = 0.20 mm. The maximum value of 6.6863 µm was achieved at f_z = 0.20 mm and a_e = 0.25 mm. The similarity of the Ra and Rz trends supports the use of Ra as the main criterion for the subsequent selection of cutting conditions.

Test	f_z [mm]	a_e [mm]	Ra [µm]	Rz [µm]	Avg. wear [mm]
5	0.20	0.20	0.4645	3.4123	0.240
9	0.20	0.25	0.8823	6.6863	0.195
10	0.20	0.30	0.5150	4.0575	0.145
11	0.25	0.20	0.6507	5.2361	0.188
7	0.25	0.25	0.6669	5.2912	0.163
12	0.25	0.30	0.5526	4.5737	0.193
13	0.30	0.20	0.6972	5.1858	0.168
14	0.30	0.25	0.8198	6.2161	0.173
8	0.30	0.30	0.6009	5.0664	0.185

Table 3. Surface roughness and average indexable insert wear

The measured Ra and Rz values together with average indexable-insert wear for all nine parameter combinations are summarized in Table 3.

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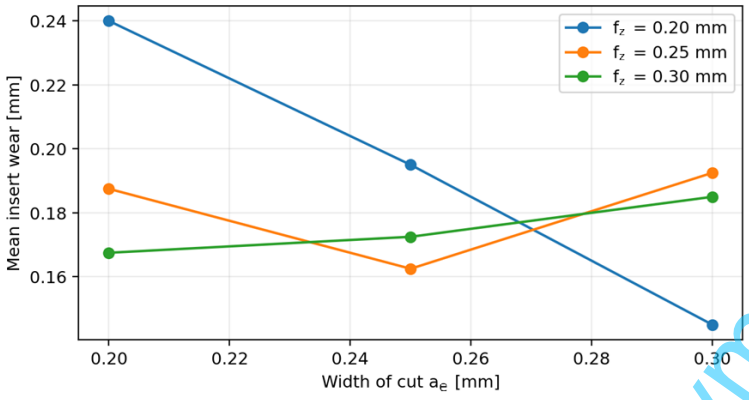
3.3 Indexable Insert Wear



Graph 3. Effect of feed per tooth and width of cut on average indexable insert wear

The wear of the indexable inserts did not show an unambiguous monotonic dependence on the cutting parameters within the investigated range. The relationship between feed per tooth, width of cut and average insert wear is shown in Graph 3. The lowest average wear in the factorial design was 0.145 mm at f_z = 0.20 mm and a_e = 0.30 mm. The highest average wear value was 0.240 mm at f_z = 0.20 mm and a_e = 0.20 mm. At f_z = 0.25 mm, the average wear ranged approximately from 0.163 to 0.193 mm, while at f_z = 0.30 mm it ranged from 0.168 to 0.185 mm.

The preliminary experiment outside the factorial design showed that inappropriate cutting conditions can lead to edge damage or significant flank wear, as illustrated in Fig. 2. The observations documented in the diploma thesis indicate that cutting-edge chipping or fracture was a prominent form of damage in several preliminary trials; pronounced flank abrasion was also observed under some conditions. The available digital-microscopy observations do not establish adhesive coating transfer as the primary wear mechanism, so this cannot be confirmed from the present data. Within the factorial design, none of the tested combinations resulted in severe tool failure. The selected parameter range was therefore suitable for evaluating the influence of f_z and a_e without the results being significantly affected by catastrophic tool damage.

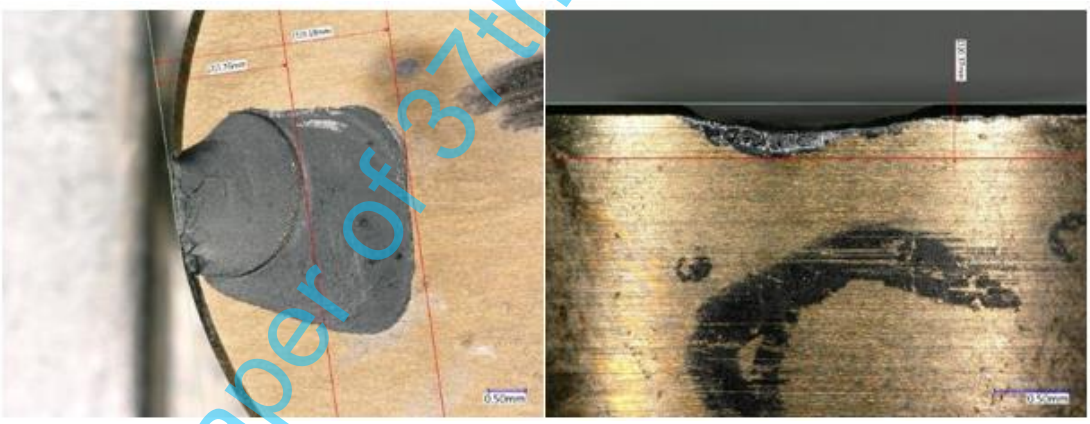


Fig. 2. Fractured insert cutting edge caused by improperly selected cutting conditions

3.4 Combined Evaluation of Cutting Conditions

Optimization according to a single output parameter leads to different preferred settings. The lowest surface roughness was achieved at f_z = 0.20 mm and a_e = 0.20 mm. The smallest absolute radius deviation was achieved at f_z = 0.25 mm and a_e = 0.20 mm; however, the measured value was slightly below the nominal dimension. The lowest average wear together with a low Ra value was achieved at f_z = 0.20 mm and a_e = 0.30 mm.

Criterion	**Best setting**	Result
Minimum Ra	f_z = 0.20 mm, a_e = 0.20 mm	Ra = 0.4645 µm
Minimum Rz	f_z = 0.20 mm, a_e = 0.20 mm	Rz = 3.4123 µm
Value closest to nominal radius	f_z = 0.25 mm, a_e = 0.20 mm	R = 24.99971 mm
Minimum average wear	f_z = 0.20 mm, a_e = 0.30 mm	0.145 mm
Best overall compromise	f_z = 0.20 mm, a_e = 0.30 mm	Ra = 0.5150 µm; Rz = 4.0575 µm

Table 4. Selection of cutting conditions according to individual and combined criteria

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For practical application, the combination of v_c = 500 m/min, f_z = 0.20 mm, and a_e = 0.30 mm was selected as the best overall compromise. This setting does not provide the absolutely lowest surface roughness, but it combines a low Ra value with the lowest measured average indexable insert wear and an acceptable positive dimensional deviation. Such a multi-criteria selection is more relevant from a manufacturing perspective than optimization based solely on surface roughness. The comparison of individual criteria and the selected compromise is summarized in Table 4. The resulting machined spherical surface is shown in Fig. 3.

Fig. 3. Resulting machined spherical surface

3.5 Productivity and Economic Comparison

The selected milling conditions required a measured machining time of 514 s per workpiece. For comparison, the grinding time was theoretically calculated as 1972 s per workpiece according to the assumptions of the original experiment. The milling time therefore corresponds to approximately 26% of the calculated grinding time, representing a theoretical saving of approximately 74% of the unit machining time, as shown in Table 5.

Technology	Unit machining time [s]	Time for 5 pcs [min]
Finishing milling	514	42.8
Grinding	1972	164.3

Table 5. Comparison of unit machining times

The simplified economic model used in the original study assumed an hourly rate of CZK 2.000/h for CNC milling and CZK 1.100/h for grinding, a price of CZK 250 per LX11 indexable insert, and a price of CZK 1.000 for a diamond grinding wheel. For a batch of five workpieces, the calculated cost was CZK 1.928 for milling and CZK 3.263 for grinding. This corresponds to an estimated cost reduction of approximately 40% in favour of milling. The result should be understood as a theoretical comparison, as energy consumption, machine depreciation, maintenance, and other overhead costs were not included in the calculation.

4. Conclusion

- This study addressed the challenge of finishing a hard Ni-Cr-B-Si coating deposited by the HVOF process on a spherical surface, where grinding is conventionally used but can require a relatively long machining time. The problem was investigated experimentally by finishing milling the coated workpiece on a five-axis machining center using a 3 × 3 factorial design with three feed-per-tooth values and three widths of cut at a constant cutting speed of v_c = 500 m/min.
- Finishing milling was experimentally verified as a technically feasible finishing process within the investigated range of cutting conditions. The parameters f_z and a_e affected surface roughness, dimensional accuracy and insert wear nonlinearly; therefore, no single parameter combination was optimal for all criteria simultaneously.

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- The lowest surface roughness was achieved at v_c = 500 m/min, f_z = 0.20 mm, and a_e = 0.20 mm, with Ra = 0.4645 µm and Rz = 3.4123 µm.
- The lowest average indexable insert wear was achieved at v_c = 500 m/min, f_z = 0.20 mm, and a_e = 0.30 mm, where it amounted to 0.145 mm.
- The best overall compromise was achieved at v_c = 500 m/min, f_z = 0.20 mm and a_e = 0.30 mm. Under these conditions, Ra = 0.5150 µm, Rz = 4.0575 µm, the spherical-radius deviation was +0.00338 mm, and the lowest measured average insert wear was 0.145 mm.
- The measured milling time under the selected conditions was 514 s per workpiece, compared with a theoretically calculated grinding time of 1972 s. This represents a theoretical reduction of approximately 74% in unit machining time. Under the simplified economic assumptions, the estimated cost of producing five workpieces was approximately 40% lower for milling than for grinding; this estimate excludes energy consumption, machine depreciation, maintenance and other overhead costs.
- Further work should evaluate process repeatability using a larger number of workpieces, establish tool life over longer machining runs, investigate cutting-edge chipping and flank wear in more detail, and perform a more comprehensive economic assessment including energy consumption, machine depreciation, maintenance and other operating costs.

5. Acknowledgments

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