Influence of drag finishing parameters on the cutting edge radius of solid carbide mills

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Abstract. Paper deals with the cutting-edge preparation of milling tools by drag finishing. The aim of the experiment was to determine the optimal parameters of the process on a prototype device for edge preparation. The prototype device was based on a 3-axis milling centre and the drag finishing media used was Al$_2$O$_3$ granulating. Tools for the experiment were manufactured on a tool grinding machine Reinecker WZS 60 from the cemented carbide rod with chemical composition WC+Co (10%). After that, the tools were drag finished. Then, cutting edges radii were measured on a Zeiss SURFCOM 5000 surface and form measuring machine. The effect of process parameters such as spindle rotation speed, feed rate and time of the drag finishing on the size of the cutting-edge radius and shape was examined. The experiment design was described as well as measurement and evaluation of the output values. Purpose of the experiment and multi-criteria analysis described in this article was to determine the influence of process parameters on the cutting-edge radius sizes when drag finishing the cemented carbide mills.

1. Introduction
The issue of edge preparation of carbide cutting tools is of high importance from the standpoint of tool wear cycle and tool life. It has been stated by author Denkena that cutting-edge microgeometry has significant impact on the tool wear [4], surface quality of machined workpiece [3], as well as on the subsurface residual stresses [10]. Having optimized tool microgeometry also allows for more economic manufacturing, which is the reason why research in this field is important. Controlled application of cutting-edge preparation has several main purposes to add strength to the edge, to eliminate the previous defect on the edge, to increase tool life, to minimize the edge chipping and to prepare the tool surface for the coating [11]. The tool edge rounding affects significantly the developed mechanical and thermal loads during material removal [4].

Using various edge preparation methods different shapes of the cutting edge can be achieved. Sharp cutting edge can be turned into either rounded shape and chamfered shape. Moreover, there are several variants or combinations of these shapes, such as trumpet form and waterfall form of rounded edge or double chamfer, uneven chamfer or combination of chamfer and rounding [9]. The most used methods for cutting edge preparation of solid carbide tools or inserts are abrasive jet machining and brushing, in addition to those there are also other methods that can be used to achieve desired cutting edge microgeometry, such as ultrasonic machining, laser beam machining etc. [6, 9]. One of these methods is drag finishing. The method is widely used for finishing parts that need to have good...
surface quality; its advantage is relatively short time needed to obtain the needed results [2]. However, with the modification of certain process parameters such as the type and size of granulate, feed rate or process time, it can also be used for stable cutting-edge preparation of solid carbide tools [4]. There are manufacturers of drag finishing machines specifically designed for edge preparation and surface modification of cutting tools, such as OTEC GmbH or Rösler GmbH.

![Figure 1 Cutting edge after preparation](image)

Using this method has positive impact on the coating adhesion on the finished surface, moreover, with modified parameters it can also be used to remove macro-particles and droplets from the coating, resulting in even lower roughness of the coated surface [1].

The purpose of the carried out experiments described in this article is to investigate the influence of process parameters of drag finishing on the cutting edge microgeometry of cemented carbide mills as well as to investigate the possibility to use machining centre for cutting edge preparation. Use of statistical tools such as multi-criteria optimization can help with determining optimal process parameters without extensive experimental testing, therefore saving time while allowing for better experiment results [5].

2. Materials and methods

| Tool parameter         | Value  |
|------------------------|--------|
| Maximum depth of cut   | 18 mm  |
| Cutting diameter       | 9.8 mm |
| Shank diameter         | 10 mm  |
| Center diameter        | 5 mm   |
| Cutting edge count     | 2      |
| Flute helix angle      | 40°    |
| Rake angle $\gamma$    | 8°     |
| Flank angle $\alpha_1$| 8°     |
| Flank angle $\alpha_2$| 22°    |

Before the mills could be drag finished, they first had to be manufactured, because there was a need to have tools with sharp cutting edge. For the purpose of the experiment the tools were manufactured from cemented carbide rod of 10 mm diameter. Specific grade of the cemented carbide was PCG F10
that is equivalent to K20-K30 by ISO. Volume of Cobalt in the material was 10% and achieved hardness was 1580 by Vickers. Material density was 14.35 kg.m$^{-3}$. [8].

The wire electrical discharge machining method was used to make workpieces with dimension Φ10h6 x 63 mm. Monolithic solid carbide mills were manufactured on the Reinecker WZS 60 tool grinding machine in the Centre of Excellence of 5-axis Machining at the Faculty of Materials Science and Technology of Slovak Technical University. CNC program was made according to the geometry of the tools in the NUMROTOPlus simulation software. Specific tool parameters can be found in table 1. A number of different grinding wheels were used in order to achieve the correct shape of the mills.

2.1. Measuring the tools
After the mills were manufactured, their macrogeometrical as well as microgeometrical shapes were measured and compared. ZOLLER genius 3 universal optical tool measuring machine was used for the purpose of measuring tool macrogeometry. It was necessary to verify, if all the required parameters were manufactured correctly. Microgeometry of the cutting edge after grinding was measured on the CNC measuring station Zeiss Surfcom 5000. This shape measuring machine is capable of measuring both the contour and the roughness of the surface. It is equipped with laser interferometer which allows for a high precision measuring resolution up to 0.31 nm. Its measuring error is ± (0.2+L/1.000) μm with L being measured length in mm. Therefore, it is a viable measuring machine to obtain cutting edge microgeometry data before its preparation [12].

Cutting edge radius was measured on every manufactured mill, so that it could be compared to the edge shape after drag finishing. Edge radii values are in the table 2.

| Tool | Edge radius (rake face-outside) [μm] | Edge radius (rake face-centre) [μm] | Edge radius on the helix [μm] |
|------|-----------------------------------|-----------------------------------|-------------------------------|
| T1   | 3.04                              | 2.31                              | 1.26                          |
| T2   | 2.12                              | 1.92                              | 3.59                          |
| T3   | 2.55                              | 2.87                              | 1.85                          |
| T4   | 2.02                              | 2.19                              | 2.23                          |

2.2. Cutting edge preparation
Drag finishing of the manufactured mills was carried out on a prototype device based on the Dugard EAGLE 1000 3-axis machining centre. Abrasive media used for the drag finishing was Al$_2$O$_3$ granulate QZ 1-2 W with grain size ranging from 1.0 to 2.0 mm, which is used for preparation of edges with radii up to 30 μm.

![Figure 2 Prototype machine for cutting edge preparation](image-url)
Moreover, prepared edges and tool surface should have very low values of roughness parameter after finishing [7]. Multiple toolpaths alternatives were drawn in Autodesk PowerShape CAD software, based on the information from manufacturers of drag finishing machines. Toolpaths were exported into Autodesk PowerMill CAM software, so that their simulations could be run. After simulations, one of the strategies that were going to be used for the experiment was chosen based on the required feed rate and tool dynamics. NC code of the chosen toolpath was generated and exported, then loaded into the milling centre. After that, the mills were drag finished with multiple different parameters that are described in table 3. The reason of choosing the parameters was to achieve constant cutting edge radius after a certain time as well as ensure the repeatability of the drag finishing process.

### Table 3 Drag finishing parameters

| Tool no. | Spindle speed [min⁻¹] | Feedrate [mm.min⁻¹] | Time [min] |
|----------|------------------------|---------------------|------------|
| 1        | 75                     | 2100                |            |
| 2        | 1000                   | 2100                | 15 30 45   |
| 3        | 75                     | 6000                |            |
| 4        | 1000                   | 6000                |            |

### 3. Results and discussion

After all the mills were drag finished, they were measured on the SURFCOM 5000 surface and form measuring machine. Results of the measurement of the cutting edges of the face teeth ($r_{n1}$ values) and helical teeth ($r_{n2}$ values) of the mills are in the table 4.

### Table 4 Measured values of cutting edges radii after drag finishing

| Tool | Cutting edge preparation in time $t_1 = 15$ min | Cutting edge preparation in time $t_2 = 30$ min | Cutting edge preparation in time $t_3 = 45$ min |
|------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
|      | Rake face (center) | Rake face (outside) | Helix | Rake face (center) | Rake face (outside) | Helix | Rake face (center) | Rake face (outside) | Helix |
| T1   | 6,79 [μm]          | 5,66 [μm]          | 7,13 [μm] | 7,02 [μm]          | 6,69 [μm]          | 8,2 [μm] | 7,14 [μm]          | 6,7 [μm]          | 8,4 [μm] |
| T2   | 4,99 [μm]          | 12,48 [μm]         | 16,01 [μm] | 6,16 [μm]          | 14,75 [μm]         | 19,17 [μm] | 6,4 [μm]          | 17,73 [μm]        | 21,34 [μm] |
| T3   | 6,59 [μm]          | 8,14 [μm]          | 7,91 [μm] | 7,97 [μm]          | 8,16 [μm]          | 8,5 [μm] | 8,03 [μm]          | 8,22 [μm]         | 9,23 [μm] |
| T4   | 6,25 [μm]          | 13,74 [μm]         | 17,47 [μm] | 7,73 [μm]          | 15,7 [μm]          | 22,24 [μm] | 7,92 [μm]          | 19,45 [μm]        | 24,86 [μm] |

Measurement was performed as follows-the tool was clamped into holder, to measure rake face surface and helix surface too. On the machine was set a curve on which the touch of the tool would pass. The contour of rake face and helix surface was obtained. Secondly, the tangent lines were attached to rake and flank contour surfaces of milling tool. After that, the circle based on 3 points was drawn. Two points were located on tangent lines and third point was located on radius of tool (figure 3). The evaluation was performed with magnification of 10000 times.

Once the results were obtained, it was possible to move on to the evaluation in order to determine what input parameters of the drag finishing process have the most significant impact on the achieved cutting-edge radii.
3.1. Size of the cutting-edge radius

The cutting-edge radius increases with the increasing time of cutting-edge preparation. The measuring was done on the different locations, on the rake face close to middle of the tool (centre), on the rake face close to edge of the tool (outside) and the helix surface on the tool. Every cutting-edge radius is different and the smallest is on the rake face close to middle of the tool. It was caused by zero rotation speed in the tool axis and this part of the tool performs movement based only on feed rate. The abrasive granulate was not so effective in the tool axis and effectiveness increased with more distance from the tool axis.

On the graphs can be seen, that with the higher spindle rotation speed, the cutting edge radius increases. In the first graph where the spindle rotation speed of the preparation was 75 min\(^{-1}\), the cutting edge radius after 45 min of cutting edge preparation was only about 7 to 8 μm. But when the spindle rotation speed was 1000 min\(^{-1}\), the cutting edge radius was almost three times higher than in first situation.

![Graph 1 Dependence of cutting-edge radius \(r_n\) on time \(t\) on tool 1](image)
Graph 2 Dependence of cutting-edge radius $r_n$ on time $t$ on tool 2

Graph 3 Dependence of cutting-edge radius $r_n$ on time $t$ on tool 3

Graph 4 Dependence of cutting-edge radius $r_n$ on time $t$ on tool 4

After evaluating all graphs it can be seen that feed rate does not have a significant effect on the cutting edge radius. The values of cutting-edge radius with feed rate $6000 \text{ mm.min}^{-1}$, was only about $1\mu m$ higher than in first situation where was feed rate $2100 \text{ mm.min}^{-1}$. But, what can be seen is that, the higher spindle rotation speed has effect on uneven cutting edge radius on helix and rake surface, where for tool 2 the difference between cutting edge radius in centre and cutting edge radius on helix was $15\mu m$ and for tool 4 the difference was $16\mu m$. Spindle rotation speed has the most significant effect on the cutting edge radius.
3.2. Multi-criteria analysis

When dealing with the multi-criteria analysis, the desired outcome is usually an optimization of the process based on the chosen weight of the criterion. The assigned weight is a numerical value that reflects the importance of the criterion from the author’s standpoint. In the case of multi-criteria analysis, the partial weights should add up to one. Solving an issue through the multi-criteria analysis, it’s recommended that all of the evaluated criteria are of one type - that is either minimum or maximum. In the case of the values obtained from the experiment, all are quantitative and measured in the same units -µm, there was no need to transform them in any way, and it was possible to proceed to their evaluation. Chosen weight values for each criterion were set as follows:

- Criterion of cutting-edge radius on the helix - \( v_1 = 0.5 \). This criterion is deemed as the most important, as it affects the dimensional parameters of the milling tool, namely the tool diameter and its tolerance. Controlling this parameter is important because it directly affects the precision of the machining process.
- Criterion of the deviation of the cutting-edge radius on the face teeth from the radius in the helical teeth - \( v_2 = 0.4 \). This criterion describes how uniform is the drag finishing process, higher deviation means worse repeatability.
- Criterion of cutting-edge radius on the face teeth - \( v_3 = 0.1 \). While it can still affect dimensional accuracy for axial machining to some extent, this criterion is not deemed as important as the previous ones, therefore it was assigned the lowest weight.

All the criteria above were evaluated as maximization criteria, used method was weighted sum model, where the values of the criteria are multiplied by their weight and then added together according to the following formula (1):

\[
w_i = r_{n2} \cdot v_1 + r_{nMAX} \cdot v_2 + r_{n1} \cdot v_3
\]

where:
- \( w_i \) is value of weighted sum of criteria of \( i \) variant
- \( r_{n2} \) is cutting edge radius on the helical teeth [mm]
- \( r_{n1} \) is cutting edge radius on the face teeth [mm]
- \( v_{1,2,3} \) is weight of the criterion 1-3
- \( r_{nMAX} \) represents the maximized criterion value of the edge radius difference between the teeth on the face and on the helix of the tool.

The calculated results of this method are listed in the table 5. The analysis was done in the statistical software Minitab.

**Table 5 Results of the multi-criteria analysis**

| Order | \( \sum w_i \) | Variant | \( n \) [min⁻¹] | \( vf \) [mm.min⁻¹] | \( t \) [min] |
|-------|----------------|---------|----------------|----------------|---------|
| 1     | 12,66          | 12      | 1000           | 6000           | 45      |
| 2     | 12,17          | 10      | 1000           | 2100           | 45      |
| 3     | 10,14          | 6       | 1000           | 2100           | 30      |
| 4     | 10,07          | 8       | 1000           | 6000           | 30      |
| 5     | 9,74           | 4       | 1000           | 6000           | 15      |
| 6     | 9,04           | 2       | 1000           | 2100           | 15      |
| 7     | 7,41           | 7       | 75             | 6000           | 30      |
| 8     | 7,38           | 3       | 75             | 6000           | 15      |
| 9     | 7,39           | 11      | 75             | 6000           | 45      |
| 10    | 7,25           | 9       | 75             | 2100           | 45      |
| 11    | 70,2           | 5       | 75             | 2100           | 30      |
| 12    | 6,72           | 1       | 75             | 2100           | 15      |
The order of the variants was determined in regard to the weighted sum value, where the lowest number represents the best variant according to the chosen weight of the criterion.

Based on the results of the analysis, following can be stated:

- For variants with higher spindle speed $n=1000 \text{ min}^{-1}$, better results were achieved than for variants with $n=75 \text{ min}^{-1}$, this indicates higher productivity when drag finishing with higher spindle speeds.
- The longer the process time was, the better the results were in consideration with the assigned weight values. Higher feed rates $v_f=6000 \text{ mm.min}^{-1}$ allowed for better results compared to the $n=75\text{min}^{-1}$.

3.3 Determination of the influence of the drag finishing parameters

The influence of the input parameters of the process on the radius of the cutting edge was determined by the DoE (Design of Experiments) method. The observed variable was radius of the cutting edge $r_n$ and influence of the following parameters: spindle rotation speed ($n$), feed rate ($v_f$) and time ($t$). In the figure 2, there is a Pareto chart of standardized effects of the factors.

The influence of the factors and their interactions can be determined based on this chart, the most significant influence have the factors spindle rotation speed ($n$), time ($t$) and combination of these factors as well.

![Pareto chart of standardized effects](image)

**Figure 4** Pareto chart of standardized effects

4. Conclusion

After drag finishing solid carbide tools in an $\text{Al}_2\text{O}_3$ granulate on an experimental device based on the Dugard Eagle 1000 3-axis machining centre, the radius of the cutting edge was measured on the Zeiss Surfcom 5000 surface and form measuring machine. The drag finishing process was carried out with set values of three different parameters-spindle rotation speed, feed rate and time. Various combinations of values for these parameters were tested in the experiment, in order to determine the influence of each parameter, as well as their combinations. Twelve different variants of the drag finishing process were tested and after every test the radius of the cutting edge was measured.

There was investigated that the greatest influence on cutting edge radius has spindle rotation speed, the size of cutting-edge radius increases with the rise of the time. However, with the higher spindle rotation speed increases the difference of cutting-edge radius in different location on the cutting tool. The uneven cutting-edge radii were reached on the tools. The feed rate influences the size of cutting-edge radius only marginally, because the comparison between tool 1 and tool 3 where was different feed rates was influenced only by 1$\mu$m. The size of cutting-edge radius was most influenced by spindle...
rotation speed and when the spindle rotation speed was 1000 min\(^{-1}\) size of the cutting edge was 3 times higher than when the spindle rotation speed was 75 min\(^{-1}\). However, the difference between size of the cutting-edge radius on rake face and helix with usage of previously mentioned condition was 15 to 16\(\mu\)m. This causes uneven size of cutting-edge radius.

The obtained data were then used in a multi-criteria evaluation of the drag finishing process. Depending on the assigned weight that reflected the importance of the measured values, the data were used for a weighted sum model that allowed for sorting out the process parameters and their combinations according to their effectiveness. Furthermore, design of experiments (DoE) model was used so that the results of the previous statistical model could be verified. Based on the results of the multi-criteria analysis, the parameters with most significant influence on the drag finishing process were identified, as well as with what values of these parameters were achieved the best results of the edge preparation as far as reliability and repeatability of the process goes. The most important parameters of the drag finishing process according to the multi-criteria analysis were found out to be spindle rotation speed and process time.

Optimal values of the process parameters were determined to be following: spindle rotation speed of 1000 min\(^{-1}\), feed rate of 6000 mm.min\(^{-1}\) and time of 45 min. All of these values were the highest ones used in the experiment; therefore, it could be assumed that the higher the process parameters values are, the better the results of drag finishing will be. Experiment results will be used as a basis for future research of high-speed drag finishing edge preparation method.

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