

## Influences of Cutting Edge Microgeometry on Durability when Milling ISO S Material

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**This article investigated the influences of the cutting edge microgeometry on durability. Combination of cutting edge geometry, cutting conditions and the properties of the machining material all influences the cutting process. It is necessary to modify the cutting edge to increase of cutting tool life and cutting process efficiency when machining materials, which are difficult to machine, such as Inconel 718 nickel alloy. Increasing the cutting tool durability and resistance are the main goals with difficult to machine materials. The cutting edge radius is the main parameter, which is modified during the experiment described in this article. After modification of the cutting edge radius, the cutting tools are tested when milling Inconel 718. Twelve cutting tools are tested. The radii of the cutting edge of these cutting tools are 15  $\mu\text{m}$ , 20  $\mu\text{m}$  and 25  $\mu\text{m}$ . Drag finishing and abrasive water jet are used to modify the cutting edge. The cutting tool durability was evaluated by wear measurement on the clearance surface on the cutting tool. The critical cutting tool wear was 150  $\mu\text{m}$ . Linear type of wear (VB<sub>B</sub>) was measured on a Multicheck optical microscope.**

**Keywords** Cutting process, Cutting edge modification, Durability, Inconel 718, Wear

### 1 Introduction

Inconel 718 is very commonly used for components, which are highly stressed during their applications. This alloy is mainly used because of its properties and mechanical advantages over other steel alloy. The main applications are in the energetic industry for turbine components and aerospace and aviation industries for jet and rocket engines. The main reason for its very good mechanical properties is its chemical composition (Table 1). Nickel and chromium are the two main chemical elements. High creep limits (up to 700 °C), corrosivity (up to 1 000°C) and high yield strength (up to 1.4 GPa) are the most important advantages. [1] [9] It means, that products made from this alloy have excellent properties. But on the other hand, a considerable disadvantage is the complicated machining. One of the problems during machining is a workpiece reinforcement due to the high plastic deformation. Also during machining, the wear of the cutting tool increases because of the higher proportion of carbides. [2]

This alloy belongs to a group of materials with poor thermal conductivity. This feature is a problem in the machining process, because the poor thermal conductivity increases the temperature on the flank face of the cutting tool up to 1 200 °C. The high cutting temperature is another reason for low cutting tool durability and the high temperature can cause damage to the surface layer of the workpiece. The cutting temperature affects the surface integrity (residual stress, hardness, micro-cracks and chemical composition of surface layers). [3] Any unfavourable change in residual stress can lead to micro-cracks on the workpiece surface. A critical density of these micro-cracks leads to fatigue fracture. Micro-cracks also cause a reduction in the workload capability of the workpiece. Diffusion wear of the cutting tool is another problem when machining nickel alloys. These alloys have a high chemical affinity for a large number of cutting materials. This is the reason for diffusion wear. High adhesion between the cutting tool and the machined surface is another disadvantage. Adhesion causes micro-welding and the

thin layer on the cutting edge can tear. This is another type of wear, called notch type wear.

There are many tried and tested methods for increasing the durability of the cutting tool. Modification of the cutting edge is one of these. During cutting edge modification, the cutting edge radius is modified to a predetermined value. [4] [5] At the top of the ground cutting edge there is a high ratio of stress concentration. This stress can cause a sudden cracking and destruction of the cutting edge. The cutting edge radius increases as a result of the modification. The cutting edge became 'blunt', but becomes more durable. A cutting tool with cutting edge modification has a higher resistance, for example against chipping. [6] Also, the surface quality of the flank and rake faces increases as a result of the modification process. Cutting edge modification also increase the adhesion between the cutting tool surface and a resistant thin layer. The deposition of thin layers is the most frequently used technology for increasing cutting tool durability. [7] Almost every type of cutting tool has a thin layer. In many cases, cutting tools with thin layers have a durability of several times higher, than uncoated cutting tools. Currently, there are many types of thin layers with different chemical compositions which can be used for many different applications, for example, milling, drilling and broaching. Multi-layer and gradient layers are often used because they combine more features. Low friction coefficient, resistance to thermal stress, abrasion resistance and diffusion wear are the main advantages of thin layers. When machining Inconel 718, heat is produced and the cutting temperature can be a critical limit for the cutting tool material. To avoid destruction of the cutting tool, process fluid is used. By using a different type of cooling, diffusion wear can be reduced almost to zero. However, a lot of cooling fluid is used during machining. Maintaining, recycling and subsequent disposal of the fluid is, both financially and environmentally, a relatively demanding process. For this reason, there are regulations for using cooling and technological fluids. [8]

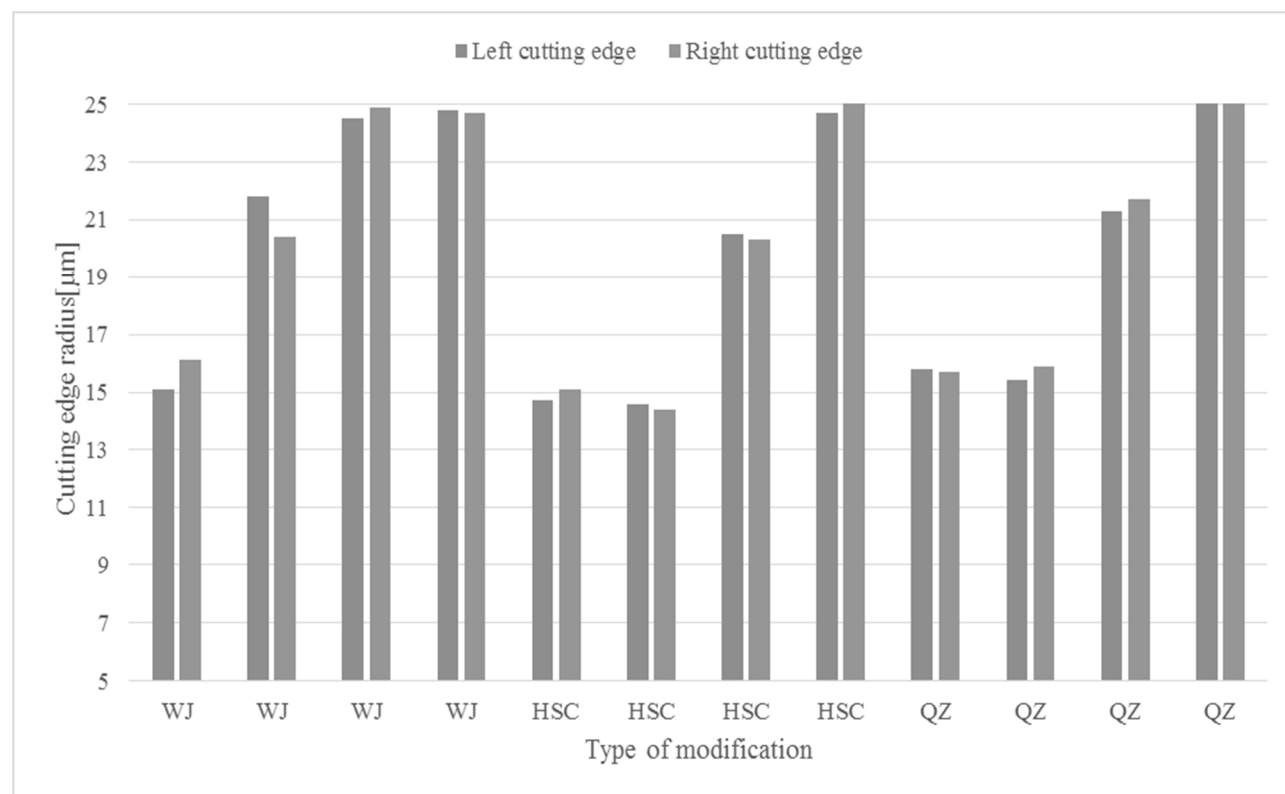
## 2 Setup of experiment

### 2.1 Cutting tool and cutting edge modification

Twelve end mill tools were used for the experiment. The cutting tool diameter was 8 mm and length 55 mm. The cutting tools were made on a CNC tool grinding machine. After grinding, the cutting edge was measured using an optical microscope. The measured parameter of the cutting edge was the cutting edge radius. The cutting edge was measured at 2 mm from the tip of the cutting tool. All twelve tools were measured in this way. The values of the cutting edge radius ( $r_n$ ) after grinding were in the range 1.98 to 2.51  $\mu\text{m}$ . The quality of the cutting edge was evaluated during measurement, to see whether the cutting edge had any defects after grinding. This control consisted of viewing the cutting edge for the possible occurrence of broken edges, etc. During measurement, the left and right cutting edges were measured. The tools in this experiment were found to have no defects, which may be due to lower cutting tool durability or the resulting bias.

After measurement, the cutting edge was modified. Water jet and drag finishing were the two technologies, used for modification. The cutting edge radii of 15  $\mu\text{m}$ , 20  $\mu\text{m}$  and 25  $\mu\text{m}$  were the target of the modification. The cutting edge radii were within a tolerance of  $\pm 2 \mu\text{m}$ . The

process parameters were selected using experience from previous research. The advantages and disadvantages of the modification methods were demonstrated during the modification. An advantage of the water jet over drag finishing was the considerably shorter process time. On the other hand, the biggest disadvantage was that only one cutting edge was modified during one process. Larger differences between the left and right cutting edges were caused by using the water jet for modification. During drag finishing, the cutting edges were modified in one process. The process media have the biggest influence on the symmetry and the quality of the cutting edge radius. Walnut shells with silicon carbide (HSC 1/300), and corundum (QZ 1-3W) were used. The most symmetrical cutting edges were achieved with HSC 1/300. But the main disadvantage of HSC 1/300 is the long process time, especially for cutting edges 20  $\mu\text{m}$  and 25  $\mu\text{m}$ . For cutting edge 25  $\mu\text{m}$ , the process time was 23 minutes. QZ modification followed drag finishing in HSC. QZ is more abrasive, so the process time was shorter, compared to HSC. However, the cutting edge has a lower quality surface; the marks after grinding were still visible on the flank and rake surface. The following graph shows the cutting edge radius after modification. Tools 1 – 4 were modified by water jet, 5 – 8 were modified by drag finishing (HSC) and 9 – 12 were also modified by drag finishing (QZ).



**Fig. 1** Cutting edge radius of cutting edge after modification

### 2.2 Workpiece material

Nickel alloy Inconel 718 was chosen as the workpiece material for the experiment. For many years it has been known that, this material is hard machined material for its properties. The cutting edge becomes intensely worn dur-

ing machining due to high abrasion and high cutting temperature. This alloy is composed of many chemical elements in varying proportions. The exact chemical composition is shown in the following table. The mechanical properties of Inconel 718 are:  $R_{p0.2} = 1040 \text{ MPa}$ ;  $R_m = 1275 \text{ MPa}$ ;  $A \text{ min } 15\%$ ;  $HB \text{ } 341$ . [9]

**Tab. 1** Chemical composition (%) of nickel alloy INC 718

Ni	Cr	Fe	Mo	Nb	Ti	Al	C
50 – 55	17 – 21	Bal.	2.8 – 3.3	4.75 – 5.5	0.65 – 1.15	0.2 – 0.8	Max. 0.8

### 2.3 Cutting process

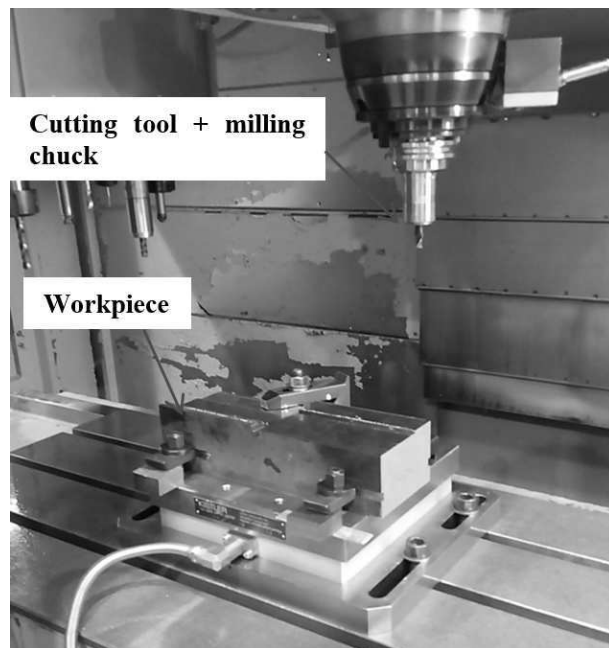
The following table shows the process parameters. These process parameters were constant throughout the experiment. Constant parameters were necessary to verify

the effect of the cutting edge radius when machining nickel alloy. The values of each process parameter were based on previous experiments. These experiments were necessary for obtaining the optimum cutting conditions for machining Inconel 718 with an end mill tool.

**Tab. 2** Process parameters for milling

$v_c$ [m/min]	rpm [ $\text{min}^{-1}$ ]	$v_f$ [mm/min]	$f_z$ [mm]	$a_p$ [mm]	$a_e$ [mm]
35	1393	111.4	0.04	3	0.5

The cutting tool was clamped into the spindle of three axis milling centre by a Tribos polygonal chuck. The workpiece was clamped to the work bench by a set of clamps. The machined length was 120 mm for each tool pass. Cooling fluid was used during machining, which was fed to the cutting area by the external cooling circuit. Cooling fluid was used to reduce the thermal load on the cutting edge. At the same time, cutting fluid was used to avoid diffuse or chemical wear on the cutting edge. The goal was to achieve abrasive cutting tool wear.

**Fig. 2** System machine – tool – workpiece

### 2.4 Experimental procedure

The experimental procedure was the same for all the tested cutting tools. It consisted of the following steps:

1. Clamping the cutting tool into a polygonal clamp with an unloaded length of 25 mm.
2. Measuring the flank face and creating an original mask used for cutting tool wear measurement.
3. Clamping the cutting tool into the milling centre. The first linear pass on the workpiece followed. Unclamping cutting tool and measuring the cutting tool wear.
4. Measuring the wear after four linear passes. When  $VB_B$  wear approached 150  $\mu\text{m}$ , the number of passes was adjusted.

**Fig. 3** Optical microscope Multicheck PC 500

## 3 Experimental analysis

Twelve cutting tools with different microgeometries were used in the experiment. Water jet and drag finishing were used to modify of the cutting edge microgeometry. The following table shows the cutting edge radius after modification for each cutting tool.

**Tab. 3** Cutting tool overview and technology used for microgeometry modification

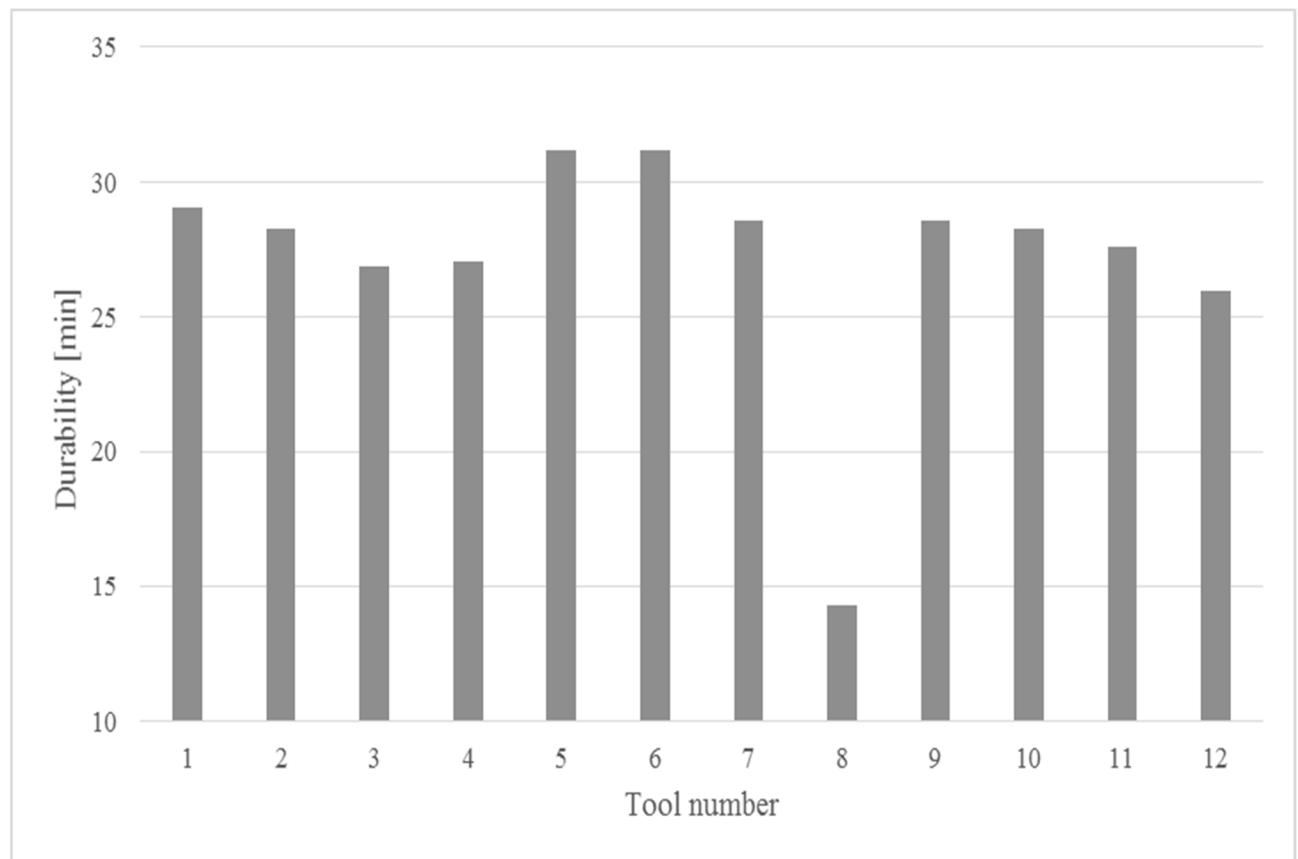
Tool number	Type of modification	Cutting edge radius [ $\mu\text{m}$ ]
1	Water jet	15.1
2		21.8
3		24.5
4		24.8
5	Drag finishing – HSC 1/300	14.7
6		14.6
7		20.5
8		24.7
9	Drag finishing – QZ 1 – 3W	15.8
10		15.4
11		21.3
12		25.0

As mentioned above, the results were evaluated on an optical microscope. The linear wear of the flank surface was the main parameter used for evaluating the cutting tool wear. The  $VB_B$  wear was measured on the flank face

according to ISO 3685. Limit wear was  $150 \pm 3 \mu\text{m}$ . As can be seen from the following figure, the cutting tools with radius  $15 \mu\text{m}$  were more durable than tools with radii  $20 \mu\text{m}$  and  $25 \mu\text{m}$ . The progressive wear increase was recorded during the first pass in the experiment. The first pass was considered to be the 'tool cut'. During the first pass, the working cutting tool geometry was created (geometry modified by cutting edge modification was changed). Rapid increase of wear was reduced and during further passes the increase of the wear was linear.

Cutting tools 5 and 6 had the highest durability. Also,

they are the only tools with durability longer than 30 minutes. It is also clear that cutting tools with a higher cutting edge radius are less durable. These tools have a larger friction area in the tertiary plastic deformation. This friction increases the cutting tool load. Increased load contributes to the wear process. Cutting tools with  $r_n \geq 20 \mu\text{m}$  have a larger area for linear types of cutting tool wear. The lowest durability was achieved by cutting tool 8 ( $r_n = 25 \mu\text{m}$ ). In this case, the wear rapidly increased until the flank face was deeply eroded.



**Fig. 4** Cutting tool durability when reaching  $VB_B = 150 \mu\text{m}$

### 3.1 Analysis of flank face wear

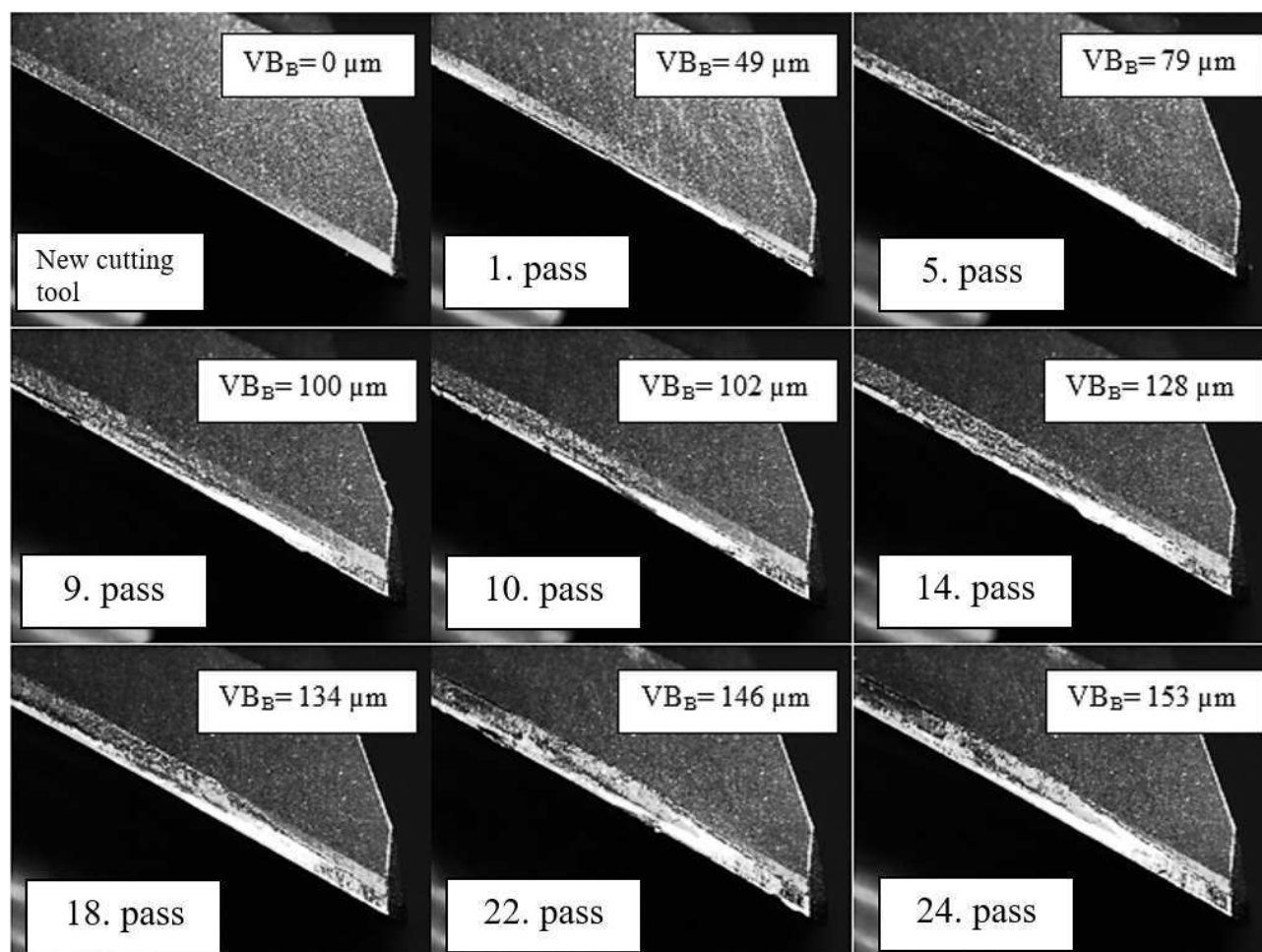
An abrasive type of wear was found on the cutting edge of all the tested cutting tools. Abrasive wear is one of the characteristic types of wear when Inconel 718 is machined, because of the high chromium content in the alloy, as can be seen from chemical composition Tab. 1. When the thin layer TripleCoating Cr was worn, the size of the flank face wear increases immediately, because the cutting tool material can not resist the force and heat loads. Also the chip formation was more energy intensive inasmuch as the cutting tool lost the advantages of the thin layer. Higher friction between the flank face and the workpiece surface was also a reason for increasing wear. Machining a reinforced layer during the experiment was another reason for increased cutting tool wear. The following figure shows the development of wear in relation to the number of passes.

The wear analysis of the cutting tools by differential

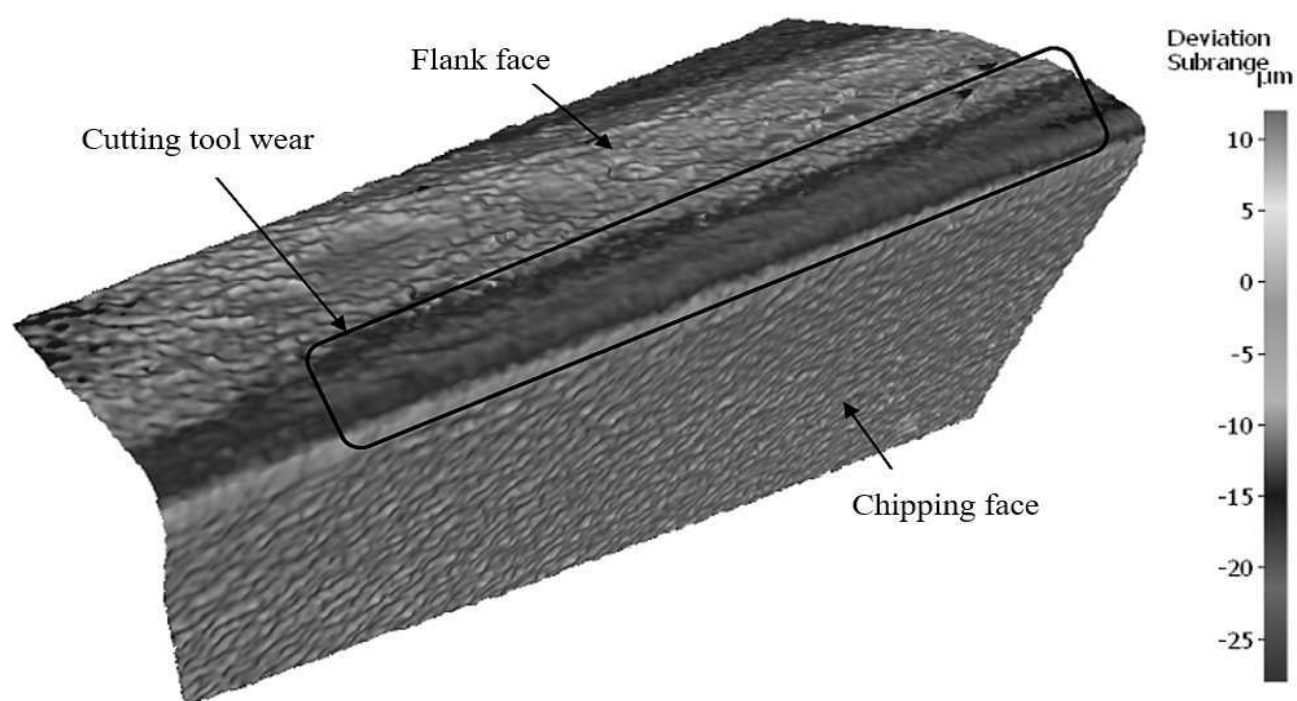
analysis was the next step in the experimental evaluation. The main principle during differential analysis is comparing the new and worn cutting edge. These two samples are folded into one another in microscope software. It was necessary to measure the cutting edge at the same distance from the tip of the cutting tool. This resulted in a unified model. The model shows the differences between the new and worn flank surfaces. The following figure shows the differential analysis of the cutting tool with  $r_n 15 \mu\text{m}$ . The width of wear was 150 microns. The maximum depth of wear was around 25 microns. A linear type of wear was found on the flank surfaces of the measured samples. The critical depth of wear is around 5 microns, because the thickness of the thin layer is just 5 microns. An area with a depth of more than 5 microns is characterized as the wear of the cutting tool material, not the thin layer. From that wear value, the wear intensity increases to the critical ( $150 \mu\text{m}$ ) value. Using differential analysis, it is also possible to evaluate, that the chipping face seems

to be without any wear. At the same time there is no built-up edge on the chipping face. Built-up edge is also an-

other, common type of wear when machining nickel alloys.



**Fig. 5** Increase of cutting tool wear in relation to the number of passes



**Fig. 6** Wear analysis of cutting edge – cutting edge radius 15  $\mu\text{m}$

## 4 Conclusion

The main focus of this article was on the durability of a milling tool when machining heavy-duty material. Nickel alloy Inconel 718 was machined during experiment. A double sided end mill tool was used for the experiment. The cutting tools were coated with TripleCoating Cr thin layer. Twelve cutting tools with different cutting edge radii were tested. The cutting edge microgeometry was modified by water jet and drag finishing. Walnut shells and corundum were used for drag finishing processes. The radii of the cutting edges were 15  $\mu\text{m}$ , 20  $\mu\text{m}$  and 25  $\mu\text{m}$ .

The following conclusions can be drawn from the experiment:

1. Cutting tools with radius 15  $\mu\text{m}$  achieve the highest durability.
2. Drag finishing is better than water jet as it achieves higher durability of tools and better surface quality.
3. It is better to use walnut shells (HSC) for drag finishing, because tools 5 and 6 achieve higher durability than tools 9 and 10 which were modified by corundum (QZ).
4. Tools with cutting edge radius 25  $\mu\text{m}$  have the lowest durability. A possible reason for this could be feed rate per tooth (0.04 mm). This low feed rate could cause problem during chip formation and also increase the time of friction between the flank face and the machined surface.

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