High Performance Machining of Profiled Slots in Nickel-Based-Superalloys

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Abstract

Broaches made of high speed steel (HSS) are state of the art for the production of complex slots in turbine discs, but they are increasingly reaching their limits in machining difficult to machine materials. The application of carbide as cutting material is a very promising approach for broaching tools and could have a significant impact on productivity. In this case, the lower fracture toughness of cemented carbide compared to high speed steel is a challenge. One effect is increased chipping of the cutting edge. Therefore, in the following paper, the influences of the carbide grade as well as the tool micro and macro geometry and cutting parameters on tool life were investigated. An analogy test set up was applied that allows a free orthogonal cut with a single cutting edge. Finally, a comparison between the productivity of HSS broaching, cemented carbide broaching and trochoidal milling was drawn.

Keywords: Cemented carbide broach, Broach design, Nickel-based-alloys

1. Introduction

Broaching is the standard machining operation for manufacturing complex profiles and has a wide field of application in automotive and aeronautic industries. This is due to the fact that by broaching high requirements on quality, regarding geometry and shape, as well as surface roughness and integrity can be fulfilled [1]. In addition to high quality demands on the components, the materials to be processed are often very demanding. Especially for turbine discs mainly high-temperature resistant super-alloys are employed and must be machined, such as Inconel 718 [2,3,4]. In turbine discs profile slots are the default feature to realize plug connections between the turbine disc and the blades [3]. This type of connections finds application in stationary gas turbines and aircraft turbines. Typical geometries of the complex shaped profiles are dovetail and fir tree profiles.

Standard tool grade for broaching nickel based alloys is high speed steel (HSS). HSS as a cutting material is relatively easy to process, which is an important requirement for the production of complex broaching tools. Besides, the high toughness of HSS is ideal for the use in interrupted cutting during broaching. However, due to the low temperature resistance, HSS has its limits in machining high-temperature alloys. Applicable cutting speeds for HSS broaches are $v_c = 2-5 \text{ m/min}$ and are thereby, relatively low compared to other machining processes. In addition, the consistent development of super alloys leads to a strong reduction of tool life of HSS broaches.

Therefore, more flexible, alternative technologies for the production of complex slots have been discussed intensively in turbo machinery industry [5,6,7,8,9]. Within the scope of technology with defined cutting edge, milling is a promising option. Different cutting strategies are thinkable, such as trochoidal milling or slot milling with ceramics. Feasibility and performance of the trochoidal milling will be discussed later in this paper by means of a benchmark comparison with broaching.

Processes for pre-machining of slots, such as grinding, water-jet cutting and wire EDM machining, are catching up [7,8,9]. Wire EDM and water-jet cutting are very flexible and
2. Investigation in analogy process for broaching with cemented carbide

2.1. Work piece material

The investigations were carried out using Inconel 718, representing one of the standard materials for turbine discs. It was delivered in solution annealed condition. To achieve aircraft industry requirements it underwent a three-stage heat treatment.

1. Solution annealing - heating to 980 °C, maintaining the temperature (60 min) and then cooling in air. 
2. Aging 1 - heating to 720 °C, keeping the temperature (480 min) and then cooling in the furnace to 55 °C
3. Aging 2 - heating to 620 °C, maintaining the temperature (480 min) and then cooling in air.

Fig. 1 shows the microstructure in a cross section after heat treatment. After the heat treatment the material had a hardness of 45 HRC. This corresponds to the material specification as required by turbine discs industry.

2.2. Experimental test setup

Due to its physical and mechanical properties, nickel based alloys such as Inconel 718 are ranked among difficult to machine materials [2,4]. Dominant types of tool wear for broaching nickel based alloys with cemented carbide is material adhesion and the appearance of chipping [6]. Hence, a cemented carbide grade has to combine a high abrasion resistance and compressive strength and at the same time high bending strength and fracture toughness to resist against micro cracking. However, these are conflicting requirements. It is well known that the cobalt content of cemented carbide grade has a significant influence on abrasion resistance and the fracture toughness [6]. Therefore in this investigation the cobalt content of the cemented carbide grades was varied between 6 % (WC-6Co) and 10 % (WC-10Co) to determine the impact on tool wear mechanism, Table 1. By grain size the grades are associated to the group of fine hard metals [2]. The WC-6Co grade has a higher hardness than the WC-10Co grade but at the same time it has lower fracture strength.

Table 1: Composition and properties of the used WC-Co carbide grades [2]

| Chemistry     | Grain size | Fracture toughness [N/mm²] | Hardness |
|---------------|------------|-----------------------------|----------|
| WC-6Co        | ~94        | 6                           | ~2200    | 1650     |
| WC-10Co       | ~89        | ~0.5                        | ~10      | >1       | 2500     | 1600     |

Table 2: Cutting parameters tool geometry and tool grade

| Cutting parameters | Tool geometry | Grade |
|--------------------|---------------|-------|
| $t_0$ [mm]         | $v_i$ [m/min] | $\gamma$ [°] | $\beta$ [°] |
| 0.050              | 10            | 6      | 30        | WC-6Co / WC-10Co |
| 0.050              | 20            | 6      | 30        | WC-6Co / WC-10Co |
| 0.075              | 10            | 6      | 30        | WC-6Co / WC-10Co |
| 0.075              | 20            | 6      | 30        | WC-6Co / WC-10Co |
| 0.075              | 20            | 0      | 30        | WC-10Co       |
| 0.075              | 20            | 12     | 30        | WC-10Co       |

Besides tool grade, cutting parameters and tool geometry were varied as shown in Table 2. First the investigation focused on the influence of cemented carbide grade and varying cutting parameters on tool life, while the tool geometry was kept constant. Second, after determining the best tool grade and cutting parameter, the rake angle was varied between 0°, 6° and 12° to discuss the influence of the tool micro geometry on tool life.

Due to the fact that broaching tools are cost intensive an analogy process, based on a single cutting edge test, was chosen for machining investigation. This allows testing varying cemented carbide grades for a wide range of cutting parameters under acceptable expenses.

The analogy test setup was developed for fundamental cutting investigations and was already introduced in former studies [10,11]. It was installed on a Forst broaching machine tool of the type 8x2200x600M/CNC. It allows testing of single cutting edge in a free orthogonal cut and with a translational movement between tool and work piece, as demonstrated in Fig. 2. Therefore an Inconel 718 sheet metal work piece (dimensions: length $l = 40$ mm, thickness $t = 35$ mm and width $w = 3.9$ mm) was mounted into a work piece fixture. In order to avoid the generation of burrs, a cast iron sheet was clamped.
into the work piece holder right behind the Inconel 718 sheet. For force measurements, the tool holder was mounted on a Kistler 3-component dynamometer. The force dynamometer was calibrated for the use on this external broaching machine. The inclination angle was set to $\alpha_{0} = 3°$, the clearance angle was kept constantly at $\alpha_{0} = 0°$. The cutting edge was prepared with an edge radius of $r_{e} = 30 \mu m$. The tool rake face of the inserts was plain without chip formers. The test neglects that in a broaching process both the cutting corners as well as several cutting edges simultaneously are in contact with the work piece. However, the test represents the cutting conditions of the broaching process at the major cutting edge and thereby the test allows fundamental investigations.

2.3. Influence of feed and cutting speed on thermo mechanical load

Before investigating the tool wear using the fundamental cutting test setup, the thermo mechanical load during broaching was analyzed. By substitution of HSS by cemented carbide accompanied with increasing cutting parameters, the thermo mechanical load at the cutting edge will change. It is well known that increasing the cutting speed the process temperature rise. In an earlier investigation process forces and temperatures were measured when broaching Inconel 718 [1]. The following discussion is based on these results. The temperatures were measured with a 2-color-pyrometer, using an optical fiber (320 µm diameter). The optical fiber was positioned in a through hole in the work piece and pointed on the cutting edge of the passing tool. Flood cooling would disturb the temperature measurement and therefore the broach was brushed with lubricant coolant before each cut. The broaching process requires that each cutting edge runs through the groove that was cut by the previous cutting edge. Thereby, after the entry of the cutting edge into the material, only a small amount of lubricant coolant is supplied to the cutting zone, anyway. Under this assumption, the measurement method is roughly representative for the broaching process.

The diagram in Fig. 3 shows the results for an HSS broach and a cemented carbide broach which had the same tool geometry. For a better comparison to the results of the fundamental cutting test, forces were normalized on the width of undeformed chip according to the method of Kienzle [12]. The left side of the diagram shows the normalized forces and temperatures measured for the HSS broaches for cutting speeds between $v_{c} = 2.5$ m/min to 7.5 m/min. The right side of the diagram shows the results for an HSS broach and increasing the cutting speed, only from $v_{c} = 2.5$ to 7.5 m/min an increase of temperature was clearly observed, correlating to decreasing cutting forces. The decrease of cutting forces can be explained by a softening effect of the material at higher temperatures. The higher heat resistance of cemented carbide enables an increase of the cutting speed from $v_{c} = 10$ to 30 m/min. At a cutting speed of 30 m/min, the temperature at the flank face of the tool reaches a value of $T = 497 °C$. Due to the fact that the temperature is measured on the flank face of the broach, it can be assumed that the temperatures in the secondary contact zone on the rake face of the tool are significantly higher [1]. It can be estimated that the high temperature strength of HSS, which is limited by a temperature of $600 °C$, would be exceeded. Normalized process forces measured with the analogy test setup for varying cutting parameters are shown in Fig. 4.

On the right side the normalized forces and temperatures recorded for the cemented carbide broach for cutting speeds between $v_{c} = 10$ m/min to 30 m/min are illustrated. Using the HSS broach and increasing the cutting speed, only from $v_{c} = 2.5$ to 7.5 m/min an increase of temperature was clearly observed, correlating to decreasing cutting forces. The decrease of cutting forces can be explained by a softening effect of the material at higher temperatures. The higher heat resistance of cemented carbide enables an increase of the cutting speed from $v_{c} = 10$ to 30 m/min. At a cutting speed of 30 m/min, the temperature at the flank face of the tool reaches a value of $T = 497 °C$. Due to the fact that the temperature is measured on the flank face of the broach, it can be assumed that the temperatures in the secondary contact zone on the rake face of the tool are significantly higher [1]. It can be estimated that the high temperature strength of HSS, which is limited by a temperature of $600 °C$, would be exceeded. Normalized process forces measured with the analogy test setup for varying cutting parameters are shown in Fig. 4.
In the top left side of the diagram, the influence of the cutting speed on the cutting forces is shown. Increasing the cutting speed from $v_c = 10 \text{ m/min}$ to $30 \text{ m/min}$, the normalized cutting forces decreases by 17%. This correlates to the decrease of 16% in the broaching process, see Fig. 3.

In the top right side of Fig. 4, the influence of the feed is drawn. An increase of feed from $f = 0.05 \text{ mm}$ to $0.075 \text{ mm}$ at a cutting speed of $v_c = 20 \text{ m/min}$ results in an increase in cutting forces by 38% (322 \text{ N/mm}). In the bottom of the diagram, the forces normal to the cutting direction are shown. They are more or less on the same level as the cutting forces and show the same trend regarding increase of cutting speed and feed. The softening of the material by increased cutting speed has a favorable effect. The increase of cutting force caused by higher feeds was partly compensated by material softening at higher cutting speeds.

2.4. Influence of cemented carbide grade on tool life

The primary tool life criteria was set to $VB = 200 \mu\text{m}$ for abrasive tool wear. In addition, the presence of cutting edge break outs was an abort criterion. The test series was limited to a maximum number of 400 cuts per parameter combination, which means 16 m of cutting length. Each test was repeated at least once whereby the diagram shows the average values. In Fig. 5, flank wear is plotted depending on tool path length for the two tool grades WC-6Co and WC-10Co at varying cutting speeds and feeds.

Overall, the carbide grade with a cobalt content of 10% showed better tool wear behavior than the grade with 6% cobalt, independent on the cutting parameters.

The best result was documented for the carbide grade with a cobalt content of 10% at a cutting speed of $v_c = 10 \text{ m/min}$ and a feed of $f = 0.075 \text{ mm}$. A continuous flank wear was observed and the wear criterion of $VB = 200 \mu\text{m}$ was not reached up to 400 cuts. Moreover, no cracking occurred, see Fig. 6 bottom. In contrast, using the carbide grade with a lower cobalt content of 6%, micro cracks on the flank face were detected, Fig. 6. The cracks run parallel to the cutting edge. It is therefore estimated that they were caused by the mechanical alternating load due to the interrupted cut. The micro cracks abets cutting edge break outs which were finally tool life limiting.

Beside the cracks, a second wear mechanism occurred. Inconel 718 is very ductile and has a strong affinity to adhesion. This was observed for all cutting conditions and independent of the tool grade. The adhesion of the material causes micro welding and material smearing on both rakes and flank face of the tool. These material adhesions are partially removed when the cutting edge reenters the work piece material. In combination with the micro cracks, observed for WC-6Co running parallel to the cutting edge, the removal of the adhered material causes micro chipping. The surface topography of the cutting edge after chipping supports new material adhesion and amplifies thereby the wear progress. The cemented carbide grade WC-10Co has higher fracture toughness than WC-6Co. This reduces the risk of micro cracks and thereby the occurrence of break outs, even though material adhesion is still observed.

Beside the carbide grade, the tool geometry has a significant influence on tool wear. Even though cutting forces are lower for a feed of $f = 0.05 \text{ mm}$, the higher feed of $f = 0.075 \text{ mm}$ shows a better wear behavior for both tool grades. Due to the fact that for a low feed rate the undeformed chip thickness is in the same scale as the cutting edge roundness, the risk of squeezing and rubbing increases and could have enhanced chipping at the cutting edge.
As well, the cutting speed had a significant influence on the tool wear mechanism. Even though material adhesion was observed for all combinations of cutting parameters and tool grades, a reduction of adhesions was observed for higher cutting speeds. At the same time, the higher cutting speed causes a higher impact when the cutting edge cuts into the work piece, amplifying chipping at the cutting edge.

As an intermediate conclusion, it can be pointed out that cemented carbide with cobalt content of 10% is suitable for broaching Inconel 718 under the investigated process parameters. For realizing of higher cutting speeds, a further stabilization of the cutting edge is necessary.

2.5. Influence of rake angle on tool life

In order to stabilize the cutting edge, the edge micro geometry can be modified. Earlier investigations using the described test setup showed that the rake angle has a significant impact on cutting edge stability [10]. For the tool grade WC-10Co the rake angle $\gamma$ was varied in between $0^\circ$, $6^\circ$ and $12^\circ$. To increase material removal rate the highest process parameters were taken for the investigation. Fig. 7 shows tool wear development for a feed of $f = 0.075$ mm and a cutting speed of $v_c = 20$ m/min. Each test was repeated at least once. Even though a rake angle of $\gamma = 12^\circ$ caused approximately 15% lower cutting forces compared to $\gamma = 0^\circ$, the higher positive rake angle of $12^\circ$ showed chipping of the cutting edge even after the first cuts. Reducing the rake angle increased tool life. An explanation could be a reduction of normal stress applied on the rake face. An investigation on plastic contact length showed a decrease of length when increasing the positive rake angle. Using the model of Merchant [13] the normal stress $N$ on the surface were calculated by the formula $\sigma_N = \frac{F_N}{A_p}$ what led to the following result for $\gamma = 12^\circ$ to $769$ N/mm$^2$ and for $\gamma = 0^\circ$ to $662$ N/mm$^2$. Meaning even when the absolute cutting forces are higher for $\gamma = 0^\circ$, the normal stress is lower than for $12^\circ$ rake angle.

It can be summarized that by using a rake angle of $\gamma = 0^\circ$ the cutting edge is stabilized and allows an increase of cutting speed from $v_c = 10$ m/min to $20$ m/min without chipping at the cutting edge. Further investigation could be done to determine the effects of negative rake angles and the influence of edge preparation on tool wear.

3. Alternative high performance machining operations

Considering the high potential of broaching with cemented carbide, a comparison of productivity between alternative high performance machining operations with state of the art technologies, in the scope of cutting with defined cutting edge, is interesting. To answer the question, a comparison of mean machining times was done between cemented carbide broaching, HSS broaching and trochoidal milling. For the calculation, standard cutting parameters and tool life for machining nickel based alloys were used. Hence, the comparison based on mean machining time is still reasonable without directly taking tool life and manufacturing costs into account.

For the benchmark a slot with a depth of 34 mm, maximum width of 17.8 mm and a minimum width of 9 mm at a length of 45 mm was defined as shown in Fig. 8. The slot shape estimates the geometry and volume machined by a standard rough broaching process with HSS. For a HSS broach the rise per tooth was defined between 0.043 to 0.063 mm. With a pitch of 11 mm, the broach would have a total length of approximately 5.9 m.

It can be seen in Fig. 8 that the mean machining times for broaching, HSS broaching and trochoidal milling are estimated to be $4.5$ min. With a pitch of 11 mm, the broach would have a total length of approximately 5.9 m.

- Milling trochoid: uncoated carbide, 3 different tools needed, $f_z = 0.032$ mm/tooth
- Broaching: no. of details: 12, total broach length 5.9 m, $f = 0.043 – 0.065$ mm/tooth, with HSS
- Milling with cemented carbide

Material: Inconel 718
Tool grade: WC-10Co
Cooling lubricant: Ilobroach 9CF
Process: Orthogonal cutting

Fig. 7: Tool wear depending on tool path length [10]

Fig. 8: Comparison of total machining time per slot for pre-slotting with trochoidal milling, broaching with HSS and cemented carbide tools acc. to MTU Aero Engines [10]
The mean machining time for the HSS broach was calculated based on a lower cutting speed of \( v_c = 2 \) m/min and a higher speed of 5 m/min, resulting in a mean machining time of 2.9 to 1.2 minutes per slot.

Due to the high thermo mechanical load when machining Inconel 718, standard slot milling would not be useful. Therefore, a more advanced milling strategy was taken for the comparison. By trochoidal milling the warp angle is reduced. Thereby tool load is reduced and a higher depth of cut can be realized. The slot is divided into four sections, taking the slot geometry into account. This has two reasons: First of all, the use of the maximal applicable tool diameter increases the material removal rate. Secondary, an overload of the end mill has to be avoided. The four sections are illustrated in the lower left corner of Fig. 8. Thus the last section is machined with the same tool diameter. The mean cutting time per cut was calculated for a feed per tooth of \( f_z = 0.032 \) mm and a cutting speed of \( v_c = 80 \) m/min. These are standard cutting parameters used in industry to machine Inconel 718 by trochoidal milling. Even though the specific material removal rate is relatively higher for trochoidal milling, it takes 4.5 minutes per total slot. This is caused by the fact that the slot has to be machined in four steps. Hence, it takes significantly longer than the standard HSS broaching operation. Milling with ceramic tool material could be an interesting approach for pre-slots into nickel basis alloys in order to reduce the mean cutting time.

The use of cemented carbide as cutting material could enable cutting speeds between \( v_c = 10 \) to 20 m/min. Starting with the same tool geometry used for HSS broaching a mean cutting time of 0.6 to 0.3 min is calculated. This results in a reduction of machining time by 49 to 75 \%, compared to HSS broaching. For that reason, high potentials lie in the improvement of the broaching process, particularly the development of cemented carbide technology. Estimating a tool life development as achieved in fundamental cutting tests would make carbide broaching applicable with high productivity in industry.

4. Conclusion and outlook

In this study, the performance potential of cemented carbide for broaching is investigated and discussed in the scope of high performance cutting and compared to alternative machining operations.

For a successful implementation of carbide broaching tools, the determination of suitable carbide grade is essential. In an analogy test it was shown that WC-10Co compared to WC-6Co showed a better ratio of tool material abrasive resistance and fracture toughness for the investigated process window. The use of cemented carbide enables an increase of cutting speed from \( v_c = 2 \) to 5 m/min as used in HSS broaching up to \( v_c = 20 \) m/min. Best results were achieved for a rake angle of 0° at a feed of \( f = 0.075 \) mm.

A direct comparison between milling and broaching was done based on mean cutting time. It is shown that state of the art HSS broaching is still more efficient than trochoidal milling. The implementation of cemented carbide would significantly increase the productivity of broaching technology. Implementing cemented carbide into industrial application, broaching would fulfill all requirements of a high performance cutting process.

Further steps would be to transfer the results from fundamental cutting tests to a broaching process.

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