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Multi Flank Chip Formation in Fir-Tree Broaching Inconel 718 with Cemented Carbide

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Abstract

In aero engines sector, the connection between turbine discs and blades is realized by profiled grooves. The standard process to manufacture these fir tree or dove tail slots is broaching with tools out of High Speed Steel (HSS). On the one hand HSS has a high toughness, on the other hand though only a low hot hardness compared to other cutting materials like cemented carbide. However, for the introduction of cemented carbide broaching tools a redesign of the tool micro and macro geometry is necessary. For this development of broaching tools made out of alternative cutting materials as cemented carbide, especially in the finishing sector, the chips are from major interest due to the multi-flank chip formation and the resulting mechanical tool load.

In this work, the multi-flank chip formation in manufacturing internal radii with cemented carbide tools was investigated. High speed recordings and cutting force measurements were implemented to analyze the chip formation with regard to the typical chip formation phenomena like wrinkling and folding, which are already examined in gear manufacturing sector for gear hopping.

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Keywords: Broaching, Multi flank chip formation, cemented carbide

1. Introduction

Within the next 20 year the number of single and twin aisle passenger aircrafts will double [1]. In addition to the high demand on aircraft engines, an increase in the efficiency with simultaneous reduction of pollutant emissions is sought. One way to increase the efficiency is to increase the turbine inlet

temperature [2; 3]. This increase in temperature requires the use of higher heat-resistant materials in the turbine disk area, which, however, make the machining considerably more difficult [4; 5].

A key process in the manufacturing route of turbine disks is the machining of the profiled grooves by broaching. During the broaching process, the production of the grooves can be carried out in the

three steps: roughing, semi-finishing and finishing. In roughing, The slot is machined in slot depth direction by orthogonal cuts. In the second step, the semi-finishing, the first undercuts are performed also by rectangular cuts [6]. Particular demands are placed on the finishing process with regard to the geometrical accuracies and the tolerated influence of the broaching process on the rim zone [7–9]. In addition, during the finish machining, a chip formation takes place over the entire spline length of the unwound groove contour. This results in the formation of multi-flank chips, which are especially critical in small internal and external radii because of the chip removal and the chip forming.

In gear manufacturing processes like gear hopping, in which multi-flank chip formation also occurs, formation phenomena, such as buckling and tearing of the chips, have already been classified by many research studies [10; 11]. A simple transferability of multi-flank chip formation from gear hopping to broaching is not possible because of the completely different cutting conditions.

In addition, high-speed steel (HSS) is used as the state of the art cutting material in broaching because of its high toughness and therefore the high process stability. However, HSS has a significantly lower hot hardness compared to cemented carbide, whereby only very low cutting speeds between $v_c = 3$ and 5 m/min are possible [6; 12]. For the design of HSS broaching tools there is a lot of experience due to the widths application. Additional, many research works were done regarding the tool and process design for broaching with HSS cutting tool material [13–17]. However, this experience does not exist for cutting material of cemented carbide, which results in a high research demand for the application of this alternative cutting material.

In this paper, the multi-flank chip formation in carbide broaching is investigated and described in detail in order to enable a knowledge-based design of carbide finishing tools. For this purpose, fundamental cutting experiments as well as FEM chip formation simulations were conducted in this work.

2. Investigations in analogy process of the multi flank chip formation in broaching

When finishing dove tail or fir-tree slots, internal radii have to be manufactured. In order to carry out the largest possible number of tests with a manageable amount of material, analogy tests were carried out with

four different inner radii with cemented carbide tools, see Fig. 1. The experimental setup allows an analysis of the chip formation by high speed recordings.

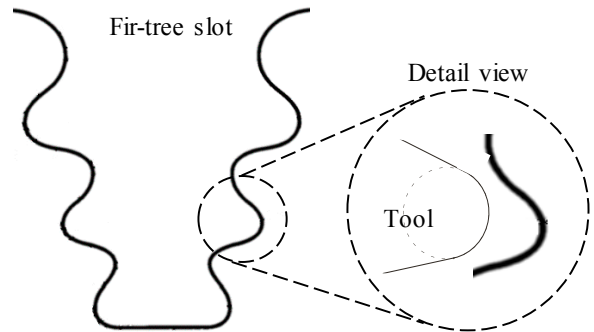


Figure 1: Manufacturing of internal radii of fir tree slots

2.1. Work piece material

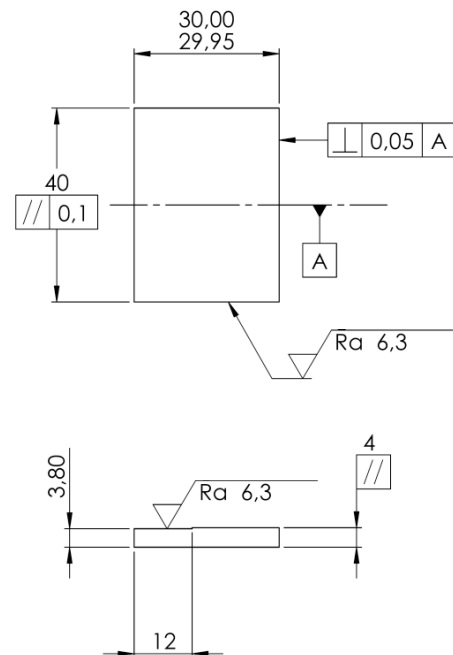


Figure 2: Inconel 718 work piece

For all experimental investigations Inconel 718 in annealed condition was used as work piece material. To achieve aircraft industry requirements it underwent a three-stage heat treatment. After the heat treatment the hardness was 45 HRC. The format of the work piece, which was fixed in the broaching tool holder is shown in Fig. 2. Below the work piece in cutting

direction a cast plate was mounted to ensure comparable conditions to the turbine disc production.

2.2. Experimental test setup

All cutting tests were conducted on a vertical CNC broaching machine from the supplier Forst Technologies. The machine type RASX 8x2200x600 M / CNC is characterized by a maximum broaching force of 80 kN, a maximum tool length of 2200 mm per stroke and a maximum cutting speed of $v_c = 150$ m/min. The positioning accuracy is 1 μ m. In order to capture the chip formation with high-speed camera, it was advantageous to reduce the broaching process to one-tooth trials. In addition, the kinematics of the process with regard to the stationary tool and the moving work piece were reversed. The work pieces to be machined were fastened in the vertical broaching machine carriage by means of clamping elements. The tool was clamped in the tool holder, which was mounted on a Kistler dynamometer type Z21289.

The dynamometer itself was fixed on the machine table. The feed and thus the rise per tooth h was set by the CNC control of the machine tool.

Furthermore, a high-speed camera was mounted in alignment with the tool holder and at a 45° angle to the horizontal machine slide. The recorded videos are used to identify characteristic phenomena in chip formation. The tool holder used was a modified turning holder from Sandvik. This corresponds to the model series T-Max® P with the standard designation MTENN 3232P 22M1. A modification of the holder and the inserts was carried out to obtain a nominal clearance angle of $\alpha_{nom} = 3^\circ$ and a nominal rake angle of $\gamma_{nom} = 0^\circ$ for all the experiments. For this purpose, material from the tool holder was removed. The test tools were Sandvik TNMG 2204 inserts with the different corner radii $r = 0.4$ mm, 0.8 mm, 1.2 mm and 1.6 mm. The chip breaker geometry of the inserts has been removed by grinding. After the grinding process no special cutting edge preparation was done. As cutting material, the substrate H13A with a WC content of 94%, a cobalt content of 6% and a grain size of 1-2 μ m was used. The experimental design is shown in Table 1.

Table 1: Experimental Design.

No. # / -	Radius r / mm	Rise per tooth h / mm	Cutting speed v_c / m/min	Rake angle γ / °	Clearance angle α / °
1	0.4	0.02	10	0	3
2	0.8	0.02	10	0	3
3	1.2	0.02	10	0	3
4	1.6	0.02	10	0	3

3. Experimental results

In the this section, the test results with regard to chip formation, process forces and surface integrity of the work piece will be shown and discussed.

In Fig. 4 the chip formations for different radii are shown. It's obvious that in the transition from the radius to the straight cut a significant wrinkling of the chip occurs. This wrinkling effects increase with decreasing edge radius. At a edge radius of $r = 1.6$ mm only a slight folding compared to the three smaller radii could be observed. Due to the lower unwinding speed of the chip on the flank compared to the corner radius, the chip was broken on the flank. An increase of the cutting speed did not result in a change of the phenomena. For this reason, Therefore, the results in

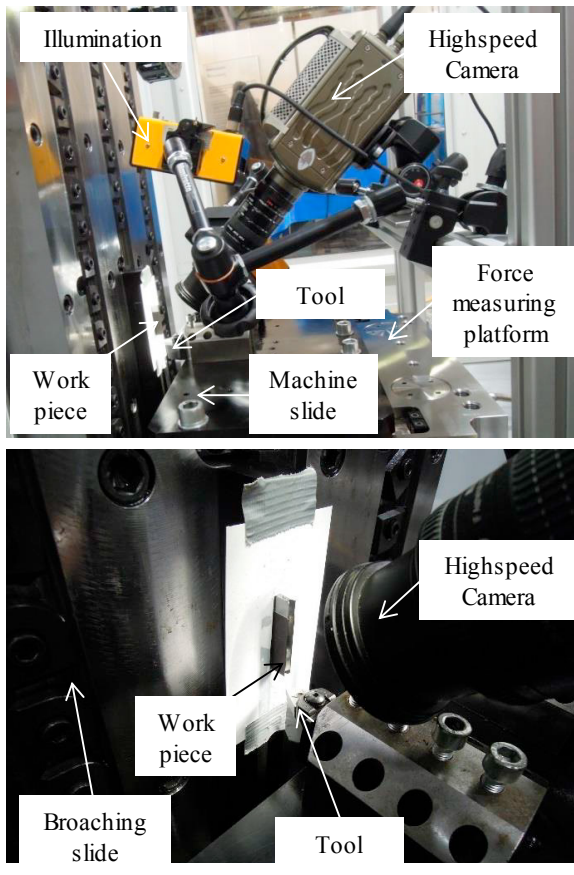


Figure 3: Experimental setup

this paper are only discussed for the cutting speed $v_c = 10$ m/min.

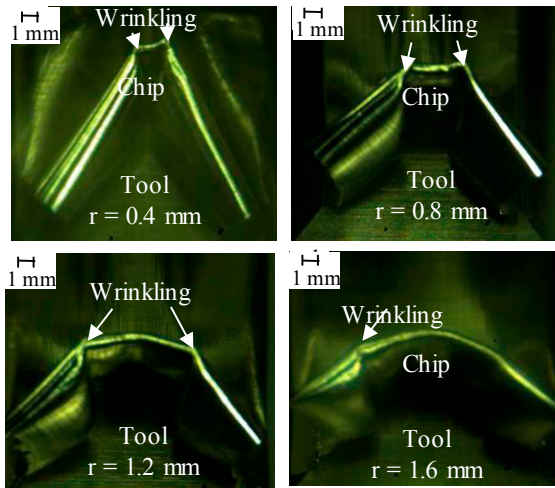


Figure 4: Multi flank chip formation in broaching with different radii

In order to investigate the influence of multi-flank chip formation on the cutting forces, a comparison of the measured process forces and analytically determined forces was carried out. The analytical determination of the cutting force was carried out according to Ozlu et al. [18]. Therefore the cutting edge radius, which was in mesh, was divided into a number of sections. For every section the local rake angle was identified. Due to the in this work chosen cutting conditions the local rake angle anywhere on the cutting edge is $\gamma_{loc} = 0^\circ$. Based on this cutting edge geometry orthogonal cutting test were performed to determine the specific cutting force without the effect of the multi-flank chip formation phenomena. The orthogonal cutting tests were performed with a rake angle of $\gamma = 0^\circ$, a clearance angle of $\alpha = 3^\circ$ and a rise per tooth of $h = 0.02$ mm. On that basis the cutting force of the different radii was calculated with disregard of the multi-flank chip formation. The comparison of the analytically determined forces with the measured forces is shown in Fig. 5. The analytically determined forces (Simulated) are at the same level or higher than the measured forces in the multi-flank chip formation tests. Regarding to the investigation it can be concluded that the multi-flank chip formation had no influence on the cutting forces in case of finishing. A declaration for this phenomena could be the low undeformed chip thickness of $h = 0.02$ mm in finishing. The forming of the resulting chips requires only a little energy which could not

measured. A reason for the overestimation of the calculated forces for the $R = 0.8$ and 1.2 mm radii could be the high rate of change in the undeformed chip thickness at the flanks of the cutting inserts.

The surface integrity regard to the work piece rim zone is also one of the important research focuses in

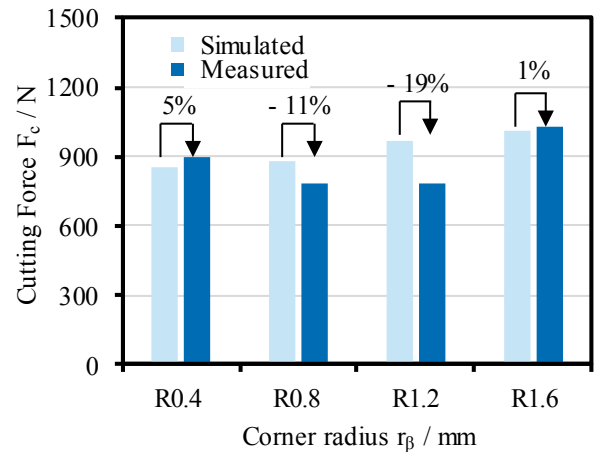


Figure 5: Comparison of the measured and the calculated cutting force

manufacturing processes. To evaluate these, metallographic cut-ups longitudinal and transversal to the cutting direction were created. Two of these cut-ups are shown in Fig. 6. In all examined cut ups, the influence of the marginal rim zone was less than $12 \mu\text{m}$.

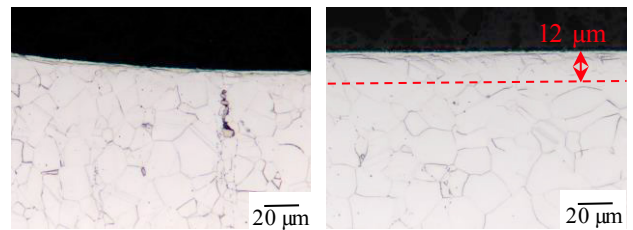


Figure 6: Longitudinal (left) and transversal (right) cut-ups

4. FEM-chip formation simulation

In addition to the experimental investigation of chip formation, which has been conducted and captured by high speed recordings, Finite Element chip formation simulations have also been performed.

The multi-flank chip formation simulations of Inconel 718 has been modelled with the coupled Eulerian-Lagrangian (CEL) formulation. Compared to the conventional pure lagrangian model for chip

formation, the CEL based FE-model is more robust and has fewer problems of element distortion and convergence. Element deletion is not necessary for the modelling. Fully coupled thermos-mechanical analysis has been performed with ABAQUS Explicit 6.14. The Johnson-Cook constitutive material model has been used to describe the flow stress of Inconel 718 with respect to the strain, the strain rate and the temperature. The concept as well as details of the CEL based FEM-model can be found in previous works [14].

A case study of the experiment No.4 with a cutting speed of $v_c = 10$ m/min and an edge radius of $r = 1.6$ mm has been conducted. Due to the high computing time, the chip formation simulation is usually performed in a short time step especially for the 3D case with large radii. For this case, a cutting time of 3.5 ms has been investigated. The equivalent plastic strain (PEEQ) distribution of the work piece is shown in Fig. 7.

Due to continuously changing of the undeformed chip thickness along the cutting edge, multi-flank chip formation cannot be simplified to a 2D case. According to Fig. 7, the wrinkling happened both in the place of the simulation and the experiment, where the undeformed chip thickness is relatively small.

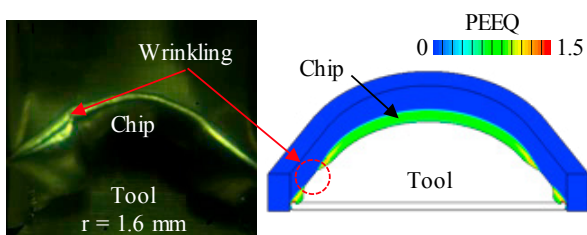


Figure 7: FEM simulation of the multi flank chip formation

5. Conclusions

In this paper the multi-flank chip formation in broaching internal radii with cemented carbide broaching tools was investigated. Based on the investigations, the following results can be derived.

- An analogy process for manufacturing internal radii with standard carbide inserts was developed. The selection of the radii was done according to the measured radii of a standard High Pressure Turbine (HPT) profile.
- Based on the presented research work, chip formation phenomena in carbide broaching could be classified.

- With increasing of the radius a reduction of wrinkling and folding effects of the chip could be observed. A radius of 1.6 mm showed nearly no folding in the transition from the radius to the flank.
- At the different chip flow speeds in combination with the different undeformed chip thicknesses and the different chip compression at the different sections of the cutting edge, a fracture of the chip at the flank can be observed after approx. $l_c = 25$ mm length of cut.
- Cutting forces, calculated from fundamental cutting tests in the orthogonal cut, were on the same level in comparison to the measured cutting forces in the radius cutting tests. The multi-flank chip formation and thereby the wrinkling and folding effects do not lead to higher cutting forces. A possible explanation are the low uncut chip thicknesses in case of finishing.
- In all investigations the maximum width of the distorted layer on the rim zone was $12 \mu\text{m}$.
- The wrinkling and bulking phenomena could also be observed in FEM chip formation simulations. This recognition allows a simulation of different profiles without time-consuming experiments.
- The study in this paper was done based on standard cutting edge geometry for carbide broaching tools which is based on previous research work [19]. A comparative study on the chip formation phenomena with typical HSS cutting edge geometries will be a part of further investigations.

Acknowledgements

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