Scaling Effects on Chip Formation and Forces in Hard Turning

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The cutting edges of tools in metal cutting are often rounded, with the advantage that the cutting edge remains stable, and chipping is avoided. There are significant differences in the chip formation with rounded cutting edges and “sharp” edges. This also depends in a wide range on the undeformed chip thickness during the process. Both variables, the rounding of the cutting edge and the undeformed chip thickness, do not only have a singular influence on the process, but also a connective one. The content of this report is the interaction of these parameters, so called scaling effects, on chip formation and the process forces in hard turning. The ratio between the radius of the cutting edge and the undeformed chip thickness was scaled for that matter. The results of this analysis indicate a significant change on chip formation and forces depending on the above-named parameters.

1 Introduction

The investigations of the shape of the cutting edge show that they are never completely sharp, but always display a certain rounding [1]. Therefore there is no direct contact between the rake face and the flank face of the cutting tool, but they are linked to another through a seamless transition area, that can be regarded, with sufficient accuracy, as a cylindrical surface. With a large undeformed chip thickness h, the cylindrical transition zone is rather small in comparison to the contact zone of the chip and the rake face. Therefore, the influence of the cutting edge radius $r_ß$ on the general characteristics of the cutting process (chip formation, residual stress, heat conduction) is marginal and can be regarded as negligible [2]. Degner has shown, that this is the case when the ratio $r_ß/h$ becomes smaller than 1 [3]. It changes radically when $r_ß/h$ gets bigger than 1. In that case, the original tool orthogonal rake angle is inactive. The actual tool orthogonal rake angle (effective tool orthogonal rake angle), is highly negative and can take values up to γ_{eff}=-75° [4, 5]. It is also comprehensible, that the cutting process with a ratio $r_ß/h = 1$ with smaller rounded cutting edges differs from a ratio $r_ß/h = 1$ with larger rounded cutting edges. For this reason, experiments were conducted in the context of SPP 1138 “Modeling of scaling effects on manufacturing processes”. The ratio $r_ß/h$ was scaled on basics of similarity mechanics, and its influences on chip formation and process forces were examined. A scaling with the ratio $r_ß/h$ with varying values at different undeformed chip thickness h was accomplished in these investigations.

2 Experimental Set-up and Procedure

To perform the experiments with smaller undeformed chip thicknesses a CNC slope-bed-turning-tool “Mikroturn” (manufacturer: Hembrug, Netherlands) was used. The maximum spindle drive power is P_A =7.2 kW and its maximum rotational speed is n_{max}= 3000 min^{-1} This machine is designed for the high precision machining of high-strength materials. The Spindle and the tracks are mounted on a (natural) granitic bed and are equipped with hydrostatic bearings. The high resolution CNC-control and the system stiffness combined with highly precise feed drive components allow workpiece qualities that have only been known to be achieved by grinding respectively fine grinding operations.

The investigations with larger undeformed chip thickness were accomplished by a CNC-slope-bed-machine MD10S (manufacturer: Max Müller/Gildemeister): maximum spindle drive power $P_{A\ max}$ = 50 kW, maximum rotational speed n_{max} = 10000 min^{-1}.

To detect influences of the machines regarding the results, several investigations were carried out with equal process parameters on both machines. It can be shown that there are deviations up to 5% concerning the process forces.

A bearing steel 100Cr6 (1.3505) was used for the investigations. Since the heat treatment also depends on the geometry of the specimen it was tested in pre-investigations, if the specimens should be prepared before or after the heat treatment. The results indicate a definite advantage regarding a consistent hardness profile and structure, when the specimen are "softly" prepared before the heat treatment. **Fig.1** describes the hardness and the structure of the specimen. All specimen were heat treatened in one lot.

The observed hardness of the specimens after the heat treatment is situated in a range between 780-840 HV0.1 (HRC 63-65) and is uniformly distributed over the complete cross section of the bases.

For this purpose, full face PCBN (cubic boron nitride) indexable inserts with SNMN 090412 geometry, that show varying rounded cutting edges (r_β = 8; 21; 60; 120 µm), are used.

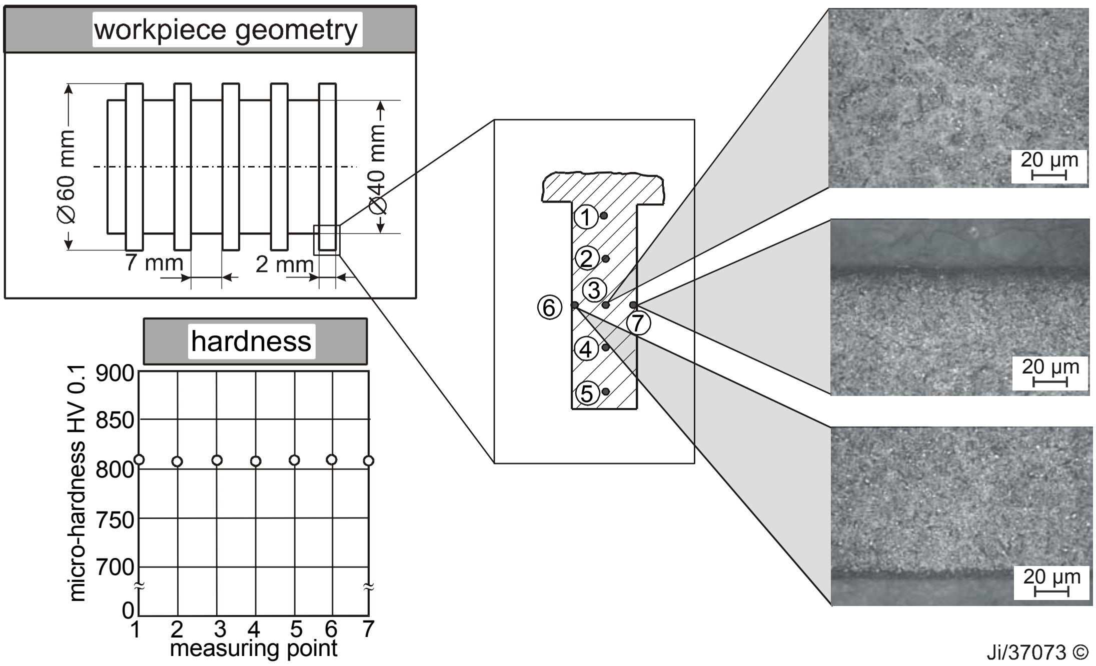

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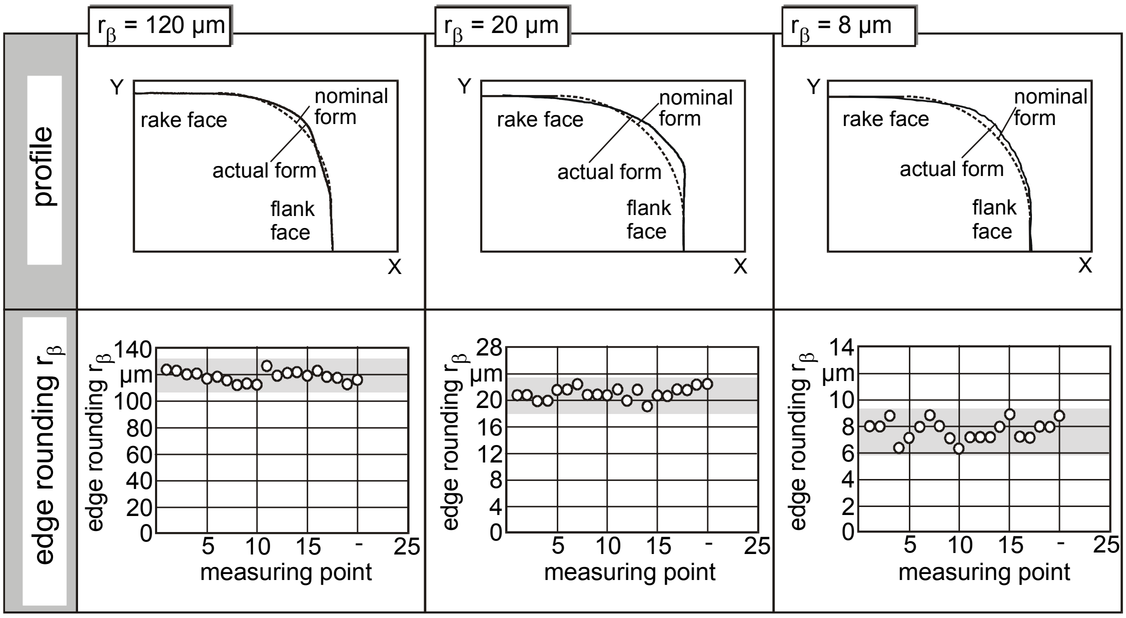
Fig. 1: Workpiece material 100Cr6 (1.3505)

The rounded cutting edges are measured with a contour measuring station from the manufacturer "Mahr". The measurement results of three out of four cutting edge radii are diagrammed in **Fig. 2.** The analysis of the measurement results show a dimensional as well as a form- and geometrical deviation.



cutter material: PKB, KD050
SNMN 090412

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Fig. 2: Cutting edge rounding

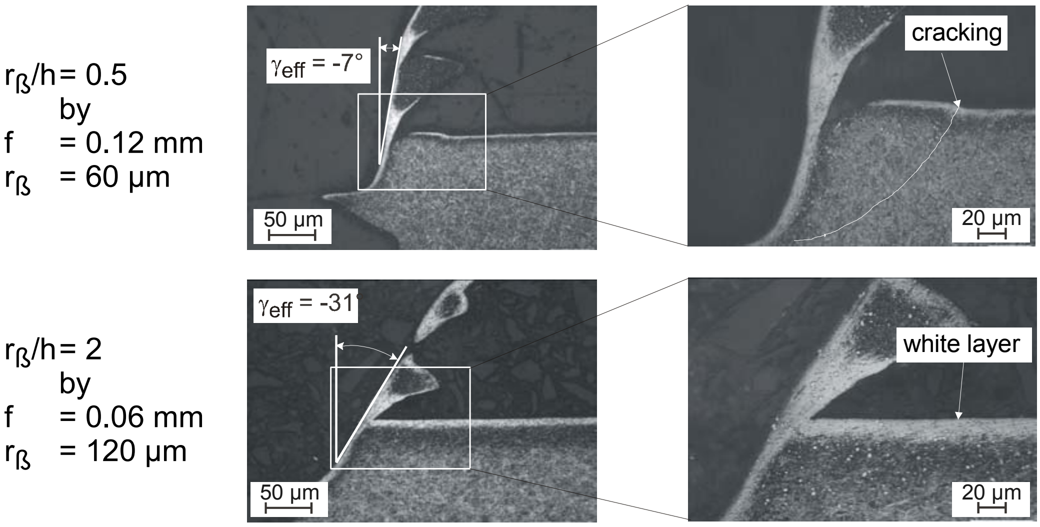
The workpieces are prepared and hardened for the orthogonal turning investigations. As described above, four different cutting edge radii are used for this analysis. The feed rates f= 0.008; 0.02; 0.06; 0.12 mm (h = f) were selected so that by every cutting edge radius the ratio $r_\beta/h = 1$ is adjusted amongst others. For smaller cutting edge radii, feed rates from min. 0.002 mm are chosen. For larger cutting edge radii, feed rates range up to max. 0.24 mm to get a definite scaling effect. All investigations are accomplished with 3 different cutting speeds v_c = 100, 180 and 250 m/min. The analysis is carried out with a special tool holder which has a tool orthogonal clearance angle of 6° and a tool orthogonal rake angle of -6°.

Subject of these investigations are chip formation and the process forces. For the analysis of the chip formation under varying cutting conditions, chip roots are generated and the chips are collected. The generated chip roots and chips are examined afterwards by metallographic analysis. In order to investigate the influences of scaling effects on the forces, the forces are measured during the process with a measuring platform from the manufacturer “Kistler”.

3 Results

3.1 Scaling Effects on Chip Formation

The geometrical analysis of the contact ratio by turning shows that the effective tool orthogonal rake angle γ_{eff} changes depending on the ratio r_β/h. The chip roots represented in **Fig.3** make this clear. It can be seen on the illustration that the effective tool orthogonal rake angle reaches up to -7° when the ratio r_β/h is below 1. This is a usual ratio for the "conventional" cutting; in other words, the undeformed chip thickness is bigger than the cutting edge radius, and, therefore, the effective tool orthogonal rake angle does not change. The effective tool orthogonal rake angle of γ_{eff}=-7° measured in **Fig.3** is thereby considerably determined by the geometry of the tool holder which, in combination with the geometry of the indexable inserts, leads to a tool orthogonal clearance angle of 6° and to a tool orthogonal rake angle of -6°. The chip root in produced with the same tool holder and indexable insert but by the ratio r_β/h above 1 shows an effective tool orthogonal rake angle of γ_{eff}=-31°. This proves that the edge radius influences the effective tool orthogonal rake angle when the ratio r_β/h is above 1. Moreover, the edge radius influences the process thermally when $r_\beta/h > 1$. The deformation zone at the cutting edge is larger with a bigger edge radius and this leads to the rise of the temperature during the process. This also shows by the thickness of the white layer when $r_\beta/h >1$. The chip form does not change significant.



process: orthogonal cutting	workpiece material: 100Cr6 (1.3505) feed rate: f = var. cutting speed.: v_c = 100 m/min edge radius: r_β= var.	cutter material: PCBN coolant: none width of cut: 1 mm hardness: 63 - 65 HRc	tool geometry SNMN 090412				
			cham.	α_{eff}	γ_{eff}	ε_r	κ
			-	6°	-6°	90°	-

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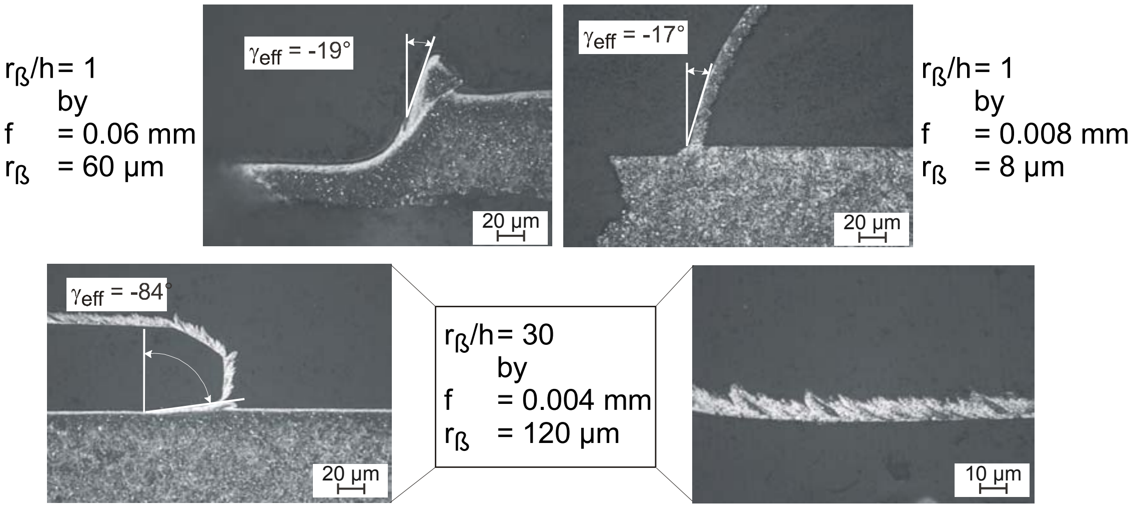
Fig. 3: Chip roots

The comparison of the chip formation in **Fig.4** shows that the chip formation by the ratio $r_\beta/h = 1$ and by the chip thickness h = 0.06 mm differs very considerably from the chip formation by the ratio $r_\beta/h = 1$ and by h = 0.008 mm. It can be also seen in **Fig.4**, that a typical hard machining chip (saw tooth chip) is produced by the ratio $r_\beta/h = 1$ and by the undeformed chip thickness h = 0.06 mm, while by the ratio $r_\beta/h = 1$ and h = 0.008 mm rather a continuous chip formation occurs. Similar continuous chips are also formed by smaller undeformed chip thicknesses with a bigger cutting edge rounding in **Fig.4**, whereby white layers in the chip formation zone and in the chip can be seen clearly in the micrographs. Previous publications show that no chip can be produced by bigger cutting edge radii and by very small undeformed chip thicknesses. This is a complicated combination of the material characteristics, of the machine stiffness (system stiffness) and of the cutting conditions. On a very stiff machine and with certain cutting conditions, a chip can be produced even with a big ratio $r_ß/h$. The results generated within the scope of the present experiments also prove that. Further results of the investigations show, that the chip formation changes considerably depending on the cutting speed. At high cutting speeds with small undeformed chip thicknesses and a big cutting edge rounding the chip even melts.



			tool geometry SNMN 090412				
process: orthogonal cutting	workpiece material: 100Cr6 (1.3505) feed rate: f = var. cutting speed.: v_c = 100 m/min edge radius: r_β= var.	cutter material: PCBN coolant: none width of cut: 1 mm hardness: 63 - 65 HRc	cham.	α_{eff}	γ_{eff}	ε_r	κ
			-	6°	-6°	90°	-

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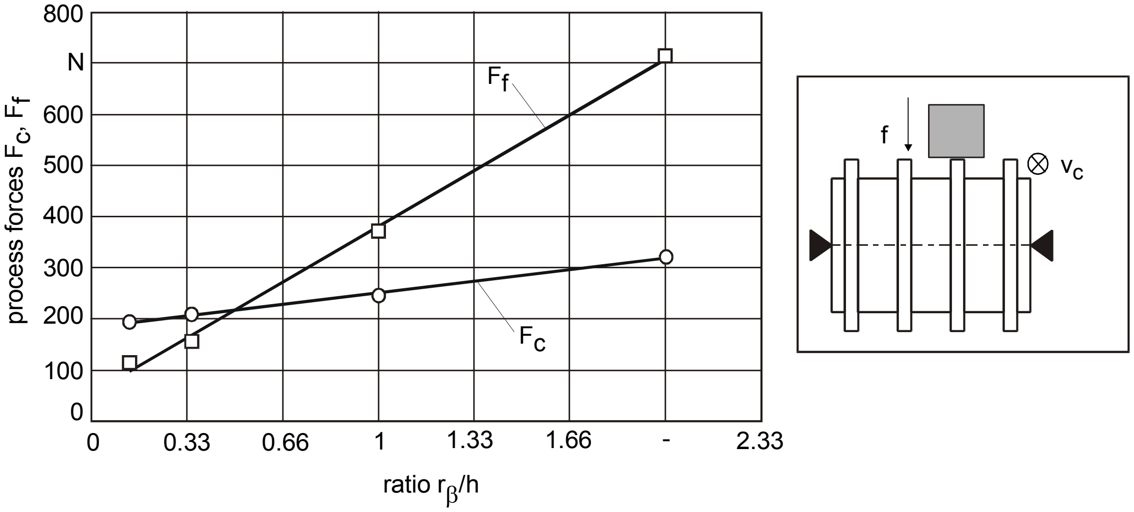
Fig. 4: Scaling effects on the chip formation

3.2 Scaling Effects on the Forces

The effects of the cutting edge radius on the process forces have not yet been investigated completely. The results regarding the process force are presented in **Fig.5**. It can be seen that the cutting force F_c and the feed force F_f rise with an increasing cutting edge radius, whereby the feed force rises almost straight proportionally with the increasing ratio r_β/h or rather with the increasing edge radius. This is comprehensible, because the stagnation zone at the cutting edge and the tool orthogonal rake angle deepens in negative direction and thereby the forces increase. The still stronger rising of the feed force by the increasing cutting edge radius depends on the material and on the process.

Fig.6 shows the curve progression of the forces by two different edge radii with smaller undeformed chip thicknesses. It can be seen that the curve progressions of the cutting force above the feed rate are almost identical, whereby the force level changes depending on the radius of the cutting edge rounding. The curve proportions of the feed force, on the contrary, are different; in other words, the feed force by a bigger cutting edge rounding increases more rapidly than the feed force by a smaller cutting edge rounding.



process:	workpiece material: 100Cr6 (1.3505)	cutter material: PCBN	tool geometry SNMN 090412				
orthogonal	feed rate: f = 0.06 mm	coolant: none					
cutting	cutting speed.: v_c = 250 m/min	width of cut: 1 mm	cham.	α_{eff}	γ_{eff}	ε_r	κ
	edge radius: r_β= var.	hardness: 63 - 65 HRc	-	6°	-6°	90°	-

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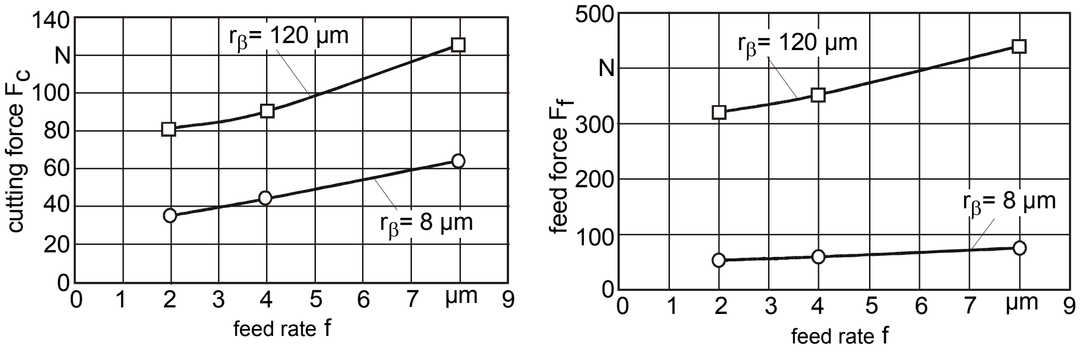
Fig. 5: Forces by variation of the ratio r_β/h



process:	workpiece material: 100Cr6 (1.3505)	cutter material: PCBN	tool geometry SNMN 090412				
orthogonal	feed rate: f = var.	coolant: none					
cutting	cutting speed.: v_c = 100 m/min	width of cut: 1 mm	cham.	α_{eff}	γ_{eff}	ε_r	κ
	edge radius: r_β= var.	hardness: 63 - 65 HRc	-	6°	-6°	90°	-

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Fig. 6: Forces by variation of the chip thickness/the feed rate

The different levels of the curves, which depend on the radius of the cutting edge rounding, are thereby considerably bigger than by the progressions of the cutting force.

4 Summary

The investigations carried out with a scaling of the ratio r_β/h by different undeformed chip thicknesses h show that both the chip formation and the forces change considerably depending on the parameters cutting edge rounding and undeformed chip thickness in orthogonal turning operations. The chip formation changes depending on the scaling effects from a segmented chip formation to a continuous chip formation. The cutting force and the feed force rise rapidly with the increasing cutting edge radius. This is the consequence of the extension of the deformation zone at the cutting edge. This results of the investigations show that some more investigations concerning the influence of the scaling effects by the hard cutting have to be carried out.

5 Literature

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