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Micro cutting of steel

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Abstract Micro-cutting offers good potentialities in order to manufacture small and medium lot sizes of micro-parts with arbitary geometry at an economically reasonable expense. Either by direct machining or as a means to fabricate moulds for micro injection moulding, the major advantages turn out to be large removal rates, good compliance with tolerance ranges, high surface quality and a wide choice of materials which can be processed. Particularly if highly wear resistant materials are to be processed, as it is the case in mould fabrication for powder injection moulding, micro cutting of steel is a very eligible option. Consequently, the possibility to manufacture wear resistant micro structures of high aspect ratios by mechanical cutting is demonstrated with regard to its specific requirements in terms of transferability of the laboratory process into an industrial manufacturing process. Accordingly the paper focuses on process parameters and repeatability of machining results and machining capabilities.

1 Introduction

The aim of the here described research is to obtain mastery of mechanical cutting of three-dimensionally designed micro structures in hard steels for mold making with a given process capability and in doing so exceeding the performance of commercially available micro cutting tools.

Criteria for the achievement of this goal are: minimum structure size, geometrical accuracy, properties of the newly created boundary layer as well as wear life of the cutting tools.

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2 Experimental conditions

2.1 Work piece materials

The practical examinations of the cutting process have been conducted with tool steel that has been heat treated to be in the hardness range between 42 and 56 HRC. The chosen tool steel finds practical application mostly in polymer processing.

The parallelism and evenness of the work pieces was adjusted to ± 0.001 mm, the surface was ground to R_z = 2.5 μm. After clamping on the machine tool the evenness could be kept below 0.002 mm in respect to the machine axes.

2.2 Cutting tools

The utilized cutting tools were cylindrical end mills cutting over the center, with diameters ranging between 0.1 mm and 0.5 mm, manufactured from ultra-fine grain tungsten carbide hard metal. The grain size of the employed hard metal grade was in average 0.7 μm and represents the theoretical lower limitation of the cutting edge roundness resp. sharpness.

2.3 Machine tool

In order to obtain a tailored experimental equipment, a three axes micro-milling-machine has been designed, built, run-in and evaluated complementarity to the cutting experiments. The table of the machine is driven by AC servo motors connected to planetary thread screws with a machining envelope of 400 mm by 150 mm by 220 mm. The evaluation of the machine proved that the positioning error as well as the minimum step width is better than 1 μm. As milling spindle, mainly an ultra-high speed spindle by The Precise Corporation, rotated with 160 000 rpm is used. This kind of extremely high spindle rotation is essential in end-milling with small tool diameters, because otherwise the cutting speed is insufficient. The high-speed spindle is equipped with hybrid ball bearings, i.e. steel bearings with ceramic balls, which provides for higher stiffness compared to air bearings and therefore makes the spindle very suitable for the machining of hard materials like steel. The run-out of the spindle bearing is <0.3 μm.

3
Cutting forces

3.1
Theoretical considerations on the cutting force

The cutting forces represent a decisive boundary condition for the limitation of tool wear life by tool breakage as well as for the deflection of the tool influencing the geometrical accuracy. Therefore as a preparatory for the cutting force measurements, theoretical calculations of the cutting forces have been carried out. In parallel with the cutting force measurements, calculations following Victor and Kienzle have been carried out. All derivations of the following equations are exhaustively elucidated e.g. in [1]

$$F_i = k_i \cdot a_p * h^{1-m_i} \cdot K_{wv} \cdot K_{ver} \cdot K_v \cdot K_\gamma \cdot K_{ws} \quad (1)$$

The specific cutting force k_i is classified, depending on the undeformed chip thickness, into three areas ranging from 0.001 mm through 1 mm, for each of which there are different specific cutting forces k_i and gradients m_i, are valid. For an undeformed chip thickness between 0.001 and 0.01 – which is appropriate for micro cutting – the specific cutting force $K_{c1\times0.01}$ and the gradient $m_{c1\times0.01}$ are relevant.

With a transformation of coordinates (Eqs. 2 and 3), cutting force and thrust force can be transferred into the workpiece-related coordinate system.

$$F_f = \frac{F_c(\phi)\cos\phi + F_{cn}\phi\sin\phi}{\sin^2\phi + \cos^2\phi} \quad (2)$$

$$F_{fn} = \frac{F_c(\phi)\sin\phi - F_{cn}\phi\cos\phi}{\cos^2\phi + \sin^2\phi} \quad (3)$$

The parameters, being based on concise empirical examinations, are only available mostly for turning of standard steels with conventional dimensions of the undeformed chip thickness, but not for micro end milling of the latest tool steels, and therefore a lot of assumptions had to be made. The calculation of the cutting forces following Victor and Kienzle can therefore in this paper only fulfill the purpose of contrasting to the measurements of cutting forces some theoretical results in the sense of an estimation, thus facilitating an assessment of the plausibility of the measurements.

The cutting forces are stated in the fixed workpiece-related coordinate-system as thrust force F_f, which is directed in feed direction, and cutting force F_{fn}, directed perpendicular to the feed direction. In the tool-related rotating coordinate-system, there occurs the radial thrust force F_{cn} and the tangential performance-carrying cutting force F_c. All tool-related force components F_i, i.e. the cutting force F_c and the thrust force F_{cn}, can be calculated using the cutting force equation of Victor and Kienzle (Eq. 1). The material used in the experiments has been chosen for its particular suitability for micro-cutting, and is not documented with values for specific cutting forces. Therefore, the steel AISI 4041 as the most comparable among the available materials was consulted.

Applying Eqs. 1 through 3 on the values given in Table 2, the following results for F_f and F_{fn} are obtained:

$$F_f(\omega = 90°, f_z = 3\,\mu\text{m}) = 0.32\,\text{N}$$

$$F_{fn}, (\omega = 90°, f_z = 3\,\mu\text{m}) = 0.66\,\text{N}$$

3.2
Cutting force measurements

The cutting forces were measured using a 3-component Kistler type 9259 force gauge. It has a measurement range of ±1500 N at an operating threshold of 0.01 N. In Fig. 1 a sample of a measurement curve is given. Clearly visible are the force signals of the two cutting edges, one of which is

Table 1. Workpiece materials

Material	Heat treatment	Hardness[HRC]
AISI H11/1.2343 (X38CrMoV51)	Quenched and tempered at 520 °C	52
AISI H11/1.2343 (X38CrMoV51)	Quenched and tempered at 560 °C	49
AISI H11/1.2343 (X38CrMoV51)	Quenched and tempered at 610 °C	42

Table 2. Boundary conditions and assumed parameters for the cutting force calculations following Victor and Kienzle /Tön90/

Boundary condition	Assumption	Corresponding parameter [Tön90]	Value [Tön90]
Material	AISI 4140 (1.7225 / 42 CrMo 4)	$K_{c1.0,01}$	2370
		$K_{cn1.0,01}$	2720
		$1\text{-}m_{c1.0,01}$	0.86
		$1\text{-}m_{cn1.0,01}$	0.71
Tool	Tungsten carbide end mill, (diameter 0.3 mm)	K_{wv} (Influence of tool material)	1.3
		K_{wver} (Influence of method)	1.3
Cutting velocity v_c	30 m/mm	K_v (Influence of cutting velocity)	1.2
		K_γ(Influence of rake angle)	1.1
		K_{ws} (Influence of tool wear)	1.3
Penetration angle ω	90°		
Depth of cut a_p	0.01 mm		
Feed rate f_z	0.003 mm		

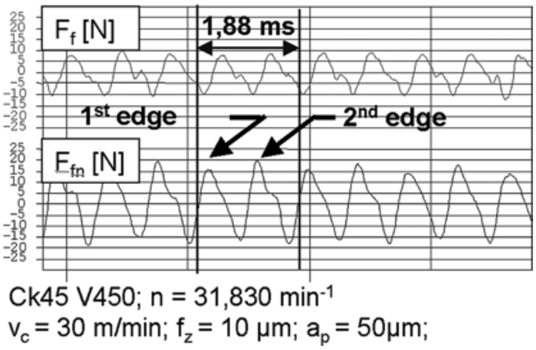


Fig. 1. Measurements of the cutting forces

cutting deeper due to the added up run-out of spindle, tool shank and cutting edges.

The cutting forces have been determined with sharp cutting tool (0 mm tool path) and are displayed in the following diagrams (Fig. 2) in respect to the feed rate for work piece material AISI HI 1 (X 40 CrMoV 5 1) with a hardness of 52 and 42 HRC.

Compared to the section "theoretical considerations on the cutting forces" these values are higher, which can be attributed both in the uncertainty from the difficult to estimate correction factors of the cutting forces equation and to the unknown transfer function of the dynamometer.

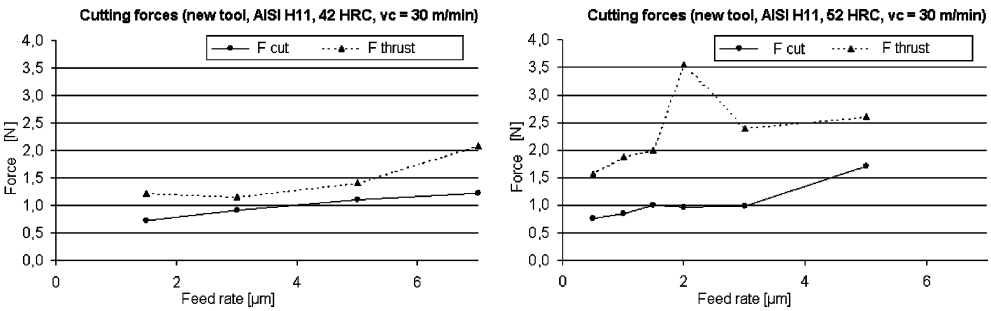


Fig. 2. Cutting forces at begin of cutting operation (sharp cutting edge) in respect to the feed rate for a material AISI H11, $v_c = 30$ m/min, $a_p = 10$ μm

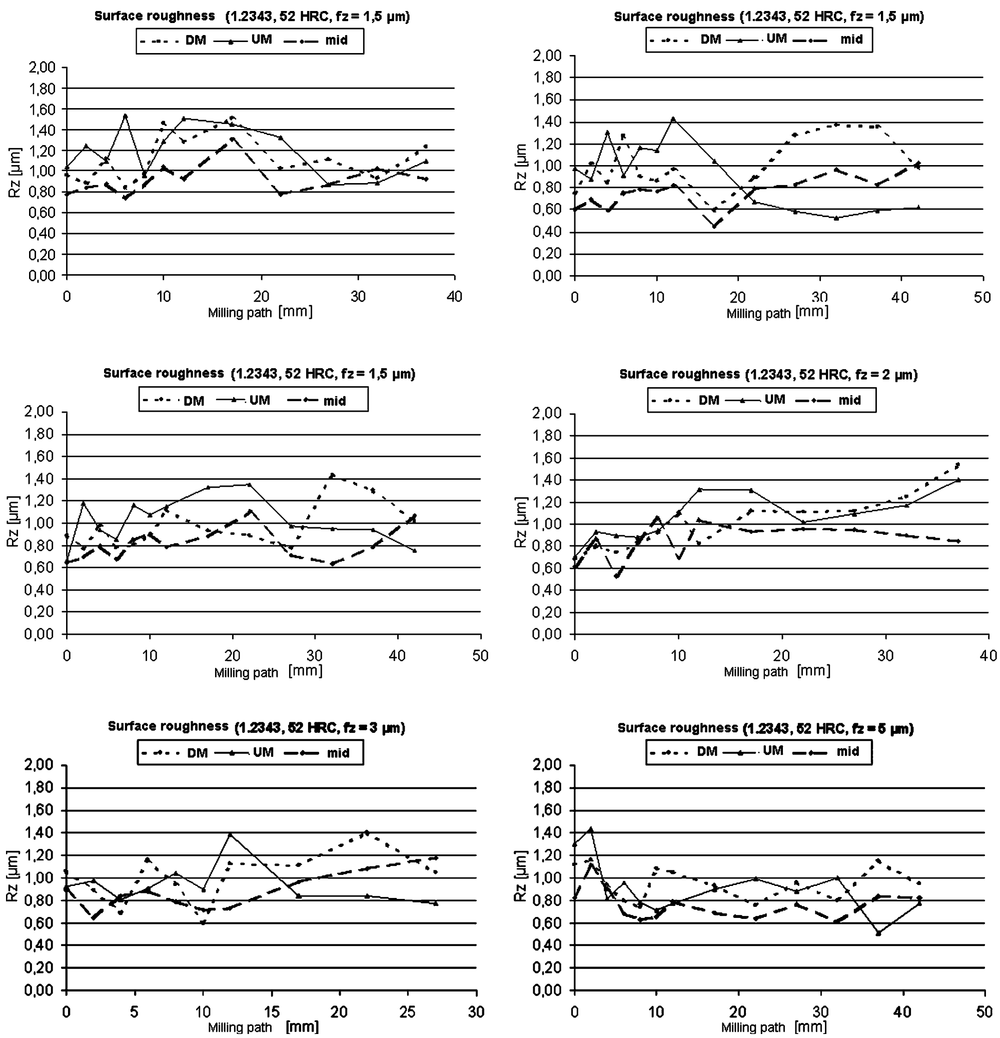


Fig. 3. Hard workpiece material, surface roughness in respect to milling path, milling strategy (DM = down milling, UM = up-milling, mid = middle of the cutter trace) and feed rate (cutting velocity = 30 m/min)

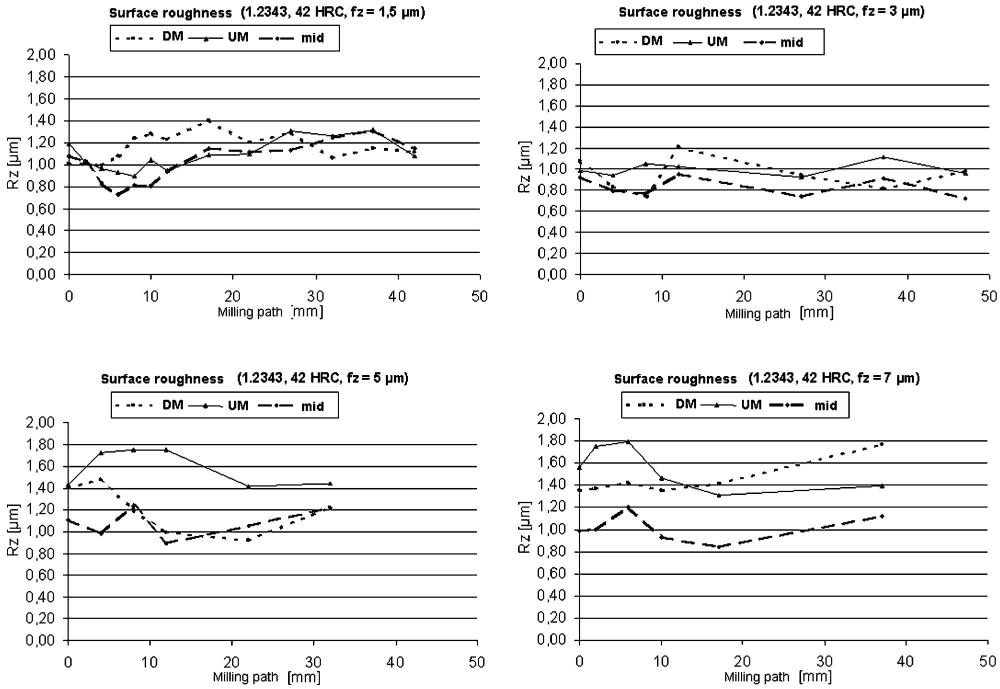


Fig. 4. Soft material, surface roughness in respect to milling path, milling strategy (DM = down milling, UM = up-milling, mid = middle of the milling trace) and feed rate (cutting velocity = 30 m/min)

3.3
Theoretical considerations on tool deflection

On the basis of both the estimations of the cutting forces following Victor and Kienzle and the measurements of the cutting forces, the tool deflection, i.e. the deflection off the rotary axis, was calculated. The values lie in an area of 1 µm to 5 µm depending on the spatial orientation, thus corresponding to tool deflections found in cutting experiments.

4
Surface quality

The following observations in the machined surfaces on hard tool steel AISI H11, annealed to 52 HRC hardness, have been made (Fig. 3):

The surface roughness ranges between $R_z = 0.5$ µm and $R_z = 1.6$ µm, depending on work piece material hardness, feed rate and measurement location within the area of machined surface. Contrary to the experience of cutting with conventional chip cross sections, a significant decrease in surface roughness resulting from a decrease of feed rate from 5 µm to 0.5 µm cannot be observed. In contrast, a larger influence can be ascribed to the location of measurement (up-milling-side, down-milling-side, mid of milling trace). In this it can be observed that in the course of the first 20–30 mm of milling path the arrival at work sharpness takes places. This has the effect that before the concerning point of time the surface roughness is subject to strong fluctuations, which can be seen as an indication for an unstable process with changing tool edge geometry due to partial disintegrations of the cutting edge. In this area, the up-milling-side shows the largest roughness, while the middle of the milling trace shows the lowest roughness. After the stabilization of the cutting edge the conditions are inverted and on the down-milling-side a lower surface roughness can be observed. The surface quality of the down-milling-side falls back behind that of the middle of the milling trace. In the further course indications emerge of a steady and stable increase of the surface roughness with progressing tool wear. The improvement of the surface on the up-milling-side and synchronistic degradation on the down-milling-side with increasing tool wear could be explained with the effect that with increasing wear mark width and increased effective relieve-angle combined with it, at the incoming cutting edge there is a smoothening of the surface taking place, whereas at the outbound cutting edge with increasing rounding of the cutting edge residual particles from the chip root increasingly contribute to the surface roughness.

In the comparatively soft AISI H11 of 42 HRC hardness, surface roughness values between $R_z = 1.8$ and 0.7 µm have been measured (Fig. 4). It is particularly striking that the surface creation in respect to wear progress is running considerably more stable. The strong fluctuations observed in the harder heat treatment state during the arrival at work sharpness practically did not appear at all. Instead, this process was shown as a swift rise with subsequent decay and eventually slight and continuous increase of the surface roughness. Also the above described change of the lower roughness of the down-milling-side to the up-milling-side could not be demonstrated in the considered tool wear path of 50 mm. The lowest surface roughness was found in the middle of the milling trace at a feed rate of 3 µm. In the observed measurement range it remained stable between $R_z = 0.9$ and $R_z = 0.7$. The measured data of the experiment with a feed rate of 7 µm (Fig. 4) was acquired only in the relatively soft work piece state (42 HRC), since this feed rate cannot be considered feasible for the hard work piece state (52 HRC) any more. Here, the assumed idealized characteristics of the surface roughness in respect to the tool wear path at the different locations (up-milling-side, down-milling-side, middle) is clearly to be seen.

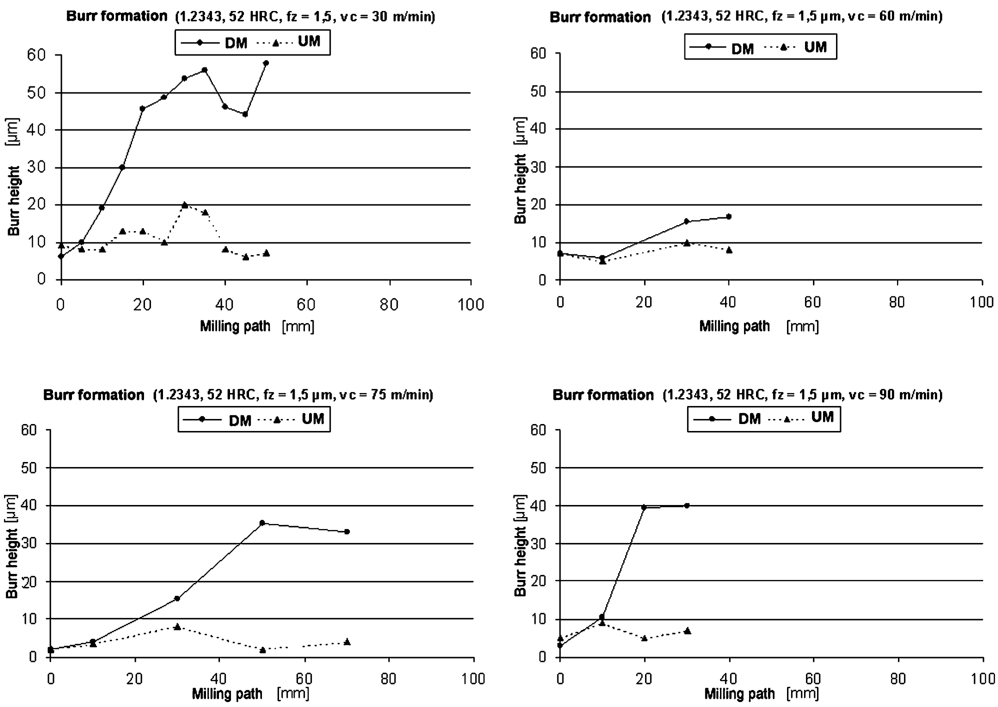


Fig. 5. Burr height in respect to tool wear, strategy (DM = down milling, UM = up-milling) and cutting velocity; material: AISI H11, 52 HRC

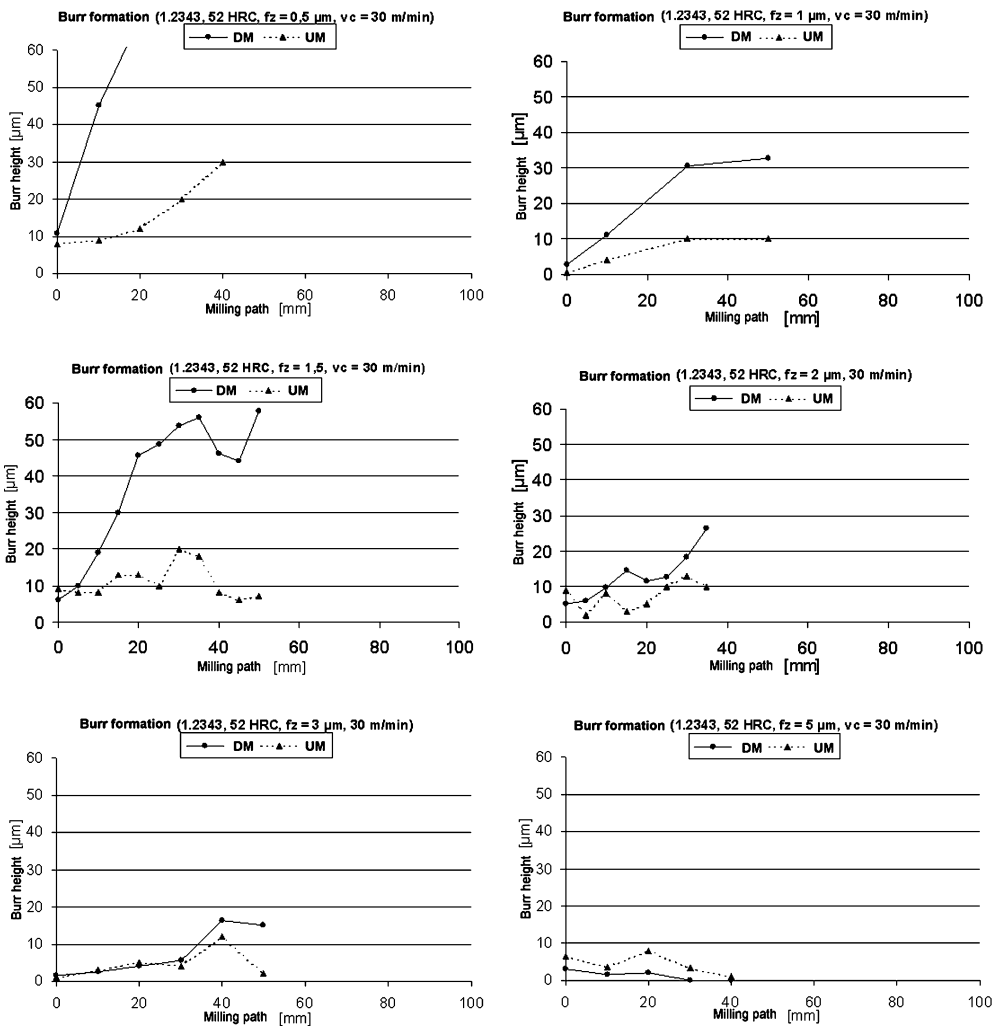


Fig. 6. Burr height in respect to tool wear, strategy (DM = down milling, UM = up-milling) and feed rate, material: AISI H11, 52 HRC

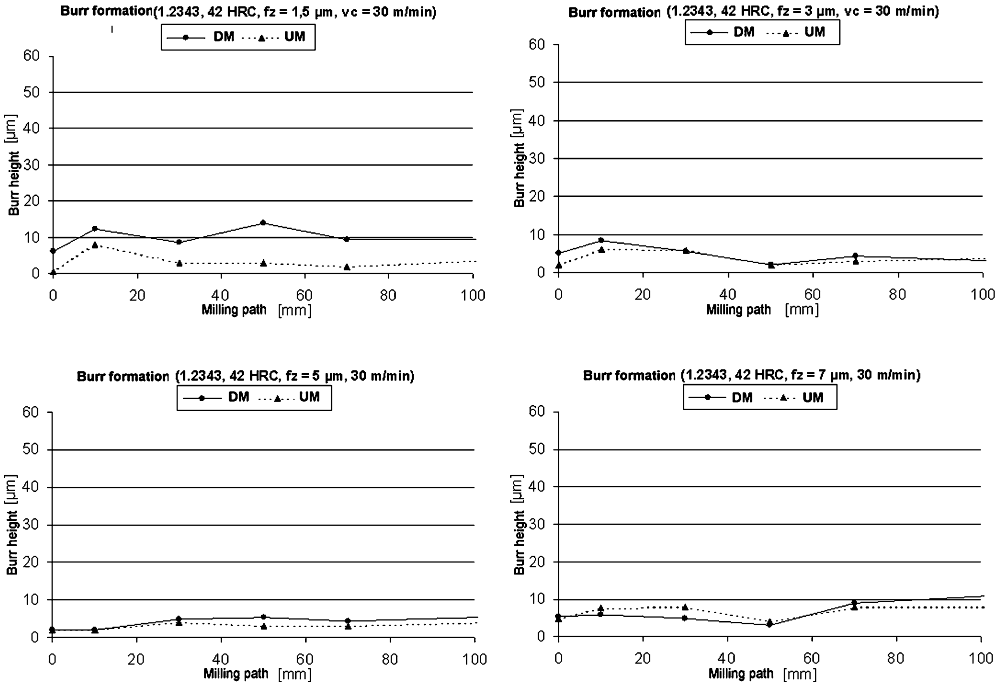
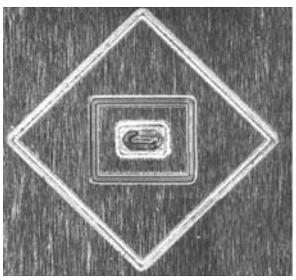


Fig. 7. Burr height in respect to tool wear, strategy (DM = down-milting, UM = up-milling) and feed rate; material: AISI H11, 42 HRC



Parameter	Value
Feed rate	f_z = 3 µm
Cutting velocity	v_c = 28 m/min
Feed speed	v_f = 180 mm/min
Spindle rotation	n = 30,000 min^{-1}

Fig. 8. Test-workpiece for assessment of process capability

5
Burr formation

The examinations concerning burr formation are based on burr height measurements with the UBM laser-autofocus-measurement device.

The burr height mostly ranges between 5 µm and 60 µm, with the former inflicting almost no problems at all for the practical application, therefore being considered satisfying. Merely at a feed rate of 0.5 µm the burrs ranged in the area of several millimeters, while on the other hand in the hard material state (52 HRC) at a feed rate of 3 µm and the machining result can practically be considered burr free (Fig. 7). Common to all measurements is the overweighing influence of the milling strategy. Nearly always a much stronger tendency to burr formation can be observed in the down-milling side of a milled groove, particularly with a higher base-level of burr formation. Furthermore, burr formation increases strongly with progressing tool wear, most of all in up-milling. Moreover, with the harder material (AISI H11, 52 HRC) a stronger burr formation than in the softer material (AISI H11, 42 HRC) could be registered, (Figs. 6 and 7), which on the one hand can be again put down to the stronger tool wear progress and on the other hand to the higher cutting forces, which partly trace back from plastic deformation forces. Considering the influence of the cutting velocity on the burr formation (Fig. 5), a further slight decline of the burr formation tendency with increasing cutting velocity can be discovered on the up-milling-side, which is characterized through little burr formation as described above. On the down-milling-side, where a significantly stronger burr formation appears, a minimum of the burr height seems to exist at a cutting velocity of 60 m/min. A possible explanation for this are two opposing tendencies depending of the cutting velocity. On one hand, at a higher cutting velocity an unhardening of the work piece material is to be expected as a well-known phenomenon in conventional cutting, which minimizes the cutting forces responsible for the burr formation. On the other hand, at higher cutting velocities a stronger tool wear can be expected, which increases the cutting forces and the degree of plastic deformation in the chip forming area. This in turn would bring forward the formation of burrs. From the super positioning of the opposing tendencies a local minimum of the burr height in respect to the cutting velocity could be explained.

6
Process capability

The test work piece proposed in VDI-guideline 2851 served as guide in the definition of a test work piece for the process capability in micro milling (Fig. 8). By means of the test workpiece and the method of examination that were adapted to the concerns of micro milling, it was the aim both to put the statements on accuracy that were so far mostly based on single tests to a more statistically based foundation and to develop a characterization methodology portable to other micro milling machines for comparison. Corresponding to the minimum requirement of short term capability tests following the VDMA-

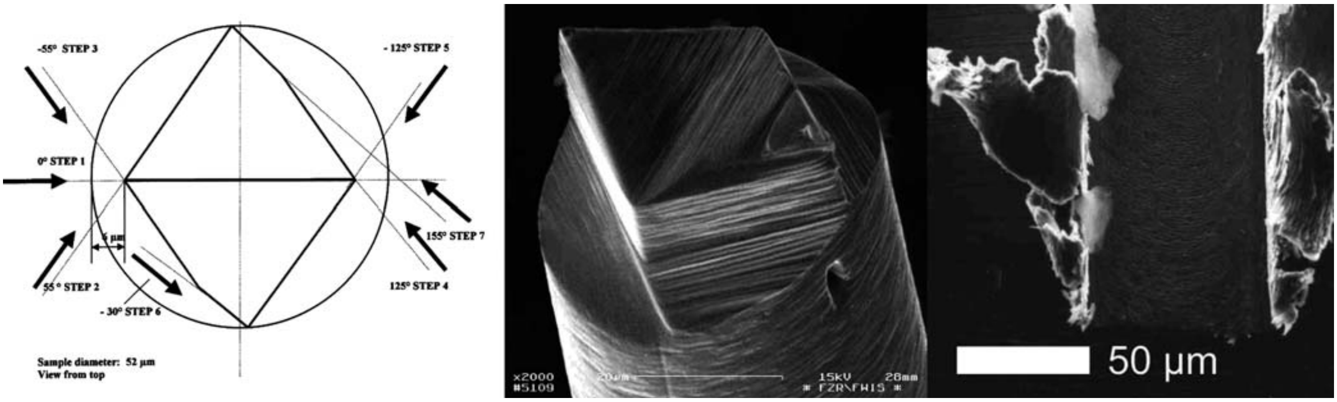


Fig. 9. Two flute tool (mid) machined using focused ion beam, sketch (left) and milling result (right)

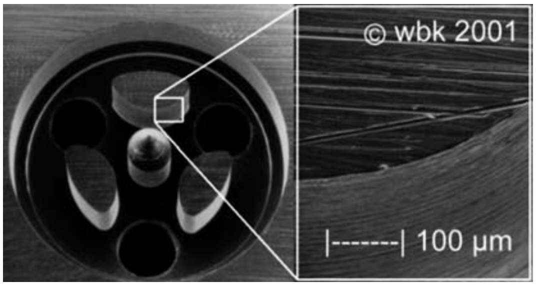


Fig. 10. Steel mold cavity (52 HRC) for wheel of model car (1.) and detail of milled edge (r.)

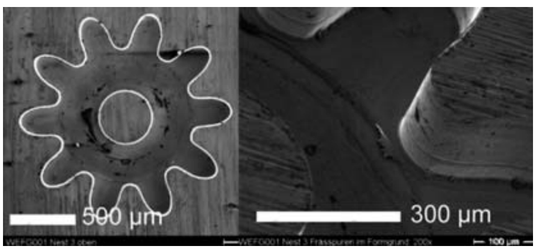


Fig. 11. Steel mold cavity (52 HRC) for micro gear (I) and detail of milled edge (r.)

recommendation 8669, the number of identical pieces to be machined was defined to 25 pieces.

For a capability test of $c = 1.33$, feasible tolerance gaps lying mostly between 0.02 and 0.05 mm have been found.

7
Optimization of micro cutting tools

The potentialities of focused ion beam cutting as an alternative to tool grinding was examined. For a two flute geometry a ion milling strategy corresponding to Fig. 9 (left) was applied.

From Fig. 9, it can be concluded that focused ion beam milling is in principle suitable to produce micro milling tools from tungsten carbide. The manufacturing result is still unsatisfying regarding burr formation, which in such a manner only occurs with totally un-optimized process parameters like e.g. too low feed rate, or strong cutting edge wear-out.

8
Manufacturing of molds

With commercially available end milling tools, micro structures in hardened tool steel can be manufactured with an accuracy of better than 0.01 mm and a surface quality that is suitable for molding in less than an hours machining time (e.g. Figs. 10 and 11).

Suitable process parameters, strategy and tool geometry provided, little or no burr formation occurs. One of the major drawbacks, though, is that concave structures cannot be machined smaller than 0.1 mm with commercial cutting tools due to the available tool diameters.

9
Conclusion and outlook

The feasibility of manufacturing annealed steel molds for micro components using ultra fine grain tungsten carbide end mills could be demonstrated. The experiences from the research of the last years display, consistently with indications from industry, that the cutting tools represent the present bottleneck for the ongoing development of micro cutting technology. The focus of the research presented here lies therefore aside from process development in the dimensioning and manufacturing of the cutting tools. The approach for the tool development lies most of all in the utilization of simulation aided dimensioning, novel cutting materials and tool manufacturing methods involving low process forces. Regarding the cutting process, the extension of the milling kinematics towards five axis milling., partly with simultaneous movement of all axes involved, will play an essential component of the research work. This aims at an enhancement of geometrical freedom as well as an optimization in respect to the boundary layer properties and the manufacturing time exposure.

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