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A new tool concept for milling automotive components

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Abstract

Due to the rising number of car variants, the production systems in automobile industry are driven by a strong demand for flexible production processes. In the production of thin-walled workpieces, forming and cutting processes stand in concurrence to each other. In many applications, cutting processes facilitate higher flexibility regarding possible workpiece geometries. However, the required productivity is demanding. In this paper, a multi-sectional milling tool is developed to reach the required cutting performance by minimizing secondary processing times. Tool geometry is optimized with statistical methods to enable a target oriented tool development and reduce iterative development steps in milling tool design processes.

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Keywords: milling, end-milling, tool geometry, steel, wear

1. Introduction

The main trends influencing future developments in automobile industry are [1]:

- Reduction of CO_2 emission
- Increasing variant diversity
- Increasing pressure on return on investment (ROI)
- Economic growth and new markets

This can only be achieved with highly flexible and productive machining processes like HPC milling. Limiting factors are tool wear [7] and process stability [2]. In this paper, a new tool concept for HPC milling is introduced to enhance productivity and flexibility in the machining of thin walled automotive components. To allow for an optimum tool design, the influence of geometric tool parameters on tool wear behavior is investigated.

Tool geometry influence on process stability in milling processes is subject to several research activities [2, 3, 4, 13, 9, 15, 17]. In contrast to high performance milling of aluminum, where tool load is low, high mechanical and thermal loads limit tool performance in milling of steel. Regarding tool life, significant influence arises from the cutting wedge macro- and microgeometry [5, 6, 7]. Kolar et al. investigate the influence of helix angle, clearance angle and rake angle on process forces and tool wear in a full factorial test plan for milling AISI 1045 [8]. Significant influences on process forces are shown for rake angle (decreasing forces for increasing values) and helix angle (increasing forces for increasing values), while clearance angle influences are of minor magnitude. Gu et al. analyze different wear phenomena [10] in milling of steel and develop a wear map, which predicts the dominant wear form (attrition, abrasion, chipping) in dependency from feed per tooth and cutting speed. In [11] the main wear mechanism in high-speed face milling with carbide tools are subdivided into rake face wear, flank wear, chipping and breakage and analyzed for different cutting speeds and substrate types.

Within the tool development process, which is still largely iterative, engineers try to optimize a specific tool regarding a certain output variable, e.g. cutting edge chipping. Knowledge in literature is only providing suggestions for a single or a few geometrical tool aspects at a time. In a specific use case, this knowledge is often not applicable, because the observed tool behavior is a result of the interactions of a plurality of parameters.

The approach of this paper is to separate and identify the main effects of tool geometry on tool wear behavior in milling carbon steel by means of DoE (Design of experiment)-methods to enhance tool development process.

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2. Experimental Setup

Basically, two main concepts have to be distinguished allowing for a combination of roughing and finishing milling within one tool. The first concept combines roughing and finishing cutting edges in angular sequence. In a second concept, which was used in the investigations, roughing and finishing part are divided axially (Fig. 1).

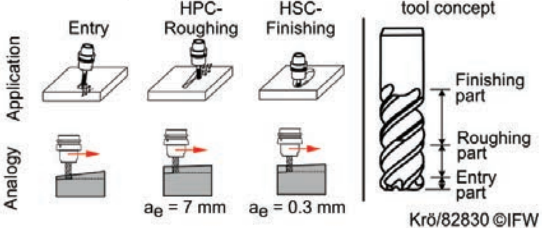
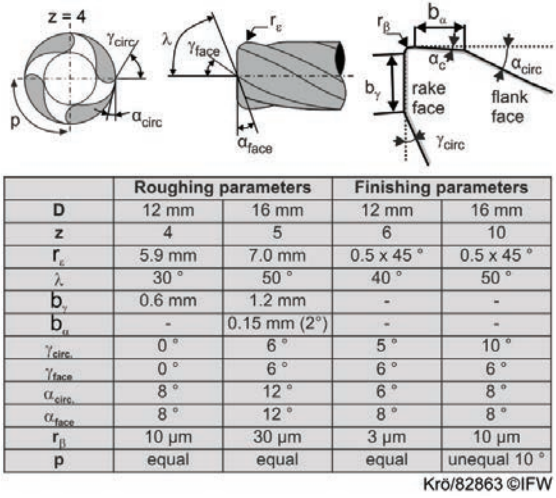


Fig. 1: Milling tool concept and process strategy in the regarded use case

This tool concept allows for high productivity and material removal with the roughing part. The required surface finish is achieved with the finishing part, after shifting the tool in axial direction.

The optimization of the tool parts is realized separately in analogy tests and presented in the following. After the optimization of each part, the tool parts will be combined to one milling tool.

To enable the geometric optimization of both milling tool parts, several parameters are varied within two fractional factorial test plans [16, 21], see Fig. 2.



	Roughing parameters		Finishing parameters	
D	12 mm	16 mm	12 mm	16 mm
z	4	5	6	10
r_ε	5.9 mm	7.0 mm	0.5 x 45 °	0.5 x 45 °
λ	30 °	50 °	40 °	50 °
b_γ	0.6 mm	1.2 mm	-	-
b_α	-	0.15 mm (2°)	-	-
$\gamma_{circ.}$	0 °	6 °	5 °	10 °
γ_{face}	0 °	6 °	6 °	6 °
$\alpha_{circ.}$	8 °	12 °	6 °	8 °
α_{face}	8 °	12 °	8 °	8 °
r_β	10 µm	30 µm	3 µm	10 µm
p	equal	equal	equal	unequal 10 °

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Fig. 2: Geometrical parameters of end mills for roughing and finishing part

Regarding the roughing part, eleven parameters are analyzed. For the finishing part, a variation of seven parameters is conducted. All parameters are varied on two levels. To ensure that main effects are not confounded with each other, a test plan resolution of IV is chosen [16, 21]. Therefore the number of treatment combinations is set to 32 for the roughing tool geometry and 16 for the finishing tool geometry. The level values are set up according to industrial standards. For all milling tools a WC-10Co submicron substrate in combination with a AlCrN monolayer PVD-coating is applied.

Milling tests are conducted on a HELLER MC16 4-axis milling machine. All machining tests are run dry. As workpiece material the heat treatable steel AISI 1045 is used in soft-annealed condition (Hardness 210 HV1). Process forces are measured using a Kistler 9255C three-component dynamometer. Wear measurements are conducted using a Keyence VHX 600 digital microscope and supported for selected milling tools with scanning electron microscope measurements (SEM). The evaluation of the measurement data is performed using the software Cornerstone and Eureqa Pro.

3. Results and discussion

Regarding the machining of pockets in thin walled workpieces, the machining consists of an entry into the workpiece and a subsequent milling of the pocket contour (compare Fig. 1). In the following approach, both steps, entry and roughing of the contour, are evaluated separately.

To compare the results for different geometries in the workpiece entry, the force is integrated over covered feed path to calculate the entry work W_E:

$$W_E = \int_0^{x(a_p=5mm)} F_{fN} dx \qquad (1)$$

with F_{fN} as the feed normal force.

For the evaluation of the contour roughing after the entry, the process force F_{fN} at full cutting depth a_p = 5 mm is analyzed.

The result regarding the influence of the tool parameters are given in Fig. 3. For presentation of the effects, pareto charts are generated. These diagrams illustrate the effect of a parameter change compared with the mean value over all experimental results. Positive effects mean an increase in output value for increasing parameter value acc. to Fig. 2. Furthermore, the cumulated effect values are calculated and shown as a line graph. The analysis of the cumulated effect values allows for the identification of the most important parameters according to the pareto principle: 80 % of the effects are caused by 20 % of the causes.

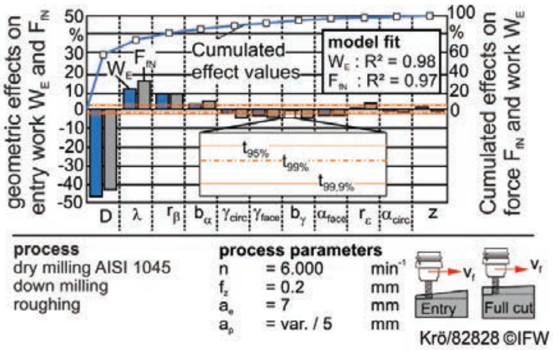

Fig. 3: Effect pareto chart for entry work W_E and cutting force at full cutting depths F_{fN} for roughing tools

The significance of the effects is evaluated concerning the 95 %, 99 % and 99.9 % limits of the Student´s t-distribution. For calculation the standard deviation, 12 of the 32 tests were repeated. Most significant effects are found for the diameter D, the helix angle λ and the cutting edge rounding r_β, with a significance above 99.9 %. The three named parameters determine the force value to approximately 81 %.

The increase in helix angle leads to an increase in cutting edge contact length with the workpiece and therefore higher friction force [8, 18]. The influence of the cutting edge rounding on process forces is induced by the increase of the ploughing zone, which leads to higher forces within the chip formation process [6]. Regarding the tool diameter D the major effect for the force decrease is the decreasing maximum undeformed chip thickness in consequence of a lower immersion angle ϕ. Furthermore, the application of the same feed velocity (=productivity) results in an increase in the effective feed per tooth, which is also beneficial regarding specific cutting forces [12]. Also the cutting speed is 33.3 % higher compared with the small diameter tools, which leads to a cutting force decrease of approximately 10 % [14].

The influence of process stability for the regarded tool geometries in roughing is analysed in [4]. Regarding tool wear 16 (all z = 4) of the 32 variants were investigated in wear experiments up to a milling time of t_c = 64 min. For statistical reasons four experiments are repeated.

Table 1: Process parameters HPC roughing wear experiments

v_c	f_z	a_e	a_p
225 m/min	0.12 mm (Ø12)	7 mm	5 mm

Wear investigations of the applied tools show the occurrence of different wear forms (compare Fig. 4 (A)). These are depth of cut notch wear, abrasive and adhesive wear, chipping and radius wear. The effects of the geometric tool parameters on the different wear forms are shown in Fig. 4 (B).

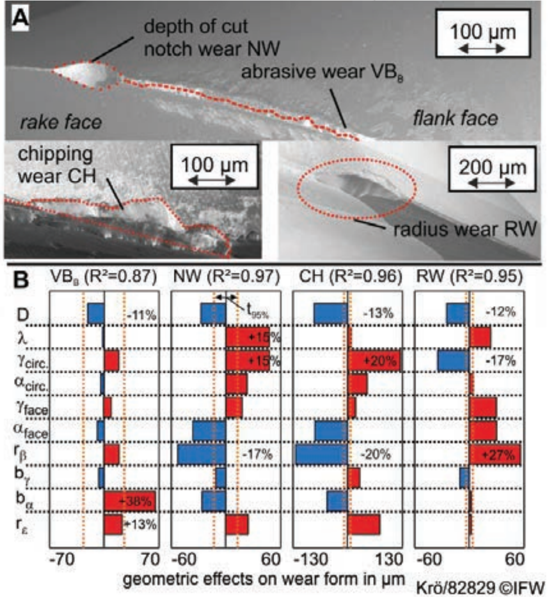

Fig. 4 (A) wear forms in roughing experiments for etched tools; (B) effect pareto of wear form occurrence in roughing

Within the given diagrams, blue bars represent a decrease in the regarded wear phenomena for rising parameter value whereas red bars indicate an increase in tool wear by increasing parameter value. Regarding the influence on the overall wear effect the percentage of the three most important geometric effects is calculated and specified. Effect significance is calculated taking into account standard deviation of each experiment. Values are σ = ± 21 µm for VB_B; σ = ± 9 µm for NW, σ = ± 11 µm for CH and σ = ± 9 µm for RW. Clear tendencies can be observed for the tool diameter. A larger diameter leads, caused by differing engagement properties, to 14 % reduction of the overall cutted length, which is significant for the propagation of continuous wear forms. Large helix angles are not beneficial for tool wear, especially notch wear is triggered by large helix angles. A reason is hindered chip transport and a longer frictional contact between chip and tool caused by the differing chip flow [20]. A rise in the cutting angles induces less cutting wedge stability [20, 5], which leads to higher tool wear regarding most of the observed wear phenomena.

A rounded cutting edge of r_β = 30 µm in comparison to r_β = 10 µm induces significantly less chipping and notch wear whereas abrasive wear and radius wear are increased. The reason for this effect is the increase in cutting edge stability on the one hand and the increase in friction and ploughing forces which result in higher abrasion on the other hand. The flank face chamfer mainly leads to significant increase of the wear land on the flank face VB_B due to the increased contact with the workpiece. The higher stability of the cutting wedge leads to less notch and chipping wear at the same time. Large corner radii show disadvantageous effects on tool wear propagation. The reason for this are increasing ploughing effects and friction due to the decreasing chip thickness and effective cutting speed in the radius area.

In analogy to the roughing part investigations, force measurements of the workpiece oriented process forces are performed in finishing. Results are presented in Fig. 5.

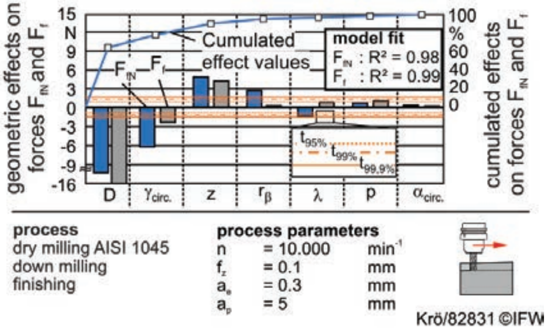

Fig. 5: Effect pareto process forces for finishing tools

The 80 % limit of the cumulated effect values is exceeded for the accumulation of the effects of diameter, rake angle and number of teeth. It is clearly visible that the increase in number of teeth leads to a most significant increase in process forces due to the higher frictional contact zone between tool and workpiece. Cutting edge rounding increases force values because of higher ploughing forces [7]. Significant reduction of the cutting forces is achieved with highly positive rake angle (compare chapter 3.1) [19]. High tool diameters are beneficial according to the argumentation given above for roughing tools. Regarding tool wear, milling experiments with the previously presented process parameters are conducted up to a milling time of t_c = 38 min. The dominating detected wear form is cutting edge chipping CH. The influence of the different tool geometries on chipping is displayed in Fig. 6.

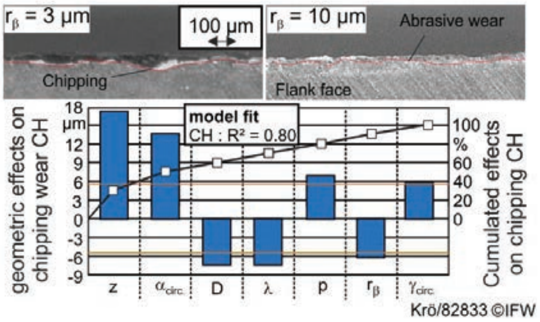

Fig. 6: Effect pareto chipping wear in HSC finishing.

The increase in number of teeth results in higher cutting edge chipping. As the nominal feed per tooth for higher number of teeth decreases when keeping v_f constant, chip size reduces and heat transport from the cutting zone is inhibited. Therefore, an excessive number of teeth is disadvantageous when feed velocity is limited, for example because of maximum machine accelerations when milling contours. Increasing rake and clearance angle leads to reduced stability of the cutting wedge [5] and therefore increased chipping wear. Due to the higher load on some teeth, unequal pitch also enhances chipping wear. Reduction of cutting edge chipping is achieved using a cutting edge rounding, which leads to higher wedge stability compared to sharp tools. Also bigger tool diameter results in higher tool stability. The increase in helix angle shows beneficial effect on chipping wear in finishing application.

Surface roughness was analysed for all finishing tool variants in unworn condition. Mean values were Ra = 1,17 µm (Min: 0.59 µm; Max: 2.24µm) and Rz = 5.15 µm (Min: 2.84 µm; Max: 8.55 µm) respectively. However, a statistically significant correlation between the geometrical parameters and surface roughness could not be obtained. There is a tendency for better surface roughness with increasing helix angles.

4. Conclusions

From the results, the following conclusions can be drawn:

- Roughing forces are mainly determined by tool diameter, helix angle and cutting edge rounding (81% of effects).
- Finishing forces are mainly determined tool diameter, rake angle and number of teeth (90% of effects)
- Regarding the predominant wear phenomena, the three most important geometric parameters were identified in roughing and finishing.
- For the roughing operation, optimum results can be achieved with large tool diameter (D = 16 mm) in combination with helix angle of λ = 30 °. High stability of the cutting edge is achieved with slightly positive rake and clearance angles and a cutting edge rounding of $r_\beta = 30$ µm.
- Regarding the finishing operation, a large diameter with a high helix angle of λ = 50 ° is beneficial. An intensively high number of teeth is disadvantageous, if maximum feed velocity is limited. Furthermore, a small cutting edge rounding of $r_\beta = 10$ µm decreases the risk of cutting edge chipping significantly.

5. Acknowledgement

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