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Development of cutting edge geometries for hard milling operations

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ABSTRACT

Milling of hardened steels is a challenging task for mould and die manufacturing due to the high material strength. One major drawback is the tool wear, which is a result of the high thermo-mechanical stress on the tool. The wear rate can generally be influenced by the tool geometry, coatings and substrates. A further approach is to modify the flank face of the tool, which leads to geometrical limitation of the flank wear. The challenge of this approach is to design flank face modifications, which offer process reliability and increased performance. Against this backdrop a finite element simulation has been constructed to analyze tool stresses. Therefore, different material and friction models were investigated. Based on this simulation a regression model has been developed. Due to the regression model the flank face modifications have been designed and manufactured by laser machining. In cutting tests the potential of the flank face modifications compared to conventional hard milling tools was investigated. The flank face modifications enable the increase of tool life time and the production of workpieces with reduced tensile residual stresses.

Introduction

In production industry, especially in die and mould engineering, steel parts are used, which are subjected to high loads and therefore are hardened or quenched and tempered [1].

After heat treatment the final contour has to be manufactured. Apart from abrasive processes, machining with geometrically defined cutting edges is established to machine hardened steel components as a substitution method. The advantages of hard machining compared to grinding are high removal rates, short machining times, a flexible process design and eschewal of coolant. However, a disadvantage of hard machining is an increased tool wear compared to machining materials in none hardened state. Under these conditions hard milling presents a particular challenge due to the dynamical thermo-mechanical load at the cutting edge. Current research aims to increase the tool life in hard machining. Besides the choice of the tool substrate and the machining parameters, the geometric design of the cutting edge significantly influences the wear behaviour [2,3].

A variety of researchers have shown that the use of a negative rake angle increases the tool life due to induced compressive loads on the tool cutting edge [4–6]. Besides the investigations regarding tool wear, surface quality in hard machining has been in focus [7]. Due to the fact, that hardened components are exposed to high loads, the surface quality and surface integrity have to present required characteristics. Thereby, the tool wear has a significant influence on the surface integrity of the component. Increasing flank wear leads to increased thermo-mechanical stress and thus to an increase of tensile residual stresses on the workpiece surface [8]. An approach to influence both disadvantages, residual stresses and tool life, has been achieved by specific modification of the tool flank face as shown in Fig. 1. Here, an undercut of the flank face limits the wear on the defined area of the cutting edge. Consequently, by a systematic tool development, a rise in efficiency can be achieved in hard turning [8,9]. However, due to the flank face modification the mechanical stability of the cutting edge is reduced. For designing these tools, the knowledge of the stresses in the undercut is necessary. In experiments these stress values can be only detected with higher complexity. Hence finite element simulations are a suitable tool to avoid tool fracture at the undercut and to analyze the influence of specific cutting edge geometries in machining.

In addition, due to simulations, cost and time intensive experimental investigations can be reduced [3,10,11].

Many studies deal with the calculation of thermo-mechanical loads of the cutting tools using solid-state simulations, which are based on the finite elements method [3,11]. Denkena [12] and Scherbarth [13] interpreted the tool wear and additional tool failure based on the principal stress hypothesis, which were analyzed by using solid-state simulations. Thus, tool failure

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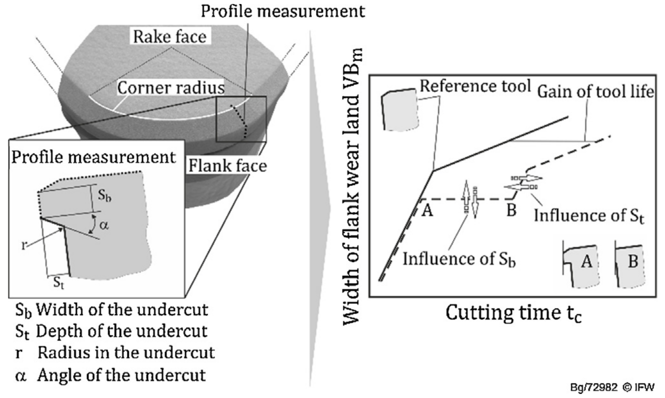

Fig. 1. Definition of flank face modification and effect on tool wear.

appears if the first principal stress exceeds the tensile strength of the tool substrate. This was also demonstrated by Zhou et al. [14]. Accordingly, optimized chamfer geometry leads to reduced minimal principle stresses in the wedge, which favours tool life time. This was also shown in hard turning AISI H13. Thus higher tool life time occurs due to reduced tensile principle stresses by applying chamfered cutting edges [15]. Further application of chip formation simulations according to the design of the cutting edge, especially rounded cutting edges, can be found in [16–18]. Thus the reduced stresses in the wedge lead to higher tool lifetime.

By using the chip formation simulation Meyer designed the flank face modification for hard turning operations [8]. However, a comparison of the calculated stresses with tool failure was not executed. This paper deals with the modelling of a hard milling operation by means of chip formation simulation for tools with a flank face modification. Besides the approximation of the milling operation to a two-dimensional orthogonal turning process, the tool failure is interpreted by the calculated tool stresses. Afterwards the designed tool was investigated regarding its wear behaviour in hard milling AISI H13.

Experimental setup

Experimental cutting tests were carried out on a Heller 4-Axes Machining Centre MC16 in face milling operations without coolant. As workpiece material AISI H13 hot work steel was used. The material possesses a martensitic microstructure with finely dispersed carbides. With a value of 56 HRC maximum attainable hardness of hot-work steel was used. The properties of hardened AISI H13 are listed in Table 1.

Due to the high strength, good resistance to thermo softening, heat checking, high hardenability and high toughness, AISI H13 is widely used as material for dies [19]. The experiments have been conducted with a single tooth face mill. Inserts with round geometry of the type RPHW1204M0T with a PVD TiAlN-coating were used. The properties of the cutting tool, based on data from the manufacturer and literature, are summarized in Table 2. The reference tool geometry and the modified geometries were characterized by SEM and tactile measurement. The reference tools were provided by an angle of chamfer $\gamma_f = -20^\circ$ and a chamfer width of $b_n = 0.20$ mm, cutting edge radius exhibits a value of $r_\beta = 30$ μm. The modification of the flank face, the so called undercut, was performed with laser machining on a Sauer Lasertec 40 Precision Tool. In preliminary studies it was ensured that the method of preparation of the laser did not affect the substrate properties and wear behaviour of the cutting tools. The accuracy of the laser machined undercut geometries was about 5 μm, which only depends on the optical set up for reference point. However, rectangular undercuts and without a rounding could not produced due to the properties of the laser source and the hardness of the cemented carbide.

Table 1
Mechanical properties of hardened AISI H13.

Tensile strength R_m [N/mm^2]	Yield strength $R_{p0.2\%}$ [N/mm^2]	Young's modulus E [GPa]	Hardness [HRC]
2006	1515	211	56

Table 2
Thermal and mechanical properties of the workpiece and tool.

Parameters	Workpiece (AISI H13)	Cutting tool (WC)
Young's modulus (GPa)	211	678[***]
Poisson's ratio	0.28[*]	0.22[***]
Density (kg/m^3)	7800[*]	14,800[***]
Specific heat (J/kg K)	$420 + 0.504T$ (T in °C)[*]	196[***]
Thermo conductivity (W/mK)	28.4 (350 °C); 28.4 (475 °C); 28.7 (605 °C)[*]	129[***]
Hardness (HRC/HV30)	56 HRC	1782 HV30[***]
Thermo expansion (10^{-6}/°C)		4.63[***]
Compressive strength		~6500 MPa[**]
Fracture toughness (MPa $\sqrt{m}$)		9.44[***]

[*] Data from [25].
[**] Data from [26].
[***] Data from tool manufacturer SECO tools.

The face mill diameter is $D = 25$ mm. Because of round cutting inserts the diameter depends on the depth of cut. In this investigation constant depth of cut $a_p = 0.5$ mm was used, which results in an effective diameter of $D_{\text{eff}} = 17.8$ mm. As reference process parameter a cutting speed of $v_c = 120$ m/min, feed per tooth $f_z = 0.2$ mm and width of cut $a_e = 5$ mm was applied, which is comparable to hard milling parameters in industry.

For wear detection a digital microscope Keyence VHX-600 and a scanning electron microscope Zeiss EVO 60 VP (SEM) were used. Tool life criteria has been defined as a maximum flank wear land width of $VB_m = 200$ μm or the occurrence of tool failure. Process forces were measured by a 3-component-dynamometer of type Kistler 9257B. Residual stresses of the workpiece were determined by X-ray diffractometer analysis, using the $\sin^2 \psi$ method.

Finite element modelling

The design of the undercut depends on the tool stresses. By using three-dimensional finite simulations tool stresses can be calculated over the cutting edge. However, three-dimensional chip formation simulations are time-consuming in comparison to two-dimensional chip formation simulations. For this reason, the milling process was approximated to an orthogonal machining process. The milling process is presented in Fig. 2. Additionally, relevant parameters are shown.

For transformation and approximation of the milling process, it is particularly important to determine the engagement parameters. Their calculation is hereinafter exhibited. As can been seen in the bottom of Fig. 2, the undeformed chip thickness varies along the cutting edge b_{eff}. The undeformed chip thickness depends on the feed motion angle φ and tool cutting edge angle κ. Thereby, the tool cutting edge angle shifts from $\kappa = 0^\circ$ up to a maximum value. Due to this the undeformed chip thickness varies from $h = 0$ over the effective undeformed chip thickness h_{eff} up to the maximum undeformed chip thickness h_1. Here, h_{eff} differs from the average chip thickness h_m. With respect to small cutting edge angles κ Köhler [20] shows, that the cutting forces can be calculated with a higher accuracy in comparison to the approach of Kienzle due to