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Size effect in micro machining of steel depending on the material state

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Abstract

In machining of steel changes of the surface and boundary layer are induced through mechanical and thermal loads. The controlled generation of these material modifications, which determine the functional properties of components, is still an iterative process based on experience. An enhanced knowledge on the generation of these modifications can only be gained through fundamental investigations. Therefore, this paper investigates mechanical loads in micro machining of 42CrMoS4 by precision turning with focus on the size effect, occurring due to the ratio of undeformed chip thickness to cutting edge radius. Resulting material modifications are examined and discussed regarding the induced loads.

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Keywords: Micro machining ; Surface modification ; Size effect

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1. Introduction and target of investigation

The manufacturing of components with desired functional properties is still an iterative process. To generate well-defined properties on the surface and in the surface layer, which fulfill the intended functions, knowledge-based interactions between process-related loads and resulting material properties have to be known. To enable the function-oriented machining of workpieces with different machining processes, these correlations shall be determined to deliver a first approach for a novel knowledge-based material centered view, called Process Signatures [1]. This approach is pursued on the basis of tempered steel 42CrMoS4, which is mainly used in the automotive industry for highly stressed components, e.g. gears and crank shafts or connecting rods. First results for micro turning of steel with geometrically defined cutting edge are presented in this paper. The results contribute to the concept of the Process Signature by investigating small loads and scaling effects.

2. Micro turning of steel

In turning of steel, mechanical and thermal loads prevail, which cause strains and stresses as well as temperature fields in the machined workpiece. As a consequence, state variables like roughness, microstructure, hardness, Young’s modulus or residual stresses are changed [2, 3, 4]. The changes of these quantities, which take place on the surface and in the surface layer of a workpiece, are called modifications.

On the one hand the load during machining depends on the material behavior which is determined by the material composition, as well as the heat treatment. Also, the loads depend on the applied manufacturing process and the selected machining parameters. Furthermore, in micro machining processes, size effects can occur, depending on the microstructure and cutting edge geometry [3]. In conventional machining a perfectly sharp cutting edge is assumed. Compared to this, in micro machining the cutting edge is rounded and an effective negative rake angle has a strong impact on the mechanics of the machining process [4]. In metal cutting this is characterized by a non-linear increase of the specific cutting force and energy, dependent on depth of

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cut. The non-linear increase occurs for decreased undeformed chip thickness below a critical chip thickness and is described as a size effect [5, 6].

As a contribution to the Process Signatures this scaling effect, which occurs in the specific cutting force, shall be examined in machining of 42CrMoS4 and in addition, whether such an effect also occurs in the induced material modifications, too.

Therefore, depending on the material initial state and the ratio r_r of undeformed chip thickness h to cutting edge radius r_β, the mechanical loads, respectively forces, are investigated by performing precision turning experiments. Additionally, the modifications on the surface and in the surface layer generated by the machining are analysed.

Nomenclature

A	cross-section of undeformed chip (µm²)
b	width of undeformed chip (mm)
f	feed (µm)
F_c	cutting force (N)
F_f	feed force (N)
h	undeformed chip thickness (µm)
k_c	specific cutting force (N mm^{-2})
r_r	ratio of undeformed chip thickness to cutting edge radius (-)
r_β	cutting edge radius (µm)
r_ε	corner radius (µm)
Sa	arithmetic mean height (nm)
v_c	cutting speed (m min^{-1})
v_f	feed velocity (mm min^{-1})
ω	angle of measuring location on workpiece (°)
ϑ	temperature (°C)

3. Experimental work

3.1. Workpiece material

Cylindrical workpiece specimens consisting of 42CrMoS4 (SAE 4140RH, cf. Tab. 1) were investigated. They were made of hot rolled, quenched and tempered steel rods with a diameter of 60 mm. On the front face the specimens have a 1 mm wide ring with an outer diameter of 58 mm. To avoid the induction of loads by clamping, the workpieces were designed with a cylindrical recess (Ø 50 mm). After their fabrication, the samples were heat treated to achieve a well-defined initial state. Three kinds of heat treatments were applied on this steel as indicated in Table 2. Depending on the heat treatment, the workpieces reveal a hardness of 30 HRC, 36 HRC and 42 HRC.

Table 1. Chemical composition of the steel 42CrMoS4 (values in %)

C	Si	Mn	P	S	Cr	Ni	Mo
0.45	0.23	0.78	0.014	0.021	1.12	0.09	0.20

Table 2. Heat treatments applied to 42CrMoS4 steel

	Heat treatment
30 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 685 °C in vacuum
36 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 560 °C in vacuum
42 HRC	Austenitisation at 850 °C, then oil quenching and tempering at 475 °C in vacuum

3.2. Cutting tool

The tools are made of fine grain carbide with a titanium nitride coating. These are 3 mm ± 0.2 mm wide grooving inserts with a cutting edge radius of $r_\beta = 10$ µm ± 1.9 µm (measured with a Profiler P-15, KLA Tencor).

3.3. Experimental setup and design

The experiments were performed on a precision lathe (Benzinger Go-Future B2). A multicomponent dynamometer (MiniDyn 9119AA1, Kistler) was attached to the tool revolver with the tool fixed to it. The dynamometer was connected to a multi-channel charge amplifier (5080A with 3 channels, Kistler) with a data acquisition card (NI-USB 6361, National instruments).

Through a free orthogonal cut during turning with uniform engagement conditions, the complexity of the process is reduced (cf. Fig. 1 and Fig. 6). This was ensured by two factors: on one hand, only the ring of the specimen was machined and on the other hand the tool being wider than the workpiece. To analyse the mechanical load as well as modification at different ratios r_r of undeformed chip thickness h to cutting edge radius r_β, the feed in the axial direction f was varied between 3 µm and 90 µm, while the cutting edge radius was kept constant. This results in a ratio r_r between 0.3 and 9. Here, the feed and undeformed chip thicknesses were calculated. To ensure steady process conditions, in each experiment 50 workpiece revolutions were completed. The cutting speed was set to $v_c = 80$ m min^{-1}. For every single experiment a new tool was used to avoid wear effects. In addition, every parameter set was performed three times.

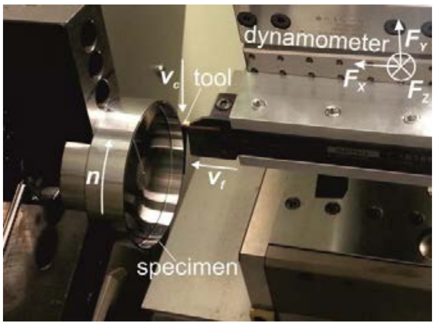

Fig. 1. Experimental setup