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Surface roughness of precision turned hardened steel

Melanie Willert and Oltmann Riemer

Laboratory for Precision Machining (LFM), Badgasteiner Str. 2, 28359 Bremen, Germany

m.willert@lfm.uni-bremen.de

Abstract

For the machining of hardened steel, a manufacturing process with geometrically defined cutting edge, like hard turning, is an economic and ecological manufacturing option, compared to grinding. As well as for other manufacturing processes, the generation of a desired surface integrity of high performance components by hard turning is still an iterative process based on experience. To solve the inverse problem, i.e. deriving the appropriate and significant machining parameters to achieve the required and intended surface properties, a novel, knowledge-based and material centered view has been proposed [1]. First fundamental findings on material separation, surface generation and especially the material modification have to be analysed on macro but even more on small scale, to consider the size effects; the latter occurs in precision machining.

As a first approach, this paper investigates changes in surface roughness introduced by mechanical loads through hard turning. For the experiments, an orthogonal cutting process, a grooving tool made of CBN and specimens of hardened steel (AISI 4140) were chosen. The roughness modification was examined by optical metrology. Furthermore, the mechanical loads were determined by force measurement and correlated with the material modification.

surface roughness, force measurement, hard turning

1. Introduction

Compared with conventional hard machining (soft machining before and finishing by grinding after heat treatment) the turning of hardened steel with geometrically defined cutting edges allows to shorten the process chain significantly. Due to the resulting shorter processing times, lower machine and equipment costs and the possibility of dry machining, hard turning has both economic and environmental benefits [2].

The production of components with desired functional properties is still an iterative process. To induce well-defined changes of state variables, respectively surface integrity, knowledge-based interactions between process-related loads and resulting material modifications must be known. For tempered steel AISI 4140, mainly used in the automotive industry for highly stressed components, e.g. connecting rods, crank shafts and gears, these correlations will now be determined to deliver a first approach for a novel knowledge-based material centered view [1]. Initial findings are presented in this paper.

2. Material loads and modifications

During hard turning mechanical and thermal loads occur, which act on the workpiece surface layer and cause corresponding changes in the material. These modifications, e.g. changes in roughness, microstructure, hardness, modulus of elasticity or residual stresses, depend on the material itself, its input state and the thermo-mechanical effects acting on the material [3].

2.1. Machining experiments

To estimate the correlations between mechanical loads and modifications by hard turning processing, machinability experiments were performed. For the evaluation of mechanical loads during hard turning, a force measurement was carried out. Furthermore, the state variable 'roughness' has been measured both before and after machining.

The experiments were performed on a precision lathe (Benzinger Go-Future B2). A 3-component dynamometer (9119AA1 by Kistler) with the cutting tool was attached to the tool revolver. The tool was a 3 mm wide grooving tool with a corner radius of r_ε = 0.2 mm and a sharp cutting edge radius of approximately $r_\beta \approx 3\ \mu m$ (measured with the AFM Nanoscope III by Digital Instruments). The tool is composed of 50 % CBN and binder titanium nitride as well as titanium carbide with a grain size of 1 – 4 µm.

The cylindrical workpiece specimens consist of AISI 4140 (cf. Tab. 1). On the front face the specimens have three 2 mm wide protrusions with a mean diameter of 96 mm, 82 mm and 68 mm (cf. Fig. 1, right). To avoid the induction of external stresses in the material to be machined by clamping, the workpieces were designed with a cylindrical recess (Ø 90 mm). After their fabrication, the samples were heat treated to achieve a well-defined homogeneous condition and a hardness of approximately 52 HRC ± 1 HRC.

Table 1 Chemical composition of the steel AISI 4140 (in %)

C	**Si**	**Mn**	**P**	**S**	**Cr**
0.41	0.23	0.81	0.012	0.026	1.06
Ni	**Cu**	**Mo**	**V**	**Ti**	**Al**
0.03	0.05	0.18	0.02	0.01	0.03
H_2 (*10^{-4})	**O_2 (*10^{-4})**	**N (*10^{-4})**	**Sn**		
0.77	10	83	0.006		

For the experiments, the specimens were clamped in a three-jaw chuck and face turned first. Due to the heat treatment distortion, this preliminary step was necessary to ensure a plane surface and thus a constant cross-section of the undeformed chip. Based on a reference workpiece, the initial surface roughness was measured with a white light interferometer (Talysurf CCI HD, Taylor Hobson), adjusted to a cut-off of 0.8 mm: Sa_{in} = 192 nm ± 13 nm.

The actual experiment was then carried out in the same setup, as orthogonal turning process, with an axial feed of f_U = 0.1 mm/rev parallel to the rotation axis (cf. Fig. 1, left). The process parameters cutting speed v_c and cutting depth a_p both were varied at three different levels. Each parameter set was repeated two times.

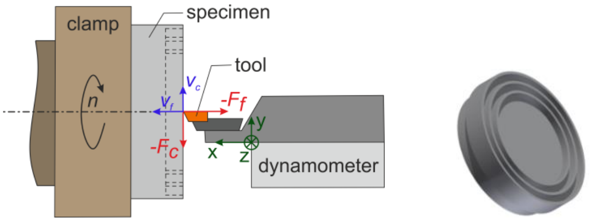

Figure 1. Experimental setup (left) and specimen view (right)

2.2. Correlation of process forces and roughness

As expected for the orthogonal hard turning, no force acts in radial direction (F_z = 0 N) and the cutting force F_c is higher than the feed force F_f.

For cutting speeds between v_c = 100 m/min and 200 m/min, at a constant depth of cut, F_c and F_f remain on a constant level of F_c = 384 N ± 31 N and F_f = 165 N ± 7 N.

At a constant v_c of 150 m/min larger cutting depths cause larger forces. For varying depth of cut from a_p = 30 µm to 120 µm, F_c is approximately 2.5 and F_f 1.5 times higher. This means that both F_c and F_f increase linearly, with a significantly stronger increase of F_c compared to F_f (cf. Fig. 2).

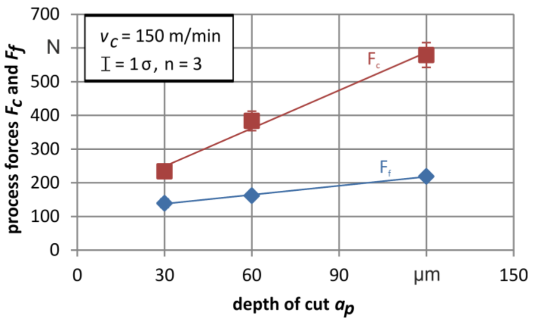

Figure 2. Process forces against depth of cut

The process forces are measured to determine the mechanical loads working externally on the material and then to derive the internal loads (stresses and temperatures). Internal loads will be correlated with resulting material modifications like microstructure, hardness or residual stress state; so far, this correlation is not possible.

For the investigated process, the roughness values lie in the range of Sa_{out} = 135 nm ± 14 nm (cf. Fig. 3 and Fig. 4). Therefore, the roughness is improved compared to the input state after preprocessing by face turning. At v_c = 150 m/min and a_p = 60 µm, a slight tendency to lower roughness values can be supposed. With these parameters, the best roughness was measured. Nevertheless, a significant influence on surface roughness of different cutting parameters, even with strongly changing process forces, is not observed.

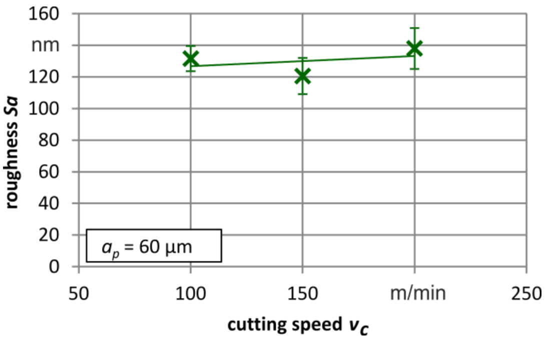

Figure 3. Surface roughness against cutting speed

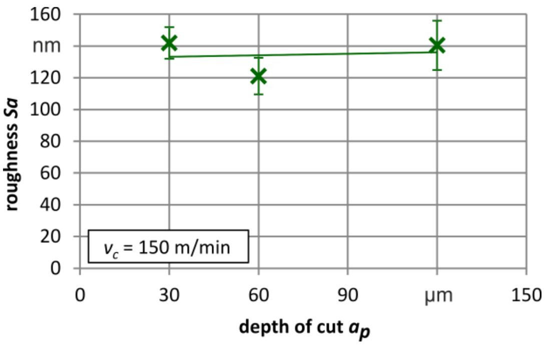

Figure 4. Surface roughness against depth of cut

3. Conclusion

The orthogonal turning of the hardened material AISI 4140 (approx. 52 HRC), with a sharp 50 % CBN-grooving tool was investigated, in the range of the machining parameters f_U = 0.1 mm/rev, v_c = 100 m/min to 200 m/min and a_p = 30 µm to 120 µm. In these conditions process forces of F_z = 0, F_c = 212 N to 613 N and F_f = 125 N to 224 N occur. Surface roughness of *Sa* = 135 nm ± 14 nm is achieved. Thus, higher mechanical loads do not have any negative effect on the surface roughness.

Future research will focus on two important aspects: Firstly, the energy input and dissipation in the material has to be determined in conjunction with the external mechanical and thermal loads as well as shear conditions. Therefore, chip geometry and chip compression ratio will be analysed experimentally and applied to analytical cutting models. Secondly, the internal stresses, depending on the external loads, will be estimated. Here, analytical methods for determining the internal stresses have to be chosen and verified using modeling and simulation tools like FEM.

To generate a novel knowledge-based material centered view for precision machining processes further parameters and loads need to be investigated in experiments and simulations and correlated with surface integrity.

Acknowledgement

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