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Analysis of mechanical impact in precision cutting processes

Melanie Willert, Oltmann Riemer, Bernhard Karpuschewski

Laboratory for Precision Machining, Foundation Institute of Materials Science, University of Bremen, 28359 Bremen, Germany

m.willert@lfm.uni-bremen.de

Abstract
For functional-oriented manufacturing, knowledge how the surface integrity of components is affected due to machining is of great interest. At the same time, the size effect occurring in precision machining, when undeformned chip thickness and cutting edge radius are of the same order of magnitude, hampers the prediction of process variables as well as surface and surface layer properties. In this paper fundamental research work is presented for precision cutting of steel with cemented carbide tools by means of varied process dynamics. Mechanical impact in continuous and interrupted cutting is examined by means of quantifying the process variables and material modification related to the feed. The experimental investigation shows that in cutting with geometrically defined cutting edge in a free quasi-orthogonal cut, the plowing effect is stronger in continuous cutting than in discontinuous tool engagement. When transferring process models between microturning and micromilling, this aspect must be taken into account. Furthermore, the analysis of the plastic deformation below the workpiece surface and correlation with measured process forces shows that the subsurface zone depends only indirectly on the kinematics and the process parameters. With regard to the generation of specific surface layer properties and thus a material-oriented machining, the loads and contact conditions resulting from the system and the selected machine control variables must be considered.

In-process measurement, Machining, Precision, Steel

1. Introduction

Precision machining is a finishing operation that determines the surface quality and final surface layer properties of a workpiece and thus also the functional properties of components. Consequently, understanding the precision machining processes is of particular interest in terms of surface integrity. Several studies have shown that precision cutting processes are dominated by various process mechanisms: chip formation by shearing, plowing and rubbing, depending on the microgeometric engagement conditions of the cutting tool, which are determined by the aspect ratio of the undeformed chip thickness to the cutting edge radius h/r_β [1-2]. This is manifested in a non-linear profile of the specific cutting force when the undeformed chip thickness h and the cutting edge radius r_β are of the same order of magnitude. In the field of manufacturing technology, this is referred to as the "size effect". In their study of micromilling hardened tool steel, Aramcharoen and Mativenga found that roughness is lowest at a ratio of $h/r_\beta = 1$ [3]. Cuba Ramos et al. found that in process transition from pure ploughing to chip formation the surface roughness increases and the compressive residual stresses switch to tensile residual stresses [4]. For the prediction of surface integrity, this phenomenon is therefore a particular challenge.

In order to investigate the influence of the mechanical impact of the plowing effect in microturning and micromilling with respect to the process dynamics, microcutting experiments with force measurement and subsequent surface layer analysis were performed with different cutting length by constant and interrupted tool engagement.

2. Experimental procedure

The experiments were performed on a precision lathe GoFuture B2 (Carl Benzinger GmbH, Germany). While the turning process was carried out in the free, quasi-orthogonal cut with feed in the axial direction, the process forces were measured on the tool side by means of a KISTLER 3-component dynamometer Type 9119AA1 with a sampling rate of 20 kHz. In order to realize both continuous and discontinuous cutting, the geometry of the tubular workpieces with 1 mm wall thickness and a diameter of 58 mm was varied: as a cylindrical ring and 15 mm long single tooth (cf. Fig. 1). The material was quenched and tempered steel AISI 4140 (42CrMo4) with 47 HRC. As tools 2 mm wide cemented carbide grooving inserts were used with a titanium aluminum nitride coating and a cutting edge radius r_β of 9.9 ± 0.5 µm. Corresponding to r_β, the feed f was varied between 7 µm ($h < r_\beta$) and 70 µm ($h > r_\beta$) in order to cause different process mechanisms, at a cutting speed of $v_c = 300$ m·min^{-1}. Accordingly, a workpiece rotation on the mean ring diameter takes 36 ms.

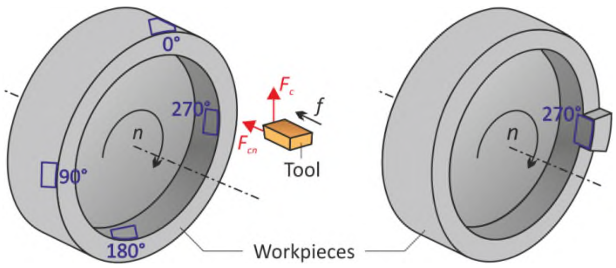

Figure 1. Experimental setup for continuous (annular workpiece, left) and discontinuous (tooth-like workpiece, right) turning with labeling of sampling points

2.1. Process forces

The measured process forces for varied cutting length by constant and interrupted tool engagement were evaluated for $f \approx h$ on the basis of the average maximum cutting force $\overline{F}_c$. For the analysis of the plastic deformation in the surface layer, the last workpiece revolution is relevant where the tool retraction takes place (cf. Fig. 2).

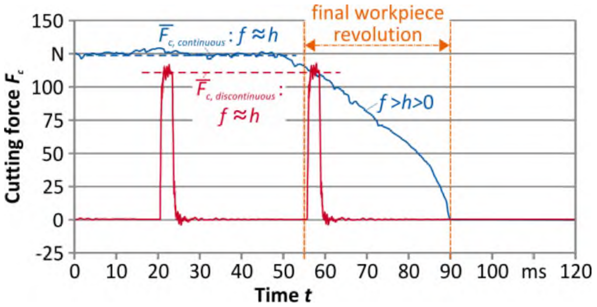

Figure 2. Force measurement plot of the cutting force with constant and interrupted tool engagement at f = 35 µm·rev^{-1}

2.2. Plastic deformation in the surface layer

Subsequently, for the analysis of the surface layer, metallographic sections and scanning electron micrographs were taken on selected machined workpieces. For this purpose, samples were eroded out of the workpieces, embedded in epoxy resin, ground, polished and etched (15 seconds with 3 % nitric acid). The material microstructure was characterized by means of a Tabletop Scanning Electron Microscope TM3030Plus (Hitachi, Japan) with an acceleration voltage of 15 kV, at 7000x magnification in BSE mode, as seen in Fig. 3.

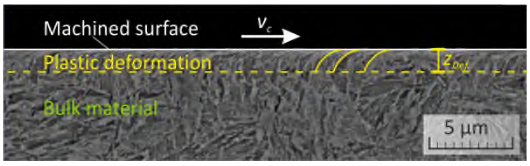

Figure 3. Plastic deformation in the workpiece surface layer after cutting with f = 35 µm·rev^{-1}

3. Results and Discussion

The graphs of specific cutting force and cutting normal force show the typical non-linear increase at smaller feeds, which correspond to the undeformed chip thickness due to the process kinematics. When comparing the specific cutting forces k_c for continuous and discontinuous microcutting, it is noticeable that the values at the ratio of $h/r_\beta = 7$ are very close to each other with a difference of only 134 N·mm^{-2}, while the discrepancy is significantly greater at a ratio of $h/r_\beta = 1$ with 1054 N·mm^{-2}. The difference is even greater for the specific cutting normal force k_{cn}, as shown in Fig. 4.

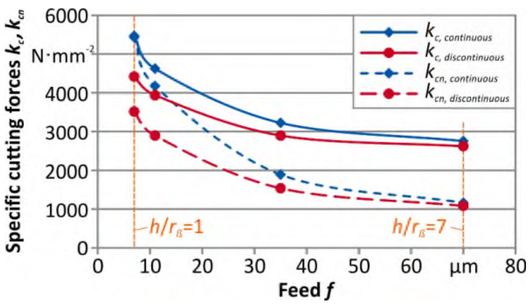

Figure 4. Specific cutting forces for continuous and discontinuous cutting

At a feed of 35 µm, discontinuous microcutting generates a plastic deformation down to a depth of 2.6 µm below the surface. Continuous cutting with the same feed causes deformation up to a maximum depth of 1.7 µm, varying over the circumference of the workpiece by 0.15 µm (cf. Fig. 5).

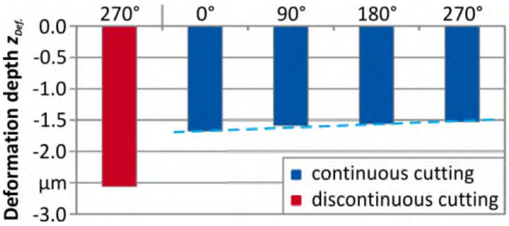

Figure 5. Deformation depth in continuous and discontinuous cutting

4. Conclusion and Outlook

For the transferability of models for microturning and micromilling processes, the following conclusions can be drawn with regard to the mechanical impact:

- As is known, due to the transition from cutting to plowing with decreasing undeformed chip thicknesses, a size effect in the specific cutting forces occurs in the form of a non-linear increase when undeformed chip thickness and cutting edge radius are of the same order of magnitude.
- The plowing effect is more pronounced with larger cutting lengths.
- The kinematics of grooving causes unsteady engagement conditions when the tool is retracted after cutting is completed. Consequently, the undeformed chip parameters are undefined ($f \geq h \geq 0$), which prevents analysis of the mechanical impact by correlating process forces and surface layer properties.

Finally, the development of models for the prediction of surface integrity in precision machining requires a high spatial and temporal resolution of the mechanical impact in-process, so-called material load, as well as ex-process, the material modification. For this purpose, in addition to the knowledge of the process forces, the contact conditions are crucial. Based on this, a transfer of existing process models for microturning and micromilling would be possible. Therefore, in future work, investigations will be carried out with further variation of the cutting length, by adjustment of the workpiece geometry or the length of the tooth, in order to identify their functional relationship with the intensity of the plowing effect as well as other process kinematics for the correlation of material loads and modifications.

Acknowledgement

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