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Identification of an optimal cutting edge microgeometry for Complementary Machining

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ABSTRACT

The process strategy Complementary Machining combines machining and surface modification, resulting in optimal workpiece properties like fatigue strength. Right after machining the cutting tool is used reversely acting as a tool for a mechanical surface modification. The challenge of designing a cutting edge microgeometry that withstands the load spectrum and induces optimal surface layer states during Complementary Machining is solvable by modeling the resulting surface layer using FEM-simulation. Using the simulation-based analyses a deep process understanding is accomplished enabling further optimization of surface integrity (e.g. grain refinement) which is proven by measurements.

1. Introduction

In industrial production of metallic components, the workpiece properties like fatigue strength, wear resistance or tribological behavior are of great importance, in particular during manufacturing high performance components. These workpiece properties are mainly influenced by workpiece states like surface topography (e.g. *Ra*, *Rz*), hardness *HV*, residual stresses σ^{rs}, or microstructure in the surface layer [1,2]. A microstructure composed of nanocrystalline grains shows favorable properties. Past investigations show that metallic components with a nanocrystalline surface layer have improved properties in fatigue strength, wear resistance and tribological behavior [3–5].

In recent investigations, it was shown that under specific conditions machining can be used to induce a nanocrystalline surface layer [6]. Thereby the cutting edge microgeometry is a relevant factor for grain refinement [7]. However, the thermo-mechanical load on the cutting edge controls the tool wear [8]. For this purpose, the load-specific design of cutting edges is an important contribution to improve the machining process [8]. A focus of research is the aimed and reproducible preparation of cutting edge microgeometries [9].

Widespread possibilites to influence the surface layer states are the mechanical surface modification processes, which include both burnishing technologies and machine haminer peening processes [2]. With mechanical surface modification processes, nanocrystalline surface layers can be generated. Due to high plastic strains and plastic strain rates as well as process temperatures grain refinement can be achieved using surface severe plastic defomation (S^2PD) processes like surface mechanical attrition treatment (SMAT) [10] or surface mechanical rolling treatment (SMRT) [11].

Because of growing requirements to apply smart process chains several approaches are developed to integrate the mechanical surface treatment in a previous manufacturing process. One of the hybrid machining strategies is turn-rolling, which combines hard turning and deep rolling to produce roller bearings in a very efficient process [12]. With turn-rolling the surface roughness is reduced and the micro hardness is increased [13].

Another approach is the orthogonal turn-rubbing [14]. After the machining process, the surface modification takes place with a rubbing element. With this process strategy, the surface layer states like residual stresses are influenced.

The process strategy Complementary Machining is a further approach to integrate mechanical surface modification in the machining process step. Previous investigations of Complementary Machining showed the sensitivity of penetration depth a_p and surface modification velocity v_{st} on the process forces and plastic deformations of the surface layer during the process step surface modification [15]. This plastic deformation results in the reduction of surface roughness (*Ra*, *Rz*) and an increasing micro hardness *HV* [16], making the Complementary Machinig a promising process strategy that also shows a high potential to influence the residual stress state. However, standard cutting edges are not designed to withstand the occurring loads. This paper presents the simulation-based identification of a suitable cutting edge microgeometry with high wear resistance that is capable to generate a thick nanocrystalline surface layer.

2. Complementary Machining

The process strategy Complementary Machining is the combination of machining and the reverse utilization of the cutting insert for mechanical surface modification right after the machining process. Due to the inverse machining direction during the mechanical surface modification process a high plastic deformation is induced in the surface layer which result in grain refinement. Fig. 1 shows the contact conditions for Complementary Machining. The nomenclature for machining is based on orthogonal cutting,

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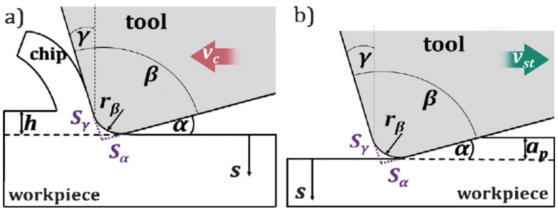

Fig. 1. Contact conditions for Complementary Machining. a) machining, b) mechanical surface modification.

while for mechanical surface modification it is based on mechanical surface treatment.

The cutting edge microgeometry used has a substantial influence on the process forces and maximal temperature during Complementary Machining. Consequently, the resulting surface layer states depend on the cutting edge microgeometry as well. However, the design of a cutting edge microgeometry that withstands the thermo-mechanical load spectrum and optimally influences the surface layer states is a central challenge in developing the process strategy. It is possible that although a cutting edge microgeometry allows the generation of nanocrystalline surface layers, this cutting edge is not inevitable appropriate regarding the thermo-mechanical load spectrum which results in premature tool wear.

3. Experimental setup

For the investigations, a test bench is used which is comparable to the one described in [17,18]. It was previously used to study friction phenomena and thermal softening caused by frictional heat generation and plastic deformation during machining. Quasi-orthogonal cutting experiments with AISI 4140 were carried out on a MAG 5-axis mill-turn machining center. Workpieces with dimensions of $40 \times 4 \times 20$ min^3 were clamped on the outermost radius ($r = 350$ mm) of the rotating machining table. This experimental setup ensures quasi-othogonal cutting conditions. Uncoated cutting tools (type WKM P8TN 6028833) with a cutting wedge angle of 90° and a initial cutting edge radius $r_\beta = 40 \pm 10$ mm were used. The tool was fixed with a rake angle $\gamma = -7°$. The workpiece was machined on the surface with the width $w = 4$ mm. For both steps of Complementary Machining (machining and mechanical surface modification) the same velocities, meaning a cutting velocity v_c and a surface modification velocity v_{st} of 100 m/min, but different depths, meaning a cutting depth $h = 120$ μm and a penetration depth $a_p = 20$ μm were used. For characterization of the cutting edge microgeometry the form-factor method by [19] was applied which includes the description of the average cutting edge rounding S. Three cutting edges (form-factors $K = 0.2$, 1 and 2) were prepared by brushing. The measurements of the cutting edge microgeometries were carried out using a Mahr perthometer. Focused ion beam-technique was applied using a FEI Strata 400S Dual Beam FIB/SEM to study the microstructure. The ion channeling contrast imaging was performed by detecting secondary electrons emitted due to the irradiation of the cross-section area with an ion beam of 9 pA.

4. FEM-simulation

4.1. Modeling of machining

Modeling of the two process steps was performed using different models. The orthogonal machining process step was performed using the well validated 2D-FE-simulation with ABAQUS/Standard by [5,7]. The model including the boundary conditions used is described in [5]. The full-coupled thermo-mechanical analysis and user defined subroutines ensure the simulation of the thermo-mechanical load at the cutting edge and the grain refinement in the surface layer during machining.

4.2. Modeling of mechanical surface modification

The mechanical surface modification step needed a 3D-FE-simulation because of the material displacement in all three dimensions. Based on the 2D-FE-simulation of the machining step a 3D-FE-simulation in ABAQUS/Standard using the same material models and boundary conditions was used.

4.3. Material model

In the 2D- and 3D-FE-simulations for the workpiece material a physics based material model was used and implemented in a UHARD subroutine. The material model, based on an approach by, [20–22] describes the plastic behavior dependend on plastic strain ε_{pl}, plastic strain rate $\dot{\varepsilon}_{pl}$ and temperature *T*. The grain refinement was modeled using the Zener-Hollomon parameter *Z* which describes the dynamic recrystallization dependent on plastic strain rate $\dot{\varepsilon}_{pl}$ and temperature *T*. The model used is based on an approach by [23–27]. The material models are describing the plastic behavior and grain refinement and have already been validated in the past [5,7,22].

5. Results and discussion

5.1. Nanocrystalline surface layer

In Fig. 2 the influenced microstructure in the surface layer after the Complementary Machining experiments and simulations using a cutting edge with a form-factor *K = 2* is shown. A nanocrystalline surface layer can be observed up to a distance from surface d_s of 2.41 μm. Below this layer a microcrystalline sheared layer follows and finally the bulk material with a grain size $d_g > 1$ μm. The same tendency is depicted in FE-simulation with a somewhat over-estimated affected depth.

In Fig. 3 the thicknesses s_{gr} of the grain refined surface layers with a nanocrystalline microstructure after the process steps machining and mechanical surface modification are plotted. According to, [7] the highest thicknesses of nanocrystalline surface

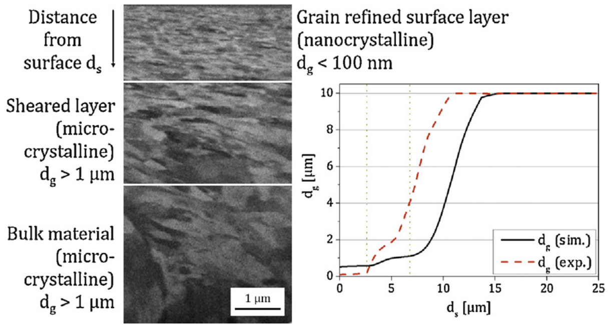

Fig. 2. Analyzed surface layer (FIB) after Complementary Machining (cutting edge microgeometry with the form-factor $K = 2$).

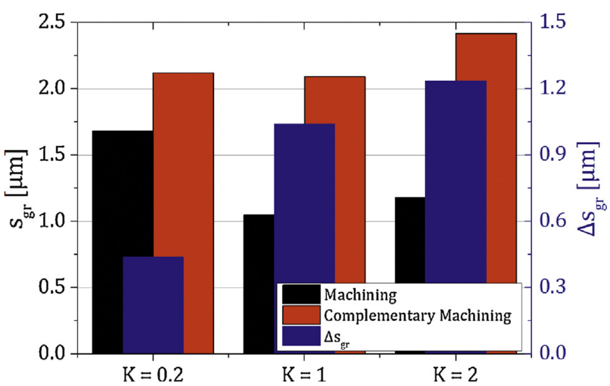

Fig. 3. Resulting thickness of nanocrystalline surface layer after machining and Complementary Machining.