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Influence of the cutting edge microgeometry on the surface integrity during mechanical surface modification by Complementary Machining

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Abstract

In metal production, mechanical surface modifications are used to optimize workpiece characteristics to improve properties such as fatigue strength. Machining and mechanical surface modification can be integrated in the process strategy Complementary Machining. After machining the cutting tool is used reversely acting as a tool for mechanical surface modification. This paper shows the influence of the cutting edge microgeometry on process forces and temperatures as well as process induced grain refinement in the surface layer during the mechanical surface modification of Armco-Iron and AISI 4140. The mechanical surface modification is simulated in a 3D-FEM-simulation with ABAQUS/Standard.

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1. Introduction

In machining operations of metallic components, it is of great importance to produce surfaces with high geometric accuracy and surface integrity due to the machining process. In this context, surface integrity includes to enhance workpiece characteristics like fatigue strength, wear resistance, tribology or corrosion [1]. The surface layer state (e.g. residual stresses, roughness, micro hardness or grain size) has a significant influence on these workpiece properties [2-5]. During machining the cutting edge microgeometry substantially influences the resulting surface layer states as a result of the impact of high thermal and mechanical loads [6]. For this reason the cutting edge microgeometry and the preparation of these are in focus of research investigations [7-9].

In industrial applications a machining process is followed by a mechanical surface modification processes to improve surface integrity. Mechanical surface modification processes aim to smoothen the surface topography, influence residual stresses, increase the hardness or influence the microstructure. The surface layer states can be achieved by a local plastic

deformation of the surface layer during the surface modification.

The process strategy Complementary Machining combines the machining and the mechanical surface modification [10]. After the machining process the cutting tool is used in opposite direction resulting in a plastic deformation of the surface layer. On the one hand, the process is reciprocal because the tools are used in the opposite direction. On the other hand the process is integral because standard machining is supplemented by mechanical surface modification. For that reason the machining strategy is called Complementary Machining. Previous investigations of Complementary Machining showed the reduction of surface roughness and an increased strain hardening [11].

One of the objectives of the current investigation is to generate knowledge about the influence of the cutting edge microgeometry on the resulting process forces, temperatures and microstructure during mechanical surface modification by Complementary Machining of Armco-Iron and AISI 4140. The mechanical surface modification is simulated in a 3D-FEM-simulation with ABAQUS/Standard.

2. Setup and Materials

2.1. Cutting edges

To analyze the influence of cutting edge microgeometry on surface integrity, the microgeometry has to be defined. In Fig. 1 the contact conditions between the tool and the workpiece during the mechanical surface modification by Complementary Machining are shown. After the machining process with process parameters cutting velocity v_c and cutting depth h the cutting tool is used in opposite direction for the mechanical surface modification. For the surface modification the penetration depth a_p and the surface modification velocity v_{st} are the characteristic process parameters for this process step.

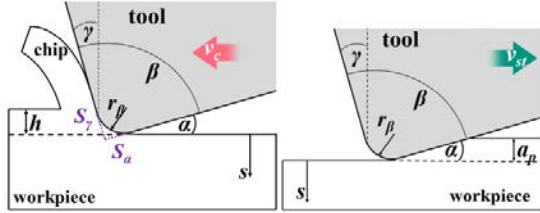


Figure 1. Contact conditions for Complementary Machining

In this paper the microgeometry of the cutting edge is characterized by the form-factor method following the approach of Denkena [12] for the machining process. The form-factor K is defined as

$$K = \frac{S_\gamma}{S_\alpha} \quad (1)$$

S_γ is the cutting edge segment on the rake face, S_α is the cutting edge segment on the flank face. This definition is the basis for machining and surface modification.

2.2. Finite element model

The finite element model is described as a three-dimensional orthogonal cutting process with the FEM software ABAQUS/Standard. The model consists of two bodies, the tool and the workpiece. The tool is defined as a rigid body only allowing the workpiece to be deformed and to be meshed with hexahedral coupled temperature-displacement (C3D8T) elements. The width was fixed at 600 μm and the other geometry parameters varied according to the penetration depth a_p and the form-factor K . The workpiece is defined as a rectangular solid with a width of 500 μm , a length of 700 μm and a height of 300 μm . Moreover it is meshed with tetrahedral coupled temperature-displacement (C3D4T) elements.

During the process the tool moves with the surface modification velocity v_{st} along the fixed workpiece. The microgeometries of the tool are generated through fitting ellipses, determined by S_γ and S_α . In addition, two sources of heat generation were implemented into the model. On the one hand, heat generation through friction. Therefore, a constant friction coefficient μ was used following the approach of Coulomb's law. On the other hand, heat generation through plastic deformation was implemented. The description of the flow behavior and the grain size of the material model AISI

4140 and Armco-Iron are implemented through a UHARD subroutine into the ABAQUS/Standard model.

2.3. Modelling of flow stress and grain refinement

The flow stress σ depends on the temperature T and the strain rate $\dot{\epsilon}$. Thereby, the flow stress can be decomposed in an athermal component σ_G and a thermal component $\sigma^*(T, \dot{\epsilon})$. These are based on the approaches of [13-15].

$$\sigma = \underbrace{\sigma_0^* \cdot \left(1 - \left(\frac{T}{T_0}\right)^n\right)^m}_{\sigma^*} + \underbrace{\left(\sigma_{G0} + (\sigma_1 + \theta_1 \cdot \bar{\epsilon}_p) \cdot \left(1 - \exp\left(-\frac{\theta_1 \cdot \bar{\epsilon}_p}{\theta_0}\right)\right)\right) \cdot \frac{G(T)}{G(0K)} \cdot g(T, T_{tr})}_{\sigma_G} \quad (2)$$

Due to short range dislocation obstacles the thermal component $\sigma^*(T, \dot{\epsilon})$ depends on temperature T , the strain rate $\dot{\epsilon}$ and the material constants n and m . The thermal component $\sigma^*(T, \dot{\epsilon})$ increases with decreasing temperature and an increasing strain rate. Above the temperature T_0 the thermal component will be neglected. T_0 is defined as

$$T_0 = \frac{\Delta G_0}{k_B \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}_p}\right)} \quad (3)$$

with the free activation enthalpy ΔG_0 and the Boltzmann constant k_B .

Due to long range dislocation obstacles the athermal component σ_G slightly depends on the temperature T and the shear modulus G . The term $g(T, T_{tr})$ describes the high temperature softening and is 1 for $T \leq T_{tr}$. For $T > T_{tr}$, $g(T, T_{tr})$ is defined as

$$g(T, T_{tr}) = \left(1 - \left(\frac{T - T_{tr}(\bar{\epsilon}_p)}{T_m - T(\bar{\epsilon}_p)}\right)^\xi\right)^\varsigma \quad (4)$$

with

$$T_{tr}(\bar{\epsilon}_p) = \vartheta_0 + \Delta\vartheta \cdot \ln\left(1 + \frac{\bar{\epsilon}_p}{\dot{\epsilon}_n}\right) \quad (5)$$

including the material constants ϑ_0 , $\Delta\vartheta$, ξ , ς and the melting temperature T_m .

The modelling of the grain refinement bases on the Zener-Hollomon parameter Z . The Zener-Hollomon parameter Z depends on the plastic strain rate $\dot{\epsilon}_{pl}$ and the temperature T . The validation of this approach is published in [16] for machining of AISI 4140.

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