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On the Applicability of the Concept of Process Signatures to Hard Turning

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Abstract

Process Signatures correlate the thermo-mechanical load within the workmaterial during the manufacturing process with resulting modifications of the material properties. In the case of hard turning, new mechanical and metallurgical material properties in the workpiece surface may severely influence the structural stability and fatigue resistance.

This work investigated whether the concept of Process Signatures is applicable to hard turning of steel AISI 52100. Experimentally obtained surface properties are correlated with numerically simulated material loads, which the surface was subjected to during turning. The process was analyzed under consideration of different tool wear states in order to assess the material modifications for different thermo-mechanical loads.

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Keywords: Process Signature; Hard Turning, Surface Integrity

1. Introduction

In mechanical engineering the functional performances of many parts increase with their mechanical and topographical surface qualities [1]. Quantities of importance in this respect include hardness, residual stresses and surface roughness, which are often summarized by the term of Surface Integrity. Concerning the design of processes and tools of material removal processes the identification of parameters, which result in acceptable Surface Integrity characteristics, is of major importance. This identification is still mostly achieved by time- and cost intensive empirical approaches so that manufacturing research aims at introducing suitable process models. In order to compare seemingly categorially different processes to each other with respect to their impacts on micro- and macrostructural modifications of the surface layer, Brinksmeier et al. introduced the concept of Process Signatures [2-3]. The central idea is to generate an understanding of process-independent correlations between the thermo-mechanical loads within the workpiece material and the resulting material modifications. Therefore, processes can be compared to each other by means of the developing material load, which then also allows to reversely engineer manufacturing processes: Starting with desired values of Surface Integrity the required thermo-mechanical material load is identified, which then determines the process parameters.

Due to the complex interactions of mechanical and thermal effects determining Surface Integrity during metal cutting, numerical modeling approaches like the Finite Element Method (FEM) are widely present in the literature [1]. In the field of hard turning extensive works have been published, e.g. on residual stresses and white layer formation including contributions of Liu and Guo [4], Outeiro et al. [5], Umbrello and Jawahir [6] or Umbrello et al. [7]. In this respect white layers refer to surface layers, which are characterized by modified, micro/nano-crystalline grain structures with varying distributions of hardness and residual stresses, which may be undesired or desired depending on the technical application of the considered part. Its is generally accepted that these layers form under characteristic conditions of thermal and mechanical loads, which may even yield phase transformations, as discussed in detail by Rech and Moisan [8].

In this paper, an interpretation of cylindrical hard turning experiments on hardened steel AISI 52100 is presented by

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means of comparing the empirically obtained surface characteristics with numerically calculated material loads during the process. Therefore, the present work investigates whether to concept of Process Signatures is applicable to hard turning.

At first, the hard turning experiments and the characterization of the white layer formation are described, followed by the description of a Finite Element process model and its validation. Finally, calculated distributions of equivalent stress and temperature are correlated with the experimentally obtained depths of the white layers and heat affected zones (if detected).

2. Hard Turning Experiments on AISI 52100

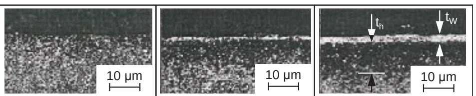
External, longitudinal turning experiments were conducted on hardened steel AISI 52100 with 60 HRC [9]. The applied tool geometries were RNMN02020 with rake angle γ = -6° and inclination angle λ_s = -6° (cutting material: Cubic Boron Nitride CBN). The cutting edges were chamfered (0.2 mm x 20°). The cutting force components were measured with a piezo-electric measurement platform. The force measurement were conducted under the following cutting conditions:

1) Reference: Feed f = 0.125 mm, depth of cut a_p = 1.5 cutting speed v_c = 100 m/min
2) Impact of cutting speed: f = 0.125 mm, a_p = 1.5 mm, v_c = 200 m/min
3) Impact of feed: f = 0.125 mm, a_p = 3.0 mm, v_c = 100 m/min

For the investigations of the surface modifications during hard turning, finishing cutting conditions were chosen to f = 0.08 mm, a_p = 0.2 mm, v_c = 120 m/min. The experiments distinguished by the tool flank wear land widths VB, which were documented before the metallographic investigations of the surface characteristics as follows:

VB = 0.06 mm; 0.11 mm; 0.19 mm

Figure 1 shows the metallographic documentations of the modified surface layers of the workpiece. The depths of the heat affected layers and the white layers are given.



Flank wear	VB = 0.06 mm	VB = 0.11 mm	VB = 0.19 mm
Thickness of Heat affected zone	t_h = 1.42 µm	t_h = 4.54 µm	t_h = 10.5 µm
Thickness of White layer	t_W = 0 µm	t_W = 1.42 µm	t_W = 3.12 µm

Material	AISI 52100, 60 HRC	Cutting speed	v_c = 120 m/min
Tool corner radius	r_ε = 1.2 mm	Feed	f = 0.08 mm
Cutting material	CBN	Depth of cut	a_p = 0.2 mm

Figure 1: Metallographic investigations of the surface modifications in hard turning of AISI 52100

The depths of the heat affected zones and white layers increase with increasing tool wear. This is due to the increasing temperatures and contact pressures in the tool workpiece interface, which are involved with increasing values of VB. In the following, a Finite Element Model of the process is used to interpret this empirical observation in terms of stresses and temperatures.

3. Finite Element Model of Cylindrical Hard Turning of AISI 52100

3.1. Model Creation

A 3D FE model of the external longitudinal hard turning process of hardened AISI 52100 was developed. The commercial FE code Deform 3D (v10.2.1) was utilized, which is based on the implicit updated Lagrangian formulation. The tool was assumed to be rigid while the workpiece-material was modeled to be elasto visco-plastic. The constitutive equation of Johnson and Cook was applied for the calculation of the yield stress σ_{yld} as a function of the strain ϵ, strain rate $\dot{\epsilon}$ and temperature T as follows [10]:

$$\sigma_{yld} = (A + B \cdot \epsilon^n) \cdot \left(1 + C \cdot \ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)$$

A, B, n, C and m are material constants, which are adopted in this work from Arrazola and Özel for the considered steel AISI 52100 with 62 HRC [11]. Poulachon et al. proposed a modified version of the Johnson-Cook equation for AISI 52100 with 63 HRC [12].

The frictional stresses acting between workpiece and tool are calculated by the Coulomb friction model with a friction coefficient of μ = 0.35, which was calibrated by Guo and Liu [13]. Figure 2 shows a graphical representation of the simulation model. The parts of the workpiece, which lie in the generated surface, were discretized by finite elements of the size 0.001 mm. The element size was increased for the other parts of the workpiece according to Figure 2. The chamfered cutting edge of the insert was meshed with elements of 10 µm. The tool flank wear length VB was considered purely geometrically in the CAD files of the inserts.

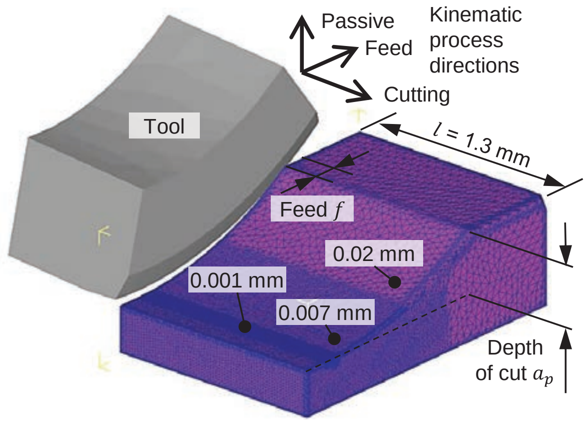


Figure 2: Graphical representation of Finite Element Model of hard turning

3.2. Model Validation

The proposed model was validated by comparing the measured and predicted cutting force components. The error between simulation and experiment for the cutting force