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A simulation based development of Process Signatures for manufacturing processes with thermal loads

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Abstract

The newly developed concept of Process Signatures enables the comparison of surface integrity achieved by seemingly different manufacturing processes. This paper suggests Process Signatures for grinding and induction heating. Based on finite element simulations of both processes the relevant internal material loads are identified and are correlated with the simulated residual stress state. To provide a comparable simulation approach the moving heat source theory is applied and combined with energetic quantities. The investigations show that grinding and induction heating are similar for certain parameter regimes regarding the generated residual stress state of the workpiece surface layer.

Keywords: Residual Stress, Grinding, Induction-heating, Process Signature

1. Introduction

The importance of manufacturing processes on the functional performance of components is generally known [1,2,3]. This is especially true for finishing processes such as grinding or hard turning which affect the functional performance by changing the workpiece surface layer properties, e.g. residual stresses, microstructure, and hardness. However, even under laboratory conditions a controlled generation of surface layer properties is not state of the art in machining [2].

It is assumed that this knowledge gap is the result of a process-oriented view that has been prevailing in the scientific analyses in which predominantly the resulting workpiece material modifications are correlated with the machining parameters and/or process quantities [4,5,6,7]. The reason is that internal material loads, i.e. stresses, strains, strain gradients, temperatures, and temperature gradients, which actually lead to the observable modifications are hard to determine or even not known at all. As a consequence the validity of the findings is very limited.

A material-oriented view which focusses on the mechanisms leading to workpiece material modifications by manufacturing processes, as the newly introduced concept of Process Signatures [8] intends, should resolve this lack of knowledge. In the frame of Process Signatures, the material modifications are correlated with the internal material loads that are assumed to cause the modifications by activating mechanisms such as plasticity (yielding) and/or phase transformations.

The Collaborative Research Center (CRC) 136 - Process Signatures aims at developing these correlations for different manufacturing processes to prove the validity of the concept. Moreover, the correlations between internal material loads and process quantities (e.g. in the case of grinding: process power, process forces, and machining parameters) will be developed to be able to utilize Process Signatures for a reproducible and defined generation of surface layer properties.

2. Objectives and Procedure

The present work aims at an exemplary simulation-based development of correlations between material modifications

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and internal material loads (Process Signature) and between internal material loads and process quantities. In order to reduce the complexity of the analyses, only yielding in the workpiece surface layer caused by thermal loads are taken into account. This can approximately be realized by shallow cut grinding and induction heating in certain parameter regimes where austenitization of the workpiece material not occurs.

Both processes were modelled as a moving surface heat source and a moving volume heat source, respectively (Fig. 1). The mechanical material load in grinding was neglected.

Temperature increases and temperature gradients can be viewed as the relevant internal material loads. This is evident because the temperature governs the thermal and mechanical material behavior, and temperature gradients $d\theta/dx$ are the origin of plastic strains. However, the results will show that for an appropriate description of the material loads other parameters also have to be taken into account.

In the present work material modifications were characterized by the surface residual stresses and the zero crossing of the residual stresses below the workpiece surface.

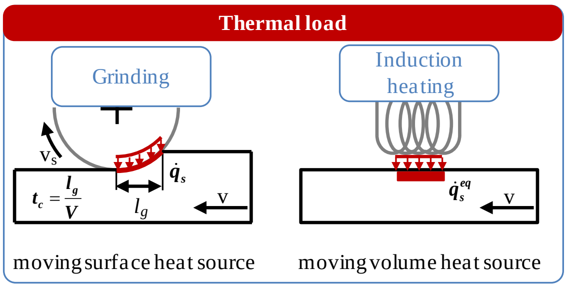

Fig. 1. Basic models of external thermal loads due to grinding and induction heating.

Nomenclature

a	thermal diffusivity [mm²/s]
b	exponent for calculating $\dot{q}_{Vol}$ [1/mm]
e	thermal effusivity [J/(K mm^2 s^{0,5}]
l_g	contact length [mm]
P_C''	specific grinding power [W/mm²]
Pe	Peclet number $l_g \cdot V/(4 \cdot a)$ [-]
$\dot{q}$	heat flux ($\dot{q}_S$ or $\dot{q}_S^{eq}$)[W/mm²]
$\dot{q}_S$	heat flux through the workpiece surface [W/mm²]
$\dot{q}_S^{eq}$	equivalent heat flux (calculated with $\dot{q}_{Vol}$) [W/mm²]
$\dot{q}_0$	factor for calculating $\dot{q}_{Vol}$ [W/mm³]
$\dot{q}_{Vol}$	heat per volume unit [W/mm³]
$\sigma\|$	residual stress parallel to workpiece velocity [MPa]
θ	temperature [°C]
θ_{max}	maximum temperature [°C]
$d\theta/dx$	temperature gradient normal to surface [K/mm]
t_c	contact time [s]
V	workpiece velocity [mm/s]
x	distance from the heated surface [mm]

3. Methods

3.1. Preliminary considerations

After Malkin [9] maximum temperatures for a moving surface heat source occur at the surface and can be approximated by the following analytical function:

$$\Theta_{max} = 1.13 \cdot \frac{1}{e} \cdot \dot{q}_S \cdot \sqrt{t_c} = 1.13 \cdot \frac{1}{e} \cdot \dot{q}_S \cdot \sqrt{\frac{l_g}{V}} \tag{1}$$

in which the factor 1.13 results from assuming an infinite Peclet number. In a double-logarithmic plot proposed by Heinzel et al. [10] constant $\dot{q}_S \cdot \sqrt{t_c}$ values describe straight lines of constant maximal temperatures at the surface (Fig. 2). For higher temperatures than 750 °C a martensitic phase transformation might occur as intended in grind-hardening (grey framed area).

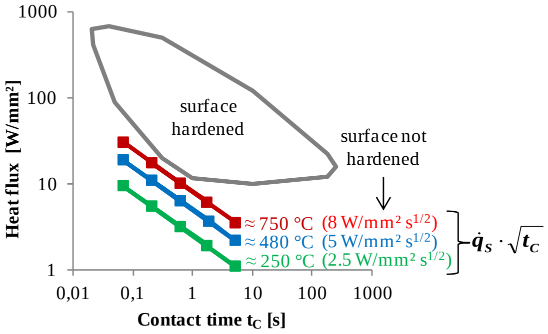

Fig. 2. Process window for grind-hardening [10].

In case of a volume heat source an equivalent surface heat flux $\dot{q}_S^{eq}$ has to be defined:

$$\dot{q}_s^{eq} = \int_0^\infty \dot{q}_{Vol} dx = q_0 \cdot \int_0^\infty e^{-bx} dx \,. \tag{2}$$

$\dot{q}_{Vol}$ represents the heat per volume unit depending on the distance x to the heated surface. The penetration depth of $\dot{q}_{Vol}$ is defined by *b* which equals 3.56·1/mm. This value describes approximately an induction heating with 12 kHz [11]. In the following $\dot{q}_S$ and $\dot{q}_S^{eq}$ will be used as equivalent values and will be denoted with $\dot{q}$.

3.2. Simulation parameters

According to the preliminary considerations in section 3.1 the process quantities in the simulation study were chosen in such a way that maximal temperatures at the surface of about 250, 450, and 750 °C were achieved: $l_g = 4 – 20$ mm, V = 4 - 60 mm/s, $\dot{q}$: = 1 – 39 W/mm².

The 3D simulations with the finite element code SYSWELD were carried out under the following conditions:

- Geometry: length 50 mm, width 30 mm, height 18 mm
- Temperature dependent material parameters for 42CrMo4 (Ferrite and Pearlite) [13]. Stress strain curves for temperatures up to 750°C were measured with a strain rate of approximately $3 \cdot 10^{-3}$ s^{-1}