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ScienceDirect

Procedia CIRP 45 (2016) 51 – 54

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Experimental and numerical analysis of residual stress change caused by thermal loads during grinding

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Abstract

A realistic modelling and simulation of the resulting surface integrity e.g residual stresses caused by grinding is limited due to the lack of knowledge to estimate the amount of thermal load affecting the workpiece. This paper deals with the inverse determination of the heat partitioning during grinding and the prediction of the resulting residual stress state due to the thermal impact by using 2D FEM-simulation without phase transformations. Grinding tests have been performed and the temperatures beneath the contact zone have been measured. For the first time, the concept of Process Signatures is applied on a machining process, providing basic functional relationships for process quantities, internal material loads and material modifications for predominantly thermal loads.

Keywords: Grinding, Modelling, Process Signatures

1. Introduction

The surface integrity in terms of e. g. residual stresses has a strong influence on the functional performance of the manufactured components [1]. Machining processes cause thermal, mechanical and/or chemical loads affecting the surface and subsurface properties of the workpiece material. As a consequence, the modeling and simulation of the resulting surface and subsurface properties after machining has become more and more relevant for current research and industry. Many research activities in the field of numerical [e.g. 2, 3] and analytical [e.g. 4, 5] models for machining processes have been focused on the process layout not reliant on preliminary test series. Regarding the prediction of residual stresses induced during grinding different approaches can be derived from literature [6, 7]. Based on the analytical calculation of surface temperatures and/or temperature fields, Finite-Element-(FE)-based simulations are used to determine the residual stress state within the subsurface area of ground components. In general, the generation of residual tensile stresses during grinding of hardened steel is dependent on specific temperature limits which have to be exceeded at the surface [8, 9] and which are in agreement with the findings by Malkin and Guo [10].

However, the mentioned approaches are process-oriented, correlating changes of surface and subsurface properties with process parameters. The direct selection of machining parameters to achieve a desired surface integrity state is generally not possible [11]. In this regard, the concept of Process Signatures is proposed, enabling a material-oriented view on machining taking into account the acting internal material loads [11, 12]. In this context, Process Signatures describe correlations between the mentioned loads during a certain process and the resulting material modifications.

2. Objectives and procedure

This paper aims to predict the residual stress state change at the surface due to grinding to provide a first approach in generating a Process Signature for a machining process with a

doi:10.1016/j.procir.2016.02.051

predominant thermal load. In order to reduce the complexity, grinding tests were performed achieving temperatures in the workpiece not higher than the austenitizing temperature. This procedure ensures that no phase transformations occur and the residual stress state will be changed due to thermal load and plastic deformations only. Based on temperature measurement in the subsurface of the workpiece, FE-based simulations were used to determine the heat partition fraction to the workpiece through an iterative approach, as the fraction of grinding power induced into the workpiece cannot be determined by experiments. The calibrated model was used to determine the internal material load state in terms of the quasi-stationary temperature distribution in the workpiece during the process as well as material modifications through the residual stress state resulting from grinding. For validation purposes, the simulated surface residual stresses were compared with measured surface residual stresses acquired after the grinding experiments using X-ray diffraction.

3. Methods

3.1. Workpiece Preparation

For temperature measurements during grinding, thermocouples (diameter 0.25 mm) have been placed into the workpieces at a distance of 2 and 7 mm from the grinding zone. In this regard, the workpieces (length 150 mm, width 29 mm, height 30 mm, AISI 4140 (42CrMo4), normalized state) has been provided with a groove (30 mm length, 11.9 mm height) from the bottom side at the lateral position where the thermocouples were located to ensure machining of the holes by conventional drilling, as well as guiding properly the electric cables out of the machine tool. Distances of the holes' tip to the workpiece surface have been measured in order to assure a sufficient accuracy for the calibration as well as for the validation of the FEM-model and simulations ($Z_{tc.2mm}$ and $Z_{tc.7mm}$ in table 1).

3.2. Grinding Experiments

A corundum grinding wheel type 9A60D28VCF2 with a width of 30 mm and 400 mm in diameter has been used at a constant wheel speed of v_s = 35 m/s. As maximum contact zone temperatures above AC_1 = 750 °C (conversion temperature) should be avoided, a very low specific removal rate of Q'_w = 1.5 mm³/(mm·s) has been set constant for the experiments whereas the depth of cut a_e and the tangential feed speed v_{ft} have been varied (table 1).

3.3. Finite Element Model

The process was modelled as a 2D uniform moving band heat source in the FEM-Software DEFORM (Fig. 1). The grinding operation itself was not modelled, the mechanical impact of the process was therefore neglected. Input parameters for the heat source were derived from the experimental setup, providing v_{ft} as moving speed of the heat source and l_g as heat source length:

$$l_g = \sqrt{a_e \cdot d_s}. \tag{1}$$

The heat source intensity (heat flux) $\dot{q}$ was modelled as a fraction of the grinding power, measured in the experiments:

$$\dot{q} = k_w \cdot P_c''. \tag{2}$$

An initial simulation with a rough estimation of the half specific grinding power (k_w = 0.5) is provided as input (heat flux) for the simulation (Fig. 2). The maximum temperature difference at $Z_{tc.2mm}$ between simulation and measurement was used to adjust the heat flux until the criterion $\Delta\vartheta < 1$ °C was achieved.

Table 1. Process parameters for grinding tests and distances Z_{tc} of the borehole tip from the workpiece surface

Test series	Q'_w [mm³/(mm·s)]	a_e [mm]	v_{ft} [m/min]	$Z_{tc.2mm}$ [mm]	$Z_{tc.7mm}$ [mm]
1	1.5	0.02	4.500	1.931	6.926
2	1.5	0.04	2.250	1.883	6.836
3	1.5	0.06	1.500	2.025	7.078
4	1.5	0.08	1.125	1.871	6.904
5	1.5	0.10	0.900	1.945	6.935

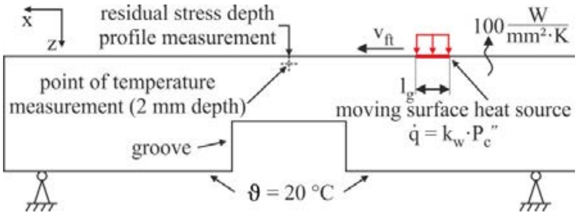

Fig. 1. Schematic overview of the used model, parameters and boundary conditions

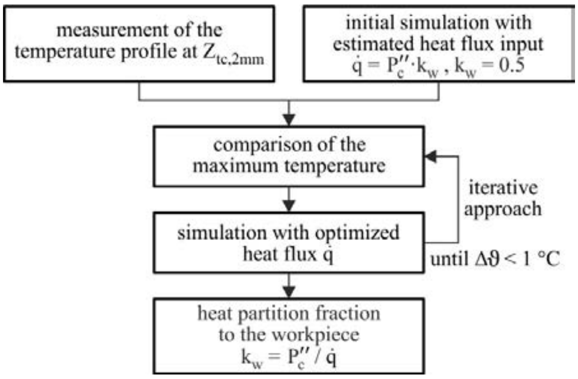

Fig. 2: Determination of the optimized heat partition fraction to the workpiece k_w

The heat partition to the environment was set to 100 W/(mm·K). Thermophysical properties were modelled according to [13], stress strain curves for temperatures up to 750°C were measured with a strain rate of approximately $3 \cdot 10^{-3}$ s^{-1} and were used to model the plastic behavior. To