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Procedia CIRP 45 (2016) 367 – 370

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Electron microscopic characterization of mechanically modified surface layers of deep rolled steel

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Abstract

Process Signatures describe the relationship between the applied material loads and the resulting surface modification according to the predominant effect of the production process used. This approach is supposed to allow the adjustment of surface layer properties prior to the production process. In this paper, the surface modifications of turned, turned + deep rolled and deep rolled metastable austenitic steel with predominantly thermo-mechanical/ mechanical effects are analyzed by electron microscopic methods like Electron Backscatter Diffraction (EBSD) and Transmission Electron Microscope (TEM) analysis. The modified surface layers show an increase in hardness as a result of the induced Hertzian pressures. TEM investigations of FIB-lamellae cut from the surface zone of the turned/ turned + deep rolled workpiece reveal a nanocrystalline microstructure. A superposition of surface modifications from turning and deep rolling is identified in the turned + deep rolled workpiece.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords: Surface analysis; Surface modification; Scanning electron microscope; Process signatures; X210Cr12 (AISI D3)

1. Introduction

Reproducible properties of surface layers, such as residual stress, are in high demand in industrial production processes. So far these have been developed by determining appropriate boundary and process conditions by means of several time-consuming iterative procedures. Since these boundary and process conditions only refer to the examined process and its specific process parameters, it is not possible to transfer these conditions to other production processes in order to achieve the same surface layer properties. Therefore a new energy based approach called Process Signatures was established by Brinksmeier et al. [1], which describes the relationship between internal material loads from the production process and material modifications in the generated surface layers. Therefore the functional properties of the generated surface layers are described by the influence of mechanical, thermal and chemical effects of the production process.

Turning is considered to have a predominantly thermo-mechanical effect whereas deep rolling is considered to have a predominantly mechanical effect [2]. In the production line, turning is usually used for machining and deep rolling as finishing process to achieve a high surface quality. However, the high Hertzian pressures induced by deep rolling also result in a surface hardening either by strain hardening or – depending on the material used – by phase transformations [2, 3, 4, 5]. Since phase transformations – such as the α-martensitic transformation – occur by applying a defined energy into the workpiece, a correlation between induced internal material loads and the resulting surface modifications is possible [6].

In order to achieve α-martensitic transformation just by mechanical effects, TRIP-steels with high content of metastable austenite are necessary [6]. Alloying elements like Cr, Ni, Mn or C allow the formation of metastable austenite and reduce the stacking fault energy of the steel [7, 8].

The indirect transformation of austenite to a high density of stacking faults and finally to ε-martensite is a simple shear

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doi:10.1016/j.procir.2016.02.147

Nomenclature

a_p	depth of cut
d_k	ball diameter
EBSD	Electron Backscatter Diffraction
FIB	Focused Ion Beam
f	feed
F_r	rolling force
KAM	Kernel Average Misorientation
STEM	Scanning Transmission Electron Microscopy
TEM	Transmission Electron Microscopy
TRIP	transformation induced plasticity
v_c	cutting speed
v_u	circumferential speed of workpiece
v_p	rolling speed

mechanism and occurs preferentially at lower stacking fault energies and external applied mechanical loads. If the applied mechanical loads exceed a critical value, nucleation of α-martensite occurs at crossing regions of stacking faults or ε-martensite [7].

The purpose of the present study is to identify and compare the surface modifications of turning and deep rolling and therefore allowing a first step towards posting Process Signatures.

2. Experimental set-up

In our study, the steel X210Cr12 (AISI D3) with a high content of metastable austenite at room temperature was used. In the production line workpieces are usually machined before the final surface hardening through deep rolling resulting in surface modifications generated by both processes. To distinguish between the surface modifications of turning and deep rolling and to gain information about their interaction a turned, turned + deep rolled and a defect-free polished + deep rolled workpiece were characterized (table 1 and figure 1).

As a means to show the change of phase contents of martensite/ austenite and the induced strain in the modified surface layer, EBSD measurements were performed on the longitudinal cross-section of the turned and turned + deep rolled workpieces and on the cross-section of the polished + deep rolled workpiece.

Table 1. Machining parameters

longitudinal turning	longitudinal turning + deep rolling of cylindrical workpiece	deep rolling of flat workpiece
v_c = 80 m/min	F_r = 1130 N (400 bar)	F_r = 469 N (165 bar)
a_p = 0,2 mm	d_k = 6 mm	d_k = 6 mm
f = 0,2 mm	v_u = 100 m/min	v_p = 1 m/min
	f = 0,02 mm	f = 0 mm

The EBSD measurements were performed using a JEOL JSM7000F scanning electron microscope equipped with Schottky field-emission gun and a combined EDX/ EBSD-

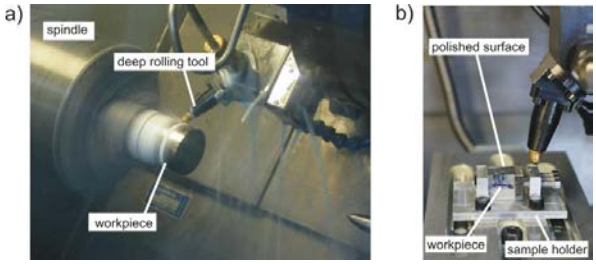

Fig. 1. (a) deep rolling of a turned, cylindrical workpiece [Bri07]; (b) deep rolling of a flat, defect-free polished workpiece.

system from EDAX-TSL consisting of an Octane Plus SSD EDX detector and a "Hikari" EBSD camera. For the measurements the system was operated at an electron energy of E = 20 keV and a probe current of approximately i_P = 20 nA. The measured areas have been scanned with a step size of x_{SD} = 100 nm each. The software used for measurement and data evaluation was OIM Data Collection and OIM Analysis by EDAX-TSL, both in version 6.2.

3. Results and discussion

3.1. Hardness and KAM

In figure 2 a-c, kernel average misorientation (KAM) of austenite grains and the hardness are compared according to the penetration depth of the modified surface layer of the turned, deep rolled and turned + deep rolled workpieces. The kernel average misorientation maps in figure 3 a-c show the average misorientation of diffraction patterns of neighboring points in rainbow color for a misorientation range of 0°-3° for austenite grains. As figure 2 depicts, both graphs (hardness and KAM) have the same trend. Since defects like dislocations or stacking faults change the orientation between neighboring data points, the KAM-maps qualitatively indicate the induced strain and dislocation density [9]. Therefore

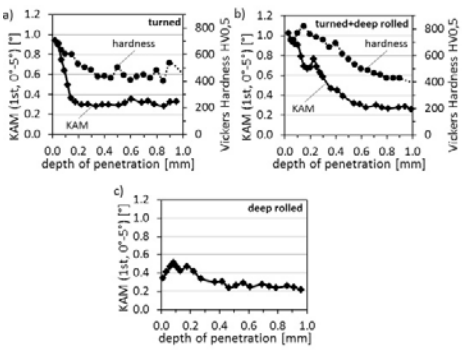

Fig. 2: Average KAM and hardness distribution as a function of the penetration depth of a) turned, b) turned + deep rolled, c) deep rolled workpiece. The KAM values only refer to the average KAM distribution of austenite grains.