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# Surface integrity of AISI 4140 after deep rolling with varied external and internal loads

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**Abstract**

To achieve favorable surface and subsurface properties by means of compressive stresses, low surface roughness and strain hardened microstructures, deep rolling is a well-established manufacturing process. To gain a better understanding regarding the correlations between the rolling forces (external load), the resulting Hertzian stresses (internal material load), and the modification of surface and subsurface properties, in this paper, deep rolling parameters were varied in a defined way under consideration of the correlations between external and internal loads. It is shown that at identical external loads, different surface and subsurface properties may result due to a defined variation of the internal loads.

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## 1. Introduction

The functional performance of components, such as fatigue life, is strongly dependent on the surface integrity resulting from the applied manufacturing process. Processes with predominantly mechanical impact such as deep rolling are well-described to increase hardness, to induce compressive residual stress, and to change the microtopography [1]. Although the correlation between process parameters and resulting surface and subsurface properties is often discussed [2-4], the generation of defined changes in the functional material properties of components is still an iterative or experience-based process. To solve the inverse problem of generating a given desired surface integrity, a better understanding of mechanisms leading to a material modification is required. Byrne describes the need of an observation from within the workpiece to consider the effects (e.g. strain hardening) induced to the material while the tool influences the surface and subsurface of the workpiece [5]. This approach was further developed by Brinksmeier et al. to establish a mechanism-based description of machining processes and its resulting material modification [6]. For this, energy conversion and dissipation lead to a specific internal load in the material, resulting in a change of surface and subsurface properties (material modification) after machining [7]. According to this approach, deep rolling can be described as a moving pressure source, which induces internal mechanical loads such as stress and strain fields during the process (Fig. 1). The correlation of internal material load with the modification of state variables (residual stresses, hardness and microstructure) can be described as process signatures [7].

To characterize the internal material loads during deep rolling by means of equivalent stresses, Hertz allows for describing the pressure and contact conditions between two bodies of a defined geometry under elastic conditions [8,9]. In line with this approach, deep rolling of cylindrical workpieces can be assumed to correspond to the contact between to spheres [10], which allows the analysis of internal material loads. This approach was e.g. used in [11] to quantify the mechanical load in a cryogenically assisted deep rolling process.

This paper aims at establishing a changed perspective on the process from an external load oriented view, to an approach which focusses on the resulting internal material loads to predict the material modifications in surface and subsurface layers.


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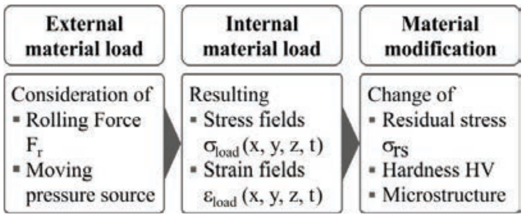


Fig. 1: transfer function for mechanical processes.

## 2. Experimental setup

The deep rolling experiments were performed on a conventional CNC turning lathe. As workpiece material, an AISI 4110 (42CrMo4) in a quenched and tempered state with hardness of 21 HRC was chosen. A spherical, hydrostatic guided deep rolling tool was used. Deep rolling of a cylindrical workpiece with an initial diameter of 60 mm is shown in Fig. 2.

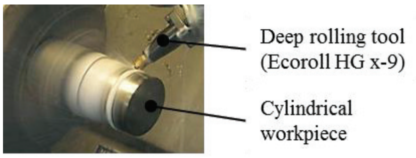


Fig. 2: experimental setup for deep rolling of cylindrical workpieces.

By choice of the deep rolling parameters, the external loads, the rolling force $F_r$, as well as the internal material loads resulting in a load dependent stress field are influenced. The basis for these investigations is the variation of tool diameter $d_b$ and deep rolling pressure $p_r$, summarized in Table 1. To exclude the effect of multiple overlaps, a high feed was chosen leading to the separation of the single deep rolling tracks.

Table 1: chosen deep rolling parameters.

| Parameters | Values |
|---|---|
| Ball diameter $d_b$ | 6 and 13 mm |
| Rolling pressure $p_r$ | varied |
| Feed f | 2.4 mm |
| Circumferential speed $v_w$ | 95 m/min |

## 3. Parameter selection and results

The basis for the analysis of external loads is the deep rolling force $F_r$, whereas here, the equivalent stress $\sigma_{eq}$ according to Hertz is used for the analysis of the internal material load. These values are subsequently related to the resulting residual stresses $\sigma_{rs}$.

### *3.1. External load oriented parameter selection*

In many publications in the past, a conventional approach aims at the comparison of external loads. Thus, in the presented study, one part of the experiments was used to keep the rolling force constant. The rolling force $F_r$ can be calculated by formula 1 as a result of the ball diameter $d_b$ and the rolling pressure $p_r$ [10]:

$$F_r = p_r \cdot \pi \cdot \left(\frac{d_b}{2}\right)^2 .$$

The deep rolling forces are kept at $F_r$ = 1130 N to generate (supposedly) comparable process conditions for varied tool diameters. The resulting rolling pressure $p_r$ for a tool diameter $d_b$ = 6 mm and $d_b$ = 13 mm is summarized in Table 2.

Table 2: chosen rolling pressure $p_r$ resulting from constant rolling force $F_r$.

| Rolling force $F_r$ | Rolling pressure $p_r$ | |
|---|---|---|
| | $d_b$ = 6 mm | $d_b$ = 13 mm |
| 1130 N | 400 bar | 85 bar |

Fig. 3 shows the residual stress depth profiles in feed direction for a constant rolling force $F_r$ but for varied tool diameters $d_b$. The measured (XRD) residual stresses follow a similar trend, but vary regarding the maximum compressive residual stress $\sigma_{rs,max}$ and the depth of penetration. The constant force results in max. residual stress of -519 MPa for a tool diameter $d_b$ = 6 mm in contrast to -575 MPa for $d_b$ = 13 mm. The considerable deviation of the depth profiles indicates that the external load is not sufficient to predict the material modification.

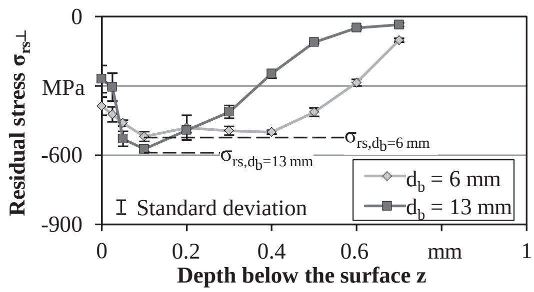


Fig. 3: residual stress depth profile $\sigma_{rs}$ for varied tool diameters $d_b$ on basis of constant rolling force $F_r$.

### *3.2. Internal material load oriented parameter selection*

The target pursued in these experiments is a material-oriented way of choosing parameters for the generation of desired surface and subsurface properties. The operating rolling force $F_r$ manifests in a stress field within the material. To describe the maximum stress just below the center of the tool, the Hertzian stress is taken into account based on the equations in [9]. This approach enables a qualitative approximation of internal material load for varied rolling parameters despite of limitations such as e.g. consideration of normal forces exclusively as well as a pure elastic material behavior [9].

For deep rolling of cylindrical workpieces, the contact between two spheres is considered. This case gives the best approximation between the effective contact of the deep rolling tool and the surface of the cylindrical workpiece. In order to generate a comparable uniaxial stress state, the equivalent stress is calculated according to von Mises. The depth profile of the equivalent stress $\sigma_{eq}$ is presented in Fig. 4, while the applied parameters are summarized in Table 3.