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Surface integrity after internal load oriented multistage contact deep rolling

J. Kämmler[a]*, N. Wielki[a,b], D. Meyer[a,b]

[a]Leibniz Institute for Materials Engineering IWT, Badgasteiner Str. 3, 28359 Bremen, Germany
[b] University of Bremen, MAPEX Center for Materials and Processes, Badgasteiner Str. 1, 28359 Bremen, Germany

* Corresponding author. Tel.: ++49 (0)421 218-51131; fax: ++49 (0)421 218-51102. *E-mail address:* kaemmler@iwt-bremen.de

Abstract

Mechanical treatment by deep rolling generates an improvement of the surface integrity by inducing compressive residual stress, strain hardening as well as a reduction of the surface roughness. The resulting material modification is based on the plastic deformation of surface and subsurface layers caused by the movement of a deep rolling tool across the workpiece surface under defined conditions in terms of rolling force, ball diameter and number of contacts. A correlation between the process parameters and the surface integrity to predict the modification in the workpiece is of limited validity. It is more useful to consider the internal load during the mechanical treatment in form of stress fields occurring during the process. This paper shows an approach to describe the internal load based on the hertzian stress in combination with the elastic model considering the multiple contacts in a deep rolling process. A defined variation of process parameters regarding the internal loads and the number of contacts was performed. It is shown that the correlation between internal loads and material modification (process signature) offers a good approximation to describe the surface integrity of workpieces after multistage contact in deep rolling processes. The description of material modification based on equivalent stress depth profiles enables the prediction of maximum of compressive residual stress after multistage deep rolling.

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Keywords: *Surface Integrity; Residual Stress; Process Signature, Deep Rolling; Material Characterisation*

1. Introduction

The functional performance of workpieces such as fatigue life and wear resistance is a result of the geometrical properties as well as the material behavior of workpiece material. While the geometrical accuracy is well-controllable in close tolerances, the resulting surface integrity of workpieces is influenced characteristically by every single process and the interactions of surface modifications along the whole process chain. Although many works describe the resulting surface integrity in material removal process [1;2] as well as in mechanical surface treatment processes [3;4] in dependence of the applied process parameters, the adjustment of a favorable surface integrity by means of compressive residual stress and hardened surface and subsurface layers is still an iterative or experience-based process [2]. To gain a better understanding of surface modification induced by manufacturing processes, a description of changes of surface integrity induced by the contact between tool and workpiece based on physical mechanism is necessary [5]. Byrne [6] describes the need of a workpiece-oriented view in processes with multiple occurrences of internal loads. Brinksmeier et al. [7] support this approach by a description based on the acting loads in the workpiece during the processing: The internal material load is a combination of thermal, mechanical and chemical loads induced by the manufacturing process. The Deep rolling process is characterized by a dominantly mechanical impact resulting in a plastic deformation of surface and near-surface layers. Prior investigations show, that considering the deep rolling force F_r is not sufficient to predict the surface and subsurface properties. However, a consideration of internal material load enables a correlation

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with the resulting material modification [8]. Broszeit [9] emphasizes the relevance of the contact area influenced by the chosen process parameters in deep rolling and material behavior on the resulting internal material load based on the equivalent stress of the hertzian contact. By multiple contacts of the workpiece with the deep rolling tool a single material element is influenced a serval times. Thereby, the material modification in each contact changes due to the prior plastic deformation.

This paper presents the approach of describing the changes of the residual stress state for multiple contacts on the basis of process signatures as a correlation of internal material loads and the changes in residual stress. The internal load is described as the equivalent stress based on the hertzian stress and an elastic-plastic approach by Johnson [10]. Therefore, analysis of contact forces as well as the induced plastic deformation as approximation for varied contact areas is necessary.

Nomenclature

2a	track width
a	half track width
a_c	radius of the contact circle
F_r	deep rolling force
$F_{r,theo}$	theoretical deep rolling force
$F_{r,meas}$	measured deep rolling force
d_b	tool diameter
p_r	deep rolling pressure
n	number of contacts
σ_{eq}	equivalent stress
$\sigma_{eq,max}$	maximum of equivalent stress
σ_{rs}	residual stress
$\sigma_{rs,max}$	maximum of residual stress
v_f	feed velocity
z	depth below the surface

2. Experimental procedure

2.1. Experimental setup

To investigate the surface modification of multistage contact induced by mechanical treatment, deep rolling investigations were performed on a conventional machining center ensuring a defined positioning between tool and workpiece (figure 1). As workpiece, prismatic AISI 4140 in a quenched and tempered state with hardness of 47 ± 2 HRC was used. A pre-grinding step produces a smooth surface with low surface modification in the near surface area.

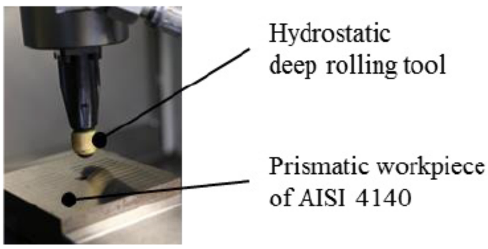

Fig. 1. Experimental setup for deep rolling of prismatic workpieces.

The use of a hydrostatic deep rolling tool generates a pressure controlled system, resulting in a constant rolling force F_r dependent of the deep rolling pressure p_r and the tool diameter d_b. Furthermore, an almost frictionless contact between tool and workpiece results. A force-measurement is realized beneath the workpiece by a piezo-electric 3-component dynamometer measuring a normal force up to 10000 N. To ensure defined contact conditions in the experimental investigations of multiple contacts, single tracks were generated with a feed velocity of 300 mm/min. For the variation of the number of contacts, a repetition of feed motion was realized without spacing between the single tracks. Tool diameters of 6 and 13 mm were used, while the rolling pressure p_r was varied based on considerations regarding the internal material load, see table 1.

Table 1. Parameters of deep rolling process.

Parameters	Values
Tool diameter d_b	6 and 13 mm
Deep rolling pressure p_r	varied
Number of contacts n	1 to 3
Feed velocity v_f	300 mm/min
Lubricant / bearing	5%-emulsion

2.2. Internal load oriented selection of parameters

The tool diameter d_b and the deep rolling pressure p_r were varied aiming at a defined variation of the maximum equivalent stress of the hertzian stress in the workpiece following the example of [8]. Thereby, the deep rolling tool is simplified as a moved pressure source, inducing an internal stress field in the material, which leads to remaining material modification in surface and subsurface layers. The hertzian contact allows for describing the internal stress state of the body with defined geometry. This stress state causes the resulting material modifications. To describe the deep rolling process of prismatic workpieces, the process is characterized as a sphere-plane model. The equations are summarized in [10]. In the calculation of hertzian stress, the normal force and the material characteristics by means of the elastic modulus and the poisson's ratio are considered. The material properties of AISI 4140 were analyzed in tensile tests, while the tool properties are manufacturer specifications, summarized in table 1.

Table 1: Parameters for the analytical approach to define internal material loads according to Hertz.

Parameters	Workpiece	Tool
Material	AISI 4140 QT	Ceramic
Poisson's ratio	0.28	0.25
Elastic modulus	203.75 GPa	305.00 GPa

Although the hertzian model is limited by restrictions e.g. exclusively normal force in frictionless contact and a pure elastic material behavior, the approach allows a quantitative approximation of the internal material load [8]. To achieve comparable states, a uniaxial stress state is generated by the shape modification analysis of von Mises.

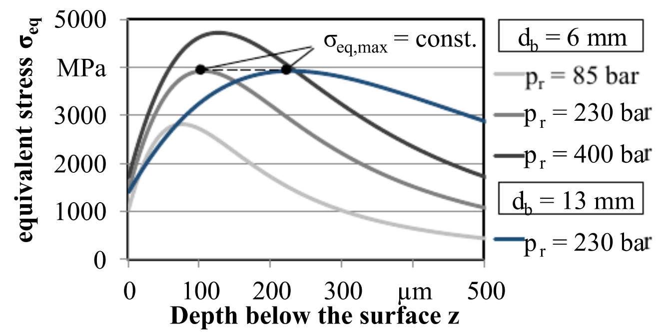

Fig. 2. Experimental setup for deep rolling of prismatic workpieces.

Figure 2 shows the development of equivalent stress in the depth of the workpiece for varying deep rolling pressure p, resulting in an increased maximum of stress as well as a higher penetration depth. A similar trend is expected for the resulting residual stress depth profile. A parameter selection of deep rolling pressure and tool diameter based on the maximum of the equivalent stress $\sigma_{eq,max}$ enables a comparison of different process strategies on the basis of internal load. Figure 2 shows a parameter selection for a tool diameter d_b of 6 and 13 mm and a constant maximum equivalent stress of $\sigma_{eq,max}$ = 3923 MPa. Based on this approach, table 2 shows the resulting theoretical deep rolling force $F_{r,theo}$ for constant maximum equivalent stresses and varied tool diameters d_b. The calculation of the theoretical deep rolling force $F_{r,theo}$ in dependence of the tool diameter d_b and the deep rolling pressure p_r is summarized in [11].

Table 2: Calculation of theoretical deep rolling force by parameter selection based on calculation of max. equivalent stress.

No.	Max. equivalent stress $\sigma_{eq,max}$	Deep rolling pressure p_r	Theo. deep rolling force $F_{r,theo}$	
			d_b = 6 mm	d_b = 13 mm
1	2815 MPa	85 bar	240 N	1128 N
2	3923 MPa	230 bar	650 N	3053 N
3	4718 MPa	400 bar	1131 N	5309 N

3. Results

3.1. External load calibration

For the load oriented process management based on the equivalent stress, it is necessary to validate the calculated, theoretical deep rolling force $F_{r,theo}$. For this, the external load is measured for calibration of the deep rolling system. Due to the hydrodynamic system, the measured normal force deviates from the theoretical force, so that an adaptation of process parameters is essential. Figure 3 shows the theoretical deep rolling force in comparison to the measured normal force in deep rolling. With increasing volume flow of lubricant by rising deep rolling pressures p_r, the deviation between theoretical and measured deep rolling force increases. For the calculation of internal material load based on equivalent stress, the measured deep rolling force $F_{r,meas}$ is an input variable, and thereby important for the comparison of varied parameters. To realize the needed deep rolling pressure p_r and the resulting deep rolling F_r in the contact area during the process, the used deep rolling pressure p_r at the hydraulic unit is increased to react on the pressure losses.

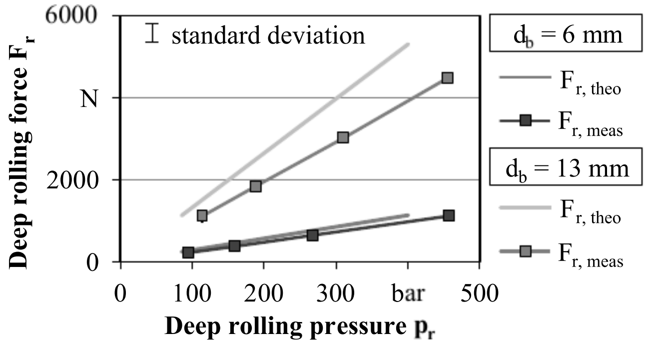

Fig. 3. Comparison of theoretical and measured deep rolling force F_r.

3.2. Surface modification – track geometry

The deep rolling process induces plastic deformation leading to strain hardening in surface and subsurface layers of the workpiece. Since the resulting track profile is dependent on the flow behavior of the material, which is influenced by the strain hardening, a reduced deformation ration with an increasing number of contacts could be used for a fast material characterization. Therefore the track depth and width could be considered as an indirect descriptor comparing the material behavior of different alloys or microstructural states. The geometrical contact of tool and workpiece is significant for the depth and height of the resulting internal material load profile and is strongly influenced by the process parameters, the tool diameter d_b and the deep rolling pressure p_r as well as the number of successive contacts n. Figure 4 shows the track width 2a in dependence of the process parameters under variation of the number of contacts. With increasing deep rolling force F_r the track width is more pronounced. A similar deep rolling force of approximate 1110 N for varied tool diameters (d_b = 6 and 13 mm) leads to comparable track widths due to the geometrical conditions in contact. In contrast, the multistage contact (n = 1 to 3) shows limited influence. While an increase in depth width of an average factor of 1.15 for d_b = 6 mm and 1.05 for a tool diameter of 13 mm can be registered from first to second contact, the third repetition shows no significant growth of plastic deformation, which can be traced back to strain hardening of material and the thereby reduced plasticity.

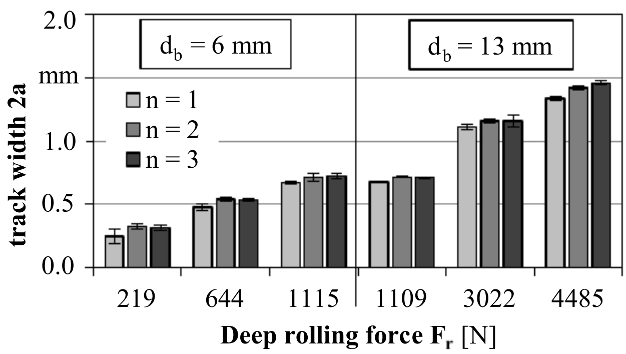

Fig. 4. Track width 2a for varied process parameters under variation of number of contacts n.

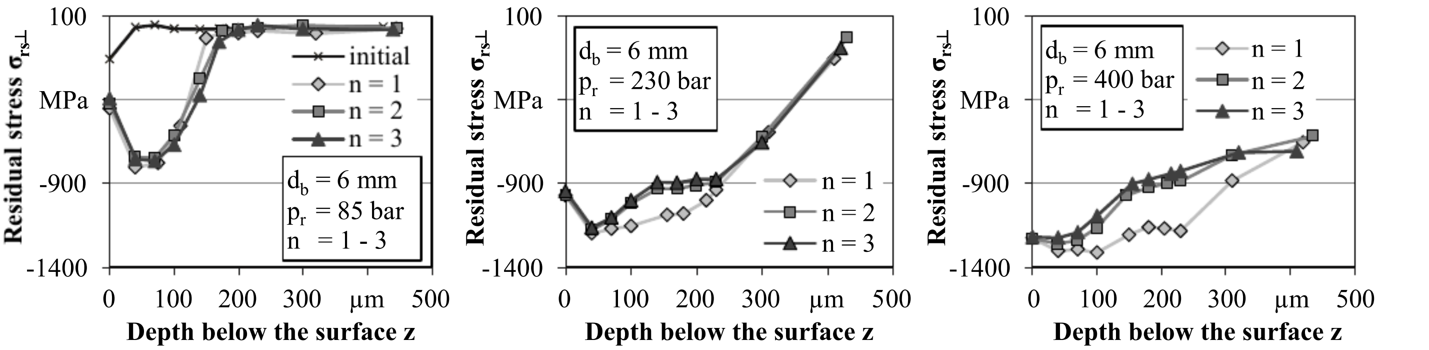

Fig. 5. Exemplary residual stress depth profiles of a tool diameter of d_b = 6 mm under variation of number of contacts n.

3.3. Subsurface modification – residual stress σ_{rs}

The residual stress was measured with the sin²ψ-method and a spot size of 1 mm. For the residual stress measurement, a surface was prepared with defined distances between the single deep rolled tracks of the half track width a to create comparable material load. Figure 5 shows exemplarily the resulting residual stress depth profile for varied deep rolling pressures p_r for a tool diameter d_b of 6 mm. The initial residual stress after grinding is shown in the graph on the right. The ground surface is characterized by compressive residual stress. All deep rolled profiles show a characteristic development in the depth with a maximum compressive residual stress below the surface. With increasing load, the growth in the maximum and the penetration depth of the residual stress can be observed from $\sigma_{rs,max}$ = -800 MPa for p_r = 85 bar up to compressive residual stress in the range of yield strength of the material over $\sigma_{rs,max}$ = -1300 MPa for the maximal deep rolling pressure p_r = 400 bar. In comparison, the repeated contact in deep rolling shows no significant influence on the residual stress depth profile. The maximum of the compressive residual stress is constant for varied numbers of contact. While for low deep rolling pressure p_r, the depth profile show comparable profiles, higher deep rolling pressures induce compressive residual stress profiles which deviate after the maximum to reduced stresses. The observed residual stress profiles for multistage contact can be explained by the resulting equivalent stress depth profile as a consequence of the contact conditions. The repeated contact solely influences the contact width 2a in multistage deep rolling process (compare figure 3) and thereby the contact area of the hertzian pressure.

In a sphere-plane model, the sphere size has no influence on the maximum of internal load, exclusively the normal force changes the maximum, see figure 6. By adapting the radius of the contact circle a_c of the analytical model by the factor of changes in track width under variation of the contact Δa, the equivalent stress under variation of the number of contacts can be illustrated. Thereby, the third contact show an identical depth profile compared to the second contact. The minor changes in the stress depth profile justify the constant maximum and a comparable residual stress depth profile.

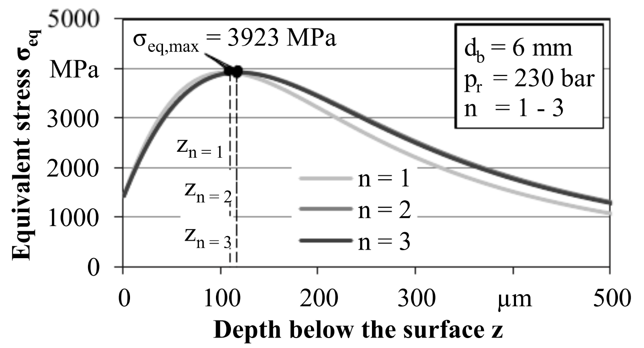

Fig. 6. Adapted equivalent stress depth profile σ_{eq} under variation of number of contacts n.

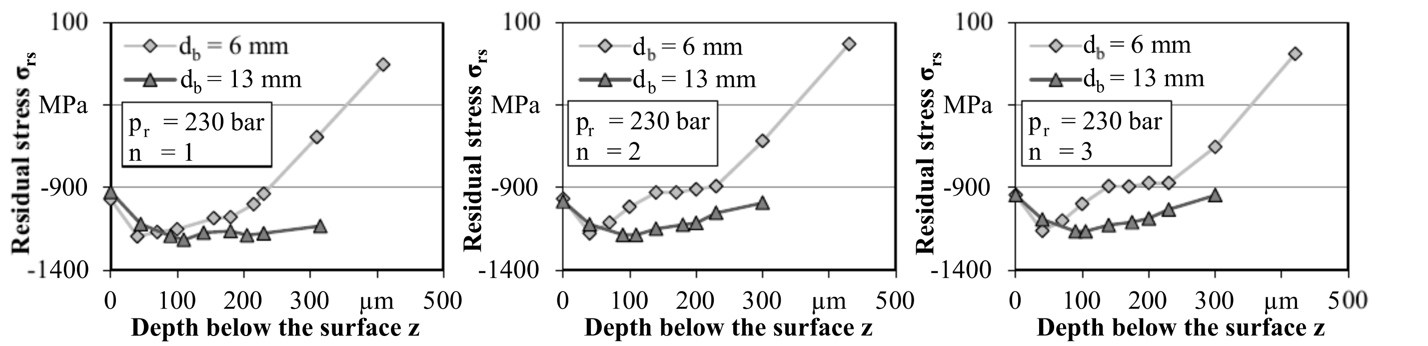

Fig. 7. Comparison of residual stress depth profile of varied tool diameter under variation of number of contacts n.

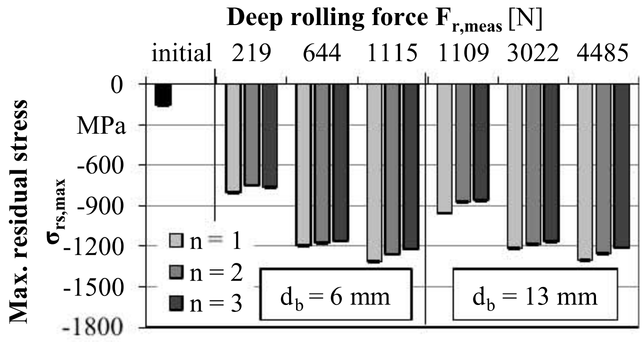

Fig. 8. Resulting maximum residual stress $\sigma_{rs,max}$ for varied process parameters under variation of the number of contacts n.

3.4. Load oriented material modification - process signature

To compare varied process parameters in deep rolling, a load-oriented variation of tool diameter by means of a comparable maximum equivalent stress is chosen. Figure 7 shows the development of residual stress depth profile for a 6 mm and a 13 mm-tool at a deep rolling pressure p_r of 230 bar with a constant maximum equivalent stress of $\sigma_{eq,max}$ = 3923 MPa under variation of the number of contacts in multistage processing. The graphs for varied tool diameter show a good agreement regarding the maximum of the compressive residual stress. A maximum for the 6 mm-tool reaches $\sigma_{rs,max}$ = 1197 MPa, while the residual stress for d_b = 13 mm deviates only 1.8 %. In contrast, the penetration depth of the bigger tool is significantly higher than the smaller tool as a consequence of the deeper internal stress field (see figure 2). The same can be observed for the multistage contact.

A similar trend can be revealed for the varied deep rolling forces of the 13 mm-tool. Figure 8 shows the evaluation of the maximum compressive residual stress for the chosen process parameters as a function of the deep rolling force $F_{r,meas}$. With increasing external load, the maximum of the compressive residual stress raises, while repeated contacts leads to a slight decrease of the maximum. In contrast to the surface modification analyzed by the track width 2a the maximum compressive residual stress shows no dependence of the deep rolling force F_r. Leading to the conclusion that an external load oriented comparison of process parameters is not sufficient to describe the internal modifications of the material.

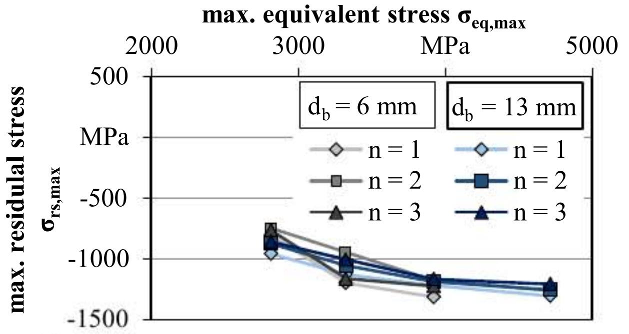

Fig. 9. Process signature as a correlation of maximum equivalent stress $\sigma_{eq,max}$ to maximum compressive residual stress $\sigma_{rs,max}$.

This knowledge of the correlation between the maximum equivalent stress and the maximum compressive residual stress allows a load-oriented description of material modifications. Figure 9 presents the process signature component to describe the internal load dependent changes in residual stress state for multistage deep rolling of prismatic workpieces. All graphs show a polynomial trend, which can be traced to the yield strength of the material reached by the high plastic deformation with rising internal load. As can be seen by the results before, the deviation between the multiple contacts are relatively modest and show a deviation of 6.7 % for n= 1 to 3.8 % for n = 3. However, the chosen analytical approach enables a description of the combined mechanical impact on the material in a more complex deep rolling process. A parameter-independent description of the energy dissipation in the material should allow a prediction of material modification on a knowledge based way to solve the inverse problem of generating a desired surface integrity.

4. Conclusion

This paper presents an approach to describe material modification in multistage deep rolling based on characteristic process signatures. For this, deep rolling experiments were conducted under a variation of process parameters regarding a load-oriented parameter selection based on equivalent stress depth profiles by hertzian contact.

The analysis of track width as a result of plastic deformation of the material induced by the contact pressure in deep rolling process allows an approximation of contact area, which increases with die deep rolling force. Furthermore, it reveals the behavior of the material regarding the plastic deformation in multiple stages and justifies the consideration of track width and depth as descriptor. While the first repetition of the contact still induces an increase of the track width, the third contact induces no further plastic deformations due to strain hardening of material. However, in multistage deep rolling, no significant change in the residual stress depth profile can be registered. An adjustment of the equivalent stress model by the consideration of track width enables the validation of residual stress profile, leading to only slight changes in the penetration depth, while the maximum of residual stress $\sigma_{rs,max}$ stays almost constant independent from the number of contacts. The description of the correlation of the maximum equivalent stress and the maximum of compressive residual stress in multistage processing generates a process signature component, allowing a process parameter independent description of the mechanical impact. Even if the calculation of elastic equivalent stress is just a simplification of internal material load, the approach enables a new way to select process parameters in deep rolling process.

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