Investigation of the surface residual stresses in single and multiple trace deep rolling on flat AISI 4140 specimens

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Keywords: surface modification, deep rolling, surface residual stresses, finite element modeling, AISI 4140 steel, stress anisotropy

Abstract

Mechanical surface treatments like deep rolling (DR) can be implemented in the components' process chain in order to increase their fatigue strength. Even the benefits of the application of DR are well known, its implementation is nowadays still supported with extensive experimental work. Many attempts were made to simulate the DR process with the finite element modelling (FEM) in order to reduce the experimental costs. Nevertheless, the complexity of the process hinders the establishment of the FEM as a standard implementation tool. This paper describes another endeavor to simulate the DR process which contrary to most available finite element (FE) models was applied on a flat instead of on an axis-symmetric geometry. Furthermore, the model represents a DR as a single trace instead of an area treatment. For this task the Explicit module of the FE code ABAQUS was employed and the investigation focused on the residual stress surface distribution. Different process parameters were varied in order to observe their influence on the calculated residual stresses. Additionally, X-ray diffraction (XRD) measurements were compared to the FE results for the sake of the FE model verification. In some cases, the measurements and the calculations in the area of the DR trace were in acceptable agreement. However, there were some deviations between predictions and actual measurements. To minimize the deviations, the FE model must be further optimized, as well as the accuracy of the XRD measurements improved. Also, the FEM showed that the residual stresses induced by DR widely exceed the width of the DR trace itself. Therefore, additional experimental work must be carried out to fully validate the FE model.

Introduction

The mechanical surface treatments are commonly applied to highly-stressed components due to their ability to enhance the fatigue strength without increasing the component's weight [1]. Deep rolling (DR) belongs to this treatment group and is already an established process which has been successfully integrated in the process chain of some components [2 – 5]. Still, its implementation in a new process chain is often associated with extensive preliminary studies, demanding high costs and much time. In the past 30 years the finite element (FE) modeling transformed into a convenient tool that was used to facilitate the implementation of DR [6, 7]. Nevertheless, the modeling is often case-connected and its general application limited. The different modeling approaches and boundary conditions definitions also lead to a variation of the computed results and deviations between calculations and measurements [8 – 10]. Also, most of the existing FE studies of DR are realized on axis-symmetric components. Contrary to this trend, this paper focuses on the FE simulation and model verification of DR on flat specimens. A FE model similar to the used in this paper was already presented in other publications of the authors [11, 12] where it was employed to investigate the depth and the surface distribution of the residual stresses, by variation of numerous process input parameters. Now, these investigations were extended with the verification of the model with the means of XRD residual stress measurements. Although the XRD is one of the mostly wide used residual stress measurement method, it must be considered that its complexity as a technique and the numerous measurement disturbing factors can also alter the measured values

[13]. Therefore, several precautions were taken to improve the accuracy of the stress measurements.

Objectives

The objective of this paper is to experimentally verify a FE model of single and multiple trace DR with means of XRD measurements. The focus lies on the residual stress surface distribution. The investigation was divided into two parts: First, a FE modeling of DR process was realized on a flat geometry with varying pressure, number of passes and partly with overlapping. The second part of the investigation focused on XRD surface residual stress measurements to verify the FE model. The applied DR treatments were identical with those used for the FE modeling.

Methodology

Preparation of specimens for X-ray diffraction residual stress measurements - The material used for the residual stress measurements was AISI 4140 martensitic high strength steel with the following mechanical properties: Young's modulus - 210.0 GPa, Yield strength - 1008.0 MPa, Ultimate strength - 1081.0 MPa, Fracture strain - 15.0 % and Necking - 53,5 %. It was initially hardened at 860 °C for 60' and quenched in polymer; after that it was tempered at 560 °C for 120' and cooled in air. A square rod 25 mm / 25 mm was cut to a length of 40 mm and the top surface on which the DR was later applied was milled with the following parameters: spindle speed - 600 rpm, cutting speed - 100 mm/min, removed layer - 3 x 1 mm + 2 x 0.5 mm, with cooling lubricant. The side surfaces were milled to achieve a width of 20 mm. The next part of the process chain was different single-trace DR or DR with overlapping, performed by the ECOROLL Company. The DR treatments can be divided into three groups: variation of the DR pressure, variation of the number of passes and overlapping variation. The DR pressure was varied from medium (200 bar) to high (400 bar) which was the limit of the employed hydraulic aggregate. In Table 1 the specimens' designations and the DR treatment parameters are plotted.

Table 1 - Specimens' designation and treatment parameters

Specimen's number	**DR pressure [bar]**	**Number of passes**	**Overlapping [mm]**
1	**200**	1	No
2	**250**	1	No
3	**320**	1	No
4	**400**	1	No
5	400	**2**	No
6	400	**3**	No
7	400	1	**0.54** (app. 25 %)
8	400	1	**0.36** (app. 50 %)
9	400	1	**0.18** (app. 75 %)

X-ray diffraction residual stress measurements – The residual stress measurements were performed on a PANalytical Empyrean diffractometer in θ-θ configuration. To ensure accurate measurements, several disturbing factors were taken into account. First, it was considered that the DR single trace has a width of app. 600 µm to 1130 µm and that there are high stress gradients in this zone. This means that the accurate positioning of the specimen in X direction (transverse to the DR trace) must be ensured. Also, the alignment camera positioning error should be reduced. This was made by X scanning of a 130 µm thin specimen and analyzing the measured intensity. Considering the symmetry of the specimen, the peak of the resultant Gaussian curve was aligned with the middle of the specimen and ΔX was calculated. The same procedure was performed in Y direction. Later, during the measurement process, it was noticed that ΔX and ΔY changed slightly. Therefore, an additional X scanning was performed to ensure the correct coordinates for the stress measurements. Considering that the highest stresses should be situated in the middle of the DR trace, the highest shifting in the 2θ peak was assumed to be the middle of the DR trace. Another important adjustment was in Z direction (height) to ensure that the specimen was positioned in the center of the goniometer's circle. Here, the fact that the DR trace has a parabolic shape with a depth of a couple of hundred micrometers, made the Z adjustment with the available measurement gauge impossible. Therefore, white light interferometry (WLI) was used to measure the DR trace depth profile and ΔZ from the surface was calculated. All of the XRD measurements and the FEM evaluation were made in the middle of the DR trace and the surface distribution of the residual stresses was investigated in X direction (transverse to the DR trace), see Figure 1. The measurement and evaluation parameters were the following: scanned phase – α iron, lattice plane [211], 2θ = 151.70° to 161.30°, ψ = 0° to 50° (only positive tilting angles were used due to device's restrictions), ψ tiltings – 7, measurement spot = 50 μm, peak positioning – center of gravity at 20 %, elastic constants (taken from the available literature): s_1 = 1.36 1/TPa, $1/s_2$ = 6.10 1/TPa.

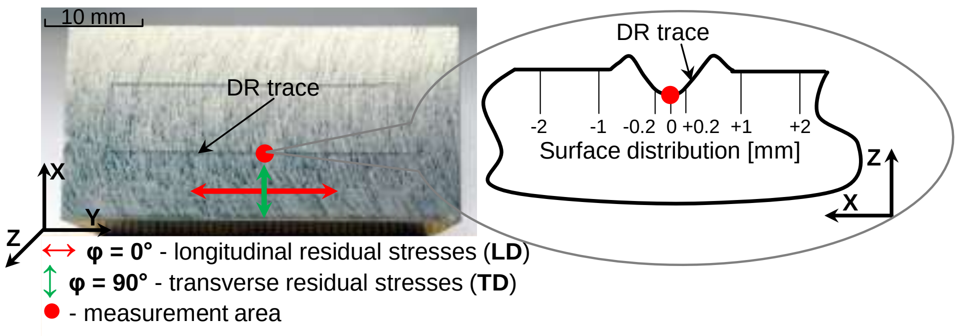

Figure 1 – geometry of the specimens and measurement area

FE Modeling - The DR model was built in the Explicit module of the FE code ABAQUS 6.14. The geometry of the workpiece was similar to the one used for the XRD residual stress measurements. The material assigned to the workpiece was AISI 4140 steel (the same as for the experimental work) and the strain hardening was defined as bi-linear isotropic. The DR tool was modeled as a rigid sphere with a diameter of 6.34 mm. The applied DR treatment parameters are described in Table 1. The measurement areas were identical with those for the stress measurements, see Figure 1. More details regarding the boundary conditions and the meshing strategies were already published by the authors [11, 12].

Results and analysis

The XRD investigation began with measurements of the specimens in milled condition, without DR. The results showed a wide variation in the measured residual stresses, i.e. the longitudinal residual stresses varied from +158 MPa to -506 MPa and the transverse – from +9 MPa to -437 MPa. This means that the initial residual stress state (after milling) may influence the material behavior during DR. Nevertheless, the already existing residual stresses before DR were neglected when calculating the occurring residual stresses due to DR by FEM. The first two diagrams in Figure 2 show the surface distribution of the measured (see Figure 2 a)) and the calculated (see Figure 2 b)) residual stresses after DR. With the value 0 on the X-axis is designated the middle of the DR trace. For all of the presented XRD measurements the measurement error lies between 10 MPa and 50 MPa and the uncertainty in the X positioning was about 100 μm. At first glance, the XRD and FEM results show the anisotropy typical for the DR in the stresses in longitudinal (φ=0) and transverse (φ=90) direction. However, changing the DR pressure does not lead to a systematic change in the stresses within the investigated area. Concerning the XRD results, it is visible that the measured values are so close to each other that the difference between them lies in the range of the measurement error.

The FEM results were able to represent the stress anisotropy. There was a moderate deviation from the XRD measurements, mainly in longitudinal direction (φ=0).

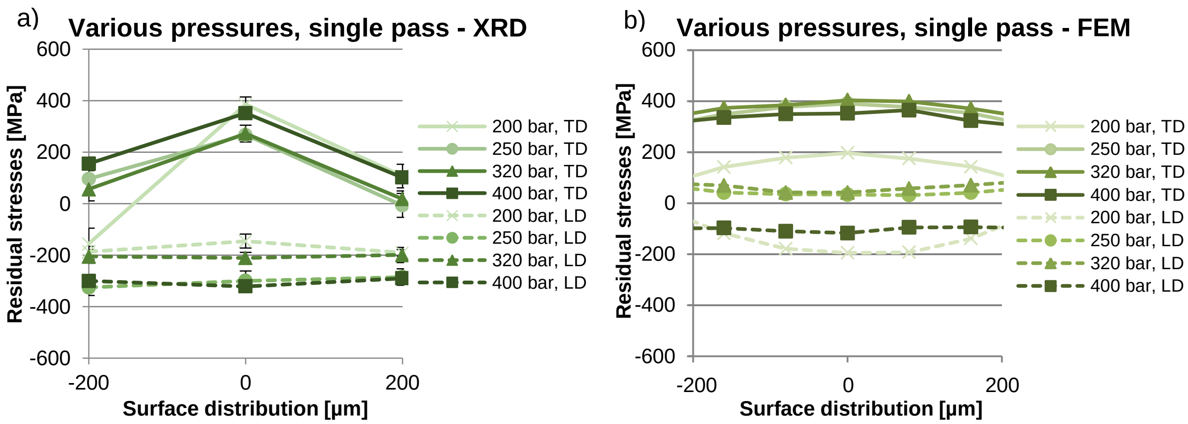

Figure 2 – Residual stresses in the center section of the DR trace for various pressures and single pass: a) XRD measurements and b) FEM calculations

The results in Figure 2 show the distribution of the residual stresses only in the middle of the DR trace which is a relatively small segment of the entire surface stress profile. Therefore, in Figure 3 the FEM surface residual stresses calculated in a larger section are plotted. Here, it is visible that the DR process generates a complex surface residual stress profile which widely exceeds the width of the DR trace itself (in this case from 642 µm to 844 µm). Also, it is clear that despite the fact that the stresses are adjacent to each other in the middle of the trace, the widest surface profile and the highest stress magnitude was produced by the DR with the highest pressure and multiple passes.

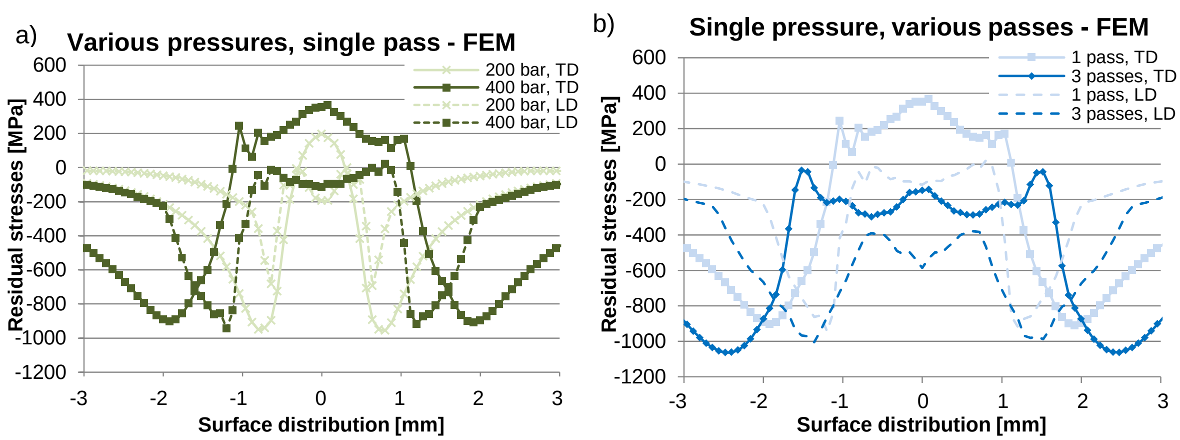

Figure 3 – Surface distribution of residual stresses transverse to the DR trace; pressure variation: a) various pressures and b) various passes

The next varied DR parameter was the number of passes (one or multiple passes in the same trace) and again, the XRD and FEM results were compared, see Figure 4 a) for XRD and Figure 4 b) for FEM. Both diagrams give a hint that more passes reduce the tensile stresses in transverse direction and enhance the compressive stresses in longitudinal direction. However, the FEM results tend to underestimate the tensile stresses at 2 and 3 passes (specimens No 16 and 17) and the compressive stresses at a single pass (specimen No 15).

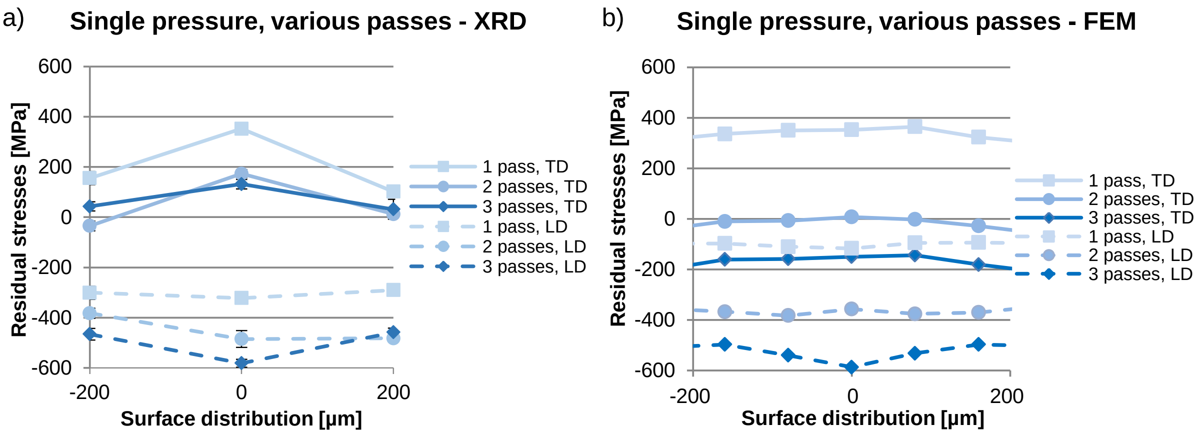

Figure 4 - Surface distribution of residual stresses transverse to the DR trace; passes variation: a) XRD measurements and b) FEM calculations

The last results show the variation of the overlapping parameter, see Figure 5 a) for XRD measurements and b) for FEM calculations. Considering the XRD and FEM results, it is noticeable that the measured and the calculated stresses comply just in longitudinal direction, whereas there is a large discrepancy in transverse direction. In search of the reason for this, some additional WLI topography evaluations of the specimens for the XRD measurements were done. They showed that the resulting overlapping diverges relatively strongly from the assigned. Even considering the deviation of the overlapping, it seems that the FEM tends to predict transverse residual stresses near 0, while the XRD measurements showed tensile residual stresses. Another clue about the deviation can be the X positioning accuracy of the XRD measurements. Considering that the specimen with the highest overlapping had a distance of less than 180 µm between both DR traces and that the positioning accuracy was app. 100 µm, it cannot be confirmed that the measurements were conducted in the middle of the first trace or between the traces.

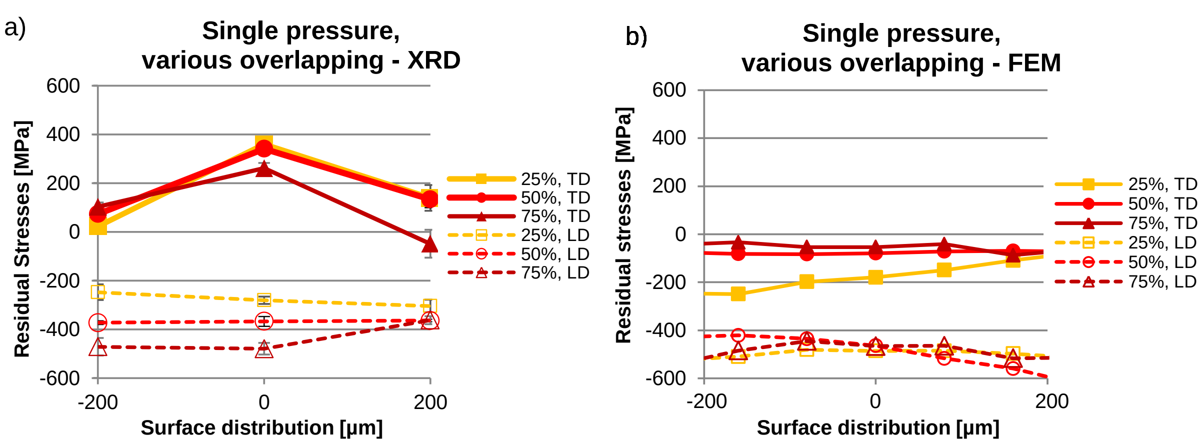

Figure 5 - Surface distribution of residual stresses transverse to the DR trace; overlapping variation: a) XRD measurements and b) FEM calculation

Conclusion and outlook

The presented paper has the aim to verify a FE model of a single-trace DR on a plane geometry, when varying the applied pressure, the number of passes and the overlapping percentage. The verification was performed with the means of X-ray residual stress measurements. Various process parameters were varied and their influence on the resulted surface residual stresses was analyzed. In general, it was observed that despite the strong deviations in the initial residual stress state (after milling), the DR was able to produce a defined surface stress profile. It was also noticed that the FE model is capable to predict the stress anisotropy produced by the DR process. In some cases, there was a satisfactory agreement between the predicted and measured surface residual stresses as well. However, it was visible that the FEM calculations seem, in some cases, to underestimate both the tensile and the compressive residual stresses induced by the DR process. In this case it would be a speculation to state that the deviations come only from the FEM calculations, because the XRD measurements were performed at the limit of the device's accuracy. Another measurement deviation results from the fact that only positive ψ angles were used, due to the diffractometer's limitation. This means that the physical ψ splitting caused by the curvature of the measurement area, particularly in the transverse direction, cannot be considered. The further validation of the FE model will be achieved by additional surface and in depth stress measurements.

Acknowledgements
This research was kindly supported by the ECOROLL Company in Celle, Germany, who performed the DR treatments. The residual stress measurements were done at the Chair of Functional Materials, Saarland University, Saarbrücken, Germany. We thank our colleagues who provided insight and expertise that greatly assisted this research.

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