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Influence of the Pre-Stressing on the Residual Stresses Induced by Deep Rolling

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Abstract. Deep rolling is a mechanical surface treatment, which main aim is to increase the fatigue life of components by reducing their roughness, increasing the surface hardening and inducing compressive residual stresses. The increase of certain process input parameters such as the applied pressure or the number of overturns leads directly to the raising of the induced compressive residual stresses. Nevertheless, a saturation point is always achieved, where the further increase of the parameters' levels does not change the induced residual stresses. For other mechanical surface treatments, like shot peening, several pre-stress techniques were employed in order to further increase the induced residual stresses without raising the shot intensity or the coverage percentage. Pre-stressed shot peening with the means of bending or torsion is an established processing. Up to now, a few investigations are available regarding the pre-stressing techniques applied to deep rolling. Therefore, this paper offers a newly designed finite element model, built to calculate the induced residual stresses by bending, consequent deep rolling and springback. A four point bending setup with different pre-stress levels was employed and the influence of pre-stress levels on the induced residual stresses was investigated. Additionally, the applied deep rolling pressure was also varied in order to optimize this hybrid processing. At the end, the anisotropy of the induced longitudinal and transverse residual stresses due to the bending and deep rolling was analyzed.

Introduction

Manufacturing processes that selectively induce compressive residual stresses (CRS) in the critical areas of highly loaded components are gaining increasing importance as design tool as they are able to increase components' fatigue strength. Several processes like shot peening, hammering and autofrettage are well established and have the ability to introduce CRS from several hundred micrometers to few millimeters in depth. Among these processes stays the deep rolling (DR), which is a recognized surface mechanical treatment that attracted the interest of the scientific community in the thirties of the last century. It has the advantage that along with the induced CRS, it reduces also the roughness, thus preventing new crack formations. All mechanical surface treatments mentioned above have in common that the raise of certain input parameters leads directly to higher and deeper induced CRS. Nevertheless, there is always a saturation level where the further increase of the input parameters does not lead to raising of the CRS and can even result in tensile residual stresses at the surface [1]. Some changes in the initial boundary conditions give the possibility to further exploit the capabilities of the mechanical surface treatments. For example, processing at elevated workpiece's temperatures leads to an increase of the induced CRS [2, 3] and longer fatigue life [2], while the decrease of the workpiece's temperature below room temperature results in higher hardness and hardness penetration depth of the treated components [4].

Another change in the initial boundary conditions can be a mechanical pre-stressing (PS) of the workpiece. The mechanism of the PS (in case of positive pre-loading) is the following: an

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external stress that causes elastic deformation is applied to the workpiece while the mechanical surface treatment is performed. When the PS is released, it causes a deformation in the direction opposite to the initial PS. This means that the PS adds CRS, increasing linearly from the center of the specimen towards the treated surface. The result is shifting in depth of the point, where the transition between compressive and tensile residual stresses is and thus the area loaded with CRS expands. PS mechanical surface treatments can be applied to any highly stressed parts which are exposed to operational bending or torsion, like leaf springs, Belleville springs, coil springs, torsion bars, propeller shafts, etc. The applied PS can be tension, bending or torsion.

The interest for the development of mechanical surface treatments in order to further increase their effectiveness rose in the forties of the last century. Staub and May [5] introduced an innovative process called stress peening, where the specimen is statically stressed in the direction of the operational loading during the conventional shot peening. They performed fatigue tests on not-shot peened, conventionally shot peened and PS shot peened specimens and observed an increase of the minimum fatigue life of the shot peened specimens by an average of 350 % while the PS shot peened specimens showed a minimum fatigue life 740 % longer than the one of not-shot peened specimens. Barrett et al. [6] investigated the effect of the elastic PS on the magnitude of CRS induced by PS shot peening of aluminum plates. They bent their specimens at 87 % of the yield strength of the material and found out that the peak of CRS in the direction longitudinal to the bending curvature was enhanced from 405 MPa for the not-stressed plate to -594 MPa for the PS plate (app. 47 % improvement). Nevertheless, the depth of the achieved CRS did not change with the application of a PS. In the perpendicular direction, the measured residual stresses were lower than the ones in longitudinal direction and even lower than those measured in not-stressed treated specimen. Xu et al. [7] studied the influence of the direction (positive or negative) of the PS on shot peening. They bent their specimens at +38 %, +57 %, +76 % and -75 % of the material's yield strength and found out that the positive bending increased the endurance limit while the negative bending significantly decreased the endurance limit, even compared with not-shot peened specimens. The measurements of the surface and depth distribution of residual stresses showed that enhancing the positive bending results in higher surface-, higher magnitude- and greater depth of the induced CRS. On the contrary, the negatively bent specimen showed no presence of CRS but rather low tensile residual stresses. Some experiments were also made about the PS of a workpiece for the deep rolling process. Müller [8] applied bending using a four point bending setup and performed consecutive DR treatment in directions longitudinal and transverse to the bending. In the longitudinal variant, the induced surface CRS did not change with the increasing PS level. Still, the enhancing of the PS led to deeper distributed CRS, which for PS at 80 % were still negative at 1 mm depth. The transverse variant resulted in a quite different residual stress distribution. The surface stresses raised significantly (more than 100 % for 80 % bending), while in depth the zero stress plateau remained unchanged at 0.80 mm depth.

Despite the available experimental data about the PS mechanical surface treatments, the prediction of the residual stress distribution still is a challenging task, when varying the numerous input parameters. The residual stress investigation is always supported by time-consuming and expensive experimental measurements. It is well known that finite element modeling (FEM) is a powerful supplement to the experimental work as it offers the opportunity to solve complex engineering problems and to simulate different types of processing. Several attempts were made to simulate the DR process [9-11] and the results qualitatively and partly quantitatively fitted the experimental verifications. Therefore, this paper offers a newly designed finite element modeling of a hybrid processing, namely elastic bending using four point bending set up, consecutive DR treatment and a springback. The model is able to calculate the resulting residual stresses for different values of bending magnitude and applied DR pressure.

Finite Element Modeling Setup

The FEM used in this paper consists of three parts. First, an elastic four-point bending at levels 30 %, 60 % and 70 % of the material's yield strength was performed using the standard module of ABAQUS CAE 6.14. Then, with the means of pre-defined field, the PS was determined as an initial stress state for the DR treatment (DR pressure applied on the DR tool was at levels 20 MPa, 30 MPa and 40 MPa), performed in ABAQUS CAE 6.14 explicit. The final springback operation was made in ABAQUS standard, using a pre-defined field from the DR operation. The material assigned for the workpiece was AISI 4140 steel with Young's modulus of 210 GPa, Poisson's ratio 0.28, Yield strength of 997 MPa and ultimate strength of 1144 MPa. The applied material model was elastic-plastic with bi-linear kinematic hardening, described in details in [10, 11]. The geometry of the workpiece was a plate with dimensions: length = 18 mm, width = 3.75 mm and thickness = 2 mm. The DR tool consisted of a sphere modeled as a rigid body of diameter = 3 mm. The DR process was applied along the bending curvature on the tensile side of the bending set up. Concerning the meshing of the workpiece, structured C3D8R hexahedral elements were used. A convergence study was performed, where the results from the FEM of the bending step were compared with the analytical solution of the bending. A progressive meshing strategy was employed to obtain more accurate results in the areas of interest, using a smallest element size of 0.04 mm and a biggest size of 0.1 mm. The FEM results differed from the analytical solution with 2.25 %, which is an acceptable error. Due to the complexity of the FEM, numerous boundary conditions were assigned. During the bending and the springback, the workpiece was restrained at the two supports of the four-point set up. The face opposite to the one on which the DR is applied was encastred during the DR process. The DR tool was only allowed to move in the vertical direction during the application and the release of the DR pressure but was free to rotate along the DR path during its movement. The DR treatment was performed with a constant velocity of 1 mm/s and the friction coefficient between the workpiece and the DR sphere was assigned to 0.1.

Results and Discussion

Fig. 1 shows the residual stress vs. depth profiles w/o PS and with 30 % PS after DR pressure variation.

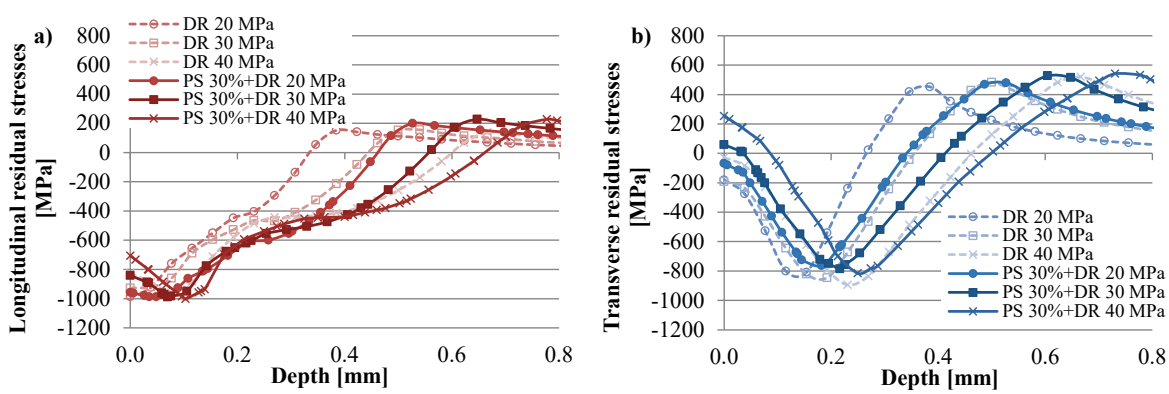

Fig. 1 – Residual stress vs. depth profiles for 30 % PS, DR pressure variation, a) longitudinal direction and b) transverse direction

Fig. 1 a) illustrates the longitudinal (along the DR trace) residual stresses, while Fig. 1 b) the transverse (transverse to the DR trace) residual stresses. The typical DR anisotropy of the stresses in both directions is clearly visible here. The anisotropy is noticeable with- as well as w/o PS. It can be noticed that in both directions, increasing the PS does not enhance the maximum of CRS. However, there is a significant raise in the depth of CRS in the longitudinal direction which reaches 650 µm for a PS of 30 % and DR with a pressure of 40 MPa. In the transverse direction, the depth of CRS raises with increasing PS levels but the surface residual stresses deteriorate with the application of PS.

Fig. 2 displays the residual stress vs. depth profiles after DR pressure variation with and w/o PS of 70 %. Here, it is also noticeable that the improvement in the CRS field is higher in the longitudinal direction. Even the surface stresses aggravate slightly, the CRS depth increases to 0.8 mm when raising the PS level. For the transverse direction, the PS reduces the surface- and the maximum of the residual stresses but still has a positive effect on induced CRS in depth.

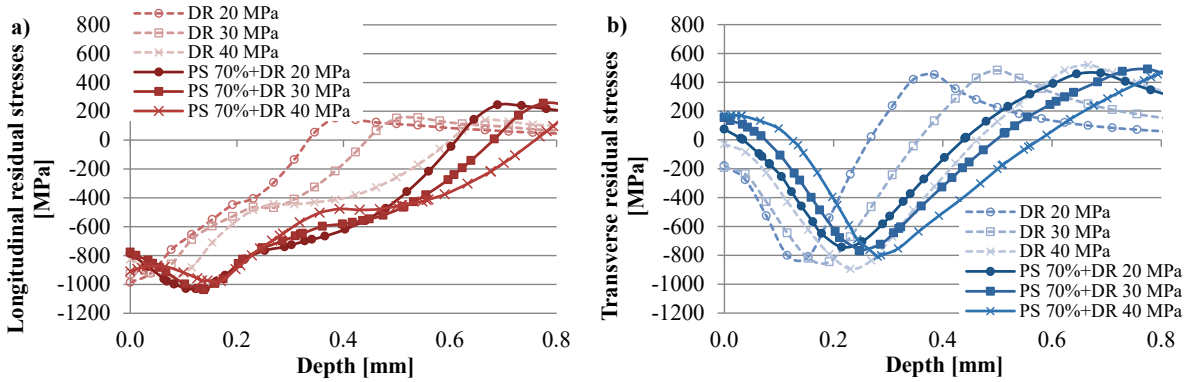

Fig. 2 – Residual stress vs. depth profiles for 70 % PS, DR pressure variation, a) longitudinal direction and b) transverse direction

In Fig. 3 are plotted the longitudinal residual stresses after variation of the PS level, as the observation was made that the CRS in the direction along the bending curvature/DR trace augment more than these in the transverse direction.

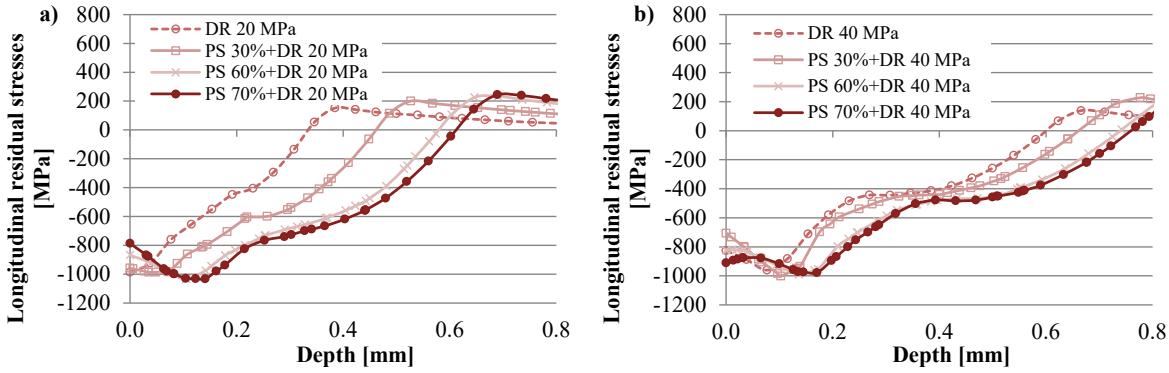

Fig. 3 – Longitudinal residual stress vs. depth profiles for different PS levels, a) DR pressure 20 MPa and b) DR pressure 40 MPa

At DR pressure of 20 MPa, see Fig. 3 a), the depth of CRS increases significantly for PS of 30 % and 60 %, and reaches a saturation point at 70 %, where almost no further improvement is observed. For the DR pressure of 40 MPa, shown on Fig. 3 b), the improvement when applying PS is not so strong but it must be taken into account that the CRS level w/o PS is higher than that at 20 MPa.

In Fig. 4 are represented the calculated areas under the curve for the tensile and compressive residual stresses for the longitudinal and transverse residual stresses profiles. In the longitudinal direction (Fig. 4 a)), the variation of the DR pressure and the PS level has no influence on the tensile residual stresses. However, by looking at the CRS, two observations can be made: first, higher DR pressure results in a higher amount of CRS and second, raising the PS level also enhances the CRS. Still, a saturation point is visible at 40 MPa, where the change in the PS has almost no impact on the CRS. The transverse residual stresses areas are plotted in Fig. 4 b). Here, it is obvious that increasing the DR pressure as well as the PS leads to higher tensile stresses while the CRS remain almost intact.

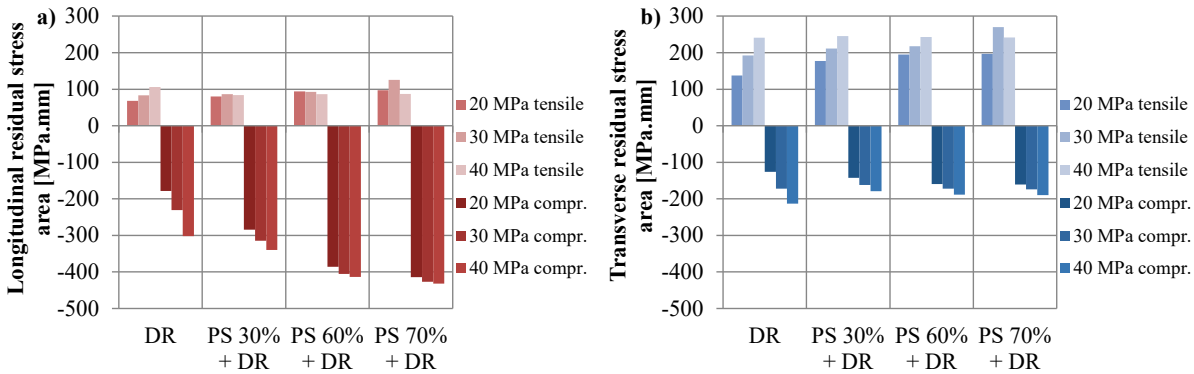

Fig. 4 – Calculated residual stress areas, variation of the PS, variation of the DR pressure, a) longitudinal residual stress areas and b) transverse residual stress areas

The results shown in this paper are expected and can be explained by the following realizations. To begin with, the observed anisotropy of the residual stresses induced in longitudinal and transverse directions by the DR process w/o PS is well described in many publications [12, 13]. The plastic deformation mechanism and shrinkage of the material after releasing of the DR pressure is always different in the both directions. Second, when applying a PS and DR in the same direction, the springback superimposes with the shrinkage of the material, thus shifting the CRS to greater depths. Therefore, the enhancement due to the PS is greater in the longitudinal direction (along the DR path/bending curvature). Müller [8] measured the stresses in both directions and observed the same trends. In the presented investigations was also modelled a pre-stressed DR in a direction which is transverse to the bending curvature. The results showed almost no enhancement of the CRS field and at higher PS levels high sub-surface tensile residual stresses appeared.

Summary and Conclusion

This paper introduced a newly designed finite element model of a hybrid mechanical surface treatment consisting of elastic PS using a four point bending setup, consecutive deep rolling treatment and a springback. The model offered the possibility to vary the applied PS and the DR pressure and to investigate the resulting surface and depth residual stresses. The DR treatment was applied along the bending curvature on the positively (tensile) loaded side of the workpiece. The resulting residual stresses in the directions longitudinal and transverse to the DR treatment were analyzed. Some important findings were concluded: it was observed a strong anisotropy in the stresses induced in longitudinal and transverse directions even w/o PS. This can be explained by the different portions of the plastic stretching in both directions. An enhancing of the CRS in the longitudinal direction was found by both increasing the DR pressure and PS level. Still, at higher DR pressures the PS had less impact than at lower DR pressures. In the transverse direction, the PS had minor effect on the CRS and resulted in slightly higher tensile residual stresses at the surface. The calculated areas under the curve of the tensile- and compressive stress vs. depth profiles confirmed these findings and gave a general overview of the interactions between the applied input parameters (DR and PS) and the resulting stresses. It can be concluded that the tensile PS has an enhancing effect on the CRS layer in longitudinal direction induced by DR. The surface tensile residual stresses in transverse direction have deteriorating influence regarding the surface crack initiation. Still, the presence of thicker CRS layer can lead to the so-called “crack-arrest” and to retard the crack propagation. The maximum of the CRS is still limited by the yield strength of the material but it can be achieved at lower DR pressures, which will result in lower deformations induced during the processing.

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