| ESRF | **Experiment title: In situ measurement of surface modification mechanisms in the deep rolling process** | **Experiment number**: ME 1387 |
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| **Beamline**: ID11 | **Date of experiment**: from: 06.10.2015 to: 09.10.2015 | **Date of report**: 04.03.2016 |
| **Shifts:** 6 | **Local contact(s)**: Jon Wright | *Received at ESRF:* |

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The aim of this experiment was an in situ characterization of the material modifications generated during a deep rolling process through the use of an adapted setup with capabilities comparable to an industrial process. With the generated data, a detailed description of active mechanisms and an experimental validation of simulation not only after treatment but also during the process should be achieved. From the physical point of view, the rolled sphere or cylinder induces mainly mechanical strains in the material from the surface, generating plastic and elastic deformations. After the process, a given volume near the surface is plastically deformed and shows property modifications including microstructural changes, increased hardness, generation of residual stresses and smoothening of the surface layer. The stress field created during the process can be roughly predicted by FEM simulations and calculated to be in the range of several mm in depth and width as a function of applied load and of the tool geometry.

A deep rolling frame was constructed and equipped with a commercially available hydrostatic tool head. The typical industrial application uses a ball-shaped tool which is rolled on the surface of the sample. However, in this case, transmission measurements through the whole sample thickness had to be performed and therefore no stress gradient in thickness direction should be present. In order to fulfill this condition, a modified tool head using a cylindrical roller tool made from tungsten-carbide has been used.

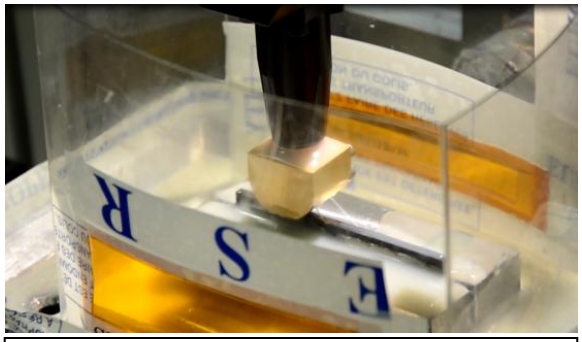

Fig.1. Rolling cylinder and sample in the experimental setup during processing

The experimental setup has been designed in order to perform measurements using a fix position of the tool head by moving the sample. As the samples are considered as semi-infinite bodies with homogeneous isotropic properties over the entire length, the position of the sample relative to the tool head is not of importance. The determining parameter is then only the relative position of the X-ray beam regarding the tool head and had to be defined by moving the whole frame with the diffractometer x-y-table. This enabled making experiments with varying deep-rolling feed rate without losing resolution as long as the sample length allowed to complete the measurement of the point grid. Fig.1 shows an enlarged view of the tool head inside the frame during processing of a sample.

The deep rolling frame was fixed on the diffractometer table of ID11 and adjusted in such way that linear sample movement and y-axis movement were parallel with the x-axis distance kept constant. A monochromatic beam with 100 keV and a square cross section of 50x50 µm was set with the slit system of ID11 and kept constant for all experiments. A FReLoN 2D detector system was used to record full diffraction rings with a constant total measurement time of 0.2 s per frame.

For the experiments, two different steel grades, with one of them in two different heat treatment conditions were investigated: (42CrMo4 ferrite/pearlite, 42CrMo4 quenched and tempered at 400°C and a high alloyed steel X210Cr12) with each 3 mm thickness and 80 mm length as sample geometry.

Two kinds of experiments were performed: static experiments where the tool is pressed to the sample surface without additional relative movement and dynamic tests where the sample was moved in translation with varying feed rate. In both cases, 2D-mappings with measurements along the depth and the sample length were performed. After initial planning considering the readout time, point grids were defined. In order to save time, most static experiments were performed by measuring only half-fields (483 points) considering the symmetric loading condition below the roller. For dynamic experiments and for few static experiments (for verification of the symmetry) full-fields with up to 960 points were measured. The programmed grid for half-field measurements is shown in Fig. 2. A high resolution is achieved in the surface region and directly at and under the contact point, where highest stress gradients are expected.

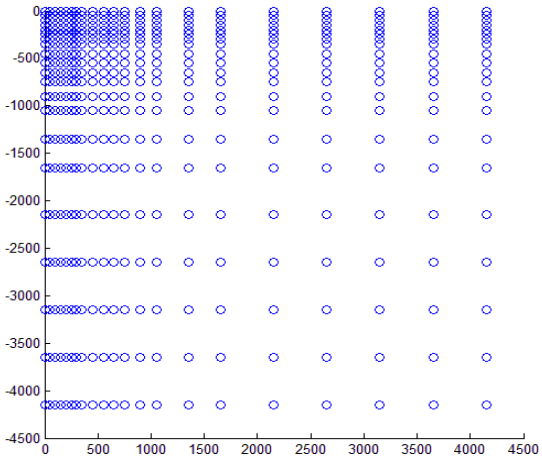


Fig.2. Point grid in y- and z-direction for for half field measurements

For static experiments, 5 zones were defined on each sample where varying pressure of the tool between 200 and 400 bars was applied. This corresponds to a contact force between 2000 N and 4000 N. All measurements were performed under load and after unloading. Moreover, each experiment was repeated on a different sample for validation, leading to 60 static experiments. For dynamic experiments, feed rates between 1.2 mm/min and 12 mm/min were used in order to evaluate the influence of strain rate on the resulting material modifications. This amounted to additional 35 experiments until the end of allocated beamtime.

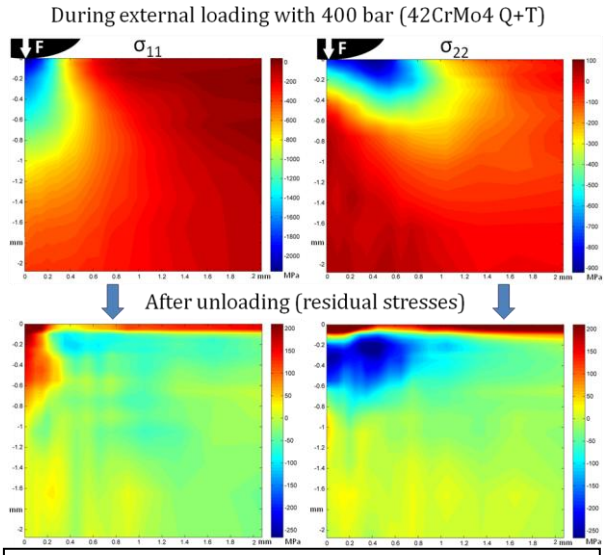


Fig.3. 2D stress mappings during static loading (internal material load) and after unloading (residual stresses) in two

The evaluation of the huge amount of data is still ongoing and at the moment, only preliminary results are available. At first, a macroscopic stress evaluation based on the use of $d_0$ values for strain calculation was performed. For this, the 2D-diffraction patterns were integrated in a range of 6° around the cardinal directions of the y- and z-axes, corresponding to the angle ranges of 90° and 180°. The x- and z- dependent positions of the {211}-martensite peak were then evaluated by fit with a pseudo-voigt function. The $d_0$ values were determined at each sample before loading in order to calculate the principal strain values $\varepsilon_{11}$ and $\varepsilon_{22}$. Under the assumption of a plane stress state, the stress values $\sigma_{11}$ (in depth direction) and $\sigma_{22}$ (longitudinal) have been calculated at each point of the grid. The obtained 2D-stress maps (half-fields) are shown exemplarily for a quenched and tempered 42CrMo4 sample processed with 400 bars during static loading and after unloading (Fig. 3). During loading, high compressive stresses are generated in both directions from the tool center up to a region of about 2 mm x 2 mm with values up to -2200 MPa in the $\sigma_{11}$ direction and lower values up to -920 MPa in the $\sigma_{22}$ direction. After unloading, characteristic residual stress formation with compressive values up to -270 MPa in the $\sigma_{22}$ direction and slight tensile residual stresses in the $\sigma_{11}$ direction up to +100 MPa are resulting. It has to be remarked that in the 2D-maps after unloading, implausibly high tensile values were determined in a surface region of about 100 µm depth in the whole measured length. The reason for this is supposed to be a shift of the sample surface (0 position) after unloading and is currently being examined. Further evaluations of the data, in particular by using the $\sin^2\psi$ method for stress evaluation but also in terms of texture evolution and peak broadening analysis are currently ongoing. Moreover, phase transformations are being investigated in the high alloyed steel as its exhibits a metastable austenitic structure. Based on the results, the effect of loading pressure and feed rate on the generated material modifications will be evaluated for the three material states. The results of these experiments will be presented at the International Conference on Residual Stresses (ICRS10) in 2016.