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DIFFERENT ASPECTS OF MATERIAL MODELING BY DEEP ROLLING

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ABSTRACT
In the following paper results of the investigation of the "Bauschinger effect" are presented. It was done by model which was made in ABAQUS and observed from deep rolling simulation results of residual stresses. Later, comparison of the results are presented by variation of forces and overlapping factor. Deep rolling (DR) is a mechanical surface treatment widely used due to its ability to increase the fatique life of the treated components. The finite element analysis (FEA) is a convenient tool which can be used to model the DR process and facilitate its implementation in to new components. A central aspect in the FE modeling is the material definition and particularly presence of the mechanical phenomenon called "Bauschinger effect". The material used for the simulation was a steel alloy 42CrMoS4 with mass density of 7720 kg/m^3, Young Modulus of 210 MPa, Poisson's ratio of 0.28 and plastic hardening type was defined as a kinematic.

1. INTRODUCTION
Residual stresses are those stresses which exists in an object after application any of force or other external loads. Those stresses remain in the material component after removal of all loads so they are also called as a locked-in stresses no matter are we speaking about thermal gradients or phase transformations or even about pure mechanical loading.
The most common reason of inducing the residual stresses in material are the manufacturing processes, particularly in the aforementioned deep rolling process. All manufacturing and fabricating processes such as casting, welding, machining, molding, heat treatment, plastic deformation during bending, rolling or forging introduce the residual stresses into the manufactured object [1].
Figure 1 shows the development of residual stresses during cooling of a hot ingot. In the cooling of a large, hot ingot of a metal which shows no phase change, the difference in the temperature between surface and the center may be enough to develop residual stresses. The edges of hot ingot cool faster than the center. The thermal contraction of the cooler edges produces a strain incompatibility between the edges and center of the ingot which results in the distribution of longitudinal stresses shown in Figure 1 (b). Because hot center has a lower yield stress, it cannot support the compressive stress established on that region what implies that centre of the ingot shrinks to relieve some of the stress, Figure 1 (c). When the centre of the ingot finally cools, the total contraction will be greater for the center than the edges and it can be said that the center will be stressed in residual tension, while edges will be in compression Figure 1(d) [2].

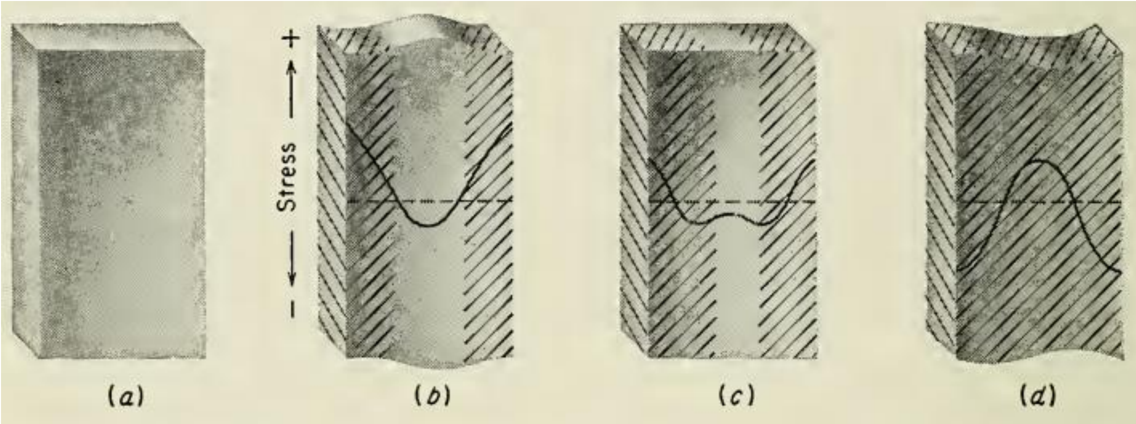

Figure 1. Development of residual stresses during cooling of a hot ingot. Cool portions shown shaded, [2]

Deformation – related residual stresses or mechanical residual stresses arise appear when the plastic deformation of the phases or the material’s grains is not homogeneous. The sources can be the anisotropy of Young’s modulus as well as the yield stress and the work – hardening of the individual phases [3]. Residual stresses can be either beneficial or detrimental, depending on whether is stress tensile or compressive. Residual stresses can be tensile and compressive. Actually, tensile and compressive stresses co-existing in the component and they are always balancing each other (compressive stresses are counter balancing tensile stresses). Tensile stresses are usually labeled as a positive (+) while compressive residual stresses are labeled as a negative (-). Tensile residual stresses can have values large enough to cause component distortion or cracking and because of that fact we say that tensile residual stresses can initiate crack propagation while compressive stresses are doing exactly the opposite effect, closing and slowing down the crack propagation. Also, surface residual compressive stresses are helpful because they reduce the effects of applied tensile stresses and they are improving fatigue strength of material [4].

Deep rolling is a mechanical surface treatment which is used because of its ability to introduce favorable compressive residual stresses, to reduce the roughness of the treated surface and improves the fatigue strength of a component. Deep rolling is similar to roller burnishing when deforming and positively influencing a component's edge zone characteristics.

This combination can improve fatigue strength up to five times and therefore significantly increase the service life of a component. Deep rolling is especially recommended for components which underlie dynamic stress during operation and can therefore be destroyed by material fatigue. One of the most well known benefits of deep rolling in comparison to other surface treatments is the great depth of the affected layer exhibiting alterations of the work hardening state. Another benefit of this particular surface treatment is generation of glossy surfaces with low roughness, as compared to treatment such a shot peening [5].

Residual stresses are produced whenever a body undergoes nonuniform plastic deformation such a deep rolling. The surface fibers of a component or a plate, for example, are cold – worked and tend to elongate, while the center of the plate is unchanged. Because the plate must remain a continuous whole, the surface and the center of a plate must undergo a strain agreement. The center fibers tend to restrain the surface fibers from elongating, while the surface fibers are seeking to stretch the central fibers of the plate. The result is a residual – stress form in the plate which consists of a high compressive stress at the surface and a tensile residual stress at the center of the plate.

Treatments like deep rolling or shot peening have not experienced widespread industrial applications in mass production until the first half of the last century. Actually, deep rolling

was first applied in the twenties of the last century in the U.S.A., as a surface treatment to strengthen axles of the Ford T and in thirties, axles of trains were also subjected to the deep rolling treatment. Significant pioneer work in deep rolling field in the U.S.A. was introduced and carried out by Horger, while in Germany, Föppl and Thum debated about causes of fatigue enhancement by deep rolling [6].
Deep rolling process and its applications are widely used in automobile industry, in turbo aircraft engine and turbine blades industry.

A suitable tool to model DR process is the finite element modeling. Finite element analysis (FEA) is computerized method used to model a part or an assembly and predict how it reacts to forces, vibration, heat, fluid flow, and other physical effects such as mechanical stress, fatigue, motion, etc. Finite element analysis try to predict whether a product will break, wear out or work in the way it was designed. It is called analysis, but in the product development process, it is used to predict behavior of a product during its usage. Element analysis (meshing) works by breaking down a real object into a large number (thousands to even millions) of elements, like it is shown in Figure 4. Mathematical equations help predict the behavior of each element. A computer then adds up all the individual behaviors to predict the behavior of the actual object [7]. Besides all previous mentioned, it is very useful when we want to design, check a quality and optimize a product. The software which was used for analysis was ABAQUS 6.14 version. ABAQUS includes two different modes: Standard and Explicit. Difference between these modes is in following: ABAQUS/Standard is a finite element analysis which employs solution technology ideal for static and low-speed dynamic events where highly accurate stress solutions are critically important, while ABAQUS/Explicit is a finite element analysis product that is particularly well-suited to simulate brief transient dynamic events [8].

To describe the characteristic material behavior, the uniaxial tensile-compressive tests are commonly used. Material behavior, which is particularly interesting for this investigation,will be introduced and explained in the following page. The Bauschinger effect manifests itself when a specimen is subjected to a tensile loading followed by a compressive loading; it is often found that since the loading in tension was carried out first, the material has hardened in tension (yield stress in-creased) but softened in compression. Figure 2 shows that the yield stress in compression is lower than that if the tests were carried out in compression first, [9].
This means that Bauschinger effect phenomenon is reversible, for had the specimen originally been stressed plastically in compression, the yield stress in tension would have been decreased.The Bauschinger effect can be observed during tension–compression conditions and is connected with a decrease of the yield stress when the loading direction is reversed (Figure 2).

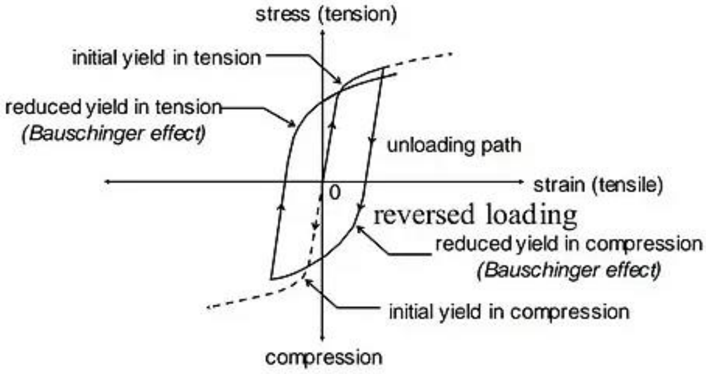

Figure 2. Schematic representation of Bauschinger effect [10]

2. FINITE ELEMENT MODELING AND SETUP

Investigation of the Bauschinger effect will be observed from DR simulation results of residual stresses. Aforementioned residual stresses will be observed at same nodes in which the stresses are measured and which are over yield stress in tensile and compressive direction. The model consists of two parts:

- A target plate of length 16 mm, height 10 mm and extruded on a 24 mm in depth,
- A rigid sphere of 3.17 mm radius.

The material used for the plate was a steel alloy 42CrMoS4 with mass density of 7720 kg/m^3, Young Modulus of 210 MPa and Poisson's ration of 0.28 and plastic hardening type was defined as a kinematic. Plastic properties of this material are given in Table 1, and the chemical composition of aforementioned material, regarding the standard EN 10277-5-2008 is given in Table 2 [11]. The assembly for this model is shown in Figure 3.

Table 1.Plastic properties of the material 42CrMoS4

Yield stress [MPa]	Plastic strain [%]
1010	0
1138.8	0.0521

Table 2. Chemical composition of 42CrMoS4 steel [11]

C	Mn	Si	P	S	Cr	Mo
0.38-0.45	0.60-0.90	0.40 max	0.035 max	0.035 max	0.90-1.20	0.15-0.30

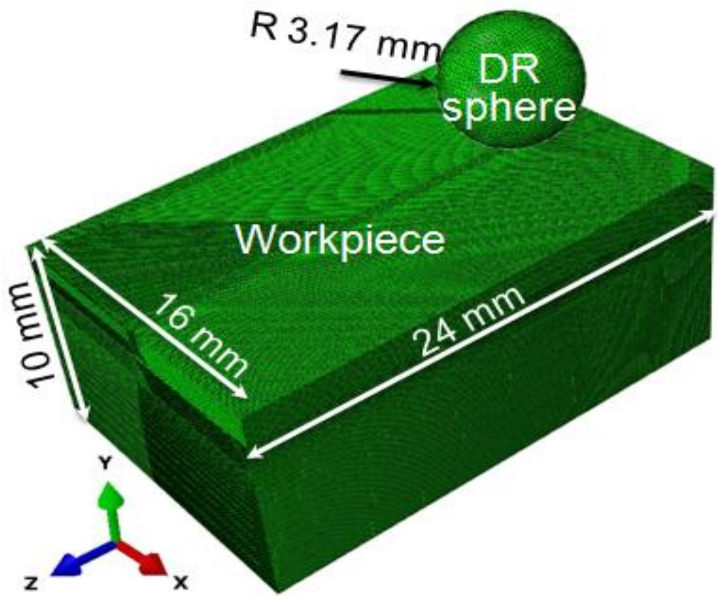

Figure 3. Assembly for the model [12]

Roller was defined as a rigid body so in order to make a movement with a roller, it is necessarily to define boundary conditions for the roller. Boundary conditions for the roller are presented in Table 3. Target plate was encastred – "fixed to the ground" during the whole simulation, which means that it cannot move in any direction. In a case of roller, the boundary conditions changed during every of 6 steps in following order which are also presented in Table 3. The DR movement or path (positive z-direction movement, x-direction movement and negative z-direction movement) is shown in Figure 4.

Table 3. Boundary conditions for a roller [12]

Modeling steps	**Translation**			**Rotation**			**DR Force**
	X	**Y**	**Z**	**X**	**Y**	**Z**	
Make contact	-	allowed	-	-	-	-	Y = -5 N
Apply force	-	allowed	-	-	-	-	Y = -1262.78 N
+ z direction movement	-	-	V=1 mm.s^{-1}	allowed	-	-	Y = -1262.78 N
x direction movement	V=1 mm.s^{-1}	-	-	-	-	allowed	Y = -1262.78 N
- z direction movement	-	-	V=1 mm.s^{-1}	allowed	-	-	Y = -1262.78 N
Reverse force	-	Allowed	-	-	-	-	-

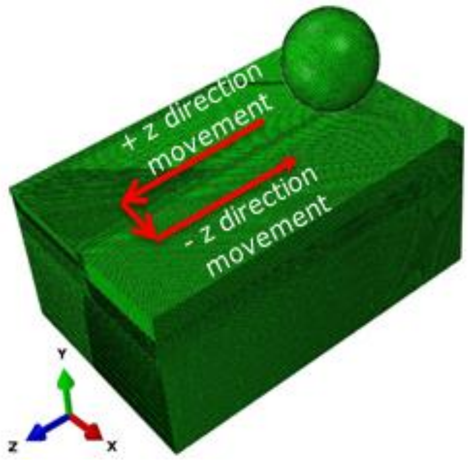

Figure 4. DR movement [12]

Other important and used parameters, which were not mentioned before, will be written in following table named as Table 4. Other used parameters for the model:

Table 4. Other used parameters for the model, [12]

Ordinal number	Name of the parameter	Value of the parameter
1.	Time incrementation	0.0001
2.	Linear bulk viscosity	0.06
3.	Quadratic bulk viscosity	1.2
4.	Friction coefficient	0.1

In Table 5 it is presented informations about the mesh of the model.

Table 5. Number and type of elements for assembly [12]

Part	Number of elements	Type of elements
Roller	3617	Linear quadrilateral elements of type R3D4
Target plate	2.820.000	Linear hexahedral elements of type C3D8R

In a used model it is implemented global size of an elements in mesh. For a smooth mesh, it was necessarily to define different size of elements in different areas of target plate. The most influenced area of a target plate is the upper surface area and area just below, because the results will be observed in those areas and that is the reason of smoother mesh in upper part of the target plate. The result of this mesh is in total number of elements and it is 2.823.617.

3. RESULTS

In order to investigate relevance of “Bauschinger effect” in a aforementioned model, it was necessarily to have the results of calculated residual stresses in ABAQUS. After writing down all results from 3 different models, investigation of the aforementioned effect was started. Difference between those three models was in overlapping value. Time period of the x – direction movement step is defined in that way that it represents percentage of overlapping – A, as following: the distance of the x – direction movement is labeled as a and a had varying value, 0.18 mm, 0.36 mm and 0.54 mm. Those values represents 75%, 50% and 25% of overlapping, because the original distance of a x – direction movement was 0.72 mm (0% of overlapping).
Results of all three models showed that in some particular nodes stress is exceeding the yield stress in tensile and compression which was necessarily to observe. In following figures will be presented investigated effect made in diagrams.

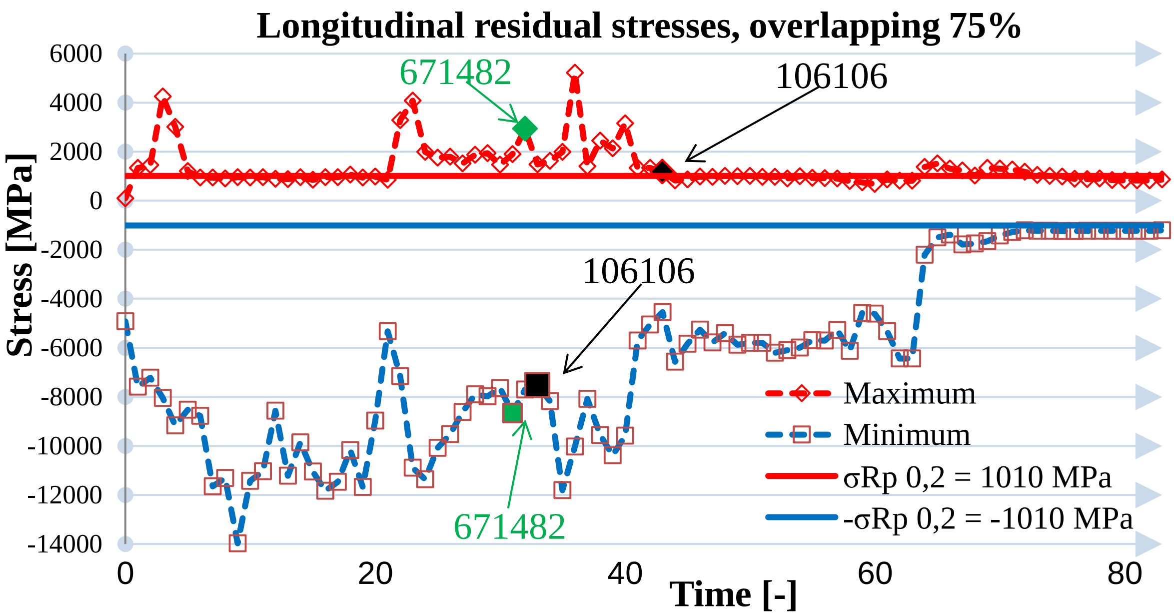

Figure 5. Investigation of “Bauschinger effect” in longitudinal direction with overlapping value of 75%

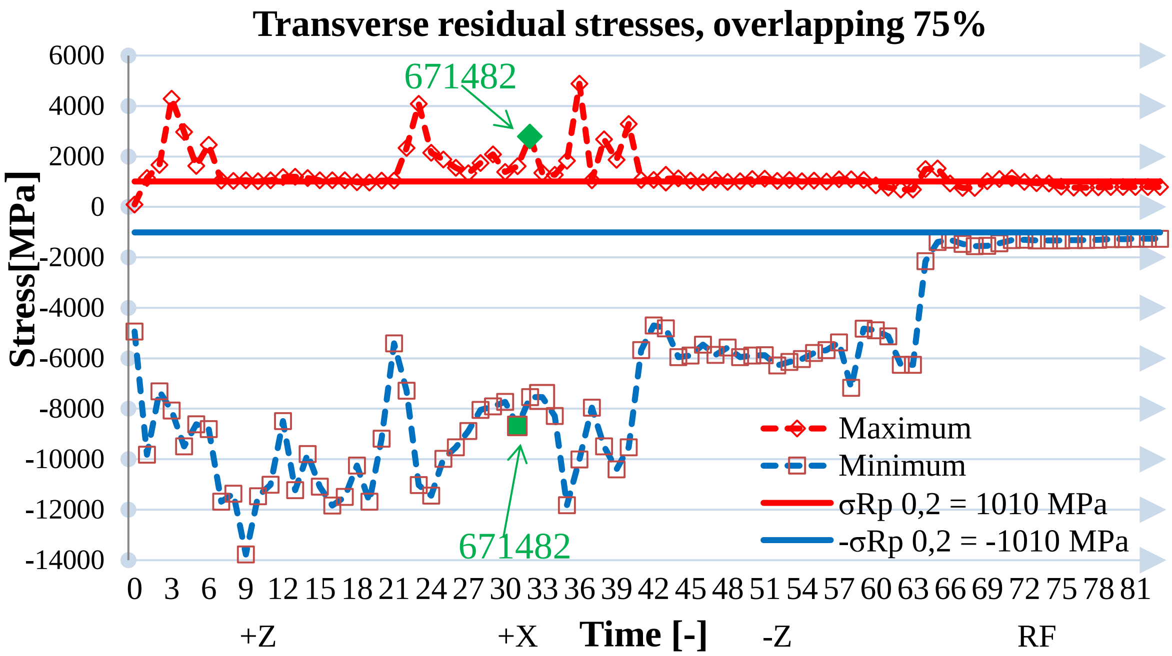

Figure 6. Investigation of "Bauschinger effect" in transverse direction with overlapping value of 75%

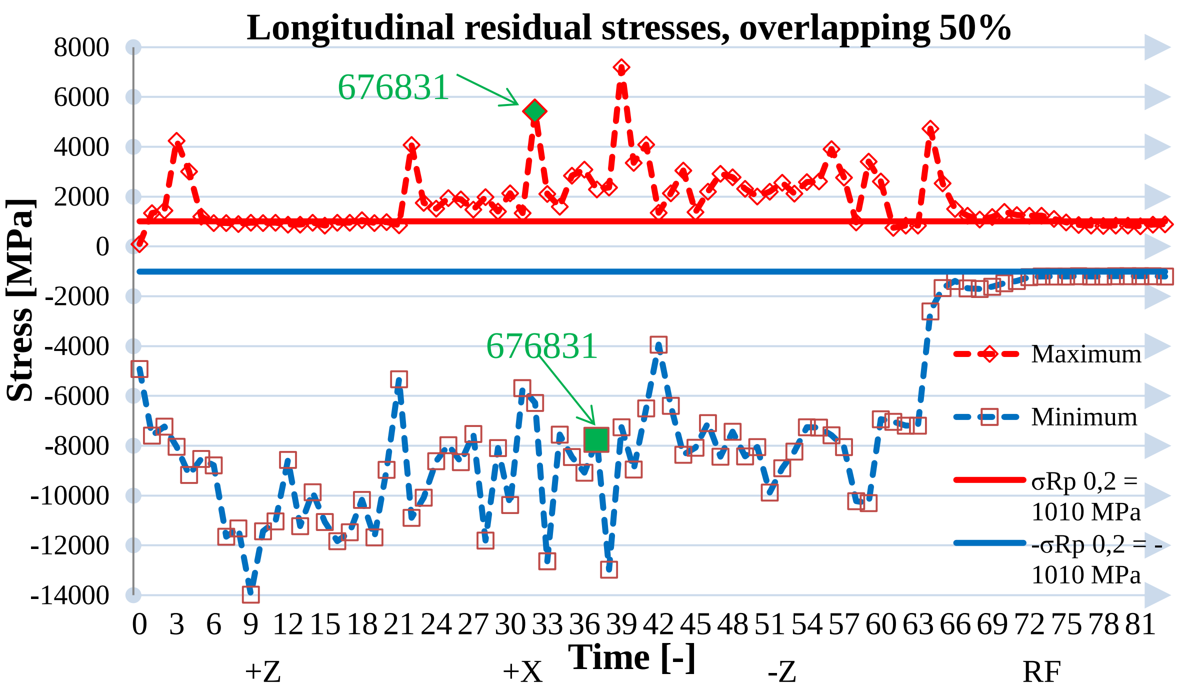

Figure 7. Investigation of "Bauschinger effect" in longitudinal direction with overlapping value of 50%

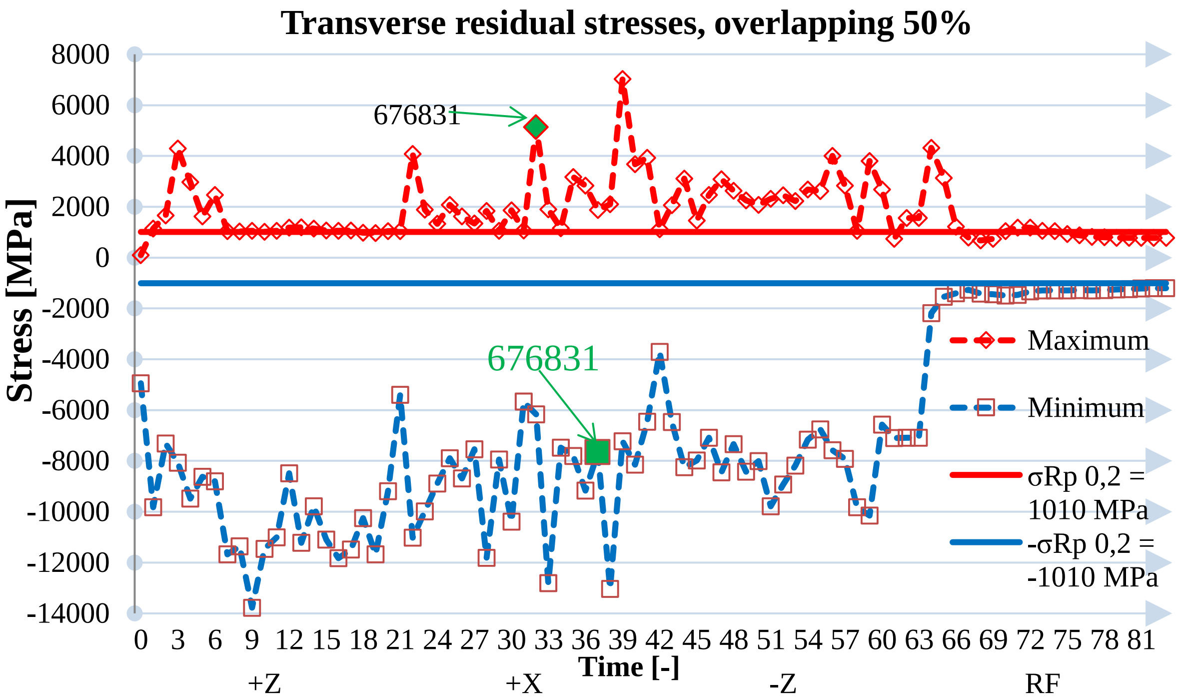

Figure 8. Investigation of "Bauschinger effect" in transverse direction with overlapping value of 50%

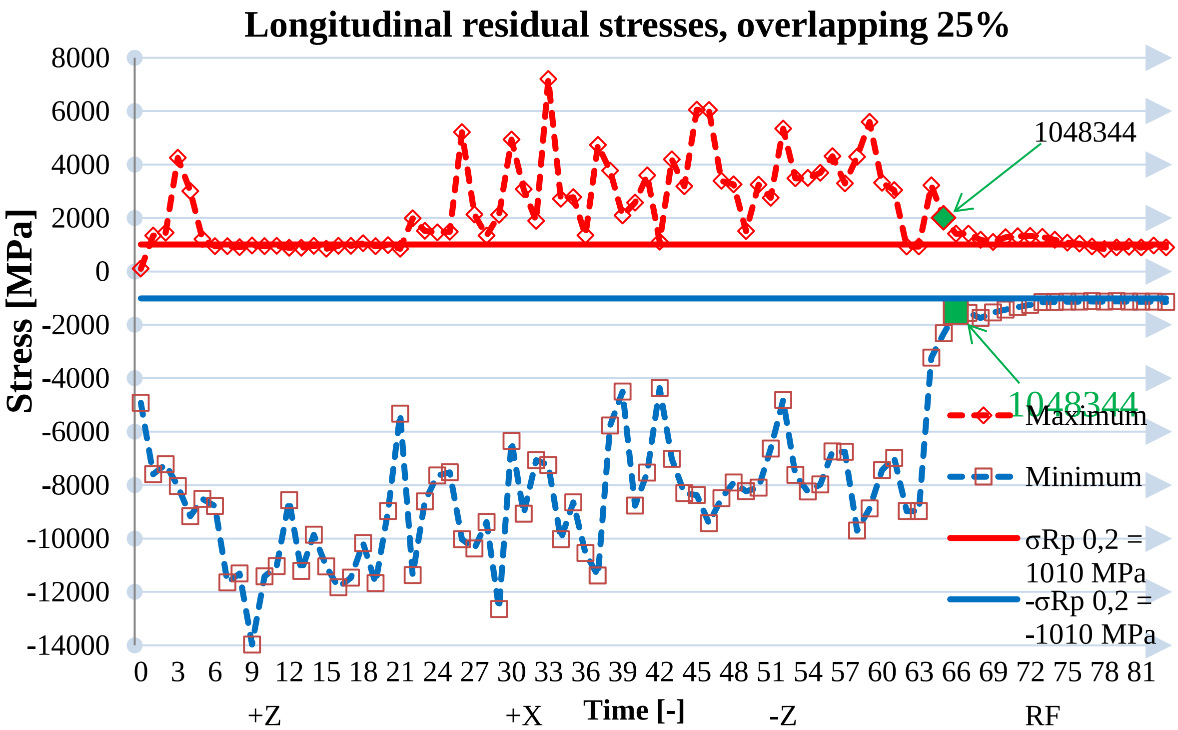

Figure 9. Investigation of "Bauschinger effect" in longitudinal direction with overlapping value of 25%

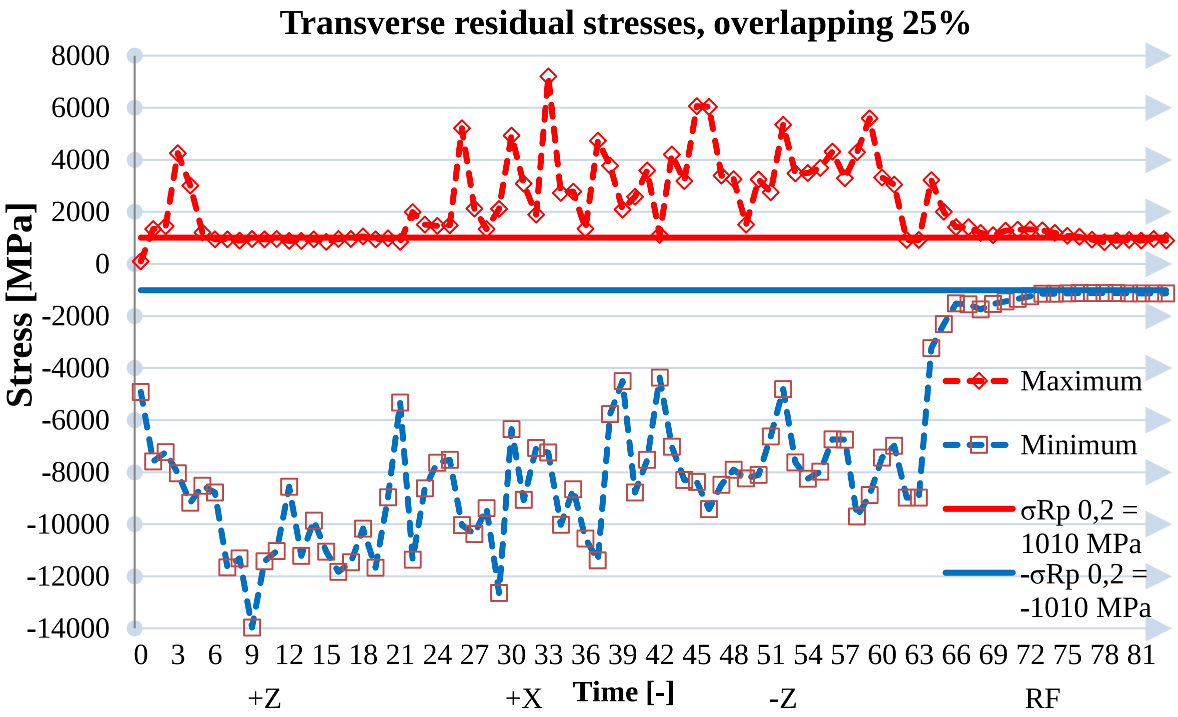

Figure 10. Investigation of "Bauschinger effect" in transverse direction with overlapping value of 25%

4. CONCLUSION

In order to investigate Bauschinger effect, it was necessarily to find values of residual stresses either in tensile or in compressive direction, which are over the yield stress. There was many sharp peaks, but it can be assumed that those peaks can be because of the nature of the deep rolling process. Those sharp peaks can be either caused by instability of the deep rolling process or in other hand because of meshing.
Indeed, as it can be seen in diagrams in previous pages, it is clearly that the process is becoming more „stable" as time is running, specially in the reverse force step. There process became stable and as a result of that we can see almost constant value of stresses either in tensile or compressive direction. Regarding the tensile stresses there are two „instability" periods: first one is in the beginning of the process when DR tool starts to apply force to surface and second one is in x-direction movement step, when DR tool changed direction of movement. In other hand, the compressive stresses, are mostly instable until the reverse force step, when is clearly seen that both of the stresses have almost constant values which is, in my opinion, logical conclusion. Also it is necessarily to mention that in the last observed case – transverse residual stresses with overlapping value of 25%, there is no presence of any nodes which have stress value over yield stress.
So, in the end, it can be concluded that "Bauschinger effect" can be taken into account in this process and the sharp peaks can be attributed to the instability of deep rolling simulation.

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