A systematic investigation of the induced residual stresses by deep rolling in dependence of the prestress at spring steel

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Introduction

Today reduction of weight or material is a current subject in wide areas of automotive and mechanical engineering. Several possibilities are available, like better utilization of the material by higher hardness or optimizing the construction by finite elements. Another possibility is inducing compressive residual stresses in the surface layers, especially used at tensile pulsating load to enlarge the dynamic life time or respectively reducing the weight. Two possibilities are deep rolling and shot peening, which have different advantages. Deep Rolling is more expensive but gives a higher amount of compressive residual stress as shot peening. In the shot peening process, the amount of compressive residual stress can be increased by stress peeing. In an equivalent way, this technique is also possible for deep rolling. In this investigation, the amount of residual stresses is measured in dependence of the prestress and rolling force.

Basics

Deep Rolling

Deep rolling can be regarded as a continuously made plastic deformation of material near the surface. In this procedure, a tool (ball, profile roll) is pressed against the work piece with a special pressing force. Here the important parameters are the pressing force and the overlap. This standard procedure is described many times, for example in [1; 2; 3; 4; 5].

Stress Rolling

At the shot peening procedure, sometimes the work piece has been loaded before peening, the so-called stress peening to get after peening and unloading a higher amount of compressive residual stresses [6; 7; 8]. The same procedure can be done within the deep rolling process. The work piece is also loaded with a tensile stress before rolling. In addition, there is the original deep rolling process. Subsequently the work piece is unloaded and in the direction of the load an increase of the compressive residual stress can be expected, which has different effect, if the rolling and loading direction are the same or perpendicular. The first results have been described in some publications before [9; 10].

Methodology

Preparation of the specimens

The specimens were pieces of flat steel, which is normally used for leaf springs, with a length of around 330 mm, a width of 80 mm, and a thickness of 9 mm. The material was normal spring steel 51CrV4. The specimens were heated up to 880 °C and quenched in oil to get a martensitic structure. Then they were heat treated to obtain a tensile strength of R_m = 1520 MPa. To avoid spreads of the hardness in the surface layer because of decarburization, the specimens were ground to remove a layer of at least 0.5 mm.

Treatment of the specimens

The specimens were rolled with the help of a device type HG 6-9 from Ecoroll. It has a ball of 6 mm diameter, which were used to induce the residual stresses. The pressure against the ball by the liquid was p = 100 bar and 300 bar, which is equivalent to a force of around 275 N and 825 N. In case of a preload the mounting device is shown in figure 1, in which the samples were fixed and loaded to get a zone of constant prestress. Then the stress rolling was done under the different loads σ_{pl} = 260 N/mm²; 370 N/mm²; 710 N/mm² and 900 N/mm². (one sample was without prestress.)

The optimal distance between the rolling tracks was Δx = 0.15 mm, which was determined in a separate investigation [9]. The rolling area was 55 mm * 55 mm and was rolled in the way of a meander. The tracking is shown in figure 2.

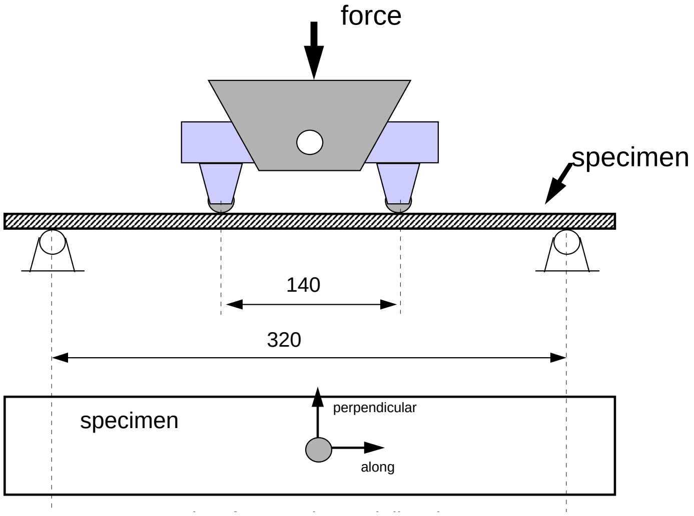

Figure 1: mounting device and measuring directions of the stress rolled specimen. The stress is along the sample.

Residual stress measurements

With the help of an x-ray diffractometer (type Rigaku Strainflex MSF-2M) the stresses were determined. In this case the distance between the [h,k,l]-layers [2,1,1] is measured. The diameter of the x-ray spot on the surface was 8 mm. The determination was done with the help of the sin²Ψ-Θ-method. To get a residual stress profile up to a depth of 1.0 mm the surface layers were removed electrolyticly. The measuring error is 8 % of the value at least minimum +/- 30 MPa.

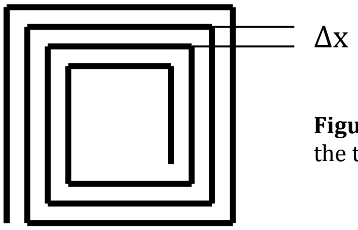

Figure 2 : shape of the tracking

Results and analysis

There are four interesting configurations, which were measured. If you do the deep rolling without prestress, you receive an asymmetric residual stress distribution. In the direction of the rolling track is less compressive residual stress than perpendicular to the rolling direction. The results are shown in the diagrams figure 3.

In the case of 100 bar two typical residual stress profiles are shown with the shape of inducing the residual stress by Hertzian pressure. The maximum of the compressive residual stress is under the surface. The compressive residual stress perpendicular to the rolling direction is always higher. At 300 bar the maximum of the residual stress profile goes deeper in the case along the track. Perpendicular to the track a continuous decrease of the compressive residual stress from the surface can be detected like also in former investigations [10].

If you roll under prestress the load is along the specimen. Because of the rolling pattern you have rolling direction and preload direction in the same way or perpendicular to each other. The residual stress profile depends on the measuring direction along or perpendicular to the rolling direction. In direction of the preload after unloading the compressive residual stress is enhanced [10].

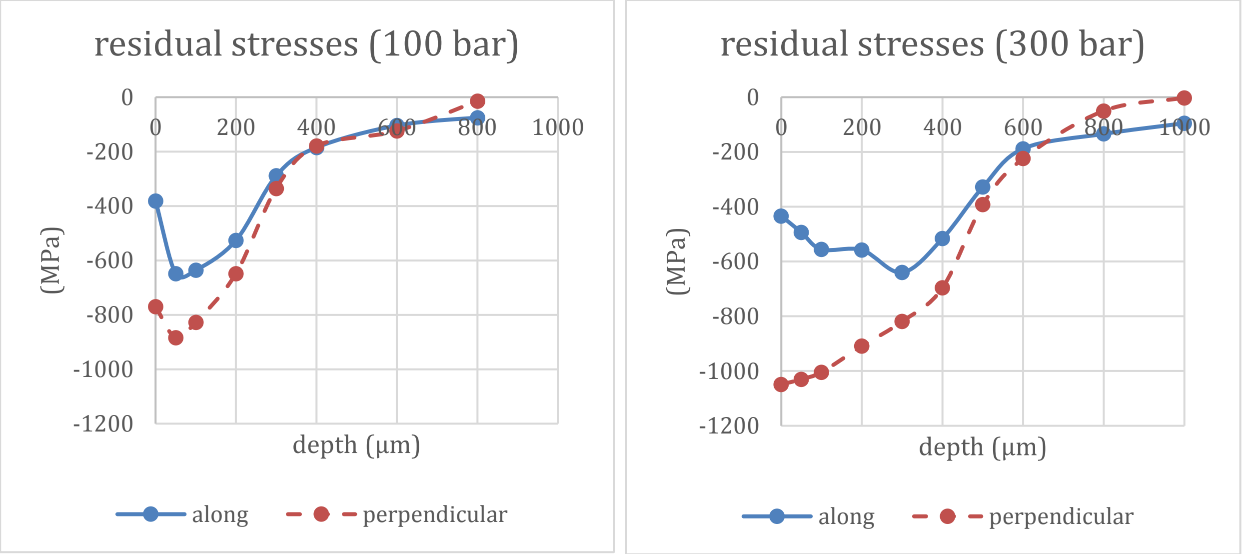

Figure 3 a+b: residual stress profiles for two different pressures of the ball without any preload

Now you have four different cases: rolling direction and preload in the same direction and residual stress in rolling or perpendicular to the rolling direction on the one hand and on the other hand rolling direction and preload perpendicular and the residual stress again in rolling or perpendicular to the rolling direction.

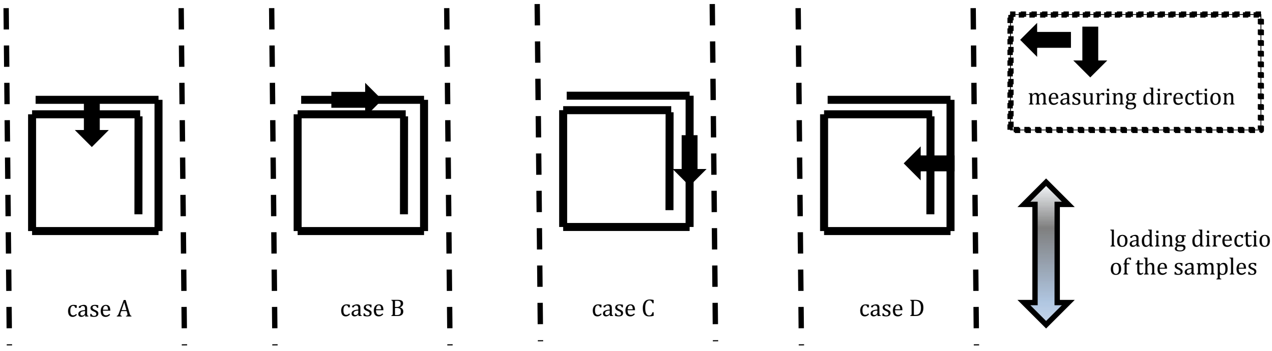

Figure 4: the different cases of rolling direction, loading direction and measuring direction

Now the lines in the diagrams spilt into two lines. One is the old line without increase of the compressive residual stresses, due to the fact there is no preload (case B and case D), because it is perpendicular to the loading direction and the other line shows the increase of the compressive residual stresses causes by unloading the sample.

The following figures shows exemplary the residual stress distribution for two preloads in dependence of the depth. For 100 bar, you see a residual stress distribution for all cases as it is obtained by Hertzian pressure. It is a little bit more than without preload (case A+C). Also for 300 bar you see an enhancement of the compressive residual stresses for these both cases. The other cases it is within the measuring errors the same distribution as without preload. At a preload of 710 MPa it can be seen that the cases without preload slight reduction of the compressive residual stresses is obtained. The same effect was detected at stress peened samples [8]. In preload direction, an enhancement of the compressive residual stress is reached (more or less, depending on the case). For both cases the penetration of the residual stresses into the depth is more better.

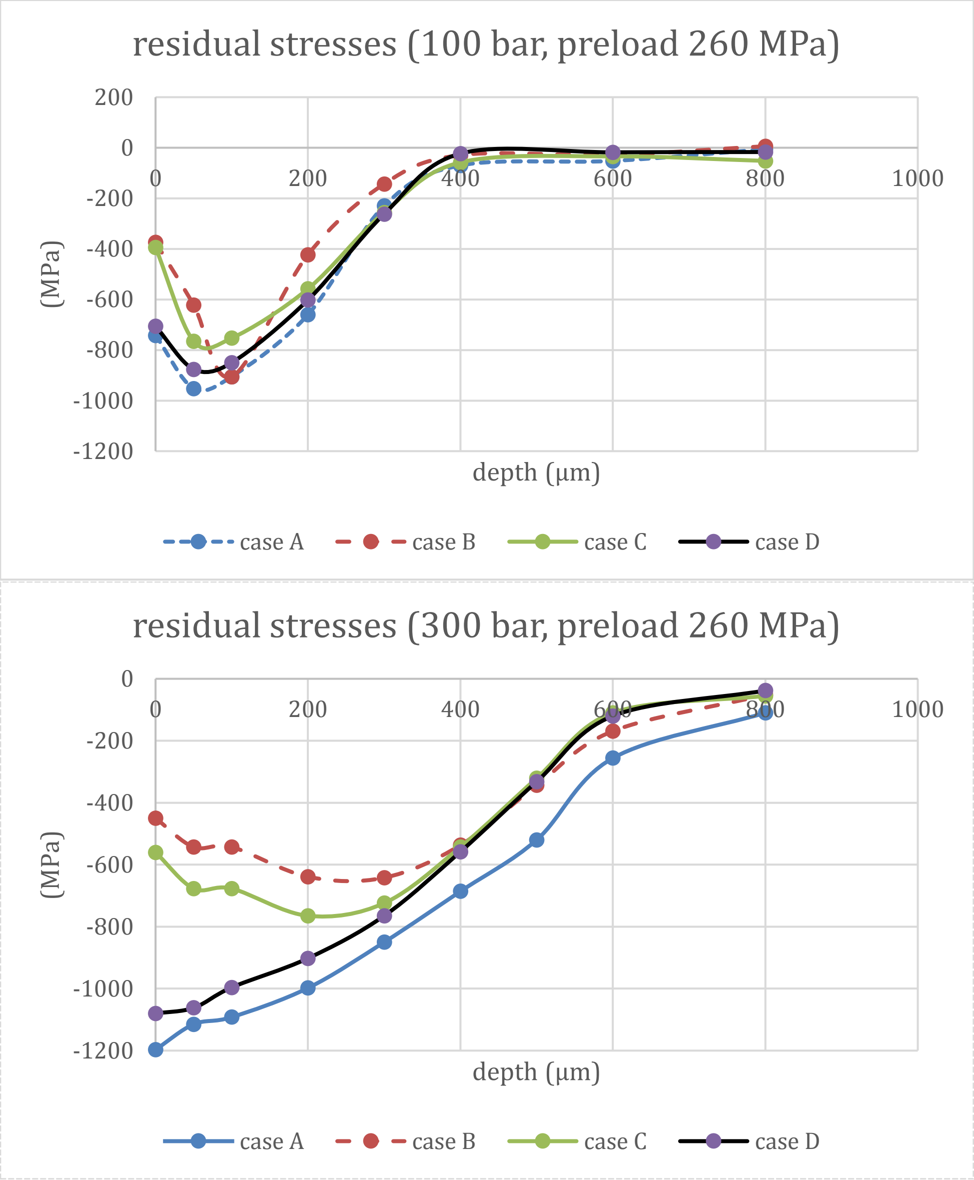

Figure 5 a+b: residual stress distribution rolled with a preload of 260 MPa

The diagrams in figure 7 show the evolution of the residual stress in dependence of the preload. There is an increase with the preload of the compressive residual stress. In case of 100 bar a constant increase is detected up to around -1000 MPa in case A. Here the maximum of the compressive stress is nearly reached., which is about 71 (+/-6) % of the tensile strength for spring steel [11]. In case A at 300 bar the compressive residual stress was reached with normal deep rolling. The variation in this case causes from the measuring mistakes. You can say that the compressive residual stress is independent of the preload, because it is at the limit.

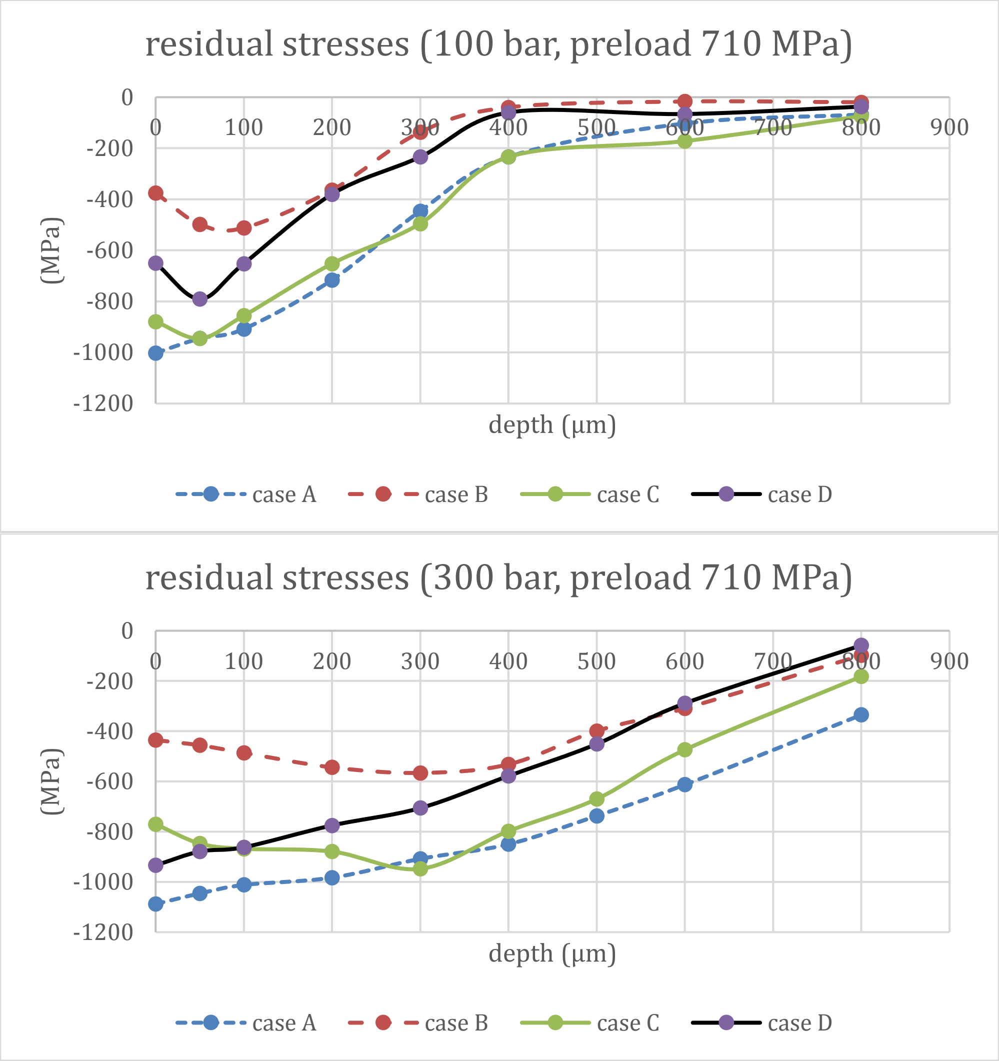

Figure 6 a+b: residual stress distribution rolled with a preload of 710 MPa

Conclusions

Stress rolling is a way to get high residual stress in all direction in a surface and the depth. Specially an increase of the compressive residual stress along the rolling track can be detected. The investigation shows the increase of the compressive residual stress is dependent of the preload. The limit of the maximum compressive residual stresses was reached.

For practical applications, the rolling pattern is important and the tracks should be perpendicular to the loading direction to get a uniform distribution if it is necessary. Otherwise the loading direction under dynamic load and the compressive residual stress should be in the same direction, which cannot always be realized in an optimal way. One example for this configuration are torsion loads, which you have on torsion bars.

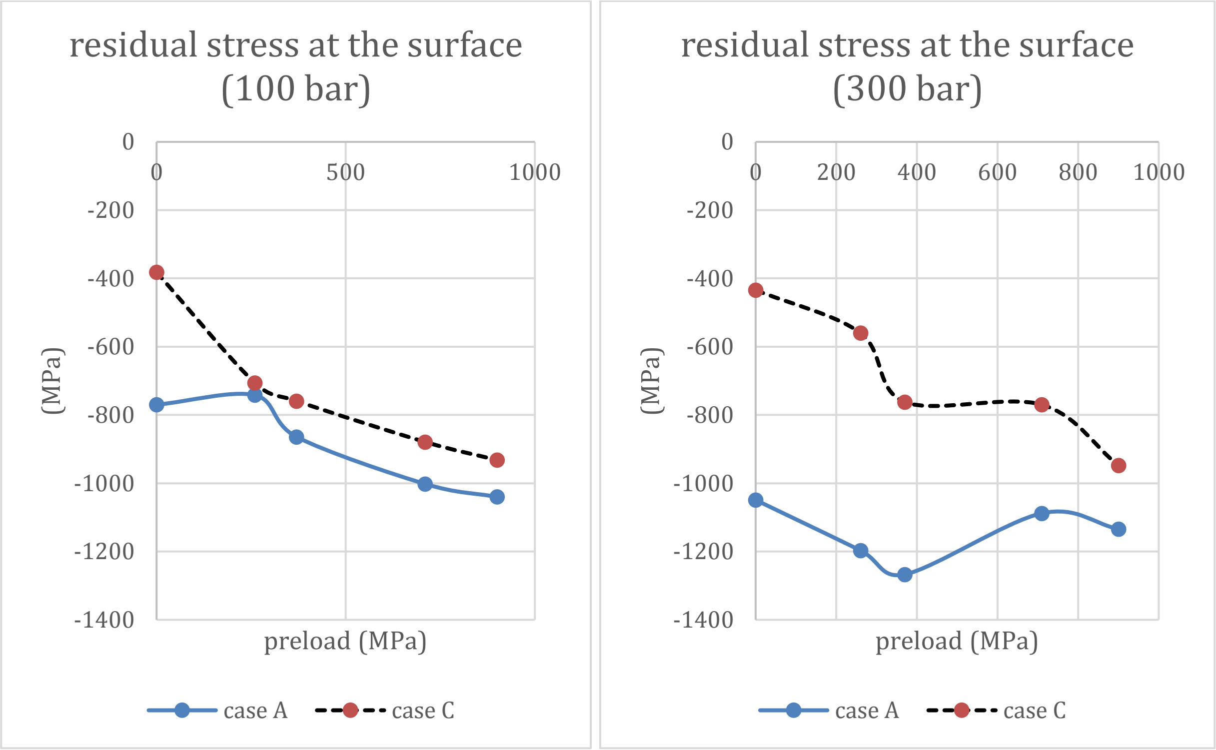

Figure 7 a+b: the increase of the compressive residual stress at the surface in dependence of the preload

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