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A Way to Determine the Maximum Inducible Residual Stresses in Steel by Mechanical Surface Treatment

Eckehard Mueller[1,2]

1. Faculty of Mechanical Engineering, Bochum University of Applied Sciences, Bochum 44801, Germany

2. Steinbeis-Transfer Center for Spring Technologies, Component Behavior and Process, Iserlohn 58638, Germany

Abstract: The issue of determining the maximum compressive residual stress that can be induced through mechanical surface treatment is of great significance. There are two possible approaches, namely stress peening and stress rolling, both to determine the limit. Steel with high hardness may be under the yield strength, while for those with lower tensile strength, the hardness is increased, and the limit is above the tensile strength.

Key words: Residual stress, deep rolling, shot peening, stress peening, stress rolling.

1. Introduction

Mechanical surface treatment is a widely used technique to improve the durability of components under dynamic loads. However, there is often a debate on what the maximum compressive residual stress is that can be induced. This aspect is also crucial for guidelines and standards, as incorrect values may lead to unfulfilled expectations.

When attempting to induce compressive residual stresses through mechanical surface treatment, two factors must be considered: the level of hardness the steel attains and how great amounts of compressive residual stress can be induced in the material. In the upcoming report, two methods will be presented.

2. Basic Considerations

In this chapter, the basics of the procedure and a new method for determining residual stress are briefly described.

2.1 Idea and Way

Typically, leaf springs are subjected to shot peening, a process which enhances performance and durability through the application of stress peening [1]. Parabolic leaf springs, in particular, have a constant stress throughout the arm (see Chapter 3.2.1) and are loaded up to their tensile strength for stress peening, resulting in the appearance of high tensile residual stresses on the surface. By applying a sufficient stress peening process, a good level of compressive residual stress can be achieved, which is independent of the preload [1]. Upon the unloading of the leaf, the compressive residual stress increases up to its limit, as the preload was at the tensile strength, which should theoretically be added to the induced compressive residual stress. This process can be simulated in a laboratory experiment.

Alternatively, a flat specimen, such as a plate with a minimum thickness of 10 mm (Fig. 1), can be used to achieve a high amount of compressive residual stress at the surface after unloading. The specimen is first loaded in a 4-point bending rig and then deep rolled at the middle area. Upon unloading, stress calculations similar to those employed in shot peening can be performed.

2.2 Determination of the Residual Stresses

The residual stresses were determined using X-ray

Corresponding author: Eckehard Mueller, Dr., Prof., research fields: Mechanical surface treatments, automotive springs.

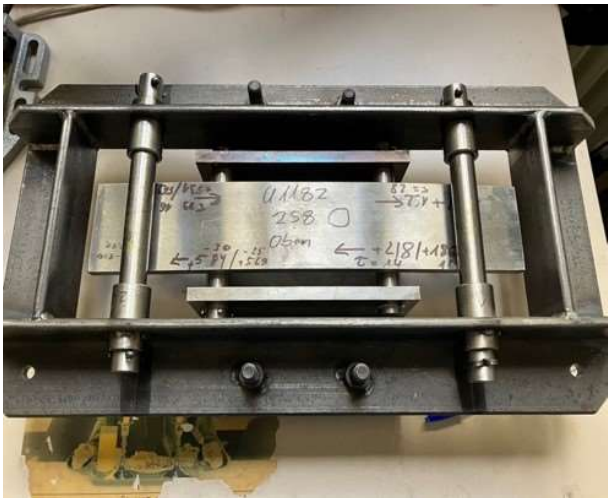

Fig. 1 4-point bending rig for the experiment.

diffraction through the Cos-α-method. A detailed description can be found in references such as Refs. [2, 3]. The measurement error is 6%. The values presented represent normal stress, without any shear stress by recalculations.

3. Experiment

3.1 Materials

The experiment was done with two different grades of steel: 51CrV4 (1.8159) and 25CrMo4 (1.7218).

All properties are given in Table 1.

Table 1 Properties of the used steel.

	51CrV4	25CrMo4
Tensile strength R_m (MPa)	1,650	710
Yield strength $R_{p0.2}$ (MPa)	1,480	560
Treatment	annealed	annealed
Elongation at break A (%)	> 50	64
Method	stress peened	stress rolling

3.2 Specimens

3.2.1 51CrV4

In this study, a parabolic leaf spring (as shown in Fig. 2) was utilized. The thickness of the spring varies depending on its distance from the middle, with a typical thickness profile illustrated in Fig. 3. This shape ensures that the loading stress is constant throughout the entire arm. The average thickness of the spring is approximately 25 mm. Notably, the spring was subjected to a preload of more than 1,500 MPa during the peening process.

Fig. 2 Used spring for the experiment (black area caused by an acid for electropolishing).

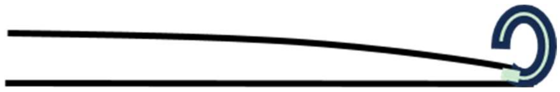

Fig. 3 Schematic shape of a parabolic leaf spring.

3.2.2 25CrMo4

A depiction of the specimen used in the experiment is presented in Fig. 1. The dimensions of the specimen are 350 mm × 80 mm × 10 mm. The plate was ground to eliminate any potential decarburization.

3.3 Performing of the Experiment

3.3.1 51CrV4

The leaf spring underwent loading to a stress of 1,500 MPa, after which it was peened using a conventional turbine equipment commonly used in spring production. The grain used for the peening process was steel shot with an average diameter of 1.2 mm and a shot velocity of 80 m/s. Two turbines were employed during the peening process, for a duration of about 5-10 s. Notably, at a tensile strength of 1,650 MPa, no significant increase in hardness was observed. Standard shot peening produced a consistent residual stress distribution on the surface without any shear stress on the loaded leaf. As the loading direction was along the leaf, the compressive residual stress limit can be observed in this direction.

3.3.2 25CrMo4

At first, the specimen was subjected to pre-stressing at a level of 380 MPa. Following this, it underwent deep rolling in a meander shape, as described by Ref. [4]. Subsequently, the measurement of residual stresses perpendicular to the rolling direction was conducted, as they were found to be significantly higher in compressive stress compared to along the track. The specimen was then unloaded, and a subsequent measurement was taken.

The deep rolling process utilized with a 6 mm diameter ball with pressures of 300 bar and 500 bar. The distance between each track was set at 0.15 mm.

4. Results

4.1 51CrV4

To determine the residual stress beneath the surface layers of the leaf spring, a depth-wise residual stress profile analysis was deemed necessary. This was because leaf springs tend to have decarburization in the surface layers. In order to accomplish this, the surface layers were removed via electropolishing. Fig. 4 displays the residual stress profiles in both perpendicular and longitudinal directions, with an error rate of approximately 7%. It is important to note that the stress induced by shot peening is represented in the perpendicular direction, as with the load stress during peening was applied along the leaf as noted by Ref. [1].

The blue line on the graph represents a combination of Hertzian pressure and decarburization effects. It is anticipated that the maximum compressive residual stresses would occur at a depth of approximately 200 µm. However, due to the presence of decarburization (resulting in reduced hardness), this maximum point is suppressed and instead occurs at a depth of 300 µm where decarburization is no longer present.

The red curve on the graph illustrates the distribution of residual stress along the spring. Post-unloading, the theoretical compressive residual stresses should be significantly higher due to the applied prestress of 1,500 MPa. Notably, the region between 300 µm and 400 µm (indicated by the bold line) is particularly important. Within this range, the residual stress curve becomes relatively flat, indicating that the limit of the residual stress has been reached as observed by Ref. [5]. Similar findings have been reported in other investigations concerning coil springs [6].

In conclusion, it can be deduced that the compressive residual stress limit (σ_{limit}) achievable through mechanical surface treatment is approximately $\sigma_{\text{limit}} = 2/3 \times R_m$.

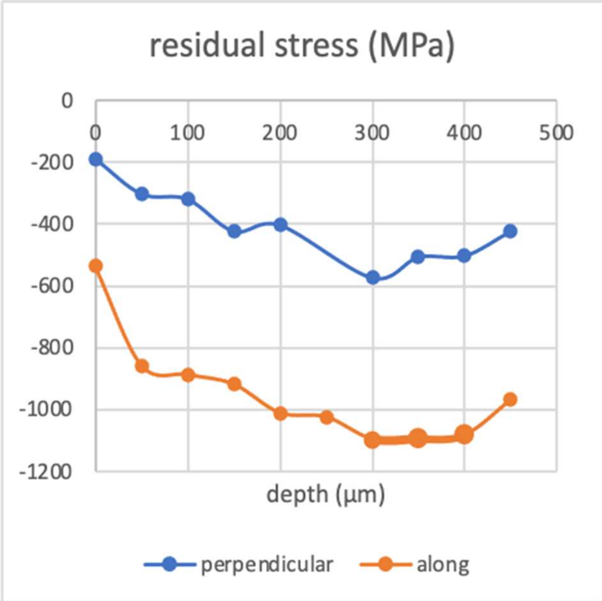

Fig. 4 Residual stress distribution.

4.2 25CrMo4

The stresses presented in Table 2 were obtained from the surface and are pure normal stresses. Any shear stresses were eliminated through calculation.

If the yield strength of 560 MPa is used for comparison, it can be observed that the compressive residual stress after rolling is higher. At a pressure of 500 bar, there is a marked increase in tensile strength due to deep rolling. After unloading, the maximum compressive stress at both areas of deep rolling is the same within the limits of measurement errors. The limit for the inducible residual stress, inclusive of hardness increase, is around -860 MPa, with a possible error margin of +/- 50 MPa. This suggests that the limit of the achievable compressive residual stress has been reached. The theoretical maximum stress calculated using preload is much higher than the observed stress of -860 MPa.

Table 2 Results of the induced compressive residual stresses at 25CrMo4.

Residual stress σ (MPa)			
Pressure (bar)	Loaded after rolling	After unloading	Calculated stress after unloading
300	-595	-849	-975
500	-800	-869	-1,180

Table 3 Summery of the results.

Material	R_m (MPa)	$R_{p0.2}$ (MPa)	Limit σ_{limit} (MPa)	Actual value (MPa)
51CrV4	1,650	1,480	2/3 × R_m	-1,100
25CrMo4	710	560	1.2 × R_m	-860

Thus, it can be concluded that the limit for inducing compressive residual stress is $\sigma_{limit} = 1.2 \times R_m$.

5. Conclusions

This investigation studied the behavior of two different steel grades with varying tensile strengths resulting from different heat treatments. The different heat treatments resulted in two distinct behavioral patterns when inducing compressive residual stresses through mechanical surface treatments. Table 3 provides a summary of the results obtained. In the case of 25CrMo4, an increase in hardness was observed, resulting in a higher maximum inducible compressive residual stress as compared to the tensile strength R_m. Conversely, in the case of spring steel that was quenched and tempered, the limit σ_{limit} was found to be significantly lower than the yield strength. Under the tensile strength R_m, a plastication in the microstructure was observed.

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