Experimental Assessment of the Effects of modified Stress Peening Treatments on Surface Layer States and Fatigue Behavior in Leaf Spring Steel 52CrV4Mo

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Abstract
This paper was derived within the EU-project “LEAFSLIM” and deals with surface states and fatigue behavior of quenched and tempered leaf spring steel 52CrV4Mo after conventional and modified stress peening treatments. An experimental setup for warm peening of specimens pre-stressed in bending was developed. A combination of inductive and continuous flow air stream heating was used in conjunction with a hydraulic load device to achieve reproducible surface layer states. Residual stresses and penetration depths in pre-stress direction reached a maximum (by amount) of approximately -1200 MPa and 0.6 mm, respectively. Warm and double peening did not significantly affect the fatigue behavior in the HCF range. Instead, a dominant influence of surface roughness on fatigue lives was found.

Keywords Modified stress peening, leaf springs, surface layer states, fatigue behavior

Introduction
Stress peening is a modified shot peening process in which mechanical pre-stress of the same direction and sign as the future operational load is applied to the work piece during the surface treatment [1,2]. After relieving the pre-load, the shot peening residual stresses are superposed by the reversed pre-stresses. By this means, residual stress amounts and penetration depths can be enhanced markedly in comparison to the conventional shot peening process, which is favorable e.g. in terms of fatigue behavior. Therefore, stress peening has been vastly applied in the steel spring industry, e.g. for parabolic leaf springs in heavy truck applications [3,4]. Leaf springs are typically made of quenched and tempered steel, such as 51CrV4 or the modified grade 52CrV4Mo. In the final stage before anti-corrosion painting, those springs are typically stress-peened under bending pre-load. For the sake of economic efficiency, the interest in optimizing the stress-peening process has increased during recent years. Besides the determination of optimum pre-stress and shot peening parameters, shot peening variants such as warm [5,6] and (warm) double peening [4,6] may be advantageous additions to stress peening.
Warm peening is a modified shot peening process mostly used on steels, in which the work piece exhibits an elevated temperature [1,2]. The latter usually ranges from 170 °C to 350 °C [5,7] and causes static and dynamic strain ageing effects stabilizing the dislocation structure in the work-hardened surface layer. Thus, more stable residual stress states can be achieved [1,8]. Double peening denotes the successive application of shot peening processes to the work piece with different parameters. Peening with coarse and subsequently with fine shot can favorably be used for surface roughness reduction and is therefore promising for fatigue resistance enhancement [2,4,6]. Therefore, a wide range of combinations of stress, warm and double peening (or more peening steps) is imaginable. However, experimental investigations on such combined treatments are rare. Wick et al. [5,8] investigated the residual stress stability and fatigue behavior in quenched and tempered 42CrMo4 after conventional shot peening, warm peening, stress peening and warm stress peening. Varying the temperature between 20 and 290 °C and the tensional pre-stress between 0 and 500 MPa, they found the largest increase of fatigue resistance after warm stress peening. Compared to conventional shot peening, temperature had the

most pronounced influence on fatigue strength. However, since warm peening is a very energy- and thus cost-expensive process, it is only applicable if used at optimum conditions. Therefore, Tange and Ando [6] investigated a multiple step warm (torsional) stress peening process on helical compression springs made of quenched and tempered Si-alloyed steel SAE5160. Comparing conventional ambient temperature double peening with warm stress single peening and warm stress double peening, they found the best fatigue behavior after warm stress double peening. In this case, shot velocity, temperature and torsional pre-stress were constant throughout both peening steps and chosen to 76 m/s, 300 °C and 735 MPa, respectively. The shot size was reduced from 0.87 mm to 0.2 mm diameter. Using leaf springs, the double stress peening process at ambient temperature has successfully been applied by Scuracchio et al. [4]. Despite those endeavors, warm stress (double) peening has so far not been carried out on leaf springs. The present study was part of the EU-project “LEAFSLIM” and aims at closing this gap. First, a warm stress peening test bench will be presented. Then, surface layer states will be shown for different parameter combinations in terms of residual stress, full width at half maximum (FWHM) and roughness. Finally, the results of 4-point bending fatigue tests will be presented.

Experimental Methods

The low-alloyed spring steel 52CrV4Mo (or 51CrV4AR, a modified grade of 51CrV4) with the chemical composition shown in Table 1 was used for the investigation. Delivered as hot-rolled bars, it was austenitized in a vacuum furnace at 900 °C for 7 minutes, oil quenched to 50-55 °C and subsequently tempered at 430 °C for 90 minutes. By this means, yield and tensile strength of approx. 1500 MPa and 1600 MPa were achieved, respectively.

Table 1. Chemical composition of spring steel 52CrV4Mo.

C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Ti	O	N
0.56	1.00	0.37	0.014	0.003	0.95	0.10	0.087	0.10	0.20	0.025	0.003	0.002	0.011

Bars of the size 740x90x15 mm^3 were used for the stress peening experiments during which they were subjected to 4-point bending as shown in the schematic in Figure 1 (left).

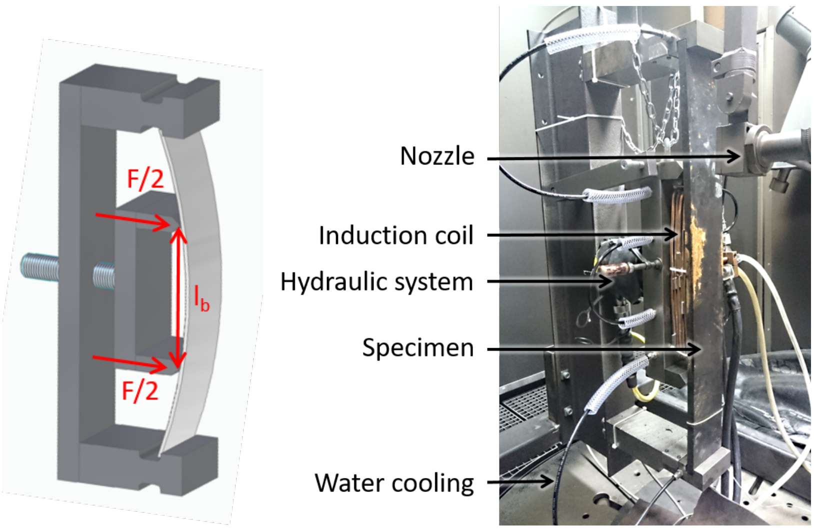

Figure 1. Schematic of 4-point bending stress peening (left) and photograph of realized warm stress peening device (right).

The outer (inner) width between supports was L = 740 mm (l_b = 370 mm). The overall hydraulic force F was limited to 50 kN, corresponding to a maximum bending stress of 1370 MPa. In Figure 1 (right), a photograph of the developed test bench is shown. A Baiker air blast shot peening machine was used. To realize warm peening, the flow heating device first presented in [8] was applied. Due to the large size of the specimens which was chosen to simulate similar stress gradients as compared to leaf springs, an additional inductive heater had to be used to reach the desired temperature of 350°C during the tests. Moreover, a water cooling system was implemented to avoid excessive heating of the stress peening device. In Table 2, the test plan of the applied stress peening campaign is shown. Three bars were shot peened with each parameter set. Almen intensity, pre-stress and temperature were varied. In parameter set P10D, a second peening step was applied (double peening). The latter was carried out using S170 (56 HRC) as shot, an Almen intensity of approx. 0,2 mmA, at room temperature (20°C) and without pre-stress.

Table 2. Parameters for stress peening campaign.

Set	Almen Int.	Shot	Coverage	Surface pre-stress	Temp.	2^{nd} step
P1S	0.22 mmC	S330 (56 HRC)	100%	1370 MPa	20°C	NO
P3S	0.22 mmC	S330 (56 HRC)	100%	685 MPa	20°C	NO
P4S	0.12 mmC	S330 (56 HRC)	100%	1370 MPa	20°C	NO
P6S	0.28 mmC	S330 (56 HRC)	100%	1370 MPa	20°C	NO
P7S	0.22 mmC	S330 (56 HRC)	100%	1370 MPa	290°C	NO
P9S	0.22 mmC	S330 (56 HRC)	100%	1370 MPa	350°C	NO
P10D	0.22 mmC	S330 (56 HRC)	100%	1370 MPa	350°C	YES

Residual stresses were measured using a Stresstech DR45 diffractometer with CrK_α-radiation. A primary collimator with a diameter of 3 mm and a secondary 2D detector were applied, allowing for measurement times of approx. 30 seconds per stress value. Cross correlation with a threshold of 85% and the $\sin^2\psi$-method were used for α-{211} peak position determination and residual stress evaluation, respectively. The elastic coefficients C_{11}, C_{12} and C_{44} (for single crystals) were extracted from the literature [9] and are $C_{11} = 2.3{\cdot}10^5$ MPa, $C_{12} = 1.3{\cdot}10^5$ MPa and $C_{44} = 1.1{\cdot}10^5$ MPa. Residual stress depth profiles parallel and perpendicular to the pre-stress direction with a maximum depth of 0.5 mm were determined by means of electrolytic layer removal.

Roughness was measured by means of a Nanofocus µSurf confocal microscope. An area of 1.5*1.5 mm^2 close to the center of the shot-peened surface was evaluated in each case. The Gaussian cut-off wave length was $\lambda_c = 0.8$ mm.

Due to the large size of the bars subjected to shot peening, direct fatigue testing was not possible. Instead, small 4-point bending specimens (sizing 100x20x5 mm^3) were extracted from the bars by milling and EDM. 12 fatigue specimens could be obtained from each bar, yielding 36 specimens per stress peening parameter set. Fatigue testing was carried out in 4-point bending with the maximum stress in the shot peened surface. The outer (inner) width between supports was L = 80 mm (l_b = 40 mm). The load ratio was 0.1. A servohydraulic testing machine was used at a frequency of 30 Hz and room temperature. Residual stress and roughness values were measured on fatigue specimens. Thus it was assumed that a direct link between fatigue life and surface state could possibly be established.

Experimental Results

In Figure 2 (top), the residual stress depth profiles parallel (left) and perpendicular (right) to the pre-stress direction are shown. The full width at half maximum (FWHM) profiles were determined parallel to the pre-stress direction and are depicted in Figure 2 (bottom, left). Anisotropic residual stress states were obtained by stress peening. Shot peening intensity had the largest influence on residual stress profiles in terms of maximum stress amount and penetration depth. The pre-stress during shot peening had only a minor influence on the residual stress profile and only in terms of penetration depth. Double peening caused markedly decreased residual stresses close to the surface. Due to the limitation of in-depth measurements, only values up to 0.5 mm distance to surface were captured. Therefore, the actual penetration depths of residual stresses can in most cases only be estimated. Regardless of shot peening parameters, FWHM values were decreased in near-surface regions. Again, shot peening intensity was the major influencing factor. An overview of the roughness values measured on the stress-peened surfaces is shown in Figure 2 (bottom, right). It is obvious that the shot peening intensity had the most pronounced effect on roughness, while warm and double peening did not affect the roughness markedly. Very favorable small roughness was obtained by stress peening at room temperature and with low intensity.

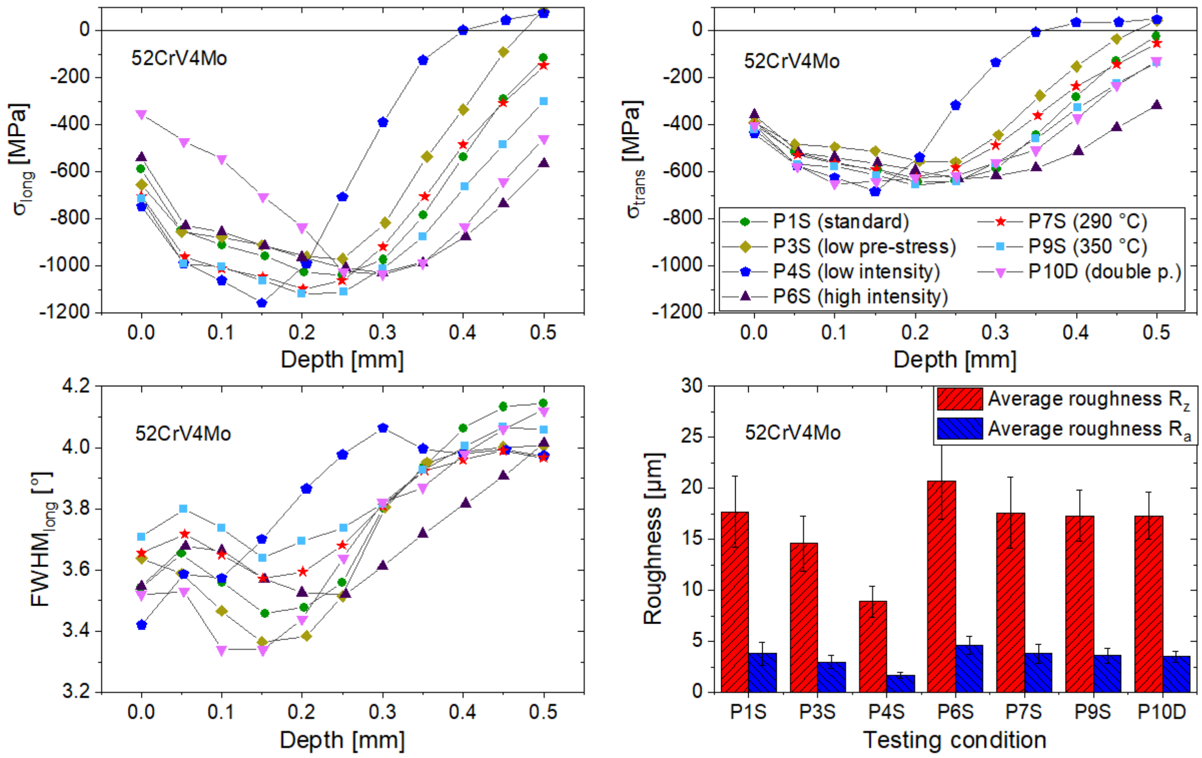

Figure 2. Top: Residual stress profiles; left side: longitudinal measurement (parallel to pre-stress); right side: transverse measurement (perpendicular to pre-stress). Bottom (left side): longitudinal FWHM profiles. Bottom (right side): Surface roughness values.

An overview of the 4P-bending fatigue test results is shown in Figure 3.

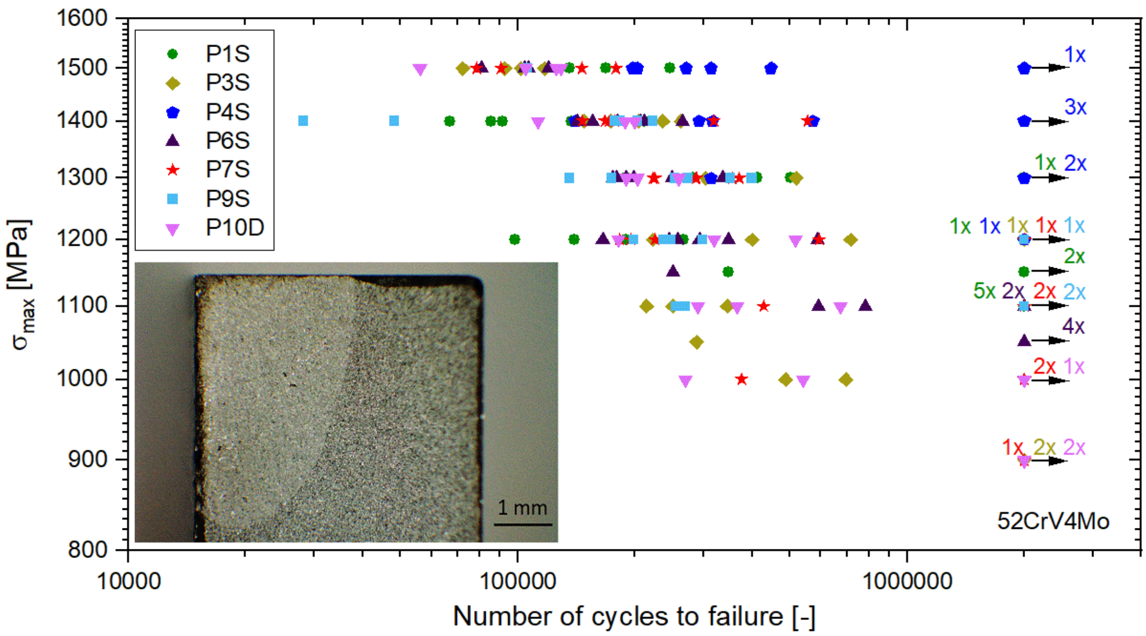

Figure 3. Overview of 4P-bending fatigue test results; edge crack (detail).

Obviously, the fatigue tests were prone to a large degree of scatter and do not allow for meaningful assessment of fatigue lives and limits. Compared to the results derived on the "standard" parameter set, P1S, the only parameter set yielding slightly improved fatigue behavior was P4S, where the shot peening intensity was reduced from 0.22 mmC to 0.12 mmC. While an effect of peening temperature is hardly recognizable, double peening may even have been detrimental to the fatigue behavior.

Discussion and Conclusions

In this study, a test bench allowing for warm stress peening of bars subjected to bending pre-stress was developed. The goal of this study was to assess the effect of modified stress peening treatments on surface states and resulting fatigue behavior on specimens similar to leaf springs. To this end, peening intensity, pre-stress and temperature were varied with reference to "standard" parameters. Moreover, the effects of double peening were investigated, using a second peening step without pre-stress at ambient temperature. Regarding surface states, only the amount of pre-stress, the second peening step and the shot peening intensity markedly affected residual stress and FWHM profiles as well as surface roughness. Different results have been derived in previous experimental studies on warm peening and warm stress peening [5,7,8,10]. Wick et al. [5,8] carried out extensive studies on warm peening, stress peening and warm stress peening of AISI4140. They did not find a significant influence of temperature on residual stresses in studies on stress-free shot peening. Only when pre-stress (tensile; 500 MPa; approx. half of the yield strength) was applied, a marked increase of penetration depth and near-surface residual stress amount was found. In contrast, Schilling-Praetzel et al. [7] and Harada and Mori [10] found increased residual stress penetration depths and slightly reduced amounts of surface residual stress after stress-free warm peening on quenched and tempered spring steels. In each case, surface roughness was increased due to warm peening, which can be explained in terms of decreasing flow stresses at elevated temperatures and thus promoted near-surface plasticity. In contrast, in our study roughness was not markedly affected by the peening temperature. Yet, according to Wick et al. [5], the effect of temperature on roughness might be reduced when shot peening is carried out in the presence of pre-stress [5]. In our study, near-surface FWHM values were decreased regardless of the stress-peening parameters. This is indicative of strain softening and is commonly observed in hardened or quenched and low tempered steels [1]. The affected depth of reduced FWHM values after ambient temperature stress peening can qualitatively be correlated with the resulting roughness values. However, despite comparable residual stress profiles and roughness values, reduction of FWHM values was rather weak after warm peening. Interactions between temperature and pre-stress could prevail and should be investigated in detail in future studies. Regarding double peening, Scuracchio et al. [4] and Tange and Ando [6] found beneficially increased surface residual stresses and roughness values in conventional stress peening and warm stress peening, respectively. Such effects were not identified in this study. Instead, near-surface residual stresses and FWHM values were markedly decreased due to the second shot peening step. The latter was carried out at ambient temperature and without pre-stress. Müller [11] pointed out that a second peening step may only be effective if applied under the same pre-load as the first peening step. In addition, Scuracchio et al. [4] found that the amount of near-surface residual stress could only be increased if the second shot was smaller than the first shot at otherwise same stress peening parameters. In the present study, the second shot was significantly smaller than the first shot and is thus expected to have no marked detrimental effect on residual stresses. Therefore, it can be confirmed that maintaining the pre-stress during the second shot peening step is essential for effective double peening treatments.

Regarding fatigue behavior, the only parameter set clearly leading to enhanced fatigue behavior was P4S (reduced shot peening intensity), which can be attributed to the significantly lower roughness values. Decreasing pre-stress and increasing temperatures, in turn, were detrimental to the fatigue behavior. Any other prevailing effects are obscured by large amount of scatter. With the chosen specimen preparation procedure, the specimen edges were severely weakened, causing fatigue initiation only at specimen edges. An exemplary edge crack, obtained by macroscopy, is shown within Figure 3. Additional scatter might possibly be caused due to process stability issues. Although no systematic investigations on process stability were involved in this study, repetitive residual stress measurements exemplarily carried out on the parameter set P10D (double peening) showed satisfactory reproducibility of residual stress values. The differences were in most cases within the range of the standard deviation.

In contrast to our findings, warm peening, warm stress peening and warm stress double peening generally enhance the fatigue behavior [4-8]. Particularly, warm peening increases residual stress stability and thus fatigue behavior due to static and dynamic strain ageing effects [1,2]. So far, the warm stress double peening process, proposed by Tange and Ando [6], seems to be the most promising stress peening strategy to improve fatigue behavior. However, process parameters have to be selected with care and must be adjusted to the overall material behavior of specimens or actual parts. In this context, Savaidis et al. [3] carried out fatigue and failure analyses on stress-peened leaf springs made of 51CrV4 and found that roughness may cancel out the residual stress effect with regard to final fatigue lives, particularly when the steel grade is prone to decarburization.

In summary, the development of a bending pre-stress device allowed for modified stress peening with pre-stress conditions similar to industrial leaf spring stress peening treatments. The new test bench allows for the implementation of promising shot peening strategies. Yet, the results derived within this study may have become blurred due to the partly unfavorable choice of peening parameters as well as the specimen extraction strategy. In future studies, further stress peening strategies with larger parameter variations should be tried out on specimens directly subjectable to fatigue tests, as long as the overall procedure is justifiable from both academic and industrial point of view.

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References

[1] V. Schulze, *Modern mechanical surface treatment: states, stability, effects,* John Wiley & Sons, 2006.

[2] A. Klumpp, et al., *Mechanical surface treatments,* Proc. ICSP 12 (2014), pp 12-24.

[3] G. Savaidis, et al., *Microstructural, surface and fatigue analysis of stress peened leaf springs*, International Journal of Structural Integrity 6.5 (2015), pp 589-604

[4] B. G. Scuracchio, et al., *Role of residual stresses induced by double peening on fatigue durability of automotive leaf springs*, Materials & Design 47 (2013), pp 672-676.

[5] A. Wick, et al., *Effects of stress- and/or warm peening of AISI 4140 on fatigue life*, Steel research 71.8 (2000), pp 316-321.

[6] A. Tange and K. Ando, *Improvement of spring fatigue strength by new warm stress double shot peening process*, Materials Science and Technology 18.6 (2002), pp 642-648.

[7] M. Schilling-Praetzel, et al., *Influence of temperature of shot peening on fatigue life*, Proc. ICSP 5 (1993), pp 227-238.

[8] A. Wick, et al., *Effects of warm peening on fatigue life and relaxation behaviour of residual stresses in AISI 4140 steel*, Materials Science and Engineering: A 293.1-2 (2000), pp 191-197.

[9] H. Wern. *Single crystal elastic constants and calculated bulk properties: a handbook*. Logos-Verlag, 2004.

[10] Y. Harada and K. Mori, *Effect of processing temperature on warm shot peening of spring steel*, Journal of Materials Processing Technology 162 (2005), pp 498-503.

[11] E. Müller, *Stress Peening—A Sophisticated Way of Normal Shot Peening*, Journal of Materials Science and Engineering A 9.3-4 (2019), pp 56-63.