Effects of Shot Peening on Surface Layer States and Fatigue Behavior in Experimental Batches of Enhanced Leaf Spring Steels

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Abstract
Shot peening under pre-stress ("stress peening") is widely used for the mechanical surface treatment of steel leaf springs in heavy truck applications. In this paper, we present the effects of stress peening, applied to experimental batches of four new leaf spring steels. After an examination by means of chemical analyses, microscopy and dilatometry, quenched and tempered specimens of the experimental steel grades were subjected to single and double shot peening under pre-stress at ambient and elevated temperature. Surface layer states were characterized by means of X-ray analyses of residual stresses and full width at half maximum (FWHM) as well as roughness measurements. The fatigue behavior was evaluated using laboratory scale (small) specimens in alternating bending. The shot peening variants gave rise to comparable results, whereas the most pronounced effect could be attributed to the selected steel grades and their respective heat treatment.

Keywords Stress peening, leaf spring steels, surface layer states, fatigue behavior

Introduction

Stress peening is a shot peening variant applied intensively in the steel spring industry, e.g. for different types of leaf springs in heavy truck suspensions [1-3]. Nowadays, leaf springs are typically made of quenched and tempered Cr-V-alloyed steel, such as 51CrV4, 52CrMoV4 or the intermediate grade 52CrV4Mo. This class of steels offers a combination of favorable processability (hot formability, hardenability, decarburization resistance), price and mechanical behavior (yield strength, toughness, fatigue strength), among others. Within the EU-project "LEAFSLIM", the applications of both modified stress peening treatments and improved steel grades for leaf springs have been assessed. The successful implementation of such measures allows for weight reduction (downsizing), cost savings and enhanced fuel efficiency. To cope with those needs, the main design driver for leaf springs during recent years has been the enhancement of strength without affecting other characteristics such as ductility and toughness [4,5].

Steel grades with higher strength are achievable by optimizing the use of strengthening mechanisms applicable to metallic materials, i.e. solid solution, grain boundary and orientation strengthening, precipitation and dispersion hardening as well as work hardening. Full martensitic hardening and subsequent tempering, the heat treatment virtually always applied to leaf springs prior to setting and shot peening, is based on a combination of those effects. Chemical composition, process chain, hardening and tempering conditions interact in a complex manner (see for instance [6]). In this context, several investigations have recently focused on enhancing service life behavior of the classic leaf spring steel 51CrV4 by different means, such as modification of chemical composition [4], microstructure refinement and removal of inclusions [5], nano-particle alloying [7], enhancement of quenching conditions [8] and application of deep cryogenic treatment [9]. All modifications have in common that their implementation must be feasible on an industrial scale at justifiable costs and that they should not affect processability. Although some beneficial treatments have been identified in the past, relationships are complex and the effects can be equivocal. Particularly, all aforementioned studies did mainly concentrate on mechanical

behavior (tensile, impact, fatigue strength), but none of them took reference to any possible interaction between the new steel grade or treatment and the finishing step, i.e. stress peening [2,3]. However, it would not only be interesting to evaluate the behavior of new steel grades, but also the implications of conventional or modified stress peening routes to their surface characteristics and service life behavior, for instance by means of warm stress peening. Warm peening has proven to produce stable surface layer states and is thus considered a promising, though expensive stress peening variant [1,10].
This study aims at providing deeper understanding of such interactions. Referring to the spring steel 52CrV4Mo, an enhanced version of 51CrV4, two different strategies to achieve leaf spring steels with enhanced strength properties are presented. The first strategy is to optimize the hardening behavior of the Cr-V-type steel by an improved balance of the elements C, Cr, V and Mo. The second strategy makes use of Silicon (Si), which in small additions can largely improve mechanical behavior and has been used for very high strength automotive spring steels such as 55SiCr6. Besides the development of new steel grades, improved stress peening treatments have a high potential to enhance service life behavior, such as fatigue strength. Therefore, the present study also aims at providing surface layer states and fatigue behavior of the modified steels after applying a set of modified stress-peening treatments.

Experimental Methods
The low-alloyed spring steel 52CrV4Mo with the chemical composition design shown in Table 1 was used as reference material for the investigation. Based on this material, three experimental steel grades were created under the following basic conditions:

- Cost-effective alloying elements like Mn and Cr must be maintained over a certain limit to not endanger steel hardenability and ensure a fully martensitic transformation.
- No breakthrough modifications are aimed for regarding the current leaf spring upstream manufacturing route: hot rolling and oil quenching and tempering.

The design and actual chemical composition of the four experimental steel casts are shown in Table 1 and 2, respectively. Silicon (Si) is known to increase the yield strength by solid solution strengthening. Furthermore, it delays the transformation of ε-carbide to cementite. However, the element may also cause a shift of the ductile to brittle transition temperature (DBTT) to higher temperature. Moreover, it causes strong decarburization during heating before hot rolling, why its use has been challenging. Nickel (Ni), combined with chromium (Cr), increases hardenability and both impact strength and fatigue resistance. The carbon content directly affects the achievable hardness. Yet, its content has to be limited due to increasing embrittlement and quench crack susceptibility [6]. Therefore, experimental casts of the reference steel and three new steels were created:

- 52CrV4Mo (heat 810): Reference cast
- 45SiCrVMo6 (heat 819): Addition of Si; reduction of C. Goal: Enhanced tensile strength and retained toughness
- 45SiCrV9Ni (heats 812, 816, 817): Addition of challenging amount of Si; reduction of C and addition of Ni. Goal: Enhanced tensile strength and retained toughness
- 55CrVMo6 (heat 818): Addition of C and Cr. Goal: Enhanced hardenability and tensile strength

Table 1. Designed chemical composition of experimental casts.

Grade	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Ti
52CrV4Mo	0.52	1.00	0.35	0.015	0.005	0.95	0.15	0.10	0.10	0.20	0.020	0.005
45SiCrVMo6	0.45	0.80	1.50	0.015	0.005	1.00	0.15	0.15	0.30	0.20	0.020	0.005
45SiCrV9Ni	0.45	0.80	2.25	0.015	0.005	1.00	0.55	-	0.30	0.20	0.020	0.005
55CrVMo6	0.55	1.00	0.35	0.015	0.005	1.50	0.15	0.20	0.30	0.20	0.020	0.005

Table 2. Measured chemical composition of experimental casts.

Heat No.	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Ti
810	0.49	0.94	0.38	0.013	0.010	1.00	0.15	0.09	0.10	0.20	0.010	0.005
812	0.45	0.81	2.31	0.013	0.009	1.03	0.54	0.01	0.29	0.20	0.018	0.006
816	0.44	0.77	2.34	0.015	0.011	1.01	0.56	0.00	0.30	0.20	0.020	0.004
817	0.44	0.78	2.35	0.014	0.009	1.02	0.56	0.00	0.30	0.20	0.020	0.004
818	0.54	0.92	0.39	0.016	0.010	1.53	0.15	0.20	0.30	0.21	0.021	0.004
819	0.45	0.78	1.56	0.014	0.009	1.01	0.15	0.14	0.29	0.21	0.022	0.004

Specimens of all heats were first austenitizied for 7 minutes in a vacuum oven and oil-quenched in an oil bath at 50-55 ºC. The austenitizing temperatures for 52CrV4Mo, 45SiCrVMo6, 45SiCrV9Ni and 55CrVMo6 were chosen to 850 ºC, 900 ºC, 950 ºC and 850 ºC, respectively. Prior dilatometry experiments were used to determine the A_{c1} and A_{c3} temperatures. After quenching, specimens were tempered for 90 minutes at the following temperatures: 350 ºC, 375 ºC, 400 ºC, 425 ºC and 450 ºC. For each condition, one tensile sample and three Charpy U-type specimens were tested.
For the stress peening experiments, the flat specimen geometry shown in Figure 1 (left) with a gauge width of 18 mm and thickness of 2 mm was used. Specimens were extracted from the experimental cast blocks by means of EDM. The green drawing will be explained later. Shot peening was carried out with a Baiker SKUK air blast shot peening machine, using the apparatus shown in Figure 1 (right) to apply tensile pre-stress. To realize warm peening, the flow heating device first presented in [10] was used. In Table 2, the test plan of the applied stress peening campaign is shown. Besides conventional stress peening (P1S), warm stress peening (P9S) and double peening (P10D) were applied to the experimental casts. The second shot peening step 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.

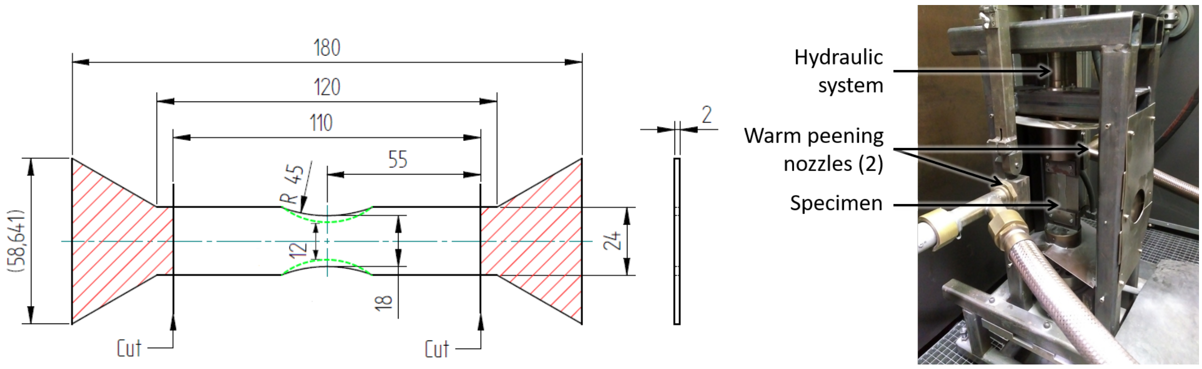

Figure 1. Photograph of tensile warm stress peening device.

Table 3. Parameters for stress peening campaign.

Set	Almen Int.	Shot	Coverage	Tens. pre-stress	Temp.	2^{nd} step
P1S	0.22 mmC	S330 (56 HRC)	100%	1350 MPa	20°C	NO
P9S	0.22 mmC	S330 (56 HRC)	100%	1350 MPa	350°C	NO
P10D	0.22 mmC	S330 (56 HRC)	100%	1350 MPa	350°C	YES

Alternating bending fatigue specimens were extracted from the shot-peened specimens by removing the hatched areas (see Figure 1). Surface states were characterized in terms of residual stress analyses, full width at half maximum values and roughness measurements.
Residual stress measurements were realized with an X-ray diffractometer of the type Stresstech G2R with CrK_{α} radiation, using the $\sin^2\psi$ method. The elastic coefficients C_{11}, C_{12} and C_{44} (for single crystals) were extracted from the literature [11] and are C_{11} = 2.3*10^5 MPa, C_{12} = 1.3*10^5 MPa and C_{44} = 1.1*10^5 MPa. Residual stress profiles with a maximum

depth of 0.5 mm were determined by means of electrolytic layer removal (50 µm steps; circle D 10 mm). Only longitudinal residual stresses (parallel to pre-stress) were measured.
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 λ_c = 0.8 mm.
Fatigue testing was carried out in alternating bending at a load ratio of -1 and room temperature. The frequency was 25 Hz. Due to the required long heating times, warm peening of fatigue specimens were restricted to 45SiCrV9Ni, using heats 816 and 817.

Experimental Results
Figure 2 shows the dependence of ultimate tensile strength (left) and impact toughness (right) for the experimental casts as a function of tempering temperature. In all experimental steel casts, an improvement of properties with regard to the reference material was achieved. The new steel grades also allow for lower tempering temperatures to achieve satisfactory toughness. The best combination of strength and toughness was found on grade 45SiCrV9Ni. All specimens for the stress peening campaign were tempered as shown in Table 4. By this means, minimum values of ultimate tensile strength (UTS), impact energy (KU) and reduction of area (RofA), as shown in Table 4, could be achieved.

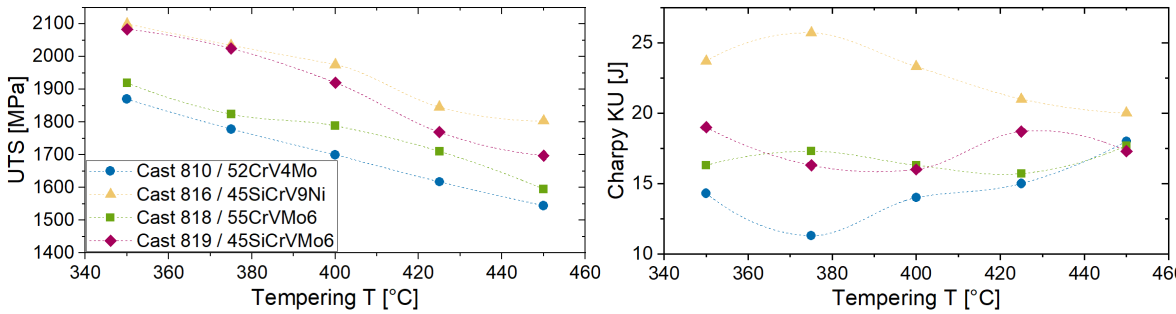

Figure 2. Influence of tempering temperature on ultimate tensile strength (left) and charpy impact toughness (right).

Table 4: Mechanical properties achieved after selected tempering treatment.

Steel grade	52CrV4Mo	45SiCrVMo6	45SiCrV9Ni	55CrVMo6
Tempering T [°C]	425	375	375	375
Min. UTS [MPa]	1600	2000	2000	1800
Min. KU [J]	13.5	15	22.5	13.5
Min. RofA [%]	35	35	40	35

The longitudinal residual stress and full width at half maximum (FWHM) profiles obtained after the different stress-peening treatments are shown in Figure 3. Regardless of the experimental material, the profiles always have a pronounced residual stress maximum with magnitudes up to 2000 MPa beneath the surface. Residual stress penetration depths can be estimated to 0.5~0.6 mm. Warm peening increases the depth of the residual stress maximum. The double peening process, carried out without pre-stress, obviously causes a decrease of the surface residual stresses. After all stress peening treatments, the lowest amounts of residual stress and FWHM can obviously be found on the reference material 52CrV4Mo. The highest amounts of residual stresses and FWHM were found in 45SiCrV9Ni.
Figure 4 shows the roughness values measured on the stress-peened surfaces. All shot peening treatments increase the roughness which was measured to approx. $R_z \approx 11$ µm in the initial state (EDM cut). In the case of 52CrV4Mo and 55CrVMo6, warm peening causes a higher roughness, which could eventually be reduced by double peening. In the case of the steels 45SiCrV9Ni and 45SiCrVMo6, the effects are less clear. Yet, lower overall roughness was found in the Si-containing steels.

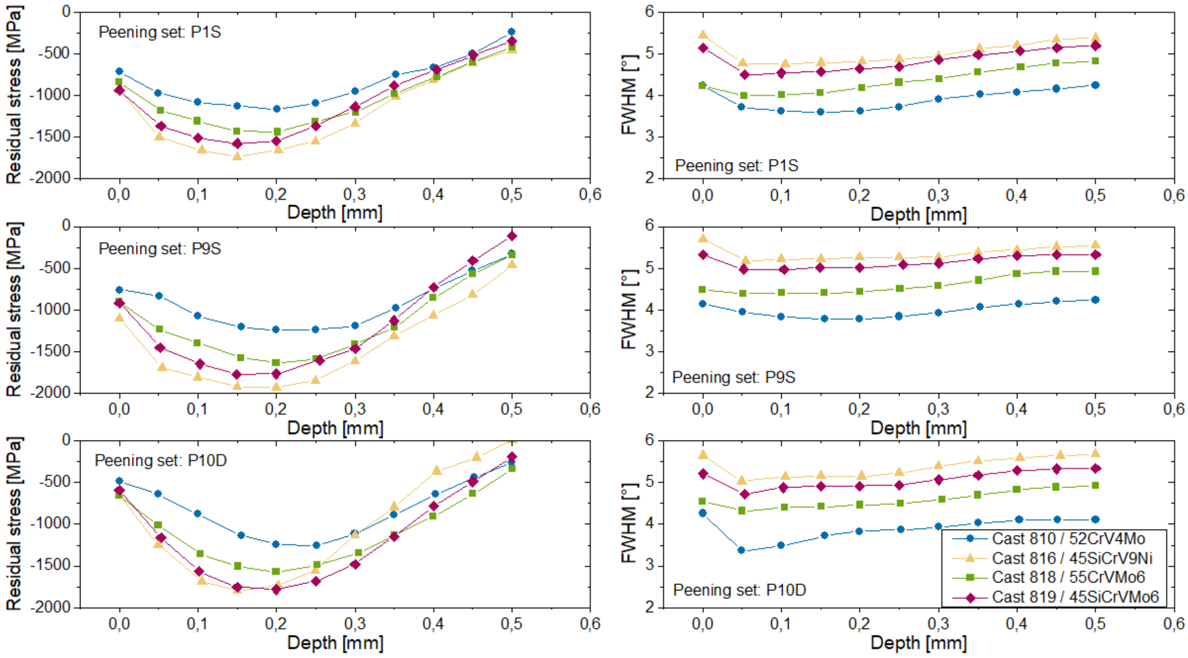

Figure 3. Residual stress (left) and full width at half maximum (FWHM) profiles (right) after different stress peening treatments.

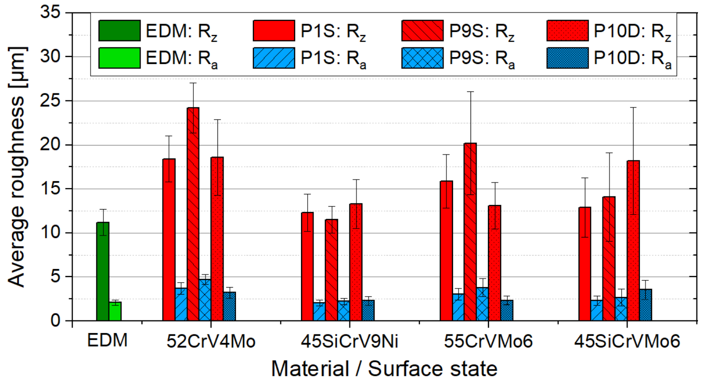

Figure 4: Roughness values after different stress peening treatments.

An overview of the fatigue test results is shown in Figure 5. The tests were commenced with a specimen gauge width of 18 mm. Unfortunately, the bending machines' load maximum was reached with the new steel grades, which is reflected in scatter and a large number of run-outs (Figure 5 (left)). Therefore, the specimen gauge width had to be reduced to 12 mm by means of EDM (drawn in green colour in Fig. 1 (left)). The corresponding fatigue test results are shown in Figure 5 (right) and allow for more interpretation.

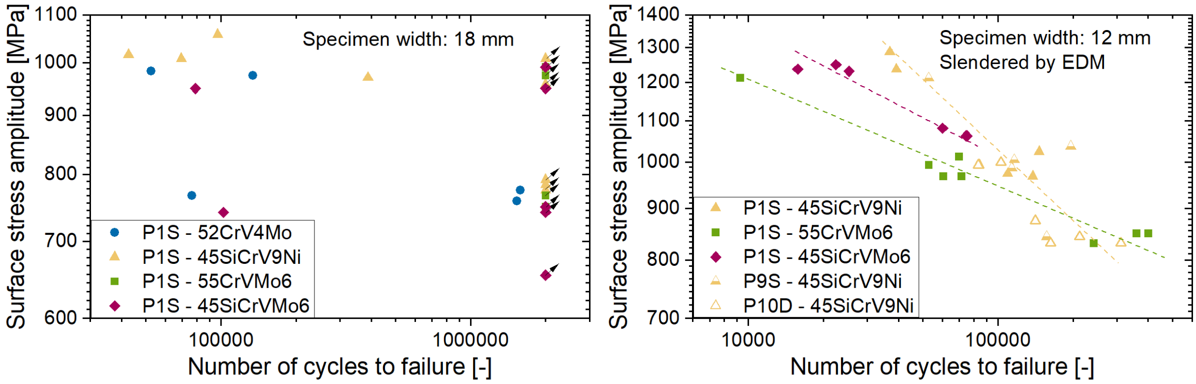

Figure 5. Overview of fatigue test results: Original (left) and slendered specimens (right).

Discussion and Conclusions

Three promising new steel grades have been developed within this study. Particularly the Si-containing grades offer extreme strength at high toughness. The steel grade 45SiCrV9Ni initially has a 25% higher tensile strength than the reference 52CrV4Mo steel. After the standard stress-peening process (P1S) the maximum compressive residual stresses become even ~50% higher as compared to 52CrV4Mo. When comparing both warm peening processes (P9S), the difference is even bigger, improving 45SiCrV9Ni up to a 55% over 52CrV4Mo. The increase in compressive residual stresses from the reference steel and stress-peening process to the warm peening and 45SiCrV9Ni reaches >65%. This growth partially corresponds to its higher strength (~25%), partially to the warm peening process (~10%) and, remarkably, to synergetic effects probably linked to the highest deformability of the 45SiCrV9Ni grade. Obviously, a direct qualitative correlation between fatigue life and residual stresses exists. An advantageous combination of higher residual stresses and lower roughness was found for the steel grades containing Si. However, for the case of 45SiCrV9Ni, no marked difference regarding the different stress peening strategies was identified in terms of fatigue life. Particularly, no beneficial effect of double peening (P10D), as identified by Scuracchio et al. [2], was found. Obviously, the second peening step is not effective and rather detrimental if carried out without pre-stress. Despite the outstanding mechanical behavior, the application of new steel grades requires a thorough analysis of the overall properties. For instance, the decarburization of Si-containing steels within this study could only be limited by means of inductive heating. This is confirmed by the study of Podgornik et al. [4], who discovered a 50% increase in fracture toughness after adding 1,6% Si, while larger contents caused marked decarburization. In summary, promising steel grades and shot peening strategies were identified, though the optimum strategy has still to be identified. In future studies, stress peening parameters such as the ratio of pre-stresses in the first and second shot peening step should be varied more markedly.

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