Influence of Optimized Warm Peening on Residual Stress Stability and Fatigue Strength of AISI 4140 in Different Material States

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1 Abstract

Using a modified air blasting machine warm peening at 20 °C $\leq T \leq$ 410 °C was feasible. An optimized peening temperature of about 310 °C was identified for a 450 °C quenched and tempered steel AISI 4140. Warm peening was also investigated for a normalized, a 650 °C quenched and tempered, and a martensitically hardened material state. The quasi static surface compressive yield strengths as well as the cyclic surface yield strengths were determined from residual stress relaxation tests conducted at different stress amplitudes and numbers of loading cycles. Dynamic and static strain aging effects acting during and after warm peening clearly increased the residual stress stability and the alternating bending strength for all material states.

2 Introduction

Shot peening is widely used as a mechanical surface treatment for many components such as crankshafts, gears, springs etc. Many studies deal with optimizing peening parameters, but the increases of fatigue life and strength obtained by conventional shot peening are limited [1]. This led to modifying the shot peening process. A possibility is stress peening with tensile pre-loads applied during shot peening [2,3]. However, the superposition of high values of residual stresses with loading stresses can lead to an early residual stress relaxation as soon as the respective yield strength is reached during quasi static and/or cyclic loading [4]. Therefore, in recent years, shot peening at elevated temperatures was investigated [5-10]. It was found that dynamic and static strain aging effects during and after shot peening can stabilize the dislocation structure and therefore contribute to a higher stability of the induced residual stresses. A procedure to evaluate the stability of residual stresses under quasi static loading and to estimate the surface compressive yield strength $R_{\mathrm{e(c),s}}$ after shot peening is given in [6] using

$$\left|R_{e(c),s}\right| = \sqrt{(\sigma_s^{rs})^2 + \sigma_s^{rs}\sigma_{s,crit}^* + (\sigma_{s,crit}^*)^2} \tag{1}$$

with the initial residual stress value at the surface σ_s^{rs} and the critical stress $\sigma_{s,crit}^*$, which initiates the onset of residual stress relaxation in compression. A measure of the cyclic yield strength at the surface $R_{e,s}^{cycl}$ after shot peening can be calculated using the modified Eq. (1)

$$\left|R_{e,s}^{cycl}\right| = \sqrt{(\sigma_{s,N=1}^{rs})^2 + \left|\sigma_{s,N=1}^{rs}\right|\sigma_{a,crit}^* + (\sigma_{a,crit}^*)^2} \tag{2}$$

with the critical loading stress amplitude $\sigma^{*}_{s,crit}$ and the corresponding surface residual stress values remaining after the first cycle at the same quasi static load, $\sigma^{rs}_{s,N=1}$ [4,6].

3 Material and Specimen Geometry

Investigations were carried out on steel samples of AISI 4140 (German grade 42 CrMo 4) with the chemical composition 0.42 C, 1.04 Cr, 0.14 Mo, 0.21 Si, 0.71 Mn, 0.01 P, 0.02 Al and balance Fe (all in wt. %). The bending samples were machined from flat material by sawing and milling, and ground to a thickness of 2.2 mm. Details about size and manufacturing can be found in [6]. Afterwards, they were heat treated into normalized (930 °C, 3h), quenched and tempered as well as martensitically hardened material states. Martensitic hardening in oil was done after austenitization at 850 °C for 20 min. Subsequent tempering was conducted at 450 °C (T450) and 650 °C (T650) for 2 h, respectively. In order to eliminate distortions, the specimens were finally ground to a thickness of 2.0 mm. Table 1 shows the yield strength, the UTS and the hardness for the different material states.

Table 1: Yield strength and hardness of the different material states

material state	yield strength [MPa]	UTS [MPa]	hardness [HV0.3]
normalized	400	740	230
T650	700	940	300
T450	1200	1375	430
hardened	1500	2400	660

4 Experimental Approach

An air blast machine was used to perform the shot peening treatments. Using an upgraded air flow heater system warm peening at $20\ °C \leq T \leq 410\ °C$ was feasible [11]. Cast iron shot S 170 with hardness 56 HRC was used at a peening pressure of 1.2 bar and a media flow rate of 1.0 kg/min. Further details are given in [11]. Residual stresses in the longitudinal direction of the specimens were determined using the X-ray technique. The {211}-interference lines of the ferritic phase were analyzed according to the $\sin^2\psi$- method [12]. The depth distributions of the residual stresses were determined by iterative electrolytic removal of thin surface layers and subsequent X-ray measurements. Residual stress values measured at the surface after material removal were corrected according to the method of [13]. The half width values as a measure of microstructural work hardening were determined as an average of those measured at $\psi = -15°$, 0° and +15°. For each S-N curve 25 to 30 specimens were used to determine the alternating bending strength R_{ab}. The failure probabilities were evaluated according to the arcsin $\sqrt{P}$-method [14]. Tests to determine the stability of the surface residual stresses by alternating bending at a fixed initial stress amplitude were performed for different stress amplitudes. For each stress amplitude exactly one specimen was used. At predefined numbers of cycles the tests were interrupted, the surface residual stress values were measured at both sides, averaged and then the tests were restarted.

5 Results and Discussion

The influence of shot peening temperatures 20 °C $\leq T_{\text{peen}} \leq$ 410 °C on the formation of half width and residual stress values at the surface of AISI 4140 quenched and tempered at 450 °C is shown in Fig 1. The initial half width value of the conventionally peened sample (T_{peen} = 20 °C) of about 3.3° 2θ in Fig. 1a is slightly increased to about 3.45 °2_ by peening at T_{peen} = 290 °C. Further increases of the peening temperature lead to a continuous decrease of this value. The variant peened at 20 °C shows a strong reduction of the half width with increasing numbers of cycles after applying an alternating bending load of $\sigma^*_{a,s}$ = 1000 MPa. The half widths of the variants peened at elevated temperatures (T ≤ 290 °C) remain stable if the fluctuations typical for half width determination are considered. The results of the shot peening induced surface compressive residual stresses for 20 °C $\leq T_{\text{peen}} \leq$ 410 °C are shown in Fig. 1b. The initial values (N = 0), each averaged from at least 5 samples measured on both sides, show a slight maximum at peening temperatures of 310 °C and 330 °C. It is conceivable that at those temperatures the speed of diffusing carbon atoms equals the velocity of moving dislocations, which is the basis for profound dynamic strain aging. Through this a very diffuse dislocation structure with a high dislocation density is created. At even higher temperatures thermally induced dislocation movement leads to rearrangement and annihilation of dislocations, resulting in a micro stress relaxation and again decreased compressive residual stresses. For T_{peen} = 310 °C and 330 °C a strongly reduced decrease of residual stress relaxation was found when loaded at alternating bending with $\sigma^*_{a,s}$ = 1000 MPa. Residual stress and half width depth distributions for variants quenched and tempered at 450 °C and shot peened at different temperatures, including T_{peen} = 310 °C and 330 °C, can be seen in [11]. No difference in the half width depth distributions of the warm peened samples can be found. There is a strong work hardening in the surface zone for all elevated peening temperatures. For $T_{\text{peen}} \geq$ 300 °C it was necessary to increase the hot air flow p_{hot} which was used to heat up the samples and to hold the appropriate peening temperature from 1.2 bar to 2.0 bar [11]. This was done without changing the actual peening pressure. This did not affect the surface residual stresses but slightly increased the penetration depth of the compressive residual stresses [11].

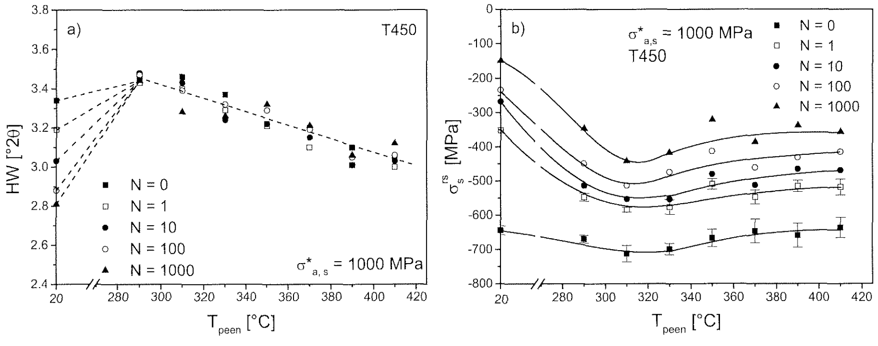

Figure 1: Half widths (a) and residual stresses (b) vs. peening temperature after different numbers of cycles

To investigate the residual stress stability after T_{peen} = 310 °C under quasi static and dynamic loading, alternating bending tests were carried out under variation of the applied stress amplitude and of the numbers of cycles after which the remaining residual stresses were determined. This is shown in Fig. 2, additionally, results of [6] for T_{peen} = 290 °C are given. The critical load for quasi static residual stress relaxation $\sigma^*_{s,crit}$ is increased from 500 MPa to 560 MPa. The surface compressive yield strengths Re(c),s calculated using Eq. 1 and the method of [4] are summarized in Table 2. Furthermore results of [6] for samples peened at T_{peen} = 20 °C and 290 °C are given. The ratio of the compressive yield strengths $R_{\mathrm{e(c),s}}$ after shot peening and the value of the core region Re [4] is also given. It can be seen that $R_{\mathrm{e(c),s}}/R_{\mathrm{e}}$ is < 1 for all variants.

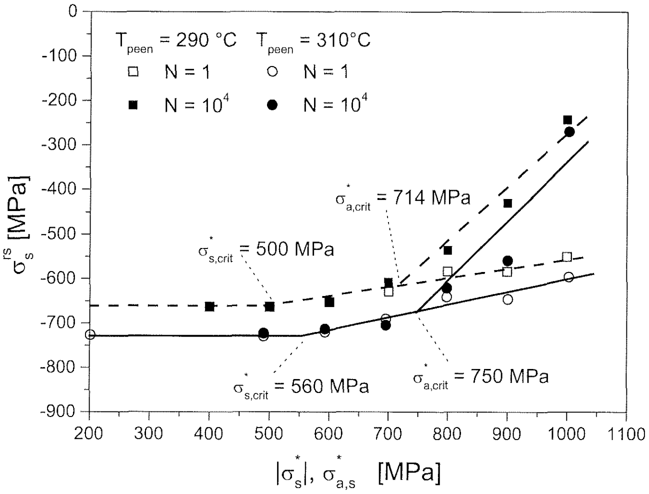

Figure 2: Residual stresses vs. loading stresses or stress amplitudes for samples peened at T_{peen} = 290 °C and 310°C

Table 2: Quasi static surface compressive yield strength for 450 °C quenched and tempered AISI 4140 after conventional peening and warm peening

material state	T_{peen} [°C]	$\sigma^*_{s,crit}$ [MPa]	σ^{rs}_s [MPa]	$\lvert R_{\mathrm{e(c),s}}\rvert$ [MPa]	$R_{\mathrm{e(c),s}}/R_{\mathrm{e}}$
T450	20	-310	-600	801	0.60
	290	-500	-660	1008	0.78
	310	-560	-700	1186	0.91

Table 3: Cyclic surface yield strength for 450 °C quenched and tempered AISI 4140 after conventional peening and warm peening

material state	T_{peen} [°C]	$\sigma^*_{s,crit}$ [MPa]	$\sigma^{rs}_{s,N=1}$ [MPa]	$R^{cycl}_{e,s}$ [MPa]	$R^{cycl}_{e,s}/R^{cycl}_{e}$
T450	20	514	-520	895	0.82
	290	714	-620	1156	1.07
	310	750	-675	1235	1.14

This work softening of the shot peened surface is a consequence of the Bauschinger effect, which is caused by the reversed deformation (compression) compared with the deformation during the peening process (tensile deformation). This effect can be relatively pronounced in quenched and tempered steels and is obviously reduced due to warm peening, especially due to optimized warm peening at T_{peen} = 310 °C. The dislocations are locked through diffusion of carbon atoms preferred to edge dislocations and the formation of very small carbides. Dislocation movement is retarded and the residual stresses are stabilized. The loading stress amplitude initiating stress relaxation $\sigma^*_{s,crit}$ at cyclic loading is also indicated in Fig. 2. Table 3 summarizes all values necessary to calculate the cyclic yield strengths at the surface after shot peening. Additionally, the ratios of those cyclic yield strengths and the values of the core region are listed. Latter were taken from [15]. The conventionally peened variant shows a work softening at the surface compared to the core region (Tab. 2, $R_{e,s}^{cycl} / R_e^{cycl} = 0.82$). Warm peening even causes a work hardening at the surface with ratios of 1.07 and 1.14 for T_{peen} = 290 °C and 310 °C, respectively. This is due to the stabilized dislocation structure caused by dynamic and static strain aging during warm peening and during cooling, respectively. In Fig. 3 S-N curves for variants shot peened at different temperatures are compared with the one of the ground state [6]. The values given are valid for a failure probability of P = 50 %. The alternating bending strength of the ground state R_{ab} = 443 MPa [6] is increased by optimized shot peening at T_{peen} = 310 °C and T_{peen} = 330 °C up to 704 MPa (+59 %).

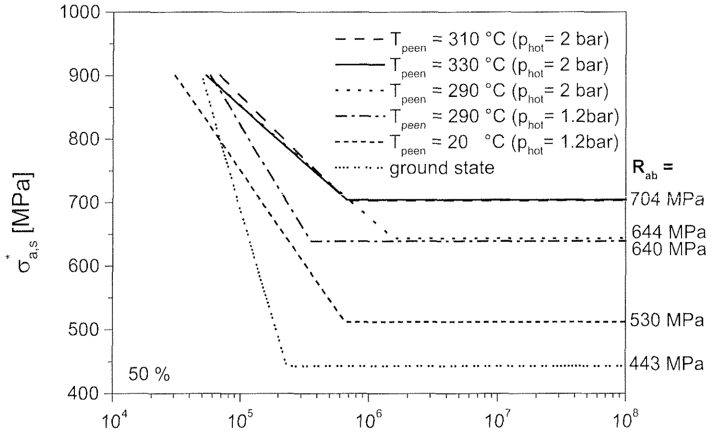

Figure 3: S-N curves for differently shot peened variants in comparison with the ground material state

According to the procedure described before, the com-pressive yield strengths and the cyclic yield strengths were also calculated for different material states which were all peened at T_{peen} = 290 °C. Detailed results as well as depth distributions can be found in [16]. Fig 4 shows a summariy of the surface yield strengths found in quasi static and cyclic loading (Fig. 4a) and of the alternating bending strengths found for the ground, shot peened and warm peened condition (Fig. 4b) spread over the Vickers hardness. Note that warm peening of the martensitically hardened material state causes a reduction in hardness from 660 HV to 560 HV. The yield strengths of the shot peened states (Fig. 4a) point out firstly that there is an increase with increasing hardness, and secondly that warm peening generally increases the quasi static as well as the cyclic yield strengths of the different material states, compared with conventional peening. Only the T450 shows clear differences between its quasi static and cyclic yield strength found for the same peening temperature. The alternating bending strengths at a failure probability of $P = 50$ % (Fig. 4b) show that warm peening leads to increases for all material states, compared with conventional shot peening. This is caused by the higher stability of the dislocation structure and residual stresses caused by dynamic and static strain aging.

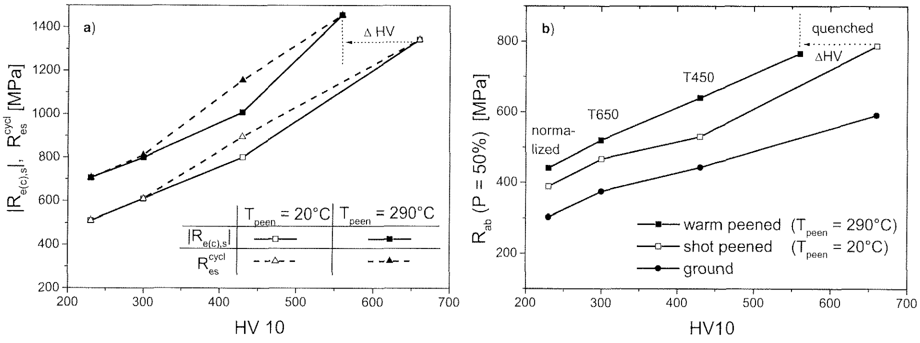

Figure 4: Compressive yield strengths, cyclic yield strengths (a) and the alternating bending strengths (b) after different peening procedures vs. the material state

5 Summary and Conclusion

A modified air blast shot peening machine with an upgraded air flow heater system was used to conduct warm peening at $20\ ^\circ\mathrm{C} \le T_{\mathrm{peen}} \le 410\ ^\circ\mathrm{C}$. Optimized peening temperatures for a material state quenched and tempered at 450 °C were identified to be between $T_{\mathrm{peen}} = 310$ °C and 330 °C. The influence of different shot peening temperatures on the stability of residual stresses at alternating bending was investigated for AISI 4140 in different material states. Compressive yield strengths $|R_{e(c),s}|$ as well as cyclic yield strengths $R_{e,s}^{cycl}$ found after shot peening and warm peening were determined and compared. Warm peening led to increases of $|R_{e(c),s}|$ and $R_{e,s}^{cycl}$. Alternating bending strengths found after warm peening were increased for all material states compared with those found after conventional peening. This is caused by pinning of dislocations by carbon atom clouds and the creation of very small carbides leading to a highly stabilized dislocation structure with a beneficial effect to the residual stress stability.

6 References

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