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Residual Stress Relaxation and Fatigue Strength of AISI 4140 under Torsional Loading after Conventional Shot Peening, Stress Peening and Warm Peening

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1 Abstract

Cylindrical rods of 450°C quenched and tempered AISI 4140 were conventionally shot peened, stress peened and warm peened while rotating in the peening device. Warm peening at T_{peen} = 310°C was conducted using a modified air blast shot peening machine with an electric air flow heater system. To perform stress peening using a torsional pre-stress, a device was conceived which allowed rotating pre-stressed samples without having material of the pre-loading gadget between the shot and the samples. Thus, same peening conditions for all peening procedures were ensured. The residual stress distributions present after the different peening procedures were evaluated and compared with results obtained after peening of flat material of the same steel. The differently peened samples were subjected to torsional pulsating stresses ($R = 0$) at different loadings to investigate their residual stress relaxation behavior. Additionally, the pulsating torsional strengths for the differently peened samples were determined.

2 Introduction

Shot peening is widely used to improve fatigue limit and fatigue life of parts and components, e.g. springs, which are subjected to cyclic loading. This is done by well directed induction of compressive residual stresses and work hardening of the near surface regions. Besides amount and penetration depth of the compressive residual stresses their stability is of high importance. In case of conventional shot peening there are many investigations dealing with optimization of the peening parameters to improve the surface characteristics and their impact on fatigue strength. However, there are far less systematic investigations of modified shot peening treatments like stress peening and warm peening. Stress peening is used to induce higher compressive residual stresses into the surface regions. This is done by applying a tensile, bending or torsional load during the shot peening process. At this, the pre-stressing has to act into the same direction as the following operating loads. Warm peening, though, can be described as conventional shot peening conducted at elevated temperatures, usually between 170–350 °C [1–5]. This enables strain aging effects, which are known to increase work hardening rates and UTS and reduce the ductility in this temperature regime [6]. This can lead to increases of fatigue life and limit under stress controlled loading. The present paper deals with surface characteristics, residual stress stability and fatigue strength of cylindrical rod shaped samples of AISI 4140 after conventional shot peening, stress peening and warm peening. Comparisons will be drawn to flat bending samples of the same steel and the same material state.

3 Material, Specimen Geometry and Experimental Approach

The investigations were carried out using samples of the steel AISI 4140 with the chemical composition 0.44 C, 1.21 Cr, 0.22 Mo, 0.28 Si, 0.81 Mn, 0.07 Ni, 0.02 P, 0.03 Al, 0.02 S and balanced by Fe (all in wt.-%). The cylindrical rods with a diameter of 5 mm were delivered in 3 m long rods and cut down to pieces of 120 mm length. Then they were austenitized for 20 min at 850 °C, martensitically hardened in oil (25 °C), tempered at 450 °C for 2 hours and cooled down in a vacuum furnace.

The shot peening treatments were performed using a modified air blast machine, which allowed peening at 20 °C $\leq T_{\text{peen}} \leq$ 410 °C. Details of the warm peening procedure can be found in [1, 5]. In this presentation warm peening was conducted at 310 °C, which was found to be an optimized peening temperature for quenched and tempered AISI 4140 subjected to alternating bending [5]. Cast iron shot S 170 with a hardness of 56 HRC was used at a peening pressure of 1.2 bar with a media flow rate of 1.0 kg/min. The Almen intensity was 0.25–0.27 mmA leading to a full coverage of the sample surface. For peening the device in Fig. 1 was used.

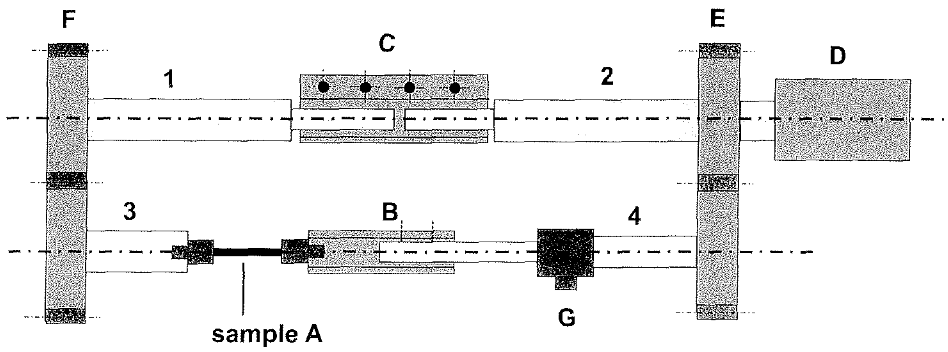

Figure 1: Device for shot peening, warm peening and stress peening of cylindrical rod shaped samples

Conventional and warm peening was conducted by mounting a sample (A) with collet chucks, closing the mechanical clutches (B) and (C) and using the geared motor (D) to rotate the shafts (1–4), which were connected by pairs of toothed wheels (E, F). Applying a torsional pre-load was done by mounting a sample, closing clutch (B) and locking shaft (1). Using a special device it was now possible to twist shaft (2), which applied a torsional pre-stress on sample (A). The pre-stress was controlled using a load cell (G). After reaching the appropriate torsional load the clutch (C) was closed and the pre-stressed system could be rotated with the gear motor (D). Peening was done by using one nozzle with a pendulum motion along the sample axis. The revolution speed of the samples was 125 rpm. The shot peened rods were cyclically tested under pulsating torsional stresses with a stress ratio $R = 0$ and a frequency of 20 Hz. This was done using torsional testing stands driven by servomotors [7]. The so-called step procedure [8] was used to determine the fatigue limit using 20 samples for each condition.

Residual stresses in the 0°, 45° and 90°-direction of the specimen axis were determined using the X-ray technique. Measuring in those three directions allowed to calculate the surface parallel residual stress tensor, whose principle axis after stress peening and torsional loading are at 45° and 135°. The {211}-interference lines of the ferritic phase were analyzed according to the $\sin^2\psi$ method [9]. 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 [10]. The half width values were determined as an average of those measured at $\psi = -15°$, $0°$ and $+15°$.

4 Results and Discussion

Residual stress and half width depth distributions of cylindrical rod samples after conventional peening, stress peening ($\tau_{pre}/\tau_{po,2} = 0.51$) and warm peening can be seen in Fig. 2.

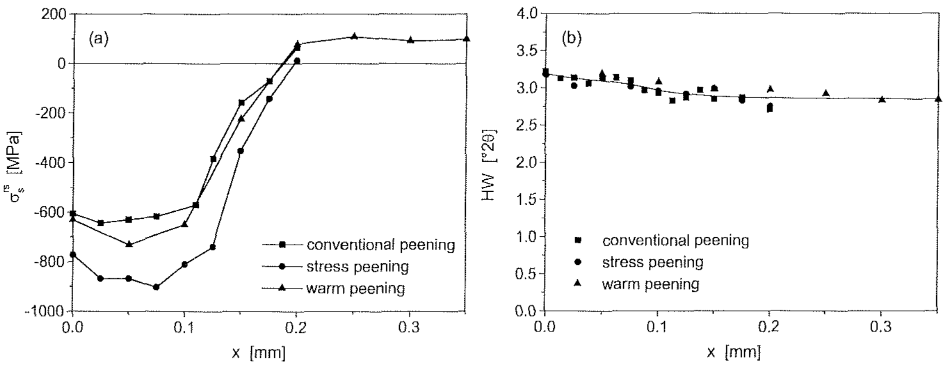

Figure 2: Residual stress (a) and half width (b) depth distributions after different peening procedures

The residual stress distribution after conventional shot peening is similar to the distribution found for flat bending samples [1]. The surface value is about –600 MPa. During stress peening principle stresses are evoked under 45° to the rod axis. This is the direction in which after shot peening clearly increased compressive residual stress values with a maximum of about –860 MPa are found. The depth where the residual stresses change their sign is slightly increased by stress peening. Warm peening yields compressive residual stresses at the surface similar to conventional shot peening. However, at the plateau under the surface the residual stresses are slightly increased. All in all the residual stress depth distributions are comparable with the ones found for flat bending samples [1]. The half width values at the surface region are increased by shot peening. However, warm peening does not lead to further increases, like it was found for flat samples [1, 5].

Fig. 3 shows the pre-stress influence on characteristic values of the residual stress state. The residual stresses found at 45° and 135° as well as the penetration depth of the compressive residual stresses are spread over the ratio of torsional pre-stress and torsional yield strength. In 45° direction the residual stresses are increasing slightly with increasing stress ratio. The residual stress relaxation found in 135°-direction, however, is more pronounced. The depth where the residual stresses change their sign is increasing with increasing pre-stress.

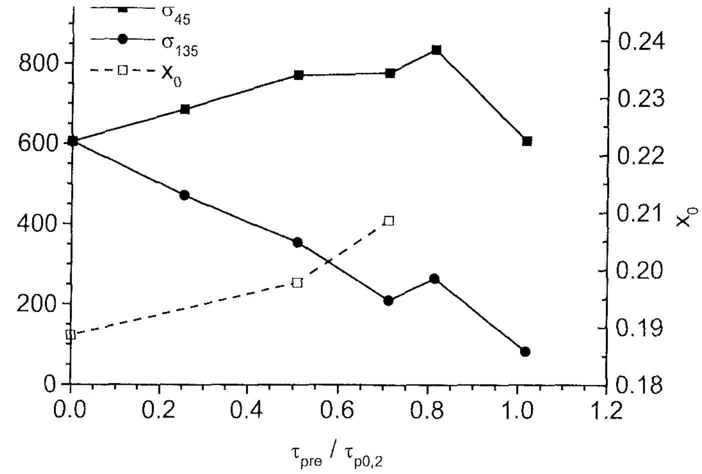

Figure 3: Residual stresses in 45° and 135°-direction after stress peening as well as the penetration depth of the compressive residual stresses spread over the ratio of pre-stress and torsional yield strength

Fig. 4 shows the residual stress relaxation of shot peened, stress peened ($\tau_{pre}/\tau_{po,2} = 0.51$) and warm peened samples which were subjected to pulsating fictitious torsional stresses of $\tau^{*}_{a,s} = 400$ MPa. The 45°-direction is the direction in which tensile pre-stresses act during stress peening and tensile loading stresses during pulsating loading. In 135°-direction, there are compressive pre-stresses during stress peening and compressive loading stresses during pulsating loading. Fig. 4a shows that there is an obvious quasi static residual stress relaxation ($N = 1$) for the conventionally peened sample. This relaxation continues with increasing number of cycles and leads to remaining compressive residual stresses of less than 100 MPa. The stress peened sample, though, which yields smaller compressive residual stresses in this direction shows hard-

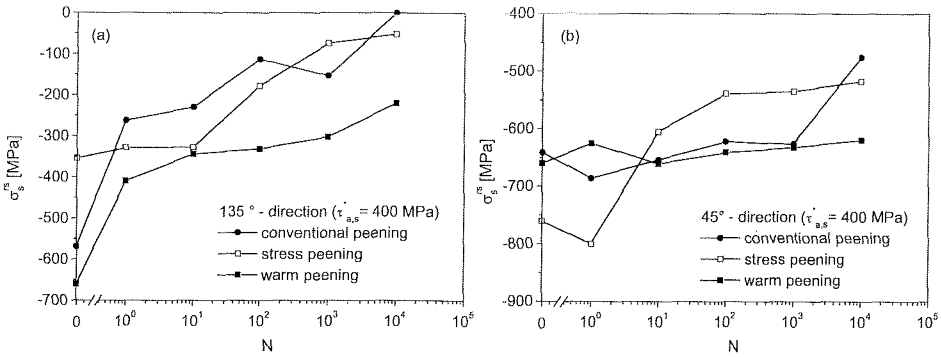

Figure 4: Residual stress relaxation in 135°-direction (a) and 45°-direction (b) due to pulsating loading stresses of $\tau^{*}_{a,s} = 400$ MPa after shot peening, stress peening and warm peening

ly any residual stress relaxation during the first loading cycles, but strong relaxation between $10 \leq N \leq 10^4$ leading to complete residual stress relaxation. The compressive residual stresses of the warm peened sample are clearly reduced during the first loading cycle like seen for the conventionally peened state, but further residual stress relaxation during cyclic loading is diminished, so that highest compressive residual stresses remain. In 45°-direction, almost no changes of the residual stresses are found for the conventionally and the warm peened sample up to $N = 10^3$. However, the stress peened sample shows a strong residual stress reduction within the first 10 cycles. This leads to smaller remaining compressive residual stresses, even though the initial stress state in this direction was clearly higher than for the other peening procedures.

This investigation shows that residual stresses obtained through stress peening are strongly diminished if sufficiently high loading stresses are applied. Therefore, the residual stress values after high numbers of cycles are in the same region (135°) or even below (45°) the values found after conventional shot peening. However, warm peening leads to increases in residual stress stability. This is caused by dynamic and static strain aging effect acting during and after the warm peening process. Those effects result in a diffuse dislocation structure, which is stabilized by carbon atoms through the formation of so-called Cottrell-clouds and very small carbides. Similar results were found for differently shot peened flat bending samples [1], where stress peening caused high residual stress values but small resistance against residual stress relaxation. However, warm peening caused clearly improved residual stress stability. Optimized peening temperatures of about 310 °C were found for the bending samples [5].

Cyclic torsional tests with pulsating loads were conducted to determine the pulsating torsional strength of the differently peened variants. The torsional strength of the only quenched and tempered material state of 285 MPa is increased by conventional shot peening up to 400 MPa. Stress peening, however, using a pre-stress of 408 MPa ($\tau_{pre}/\tau_{po,2} = 0{,}51$) does not lead to further improvements of the pulsating torsional strength. One reason for this is the high amount of residual stress relaxation seen in Fig. 4. However, it is presumed that for harder material states, where residual stress relaxation does not play such an important role with respect to improvements of the fatigue limit, stress peening should be appropriate to increase the torsional strength. Another reason why no improvements were found in this case could be the increased thickness of the rod shaped samples (5 mm) compared with the thickness of the bending samples (2 mm) which are pulled up for comparison. This leads to a reduction of the stress gradient and could stimulate subsurface cracks. Surprisingly, also warm peening did not improve the pulsating torsional strength, despite improvements of the residual stress stability. It is possible that again the reduced stress gradient in case of the cylindrical rod shaped samples caused subsurface cracks. This, however, must not be generalized as e.g. results of [4] show, where warm peening led to increases of the torsional strength. In case of flat AISI 4140 bending samples, optimized warm peening even led to increases of the alternating bending strength of 59 % compared to the ground state [5].

5 Conclusion

Residual stress and work hardening state, residual stress stability and fatigue limit of quenched and tempered cylindrical rods of AISI 4140 were investigated after conventional shot peening, stress peening and warm peening. The results were compared with results of flat alternating bending samples of the same steel after the same peening procedures were conducted. Conventional shot peening and warm peening yield same surface compressive residual stresses of about –600 MPa. Warm peening slightly shifted the subsurface plateau of the conventionally peened sample to higher compressive residual stresses, whereas the penetration depth of the compressive residual stresses did not change for those two peening procedures. After stress peening increased compressive residual stresses (about –800 MPa) were found in the previously prestressed ($\tau_{pre}/\tau_{po,2} = 0.51$) direction and the penetration depth was slightly increased. The same amount of work hardening at the surface was found for the different shot peening procedures. Stress peening caused higher residual stresses in the direction which was tensile pre-stresses during the peening procedure and lower residual stresses in the direction which was compressed during the peening. This effect was more pronounced for higher pre-stresses. The penetration depth of the compressive residual stresses was increased with increasing pre-stress. Pulsating torsional loading cycles led to pronounced residual stress relaxation for stress peened samples. The overall residual stress decrease after $N = 10^4$ led to same or even smaller values compared with conventional shot peening. However, warm peening increased the residual stress stability. This is caused by dynamic and static strain aging effects leading to a diffuse dislocation structure which is stabilized by carbon atoms and very small carbids. The torsional pulsating strength of the only quenched and tempered condition (285 MPa) was improved by shot peening (400 MPa). Stress peening and warm peening did not lead to further improvements for this steel. In case of stress peening this is caused by the high amount of residual stress relaxation. Furthermore, the 5 mm diameter of the rod specimens could stimulate subsurface cracks. It can be stated that surface characteristics and residual stress relaxation behavior is similar to previous results found for flat bending samples. However, in case of bending samples in the same quenched and tempered condition increases of the alternating bending strength were 11 % and 33 % for stress peening and optimized warm peening, respectively, compared to conventionally peening conditions.

6 References

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