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Comparison of Surface Characteristics and Thermal Residual Stress Relaxation of Laser Peened and Shot Peened AISI 4140

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1 Abstract

Laser peening is a relatively new mechanical surface treatment which causes deep zones bearing compressive residual stresses. This is accomplished by applying shock waves to the material surface using short laser pulses. Quenched and tempered steel AISI 4140 was laser peened using a Nd:glass slab laser with a pulse energy of 25 Joule and a wavelength of 1053 nm. Afterwards the mechanically affected zones were analyzed according to their topography, residual stress state and work hardening state and compared to shot peened samples. It is well known that the effect of mechanical surface treatments strongly depend on the stability of the induced residual stress state. Therefore, annealing treatments at different temperatures and times were performed to analyze the thermal residual stress relaxation behavior. Using an iterative mathematical procedure based on a least squares algorithm the activation enthalpy for thermal residual stress relaxation was determined and the responsible mechanisms were identified. The results were evaluated according to the amount of cold work caused by the different surface treatments.

2 Introduction

Laser shock processing also called laser peening is a newly developped surface hardening procedure, which affects surface zones in the mm-range without causing increases in the surface roughness in the same magnitude as shot peening. Investigations about laser induced shock waves have been conducted for almost fourty years [1, 2]. However, using laser peening to influence the surface characteristics of metallic parts was hardly investigated until the last decade of the 20^{th} century [e.g. 3-5]. Mainly Nd:glass laser, Nd:YAG laser or XeCl-Excimer laser are used to induce pulses with widths in the nanosecond regime and intensities in the GW/cm^2 range to modify the surface characteristics. The high intensity of the laser irradiation is absorbed causing ablation at the material. The ablation as well as the repulsion of the expanding plasma results in a high amplitude shock wave. Direct and confined ablation is distinguished [6]. The plasma caused by direct ablation is created directly at the surface. Very high intensities are necessary to induce sufficiently high shock waves, because the plasma can expand into the surrounding atmosphere. Moreover, the direct coupling of the laser irradiation as well as the resulting plasma with the material results in unfavorable thermal stresses with the creation of tensile residual stresses. Confined ablation, however, uses a transparent and a thermo-protective coating. The transparent coating, e.g. water, is transmitted by the laser beam and prevents a free plasma expansion into the atmosphere, which leads to intensified shock waves travelling into the material. Instead of the material, the opaque (black paint, metallic foil) thermo-protective coating is ablated within a very thin layer. Thus, no thermal stresses of the laser peened metal occur. After recombination of the plasma the hot vapor expands and induces a compressive shock wave that creates surface parallel plastic deformations, which result in a compressive residual stress state. The industrial operational area of laser peening is not widely spread yet. It is used e.g. to improve the crack resistance of turbine blades [7] or to prevent stress corrosion cracking of austenite stainless steels in power plants [8]. Furthermore, sporadic applications in the automotive and medical industries are known. In contrast to this shot peening is a very established procedure to improve the fatigue properties of metallic components for many years. Therefore a comparison of the surface characteristics after laser and shot peening is necessary to improve the number of applications of laser peening. This will be given in the present paper for the quenched and tempered steel AISI 4140. Additionally the thermal residual stress relaxation behavior will be compared in order to get informations on the stability of the residual stress states induced.

3 Material, Specimen Geometry and Experimental Approach

Investigations were carried out on steel samples of AISI 4140 steel (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 samples were machined from flat material by sawing, milling and grinding. Those used for laser peening had a final geometry of 110 mm x 25 mm x 5 mm. The samples used for shot peening had a thickness of only 2 mm. Afterwards, 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. Thermal residual stress relaxation after laser peening and shot peening was conducted by annealing in a salt bath furnace at defined temperatures and time.

The laser peening was accomplished at the Lawrence Livermore National Laboratories in Livermore CA, USA, using confined ablation. The laser used was a Nd:glass slab 25 Joule 1053 nm wavelength laser providing a very uniform rectangular "top-hat" shaped beam footprint. A laser light absorptive material was spread on the material surface in order to achieve a confined ablation. The absorptive coating was struck by the laser beam during processing and provided for the generation of the plasma discharge while protecting the surface. The plasma continued to absorb the laser light until the pulse was completed. A thin damping layer of water flowed over the process target and was used to restrain the plasma long enough for shock wave generation to occur into the part. The water was then blown clear of the surface as the remaining plasma was absorbed by the atmosphere. The samples were processed using two overlapping layers of laser shots (3.5 mm × 3.5 mm) at 168 J/cm^2 energy density and 18 ns pulse width. The second layer of shots overlapped the first layer by 50 %.

The shot peening treatments were performed using an air blast machine. 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 samples determined for shot peening were peened from both sides simultaneously in order to avoid distortions. The Almen intensity was 0.24 mmA leading to a full coverage of the sample surface [9]. The shot peening treatments of the samples used for thermal residual stress relaxation were carried out using shot S170 with a hardness of 44-48 HRC and a peening pressure of 1.6 bar [10]. However, no differences of the induced residual stresses and the Almen intensity were found for the two different peening procedures.

The resulting roughness and surface structure were measured using a confocal white light microscope (Nanofocus). Residual stresses of the specimens were determined using CrKα -X-rays and apertures of 0.3 and 2 mm diameter. The {211}-interference lines of the ferritic phase of the investigated steel were analyzed according to the $\sin^2\psi$ method [11]. 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 [12]. The half width values were determined as an average of those measured at $\psi = -15°$, $0°$ and $+15°$.

4 Results and Discussion

Fig. 1 shows the surface structure after laser peening in a region of 6.5 mm x 6.5 mm. Periodical surface structures are created due to pulse overlap. The surface shows recurrent notches of about 5 μm with a distance of about 1.7 mm, which is half of the laser beam cross section, caused by the 50 % overlap. Whereas the roughness of 2.8 μm is not changed by laser peening it is increased to 8.1 μm due to shot peening [9]. Because laser peening is only conducted on one side, the induced inhomogeneous plastic deformation causes a curvature height of 0.94 mm.

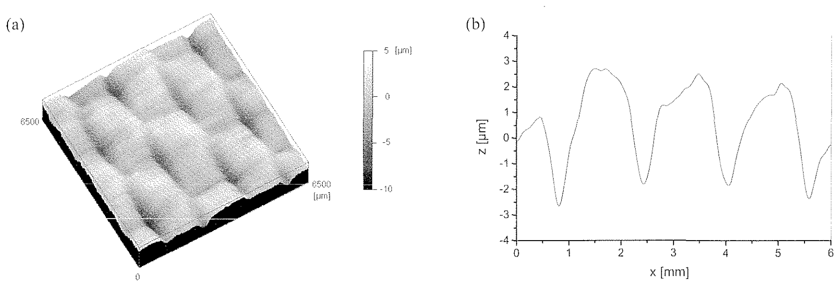

Figure 1: Surface structure (a) and profile line (b) of AISI 4140 after laser peening with two overlapping (50 %) layers

Not only the surface roughness of the laser peened samples but also the residual stresses are influenced by the pulse overlap. Fig. 2 shows that the compressive residual stresses measured using X-rays and an aperture with a diameter of 0.3 mm are varying between –400 MPa and –750 MPa. The highest compressive residual stresses occur in a distance of about 3.5 mm, which matches with the width of the pulse cross section. This indicates that the resulting residual stress state is mainly influenced by the hit of the final, second pulse. However, the oscillation of the residual stresses does not provoke tensile residual stresses like usually found for separately distributed peening shots and is positive for the fatigue properties, therefore.

Residual stress depth distributions measured using a 2 mm aperture of laser peened and shot peened [9] samples are shown in Fig. 3. It can be seen that the mean surface values are at about –600 MPa for both variants. While shot peening causes a residual stress plateau underneath the surface till about 0.1 mm, the laser peened sample shows a continuing decrease from the surface value with increasing depth. The penetration depth of the compressive residual stresses is strikingly increased from 0.17 mm to 0.87 mm by laser peening compared with shot peening. In

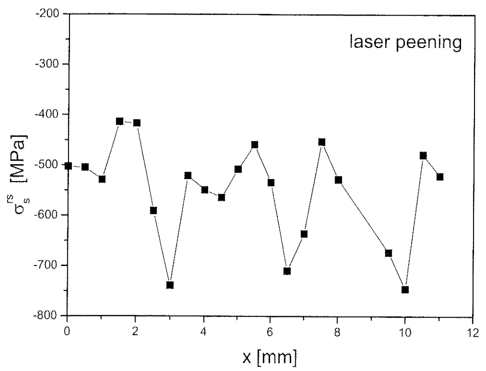

Figure 2: Surface residual stresses after laser peening with two overlapping (50 %) layers

Fig. 4 the half width depth distributions as a measure of the microstructural work hardening state are given. The core value of the laser peened sample is only slightly raised towards the surface, which is typical for laser peening [3]. The shot peened sample, however, shows distinct work hardening close to the surface. The core value of about 2.75 °2θ is raised towards the surface to a value of about 3.25 °2θ.

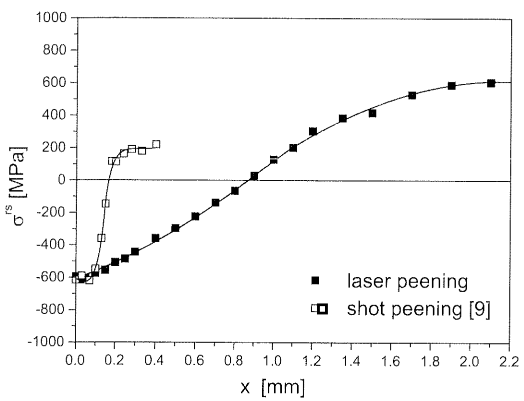

Figure 3: Residual stress depth distribution of laser peened and shot peened samples of AISI 4140

Laser peened samples were annealed in a salt bath at 300 °C as well as 450 °C for 1 min, 10 min, 100 min and 1000 min, respectively. The corresponding residual stress relaxation at the surface is shown in Fig. 5.

It can be seen that there is increasing thermal residual stress relaxation with increasing annealing time and temperature. It can be described using a Zener-Wert-Avrami function

$$\frac{\sigma^{rs}(T_a, t_a)}{\sigma_0^{rs}} = \exp\{-[C \cdot \exp(-\Delta H / kT_a) \cdot t_a]^m\} \quad (1)$$

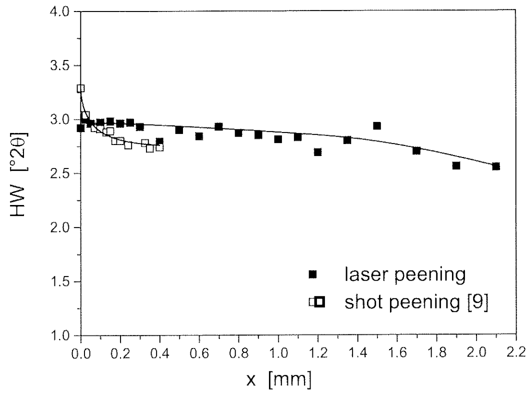

Figure 4: Half width depth distribution of laser peened and shot peened samples of AISI 4140

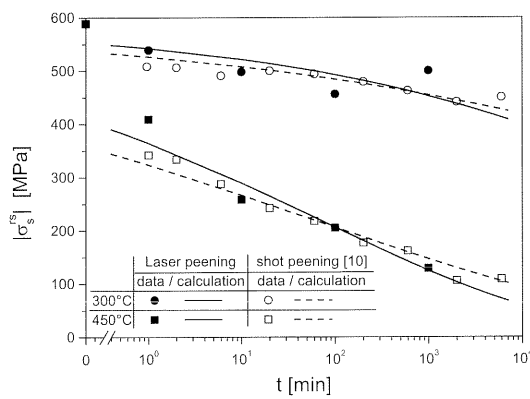

Figure 5: Measured and calculated thermal residual stress relaxation at the surface of laser peened and shot peened samples

where σ_0^{FS} is the initial residual stress state and σ^{FS} (T_a, t_a) the remaining amount of residual stresses after annealing at temperature T_a and time t_a. ΔH is the activation enthalpy, k the Boltzmann constant, and C and m are material related constants [13]. With Eq. 1 the activation enthalpy ΔH as well as the constants C and m are determined using an iterative mathematical procedure based on a least squares algorithm [10]. The results for C, m and ΔH are found to be $2.912 \cdot 10^{15}$ 1/min, 0.17 and 2.49 eV, respectively. The calculated activation enthalpy of 2.49 eV is close to the value of the activation enthalpy for self-diffusion of α-iron (2.6 eV), which implies that the main microstructural process responsible for the residual stress relaxation is volume diffusion controlled creep, which is determined mainly by climb of edge dislocations. Using Eq. 1 and the values found for C, m and ΔH the thermal residual stress relaxation is calculated. The obtained progression, also shown in Fig. 5, describes the results of the X-ray measurements well. Additionally, results of thermal residual stress relaxation of the shot peened variant [10] are spread. The thermal residual stress relaxation found for 300 °C and 450 °C is very similar to the results of the laser peened samples. An activation enthalpy $\Delta H = 3.29$ eV and constants $C = 1.22 \cdot 10^{21}$ 1/min and $m = 0.122$ for the shot peened samples are found, also using the iterative mathematical procedure [10]. However, those results were obtained using 5 different temperatures between 250 °C and 450 °C with 9 times each. This might be the reason that the activation enthalpy differs somewhat from that found for the laser peened variants although the residual stress relaxation behavior in Fig. 5 is absolutely comparable. The respective relaxation of the surface half widths as a measure of the work hardening state can be seen in Fig. 6. The surface half widths after peening [10] are slightly lower than seen in Fig. 4 [9] due to the usage of a different aperture, thus, they coincide with those found after laser peening. The relaxation behavior of the work hardening state at the surface is similar for both variants if the typical fluctuations occurring at half width determination are considered.

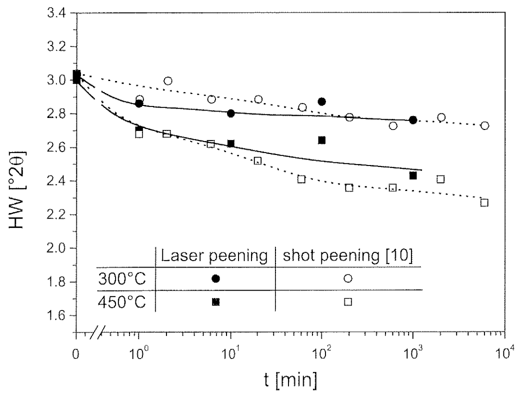

Figure 6: Measured thermal half width relaxation at the surface of laser peened and shot peened samples

At the first sight, the results of the thermal residual stress relaxation are in contrast to results reported previously. In [14] e.g., the thermal residual stress relaxation of Ti and Ni alloys used in compressor and turbine stages was investigated at engine temperatures (Ti-6Al-4V: 325 °C–475 °C, Inconel 718: 525 °C–675 °C). It was found that the relaxation of compressive residual stresses induced by shot peening is far more rapid than it is for laser peened variants. Even though the initial residual stress state at the surface was higher after shot peening, the absolute values were already lower after loading for 10 min in the temperature range given above. [14] correlates the rate and amount of thermal residual stress relaxation with the degree of cold work. They assumed that mechanical surface treatments which cause the least cold work retain compressive residual stresses for the longest time or at the highest temperatures. The work hardening caused by laser peening was about 4.2 % and 6 % for Ti-6Al-40 and Inconel 718, respectively. Shot peening, however, caused cold work of 75 % and 30 % for the two alloys. For AISI 4140 the same amount of cold work was found after laser peening and shot peening (Fig. 6). In consideration of the results of [14] this may explain why also the same rate of compressive residual stress relaxation was obtained. Therefore, the maximum operating temperatures of laser peened AISI 4140 components are similar to those of shot peened parts.

5 Conclusions

Specimens of quenched and tempered steel AISI 4140 were laser peened and shot peened and compared regarding surface characteristics and thermal residual stress relaxation. Laser peening was conducted with confined ablation using two overlapping (50 %) layers of shots, which caused a periodical surface structure with recurrent notches of about 3 μm at a distance of 1.7 mm. This distance coincides with half the distance of the laser beam cross section. Residual stress measurements with a small aperture of 0.3 diameter revealed oscillations at the surface between –400 MPa and –750 MPa, which occurred in a periodical scheme, determined by the 50 % overlap. If using a aperture of 2 mm diameter, laser peening and shot peening led to similar average surface residual stresses of –600 MPa. However, the depth of the compressive residual stresses was strongly increased by laser peening. Thermal residual stress relaxation behavior was investigated and modelled using an Avrami-function. Comparable residual stress relaxation was found for both surface treatments. The reason may be the same amount of cold work obtained at the surface, which was found previously [14] to determine the rate of thermal residual stress relaxation.

6 References

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IX Modeling