Process integration of innovative mechanical surface treatment methods with induction surface hardening

Stefan Dietrich[1], Raphael Heudorfer[1] and Volker Schulze[1]

[1]*Institute of Applied Materials - Materials Engineering, Karlsruhe Institute of Technology, Karlsruhe 76131, Germany*

The use of heat treatment techniques in combination with mechanical surface treatment processes in steels has long been applied intuitively in order to increase the mechanical performance of the surface layer. Nonetheless the interactions between both processes have become ever more complex since the introduction of short-term heat treatment processes like e.g., rapid induction hardening. Therefore, the present work deals with the optimization of the surface condition of steel components by combining induction hardening and mechanical surface treatments with the aim of increasing the service life under cyclic loading. In the first of three series of tests, the specimens are pre-hardened by shot peening prior to induction hardening. In a second, the specimens are quenched by dry ice blasting after austenitizing. For the last series of tests, the specimens are warm-peened after induction hardening. The characterization is based on the curves of hardness, residual stresses and full widths at half maximum. The rotating bending test is carried out to quantify the increase in fatigue life. An evaluation of the material behavior under cyclic loading is evaluated via Woodvine analysis.

Keywords: *shot peening, induction hardening, tempering, fatigue*

1. Introduction

Induction hardening (IH) of steels provides significant advantages regarding processing time and process control via single piece flow[1)]. Local austenitizing of the near-surface region and subsequent cooling at a sufficiently high cooling rate[2)] produces the martensitic microstructure which is responsible for increasing the mechanical strength and fatigue life of e.g. gears or shafts alike[3)]. Due to the volume jump during martensite formation, additional residual compressive stresses arise in the hardened surface layers compared with the unhardened core in surface hardening processes[4)]. The combination with a tempering process furthermore can create a well-balanced trade-off between strength and ductility suiting different applications.

Shot peening leads to elastic-plastic deformation of the blasting material and the creation of new plastic deformations and surface area. In the course of the plastic deformation, the density of disordered states in the surface (grain borders, dislocations) increases significantly[5)]. Overall, the material is work hardened by shot peening, and residual compressive stresses are generated in the surface zones with respect to the core[6)]. Similar to the surface hardening, an advantageous compressive residual stress state and higher strength support fatigue strength and increase wear properties[7)]. Through the modification by warm shot peening, the maxima and penetration depths of residual stresses achievable by conventional shot peening can be slightly increased. A decisive advantage of hot peening is also the increased stability of the residual stresses under both static and cyclic loading[8,9)]. This is due to static and dynamic strain aging processes. As a subprocess of peening, dry ice blasting has mostly been used in industry for cleaning surfaces[10,11)]. The cleaning effect is based on the rapid cooling down to -78.5 °C and respective thermal stresses, the mechanical deformation by the ice pellet impact and “micro-explosions” due to the ice sublimation all acting on the surface layer. With the afore mentioned changes of surface states in mind, the combination of heat treatment and mechanical surface treatment processes offers the potential to not only decrease processing times but also to synergistically use the mechanisms of work hardening and heat treatment in order to improve the mechanical performance of steels. Work in this direction has been carried out at the interface of fine particle peening (FPP) and IH[12)] with significant effects of the proposed treatment on the wear properties of martensitic stainless steel through a high hardness layer which is created by simultaneous work hardening and quenching. Additionally, the peening at austenitizing temperature generates fine grains near the treated surface because of dynamic recrystallization processes in the intensively deformed surface regions. This resulted in an improve in wear resistance compared to a conventional treatment by 50 % for FPP and 30 % for IH respectively. Further work on combined processes in the hardening regime[13)] with the low-alloy steel AISI 4140 explains the effects of FPP and IH with respect to peening temperature, thermal history and reference state based on the surface characteristics. The effect of combined IH-FPP on the fatigue behavior was validated in bending fatigue tests showing an increased fatigue limit of about 30 % compared to the FPP at room temperature.

This work focuses on the combination of conventional shot peening with induction hardening or tempering. As validation of the performance of the hybrid processs different experimental investigations are used as validation measures and input for a Woodvine analysis[14)] of fatigue behavior.

2. Experiment

In four processing strategies, samples of the quenched and tempered steel AISI4140 (tempered at 450°C) were treated with different peening and heat treatment combinations. In the first, a mechanically pre-strengthened condition by shot peening is subsequently induction hardened and tempered (PeenDuction I). The idea here is to decrease austenite grain size and subsequent martensite needle size in order to use this behavior as a strengthening mechanism. In the second setup, the specimens undergo only an induction hardening

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process, but instead of quenching with a water-oil emulsion, the steel is peened with pellets of solid carbon dioxide (PeenDuction II). This was intended to lead to an intensive quenching effect yielding maximum surface compressive stresses. The third setup includes an induction hardening process followed by a hot peening process at 200 °C to temper the samples (PeenDuction III). The fourth reference state (IH + Tempering) was only induction hardened. All states but PeenDuction III were tempered at 200 °C for 2 h.

In order to be able to assess the load-bearing capacity of the specimens as well as the stability of the achieved surface layer states, the specimen's hardness gradients and microstructures were examined. In addition, rotating bending tests according to DIN 50113[15)] were implemented to assess the fatigue strength. The fatigue limit is determined via staircase method with a run out cycle number of $5 \cdot 10^6$.

X-ray diffraction (XRD) profiles of the specimens are used to determine the residual stresses (RS) in the surface layer from diffraction peak shifts and the strain-hardening state from the peaks full width at half maximum (FWHM).

2. Results

In Figure 1 the hardness profiles of the different surface treatment strategies can be evaluated showing a similar surface hardness depth (SHD) between 1.6 mm and 1.85 mm.

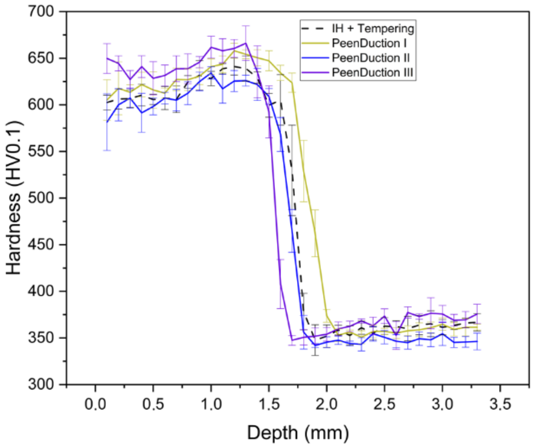

Figure 1: Radial hardness distribution for the different process variations.

The SHD was intended to be similar for all conditions in order to be able to compare the behavior under bending loads. With regard to the reproducibility of the induction hardening process and the hardness measurements this range seems adequate. The maximum hardness is measured to be between 625 and 655 HV0.1. In all induction-hardened conditions, it is noticeable that the hardness values increase by about 50 HV0.1 from the surface to the transition layer. The reason for this is the microstructure coarsening near the surface due to the high surface temperature of 1150°C. Figure 2 shows the residual stress profiles measured via XRD. While all processing strategies show compressive residual stresses within the first 2.25 mm a strong peak is only visible for the PeenDuction III process with compressive residual stresses as high as 1200 MPa.

Compressive RS of PeenDuction I are very similar to the reference state which was conventionally induction hardened and tempered indicating that in these processes the induction hardening step determines the maximum value and the profile in the first 0.25 mm.

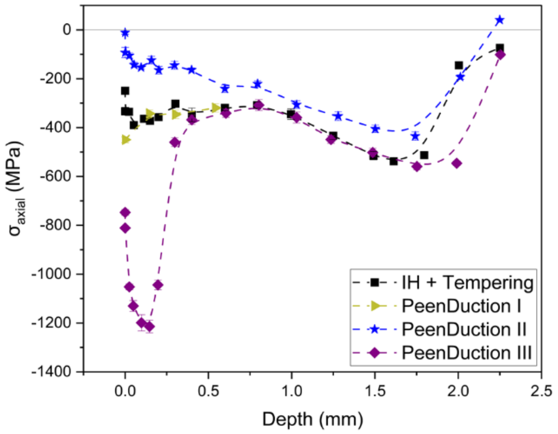

Figure 2: Axial residual stress distribution for the different process variations.

The RS profile of the PeenDuction II strategy is also similar in shape to the conventional process but shifted towards lower compressive stresses.

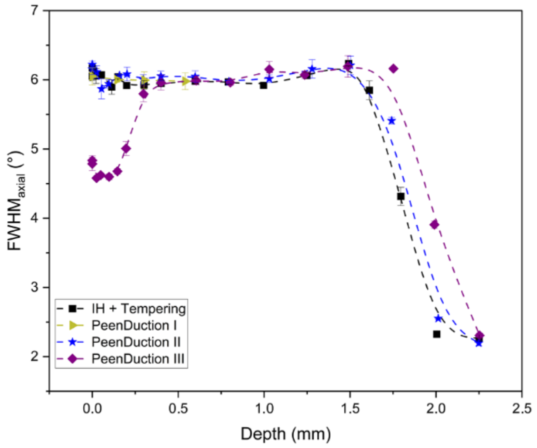

Figure 3: Axial FWHM curves of all final processing states.

This strongly indicates that dry ice blasting creates only minor plastic deformation in the surface but rather induces only conventional martensitic hardening with low cooling rates. Figure 3 gives an overview of the FWHM with only significant differences in the PeenDuction III strategy with a sharp drop of FWHM in the first 0.3 mm.

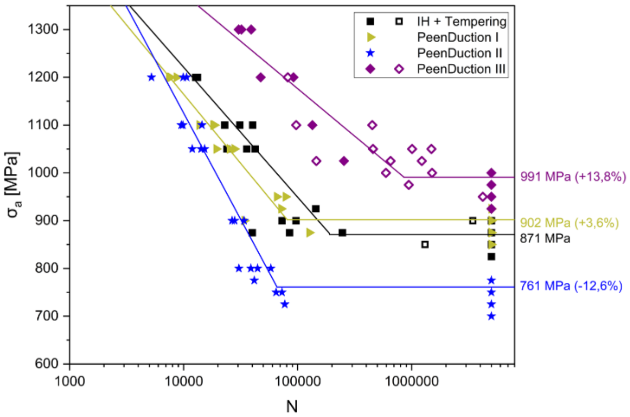

Figure 4: S-N diagrams of the different process variations.

The S-N curves of all four strategies are highlighted in

Figure 4. Obviously only the PeenDuciton III strategy provides a significant increase in fatigue limit and improvement of the LCF behavior. The S-N curves in Figure 4 indicate additionally a transition of the failure mode from surface-initiated cracks (closed symbols) to sub-surface cracks (open symbols).

2. Discussion

The fatigue strength of the PeenDuction I test series can be slightly improved by both a priori shot peening (see Figure 4). In the other measurements, however, very few significant differences can be observed compared to the reference condition. The hardness values in the surface layer deviate only slightly from the reference strategy. The residual stresses and FWHM of PeenDuction I are also similar to the reference state and reflect that induction hardening seems the most influential process. The effects of shot peening seem to be negated by austenitizing. Thus, besides rotating bending, no effect of a priori work hardening can be detected.

For the PeenDuction II state the hardness profile is slightly below the profile of the reference state over the entire hardness depth and also in the core. Furthermore, low compressive residual stresses in the axial direction near the surface are detectable, which converge to those of the reference condition in the depth profile. This indicates an unexpectedly low cooling rate while an additional work hardening effect of dry ice particle peening cannot be observed in the RS and FWHM profile. This does not reflect a positive effect through work hardening due to the dry ice quenching. A comparison of the microstructure and the hardness gradient with an analytical model furthermore indicates a fully martensitic microstructure with a cooling rate of 63 K/s[2]. The reason for the low fatigue strength of the PeenDuction II specimens is therefore the low residual compressive stress in the surface layer. The overall smallest hardness values in the hardness profile further indicate a relevant reduction in microstructural strengthening effects (e.g., grain size) since no significant differences can be observed in the FWHM compared to the reference condition.

In comparison PeenDuction III exhibits higher hardness after hot peening. Up to a penetration depth of 0.3 mm, the hardness values are about 50-60 HV0.1 higher than those of the other, induction-hardened surface layers. This can be seen even though the reduced values of the FWHM in the area affected by the warm peening should cause a decrease in the hardness values and indicate the important role of increased compressive residual stresses reflected in the measurement of increased hardness values. These compressive residual stresses are also by 150 MPa higher than room temperature peened samples of literature data[9] comparing conventional peening after IH + tempering and can be explained by the combined effect of peening and tempering with respective strain aging. The interaction of the measured material states can be compiled into a Woodvine diagram (see Figure 5) including error propagation. This explains the strong increase in fatigue limit for the PeenDuction III strategy where the high residual stress increases the tolerance of applied loads due to the local fatigue limit at the surface to nearly 1000 MPa when neglecting the probable XRD measurement error at the beginning of the RS profile.

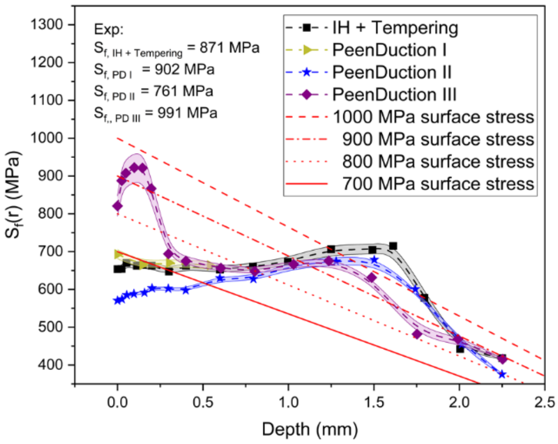

Figure 5: Woodvine analysis of the local fatigue limit according to the measured surface layer properties.

2. Conclusions

An evaluation of the material behavior under cyclic loading of differently peened and heat-treated surface layer states is summarized using a Woodvine analysis. While dry ice quenching results in a deterioration of the fatigue strength, a small improvement can be achieved by work hardening prior to induction hardening. The largest increase in fatigue strength of 13.8 % is due to by warm peening after induction hardening. These results show the high potential of a coupled process chain between heat and surface treatment through the possibility to benefit from the interaction of different thermal and mechanical effects.

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