Compressive residual stress relaxation in hardened steel during cyclic and static load

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Abstract. The benefits of applied compressive residual stress on fatigue properties of materials is a well-known phenomenon, but not well described in all respects. The fatigue life and the fatigue limit could be improved by targeted created compressive residual stress in the surface layers therefore, diversified surface compressing methods are developed and used in the engineering industry. The relaxation of the compressive residual stress state during a cyclic and static load is determinative for the life time of a component. Compressive stress relaxation was experimentally determined during the cyclic and static load. The compressive residual stress was induced by shot peening on the surface of stainless steel, micro alloyed high strength steel and hardened steel specimens. The residual stress state was investigated nondestructively by X-ray diffraction method then these specimens were loaded. After a certain number of cycles the fatigue load was stopped and the residual stress state was recorded again and again until fracture. To investigate the relaxation process during static load a four-point bending bench was used. The compressive residual stress relaxation was correlated to the applied fatigue stress level, the cycle number the quality of alloys.

1. Introduction

Various procedures exist, which result compressive residual stress at the surface and the shot peening is the most widespread surface compressing method [1], [2]. The applied compressive residual stress has a beneficial effect on the fatigue property of metals, especially on fatigue strength [3], [4], [5]. For the life time estimations, the behaviour of this directly induced compressive residual stress field during the operation of the with enhanced machine element must be well known. During the operation, which is a mixture of different kind of external loads the macro and micro residual stress states interact with the cyclic, quasi-static or dynamic load stresses and the work hardening and softening processes. The relaxation susceptibility of the surface compressive residual stress during the operation has a determinative importance. The constancy of the compressive residual stress state during fatigue load in annealed micro alloyed, medium carbon, perlitic and austenitic steels has been already investigated [6], [7], [8], [9]. It has showed that the residual stress relaxation is not monotonic in these alloys. Nevertheless, a significant portion of machine elements, which are typically exposed to fatigue loads, are mainly made of high strength hardened steels. One of our aim to investigate the stability of residual stress in hardened steels. The relaxation susceptibility of hardened, shot peened CM45MV specimens during cyclic load was investigated in one of earlier project of us [10]. The relaxation of the compressive residual stress was not observable in that steel, because of microstructure defects and specimen geometry.
In this paper the stress relaxation susceptibility of another kind of widely used hardened steel 42CrMo4 is presented. Fatigue specimens were worked out, shoot peened and exposed to cyclic load. The residual stress state was investigated non-destructively after the shot peening and recorded repeatedly during the fatigue load. The effect of static load on the residual stress was also observed. Comparative experiments were carried out on HSLA, 42CrMo4 and austenitic stainless steel specimens. The compressive residual stress field in static loaded specimens was created by used shot peening indirectly. The static load was implemented by a four-point bending bench. The residual stress was measured by X-ray diffraction in both experiment.

2. Materials
Fatigue specimens were cut from a hot rolled bar made of 42CrMo4 with 20 mm diameter (figure 1). Some specimens with 5x5 cross section on the middle quadratic part were also used, for check the size effect. The yield strength (1200 MPa) and tensile strength (1250 MPa) were measured by three parallel tensile tests on hardened test specimens made of the same piece of bar. The faults of the heat treatments could strongly influence the residual stress state [11], [12], [13] Our specimen geometry (long, thin) is especially sensitive on distortions, so the heat treatment was carried out with care. The specimens were induction hardened and oil quenched, immersed by hand. The austenitizing temperature of the specimens were controlled by Ni-NiCr thermocouple, soldered to the surface. First, the specimens were rapidly heated to 1000°C during a few seconds then the temperature was held for 2 seconds When the sample reached 850°C, the thermocouple was cut from the specimens and the specimens were immersed in quenching oil media. During the immersion the longitudinal axis was perpendicular to the surface of the media. The tempering was carried out at 600°C in an inductive furnace for half an hour, and specimens were subsequently cooled in air. The figure 2 shows the homogeneous martensitic microstructure of the cross section of the quenched and tempered sample. The HV10 (subscript) hardness data on the cross section (332, 337, 339, 361, 341, 333) confirms that the quenching was successful.

![Figure 1. Size of the shot peened specimens](image1.png)

![Figure 2. Light microscopy image of the hardened sample, cross section.](image2.png)

The effect of static load on compressive residual stress state were observed in three alloys. Hardened EN 42CrMo4, MIL–A 46100 HSLA as well as AISI 316Ti, austenitic stainless steel specimens were used in an elongated plate geometry (l:105, w:20, h:3mm). The geometry was given by the four-point bending device. The 42CrMo4 and the HSLA specimens were machined out from bulk material, after the cutting the 42CrMo4 were hardened, the HSLA specimen were used as received. The austenitic stainless steel was available in 20*3 cross section hot rolled form and after cutting the length used as received. The figure 3 and figure 4 shows homogeneous tempered martensitic microstructure in the cross section of the hardened and the HSLA specimens. The stainless-steel specimen bears a recrystallized cold formed characteristic figure 5.
After the cutting and heat-treating the subsequent step was the shot peening. It was performed in the Raba Automotive Holding Plc. The specimens were treated together with Raba manufactured shafts in the same time. The parameters of the shot peening were given by the requirements of the shaft. This means that the parameters of the applied peening method were industrial parameters. The shot peening was carried out in a WMKD 3 type shot peening equipment. The peening time was 9 minutes. Two Almen C strips were fixed on the sample holders to control the peening. The values of the Almen C probes were 0.26 and 0.24. The used peening balls were made of 1.8 mm diameter steel wire (430 HV), cut in 1.8 mm length pieces and conditioned for 4 hours. The minimal peening coverage was 150%. The average speed of the balls, which left the peening wheels was 55 m/s. As an average 117 J/mm² energy was imparted with the surface. The performance of the peening wheels was 252 kg/min.

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![Figure 3. SEM microscopy image of the hardened specimen cross section. (Mg:2500x)](image1)

![Figure 4. SEM microscopy image of the HSLA specimen cross section. (Mg:2500x)](image2)

![Figure 5. SEM microscopy image of the austenitic stainless steel specimen cross section. (Mg: 1000x)](image3)

![Figure 6. Fatigue specimens, after shot peening in socket](image4)

![Figure 7. Static specimens after shot peening in Almen analogous clamping tool](image5)
The fatigue specimens were peened in socket, such way the heads of the fatigue specimens were shadowed. The non-peened machined surface in the heads required for the clamping during the fatigue load (figure 6). The specimens, used for static measurements, were also treated by peening in lengthened, Almen analogous clamping tools (figure 7).

3. Experiments
The residual stress was measured non-destructively by a Stresstech Xstress 3000 G3R X-ray diffractometer, resident at the Institute of Physical Metallurgy, Metalforming and Nanotechnology at the University of Miskolc. Our surface results regard to residual stress values from approximately 10μm depth of the surface layer. All our residual stress values refer to this layer. In case of hardened and HSLA steels Cr Kα radiation was used and the stress was calculated from the shift of the \{211\} reflection of ferrite according to the sin2ψ method using Young’s modulus (E) of 210000 MPa and Poisson’s ratio of 0.29. The austenitic specimens were irradiated with Mn Kα radiation and the stress was calculated from the shift of the \{311\} reflection of austenite. Young’s modulus (E) of 196000 MPa and Poisson’s ratio of 0.28 were used for the calculations. ψ equipment geometry and 3 mm spot size was used in all measurements.

In case of the fatigue specimens Reflections were obtained in 3 tilting positions in the -45°/+45° range according to figure 8. The stress was measured with less error (scatter) than ±10 MPa in every point. All four sides of the specimens were monitored. The axial residual stress state was recorded at 3 spots with 3 mm spot size areas, on each side of each specimen in the initial shot peened state and during the fatigue loads. The same areas were investigated in each step of the monitoring. The represented stress value is always an average of twelve data after each step. First, the residual stress field of the shot peened state was recorded then, the specimens were fatigued with a certain number of cycles, finally the residual stress state was measured. This method repeated until the fracture of the specimen was reached. Several specimens were fatigued until fracture without stop for expected lifetime estimations. The fatigue load was tensile-compressive, the stress ratio (Rσ) was -1 (Rσ = σmin/σmax; σmax = 350; 400; 450; 500 MPa); so the absolute values of the tensile and compressive stresses were equal. The cyclic load was implemented by an MTS type universal electro-hydraulic testing machine of the Institute of Materials Science and Technology at the University of Miskolc.

![Figure 8](image)

**Figure 8.** The result of one measured data of sample No. 1, χ: the tilting angle [°], d: lattice distance [nm].

The statically loaded specimens residual stress measurements were recorded in 5-5 tilting positions in the (-45°/+45°) range. Two specimens were used from all type of steels. The residual stress state of the
shot-peened and from the clamping tool discharged specimens were recorded along a longitudinal stripe in 3*3 mm grid. The back side of the sample were also investigated and the longitudinal as well as the transverse residual stress distribution were docketed. All measured stresses lay in longitudinal direction, aside from a transverse travers on the back side.

In the possession, of residual stress data on the peened front and the back side, finally the back side were sorted out for the static load measurements, but previously the surface of the specimens were 3D scanned.

The applied bending device is a BC500 modulus measurement accessory of the X-Ray diffractometer. In this work used as a force controlled in situ external static loader machine. The specimens were fixed in the four-point bending bench under the diffractometer and the residual stress state was recorded in middle point of the sample surface bounded by the bending points. The residual stress was recorded with increasing and backward, decreasing external loads. The external loads were consecutively increased with 50MPa from zero. The needed bending force for the discrete bending stresses was calculated by the recombination of the

\[ \sigma = \frac{3F a}{b h^2} \]  

equation, were \( \sigma \): generated stress on the middle point of the surface bounded by the bending points (MPa), \( F \): the applied bending force (N), \( a \): the distance of the bending points (mm), \( b \): the width of the strips (mm), \( h \): the thickness of the strips (mm).

4. Results

The effect of the fatigue load on the compressive residual stress field in the surface layer during the cyclic load is illustrated by figure 9. The results of other stress levels were negotiated in another paper of us [14]. The most conspicuous common characteristic of the fatigues specimens residual stress relaxation is the strong initial fall. The approximately 25% residual stress relaxation happen in the beginning of the cyclic load, before the first residual stress monitoring step.

![Figure 9](image_url)
Figure 10.; figure 11.; figure 12.; figure 13.; figure 14.; figure 15. shows the residual stress distribution of the shot peened surface of the specimens made of different alloys in clamping tool, and after the discharging from it along 3*3 mm grid. The grid shown on figure 7. However, two piece of specimens were used made from all of the investigated alloys. Each pair show identical results so only one result presented here in case of each alloys.

All the investigated specimens were shot-peened simultaneously. The residual stress surface distribution results have common and dissimilar specifics. The HSLA specimen retains the highest residual stress values, nevertheless the same surface compressing treatment eventuate a significantly lower average residual stress extent in the hardened steel and in the austenitic stainless steel specimens. The discharging of the specimens from the clamping tool cause similar changes in case of all investigated alloys.

On figure 16. colored squares show the investigated areas of the backside of a specimen. The longitudinal directional residual stress travers recorded in longitudinal and in transverse direction also. The transverse directional residual stress recorded along the transverse travers. Figure 16.; figure 17.; figure 18.; figure 19.; figure 20.; figure 21.; shows the typical residual stress travers of the back side of the specimens. The longitudinal residual stress value of the shot-peened side are substantially smaller than the back side.
The asymmetric cold forming (the shot-peening stretched only the upper side of the stripes) caused residual stresses were rearranged and generated a remarkable, at least 300MPa magnitude longitudinal compressive residual stress on the back side. The transverse directional residual stress traverses are interesting. The transverse residual stress values largely exceed the longitudinal ones, which is an unexpected phenomenon.

All specimens exposed to increasing static load in discrete steps and the residual stress state was recorded in every step. The applied bending force were controlled, and fixed on calculated values during the
measurements. The applied force calculated from equation (1) so the generated stress was 50MPa or the multiple of it. The external load was increased until the measurable stress on the investigated point of the sample surface shown approximately stress less state. The unloading was done by the same schedule, and the residual stress recorded during the unload also at the same bending forces. Figure 22. present a snapshot about the residual stress measurement, while the sample loaded by the four-point bending bench. The white arrows show the impact lien of the force, black ones show the lines hold against. The side line of the specimen highlighted with white. The yellow arrow denotes the primary beam and shows on the measured point what the calculated stress values concern. Orange arrows denotes the reflected radiation and show on the detectors.

![Figure 22](image)

**Figure 22.** the bending device with a specimen under the X-ray diffractometer

Figure 23. present an example of the static loaded specimens measurement result. The measured stress values are illustrated in the function of the from force calculated external loads. Trendline was fitted on the results. The fitting and the slope (linear equation) was calculated.

![Figure 23](image)

**Figure 23.** the residual stress behavior during static load in a hardened specimen
Six specimens were investigated by the same method as it is presented in figure 23. As a result of the bending tests linear equations and fitting (R^2) data were gained, represented in table 1.

| line identification | linear equation | fitting (R^2) | average slope |
|---------------------|-----------------|---------------|---------------|
| Hardened 1 up       | y = 0.8943x - 306.03 | 0.9993        |               |
| Hardened 1 down     | y = 0.8951x - 299.07 | 0.9938        | 0.878         |
| Hardened 2 up       | y = 0.8492x - 331.24 | 0.9997        |               |
| Hardened 2 down     | y = 0.8736x - 334.36 | 0.9983        |               |
| HSLA 1 up           | y = 0.8878x - 431.96 | 0.9993        |               |
| HSLA 1 down         | y = 0.8948x - 427.66 | 0.9978        |               |
| HSLA 2 up           | y = 0.889x - 452.39 | 0.998         | 0.897         |
| HSLA 2 down         | y = 0.9147x - 451.36 | 0.999         |               |
| Austenitic stainless 1 up | y = 0.6442x - 346.36 | 0.9976        |               |
| Austenitic stainless 1 down | y = 0.6659x - 337.77 | 0.9882        | 0.653         |
| Austenitic stainless 2 up | y = 0.6351x - 398.2 | 0.9979        |               |
| Austenitic stainless 2 down | y = 0.665x - 399.9  | 0.9951        |               |
| As received, not peened austenitic stainless up | y = 0.968x + 62.959 | 0.9988        | 0.943         |
| As received, not peened austenitic stainless down | y = 0.917x + 121.56 | 0.998         |               |

Except the austenitic stainless 1 down, which fit with 0.988 R^2, all of the trendlines fit at least 0.99. The fitting is well generally. The different materials have different average slopes. The 3D scanning results of the surfaces of the static specimen help understand this phenomenon.

Figure 24. the 3D scanned image of the shot peened side of the stainless steel specimen 1, with 9 height data in the indicated points

Figure 25. the 3D scanned image of the back side of the stainless steel specimen 1, with 9 height data in the indicated points
After the discharging from the clamping tools the specimens were warped to trough form as it shown on the 3D scanned results on figure 24. and figure 25. The shot peened (top) surface of the specimens is convex in every case. Table 2. contains the 3D scanned results of all the specimens. The curvature intensity is similar the height differences on the surface. The intensity of the curvature shows material dependent characteristic. The different average slopes in table 1. correlate to the different intensity of the curvature in table 2. A not shot peened, perfectly flat specimen were also submitted to static load measurements. The slope of the not peened specimens is approximately 1, this verify the correlation between the curvature and the slope of the bending test trend lines. The higher curvature cause the lower slope, and the perfectly flat specimen has a slope of almost 1.

No relaxation was observable after the static load. Figure 23. shows result of only one hardened specimens. None residual stress values of any specimens show relaxation after the bending tests.

5. Summary

The residual stress holding stability of an untested kind of steel 42CrMo4 was investigated during fatigue load. The alloy shows 25% residual stress relaxation on the applied fatigue stress level. The most of the total stress relaxation extent happen until the first several thousands of cycles.

Three alloy, hardened, HSLA and austenitic stainless steel were examined in the aspect of residual stress holding capability during static load. The compressive residual stress of the samples has proven stable

| scanned surface | height data (mm) |
|-----------------|-----------------|
| top             | -1.03 -0.24 0.46 -0.01 -1.12 |
| back            | -1.04 -0.04 -0.55 -0.11 1 |
| Hardened 1      | 0.91 -0.17 0.46 -0.02 -1.15 |
| back            | 0.97 -0.23 0.98 |
| top             | -0.99 0.3 0.9 -1.09 |
| back            | -1 -0.16 -1.12 |
| Hardened 2      | 0.79 -0.08 -0.56 -0.3 0.9 |
| back            | 0.87 -0.24 -0.15 0.9 |
| top             | -1.16 -0.20 -0.40 0.9 |
| back            | -1.18 -0.10 -0.34 -1.07 |
| HSLA 1          | 0.98 0.12 -0.35 0.02 1.03 |
| back            | 0.97 0.16 0.24 1.07 |
| top             | -1.06 -0.08 0.09 -1.3 |
| back            | -1.01 0.04 -0.04 -1.07 |
| HSLA 2          | 0.94 -0.13 -0.57 -0.2 1.09 |
| back            | 1.01 -0.24 -0.08 1.16 |
| top             | -1.95 -0.34 -0.47 -1.91 |
| back            | -1.76 -0.26 -0.24 -1.79 |
| Austenitic      | 2.14 0.4 -1.01 0.25 1.96 |
| top             | 2.05 0.26 0.29 1.91 |
| stainless 1     | -1.91 -0.31 0.88 -0.37 -1.93 |
| back            | 1.91 0.37 0.2 1.79 |
| Austenitic      | 1.98 0.38 -0.97 0.31 1.94 |
| stainless 2     |
at the applied static load. A detailed description of the surface residual stress distribution evolution of the static samples was presented. The measurable stress during the bending test were fallen short of the from external force calculated stress. Correlation has found between this phenomenon and the extent of the warping (curvature) of the specimens. The warping was caused by the asymmetric cold forming of the surface, only one side of the specimen plates were treated by shot-peening. The correlation was verified by bend testing of a not peened, perfectly flat specimens. The extent of the warping shows material dependence. The lower strength allows higher plastic deformation, and also play important rule during the stress relaxation accompanied by permanent deformation.

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