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ANALYSIS OF RESIDUAL STRESS RELAXATION IN AUTOMOTIVE VALVE SPRING AFTER CYCLIC LOADING[1]

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Abstract
This paper presents an analysis of residual stress relaxation in automotive valve springs after several cyclic loading. The experiment was performed using fatigue bench test at room temperature, constant shear stress amplitude of 475 MPa and stress ratio of 0.2. The samples were manufactured from current Si-Cr high strength steel (HSS) quenched and tempered generating microstructures of tempering martensite and also austempering proposed showing predominantly lower bainite. Compressive residual stresses were introduced by plastic deformation from shot peening process and measured using X-ray diffractometry techniques at several depths from the surface. The results show that there not occurred relaxation of residual stresses in both samples after cyclic loading because to manufacture strategy and test parameters. The study can assist the development of components subjected to cyclic loadings since the relaxation of residual stresses can influence the total fatigue life.
Key words: Residual stresses relaxation; Fatigue; Lower bainite; Tempered martensite

ANÁLISE DO RELAXAMENTO DA TENSÃO RESIDUAL EM MOLA VÁLVULA AUTOMOTIVA APÓS CARREGAMENTO CÍCLICO

Resumo
Este artigo apresenta uma análise do relaxamento da tensão residual em mola válvula automotiva, após diversos carregamentos cíclicos. O experimento foi realizado em bancada para teste de fadiga sob temperatura ambiente, amplitude de tensão cisalhante constante de 475 MPa e razão de tensão em 0,2. As amostras foram fabricadas com aço de alta resistência Si-Cr temperadas e revenidas, gerando microestrutura contendo martensita revenida, bem como uma proposta austemperada com microestrutura predominantemente bainítica. Tensões residuais compressivas foram introduzidas através de deformação plástica utilizando jateamento com granalhas, cujas medidas foram realizadas utilizando técnicas de difratometria por raios-X em diversas profundidades a partir da superfície. Os resultados mostram que não ocorreu relaxamento das tensões residuais em ambas as amostras após carregamento cíclico devido à estratégia do processo de manufatura e parâmetros de ensaio. Este trabalho pode auxiliar o desenvolvimento de componentes submetidos à carregamentos cíclicos, pois o relaxamento de tensões residuais podem influenciar na vida total em fadiga.
Palavras chave: Tensão residual; Fadiga; Bainita inferior; Martensita revenida.

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1 INTRODUCTION

The determination of mechanical fatigue mechanisms in components under to cyclic loads is usually supported by the analysis of Mechanical Behavior. The understanding of this failure mode helps the technological development, generating a design more robust, increasing durability and the functional improvement of structures and components. A typical manufacturing strategy, normally used for fatigue life increase in coil springs, is the application of hard grit blasting, known as shot peening process. This process generates compressive residual stresses due to plastic deformation on the surface, which must to influence on fatigue life. However, during the service the residual stresses could decrease its magnitude, minimizing or neutralizing its benefic effect.
The amount of compressive residual stresses relaxation after cyclic loading could be correlated with the material, heat treatment and manufacturing strategy used for shot peening and final settings, since it affects the microstructure, mechanical properties and of residual stress magnitude/gradient. Loading amplitude and magnitude also influenced this process as well the stress ratio and the temperature/environment at which the test was carried.
Considering this scenario, the objective of this work is to verify the possible relaxation of residual stresses at room temperature, after a significant amount of cyclic loading and a relative high shear stress in automotive valve springs manufactured from current Si-Cr HSS quenched and tempered and also proposed using a heat treatment of austempering. This study is part of a research in progress, which have been analyzing other characteristics, such as the fatigue total life and fracture aspects. The overall goal of the research is the determination of the fatigue mechanisms, operating in the high cycle fatigue (HCF) and very high cycle fatigue (VHCF) regime in automotive valve springs.

1.1 Background

Fatigue is a form of damage that can occur in metallic solid materials subjected to cyclic loading with loads below (sometimes far below!) of your yield strength. Cyclic loading may induces internal changes in material, generating surfaces (cracks) in regions more susceptible, which might result in catastrophic failures.
The fatigue damage in an engineering component usually presents several stages, however for most cases exhibit the following stages:

- changes (crystallography range), nucleating permanent damage;
- formation of discontinuities (microscopic cracks);
- growth and propagation of these discontinuities generating macro-crack;
- stable propagation of dominant macro-crack;
- fracture or structural instability

The discussion about the mechanism of fatigue crack initiation can become philosophical, because the critical size that should have a crack so it should be considered end of nucleation is questionable. The "not ideal materials", presenting several initial potential sites (defects), in addition to being dependent on the level of observation range. Miller[1] showed that in polycrystalline metals can be assumed that this stage does not exist, since the material of an engineering component, typically presents 10^3 grains/cm^2 and a diversity stress concentration, as grain boundaries, machining marks, subsurface impurities among other defects intrinsic to materials. These defects may induce immediate a crack formation that can propagate up to be throttled down by a microstructural obstacle and/or a field of stress/deformation. As a result, the “metal fatigue limit” is related to the inability of crack propagation or in mathematical terms, the propagation rate (*da/dN)* is null. However, considering this point of view, the mathematical models for the crack propagation in an engineering material, should always consider that the natural defects preexist as potential sites of crack start.

1.1.1 Crack nucleation

Cracks usually begin in the free surface of the material, because, typically, have less restriction on plastic deformation, however can start at subsurface, depending on the result of local stress distribution and microstructural characteristic. Please note that inside of the materials can also exist surfaces or any discontinuities, such as porosities, interfaces of micro constituents or impurities, as well as effects of grain boundaries.
In pure metals the nucleation is associated with the dislocation movement and consequent slip plans, which are controlled by shear stresses and local stress concentration. However in non-pure or "engineering materials", the presence of discontinuities or defects in material, such as inclusions in steels, affects the crack nucleation process. Schijve[(2)] asserts that on surfaces of pure metals and alloys, the formation of cracks in the order of 100 μm, can consume of 60% to 80% of life in fatigue!
An early work who observed the growth mechanisms of micro-cracks was performed by Forsyth,[(3)] showing persistent slip bands (PSB). These bands are intrusions or extrusions on the free surface of the material, that "persist" or return to form, even after its removal to polishing, showing that the crack early stage (stage I) can occur in the region from slipping into a grain with favorable orientation (Figure 1), adapted from Lee et al.[(4)] and Suresh.[(5)] This phenomenon is most notably significant in ductile materials.

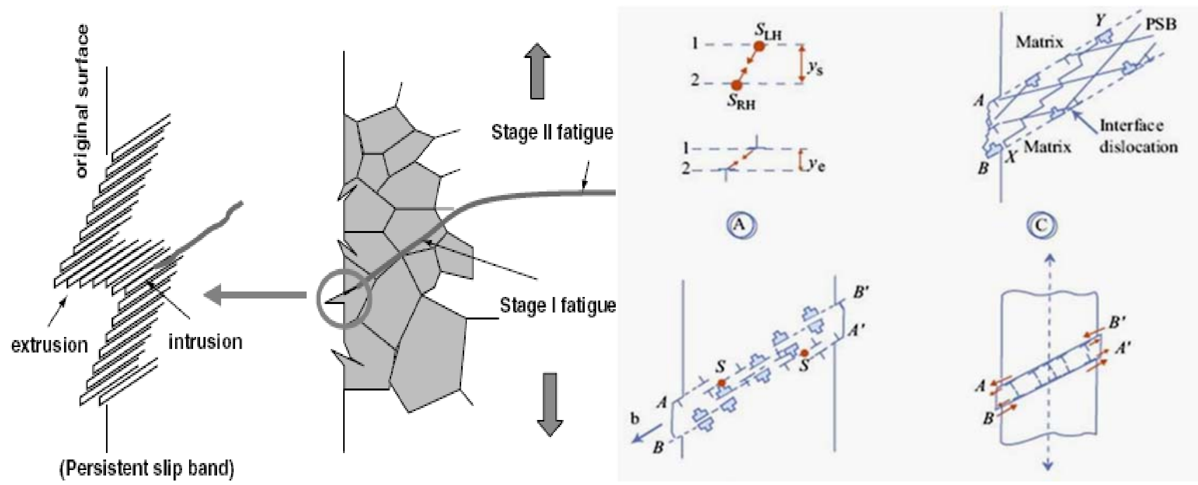

Figure 1. Illustrative sketch, showing the crack beginning by cyclic loading and respective PSB (left). Theoretical model of dislocations sliding (right).[(4,5)]

1.1.2 Shot peening

An important manufacturing step, whose goal is the increase of fatigue life, mainly for coil springs, is the use of a blasting with rigid particles (grit), which are usually spheres or cylinders from hard carbon steel or ceramic, also known as shot peening process. This process, schematized in Figure 2 consists of introducing a plastic deformation on the material surface, by multiply repeated surface impact, generating

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self-equilibrating compressive residual stresses, which increase fatigue life by limiting the crack propagating, because as previous explained, free surfaces are preferred regions for the early stages of fatigue.

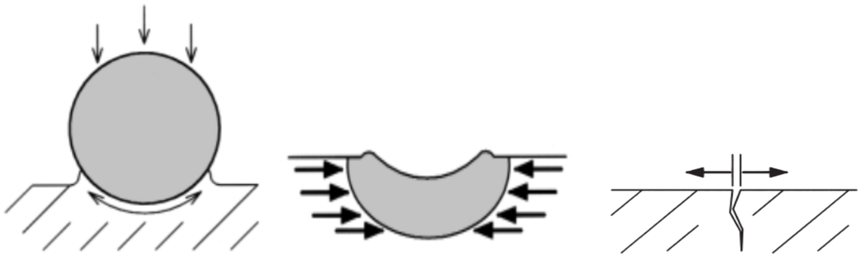

Figure 2. Schema showing plastic deformation by hard sphere impact and the formation of compressive residual stresses on surface.(4)

This process, as well as the techniques for its quality control is known since the middle of 1930, as publication of Champaigne(6) which contains a historical compilation of specifications for this process. In the current industrial practice, the surface of the material is shot pended by spheres, usually of hard steel; with a large enough kinetic energy to plastically deform the surface. The parameters of process control depending on the hardness of both materials (spheres and surface to be covered), ensuring the level and depth of desired residual stress, avoiding excess or absence not to cause problem as cracks at surface or poor surface covering, respectively. The work of Shiwaku et al.(7) shows typical values of shot peening process in automotive valve springs, being the diameter of 0.7 mm sphere with flow of 85 kg/minute, for 20 minutes and surface coverage above 95%. Residual stresses generated by this process are known as macro stress or level I, which come from the interaction between distinct "layers of materials" due to plastic deformation gradient. This classification depends on the range of observation, being that the type II corresponding to the grain size generated by the crystalline plans and/or thermal and elastic properties between grains of polycrystalline materials. The level III is an atomic scale and originated by iteration between interfaces and dislocation stress fields, as explained by Withers and Bhadeshia (8) (Figure 3).

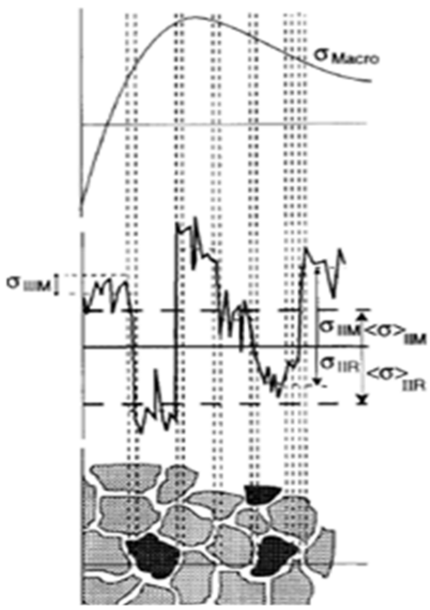

Figure 3. Classification of residual stresses fields (I, II and III) in accordance to range of observation.(8)

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This previous work describes eight commonly used techniques for the measurement of residual stresses, but currently the most common technique used by spring manufactures, is the X-ray diffraction (XRD). The measure is performed after the exposing the material surface to X-ray beam which interacts with the crystalline lattice generating patterns of diffraction with peaks, so its deformation can be measured and related to a residual stress. The stress magnitude is determined using elastic constants, assuming a linear elastic distortion of a particular plane of crystalline lattice as schematized in Figure 4.

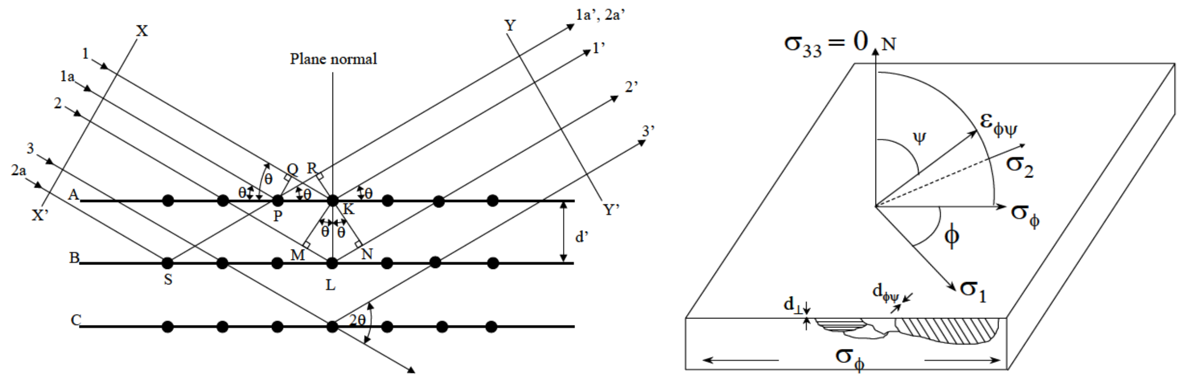

Figure 4. Diffraction of X-rays by the crystalline arrangement (left) and its schema (right) showing the surface diffraction plans, with principal stress on the sample surface.[9]

That technique utilizes Bragg's law (Equation 1) to measure the change of planar spacing *d*, correlating with the deformation ε, for a given wavelength by the change in incidence of an electron beam with angle λ, resulting in Equation 2. The resulting deformation allows calculating the stress, using the elastic constants of material.

$$\lambda = 2d \sin \Phi \quad (1)$$

$$\varepsilon = \frac{\Delta d}{d} = -\cot\theta \Delta\theta \quad (2)$$

For the general case, the stress measurement in any surface direction σ_ϕ as the theory of elasticity for an isotropic solid whose deformation is given by Equation 3 can be calculated by Equation 4.

$$\varepsilon_{\emptyset\varphi} = \frac{1+\vartheta}{E}(\sigma_1 cos^2\emptyset + \sigma_2 sen^2\emptyset)sen^2\varphi) - \frac{\vartheta}{E}(\sigma_1 + \sigma_2) \quad (3)$$

$$\sigma_\emptyset = \frac{E}{(1+\vartheta)sen^2\varphi}\left(\frac{d_\varphi - d_n}{d_n}\right) \quad (4)$$

Would be interesting to correlate the residual stress induced by shot peening and fatigue resistance; however Guagliano and Vergani[10] claim that there are currently no quantitative criteria based on mathematical models for ensure this correlation, but their study should be based on Fracture Mechanics. These researchers conducted studies using HSS, showing that shot peening is more effective to prevent the crack propagation, through their influence on the effective crack opening cycle, than to prevent the crack initiation. Figure 5, obtained by finite element simulation shows the stress fields map in front of the crack when its tip is partially closed or completely open on the surface with compressive residual stresses.

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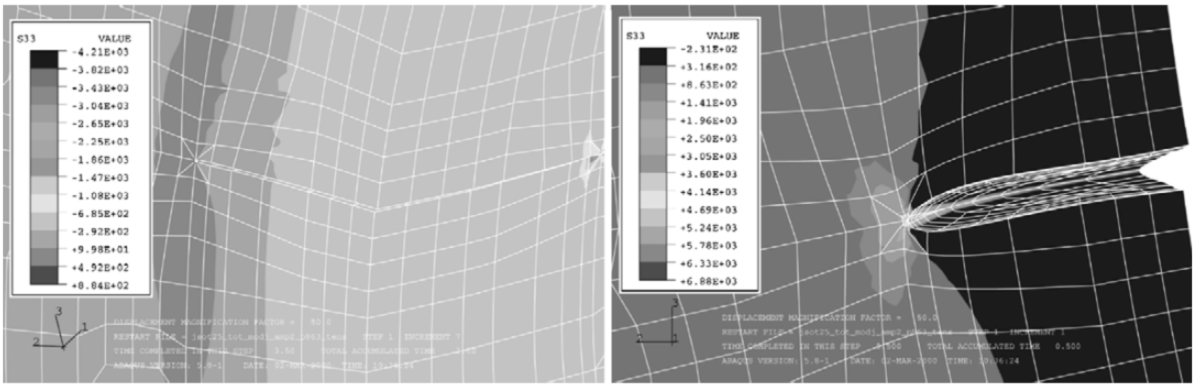

Figure 5. Calculation of stress field. Next to the region in front of the crack partially closed (left) and fully open (right) [10].

Note that for the case of the crack configuration partially closed (left figure), the crack end in free surface is also closed, while the other end into the deeper region in front of the crack is open, due to the influence of compressive residual stress, as stated by the authors.

Probably there is another very significant effect of inhibitor crack nucleation, in addition to the magnitude of compressive residual stress, mainly in stage I, which is the formation of barriers to dislocation movement, due to the generation of a greater amount of crystal lattice defects induced by plastic deformation, but the measurement and/or consideration of this factor in the effect of early fatigue was not found in the literature.

1.1.3 Residual stress relaxation

After cyclic loading, the residual stresses eventually can relax, decreasing its magnitude and consequently influence the fatigue process, since it requires a certain magnitude of compressive stresses in the preferably site to generate a condition of “shielding” the start of fatigue cracking.

Torres and Voorwald[11] performed experiments using AISI 4340 steel hardened and tempered, demonstrating that the residual stress relaxation depending on the remote stress magnitude/amplitude also the number of cycles, highlighting that a significant and progressive relaxation of residual stresses occurs in the first high loadings. This undesirable effect can be minimized through process strategies variants, such as the joint application of stress peening and warm penning, which generates a dynamic strain aging effect at the same time, as postulated by Tange, Koyama and Tsuji[12] and Wick, Schulze and Vöhringer.[13] However there are few published works that attempt to provide for this purpose through mathematical models. Recent work of Jinxiang, Huang and Ridong[14] about the prediction of fatigue crack growth and residual stress relaxations using two-dimensional finite element analysis show that the residual stress relaxes nonlinearly as the load cycles increase. However, there are several other variables, such as high temperatures, samples geometry, microstructural changes, environmental effects that can generate a relaxation, but are not related to the variables studied in this work. Figure 6, adapted from Schulze,[15] shows that warm shot peening introduces a higher level of residual compressive stresses compared to conventional processes during a cyclic loading. Note that the process named as "sp/290" (stress peening applied at temperature of 290°C) presented the lowest level of compressive residual stress at the beginning and also at the end of cyclic loading.

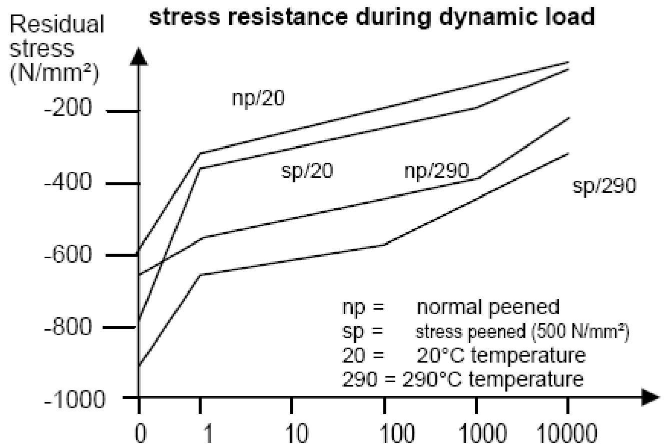

Figure 6. Reduction of compressive residual stress during a cyclic loading, performed with variants of shot peening.[15]

Although the literature present a wide discussion about the consequences of this step (shot peening) from the manufacture of springs, was not found a specific publication about the effect of retained austenite in martensite transformation, through plastic deformation at low temperature, *known as TRIP effect*, *(Transformation Induced Plasticity)* because apparently this class of products does not present a significant amount of retained austenite, which could influence its performance. Thus, this deformation-induced martensitic transformation is responsible for increasing the toughness of the material[16] and eventually may influence in fatigue life, but in the opinion of Dijk et al.,[17] he current understanding of stabilizing mechanisms of retained austenite in *TRIP* steels, is still limited. Another factor that hinders the characterization of the deformed region is the difficulty in measuring the retained austenite volumetric fraction, because in general, may include the use of destructive and also nondestructive techniques according to Anazawa.[18] In addition, this work shows that Si-Cr-Ni steel with 5% of retained austenite, generating errors relatively large mainly using the technique of X-ray diffraction, due to low resolution of the Feγ peaks whose lattice parameters may have been altered by processing or by heat treatment of the steel.

2 MATERIALS AND METHODS

2.1 Samples

The samples were taken from the same production batch was used to check the further characteristics studied by Serbino.[19] Thus, the following description is similar to the content of referenced work. The raw material chosen was a 3.70 mm wire diameter, commissioned by its trade name *OTEVA 70 SC RD40S*. It is a Si-Cr spring steel according to *DIN EN 54SiCr6* and similar to *ASTM A877* grade. The grain size was *ASTM E 112* G7.5 and the purity level was K2<30 according to *DIN EN 10247:2007*, considered "super clean", i.e., very low non-metallic inclusion content. They were manufactured in the form of helical springs with flat and parallel ends based on a normal project series. Figure 7 shows photographs of the valve spring and the respective drawing extracted from its original, which was not fully published for reasons of industrial confidentiality.

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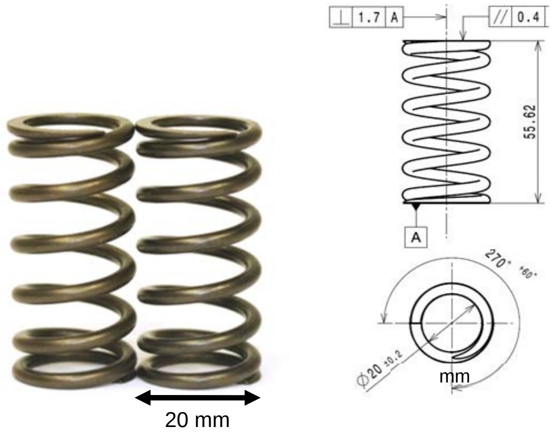

Figure 7. Samples quenched/tempered (left) and austempered (right) and respective drawings.

The spring was "cold wound" from a hardened wire. Tables 1 and 2 show the samples strategy manufacture for quenching and tempering (also referred to as "*QT*") and austempering (referred to as "*AT*").

Table 1. Shot peening and settings parameters

Samples	Surface treatment	Pre-setting/setting
QT AT	Double shot peening with 0.6 mm hard balls steel (t=10 min.) + 0.5 mm (t=10 min.)	20 min. (T=130°C) at $\tau_{\kappa(initial)}$ =1,100 MPa + 16 h (T=150°C) at $\tau_{\kappa} < \tau_{\kappa(initial)}$

Table 2. Heat treatment strategy

Samples	Austenitizing °C (min.)	Cooling °C	Tempering °C (min)
QT	850 ± 10 (12 ± 3)	50 ± 4 (oil)	400 ± 10 (30 ± 3)
AT		290 ± 5 (salt bath 25 min.)	n.a.

2.2 Material Characterization

2.2.1 Chemical composition

The chemical composition is presented in Table 3. The results indicate that the steel can be classified as 54SiCr6 grade.

Table 3. Chemical composition % mass $(\bar{x} \mp u_{A95})$

DIN EN 54SiCr6	**C**	**Si**	**Mn**	**P**	**S**	**Cr**
Specified	0.51 - 0.59	1.2 - 1.60	0.50 - 0.80	< 0.025	< 0.025	0.50 - 0.80
Obtained	0.55 ± 0.01	1.34 ± 0.01	0.72 ± 0.02	0.011 ± 0.004	0.001 ± 0.056	0.71 ± 0.02

2.2.2 Hardness

Figures 8 and 9 show the gradient hardness Vickers performed at a depth from 50 μm to 300 μm. The surface plastically deformed by shot peening presents hardness greater than 17% of the core in both samples. However, this difference must to be analyzed carefully, as was carried out by distinct loads.

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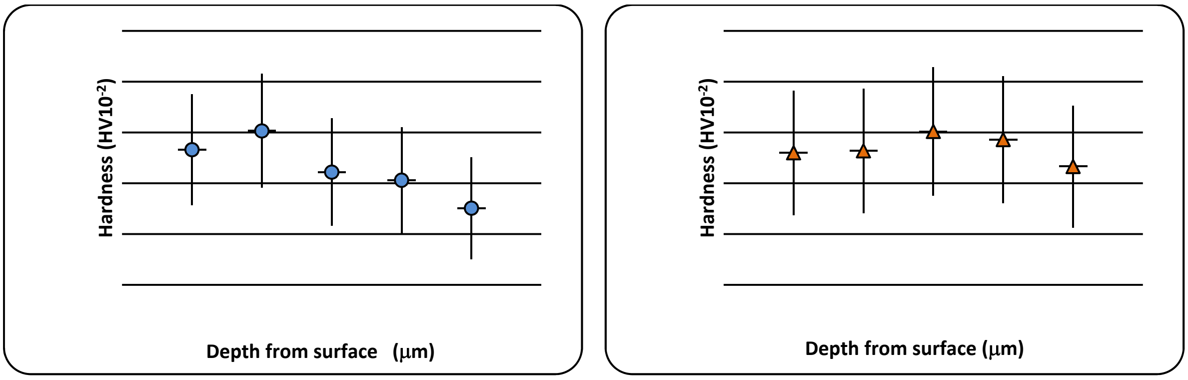

Figure 8. Subsurface hardness. QT (o) and AT (Δ) samples.

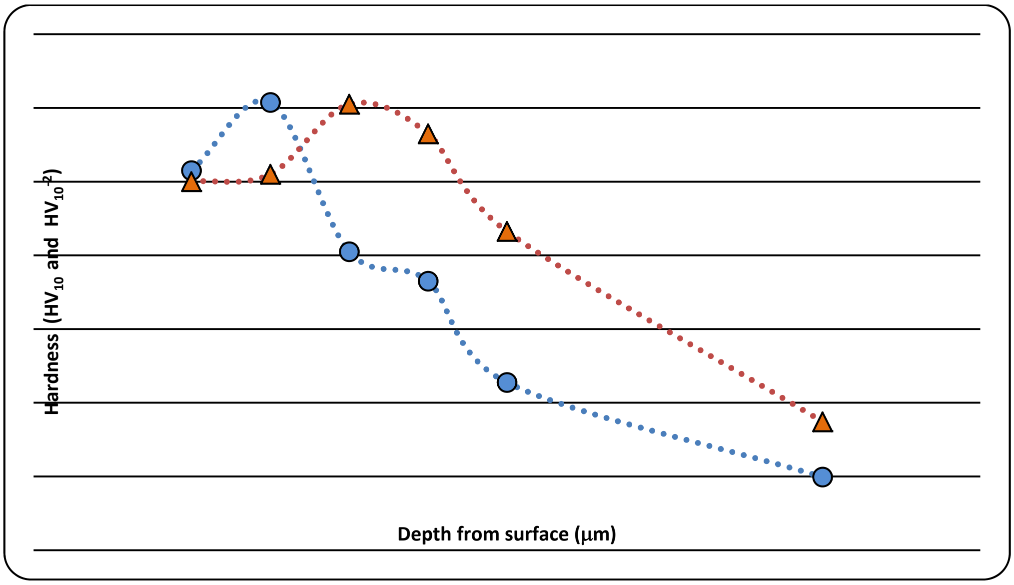

Figure 9. Hardness profile using different hardness scales. QT (o) and AT (Δ) samples.

2.2.3 Microstructure

Figure 10 and 11 shows microstructures obtained by optical microscopy (MO) and scanning electron microscopy (SEM). The QT samples showed homogeneous tempered martensite while AT samples showed a predominantly lower bainite microstructure. The shot peened surfaces present strong plastic deformation in both samples.

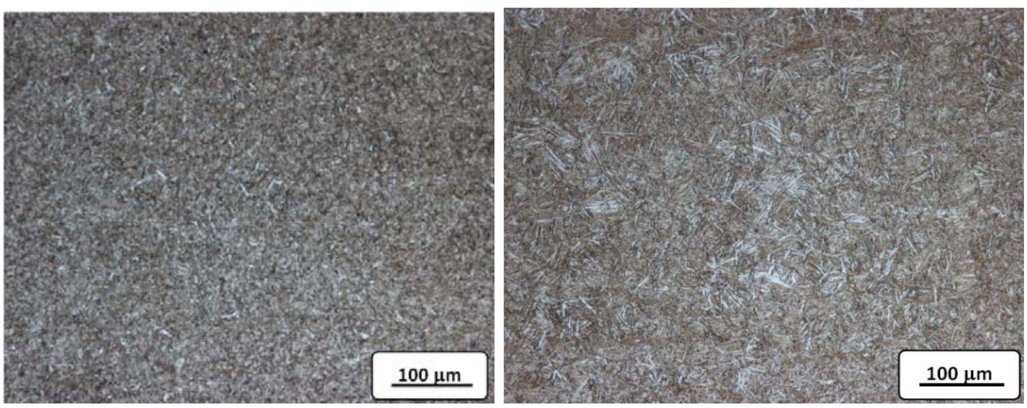

Figure 10. OM image showing the transverse cross-section of QT samples (left) AT (right) samples, tempered martensite and probably bainite, respectively. Etching: 3% Nital.[19]

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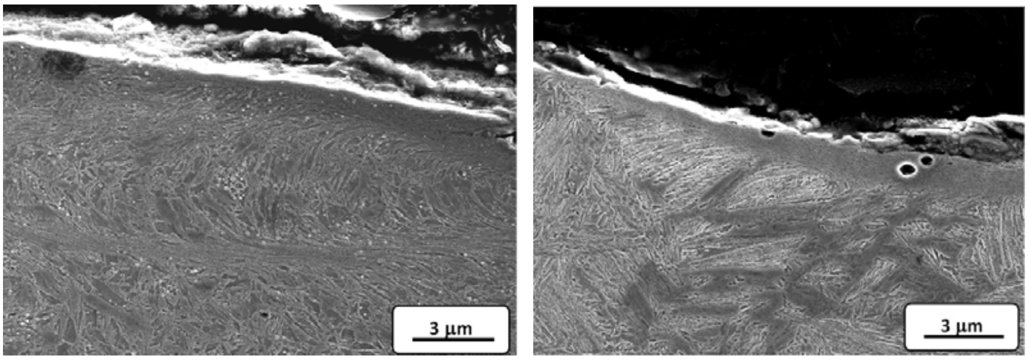

Figure 11. SEM image close to the surface showing tempered martensite (left) and lower bainite (right), both with intense plastic deformation. Etching: 2% Nital.(19)

2.3 Experimental Procedure

The analysis of residual stress relaxation was performed in a fatigue bench test at room temperature (Figure 12) whose parameters are shown in Table 4. The measure were performed by average of tree samples for each loading, after 10^4, 10^5 and 10^6 cycles under a constant corrected shear stress amplitude *(τ_{kH})*, minimum *(τ_{k1})* and maximum *(τ_{k2})* corrected shear stresses, frequency *(f)* and its stress ratio *R* and *A.*

The magnitude of residual stresses were determined by X-ray diffraction technique and calculated by the elasticity theory for an isotropic material (Equation 4). These measurements were performed using the method of multiple exposures sen$^2\Psi$, Cr-Kα, filter Kβ radiation with anode Cr-Kα, filter Kβ and a parallel beam in accordance with the Measurement Good Practice Guide.(9) For subsurface measurements the material (3 mm^2) was removed by electro-polishing process.


Figure 12. Bench used for the experimental fatigue test showing samples during cyclic loading.

Table 4. Fatigue test parameters

τ_{kH}	τ_{kM}	τ_{k2}	τ_{k1}	*R*	*A*	*f*
MPa						Hz
475	655	1,130	180	0.2	0.7	25

3 RESULTS AND DISCUSSION

Figure 13 and 14 shows the measurements of residual stresses at several depths from the surface, after cyclic loading. The results show that the compressive stress is at any analyzed depth in all samples.

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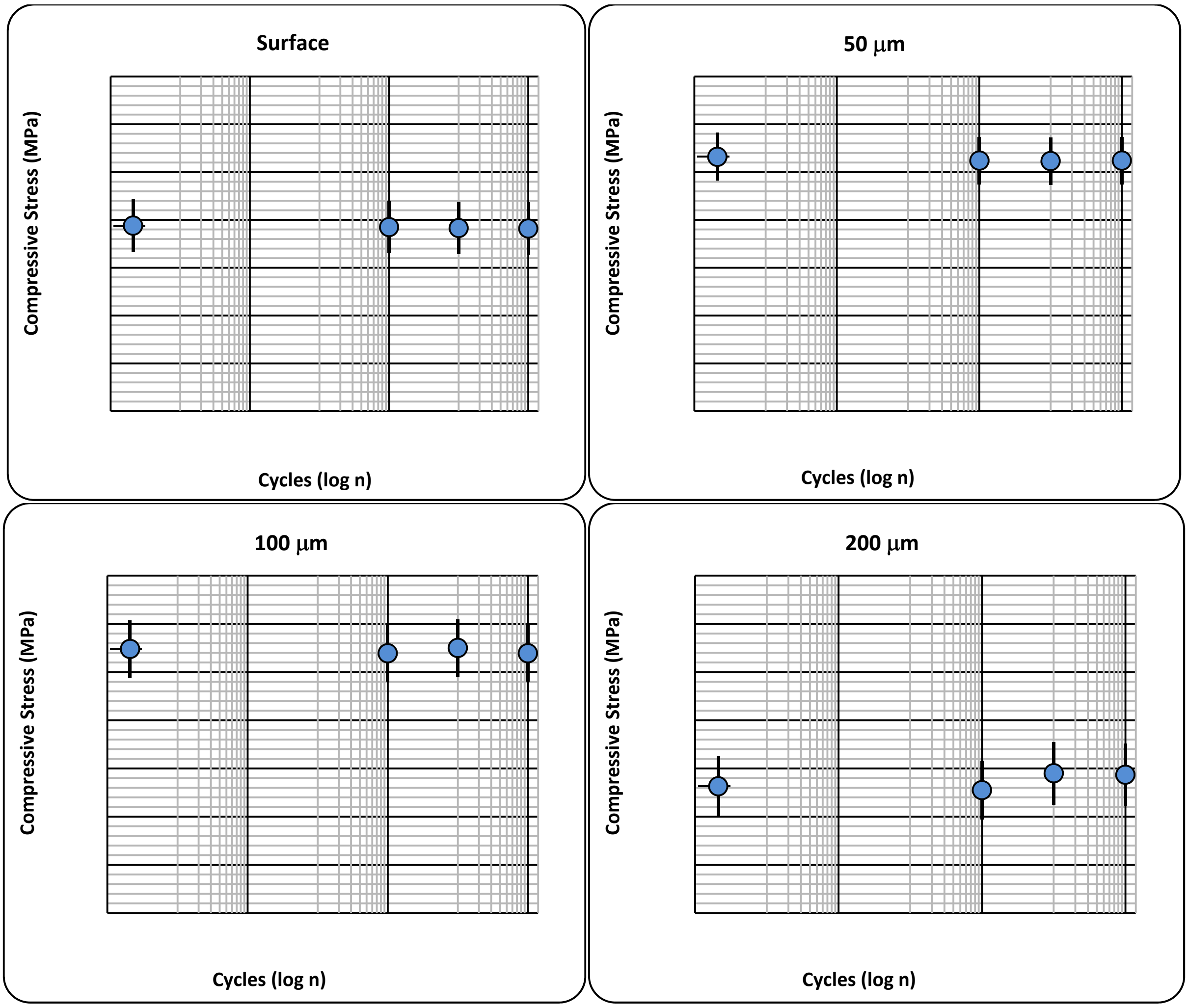
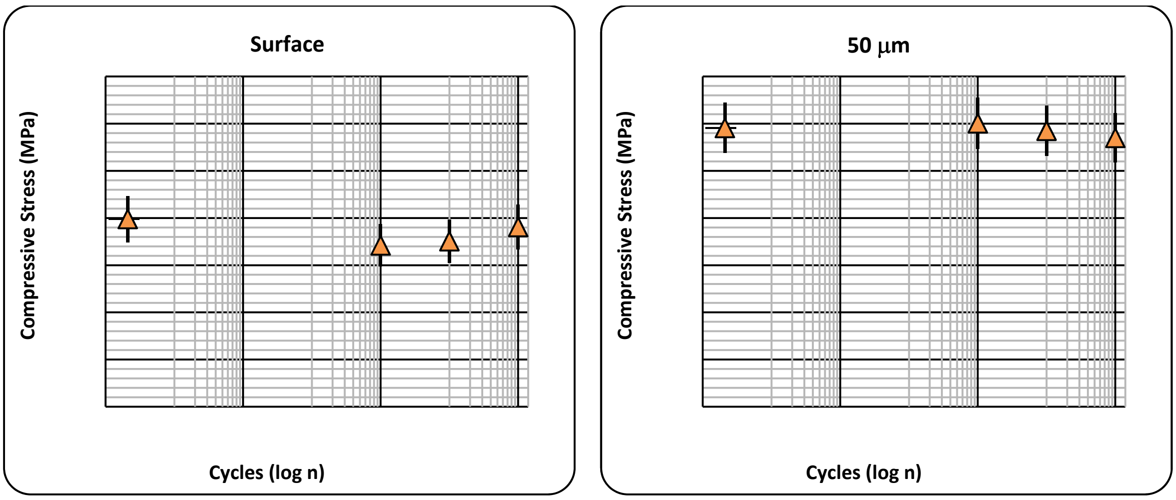


Figure 13. Residual stress after cyclic loading in QT samples at several depths.



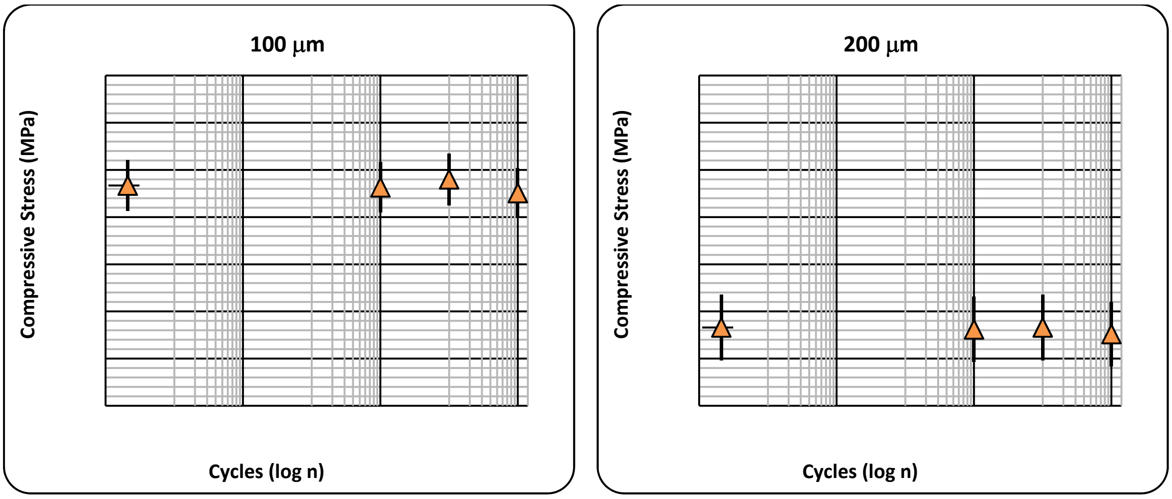


Figure 14. Residual stress after cyclic loading in AT samples at several depths.

A comparative analysis by a dotted and also softened connecting between the midpoints of residual stress, according to Figure 15 shows that the loading after 10^6 cycles has not caused compressive residual stresses relaxation in the both samples, since the difference between the initial and final values are not considered because of the measurement uncertainty.

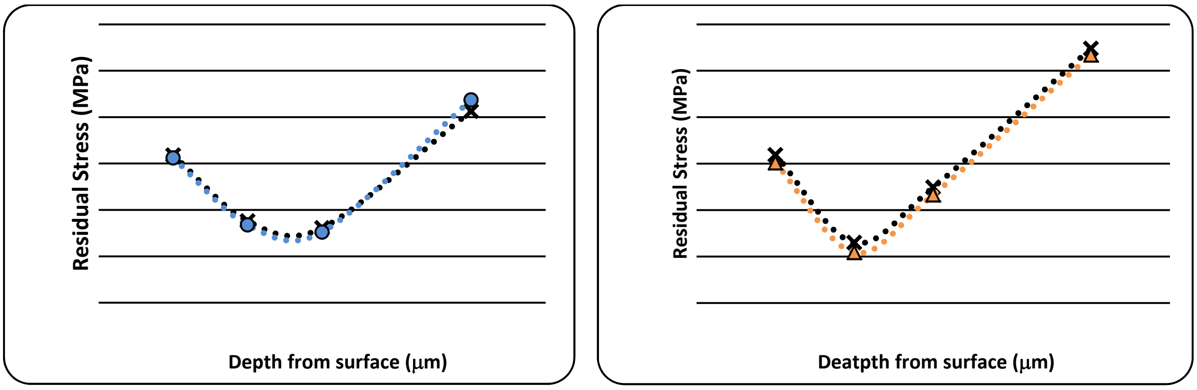


Figure 15. Comparative residual stresses after 10^6 cycles at τ_{kH} = 475 MPa and f = 25 Hz. QT samples = (o), AT samples = (Δ), initial condition = (x).

Manufacturing strategy of the samples, especially the shot peening and final settings, generated a hardened surface (Figure 9), deformed plastically microstructure (Figure 11) and compressive residual stresses (Figures 13 and 14). This material condition would have stabilized some movement of dislocations in the lattice, which could alleviate or diminish the magnitude of compressive residual stresses after cyclic loading. Beyond these features, another factor in this stabilization is associated with the parameters of experiment, which have not used reversed stress. Thus, the instability of compressive residual stresses will not affect fatigue total life of samples, so probably it does not influence the mechanism of initiation and crack propagation in the samples will be analyzed during the continuation of this research.
On the other hand the experiments mentioned in literature review were conducted with distinct parameters for this work, i.e., specimens with conventional shot peening, whose final calibration was not mentioned and also with stress amplitudes and magnitudes in addition using reversed stresses aforementioned.

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4 CONCLUSIONS

The results presented in this work show that valve springs manufactured from Si-Cr HSS, quenched and tempered also austempered, show no residual stress relaxation on its surface and subsurface, after several cyclic loading.
Stability of compressive residual stresses is related to samples manufacturing strategy and also to the test parameters used in the experiment, mainly by non-reversal stresses and ambient temperature.

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