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The Impact of Induced Shot Peening Residual Stresses on Metallic Components of SAE 1020 Steel with Pre-Existing Compressive Stresses

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An experimental study on the distribution of residual stresses induced by shot peening on samples of SAE 1020 steel with pre-existing compressive stresses is presented. Two samples with similar geometries were subjected to a heat treatment to relieve stress. Then, one of the samples was subjected to a cementation process to introduce compressive residual stresses. Both samples, with and without cementation, were subjected to the same shot peening treatment. Using X-ray diffraction and electrolytic polishing to remove superficial layers, the depth-resolved residual stress distribution was obtained. It was concluded that the effect of pre-existing compressive stresses should be considered as a factor that influences the final distribution of the residual stresses induced by shot peening, namely the maximum of shot peening induced residual stresses moves closer to the surface in a sample with large initial compressive stresses and its value is greater than the maximum value for a specimen with lower initial compressive stresses.

Keywords: *Shot peening, residual stresses, X-ray diffraction.*

1. Introduction

Shot peening is a mechanical process that consists of bombarding the surface of the desired part by metallic (typically steel), glass, or ceramic beads with sufficient force to dent the surface, and this process is widely used in industry. Among the main beneficial factors of shot peening are the treated material surface layers' hardening[1], the refining of grains, the relieving of surface tensile residual stresses and the possibility of inducing an in-depth distribution of compressive residual stresses, the possible improvement of the roughness the surface´s profile. The final objective of this process is to increase the durability and life of the treated parts.

A typical residual stress distribution profile expected from a shot peening treatment is presented in Figure 1.

The main characteristics of this distribution are the compressive stress value on the surface σ_s, the induced compressive stress maximum value σ_c, and its depth h_c through the thickness.

Several factors related to the shot peening process, such as the shot size and material, the peening intensity, the angle of impact, the percentage of peening coverage, and the application time, influence the implementation quality. The mechanical properties of the material subjected to shot peening are another factor that impacts on the shot peening process outcome. The shot peening equipment calibration is controlled relatively and indirectly using the Almen method[2].

Shot peening is one of the post-treatments capable of introducing a specific residual stress distribution on the surface and subsurface layers of the gears of automotive vehicles. The shot peening's quality is controlled by performing measurements of the residual stresses on the surface of the tooth or between two teeth and at a specific depth, where the compressive stress maximum value is expected[3]. It is frequently observed that peened gears from the same lot present some variation in residual stress values at a controlled depth even though they were submitted to the same shot peening process. Prior to shot peening, the gears are submitted to a sequence of heat treatments, such as cementation, quenching and annealing. These treatments induce high compressive stress in the gears.

In most experimental works devoted to shot peening, the residual stresses are measured using X-ray diffraction[1], neutron diffraction[4] and even the hole-drilling technique[5]. Various studies on the residual stresses resulting from shot peening have been performed using mathematical modeling and computer simulations[6-12]. Different parameters related to the shot, the peening process and the target are used as input information for these models. The shot parameters include the size, density, shape, impact velocity, rotary inertia, angle of impact and the shot hardness. Data on the target materials include

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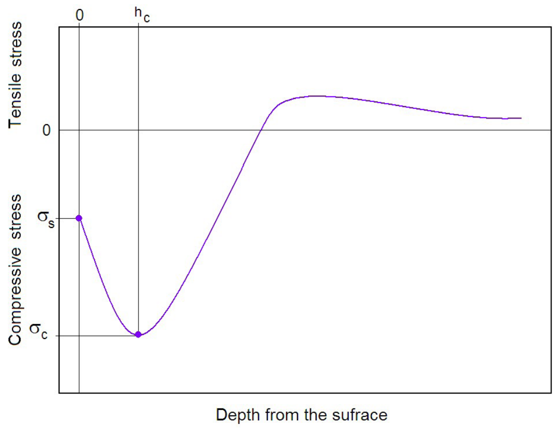

Figure 1. Schematic curve of a typical distribution of residual stresses induced by shot peening.

geometry, initial yield stress, work-hardening characteristics and hardness. The peening process parameters include the mass flow rate, air pressure, angle of impact, distance between the nozzle and component and the coverage percentage[6]. It has been reported that the temperature significantly affects the residual stress field for high shot velocities[7]. The developed numerical model is primarily used to predict the effects of the shot velocity, impinging angle and shot size on the induced residual stress profile[8]. Some authors reported that although different combinations of shot peening parameters produce the same Almen intensity, each combination results in a different through-thickness residual stress distribution[9]. Other authors noted that residual stresses induced by shot peening are directly related to the Almen intensity[10]. It has also been demonstrated that the compressive residual stress on the surface and the maximum compressive residual stress can be empirically calculated from the target metal yield stress and the ultimate tensile stress data[11].

Only a few works have considered the pre-existing residual stress state of the target as one of input parameters for the shot peening process. In most cases, the pre-existing tensile stresses were considered, so the expected result of stress relief after shot peening treatment is obtained[12,13]. However, the initial stress state knowledge can enable better prediction and control of the stress distribution patterns after the shot peening process[1,14].

There are different approaches to implement the shot peening process, including stress peening and peen forming, in which the piece subjected to shot peening treatment is pre-tensioned and consecutively pre-deformed by external acting forces[15].

This paper presents the results from experimental studies on residual stresses induced by shot peening in a specimen with pre-existing compressive residual stresses.

2. Equipment and Methods

Two samples with similar geometries of 300x35x6 mm were cut from SAE 1020 6 mm thickness carbon steel plate. The material yield stress in its original state is 350 MPa. The samples were subjected to a heat treatment to relieve stress, at a temperature of 650 °C for 1 hour followed by slow cooling. Then, one of the samples was subjected to a cementation process. The cementation treatment was carried out by the process of carburizing pack at a temperature of 950 °C for 8 hours, followed by slow cooling for 12 hours to avoid warping of the samples and to obtain a cemented layer calculated from approximately 0,8 mm.

Both samples, with and without cementation, were subjected to the same shot peening treatment using a GP-9075 pressurized blasting cabinet in manual operation mode with spherical S110 steel shot, an Almen intensity of 3C, coverage of 100%, air pressure of 0,7 MPa and angle of impact of 90°.

The metallographic preparation was carried out according to ASTM E03-11[16] and ASTM E407-07[17] with sanding between 220# and 2000# followed by etching with 2% Nital for 15s.

Hardness measurement was carried out using the Rockwell method with DIA TESTOR INSTRON WOLPERT equipment at the points of the 3 x 9 rectangular mesh (X,Y), with a step of 35 mm in the longitudinal direction and 1.25 mm in the transverse direction of the sample, having a point with coordinates (2,5) located in the center of the sample.

The absolute residual stress values were measured using a RAYSTRESS, which is a portable X-ray instrument that employs the method of double exposure[18]. The experimental accuracy of the stress measurements was 10 MPa. To avoid the appearance of additional internal stresses by the mechanical removal of the outer layer, its removal for depth measurements was performed by electrolytic polishing controlled by a digital indicator.

The principle of the stress measurements with RAYSTRESS using double exposure is shown in Figure 2. Two cassette windows capture the diffraction lines in 2θ angular intervals from 148° to 164°. The samples´s surface inclination of 12° corresponds to measurements for steel samples using Cr-K_α radiation and the {211} reflection with θ_{211}=78º.

3. Experimental Results

The surface layer of the sample with cementation has a typical cementation microstructure, this layer is characterized by high carbon content, lower detail (0,9 mm), a transition region, middle detail (0,4 mm) and the microstructure of the steel ASE 1020 (ferrite + cementite) shown in the upper detail of Figure 3.

The Rockwell hardness values for both samples after shot peening are presented at the Tables 1 and 2. As expected, the sample without cementation showed lowest hardness values, so the Rockwell A scale was used to measure hardness. To measure the hardness of the cementation sample, the Rockwell C scale was used.

For the samples after stress-relief heat treatment, a uniform distribution of the tensile residual stresses in the range of 40 MPa, in all directions, on the surface and on sub-surface layers, was observed, as shown in Figure 4, curve 1. The stress distribution after shot peening is presented in Figure 4, curve 2. In both curves, compressive stresses are reported as negative values and the tensile stresses are reported as positive values. No representative variations in the stress values with respect to the measurement directions were observed.

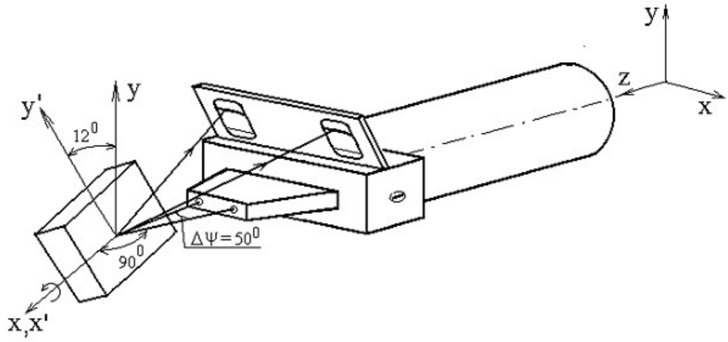

Figure 2. Scheme of stress measurements using RAYSTRESS equipment.

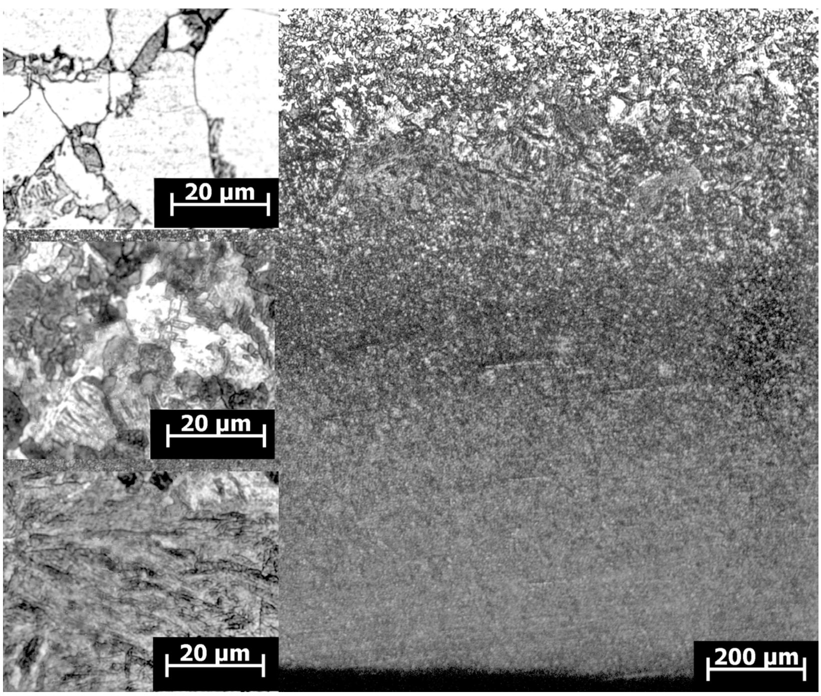

Figure 3. Microstructure of the cemented layer (50x); top detail, microstructure of the uncemented region (500x); middle detail, transition microstructure (500X); lower detail, microstructure of the cemented region (500x).

Table 1. Sample without cementation after shot peening. Rockwell hardness values (HRA).

Point (X.Y)	1	2	3	4	5	6	7	8	9
1	28.2	37.1	37.1	37.8	38.0	37.3	38.1	36.9	36.8
2	37.6	37.6	36.6	37.4	37.5	37.8	37.2	36.7	36.0
3	37.3	37.3	37.1	37.6	38.4	37.7	38.1	37.0	36.3

Table 2. Sample with cementation after shot peening. Rockwell hardness values (HRC).

Point (X.Y)	1	2	3	4	5	6	7	8	9
1	58.2	59.6	58.2	59.9	58.5	60.1	58.6	57.9	58.3
2	58.2	57.9	58.8	58.6	58.6	58.2	60.2	58.4	59.1
3	59.3	58.6	58.9	60.2	58.6	60.0	59.1	58.9	57.6

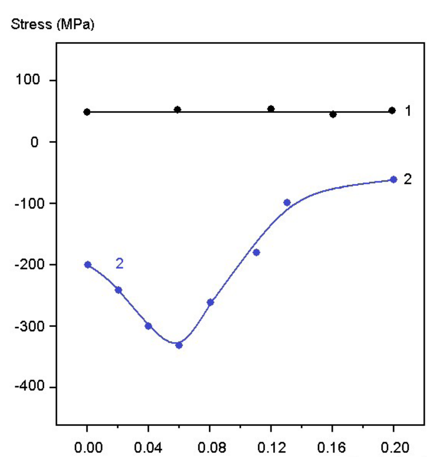

Figure 4. In-depth distribution of residual stresses for the specimen without cementation: (1) before and (2) after shot peening.

The residual stresses distribution through the depth in the samples with cementation before shot peening is presented in Figures 5 and 6, curves 3 and 5, respectively. It is observed that the values of residual stresses and their distributions along the depth are different in the longitudinal direction (along the length of the specimen) and transverse direction (orthogonal to the longitudinal direction). This result can be attributed to the thermal processes during cementation, which occurred non-uniformly in different directions because of the specimen geometry elongation; this difference is likely a result of the level of constraint against volume change restriction. Furthermore, additional measurements in the direction diagonal to both the longitudinal and transverse directions indicated that the latter two directions are the principal stress directions. The distribution of residual stresses in the specimen with cementation after shot peening is shown in Figures 5 and 6, curves 4 and 6, respectively.

The shot peening parameters applied were selected such that the maximum value ($\sigma_c \approx 330$ MPa) and the value on the surface ($\sigma_s \approx 200$ MPa) of the compressive residual stresses induced by shot peening on the samples without cementation were equal to the pre-existing compressive residual stresses values of the samples with cementation in both the transverse and longitudinal directions, respectively, as shown in Figure 7.

At the surface of the cemented samples, the compressive stress induced by shot peening are uniform in both directions, longitudinal and transverse, with a value of 380 MPa, although prior to shot peening there is a significant difference between these values (-180 MPa in the longitudinal and -350 MPa in the transverse directions), as shown in Figure 8. The maximum compressive residual stresses values in the transverse and longitudinal directions are 770 MPa and 680 MPa, respectively. The maximum compressive residual stresses in both directions for the specimen with cementation were obtained at a depth of 0.04 mm from surface. It is closer to the surface than in the case of the samples without cementation, where the

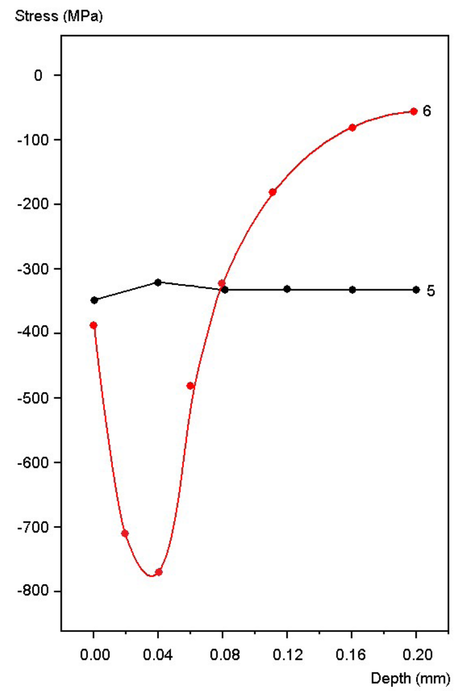

Figure 6. In-depth distribution of residual stress in the transverse direction for the specimen with cementation: (5) before and (6) after shot peening.

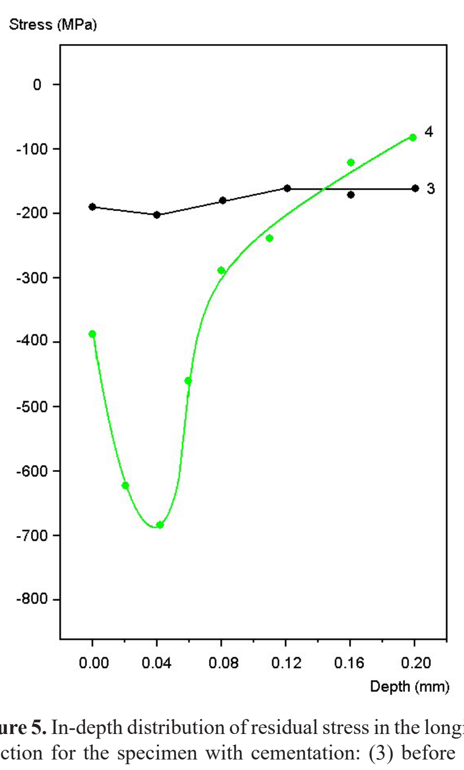

Figure 5. In-depth distribution of residual stress in the longitudinal direction for the specimen with cementation: (3) before and (4) after shot peening.

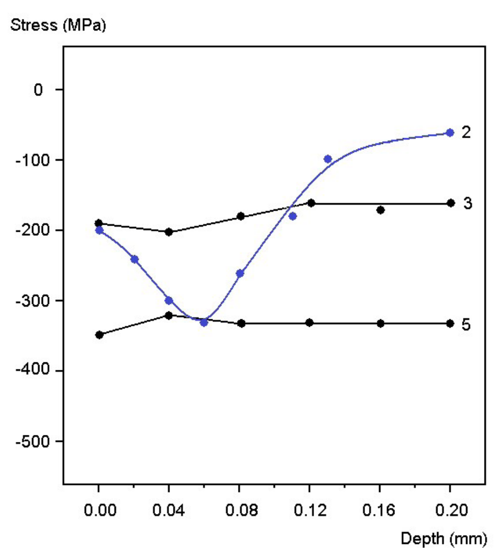

Figure 7. Pre-existing compressive residual stresses of specimen with cementation in the longitudinal (3) and transverse (5) directions and residual stresses for the specimen without cementation after shot peening (2).

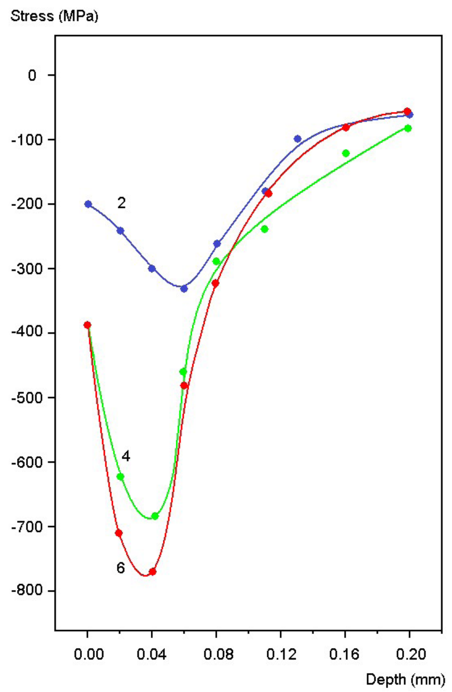

Figure 8. In-depth shot peening residual stress: (2) - specimen without cementation, (4) - specimen with cementation in the longitudinal direction and (6) - specimen with cementation in the transverse direction.

maximum compressive residual stresses were obtained at a depth of 0.06 mm from the surface. It is observed that in a depth range of 0.08 to 0.20 mm, the values of residual stresses for the cemented specimen, particularly in the transverse direction, reached the same level of stresses of the specimen without cementation.

The cementation increases the steel surface hardness and changes its mechanical properties. For the same type of shot peening treatment, with an increase of the material hardness, the maximum stress is moving closer to the surface and its magnitude notably increase. The increased hardness from the cementation would be expected to resist plastic strain (and hence changes in residual stress) caused by shot peening, but support a higher stress in response to the plastic straining that did occur. The final residual stress values are a result of superposition of the induced shot peening stresses with pre-existing residual stresses and is similar to the results observed for stress peening[15] and double shot peening[19]. In Figures 4 to 6 and 8 we observe that the maximum difference between the stress values before and after shot peening treatment is about 400 MPa for the specimen without cementation and about 500 MPa for the samples with cementation, and the maximum value of compressive stress is located at 0.6 mm and 0.4 mm depth respectively. We also observe different results of superposition of the compressive shot peening introduced stresses with the pre-existing tensile stresses for the samples without cementation and with the pre-existing compressive stresses for the samples after cementation.

4. Conclusion

The experimental results indicate the following:

- Pre-existing compression stresses, particularly those from the heat treatment, significantly influence the distribution of the compressive residual stresses induced by shot peening.
- Different values of pre-existing compressive stresses lead to different residual stress induced by the same type of shot peening.
- The difference in the values of pre-existing compressive stress is compensated by shot peening on the surface only.
- Receding from the surface and beyond the point of the maximum value of compressive stress, the profile of residual stresses induced by shot peening in the specimen with pre-existing compressive stresses becomes consistent with the profile of residual stresses induced by shot peening in the specimen with pre-existing tension stresses.

It can be concluded that the effect of the presence of compressive pre-existing stresses should be considered as one of the main factors that influence the final distribution of residual stresses induced by shot peening.

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