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STUDY OF STABILITY OF THE SHOT PEENING INDUCED COMPRESSIVE RESIDUAL STRESSES INTO C55 STEEL AT ELEVATED TEMPERATURES

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Abstract:
Results of experimental testing of the shot peened steel C55 specimens are presented in this paper. The aim was to establish behaviour of the compressive residual stresses induced by the shot peening at elevated temperatures; namely their stability in terms of temperature and time. Experimental work included verification of the tested material chemical composition, heat treatment (austenitization at 820 °C ± 5 °C for 30 minutes, cooling in the Durixol V70 oil at 20 °C ± 5 °C, high tempering at 450 °C ± 5 °C for 120 minutes, followed by cooling in air), tensile tests according to EN 10002-1 standard, hardness (HRC) measurements, shot peening with parameters Almen intensity 12A and coverage of 100 %, at the incidence angle close to 90° with respect to the specimen surface. The residual stresses state was evaluated by the X-ray diffraction measurement. It was concluded that the elevated temperature of 130 °C and after exposure of 100, 500 and 1000 hours, did not cause a significant decrease in compressive residual stresses.

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1. INTRODUCTION

The high-quality carbon steels are important materials recommended for use in transport engineering, for example in car construction. These steels typically have a carbon content of 0.3 to 0.6 wt. %. They also contain beneficial accompanying elements such as Mn, Si, Cr, which increase their final useful properties. The high-quality carbon steels are heat-treated by quenching and high tempering above 400 °C and the final structure is sorbitic. With regard to their use, these steels are subject to high requirements in terms of reliability, safety, durability in real operation, while respecting economic and environmental realities [1,2]. The strategic role in the field of cars, trucks, vehicles, is to reduce the weight, which contributes to the reduction of CO_2 and makes cars, trucks, vehicles more fuel-efficient. The shot peening can considerably contribute to vehicle's weight reduction [3]. It can be applied to a general geometry without any particular limitations and may be conveniently used both for large production volumes (thus for everyday cars) and for cars produced in limited numbers (sport cars, race cars, special cars), where the high performance is required and the machine elements are increasingly stressed [3]. The authors of [4] stated the importance of application of shot the peening process to obtain the nanocrystal surface. Description of different shot peening methods is presented. The influence of the processes is reviewed on material behavior under different loading conditions.

Shot peening is a process in which the surface layer of a material is subjected to cold plastic deformation. During the cold plastic deformation, the shape, and dimensions of the grains, which are

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among the most important microstructural factors, change in the surface layer of the material. The grain boundaries are insurmountable obstacles to dislocations' movement and are places of dislocations accumulation. In addition, the grain boundaries themselves are often sources of dislocations, places of exclusion of impurity atoms and secondary phases. The result is an increase in the yield point, ultimate tensile strength, hardness and fatigue endurance of materials, which ultimately lead to materials savings and reduced weight vehicles [3,5-9]. In paper [6], the severe shot peening (SSP) was applied to the steel 50CrMo4 and its effect in ultra-high cycle fatigue regime was investigated. Results show an unexpected significant fatigue strength increase in the ultra-high-cycle region after the SSP surface treatment and all the results are discussed in the light of the residual stress profile and crystalline size. In [8] the effect of process parameters and the kinetic energy of severe shot peening, laser shot peening and ultrasonic nanocrystal surface modification on the microstructure, as well as the mechanical properties and fatigue behavior of nickel-based super-alloy Inconel 718, have been investigated. Among the applied treatments, ultrasonic nanocrystal surface modification was found to be the most efficient one in improving the mechanical properties (as it led to the most significant fatigue performance) followed by the severe shot peening and laser shot peening. In the paper [9] different shot peening treatments, with conventional and severe parameters, were executed on aluminum 6063 alloy to assess the differences induced in the microstructure of the surface layer and to evaluate their effects on fatigue behavior. The obtained results proved the notable influence of the shot peening parameters on microstructure of the surface layer, which, at the same time, influences the fatigue behavior obtained by the rotating bending fatigue tests.

The decisive parameter of shot peening is the value of induced compressive residual stresses. In study [10] the Al7075-T6 bars have been shot peened with parameters much different from those used for the conventional shot peening. Measurements indicate the notable improvements in cases of hardness and elastic modulus in comparison to the untreated materials. The results imply that using the optimized shot peening parameters (induce compressive residual stresses) can increase the fatigue life and any other property affected by the grain size.

In study [11] authors investigated the effect of kinetic energy of the shot peening process on the residual stresses to figure out the mechanisms of fatigue crack initiation and failure. Several versions of experiments were applied so the obtained results would include the induced residual stress and residual stress relaxation.

With regard to use of materials after the shot peening, the stability of compressive residual stresses at elevated operating temperatures is an important factor [12-23]. The authors of the works [12-14] stated that the extent of residual stress relaxation is controlled by the thermal and mechanical processes. Authors of [15] stated that the experimental results showed that the peening effects, in the peened alloy 600, are valid at high temperatures below approximately 538 °C. Stability of the compressive residual stresses at elevated temperatures (> 596 K) has been clarified. In study [17] was shown that the residual stresses were not completely released, even after annealing at the highest aging temperatures (200 – 400 °C for 2 hours), which meant that the shot peening could enable Ni – Al bronze alloys to keep the excellent thermal stability of beneficial compressive residual stresses. In study [18] was reported that the superalloy GH742 was annealed at different temperatures and the stability of the surface residual stresses at high temperatures was investigated. The laser peening exhibits the better stability of compressive residual stresses in comparison to the shot peening. The authors of [19] have shown, for the quenched and tempered steel 42CrMo4, that the fatigue strength increased with increasing peening temperature. This is caused by slightly higher compressive residual stresses in the new surface area. In study [20] the carbon nanotubes (CNTs) reinforced Al-Mg-Si alloy composite was made and shot peened. The variation law of residual stresses with annealing time, at elevated temperatures (150 °C, 200 °C and 250 °C), was investigated. The addition of the CNTs could improve the thermal stability of the macro residual stresses created by shot peening. The authors of [21] obtained results that the highly dense dislocation structure and high compressive stresses, induced by the laser shock peening, significantly improved the high-temperature fatigue performance of the 7075-aluminum alloy. In study [22] authors investigated application of the laser shock peening (LSP) to improve the fatigue life of ATI 718 Plus, at high temperature of 650 °C. The retained residual stresses and the stable microstructure from the LSP increased the yield strength approximately for 14 % (140 MPa) and endurance limit close to 40 % (90 MPa) in corresponding test at 650 °C. The thermal-mechanical residual stress relaxation indicates effectiveness of the LSP in improving the fatigue life of 718 Plus at 650 °C. Laser shock peening was carried out to reveal its effects on ASTM:410L00 C(r) 12 microstructures and fatigue resistance in the temperature range 25 – 600 °C. Results show that a deep layer of compressive residual stresses was developed by the laser shock peening and, ultimately, the isothermal stress-controlled fatigue behavior was significantly enhanced. The results can serve as indicators of the fatigue strengthening mechanism of components at the elevated temperatures [23].

2. EXPERIMENTAL INVESTIGATION

The experimental investigation in this study was focused on stability, in terms of temperature and time, of the compressive residual stresses introduced into the high-quality steel by the shot peening. Verification of the chemical composition of the experimental material - chemical analysis - was performed by the spark emission on a SPECTROMAXx device. The experimental material was subsequently heat treated by the following processes: austenitization at 820 °C ± 5 °C for 30 minutes, cooling in the Durixol V70 oil at 20 °C ± 5 °C, high tempering at 450 °C ± 5 °C for 120 minutes, followed by cooling in air. After the heat treatment, the specimens for the tensile tests were prepared by the chip machining. The round cross-section specimens of diameter d = 10 mm were used. The shape and dimensions of the test specimens fulfilled the requirements of the EN 10002-1 standard. Three specimens were used. The tensile tests were carried out on a ZWICK Z050 testing machine at an ambient temperature of T = 20 ± 5 °C, with the loading range F = 0 – 20 kN and the strain rate $\varepsilon_m = 10^{-3} s^{-1}$. The HRC hardness was measured on an RR-1DAQ hardness tester; average value from five measurements is given. The specimens, substrates, were prepared by the grinding procedure. Their surface was mechanically treated by shot peening with parameters Almen intensity 12A, coverage 100 %, chosen according to [24]. Cast steel shots of diameter 0.42 mm were used for the treatment at the incidence angle close to 90° with respect to the specimen surface. To study the stability of the compressive residual stresses, specimens of a length of 70 mm and a diameter of 10 mm were used, see Fig. 1.

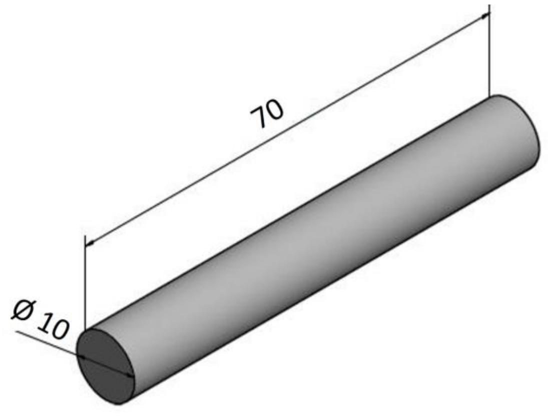


Fig. 1. Shape and dimensions of specimens for the study the stability of the compressive residual stresses

The residual stress state was evaluated by the X-ray diffraction measurement. The ProtoiXRD device was used for the measurements, using the CrKα radiation with an irradiated area of 0.5 mm^2. The diffraction signal from {222}α planes was collected at 2θ = 156.9°. The measurements were carried out using the sin2ψ method, with nine inclinations in the range ± 39°. The measurements were carried out in axial (Ø = 0°) and tangential (Ø = 90°) directions. To obtain the depth profile of the residual stresses' distribution, the surface was gradually removed by electrolytic polishing. The stability of the compressive residual stresses, at temperature of 130 °C and after 100, 500 and 1000 hours, was determined.

3. RESULTS AND DISCUSSION

The chemical composition and mechanical properties of experimental material, high-quality steel (demonstrated by experiment vs. material standard) is shown in Table 1 and Table 2 respectively. The experimental material was in accordance with the material standard (ČSN 41 2060, Ck 55, W. Nr. 1.1203) [25].

Table 1. Chemical composition of experimental material (in wt. %)

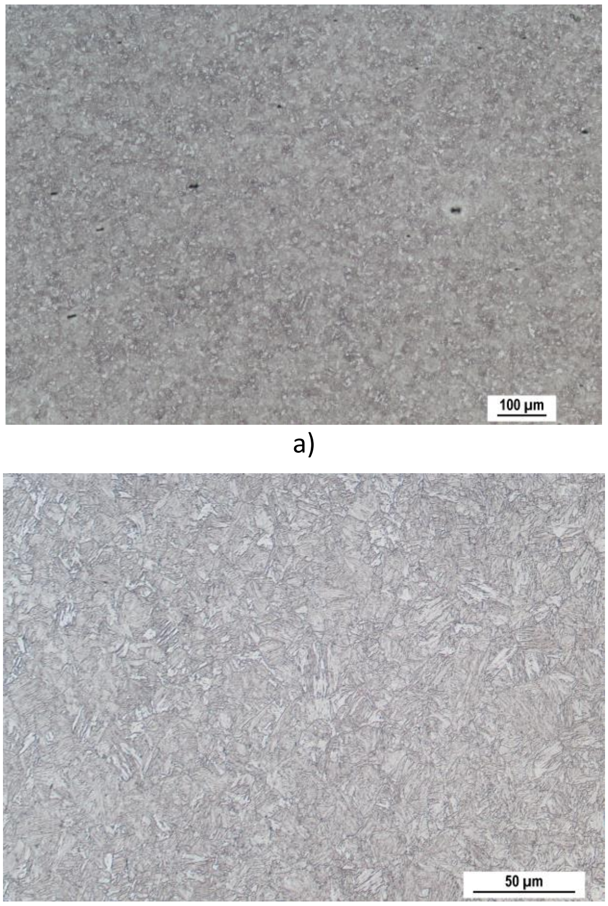
Steel grade	Chemical composition				
	C	Si	Mn	P	S
Exper. material	0.597	0.398	0.860	0.037	0.014
Standard	0.52 – 0.60	0.17 – 0.37	0.50 – 0.80	max. 0.040	max. 0.040
	Cr	Mo	Ni	Cu	Fe
Exper. material	0.345	0.033	0.193	-	Bal.
Standard	max. 0.25	-	max. 0.30	max. 0.30	Bal.

Table 2. Mechanical properties of the experimental material

Property	
Yield point (MPa)	1540
Ultimate tensile strength (MPa)	1686
Elongation (%)	10.1
Hardness (HRC)	49

This experimental material – steel C55 – is also characterized by the Si content, which increases the ultimate tensile strength, mainly the yield strength; Mn, which increases the hardenability and Cr, which increases the hardenability and inhibits the tempering processes [1,25].

The microstructure after the heat treatment (quenching and high tempering), Fig 2, was sorbitic formed by ferrite and cementite, in accordance with [26].



a)

b)

Fig. 2. Microstructure of the C55 steel, etched by the 3 % Nital, a) general view, b) detail

The specimens' surface was mechanically treated by grinding. The initial state of compressive residual stresses, after the grinding at temperature 20 °C, is shown in Fig. 3. The maximum value of the compressive residual stresses was about – 175 MPa and with increase of measurement's depth it slowly decreased and reached value close to zero, at approximately 0.2 mm under the surface. The surface layers of the specimens after the shot peening are characterized by the compressive residual stresses.

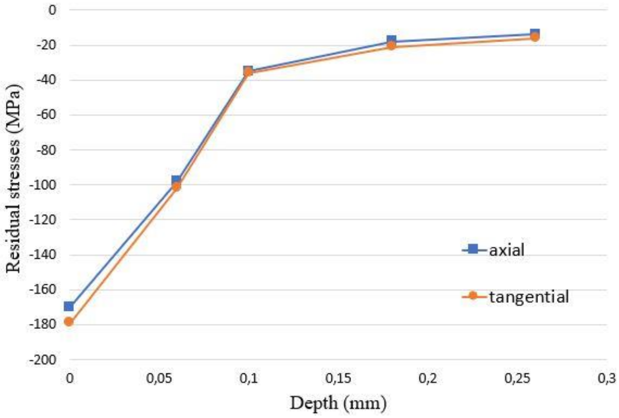


Fig. 3. Compressive residual stresses, initial state, 20 °C

The compressive residual stresses, determined at temperatures of 20 °C and 130 °C, after 100, 500 and 1000 hours are shown in Fig. 4 and Fig. 5. The experimental material, high-quality carbon steel (Tables 1 and 2) is used in car construction where the maximum operating temperature of 100 °C is assumed [3]. Therefore, a slightly higher temperature, namely 130 °C, was chosen as the experimental temperature.

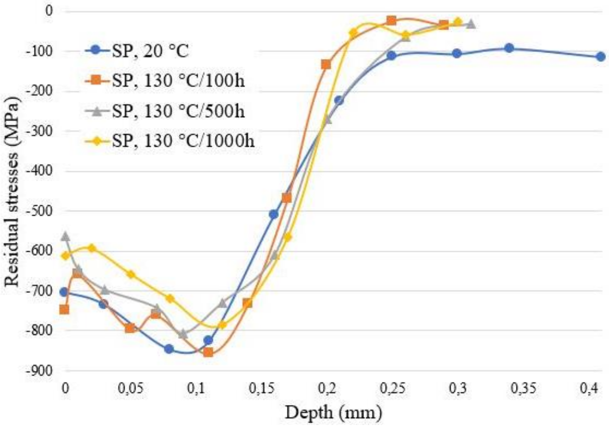


Fig. 4. Compressive residual stresses, temperatures 20 °C, 130 °C and after 100, 500 and 1000 hours, axial direction

From Fig. 4 and Fig. 5 can be seen that with increase of measurement's depth, the values of the compressive residual stresses slowly increase and at a depth of approximately 0.11 – 0.16 mm reach maximum values: in the axial direction from – 786 MPa to – 857 MPa and in the tangential direction from – 733 MPa to – 783 MPa.

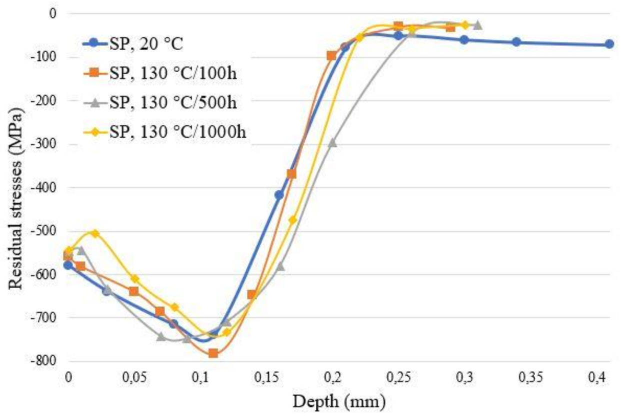


Fig. 5. Compressive residual stresses, temperatures 20 °C, 130 °C and after 100, 500 and 1000 hours, tangential direction

Beyond this point, the values decrease and reach values close to zero at a depth of approximately 0.2 – 0.3 mm under the surface. The compressive residual stresses levels are in the axial direction (Ø = 0°) and in the tangential direction (Ø = 90°) practically the same. Those facts agree with the works [3,7,18,24,27]. The authors state that application of the shot peening can produce values of the compressive residual stresses up to the size of the yield strength, usually at depths of up 0.1 to 0.2 mm (in the present case the value reached is 0.52 of the yield strength). In the real applications, components, subjected to operating conditions at elevated temperatures, may suffer the thermal relaxation effects, as well. That is the thermal recovery process in which the elevated temperatures accelerate annihilation of the crystal defects and the higher the applied temperatures the greater the relaxation. In such cases, the time, temperature, initial residual stresses and material properties have a profound effect on the resultant thermal residual stresses relaxation [3].

The obtained results, presented in this work, point to the fact that at a temperature of 130 °C after 100, 500 and 1000 hours, there was no significant decrease or instability of the compressive residual stresses [15-23].

4. CONCLUSION

Based on results of the experiments carried out, the following conclusion can be drawn:

- The compressive residual stresses were realized by the shot peening of the high-quality carbon steel C55;
- The magnitude of the compressive residual stresses has reached values of approximately 0.52 of the yield point of tested steel;
- Elevated temperature of 130 °C and times of 100, 500, 1000 hours, did not cause a significant decrease in compressive residual stresses;
- The obtained results could be used in the construction of vehicles in transport engineering;
- The future experimental work will be focused on the effect of cyclic temperature charges from -25 °C to + 35 °C during the time intervals of 100, 500 and 1000 hours, on the resulting values of compressive residual stresses.

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