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EFFECT OF SEVERE PLASTIC DEFORMATION ON MECHANICAL AND FATIGUE BEHAVIOR OF MEDIUM-C SHEET STEEL

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Abstract

The DRECE method belongs to the severe plastic deformation (SPD) processes used for the refinement of sheet metal elements. A forming device used in this method is currently being installed in the workplace in the Centre of Advanced Innovation Technologies, VSB Technical University of Ostrava. In the present work the structural characteristics and fracture morphology of Ck55 carbon steel after the application of the DRECE method with a forming tool angle of 118° are presented. The microstructure results are linked to selected mechanical properties. The tensile, hardness, and fatigue tests are performed. The methodology of non-destructive residual stresses measurement in the carbon steel after the extrusion and application of tensile tests on small samples are important for their use in technical practice. The paper presents the original results of selected properties after the application of the DRECE method on Ck55 steel, which will be used in the future to assess the application of the DRECE method and to determine other directions of the processing of ferrous alloys and steels.

Keywords*: Severe plastic deformation; DRECE method; Ck55 steel; Grain refinement; Mechanical properties; Residual stress*

1. Introduction

New technologies which use the high deformation for obtaining the fine-grained structures are intensively studied by many authors [1, 2]. This research is concerned with the whole production of ultrafine-grained (UFG) materials using Severe Plastic Deformation (SPD). Several types of the SPD technologies serving for the production of the UFG metals were already developed at the beginning of the 1990's as the following ones: ECAP (Equal Channel Angular Pressing), DCAP (Dissimilar Channel Angular Pressing), CONFORM (Continual Forming), HPT (High Pressure Torsion), CCDC (Cyclic Channel Die Compression), ARB (Accumulative Roll Bonding), and CGP (Constrain Groove Pressing) [3-5]. One of them is a new type of method called DRECE (Dual Rolls Equal Channel Extrusion) designed for obtaining UFG structures in sheets and rods [6]. The performance and applications of nanostructured materials produced by severe plastic deformation is presented in [7]. Research areas of the SPD processes as ECAP and the DRECE method are intensively developed [8, 9]. The effectiveness of this method is evaluated by the use of different simulations [10-12]. Appropriate adjustments of the forming tool have been designed to achieve a higher intensity of deformation. It allows obtaining the UFG structure. With the use of the simulation [12] the SPD is predicted to increase the intensity of deformation after 5 – 6 passes to a value $\varepsilon_{\imath max} = 3.5$, which is a region of medium deformation levels. The investigation of a new shear deformation method for the production of nanostructures in low-carbon steel was analysed by Raab et al. [13]. The functionality of the forming device with a new DRECE method by the use of the SPD process has been verified, especially in non-ferrous metals and mild steels. Experimental works on low carbon steels are given in works [14-17]. Cu and brass alloys [18, 19] and other non-

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ferrous metals [20, 21] are very often subjected to this advanced production method.

The aim of the present paper is to analyse the possibilities of the DRECE method application for strengthening the medium-C sheet steel and to find relationships between structural details and mechanical and fatigue properties.

2. Material and procedures

The study material was a cold-rolled metal sheet of medium-C steel (Ck55 grade). The chemical composition is shown in Table 1.

The strip sheet with the dimensions 58 x 2 x 1000 mm and 2000 mm length was used for the study. The sheets were extruded through the forming equipment with the DRECE method. The DRECE method is similar to the Dissimilar Channel Angular Pressing process (DCAP). The scheme of the DRECE method is shown in Figure 1 and a forming device for the extrusion of strip sheets is shown in Figure 2.

The equipment consists of the following main parts: a Nord (SK7382/22VX2WD-71S/4TF) gear with an electric drive, a disc clutch, a feed roller, and pressure rollers with the regulation of thrust, and a forming tool made of the special steel Dievar (AISI H13). A strip of the sheet is fed into the working space and it is pushed by the feed roller with the help of pressure rollers through the forming tool without a change of its cross section [6].

Mechanical properties (yield strength $R_{p0.2}$, ultimate tensile strength R_m, ductility A_{80}) on a test-stand LFV 100-HM produced by the Swiss company *Walter + Bai ag* (see Figure 3a) and hardness HV10 using a hardness tester HPO 250 were evaluated in the initial state and after the forming process. The tensile tests were performed according to the ISO 6892 - 1 using standard test-pieces according to Annex D. The sample was cut at the longitudinal direction of the sheet deformation. Five samples were used for each condition. The average values and standard deviations were calculated.

The fatigue strength was tested using a test-stand LFV 100-HM (Figure 3a) with specially prepared samples (Figure 3b) to determine the site of fatigue fracture initiation at the constriction place. An alternating load with a frequency of 40 kHz was used.

The tensile test on small samples was evaluated in the initial state and after the forming process to assess the possibility of anisotropic properties occurrence after the SPD process. The schematic representation of the sheet metal with the indication of the places for removal samples and its size are shown in Figure 4a and 4b. As it can be seen, the sample was cut at the longitudinal and perpendicular directions of the sheet deformation.

The investigations were completed by the metallographic evaluation of the microstructure at successive stages of the forming process. Light microscopy (Neophot 2) was employed to reveal the microstructure of the steels using the bright field technique. Conventional metallographic techniques (mechanical grinding with SiC paper up to 2000 grid and polishing with a diamond paste) for the samples' preparation followed by Nital etching were applied. The fracture surfaces of the samples after the fatigue tests were analyzed. The analysis was done by using ASPEX PSEM EXPLORER scanning electron microscope.

To assess the effect of the SPD process on the generation and redistribution of residual stresses the magnetoelastic method based on the Barkhausen noise was used. The precise knowledge of the level

Table 1. *Chemical composition of medium-C steel according to the standard*

Chemical composition (weight %)								
C	Mn	Si	P	S	Cr	Ni	Mo	Fe
0.52-0.6	0.6-0.9	max. 0.4	max. 0.04	max. 0,04	max. 0.25	max. 0.3	max. 0.1	base

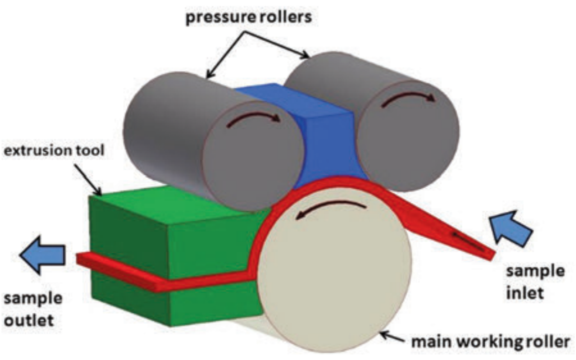

Figure 1. *Scheme of the DRECE method*

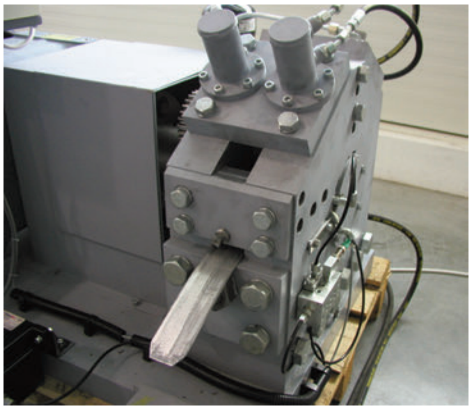

Figure 2. *Forming device for the extrusion of strip sheets*

and distribution of residual stresses are crucial for the successful application of the materials in the industry.

3. Results and discussion

3.1. Hardness and mechanical properties

A schematic illustration of the sampling used to monitor the evolution of the reinforcement after the DRECE process depending on the position in the sheet sample is shown in Figure 5. The measure of the strengthening was assessed by applying HV10 hardness.

The results of the HV10 hardness measurement depending on the position in the sheet metal and number of passes are shown in Figure 6. The hardness values represent the average of the five measurements. As can be seen, the hardness is the highest on the surface area compared to the values measured in the cross section. The hardness values increase significantly after the first passage. After further passages, the increase in hardness is slower. It is also evident from the graph that the increase in hardness of the surface layer with the increasing number of passages is greater than in the cross section, which is in accordance with the analysis of the deformation in the material volume based on the computer simulation [12].

The results of mechanical properties received from the tensile test and hardness test are shown in Figure 7. On the basis of the results obtained from the tensile tests, it can be stated with respect to the initial state that after the 2nd pass the yield strength $R_{p0,2}$ is increased by 118 MPa and the ultimate tensile strength R_m by 42 MPa.

At the same time, there is a slight corresponding decrease in ductility (approx. 8%). After the 6th pass through the forming tool, the yield strength increased by 180 MPa and the ultimate tensile strength by 80 MPa relative to the initial state. One can see that the yield strength and ultimate tensile strength after the SPD process are increased whereas the elongation is slightly decreased. It means that the applied DRECE method is an effective method of the strengthening.

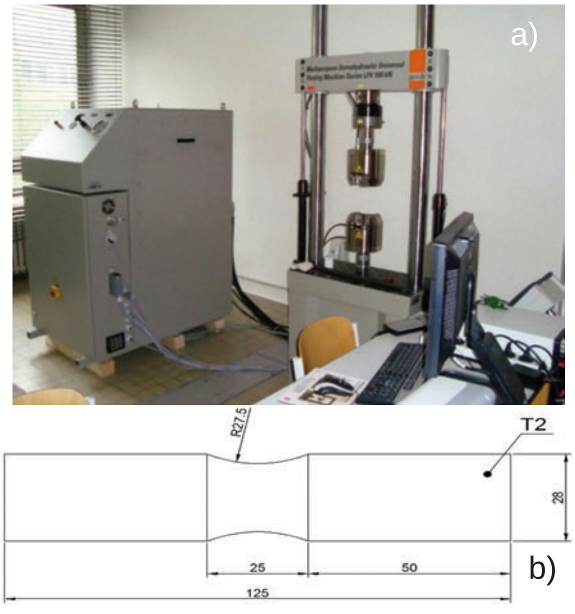

Figure 3. *Test stand LFV 100-HM (a); specimen for fatigue strength tests (b). T2 – thickness of the sample*

The results of mechanical properties from the tensile test using small samples taken at longitudinal and transverse directions are shown in Figures 8 and 9.

The values of mechanical properties in both directions are not too much different and it may be assumed that the formation of anisotropic properties

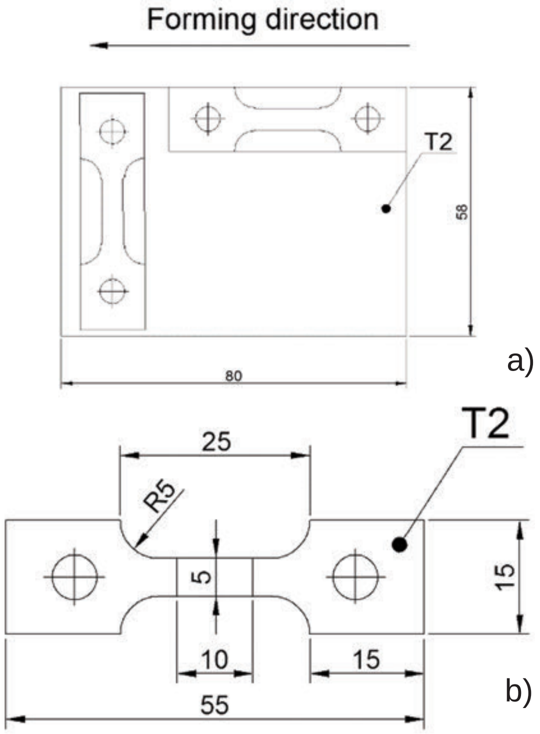

Figure 4 *.Schematic of small sheet metal specimens for the location of their places (a) and size of specimen (b). T2 – thickness of the sample*

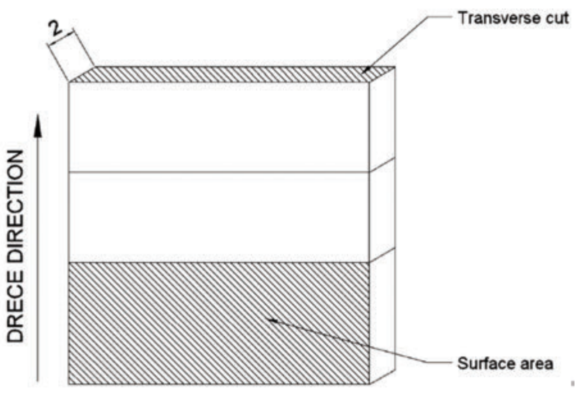

Figure 5. *Schematic of the surfaces for hardness measurement*

does not occur, which usually takes place after the conventional rolling. Compared to the results of the mechanical properties according to the ISO 6892 - 1 using standard test-pieces, they are in good consistency; the higher ductility values are due to the fact that ductility depends on the test specimen size. Average tensile properties with standard deviations (5 samples in each condition) are listed in Table 2.

3.2. Fatigue properties

The fatigue test on Ck55 steel in the initial state and after the 1st pass to assess the influence of the DRECE method on the fatigue properties of this steel was chosen. The least squares approximation method was used for the evaluation of the fatigue results [22, 23]. The values for the approximation were selected from 10^5-10^7 cycles to failure. Subsequently, the approximation of the measured points was conducted. The following equation, generally known as the Basquin equation (1), was applied for the approximation in the high cycle fatigue regime (S-N curve).

$$\sigma_a = \sigma_f^{'} \cdot \left(2N_f\right)^b \tag{1}$$

where: σ_f is the fatigue strength coefficient and b is the exponent of fatigue strength.

In the same manner the curves for double-sided confidence intervals of the approximated curves were assembled. For the reliability of calculations the tables of critical values of a Student distribution for θ degrees of freedom confidence level $\alpha = 0.05$ were used. All the calculated values and the resulting approximations are shown in Figures 10 and 11. The Matlab software was applied as a computational tool. The evaluation of sided confidence intervals was performed according to the equation (2):

$$\log N = a + b \cdot \sigma \tag{2}$$

where the unknown constants a and b were calculated by the least squares approximation method.

The results of the calculation of fatigue tests are shown in Figures 10 and 11. It can be observed that the fatigue characteristics exhibit better values compared with the characteristics of the steel in the initial state.

3.3. Residual stresses

The analysis was conducted using the magnetoelastic method (Magnetic Barkhausen Noise-MBN). A similar approach of the measurement of residual stress and the characteristics of the

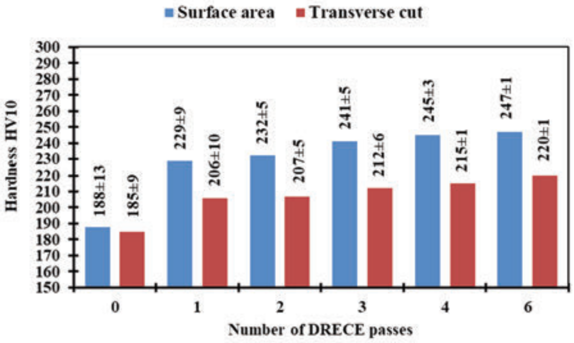

Figure 6. *Hardness HV10 depending on a position in the sheet metal and number of extrusion passes through forming device*

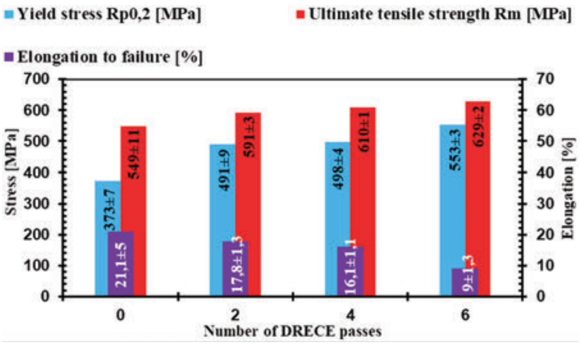

Figure 7. *Mechanical properties of Ck55 steel after the extrusion process*

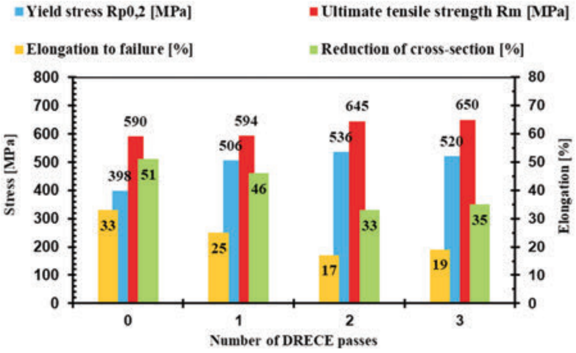

Figure 8. *Mechanical properties of Ck55 steel after the extrusion process – longitudinal direction*

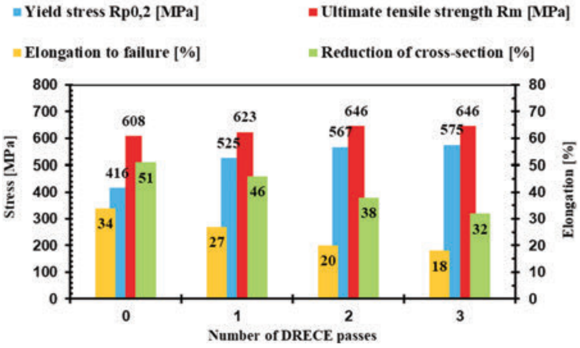

Figure 9. *Mechanical properties of Ck55 steel after the extrusion process – transverse direction*

magnetoelastic method are included in [24-27]. The MBN signal is affected by many microstructural features and also by applied or residual stresses. The fundamentals of the relation between MBN and stress are relatively well understood in the literature [25]. Ferromagnetic materials experience the magnetostriction phenomenon depending on the magnetic field and stress state. For ferromagnetic materials such as steels and cobalt which have a positive magnetostriction coefficient λ, the MBN signal shows an increasing trend in the direction of the applied elastic tensile stress. On the other hand, an applied elastic compressive stress decreases the magnetization in the materials with the positive magnetostriction. Materials with negative magnetostriction coefficients show the reverse effect [25]. To evaluate the impact of the SPD process on the distribution of residual stresses, we used samples in an initial state and after six drafts. For the residual stress analysis, the commercial measurement equipment (Intromat) with a surface sensor was used [27].

An assessment of residual stresses was conducted in accordance with the methods presented in [28-30]. The test has been done in the centre of the strip. The polar graphs depicting the magnetic parameter MBN respective residual stresses distribution are depicted in Figures 12 and 13. Application of six forming drafts led to the levelling of residual stress values over the width of the strip and to an increase of the compression stress in the draft direction. Figure 14 shows the change of MBN in the initial state and after the 2nd, 4th, and 6th passage in the main stress directions in the center of the strip. According to the calibration procedure [26, 27] the MBN values below 900 mV correspond to the compression stresses. The MBN values above 900 mV correspond to tensile stresses.

Table 2. *Tensile properties with the standard deviations*

Number of DRECE passes	Yield strength $R_{p0,2}$ [MPa]	Ultimate tensile strength R_m [MPa]	Elongation to failure A [%]	Reduction in area Z [%]
Longitudinal direction				
0	398 ± 9,4	590 ± 7,7	33 ± 1,3	51 ± 1,9
1	506 ± 5,8	594 ± 6,1	25 ± 1,2	46 ± 1,4
2	536 ± 1,2	645 ± 5,8	17 ± 1,1	33 ± 1,3
3	520 ± 1,8	650 ± 3,8	19 ± 1,1	35 ± 1,3
Transverse direction				
0	416 ± 6,9	608 ± 8,1	34 ± 1,9	51 ± 2,3
1	525 ± 3,6	623 ± 6,3	27 ± 1,9	46 ± 1,3
2	567 ± 2,8	646 ± 4,7	20 ± 1,4	38 ± 1,5
3	575 ± 2,0	646 ± 4,6	18 ± 1,2	32 ± 1,3

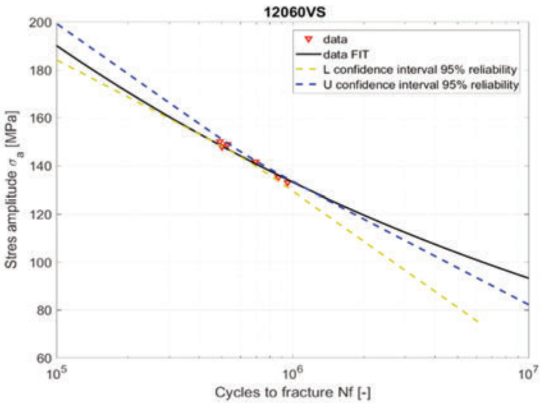

Figure 10. *Basquin's characteristics of regression lines with confidence interval (α = 0.05) for Ck55 steel - initial state*

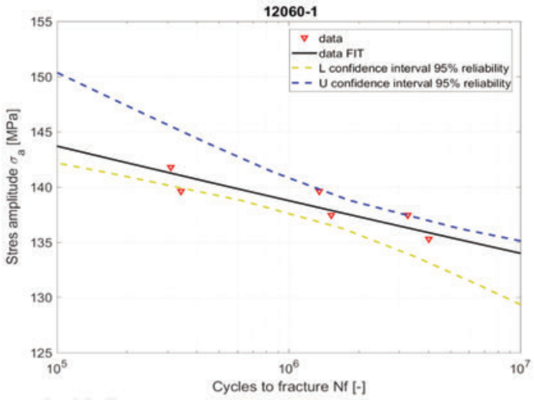

Figure 11. *Basquin's characteristics of regression lines with confidence interval (α = 0,05) for Ck55 steel after the 1st pass*

3.4. Metallographic analysis
3.4.1. Light Microscopy

Microstructures of Ck55 steel in the initial state are shown in Figure 15. The structure of the steel used is ferrite and globular precipitates of cementite. Such a microstructure is typical for the steels subjected to the spheroidizing treatment. The presence of hard particles in the soft matrix makes the steel machinable. Moreover, the present experiment shows that the steel in such a state is formable. The microstructures of Ck55 steel after the 1st pass and 3rd pass at different sections are shown in Figure 16. There are no clear microstructural differences between the initial state and after deformation by the DRECE method. There is no grain refinement but some directional arrangement of grains in the longitudinal sections can be visible for the plastically deformed samples (Figure 16a and b). However, it is rather difficult to assess at this magnification level. Other microstructural techniques are planned to confirm this behaviour. It seems that the subgrain interactions dominate grain refinement [18].

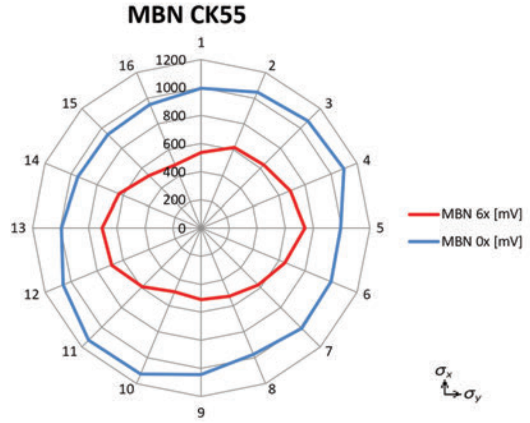

Figure 12. *Polar graph of the MBN distribution, initial state and after six passes, a centre strip*

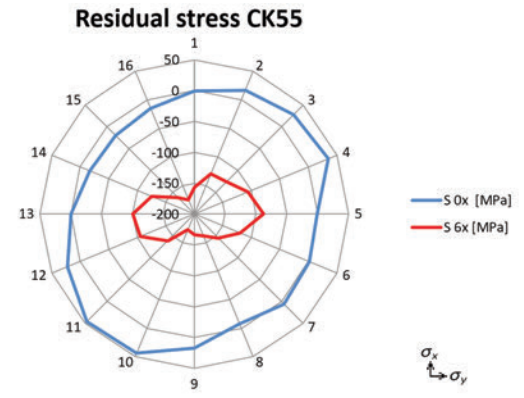

Figure 13. *Polar graph of residual stress distribution, initial state and after six passes, a centre strip*

3.4.2. Fractography

Fracture surfaces of Ck55 steel after the tensile test are shown in Figures 17-21. The set of the macrographs and corresponding details of the fracture area are presented. The comparison was made between the initial state, the first pass, and after the 3rd pass. All the fracture surfaces show a ductile fracture mode with dimples of similar size independent from a deformation stage.

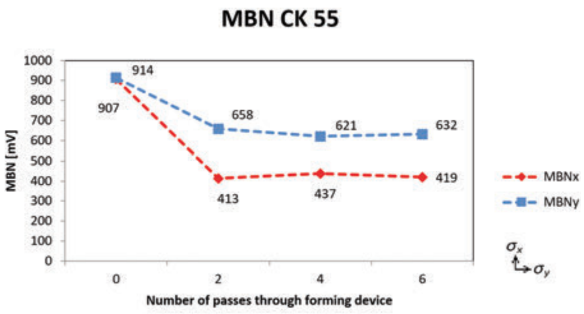

Figure 14. *Influence of number of passes through the forming tool on MBN in the major stress directions*

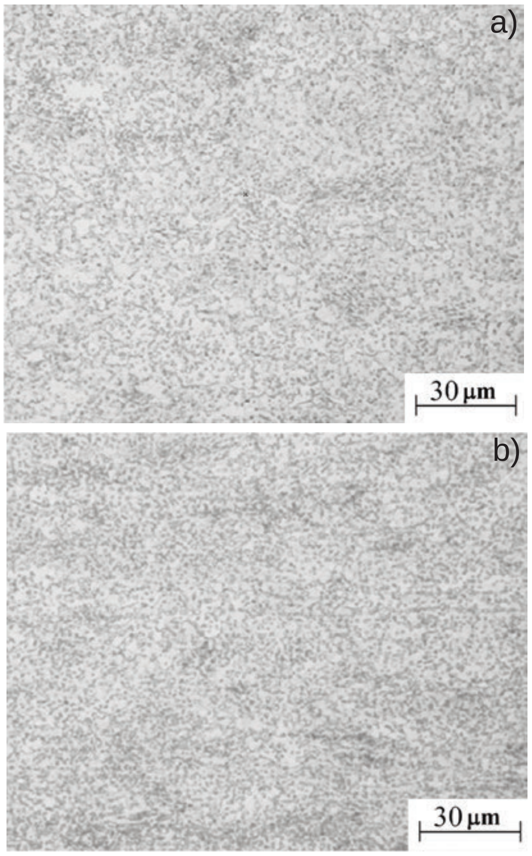

Figure 15. *Microstructures of Ck 55 steel: initial state (a) sheet section (b); cross section*

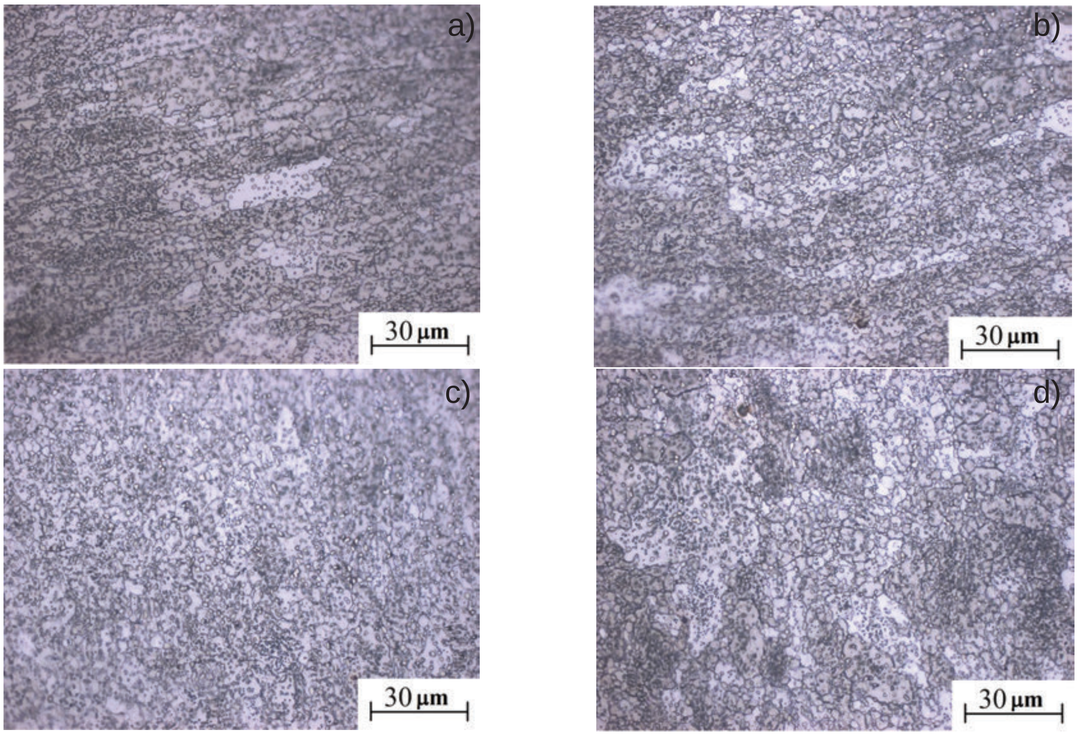

Figure 16. *Microstructures of Ck 55 steel after the 1st pass and 3rd pass at different sections: sheet section (a, b), cross section (c, d)*

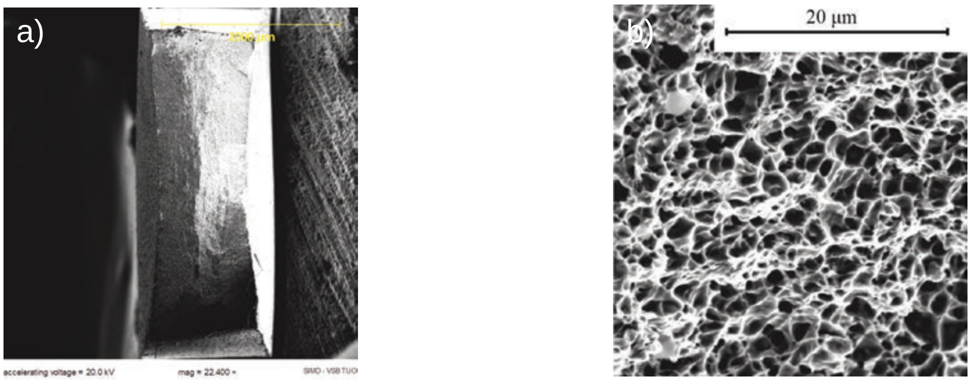

Figure 17. *Fracture area of Ck55 steel after tensile test: initial state, macrograph (a); detail (b)*

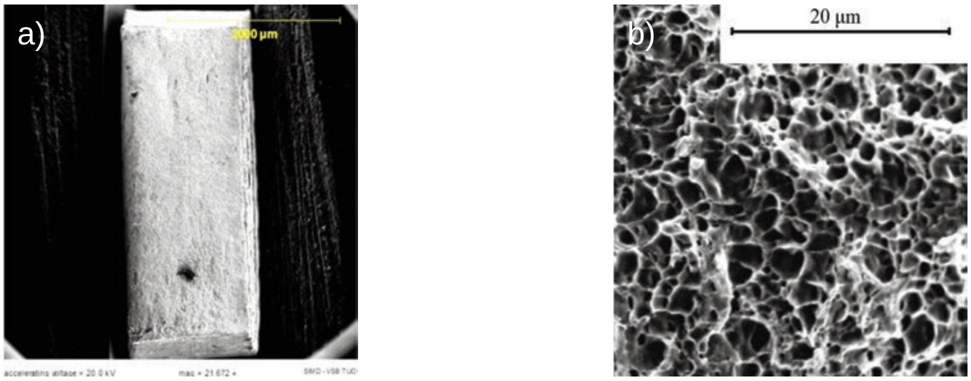

Figure 18. *Fracture area of Ck55 steel after tensile test: after the 1st pass – longitudinal sample, macrograph (a); detail (b)*

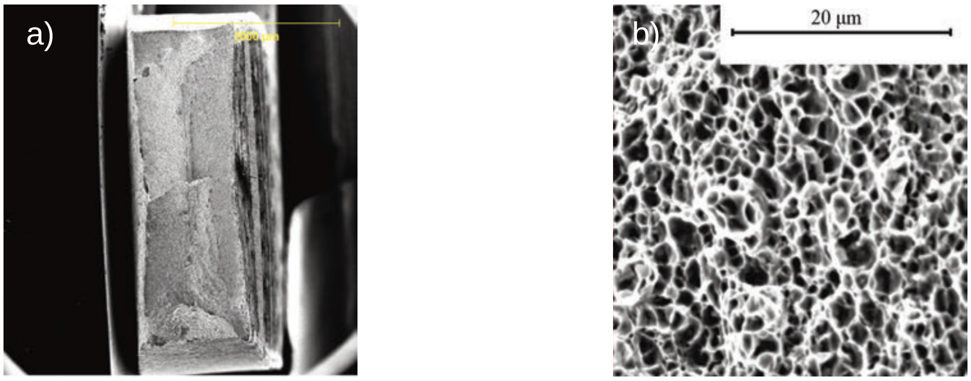

***Figure 19.** Fracture area of Ck55 steel after tensile test: after the 1st pass – perpendicular sample, macrograph (a); detail (b)*

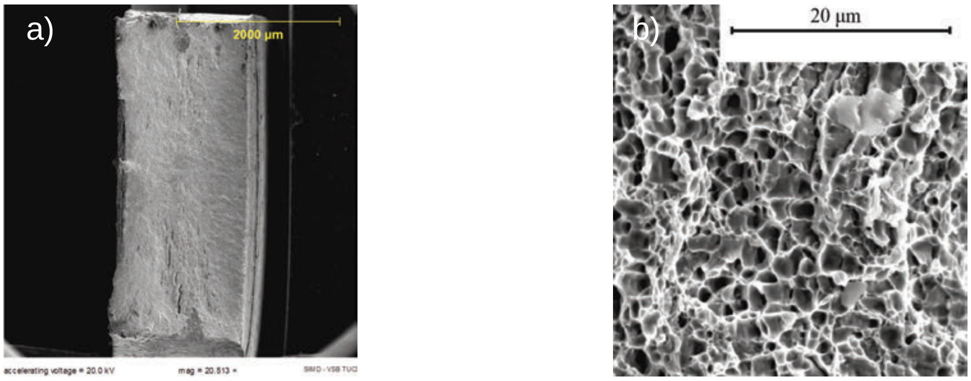

***Figure 20.** Fracture area of Ck55 steel after tensile test: after the 3rd pass – longitudinal sample, macrograph (a); detail (b)*

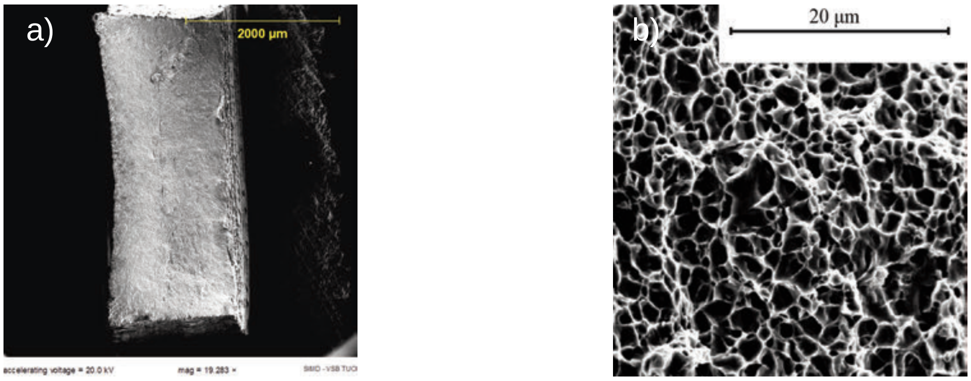

***Figure 21.** Fracture area of Ck55 steel after tensile test: after the 3rd pass – perpendicular sample, macrograph (a); detail (b)*

4. Conclusions

The DRECE equipment is suitable for the substantial enhancement of mechanical properties of metallic materials. The results of the tensile test indicate that the yield strength and ultimate tensile strength after the applied SPD process are increased, whereas the elongation is decreased. The optimal mechanical properties represented by the optimal parameters of yield stress, ultimate tensile strength and ductility can be obtained for the number of passes between 2 and 4. The values of mechanical properties in both directions are not too much different and the formation of anisotropic properties is not detected. The DRECE method brings compression stress into the material, which is favourable for the further processing and use. The largest change is seen in the extrusion direction after the first pass. More pronounced changes in the perpendicular direction to the extrusion direction can only occur with a higher number of passes. The use of the magneto-elastic method enables a detailed projection of individual technological steps for steel production and very effective optimisation of the individual parameters of the forming technology. No grain refinement is observed for deformed samples. The fracture behaviour does not change for successive deformation stages. The steel maintains ductile behaviour even after applying six passes. This fact is consistent with the results of the mechanical properties. The fatigue performance is better compared with the characteristics of the steel in the initial state.

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UTICAJ INTENZIVNE PLASTIČNE DEFORMACIJE NA MEHANIČKE KARAKTERISTIKE I ZAMOR SREDNJE UGLJENIČNOG ČELIČNOG LIMA

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Apstrakt

DRECE metod pripada procesima intenzivne plastične deformacije (SPD) koji se koriste za preradu elemenata od lima. Uređaj za oblikovanje koji se u ovoj metodi koristi se trenutno instalira u Centru za napredne inovativne tehnologije, VSB Tehnički univerzitet u Ostravi. U ovom radu predstavljene su strukturne karakteristike i morfologija loma Ck55 ugljičnog čelika posle primene DRECE metoda sa uređajem za oblikovanje od 118°. Rezultati mikrostrukturnih analiza su u vezi sa odabranim mehaničkim osobinama. Izvršeni su testovi istezanja, tvrdoće, i zamora materijala. Metodologija nerazarajućeg merenja zaostalih naprezanja u ugljičnom čeliku posle istiskivanja kao i primena testova na istezanje na malim uzorcima su važni zbog njihove primene u tehničkoj praksi. U ovom radu su predstavljeni originalni rezultati odabranih osobina posle primene DRECE metode na Ck55 čelik, a koji će biti u budućnosti korišćeni za procenu primene DRECE metode kao i za određivanje pravaca rešenja koji se tiču ovog i drugih odabranih vrsta čelika.

Ključne reči: *Intenzivna plastična deformacija; DRECE metoda; Ck55 čelik; Usitnjavanje; Mehaničke osobine; Zaostalo naprezanje*