Effect of severe plastic deformation on mechanical and fatigue behaviour 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 at the workplace in the Centre of Advanced Innovation Technologies, VSB Technical University of Ostrava. In the present work 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 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 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 solution on this and other selected 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 concerned the whole production of ultrafine-grained (UFG) materials using Severe Plastic Deformation (SPD). Several types of the SPD technologies serving for production of the UFG metals were developed already at the beginning of the nineties 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 the 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 $\varepsilon_{\text{max}} = 3.5$, 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-ferrous metals [20,21] are very often subjected to this advanced production method.

The aim of the present paper is to analyse possibilities to apply the DRECE method 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.

| Chemical composition (weight %) | C     | Mn | Si | P     | S     | Cr | Ni | Mo | Fe    |
|---------------------------------|-------|----|----|-------|-------|----|----|----|-------|
| C (weight %)                    | 0.52-0.6 | max. | max. | 0.4   | 0.04  | max. | max. | max. | max. base |

The strip sheet with 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 extrusion of strip sheets is shown in Figure 2.
The equipment consists of the following main parts: a gear of the type Nord (SK7382/22VX2WD-71S/4TF) with an electric drive, disc clutch, feed roller and pressure rollers with the regulation of thrust, 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 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 directions 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), for the reason determining 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.

![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.](image)

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 samples after the fatigue tests were analyzed. The analysis has been done 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 and distribution of residual stresses are crucial to 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 it 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].

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.

![Figure 6. Hardness HV10 depending on a position in the sheet metal and number of extrusion passes through forming device](image-url)
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.

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

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

**Figure 8. Mechanical properties of Ck55 steel after the extrusion process – longitudinal direction**
The values of mechanical properties in both directions are not too much different and it may be assumed that the formation of anisotropic properties 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 a size of the test specimen. Averaged tensile properties with standard deviations (5 samples in each condition) are listed in Table 2.

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                 |

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]. 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).

$$\sigma_a = \sigma_f' \cdot (2N_f)^b,$$

(1)

where: $\sigma_f$ 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 $\theta$ 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):

$$\log N = a + b \cdot \sigma,$$

(2)

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

![Figure 10. Basquin's characteristics of regression lines with confidence interval ($\alpha = 0.05$) for Ck55 steel - initial state](image)

Results of the calculation of fatigue tests are shown in Figures 10 and 11. One can observe that the fatigue characteristics exhibit better values compared to the characteristics of the steel in the initial state.
3.3. Residual stresses

The analysis has been conducted using the magnetoelastic method (Magnetic Barkhausen Noice-MBN). A similar approach of the measurement of residual stress and the characteristic of the 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 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 $\lambda$, 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 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. 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 levelling of residual stress values over the width of the strip and to an increase of compression stress in the draft direction. Figure 14 shows the change of MBN in the initial state and after the 2nd, 4th and 6th passages 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.
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. Microstructures of Ck 55 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 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 than grain refinement [18].

![Figure 15. Microstructures of Ck 55 steel: initial state (a) sheet section (b); cross section](image)

![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)](image)
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, first pass and after the 3rd pass. All the fracture surfaces show a ductile fracture mode with dimples of similar size independent on a deformation stage.

![Image](a)

(a)

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

![Image](b)

(b)

![Image](a)

(a)

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

![Image](b)

(b)

![Image](a)

(a)

**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 3\textsuperscript{rd} pass – longitudinal sample, macrograph (a); detail (b)

Figure 21. Fracture area of Ck55 steel after tensile test: after the 3\textsuperscript{rd} 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 has been 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 individual parameters of the forming technology. No grain refinement has been 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 to the characteristics of the steel in the initial state.

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References
1. M.Y. Gutkin, I.A. Ovidko, C.S. Pande, Rev. Adv. Mater. Sci., 2 (2001) 80-102.
2. R.Z. Valiev R. Z., Mater. Sci. Forum, 579 (2008) 1-14.
3. R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Prog. Mater. Sci., 45 (2000) 103-189.
4. L.S.Toth, C. Gu, Mater. Charact., 92 (2014) 1-14.
5. T. Tański, P. Snopiński, W. Pakiela, W. Borek, K. Prusik K., S. Rusz, Arch. Civ. Mech. Eng., 16 (2016) 325-334.
6. O. Hilšer, M. Salajka, S. Rusz S, 7th International Conference on Nanomaterials-Research and Application, NANOCON 2015, Brno, Czech Republic, 2015.
7. Y.T. Zhu, T.C. Lowe, T.G. Langdo, Scripta Mater., 51 (2004) 825-830.
8. S. Rusz, A. Kłyszewski, M. Salajka, O. Hilšer, L. Čížek, M. Klos, Arch. Metall. Mater., 60 (2015) 3011-3015.
9. E. Fakhretdinova et al., Processing ultrafine-grained aluminum alloy using Multi-ECAP-Conform technique. In: IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2014.
10. D.F. Zhang et al., Transactions of Nonferrous Metals Society of China, 20 (2010) 478-483.
11. A.V. Botkin, E.V. Varenik, M.S. Kelner, Journal of Machinery Manufacture and Reliability, 40 (2011) 467-471.
12. S. Rusz, K. Malanik, J. Dukiewicz, L. Čížek, T. Donič, J. Kedroň, S. Tylšar, Arch. Mater. Sci. Eng., 42 (2010) 111-118.
13. A.G. Raab et al., 6th International Conference on Nanomaterials by Severe Plastic Deformation, NanoSPD6, Metz, France, 2014.
14. K. Kowalczyk, M. Jabłońska, S. Rusz, G. Junak, Arch. Metall. Mater., 63 (2018) 1957-1961.
15. K. Kowalczyk, M. Jabłońska, S. Rusz, I. Bednarczyk I., Arch. Metall. Mater., 63 (2018), 2095-2100.
16. S. Rusz, L. Cizek, M. Salajka, J. Kedron, S. Tylsar, 6th International Conference on Nanomaterials by Severe Plastic Deformation, NanoSPD6, Metz, France, 2014.
17. S. Rusz, L. Cizek, M. Salajka, J. Kedron, S. Tylsar, 4th International Conference Recent Trends in Structural Materials, COMAT 2016, Pilsen, Czech Republic, 2017.
18. S. Rusz, J. Dukiewicz, M. Faryna, W. Maziarz, L. Rogal, J. Bogucka, K. Malanik, J. Kedron, S. Tylsar, Solid State Phenom., 186 (2012) 94-97.
19. J. Till, J. Michalski J. Petrů, F. F. Špalek, 27th International Conference on Metallurgy and Materials, METAL 2018, Brno, Czech Republic, 2018.
20. S. Rusz, M. Salajka, M. Kraus, O. Híšer, M. Klos, L. Čizek, Study of the properties of UFG materials after the application of new forming methods. In METAL 2015, 24th International Conference on Metallurgy and Materials, METAL 2015, Brno, Czech Republic, 3-5 June 2015.
21. P. Snopiński, T. Tański, K. Labisz, S. Rusz, P. Jonšta, M. Król, Int. J. Mater. Res., 107 (2016) 637-645.
22. F. Eliyn, Fatigue damage, crack growth and life prediction. Chapmann & Hall, 1997, ISBN 041259600.
23. P. Lukáš et al. Cyklicka deformacia a unava kovov. Vydavatelstvo Slovenskej akademie vied, Bratislava 1987.
24. S. Tiitto, Magnetic methods. Handbook of measurements of residual stresses, 1st ed.; Society for Exper. Mech., Lilburn, NJ, USA, 1996, 179-224.
25. V.L. Vengrinovich, V.L. Tsukerman, In 6th WCNDT 2004-World Conference on NDT. Montreal, Canada, 2004.
26. V. Ochodek, In ICBM 6th International Conference on Barkhausen Noise and Micromagnetic Testing, University of Valenciennes, Valenciennes, France, 2007.
27. V. Linhart, J. Sigmundová, V. Ochodek, In 24th DANUBIA-ADRIA Symposium on Developments in Experimental Mechanics, Universitatea Lucia Blaga, Romania, 2017, 79-81.
28. P.E. Mix, Introduction to nondestructive testing: A training guide, 2nd ed., John Wiley & Sons Inc., 2005, 690.
29. J. Capo-Sanchez, M. Alberteris Campos, L.R. Padovese, NDT and E Inter., 40 (2007) 520-524.
30. J. Capo-Sanchez, J. Perez-Benitez, L. Padovese, NDT and E Inter., 40 (2007) 168-172.
Figure captions

Figure 1. Scheme of the DRECE method

Figure 2. Forming device for the extrusion of strip sheets

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

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

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

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

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

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

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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)

Table captions

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

Table 2. Tensile properties with the standard deviations