INFLUENCE OF SPD PROCESS ON LOW-CARBON STEEL MECHANICAL PROPERTIES

STANISLAV RUSZ, ONDREJ HILSER, VLADISLAV OCHODEK, RADEK CADA, JIRI SVEC, PAVEL SZKANDERA

Dept. of Mechanical Technology, Faculty of Mechanical Engineering, VSB – Technical University of Ostrava

DOI: 10.17973/MMSJ.2019_06_201890

radek.cada@vsb.cz

Paper analyses the influence of different values of the angle of the deformation zone in the forming tool on severe plastic deformation (SPD) process and on mechanical properties of resulting steel strip. Forming equipment using the severe plastic deformation (SPD) process and DRECE (Dual Rolling Equal Channel Extrusion) method builded and installed in the laboratory for the development of new technologies at the Faculty of Mechanical Engineering of VSB – Technical University of Ostrava is described. Tests were carried out at selected low-carbon deep-drawing steel DC01. By magnetoelastic method the residual stresses in material after separate passes were analyzed. DRECE method of forming brings compression stress into the material, which is favorable for further use.

KEYWORDS

Steel strip, severe plastic deformation, mechanical properties, low-carbon steel, magnetoelastic method, residual stress.

1 INTRODUCTION

Sheet-metal is often used for production of parts by technologies of cutting, bending and drawing. Especially for deep-drawing technology before processing the formability of deep-drawing steel sheets must be analyzed [Cada 1997, Cada 1996]. The sheet-metal properties are significantly affected by the way they are produced. At present, the production of metallurgical semi-products by continuous casting is mainly used [Velicka 2013, Pyszko 2013]. Components with higher strength requirements should be manufactured from high strength steel sheets [Evin 2014]. For some special parts there may be a requirement for high strength and very fine structure.

Development of technologies for the production of the very fine structure is currently very intensively accelerated. Even in scientific research it is recognized that precisely controlled forming processes, including special processes, enabling control of technological parameters with regard to the structure refinement, and tied with the strengthening of materials, currently have the highest gradient of utilization efficiency of the scientific research findings in practice. Regarding these drawbacks, a new deformation approach is developed for the continuous production of sheet or strip products with ultra-fine grain (UFG) microstructure, called equal channel angular rolling method (ECAR); developed by Lee et al. by modifying the ECAP process [Lee 2001, Lee 2002]. Since the ECAR method is a continuous process, it is more worthy of attention than other SPD techniques and conventional cold rolling processes. The studies on Al, Cu and its alloys [Lee 2001, Lee 2002, Saray 2010] have shown that SPD via ECAR process causes a reduction in strength and an increase in elongation. Also, the formability was increased due to change from the basal plane to the non-basal plane of crystal orientation and propagation of twins after ECAR. This behavior of specimens of Mg alloys processed by ECAR is in contrast with the response of other metals, such as Cu [Kvackaj 2012] and steel [Saray 2010]. In the metals like Cu and steel, the deformation by ECAR increases the strength and decreases elongation. Besides the DCAP (C2S2) and ARB method for sheet-metal forming, from the perspective of industrial practice new technologies are being intensively developed, to which belongs also the DRECE (Dual Rolls Equal Channel Extrusion) method, which was improved by the use of new forming tools with a new geometry (smaller angles in the zone of deformation). The issues of production of materials with ultra-fine grain (UFG) structure in the form of sheet-metal strip are analyzed in detail. A comparison is made of basic mechanical properties of the tested material achieved after severe plastic deformation with the properties of this material in the initial state. The ECAR method is one of the similar methods of forming, approaching a continuous production process.

Unlike the DRECE method it works with totally different inputs and also with hot forming, although it has a lower strengthening, but it lacks a dislocation strengthening as a source of grain refinement. From this perspective, this used method of forming (DRECE) is completely original.

2 FORMING EQUIPMENT

Device "DRECE - Dual Rolls Equal Channel Extrusion" (Dual Rolls Pressure Combined with Equal Channel Extrusion) is used for production of metallic materials with very fine grain size. During the actual forming process the principle of severe plastic deformation is used.

The forming equipment (see Fig. 1) consists of the following main parts: “Nord” type gearbox, electric motor with frequency speed converter, multi-plate clutch, feed roller and pressure rollers with regulation of thrust, and of the forming tool itself – made of Dievar steel type.

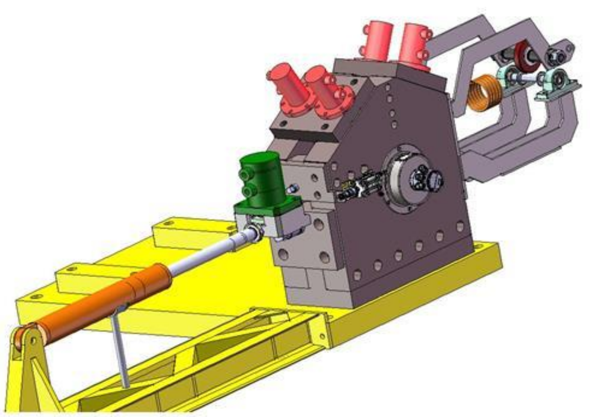

Figure 1 Diagram of innovated forming equipment (DRECE method)

The forming equipment is constructed for strip with dimensions 58 x 2 x (1000–2000) mm. Structural modifications of the equipment make possible to push at present the metal strip with the lengths up to 2000 mm. The metal strip is inserted into the working space (see Fig. 2) and it is pushed by the feed roller in interaction with pressure rollers through the forming tool without any change of the cross-section of the strip [Rusz 2014, Rusz 2013]. In this way a significant refinement of grain is achieved by severe plastic deformation.

By performed severe plastic deformation it is possible to achieve a substantial enhancement of mechanical properties while maintaining the necessary plasticity. The geometry of forming tool, in particular, the inclination angle of the approach of the forming curve in the zone of deformation (see Fig. 3) is a very important factor influencing the efficiency of the SPD process. Apart from materials, particularly the geometry of the forming tools is a very important factor of the forming method DRECE [Rusz 2015].

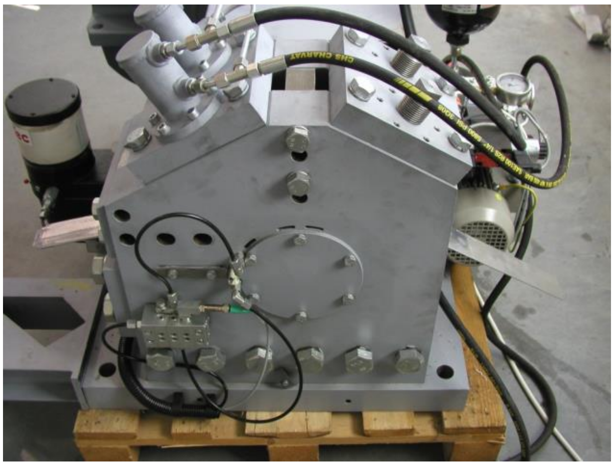

Figure 2 Forming equipment (DRECE method)

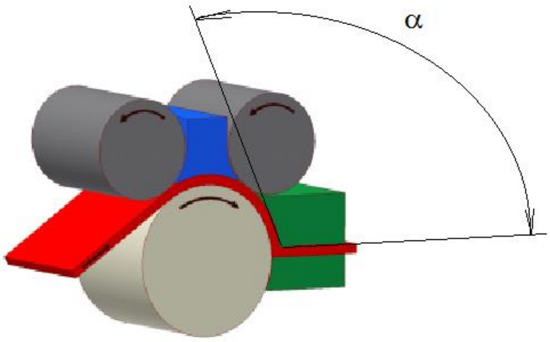

Figure 3 Scheme of deformation zone with different angle α

The effect of various angles of the deformation zone in the forming tool on influencing the basic mechanical properties, especially yield stress $R_{p0.2}$, tensile strength R_m and ductility A, was tested also from this perspective. It is known from the available literature data [Lee 2002, Saray 2010] that namely this angle determines the zone of plastic deformation.

3 TESTED MATERIAL

The low carbon deep-drawing steel DC01 suitable for cold forming was selected and experimentally tested. Chemical composition of tested steel DC01 is listed in Tab. 1.

Steel	C	Mn	Si	P	S	Al
DC01	0,029	0,211	0,009	0,008	0,013	0,059

Table 1 Chemical composition of tested steel DC01 (wt. %)

For experiments the steel strip with dimensions 58 (width) x 2 (thickness) x 1000 (length) mm was used.

4 RESULTS OF TESTS

The influence of two new geometries of forming tool for improving of mechanical properties was tested – forming tool with the deformation zone angle of 108° (see 4.1) and forming tool with the deformation zone angle of 113° (see 4.2).

The tests were performed at the upgraded forming equipment (see 2) using the principle of cold severe plastic deformation (SPD) process and DRECE (Dual Rolling Equal Channel Extrusion) method, i.e. with the constant cross-section of the extrusion channel. The test specimens were inserted into the forming equipment (see Fig. 1) in the same direction and in the same orientation for each pass.

4.1 *Tests performed at forming tool with the deformation zone angle of 108°*

Mechanical properties of tested steel DC01 both in the initial state and after 1, 2 and 3 passes through the forming tool with the deformation zone angle of 108° were evaluated by tensile tests (see Tab. 2). The obtained results are clearly graphically presented on Fig. 4.

State of tested material	Yield stress $R_{p0,2}$ (MPa)	Tensile strength R_m (MPa)	Ductility A (%)
Initial state	194	306	43,3
1st pass	319	353	18,7
2nd pass	332	375	15,3
3rd pass	349	392	18,0

Table 2 Mechanical properties of tested steel DC01 in initial state and after separate passes through forming tool with angle α = 108°

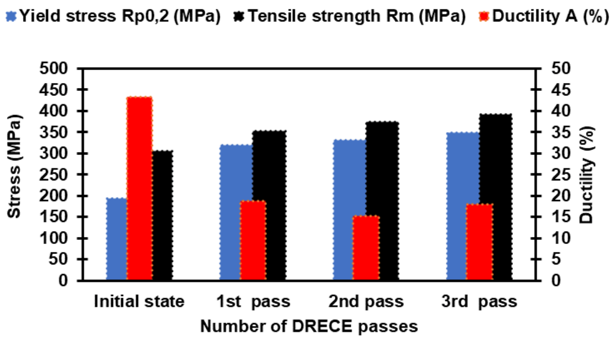

Figure 4 Comparison of basic mechanical properties of the initial material of the steel after separate passes through forming tool with angle α = 108°

4.2 *Tests performed at forming tool with the deformation zone angle of 113°*

Mechanical properties of tested steel DC01 both in the initial state and after 1, 2 and 3 passes through the forming tool with the deformation zone angle of 113° were evaluated by tensile tests (see Tab. 3). The obtained results are clearly graphically presented on Fig. 5.

State of tested material	Yield stress $R_{p0,2}$ (MPa)	Tensile strength R_m (MPa)	Ductility A (%)
Initial state	194	306	43,3
1st pass	293	366	17,3
2nd pass	302	379	16,7
3rd pass	319	397	9,3

Table 3 Mechanical properties of tested steel DC01, angle α = 113°

Initial states in all presented figures and tables were naturally not been influenced by the forming process. They are, however, shown in tables and graphs for clarity of the comparison of determined effects of the severe plastic deformation.

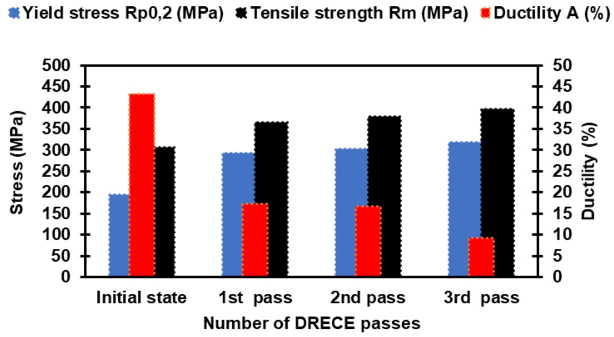

Figure 5 Comparison of basic mechanical properties of the initial material of the steel after separate passes through forming tool with angle α = 113°

5 INFLUENCE OF THE DEFORMATION ZONE ANGLE OF THE FORMING TOOL ON THE ACHIEVED MECHANICAL PROPERTIES

Graphical comparison of the effects of both types of investigated instruments on the changes of the mechanical properties of tested steel DC01, both strength and plastic, are shown in Figs. 6–8.

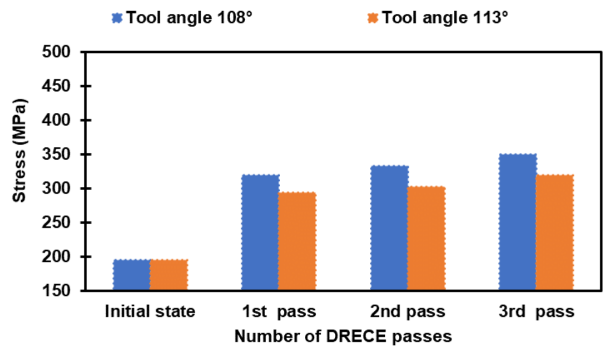

Figure 6 Comparison of the yield stress $R_{p0,2}$ of the initial material of the steel DC01 and after separate passes passes through forming tool with angles α = 108° and α = 113°

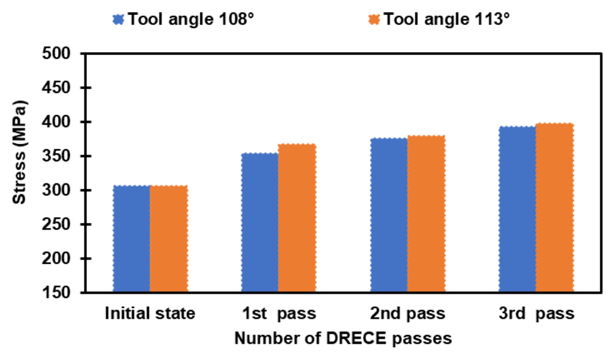

Figure 7 Comparison of the tensile strength R_m of the initial material of the steel DC01 and after separate passes through forming tool with angles α = 108° and α = 113°

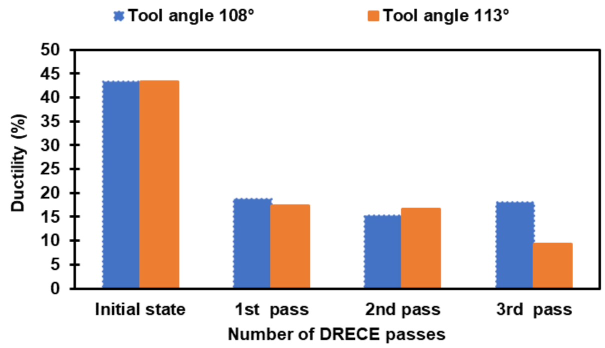

Figure 8 Comparison of the *A* of the initial material of the steel DC01 and after separate passes through forming tool with angles α = 108° and α = 113°

It is seen that a significant increase of the yield stress $R_{p0.2}$ occurs already after the first pass through the forming tool.

The slight increase in ductility after the third passage through the forming machine, at an angle of α = 108° can be due to the healing process of the given steel due to the temperature rise in the deformation zone from 22 °C to 50 °C.

6 RESIDUAL STRESS ANALYSIS OF STRIPS BEFORE AND AFTER DRECE TECHNOLOGY

Residual stress analysis of strips from steel DC01 in initial state and after DRECE technology was carried out with the use of magneto-elastic method [Tiitto 1996, Vengrinovich 2004, Rusz 2013] in the centre of every strip.

Polar graph of the magnetic Barkhausen noise (MBN) at centre of strip from steel DC01 in initial state and after two and four separate passes through forming tool is for angle α = 108° (NT – new tool) is seen in Fig. 9 and for angle α = 113° (OT – old tool) is seen in Fig. 10.

Polar graph of the residual stress distribution at centre of strop from steel DC01 in initial state and after two and four separate passes through forming tool is for angle α = 108° (NT – new tool) is seen in Fig. 11 and for angle α = 113° (OT – old tool) is seen in Fig. 12.

On Figs 9–12 the longitudinal direction, which is identical to the insertion direction of the test specimens into the forming equipment (see Fig. 1), is 0°, the transverse direction is 90°.

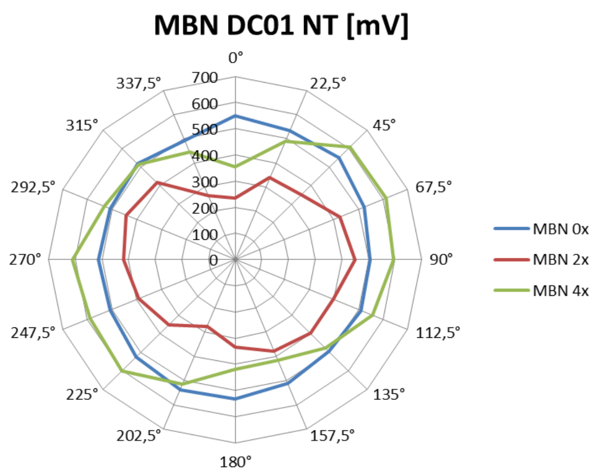

Figure 9 Polar graph of the magnetic Barkhausen noise (MBN) at centre of strip from steel DC01 – initial state, two and four separate passes through forming tool with angle α = 108° (new tool)

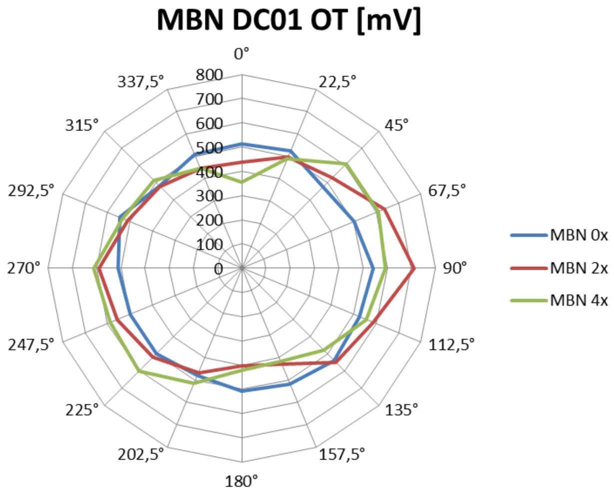

Figure 10 Polar graph of the magnetic Barkhausen noise (MBN) at centre of strip from steel DC01 – initial state, two and four separate passes through forming tool with angle *α* = 113° (old tool)

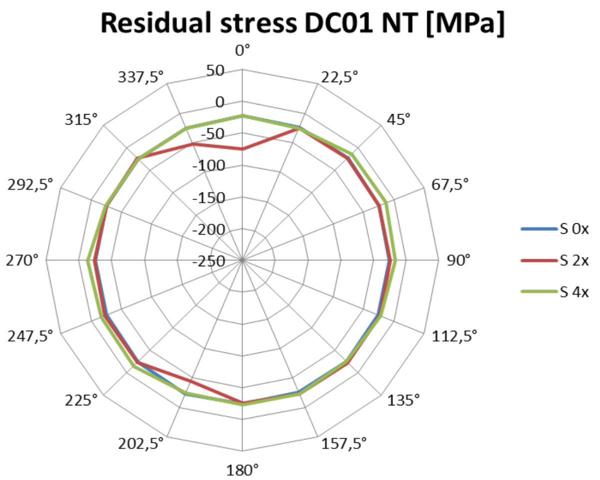

Figure 11 Polar graph of the residual stress at centre of strip from steel DC01 – initial state, two and four separate passes through forming tool with angle *α* = 108° (new tool)

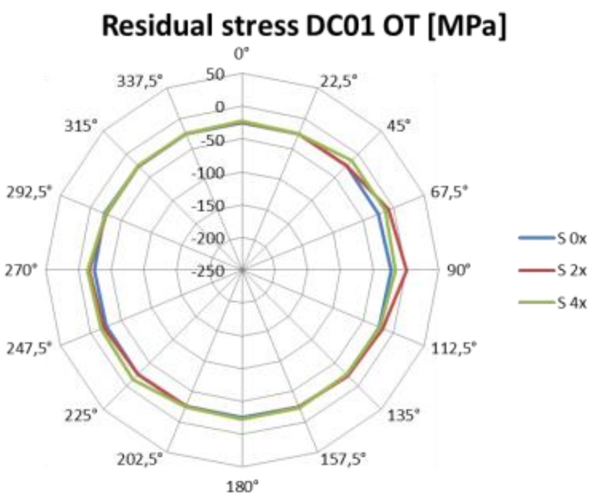

Figure 12 Polar graph of the residual stress distribution at centre of strip from steel DC01 – initial state, two and four separate passes through forming tool with angle *α* = 113° (old tool)

It is seen that the application of four DRECE drafts led to levelling of different residual stress values over the width of the strip and to an increase of compression stress in the direction of drafting.

7 CONCLUSIONS

All realized experiments demonstrated a significant effect of the newly developed forming tools with the abovementioned angles on the increase of the strength properties after various passes of tested material DC01.

When using the forming tool with the angle of 108° the higher values of the yield stress $R_{p0.2}$ and of the tensile strength R_m were achieved than with the use of the forming tool with the angle of 113°. This phenomenon is attributed to the influence of the tool geometry on the stress-strain state in the zone of deformation, which then acts on strengthening mechanisms in the structure of the tested material.

It was demonstrated that at tested steel DC01 a significant increase of the yield stress $R_{p0.2}$ was achieved already after the first pass through the forming tool. This finding is very important for industrial practice, where after possible implementation of the forming equipment into the production line it is not necessary to incorporate another - second equipment (for the 2nd pass). It is thus possible to achieve a substantial reduction of the costs for implementation of this new forming method into industrial practice.

Utilization of the magneto-elastic method enables a detailed projection of individual technological steps for production of new materials as well as a very effective optimisation of individual parameters of a technology. From analysis of steel DC01 is seen that DRECE technology brings compression stress into the material, which is favorable for further use.

The results of the effects of the tool geometry and of other parameters influencing the state of stress in the deformation zone indicate a direction for further exploration of the DRECE method in the laboratory for the development of new technologies at the Department of Mechanical Technology of the Faculty of Mechanical Engineering at the VSB – Technical University of Ostrava. At present, other type of materials are verified, which have pre-requisites for achieving an enhancement of the strength mechanical properties with still acceptable reduction of plastic properties (ductility).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding from the projects SP2018/67 "Technologic design and project management of production and material systems", CZ.1.05/3.1.00/14.0320 "Pre-seed activity of the VŠB-TUO II – Materials" and CZ.1.07/2.3.00/20.0038 "Creation of an international team of scientists and participation in scientific networks in the sphere of nanotechnology and unconventional forming of material".

REFERENCES

[Cada 1997] Cada, R. Formability of deep-drawing steel sheets. In: Proceedings of the 5th European Conference on Advanced Materials and Processes and Applications (EUROMAT 97): Materials, Functionality & Design: Volume 4 – Characterization and Production/Design. Red. L. A. J. L. Sarton a H. B. Zeedijk.

Netherlands, Maastricht: Netherlands Society for Materials Science, 1997, pp. 463–466. ISBN 90-803513-4-2.

[Cada 1996] Cada, R. Comparison of formability of steel strips, which are used for deep drawing of stampings. Journal of Materials Processing Technology, 1996, Vol. 60, No. 1-4, pp. 283–290. ISSN 0924-0136.

[Evin 2014] Evin, E. et al. The Deformation Properties of High Strength Steel Sheets for Auto-Body Components. Procedia Engineering, 2014, Vol. 69, pp. 758–767. ISSN 1877-7058.

[Kvackaj 2012] Kvackaj T. et al. TEM studies of structure in OFHC copper processed by equal channel angular rolling. Micron, 2012, Vol. 43, No. 6, pp. 720–724. ISSN 0968-4328.

[Lee 2001] Lee, J. C. et al. Controlling the textures of the metal strips via the continuous confined strip shearing (C2S2) process. Materials Research Bulletin, 2001, Vol. 36, No. 5–6, pp. 997–1004. ISSN 0025-5408.

[Lee 2002] Lee, J. C. et al. Microstructural evolutions of the Al strip prepared by cold rolling and continuous equal channel angular pressing. Acta Materialia, 2002, Vol. 50, No. 16, pp. 4005–4019. ISSN 1359-6454.

[Pyszko 2013] Pyszko, R. et al. Cooling nozzles characteristics for numerical models of continuous casting. Metalurgija, 2013, Vol. 52, No. 4, pp. 437–440. ISSN 0543-5846.

[Rusz 2015] Rusz, S. et al. New type of device for achievement of grain refinement in metal strip. Advanced Materials Research, 2015, Vol. 1127, pp. 91–97. ISSN 1662-8985.

[Rusz 2014] Rusz, S. et al. Processing of low carbon steel by dual rolls equal channel extrusion. Materials Science and Engineering 2014, Vol. 63, pp. 1–11. ISSN 1757-8981.

[Rusz 2013] Rusz, S. et al. Influence of severe plastic deformation on mechanical properties of low carbon steel. In: Proceedings of the 22nd International Conference on Metallurgy and Materials (Metal 2013), Ostrava: Tanger, 2013, pp. 316–321. ISBN 978-80-87294-41-3.

[Saray 2010] Saray, O. et al. Principles of equal-channel angular sheet extrusion (ECASE): Application to IF-steel sheets. Advanced Materials Science, 2010, Vol. 25, pp. 42–51. ISSN 1606-5131.

[Tiitto 1996] Tiitto, S. et al. Handbook of Measurement of Residual Stresses. Lilburn: Society for Experimental Mechanics, Inc., 1996. 253 p. ISBN 0-13-255738-X.

[Velicka 2013] Velicka, M. et al. Research of thermal processes for the continuous casting of steel. Materiali in Tehnologije, Vol. 47, No. 6, pp. 815–818. ISSN 1580-2949.

[Vengrinovich 2004] Vengrinovich, V. and Tsukerman, V. L. Stress and texture measurement using Barkhausen noise and angular scanning of driving magnetic field. In: Proceedings of the 16th World Conference of Non-destructional Testing (WCNDT 2004), Aug 30–Sep 3, 2004. Montreal, Canada. CD ROM and internet version, paper code: 58.

CONTACTS:

prof. Ing. Radek Cada, CSc.
VSB – Technical University of Ostrava, Faculty of Mechanical Engineering, Dept. of Mechanical Technology
17. listopadu 2172/15, Ostrava-Poruba, 708 33, Czech Republic
+420597323289, radek.cada@vsb.cz, www.fs.vsb.cz