INFLUENCE OF SPD PROCESS ON LOW-CARBON STEEL MECHANICAL PROPERTIES

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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 built 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 [Evins 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 [Kvacka 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].

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  | 0.02  | 0.21  | 0.00  | 0.00  | 0.01  | 0.05  |

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 $\alpha = 108°$

![Comparison of basic mechanical properties of the initial material of the steel after separate passes through forming tool with angle $\alpha = 108°$](image)

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 $\alpha = 113^\circ$

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.

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.

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 $\alpha = 108^\circ$ 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 [Tittio 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 $\alpha = 108^\circ$ (NT – new tool) is seen in Fig. 9 and for angle $\alpha = 113^\circ$ (OT – old tool) is seen in Fig. 10.

Polar graph of the residual stress distribution at centre of strap from steel DC01 in initial state and after two and four separate passes through forming tool is for angle $\alpha = 108^\circ$ (NT – new tool) is seen in Fig. 11 and for angle $\alpha = 113^\circ$ (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°.
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 $108^\circ$ the higher values of the yield stress $R_{y0.2}$ and of the tensile strength $R_m$ were achieved than with the use of the forming tool with the angle of $113^\circ$. 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 $R_{y0.2}$ 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).

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