Development of geometry of forming tools for extrusion of strip sheet by SPD process

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Abstract. On VSB -Technical University of Ostrava developed a method that uses the principle of severe plastic deformation to refine the structure and enhance mechanical properties of sheet metal strips. The greatest importance in practice represents an increase in yield strength and ultimate strength of sheet metal strips. The DRECE method (Dual Rolls Equal Channel Extrusion) is a newly developed method. Severe plastic deformation results in a high degree of the material deformation. The method can be used to produce metallic materials with a very fine grain structure. The paper analyses the effects of the values of angles of the newly developed forming tools on the achievement of mechanical properties in selected carbon steels by SPD process. The one type of steels (Ck55) was verified experimentally. Experiments were performed on the sheet metal strip with dimensions 58 (width) x 2 (thickness) x 1000 (length) mm with different inclination angle α.

1 Introduction

High deformation at comparatively low homological temperatures is an efficient method for manufacture of ultrafine grained (UFG) massive materials. News technologies, which use high deformation for obtaining of fine-grained structure, comprise namely the following authors [1]. This research concerned the whole production of UFG materials, using Severe Plastic Deformation (SPD). These new technologies for production of semi-finished products with ultra-fine grained structure differ from conventional technologies. Even in scientific research, it is recognized that namely the controlled forming processes, including special processes, enabling control of technological parameters with regard to the structure and its further refinement, have currently the highest gradient of utilization efficiency of scientific research findings in practice [2, 3, 8]. In the metals like Cu and steel, the deformation by ECAR increases the strength and decreases elongation. Besides the DCAP (C2S2), CONFORM and ARB [3, 4] method for sheet metal forming, from the perspective of industrial practice new technologies are being intensively developed, to which belongs also the newly developed DRECE method (Dual Rolls Equal Channel Extrusion, see Fig. 1a, b), which were improved by the use of new forming tools with a new geometry (smaller angles in the zone of deformation, see Fig. 2). The issues of production of materials with UFG structure, especially in steels and alloys of non-ferrous metals in the form of sheet metal strip are analyzed in detail. Furthermore, a comparison is made of basic mechanical properties of the tested materials achieved after severe plastic deformation with the properties of these materials in the initial state. Analysis of the structure is performed on an optical microscope. 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 newly developed forming method (DRECE) is completely original.

2 Forming Equipment
The DRECE method is based on making use of the material’s intensive plastic deformation, whereby this process is a combination of two known technologies, ECAP and CONFORM. As has already been mentioned earlier, the equipment is a prototype possessed by the Faculty of Mechanical Engineering of the VŠB – Technical University Ostrava. The equipment consists of a NORD gearbox and an electromotor with speed frequency converter which gives us the option to change the deformation rate even during the process, and thus allows us to flexibly react to the process progress. Other components include a plate clutch, a drive roller, two pressure rollers and a bottom and top forming tool. The pressure applied onto the front pressure roller is controlled by a pair of hydraulic cylinders; the pressure applied onto the rear pressure roller is controlled mechanically. This combination has so far proven itself when controlling the pressure in both non-ferrous alloys (on Al, Cu basis) as well as in sheet steel (DC01, Ck55). The machine’s design of course allows hydraulic control to be applied also to the rear pressure roller. The entire DRECE equipment is shown in Fig. 1a, b. [5].

Figure 1. a) Forming device, b) Detail of the feeding device with induction heating.
In our experiments, we use samples of dimensions 58 mm x 2 mm – 1000 mm. However, used can be also sheet metal of smaller thickness, when the deformation zone range is adjusted by inserting pads placed underneath the pressure rollers. Since this is a prototype, in the initial stages of testing on this equipment, investigated were primarily optimal pressure forces of both pressure rollers, an effective interval between lubrications and also the impact of the process speed on the resultant structure of the material. The geometry of forming tools, in particular, the inclination angle $\alpha$ of the approach of the forming curve in the zone of deformation, is a very important factor influencing the efficiency of the SPD process (see Fig. 2) [5, 6].
2.1 Mathematical simulations
Preparation of geometric data for the formed material and equipment was performed in an engineering CAD program SolidWorks. Material data for the calculation were obtained by calculation based on the chemical composition of the material with the use of the program JMatPro. The program DEFORM™, which analyses processes on the principle of finite elements, was used for computer modelling of the process itself and for subsequent numerical simulations. Simulation calculations predict for each moment of the process a distribution of temperature, strain, stress, and flow of the formed material. Moreover, it is possible to determine stress on instruments and evolution of the total forming forces.

2.2 Material data
Material data for the calculation were obtained on the basis of the chemical composition of both materials (for sheet - steel Ck55) using the program JMatPro. The program JMatPro creates a data file for the computer program DEFORM, which contains all the necessary material data, i.e. data on material flow stress, Young's modulus of elasticity, Poisson's ratio, thermal conductivity, heat capacity and thermal expansion. The simulation was conducted for an angle $\alpha = 108^\circ$.

The basic equation for calculation of the strain intensity is in the form:

$$\varepsilon_{int} = \frac{2 \cdot n}{\sqrt{3}} \left[ \cot \left( \frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \cdot \frac{1}{\sin \left( \frac{\phi}{2} + \frac{\psi}{2} \right)} \right]$$

where:
- $n$ - number of passes through a forming tool
- $\phi = \alpha$ - forming tool angle in deformation zone
- $\psi$ - angle defining the curvature of the lower tool
2.3 Process data
All the rolls in the DRECE equipment are driven by a gearbox Nord. The speed of movement of the drive wheel is 1.72755 mm/s, which equals to the angular velocity of 0.01745 rad/s. Lubrication is performed with the use of lubricant Gleit HP 515, which is supplied continuously in small portions at the point of the deformation zone of friction between the sample and the tool. The value of the friction coefficient in the defect zone was 0.1. The rolls are roughened by shot blasting so that material is drawn by a friction force (friction coefficient has a value of 3).

2.4 Mathematical simulation

Figure 3. a) Scheme of method DRECE, b) Detail of strip sheet.

Figure 4. Simulation of forming process.
Figure 5. Material flow through forming tool.

Figure 6. Effective plastic strain after 1st pass through forming tool.

Figure 7. Effective plastic strain after 2nd pass through forming tool.
Table 1. Results of mathematical simulation on angle $\alpha = 118^\circ$

| Eff. Plastic strain [-] | 1st pass | 2nd pass | 3rd pass |
|------------------------|---------|---------|---------|
| Middle of sample specimens | 1.35    | 1.92    | 2.93    |

2.5 Comments to results of mathematical simulation

The obtained magnitudes of effective plastic strain show an evident influence of the forming tool geometry on the strengthening of the formed material. The results are consistent with the theoretical knowledge when at the use of a lower forming angle of the tool a larger number of slip planes is formed and plastic deformation is more intense. The DRECE method is closing the gap between itself and the ECAP method. The obtained values of effective plastic strain should be regarded as indicative due to the accuracy of the entered boundary conditions.

3 Experimental conditions

The geometry of forming tools, in particular, the forming tool angle of the approach of the forming curve in the zone deformation, is a very important factor influencing the efficiency of the SPD process. This is currently newly developed forming equipment with 6 protected industrial designs of new geometries of the forming tools. Low carbon steel (Ck55) suitable for cold forming was verified experimentally. The chemical composition of the steel is given in Table 2. In the experiments the achieved mechanical properties and the structure at the forming tool angles 108 °, 113 ° and 118 ° were evaluated. It is known from the available literature data [2] that namely these angles determine the zone of plastic deformation. The effect of various angles of the forming tools influencing the basic mechanical properties, especially the yield stress $R_{\text{p0.2}}$, tensile strength $R_m$ and ductility $A_{80}$, determined by tensile test, was tested also from this perspective.
Table 2. Chemical composition (wt %) of Ck55 steel.

| Grade | C    | Mn   | Si  | P_{max.} | S_{max.} | Al  |
|-------|------|------|-----|----------|----------|-----|
| Ck55  | 0.53 | 0.43 | 0.3 | 0.03     | 0.035    | 0.02|

Attained yield strength for different angles forming tools depending on the number of passes are shown in Table 4 and Fig. 9.

Table 4. Yield strength $R_{p0.2}$ on different tool angles.

| Yield strength $R_{p0.2}$ [MPa] | $\alpha = 108^\circ$ | $\alpha = 113^\circ$ | $\alpha = 118^\circ$ |
|----------------------------------|-----------------------|-----------------------|-----------------------|
| initial state                    | 302                   | 302                   | 302                   |
| 1×                               | 435                   | 401                   | 400                   |
| 2×                               | 418                   | 409                   | 404                   |
| 3×                               | 431                   | 397                   | 435                   |
| 4×                               | 431                   | 431                   | 422                   |

Figure 9. Yield strength depending on tool angles.

Table 5. Tensile strength $R_m$ on different tool angles.

| $\alpha = 108^\circ$ | $\alpha = 113^\circ$ | $\alpha = 118^\circ$ |
|----------------------|----------------------|----------------------|
| initial state        | 431                  | 431                  | 431                  |
| 1×                   | 578                  | 582                  | 626                  |
| 2×                   | 591                  | 591                  | 652                  |
| 3×                   | 599                  | 599                  | 674                  |
| 4×                   |                      | 603                  | 683                  |
3.1 Comments on results

The obtained results show a significant influence of the forming tool geometry (angle $\alpha$ in the defect zone). At the angle of 108° a 45% increase of $R_{p0.2}$ took place after the first pass through the forming tool in respect to the initial state. At the angles 113° and 118° this increase is 32%. After the second and third passes through the forming tool with a tool angle of 108° a slight decrease in the size of $R_{p0.2}$ takes place. At the angles of the forming tool of 113° and 118° a significant increase of $R_{p0.2}$ takes place till the 3rd and 4th passes, while the achieved values are identical with the value of $R_{p0.2}$ achieved at the tool angle of 108° after the first pass through the forming tool. This reflects unequivocally the efficiency of the forming process (SPD) - the influence of reduction of the angle of the forming tool...
from the perspective of achieving high material strengthening already after the first pass through the forming tool. At the angle of 108 ° it was not necessary to conduct an extrusion of the strip of the sheet in the 4th pass, since the value of Rp0.2 did not increase after the second or third passes in comparison compared with the value achieved after the first pass.

The tool geometry influence in a very similar way the magnitude of tensile strength Rm after individual passes through the forming tool. The biggest increase of Rm at all forming tool angles occurs after the first pass - by approx. 34% (angle 108 °), 35% (angle 113 °), or 45% (angle 118 °). Next passes do not have any substantial effect on the increase of the Rm at all forming tool angles.

From the viewpoint of strengthening processes and application of knowledge into industrial practice, the most important is the increase in yield stress Rp0.2 after the first pass through the forming tool. The biggest increase was achieved in accordance with presumptions at the angle α = 108 °. It is necessary to emphasise the high manufacturing accuracy of the forming tool (both top and bottom parts) and its holders. The tool design was for the purposes of protection of intellectual property protected by registration of industrial designs.

The achievement of an identical magnitude of ductility A after the first pass through the forming tool -23.3% at the angle α =108° is an important finding. At the angles of 113 ° and 118 ° the ductility A decreases by 21% or by 55%. After the 1st pass through the forming tool at the angle α = 108 ° it is possible to form successfully the semi-product (strip of the sheet) into the final shape of the machine part. This is the second important and significant finding for the application of the method DRECE in industrial practice. A drop of ductility after the first pass at the angles of 113 ° and 118 ° can be explained (interpret) by the ratio Rp0.2/Rm, which is unfavourable due to the ratio achieved at the angle of 108 °.

4 Metallographic analysis

![Figure 12](image12.jpg)

Figure 12. Metallographic analyze of steel Ck55, initial state (500×).
4.1 Comments
For evaluation of structural characteristics the light microscope NEOPHOT 2 was used, with using of Nital etchant. Fig. 12 shows the structure of the analysed steel in the initial state and Fig. 13 shows the structure after the first pass through the forming tool for the angle $\alpha = 108^\circ$. Average grain size is reduced from the original size of 30-40 $\mu$m to 5-8 $\mu$m. Refining of the structure corresponding to an increase in yield stress $R_{p0.2}$ achieved in experiments after the first pass was confirmed. In the next part of the experimental works an analysis of structure with the use of TEM and SAED method will be performed.

5 Conclusions
It can be postulated on the basis of the achieved results of mathematical simulation and experimental works that the proposed new geometry of the forming tool (forming tool angle $\alpha = 108^\circ$), it enables achievement of high degree of strengthening ($R_{p0.2}$) in the steel Ck55 already after the first pass through the forming tool. The achieved magnitude of strengthening in principle does not change substantially during the next passes. A smaller increase of strengthening occurs with the tools with angles $\alpha = 113^\circ$ and $118^\circ$. This finding is consistent with the physical model UFG materials according Ovidka [7]. To increase the hardening also contributes the interaction generated dislocations with precipitates that usually observes in these steels. The issue will be verified by SEM, TEM and SAED methods. The achieved results are very important from the perspective of the use of the forming method DRECE in industrial practice. This method makes it possible to substitute materials of higher quality (steels and alloys) by materials of lower quality, which after plastic deformation reach the parameters (mechanical and forming properties) of the higher quality materials.

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