Tribological and Geometrical Analysis of the Friction Forces of Continuous Severe Plastic Deformation

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Abstract. Equal Channel Angular Rolling (ECAR), a severe plastic deformation process, is suitable for the shear deforming a long and thin sheet continuously. An interesting issue is that thickness of a sheet is not reduced during ECAR. Although the shear texture and fine grain structure are easily obtained by ECAR, yet the ECAR process’s difficulties in terms of technical control, such as surface defect, low ductility and low processing speed, still remain. The surface defects and processing speed are partially improved by applying a series deformation of rolling and ECAR. This article presents methodological and analytical procedures, adaptation of a conventional rolling mill Duo-system for processes of a SPD-representative which are represented by the method ECAR. They specify in detail the technical requirements whose new design solutions should be implemented. They present in detail the mechanical load drive shafts, as well as the calculation of compression forces with consideration of the friction forces. The geometric analyses of localisation positions of the outlet channel in terms of size and orientation of the dominant shear plane are also presented.

1. Introduction
In the framework of solving the project No. 0393-2016 – Investigation of Combined Techniques of Severe Deformation by Shear, Promising for Industrial Application – Creation of Nanostructures in Metal Materials through Intensive Plastic Deformations – a partial task developed – to make suitable technical equipment for realising experiments oriented on the continual processes. Therefore a team of designers entered the investigation group and their task is to prepare design documentation of this equipment.

From the design point of view it is a new task whose functional core cannot be taken over from other design patterns [1] [2] [3]. The process of the intensive plastic deformation has been experimentally verified at the University of Žilina, however, only with small samples in short-term processes during rectilinear motion to the place of the plastic deformation.

As several meetings of the scientific and research teams have shown the tasks of the aforementioned groups are as follows:

1. To make (design, manufacture and put into operation) equipment for realising the experiments for creating the nanostructures in the metal materials through intensive plastic deformations by the ECAR process which will be an extending module in the experimental rolling mill which is available
in the labs of the Department of Forming at the Centre of Theoretical and Technological Plastometry of Construction Materials.

2. To invent a design of equipment for carrying out the experiments of creating the nanostructures in the metal materials through intensive plastic deformations for long samples with a possibility of realising the continual process [4]. This procedure will be realised at the University of Žilina in Žilina. The working title is ECAR 1 Žilina.

As a matter of fact there are two design tasks which distinguish from each other by the assignment and realisation time deadlines. While the first task is connected with utilising the existing equipment (the rolling mill) and has strictly monitored deadlines, the second task has not that strict deadlines and is freer also from the point of view of its solution.

2. ECAR 1 Žilina

2.1. Assignment

The table 1 shows and defines the conditions and requirements of the solution. The list of requirements is still not finished. In this solution phase (the solution design) it is necessary - not only for the interested parties (designers) but especially for the users of the equipment in the future- to confirm these requirements and if there are any new ones to present all of them without any delay. This is the way how to complete the assignment for the designers to be appropriately informed and could take into account these requirements during designing the equipment.

These requirements can be divided into the general and specific ones. The designers are informed about the general requirements; they are also valid in other design tasks. They are, e.g. requirements on the strength, toughness, manufacturability, safety, etc. The designer has to learn about the specific requirements from those who assign the task, from the user of the device in the future because they are based on special requirements of the technological process, operating conditions, the available space, the goals of the ordering party in the area of its utilisation, the life span and other necessary properties but also economic possibilities in which the designed equipment will be produced and utilised.

2.2. Concept

![Figure 1](image)

**Figure 1.** The solution concept is based on the kinematic scheme of the process presented as ECAR 1. The specialist in the area of forming materials will account for its design. So we know the physical process and its effects. The figure 1 already roughly defines the solution concept. The designer’s task is to find and define such technical means that will realise this process.

| Requirements, wishes | Source | Notes, giving reasons |
|----------------------|--------|-----------------------|
| The main requirement: realising ECAR process | Task | The purpose of this task |
| The maximal permissible forces of the rolling mill DUO-210 in Žilina for the design calculations are: **2 x 150 KN** (the force under the left and right adjusting screw). | Minutes from the meeting held on 8th December 2016 | |
The maximal strength of the deformation material: $R_m = 900$ MPa

| The maximal strength of the deformation material: $R_m = 900$ MPa | Minutes from the meeting held on 8th December 2016 | Economic reason, valid for the variant |
|---------------------------------------------------------------|-----------------------------------------------|-------------------------------------|
| Utilising the existing rolling mill in Žilina | Discussion  | 
| Possibilities of adjustments for the ECAR 1 needs - angles | Discussion  | 
| The maximal width of the cross-section 100 mm | Discussion  | According to the Žilina rolling mill |
| The rolling speed 25 mm/s | Bibliography  | Approximate |
| Modular design for replacing the tool | Discussion  | Variability |
| Increase of the thrust of the rollers – grooved rollers, other pairs of driven rollers at the input - removable | Discussion  | One pair of rollers will be probably not enough |
| Simple and quick disassembly | Discussion  | Taking out the sample, cleaning |
| Modular design from the point of view of the tool variability | Discussion  | Variability of experiments |
| Modular design from the point of view of extending the system | Discussion  | Possibility to extend |
| Necessity of implementing scanners for measuring the forces and speeds (revolutions) | Discussion  | Regulation of forces and speeds. Side results of the experiments |
| Safety and protection of health, technical safety | Discussion  | A cover? |
| Possibility of cooling the tools | Research of patents  | Deformation heat |
| Using the mechanical systems, not hydraulics | Discussion  | Based on the experience |

The utilisation of the existing rolling mill is the most important requirement. It means to look for the methods of connection, the shapes, arrangement and dimensioning for the requirements presented to designers to be fulfilled.

2.3. Mechanical Load of ECAR 1 Drive – Estimation

Assumptions:
- Normal contact force on the rollers $N = 2\cdot150$ kN
- $R_m$ of the sample up to $900$ MPa
- Factor of increasing the pressure $k_{90} = 5$

$k_{90}$ is experimentally verified value of the pressure necessary for extruding a sample of the AlMg alloy through a $90^\circ$ angle in the $R_m$ ratio during experiments in Žilina.

![Figure 2. Rolling mill drive](image)
Given facts:
Engine output $P_0 = 9.5$ kW at the speed of $n_0 = 550$ min$^{-1}$ (data from the machine label)
Gears:
- Belt transmission $i_1 = 460/875$ mm
- Gearing $i_2 = 17/100$
- Roller diameter $d = 210$ mm

Calculated:
- Roller speed $n = n_0 \cdot i_1 \cdot i_2 = 550 \cdot (460/875) \cdot (17/100) = 49$ min$^{-1}$
- Roller peripheral velocity $v = n \cdot d \cdot \pi \cdot 60^{-1} = 49 \cdot 210 \cdot \pi \cdot 60^{-1} = 538$ mm s$^{-1}$

The force $F$ by which the rollers are able to press the sample to the tool (horizontal) is calculated from the output of the drive and the roller peripheral velocity (the effectiveness of the gear, dynamic effects and the possibility of overloading the electric motor are not taken into account) is approximately:

$$F = \frac{P}{v} = \frac{9500}{0.538} = 17 658 \text{ N} = 17 \text{ kN}$$

For the ECAR 1 purposes this force seems to be small and the speed too high.

To achieve the ECAR 1 parameters, i.e. the force on the roller circumference 120 kN, there are the following possibilities:
- An ideal solution: to insert another gear to multiple the torque approximately 1:7, then the force would be $F = 120$ kN; the peripheral velocity $v=76$ mm s$^{-1}$, however, this possibility would mean a principal reconstruction of the drive,
- Partial (compromise) measures,
  - to increase the gear ratio of the belt transmission by exchanging the small belt,
  - to increase the torque of the driving engine by changing the drive regulation,
  - to utilise the dynamic effects (inertia) of the drive,
  - to combine all the aforementioned measures.

A probable solution could be also reducing the required output parameters – i.e. to deal only with materials of lower strengths and samples with smaller cross-sections.

The frame of the rolling mill is designed for transmitting normal forces to the surface of the rolled materials, not for achieving such large tangential forces on the roller circumference required by the ECAR 1. This fact logically results from the function of the rolling mill. The stability of the transmission of the output to the rollers is not guaranteed too.

There is an assumption that the rollers (also the frame, bearings, shafts) are dimensioned for the thrust of 2 x 150 MPa. We can assume that the design is over-dimensioned and is able to transmit larger forces than the adjusting thrust screws. If there is no structure disruption during the first overload, it is probable that the life span of the bearings and other components will be reduced after repeated overloads. Due to the cyclic strain at higher stresses there is a higher probability of the fatigue defects. However, this fact regarding the experimental character of the equipment is not essential.

2.4. Check of the Input Shafts

This is only an approximate calculation because we do not know the exact values of the mechanic load, our calculations are based on estimated values. The shafts at the input are loaded only by rotation.

The torque on the shaft of the roller develops by the force on the roller circumference, on one roller there is half of the necessary force 120 kN; i.e. $F/2=60$ kN (see the figure 4). The shaft at the input has a diameter of 120 mm and is loaded only by the torque. The bending moments on the input shaft can be derived only from its own weight.

$$M_k = \frac{(F/2) \cdot r = 60000 \cdot 0.105 = 6300 \text{ Nm}}{where \ r \ is \ the \ roller \ radius.}$$
Check of the roller – rotation:

\[ W_k = 0.2 \cdot D^3 = 0.2 \cdot 120^3 = 345 \, 600 \, \text{mm}^3 \]

\[ \tau_k = \frac{M_k}{W_k} = \frac{6 \, 300 \, 000}{345 \, 600} = 18.23 \, \text{MPa} \]

where D is the roller diameter at the input.

If we assume the roller is made of common structural steel where \( R_e = 300 \, \text{MPa} \), the roller shaft is suitable and has high safety.

Check of the propeller shaft with square section 82 x 82:

\[ W_k = 0.208 \cdot h^3 = 0.208 \cdot 82^3 = 114 \, 684 \, \text{mm}^3 \]

\[ \sigma_k = \frac{M_k}{W_k} = \frac{6 \, 300 \, 000}{114 \, 684} = 54.93 \, \text{MPa} \]

Also these shafts are suitable.

Figure 3. Shafts of the roller drives

Figure 4. Scheme for the calculation of compression forces on the basis of friction
3. Conclusion

This article documents the complicatedness of the area – design of experimental equipment for creating nanostructures by continual method of intensive plastic deformation. The most important area of the design will be to cope with large forces and pressures which have to be generated high above the threshold of the material strengths of the samples being processed.

The design activity during the next solution stage will be concentrated on the task ECAR 1 Žilina by selecting a variant, making the building structure through necessary dimensional calculations and analyses more accurate as well working out the design documentation.

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