EXPERIMENTAL RESEARCH ON THE FORCES OF FORM TAPPING TRAPEZOIDAL PROFILES

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ABSTRACT
The researches aimed to obtain data to design technologies based on cold plastic deformation in order to achieve profiles on parts through form tapping, as well as to obtain measurement data to validate some models of simulation of the finite elements deformation process. This paper presents a part of these researches, those connected to establishing the forming equation when processing profiles corresponding to the trapezoidal thread. The experiments were conducted on four representative materials, two types of plain steel, OLC15, OLC35, and two alloy steels with Cr and Mn, 18MnCr11, 40Cr10, on profiles corresponding to trapezoidal threads, for different depths of profiles and for different values of the working feed. In order to obtain the measurement data we had to set a few adequate methods and experimental research means. There were determined the equations of the maximum forming forces, equations established represent a useful tool for technology designers.

KEYWORDS
cold plastic deformation, form tapping, forming force, trapezoidal thread

INTRODUCTION

In the automotive industry, especially in the automobile field, parts which can be found on trapezoidal profiles are frequently used. These can be achieved by cutting or cold plastic deformation processes. From an economic perspective and by taking into account the mechanical characteristics obtained, the cold plastic deformation process is more advantageous (2, 3, 5).
One of the cold plastic deformation processes used is the one with planetary rollers which consists in dividing the process into a large number of partial deformation processes by using deforming tools with the shape of the profile hole. Applying this method on a large scale is hampered by the lack of data required to design technologies based on them.
The researches aim to obtain data to allow the use of form tapping to process profiles and to validate some models of simulation of the finite element process (1, 9). Simulation is currently in the attention of researchers due to the advantages it presents. Its application requires, however, the development of models, whose validation can be achieved only experimentally, based on measurement data.
This paper presents a part of these researches, namely, those regarding the determination of the forming force on trapezoidal profiles, corresponding to thread Tr20, function of the working speed, depth of profile and material of the piece (8). The experiments were conducted on four materials with a wide use in industry and covering from the point of view of their chemical, mechanical and technological characteristics: two steels from the group of quality carbon steels, OL15, OL35; and two alloy steels with Cr and Mn, 18MnCr11, 40Cr10. The first steels from the two groups are hardening steels and the other two are improving steels. The experiments required the choice of measurement methods adequate to a dynamic process and the setting of proper experimental research means.

THEORETICAL ASPECTS REGARDING THE MODELING OF DEFORMATION FORCES

The diagram to generate a profile corresponds to the one presented in fig. 1. The rolling head with radius R, rotates with the speed of revolutions n, the rollers with radius r are free on their axis so that at contact with the material of the piece they can rotate.

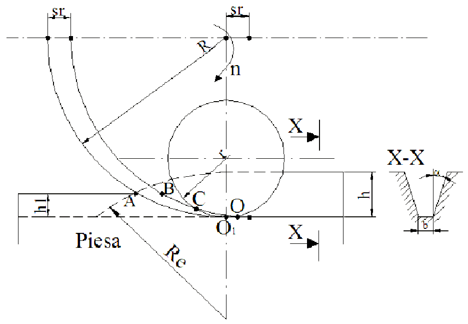


Fig. 1 The forming process in an early stage

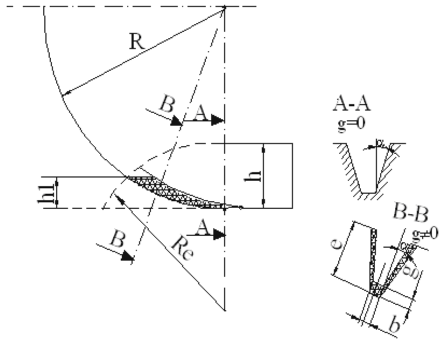


Fig. 2 Area of the material deformed in two sections

With each rotation the head advances on the direction of the profile to be achieved with the feed $s_{r,}$ and a roller with radius r moves the material from section OO_1ABO towards the exterior, so that in the area of maximum penetration of the roller into the material (vertically) the profile is obtained on arc OO_1A. The contact of the roller with the piece, for the forming position in fig. 1, takes place on arc O_1C. The profile with depth h can be followed in section X-X. The penetration of the roller into the semi-product takes place at depth h_1, and at some point in the forming process, the surface of the profile crests nearly follows radius R_e. When rotating the rolling head the forming process continues by forming roller r on arc O_1A, so that point C reaches B. Theoretically, from this point the process follows line BA.

When forming the roller with radius r, on arc OO_1A, the parameters which define the volume of deformed material are variable:

- thickness g of the section of deformed material, fig.2, which increases from zero to a maximum value and then decreases again to zero;
- area S of the deformed material, which increases from zero in section X-X to a maximum value in the section where g has a maximum value;
- length of the contact arc O1C between the roller and the piece, l_c, which varies from zero to value O1C, remains constant at this value until point C reaches B, then decreases again to zero.

The analysis of the evolution in time of the three parameters which influence the forming force, detailed in work (6), showed that there is a relation of dependence in the form of that presented in fig 3.

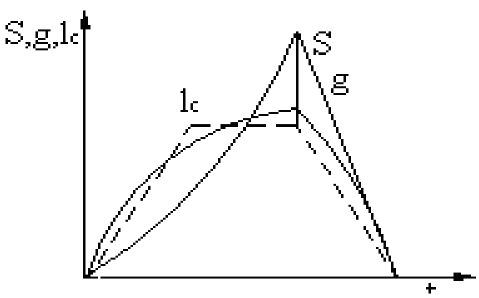


Fig. 3 The evolution in time of parameters g, S, l_c

Since the forming force is determined by the volume of material deformed by the roller at a certain point, the parameters which determine the volume of material will also determine the forming force. By analyzing the evolution of the three parameters, it results that the forming force will be variable, it starts from zero, at the first contact of the roller with the piece, it increases to a maximum value corresponding to the situation when the roller reaches g, and then, the force decreases reaching zero, at the loss of contact between the roller and the piece. We can conclude that for a geometry given by the rolling head, the forming force depends on:
- feed s_r [mm/rot];
- depth of penetration h_1 to achieve the profile;
- geometry of the forming profile, expressed by parameters b and α respectively;
- a parameter which characterizes the material, usually its hardness.

These parameters have to be taken into account when modelling the process. Since the geometry of profiles for experiments was the same, the model adopted to express the forming force has the form:

$$F = a_0 \cdot s_r^{a_1} \cdot h_1^{a_2} \cdot HB^{a_3} \quad (1)$$

where:
- a_0, a_1, a_2, a_3 are constants;
- s_r, the feed on a rotation of the rolling head [mm/rot];
- h_1, the depth of penetrating the material [mm];
- HB, the hardness of the material.

In the model adopted for the forming force, the influence of the material on the force was taken into consideration through the hardness of the materials to be processed.

EXPERIMENTAL PROCEDURE

THE EXPERIMENT STAND

In industry, the cold plastic deformation process with planetary rollers to obtain profiles is made on special machines through successive incremental deformation on the channels to be obtained. A universal milling machine and a rolling head specially conceived and achieved to replace the dividing movement were used to perform experimentally the process of cold plastic deformation with planetary rollers. The rolling head used has five rollers (r_1, r_2,...r_5) axially placed from one another with pass p, and at equal angles of 72°, as shown in fig. 4.

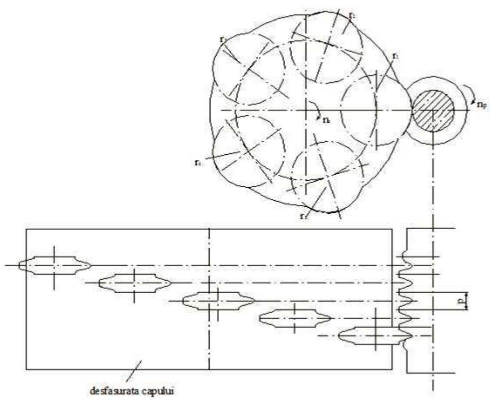


Fig. 4 The rolling head

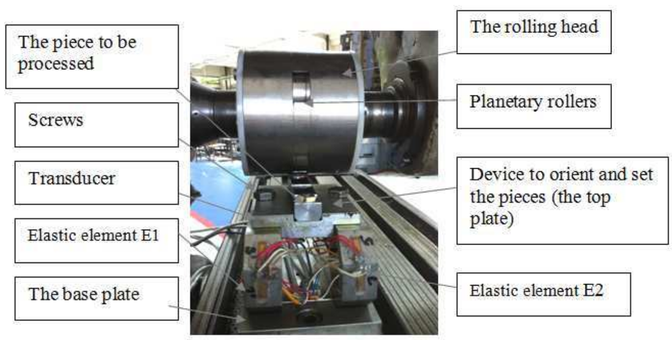


Fig. 5 The stand used for the experiments

The stand used for the experiments, fig. 4, is made on a milling machine FU 32 (7). Its block structure consists in: the rolling head with 5 rollers to obtain the trapezoidal profile; a device to orient and set the pieces to be processed; a transducer to measure the two components of the forming force; the system to acquire the forces made of: SPIDER; a computer; the program to acquire data CATMAN.

MATERIALS, PIECES AND PROFILES PROCESSED

The materials for the pieces formed chosen were four types of steel: OLC15, OLC35, 18MnCr11, 40Cr10. The materials used for the processing were chosen in order to have different mechanical properties in a wide range and to be representative for their group, tab. 1.

Tab. 1 The mechanical characteristics of the materials used at the research, obtained through measurements

Steel mark	**Mechanical characteristics of the materials measured**				**Calculated characteristic**
	HB [kg/mm^2]	Rp$_{0,2}$ [N/mm^2]	Rm [N/mm^2]	A5 [%]	CMP A5 /HB
OLC 15	156,1	298	475	15	0,10
OLC 35	177,4	248	558	13	0,07
18MnCr11	211	309	776	10	0,05
40Cr10	277,4	396	837	7	0,03

The processed parts have a rectangular shape, fig. 6, on each piece there are two areas where profiles can be processed. A working area has 25 mm and allows the processing of channels with constant parameters by removing the areas of entrance and exit of the head. The processed profiles correspond to trapezoidal profiles, Tr 20, fig. 7.

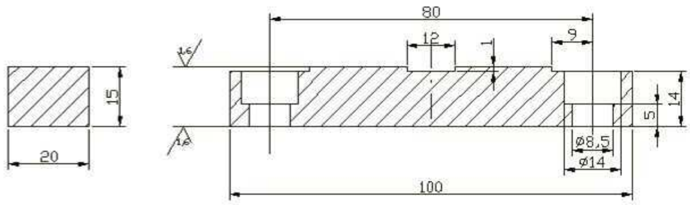


Fig. 6 Geometry of the pieces to be processed

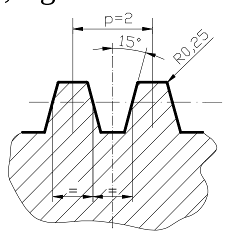


Fig. 7 Geometry of trapezoidal profile

MEASURING THE ROLLING FORCE

By taking into account the kinematics specific to the forming process with planetary rollers and the fact that the profiles to be processed are symmetrical, the forming force F develops in a plane perpendicular on the axis of the roller, fig. 8. This force appears at the contact of the roller with the piece, on the arc of circle OO1A and acts as a resultant in a point.

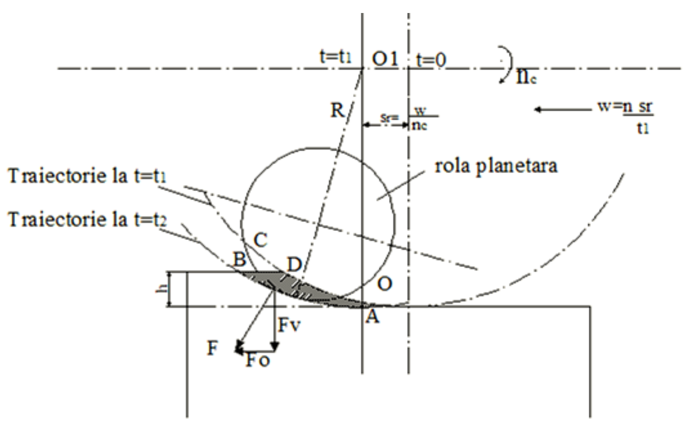


Fig. 8 The forming force and its components

To measure the two components of the force, we used a transducer with resistive strain gauges, fig. 5, specially conceived. The transducer measuring the forces is made of two plates: the base plate and the top plate. Between the two plates there are annular elastic elements E_1 and E_2. The strain gauges are stuck on these elastic elements, which allow the measurement of the two components of the forming force. On the top plate, the piece to be processed is set with screws.

EXPERIENCE PLAN

The experience plan was meant to vary two parameters for each one of the four materials: feed; depth of the processed profile. Each parameter varied on three levels, table 2. Both parameters varied step by step following geometrical progression to allow linearization by logarithms. The speed of revolutions of the head was maintained at a single value, due to the fact that preliminary tests showed that the speed does not influence the forming, which is valid for other procedures as well.

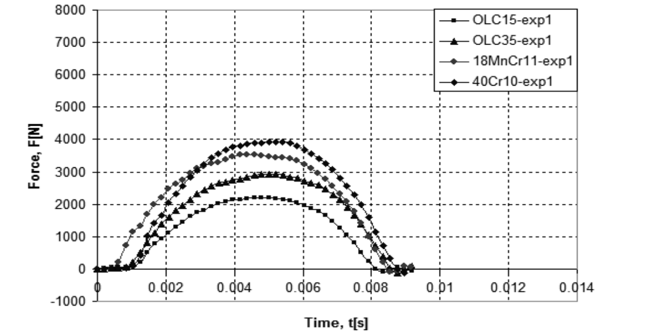
Tab. 2 The experience plan used

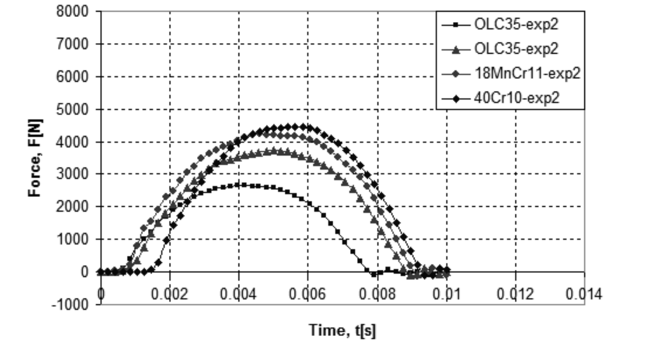
No.exp.	Speed of revolutions, n, [rot/min]	Feed, s_r[mm/rot]	Z_1	Processing depth, h_1 [mm]	Z_2
1		0,1	-1		
2		0,2	0	0,3	-1
3		0,4	+1		
4		0,1	-1		
5	235	0,2	0	0,45	0
6		0,4	+1		
7		0,1	-1		
8		0,2	0	0,675	+1
9		0,4	+1		

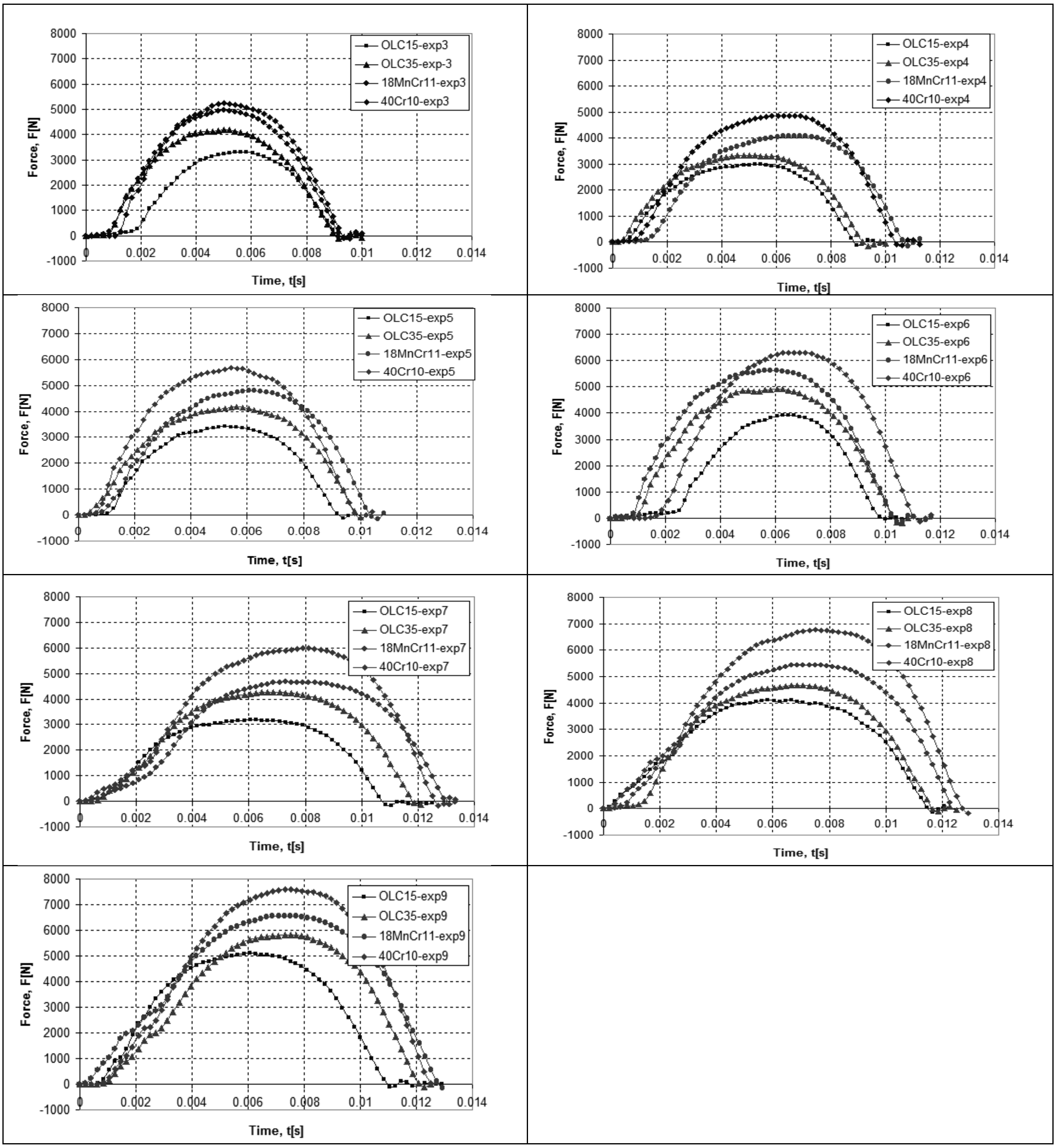
DATA OBTAINED AT MEASUREMENTS

The two components of the forming force were registered on a computer, in real time, with frequencies of 4800 Hz, for each of the four materials and the experience in the plan. By using the data registered, the graphs regarding the evolution of the forces as functions of time were obtained. Table 3 presents the graphs of the forming forces obtained using the measurement data corresponding to the 9 experiences of the plan, for the 4 materials which were subject of experiments.

Tab.3 The graphs regarding the evolution in time of the forming forces







We notice that the forming force increases from zero and reaches the maximum value when the roller penetrates the semi-product at maximum depth, then it decreases to zero again. This type of evolution of the force confirms the results of the analysis made in the first part of this paper.

PROCESSING AND INTERPRETATION THE DATA

By using the data registered, the values of the maximum forming forces corresponding to each experience were determined, table 4.

Tab. 4 The maximum forming forces for the experience plan applied

No.exp.	**Speed of revolutions, n, [rot/min]**	**Feed, s_r[mm/rot]**	**h_1 [mm]**	**F[N]**			
				OLC15	OLC35	18MnCr11	40Cr10
1	235	0,1	0,3	2363,644	3072,198	3565,57	4156,401
2		0,2		2788,325	3623,846	4122,987	4525,965
3		0,4		3421,247	4183,409	4812,199	5169,236
4		0,1	0,45	2982,354	3577,883	4138,698	5047,025
5		0,2		3548,288	4261,774	4834,88	5693,225
6		0,4		4063,093	5056,824	5831,507	6521,073
7		0,1	0,675	3267,146	4151,734	4621,644	6036,845
8		0,2		4037,440	4870,395	5173,585	6540,202
9		0,4		4944,387	5796,841	6613,771	7551,083

Function deformation force corresponding to the model adopted – relation (1) is a first order polynomial function which can be treated by multivariate regression analysis. Because each independent variable has a variation range and different natural values, expressed in different units of measurement, the regression line equation obtained based on experimental results has to be expressed in terms of natural variables, varied on two levels, -1 and +1, in order to be able to correctly interpret the results obtained and assess the significance of each process parameter.
The general equation of the normal variable regression line is:

$$Y = B_0 + \sum_{i=1}^{n} B_i \cdot z_i \tag{2}$$

where the normal variables z_i are calculated with the following change of variable relation:

$$z_i = \frac{2X_i - (X_{i\,\max} + X_{i\,\min})}{X_{i\,\max} - X_{i\,\min}} \tag{3}$$

where X_i are normal variables of the regression line and $X_{i\,min}$...$X_{i\,max}$ is their variation range.
Coefficients B_i are significant for a set level of confidence if their value is higher than their variation range, namely:

$$|B_i| \geq \Delta B_i \text{, where } \Delta B_i = \pm t \cdot s_{B_i} \tag{4}$$

where variable t is quantile to Student distribution.
Standard deviation of coefficients, s_{B_i}, is calculated function of total dispersion s_T^2 with relations:

$$s_{B_0}^2 = \frac{s_T^2}{n} \text{ and } s_{B_i}^2 = \frac{s_T^2}{\sum z_i^2} \tag{5}$$

Using the experimental data of maximum forming forces, table 4, within LINEST application from EXCEL which uses the method of least squares to determine the regression line that best describes the experimental data, there were determined:
- the coefficients of normal variables z and normal, linearized and exponential, respectively, table 5;
- the regression statistics which allow checking the model adequacy and the significance of equation coefficients etc., table 6.

Tab. 5 Equations of the forming force

Equation of force	Type of equation
ln F = 1,503119 + 0,157196·z_1 + 0,170457·z_2 + 0,236549·z_3	linearized in normal variables
ln F= -2,22131+ 0,226786 · *ln* s_r + 0,380208 · *ln* h_1 + 0,822831 · *ln HB*	logarithms in natural variables
$F = 0{,}108467 \cdot s_r^{0{,}226786} \cdot h_1^{0{,}380208} \cdot HB^{0{,}822831}$	polynomial in natural variables

Tab. 6 Values of the regression parameters calculated with application Linest - Excel

Parameter name	**Notation**	**Value**			
Regression line coefficients	B_i, i = 0,1,...,4	B_0	B_1	B_2	B_3
		1,503119	0,157196	0,170457	0,236549
Total average deviation of coefficients	S_{Bi}, i = 0,1,...,4	0,009289	0,011378	0,011713	0,012223

Parameter name	*Coefficient of determination*	*Total average deviation*	*Ficher statistics*	*Number of degrees of freedom*	*Sum of the average squared residuals from the right of representation*	*Sum of squared residuals from the right of representation*
Computing relation	$R^2 = \frac{\sum_{k=1}^{n}\left(\overline{Y}_k - \hat{Y}_k\right)^2}{\sum_{k=1}^{n}\left(Y_k - \overline{Y}_k\right)^2} = \frac{SS_A}{SS_D} = \frac{SS_A}{SS_A + SS_T}$	$s_T = \sqrt{s_T^2} = \sqrt{\frac{SS_T}{n-p}}$	$F = \frac{s_A^2}{s_T^2} = \frac{\frac{SS_A}{p-1}}{\frac{SS_T}{n-p}}$	$d_f = n - p$ *n* - number of determinations *p* – number of coefficients of the regression line	$SS_A = \sum_{k=1}^{n}\left(\overline{Y}_k - \hat{Y}_k\right)^2$	$SS_T = \sum_{k=1}^{n}\left(\hat{Y}_k - Y_k\right)^2$
Value	0,959476	0,055738	252,5538	32 (n = 36; p = 4)	2,353883	0,099417

From the analysis of statistical data, for a confidence level of 95%, it results that the model adopted is adequate and that all the independent variables taken into account are significant. The influence of each independent variable X_i on the dependent variable Y (maximum forming force) was determined in order to establish the importance of each variable on the forming force. This meant calculating indicators q_i or q_i %, defined by the absolute or relative variation of variable Y corresponding to variation $X_{i\,min}$...$X_{i\,max}$ of variable X:

$$q_i = \frac{Y_{\max}}{Y_{\min}} \text{ and } q_i\,\% = \frac{Y_{\max} - Y_{\min}}{Y_{\min}} \cdot 100\,\% \tag{6}$$

where Y_{min}...Y_{max} = Y(X_{min}…X_{max}), for set values of the other variables in the centre of experiments.

Thus, the absolute q_i and relative q_i% weight coefficients were calculated starting from the regression lines equation in natural variables; the values obtained are presented in table 7.

Tab. 7 Values of the weight coefficients and the direction of influence of variables

Independent variable	**The effect of the increase of the value of the independent variable on the value of the dependent variable**	**Dependent variable: force F [kN]**	
		Absolute weight coefficient, q_i	Relative weight coefficient, q_i%
Feed, s_r [mm/rot]	Increasing	1,3694	36,94
Processing depth, h_1 [mm]	Increasing	1,4062	40,62
Hardness of the material HB	Increasing	1,6049	60,49

It is noted that the value of the forming force increases along with the increase of the values of independent variables. From the independent variables, the initial hardness of material, followed by the depth of processing, have the greatest influence on the value of the forming force.

CONCLUSIONS AND INTENTIONS

To model the forming forces a theoretical analysis was made in order to establish the values which determine the volume of material formed at a rotation of the roller over the piece and consequently the value of the force, as well as the evolution of the force in time.
An extended plan of experiences was adopted for the experiments to vary three parameters: the processed material, the working feed, the depth of the profile. The data obtained at the measuring confirmed the evolution of the forces in time, which was established within the theoretical study.
Processing the data was made using the regression analysis and aimed to establish the equation of maximum forming forces as a polynomial function of three parameters: the processed material – its initial hardness, the working feed and the depth of profile.
The following main conclusions emerged:
- the model adopted to represent the function of maximum forming is adequate and its parameters are significant;
- the hardness of the material to be processed has the greatest influence on the deformation force: when the hardness increases from the minimum value of 156,1 HB (appropriate material OLC 15) to the maximum value of 277,4 HB (appropriate material 40Cr10), the deformation force increases with 60,49%;
- processing depth ranks second as importance: the increase of the processing depth from 0,293 to 0,706 mm determines an increase of the deformation force with 40,62%.
- the working feed has the lowest influence on the forming force: the increase of the feed from the minimum value of 0,1 [mm/rot] to the maximum value of 0,4 [mm/rot] determines an increase of the force with 36,94%.
The equation obtained allows estimating the forming forces in the case of profile Tr20 for all conditions falling in the ranges of parameters used in experiments and it is useful to validate the results of numerical simulations of the process.
By taking into account the fact that the shape of the profiles was maintained constant within these experiments, the research will continue with the influence of the shape of profiles on the forming force.

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