ANALYTICAL MODELLING OF THE RADIAL COLD ROLLING OF THE TRAPEZOIDAL PROFILES

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ABSTRACT
The methods of cold rolling of rods are widely used in manufacturing industries to obtain pieces with complex profiles. In this study, a trapezoidal profile has been formed by radial cold rolling using two rolls. This paper presents an analysis of the influence of the rolling regime parameters and of the characteristics of the material on the process parameters: the speed of penetration tools, basic action of the tool, the time required for profile deformation and the deformation force. The multivariable regression functions were determined for these process parameters.

KEYWORDS
radial cold rolling, trapezoidal profile, penetration tools, basic action of the tool, force rolling

INTRODUCTION

The advantages of radial cold rolling by, including high productivity, substantial improvement of the mechanical properties, low roughness etc. (1) or (2) are clearly apparent in the case of profiled surfaces.
A better technological knowledge of this cold forming process provided for a progressive widening of the application field from the origins in the fasteners industry to more sophisticated pieces, as regards both the geometrical shapes and the nature of rolled materials. At present, this aspect allows for such profiles as: threads, grooves, teeth to be obtained on parts that can be found in various products of the automotive industry, aeronautics, appliances etc.
This study analyzes the influence of the rolling regime parameters: the maximum adjusted force and the rolling speed, as well as the influence of the mechanical characteristics of some materials on certain parameters, such as: the speed of penetration tools, basic action of the tool, the time required for profile deformation and the deformation force, when processing through radial rolling a circular profile. For these process parameters, the multivariable regression functions were determined and interpreted function of the above mentioned variables.

EXPERIMENTAL PROCEDURE

EXPERIMENTAL STAND

A special rolling device, fig. 1, was conceived to be assembled on the lathe SN560 and to be used for the realization and control of the rolling process (3). A special workpiece 1 is oriented between dead centre 2 and running centre 3 and is additionally sustained by guide 5.

During the rolling process the part is moved by the rotation with the dog 4 set on the dead centre of the lathe headstock. The two rollers 6 can rotate freely on the axes 7 which are set on the loose tool rest 8. To achieve the in-feed movement, the tool rest can move between the guides 9. The in-feed of the tool rest is done with the help of hydraulic motors 10.

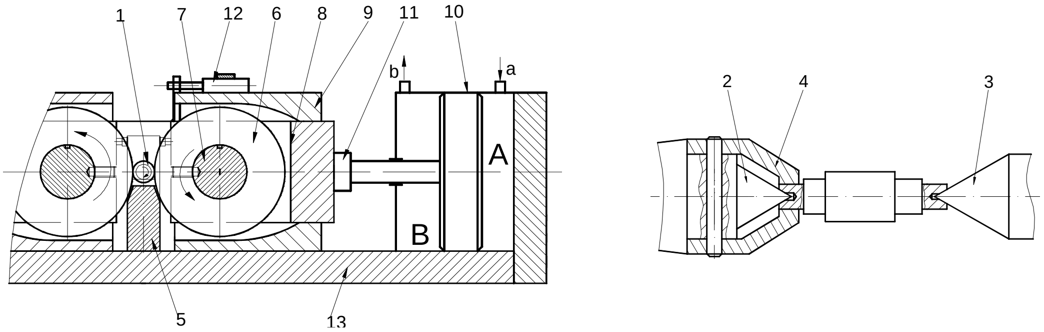

Figure 1. Constructive scheme of the radial cold rolling device

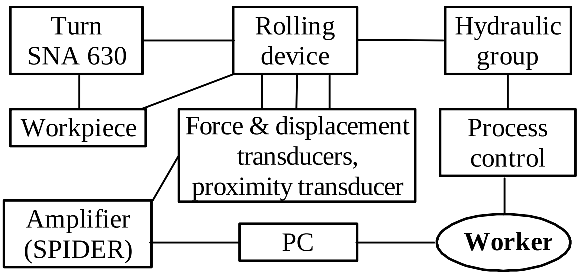

Figure 2. The experimental system

The cold-rolling process is obtained by rolling the workpiece with a number of revolutions and the in-feed working of the rolls (radial pressing) using the two hydraulic motors. By varying the working pressure of the motors the forces of the radial pressure can vary as well. To control the movement limits of the rest on a radial direction there were used buffers that limit the movement of the rest, thereby the depth of the tools penetration into the part on a radial direction. An experimental system, fig. 2, was used to control and record the process parameters: the displacement of the rollers (using the displacement transducer 12), the radial force (using the force transducer 11) and the calibration time (using a proximity transducer).

PROCESSED MATERIALS AND PROFILES

The study was made for four materials OLC15, OLC35, 18MnCr11 and 40Cr10 frequently used to generate machine parts by volumetric cold forming. Their mechanical characteristics are given in Table 1.

The processed profile is formed by 5 identical grooves in axial section to the ISO metric thread Tr20x2 SR ISO 2904:1996, their geometry being presented in fig. 2.

Table 1. Mechanical characteristics of the processed steels

Steel	HB [kg/mm^2]	$Rp_{0,2}$ [N/mm^2]	Rm [N/mm^2]	A5 [%]
OLC 15	156.1	298	475	15
OLC 35	177.4	248	558	13
18MnCr11	211	309	776	10
40Cr10	277.4	396	837	7

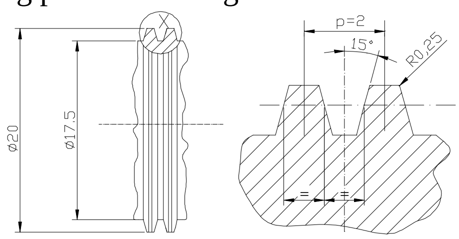

Figure 2. Geometry of the trapezoidal profile

EXPERIMENTAL PLAN OF THE RESEARCH

For each processed material were made twelve experiments, varying the parameters of the rolling regime: the maximum force, F_{max} (adjusting the pressure of the hydraulic motor) and the rolling speed, v (adjusting the number of revolutions of the piece) at the levels:
- F_{max} = 18 / 27.5 / 39 [kN]
- v = 11.81 / 23.62 / 47.25 / 94.5 [m/min]

The parameters maintained constant were: the diameter of the workpiece, $d_0 = 18.87_{-0.02}$ [mm] and the number of rotations of the piece during the calibration period, n_c = 2 [rot piece] (adjusting the calibration time function of the speed of revolutions of the piece).

RESULTS AND DISCUSSION

PROCESS PARAMETERS

The parameters measured during the process were: the depth of penetration (radial displacement) of the rolls, h, and the radial rolling force, F. The evolution in time of sizes h and F was associated with such laws as (4):

$$h(t) = h_{max}(1-\exp(-A_h t^{\alpha_h})) \quad (1)$$

$$F(t) = F_{max}(1-\exp(-A_F t^{\alpha_F})) \quad (2)$$

Starting from the evolution law (1) two important parameters of the deformation process can be determined:
- the speed of penetration of the tool, w(t) = $\dot{h}(t)$:

$$w(t) = \dot{h}(t) = h_{max}\alpha_h A_h t^{\alpha-1}\exp(-A_h t^{\alpha_h}) \quad (3)$$

- the basic action of the tool, $A_s(t)$, representing the radial deformation of a point on the circumference of the piece under the action of a roll:

$$A_s(t) = \frac{h(t)}{Nb\ tools\ \cdot Nb\ revpiece\ \ (t)} = \frac{h(t)}{2\cdot\frac{n\cdot t}{60}} = \frac{30}{n}\cdot w(t) \quad (4)$$

Curve w(t) has a maximum point, which can be determined from formula $dw/dt = 0$. We obtain:

$$t_{w\_max} = \left(\frac{\alpha_h - 1}{A_h\alpha_h}\right)^{1/\alpha_h} \quad (5)$$

Thus, there can be determined the maximum values of the parameters “speed of penetration” (6) and “basic action of the tool” (7), which offer information about the intensity of the deformation process.

$$w_{max} = h_{max}[A_h\alpha_h(\alpha_h - 1)^{\alpha_h-1}]^{1/\alpha_h}\exp\left((1-\alpha_h)/\alpha_h\right) \quad (6)$$

$$A_{s\ max} = \frac{30\cdot h_{max}}{n}[A_h\alpha_h(\alpha_h - 1)^{\alpha_h-1}]^{1/\alpha_h}\exp\left((1-\alpha_h)/\alpha_h\right) \quad (7)$$

By using relation (1) there can be established the time needed for the deformation of the profile (until the moment calibration begins), t_d, setting the condition to reach a certain depth of penetration. For example, setting the condition to reach a depth of 95% of the total one ($h=0.95\cdot h_{max}$), we obtain:

$$t_d = \left(-\frac{\ln 0.05}{A_h} \right)^{\frac{1}{\alpha_h}} \tag{8}$$

Knowing the value of t_d, the radial rolling force associated with this moment, F_d, representing the force needed for the deformation of the profile in the given experimental conditions, can be calculated using relation (2).

ANALYSIS OF THE PROCESS PARAMETERS

The sizes of the process parameters determined above are graphically represented for each one of the processed materials, function of the variable parameters of the process, fig. 3 and fig. 4.

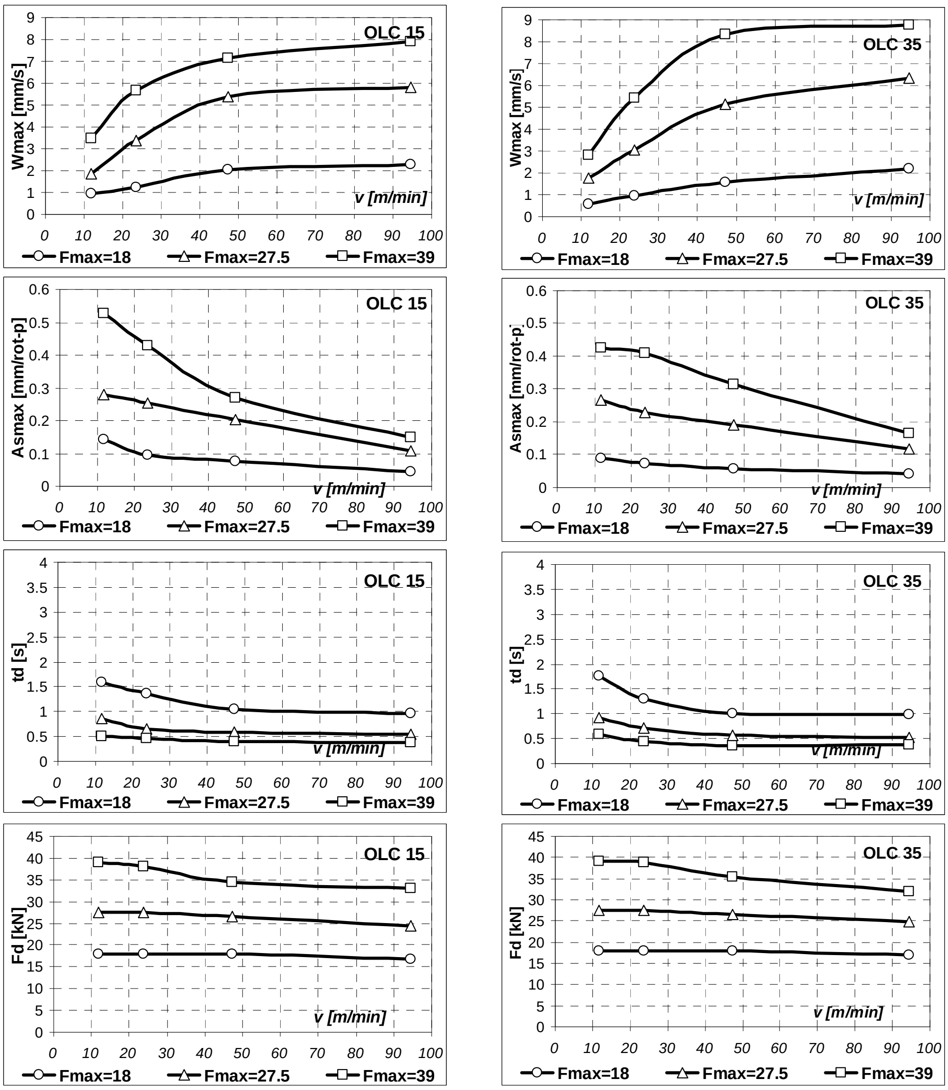

Figure 3. Dependence of the process parameters function of the variable parameters of the process: unalloyed steels

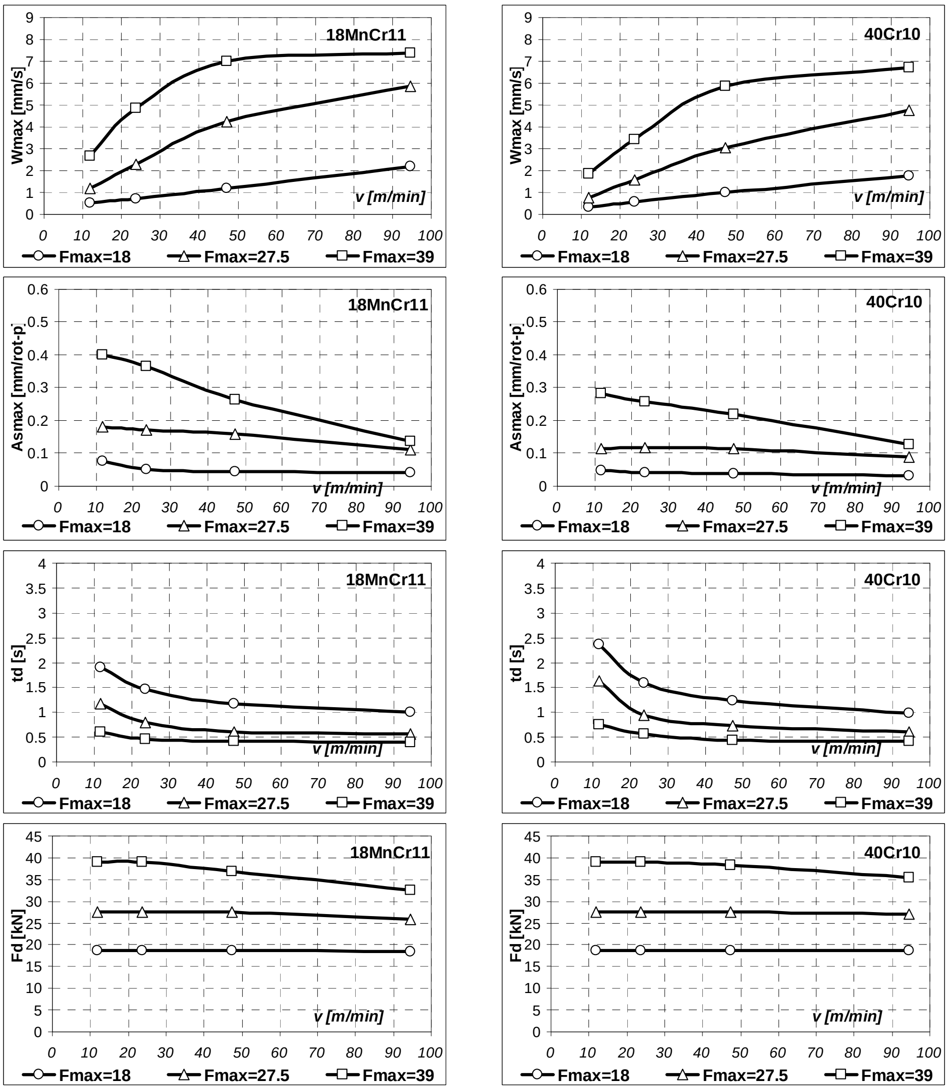

Figure 4. Dependence of the process parameters function of the variable parameters of the process: alloyed steels

The form of the dependence curves is similar for the four materials studied and the main highlighted aspects are:

- the maximum speed of penetration of the tool, w_{max}, increases with the increase of F_{max} and v.
- the maximum basic action of the tool, $A_{s\ max}$, increases with the decrease of the rolling speed and with the increase of the maximum adjusted force.
- the time required for the formation of the profile, t_d, decreases with the increase of the rolling speed and of the maximum adjusted force.
- the radial rolling force at the time of the formation of the profile, F_d, slowly decreases with the increase of the rolling speed.

The influence of the rolling speed on the process parameters is bigger for values under 30 [m/min] and acts differently, function of the size of the maximum adjusted force:

- for parameters w_{max} and $A_{s\ max}$ significant influences appear when the maximum adjusted force is higher.
- for parameter t_d the most significant influences appear when processing takes place at the lowest value of the maximum adjusted force.

MULTIVARIABLE REGRESSION FUNCTIONS

In order to model the dependence of the process parameters on the parameters of the rolling regime and on one of the characteristics of the processed material, the polynomial process functions were determined using the rate of the dependence curves of the process parameters and applying the multivariable regression analysis.

First, the functions for each type of material were determined, table 2. All the determined models were adequate and the coefficients of the functions were significant for a confidence level of 99%.

Table 2. Process functions for each type of material

Material: OLC15	**Material: 18MnCr11**
$w_{max} = 0.002148 \cdot F_{max}^{1.7276} \cdot v^{0.4646}$ [mm/s] $A_{s\,max} = 0.00375 \cdot F_{max}^{1.7336} \cdot v^{-0.5364}$ [mm/rot piece] $t_d = 116.3787 \cdot F_{max}^{-1.3422} \cdot v^{-0.1992}$ [s] $F_d = 1.490336 \cdot F_{max}^{0.9269} \cdot v^{-0.0582}$ [kN]	$w_{max} = 0.00021 \cdot F_{max}^{2.1388} \cdot v^{0.6604}$ [mm/s] $A_{s\,max} = 0.000358 \cdot F_{max}^{2.1538} \cdot v^{-0.3422}$ [mm/rot piece] $t_d = 193.2155 \cdot F_{max}^{-1.372} \cdot v^{-0.2852}$ [s] $F_d = 1.64604 \cdot F_{max}^{0.8843} \cdot v^{-0.0377}$ [kN]
Material: OLC35	**Material: 40Cr10**
$w_{max} = 0.000386 \cdot F_{max}^{2.0733} \cdot v^{0.0.6022}$ [mm/s] $A_{s\,max} = 0.000679 \cdot F_{max}^{2.0778} \cdot v^{-0.4002}$ [mm/rot piece] $t_d = 159.8155 \cdot F_{max}^{-1.3623} \cdot v^{-0.2692}$ [s] $F_d = 1.525493 \cdot F_{max}^{0.9206} \cdot v^{-0.0579}$ [kN]	$w_{max} = 9.88 \cdot 10^{-5} \cdot F_{max}^{2.1567} \cdot v^{0.7786}$ [mm/s] $A_{s\,max} = 0.000174 \cdot F_{max}^{2.158} \cdot v^{-0.2215}$ [mm/rot piece] $t_d = 261.5704 \cdot F_{max}^{-1.3112} \cdot v^{-0.3906}$ [s] $F_d = 1.37367 \cdot F_{max}^{0.9224} \cdot v^{-0.0174}$ [kN]

Subsequently, for each process parameter, there were attempts to determine the total functions which contained one of the mechanic characteristics of the processed material. Using successively the mechanical characteristics, presented in table 1 in the regression analysis, the hardness of the material, HB, proved to be the characteristic leading to the best results, table 3.

Table 3. Total process functions

$w_{max} = 0.073822 \cdot F_{max}^{2.0462} \cdot v^{0.6302} \cdot HB^{-1.0188}$ [mm/s] $A_{s\,max} = 0.129178 \cdot F_{max}^{2.0522} \cdot v^{-0.3712} \cdot HB^{-1.0192}$ [mm/rot piece] $t_d = 16.24155 \cdot F_{max}^{-1.\ 3531} \cdot v^{-0.289} HB^{0.4539}$ [s] $F_d = 0.988757 \cdot F_{max}^{0.9125} \cdot v^{-0.0433} HB^{0.0802}$ [kN]

To determine the sense of influence and the importance of each independent variable on the process functions, was determined the influence weight of each independent variables X_i on the process function Y. This was the calculation of indicators q_i şi q_i %, defined by absolute variation, respectively, relative to the variable Y corresponding of the variable variation X_i from $X_{i\,min}$ to $X_{i\,max}$:

$$q_i = \frac{Y_{max}}{Y_{min}} \text{ and } q_i\,\% = \frac{Y_{max} - Y_{min}}{Y_{min}} \cdot 100\,\% \quad (9)$$

where $Y_{min} = Y(X_{i\,min})$ and $Y_{max} = (X_{i\,max})$ for defaults of the other variables in the center of experiments.

Absolute weight coefficients qi and qi% relative as determined and sense of influence of independent variables are shown in Table 4. For example, an increased of the adjusted force to the minimum (18 kN) at maximum (39 kN) level leads to a decrease of the deformation time with 64,8%, while an increasing of the rolling speed to the minimum (11,81 m/min) at maximum (94,5 m/min) level leads to a decrease of the deformation time with 45,1%

Table 4. Weight coefficients values and sense of influence of independent variables

Process function	**Independent variable**	**Sense of the process function variation to the increase of value of independent variable**	**Absolute weight coefficient, q_i**	**Relative weight coefficient, q_i%**
w_{max}	F_{max} [kN]	increase	4.86	386.5
	v [m/min]	increase	3.70	270.8
	HB [kg/mm^2]	decreases	0.55	-44.3
$A_{s\ max}$	F_{max} [kN]	increase	4.88	388.7
	v [m/min]	decreases	0.46	-53.7
	HB [kg/mm^2]	decreases	0.55	-44.3
t_d	F_{max} [kN]	decreases	0.35	-64.8
	v [m/min]	decreases	0.54	-45.1
	HB [kg/mm^2]	increase	1.29	29.8
F_d	F_{max} [kN]	increase	2.02	102.4
	v [m/min]	decreases	0.91	-8.6
	HB [kg/mm^2]	increase	1.04	4.7

Analysis of the results of Table 4 shows that the maximum adjusting force has the highest influence of all due process functions. The second variable in importance on the functions of process is rolling speed.
It appears that to make the rolling process in as little time is necessary to adopt an adjusting force and a rolling speed as high possible.

CONCLUSIONS AND INTENTIONS

The analytical modelling of the radial rolling process based on the laws of evolution in time of the depth of deformation and of the radial rolling force allowed the determination of the dependence of the process parameters function of the rolling regime parameters and of the characteristics of the processed material. The dependence was expressed with the help of some process functions, determined through the multivariable regression analysis.
The analysis of the process functions allowed establishing the way the rolling regime parameters and the characteristics of the material, as well as their importance, influence the intensity and period of the rolling process.
In order to develop the knowledge about the rolling process, the study will continue with the analysis of the mechanical characteristics of the deformed layer and with the numerical modelling of the radial rolling process.

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