RESEARCH ON NUMERICAL MODELLING AND SIMULATION OF THE FORM TAPPING PROCESS TO ACHIEVE PROFILES

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Abstract: Processing profiles through form tapping process with planetary rollers is used in industry, especially in the automotive industry. Even though this process exists for several decades, few studies dealing with this topic were published. The main objective of this paper was to validate the numerical model achieved. For the validation of the numerical model achieved it is required to compare the entire assembly of results obtained through numerical simulation to those obtained experimentally. For the comparison there were taken into consideration: the values of the rolling forces, the level of equivalent deformations at the end of the process, of other parameters which can be deduced from these deformations and the behaviour laws of the materials deformed. The materials used are two types of steel: AISI1015, AISI1040.
The researches on achieving the numerical model to simulate the process of intermittent plastic deformation with planetary rollers to obtain profiles aimed on the one hand the accuracy of the results obtained through simulation and on the other hand acceptable simulation periods for practice.
Key words: cold plastic deformation, numerical modelling, form tapping process, process parameters, characteristics of the material, Abaqus.

1. INTRODUCTION

Industrial processes to obtain profiled parts are in a continuous development and competition concerning the high quality and cost of products. To answer these goals effective processes must be used.
A process used for this purpose is the form tapping process with planetary rollers. By using this process, there can be obtained different types of profiles in solid or hollow cylindrical pieces of larger sizes and diameters as compared to other cold deformation processes.
Also to answer these needs, the trend is oriented towards developing and implementing numerical modelling which represents a very useful and efficient tool which successfully replaces experimental research and development. Studying the deformation process (equipment kinematics, tool geometry, technological parameters etc.) experimentally represents a laborious activity which requires time, materials, energy. For these reasons, the efficient study of the process can be done by modelling and numerical simulation
Numerical modelling to simulate some complex processes has become possible as a result of significant progress made in the field of material deformation mechanics, increase of storage capacity and processing information by modern computing tools, (Warrington, 2006). Also, in order to model the processes there were developed many programmes, more or less specialised, based on the finite element (Warrington, 2006).
The FE modelling of the form tapping process started in the 1990, but the high volume of calculations and the computers incapacity to simulate the process within a reasonable time, restricted these studies.
The researches intensified in 2000, together with the development of efficient FE software and with the growing computational capacity of computers (Warrington, 2006). The main elements of interest in these researches are the material of the work-piece, piece profile and rolling process, with particular attention to the plastic behaviour of the material, the meshing elements and the software used for simulations (MARC, ABAQUS, DEFORM, MSC Super Form).
The strain-hardening laws most frequently used for the analysis and simulation of large plastic deformations at room temperature are Hollomon, Ludwik, Ludwik-Hartley and Voce. However, cold rolling processes are affected by the effects of high-speed processing and associated temperature rise; because heat generated by plastic deformation has not enough time to be evacuated by convection through the surface and by conduction to the connecting parts. These strain-rate and temperature effects are often described using the Johnson-Cook’s law (Johnson).
In this study, a complex profile with five grooves has been formed by form tapping. This paper focuses on the development of three-dimensional FE models using the stress-strain law characterized in

compression tests and an optimal mesh of the work-piece in order to obtain accurate results with a reasonable number of elements and an acceptable computation time.
The validation results are based on experimental data obtained for different depth penetration of the rolls. The form tapping process is simulated using the Abaqus/Explicit FE code.

2. EXPERIMENTAL PROCEDURE

2.1 Kinematics of the studied process

As a result of the fact that for the experiments, a special machine to allow processing with planetary rollers was not available, the process was performed on a milling machine using a rolling head specially conceived and designed. This rolling head replaces the dividing movement required by this process of intermittent deformation.
The rolling process on special machines takes place with the successive intermittent/incremental deformation on each one of the profiles to be achieved on the piece. Therefore, to obtain on a cylindrical piece, figure 1, 5 profiles (circular channels) with a rolling head 2 which has only one planetary roller r1, the following are required: rotation movement of the head 2, n; circular feed movement given by rotation n_p of the piece; the alternative dividing movement, t, which achieves the intermittent deformation on condition that it is correlated to the rotation movement a. (Boicea, 2012)

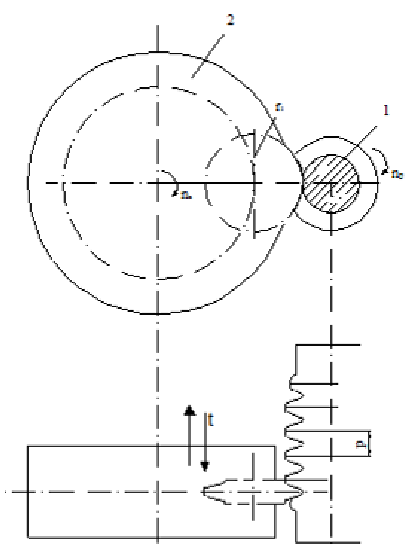


Fig. 1. Kinematics of the process with one roller

The alternative dividing movement allows for the deformation to take place intermittently/ incrementally. If the first channel would be made on the entire circumference of the piece, to achieve the second one, with the first one ready, its geometrical dimensions would be affected by the material moved during deformation when processing the second channel.
If on the rolling head there are mounted five rollers (r_1, r_2,...r_5) axially placed from one another with pass p, and at equal angles of 72°, figure 2, the dividing movement is replaced. In this case, to generate the 5 channels, the dividing movement is no longer needed, only the first two rotations are required.

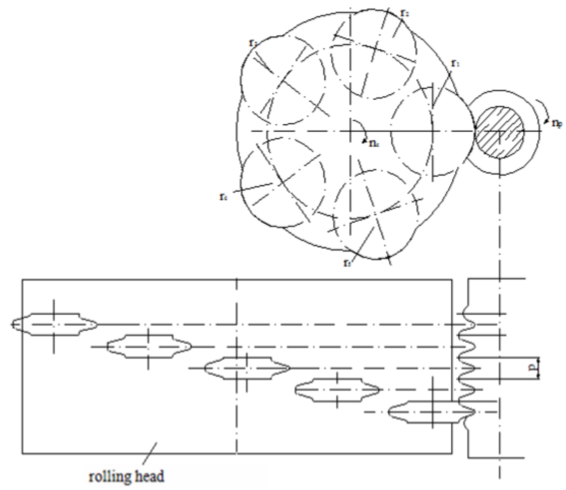


Fig. 2. Kinematics of the process with several rollers

2.2 Stand used for the experiments

The stand used for the experiments is made on a milling machine FU 32. Its structure, figure 3, consists in:
- two heads with rollers to roll the profiles, metric and trapezoidal;
- the pieces to process;
- a device for orienting and setting the pieces to process;
- a transducer to measure the two components of the rolling force;
- the system to acquire data concerning the forces.

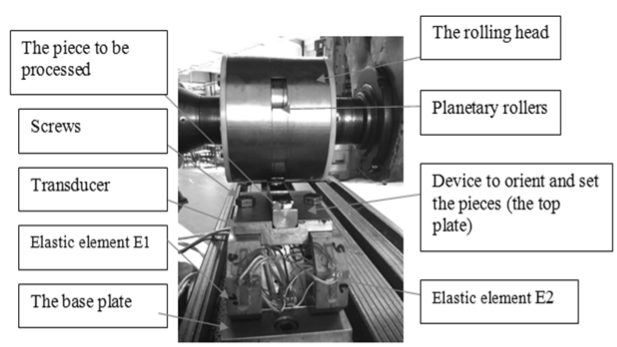


Fig. 3. Stand for experiments

2.3 Semi products, materials and profiles

The semi products used for the experiments and the pieces obtained are presented in figure 4. These were conceived so that processing can be performed in the two working areas; each one has 25 mm and allows processing channels with constant parameters by removing the input and output area of the rolling head.

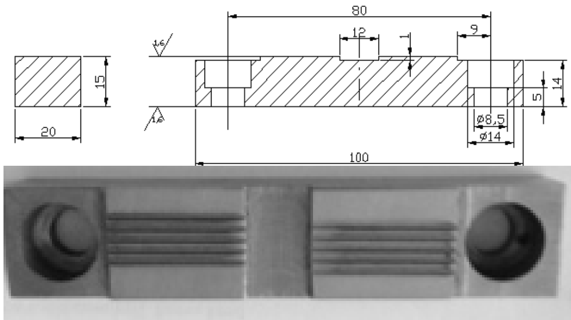


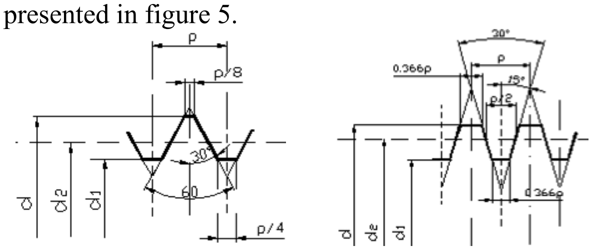
Fig. 4. Semi products and pieces used for the processing

The investigations were made for two steels: AISI 1015 and AISI 5140, frequently used to generate profiles through plastic deformation with planetary rollers. Their initial mechanical characteristics are presented in table 1.

Table 1. Mechanical characteristics of the steel used

Steel	HB [kg/mm^2]	$HV_{0.3}$ [kg/mm^2]	$Rp_{0,2}$ [N/mm^2]	Rm [N/mm^2]	A5 [%]
AISI 1015	156,1	139	298	475	15
AISI 5140	277,4	245,5	396	837	7

Concerning the geometry of profiles, two profiles corresponding to threads M20, figure 5.a, and Tr20, figure 5.b, obtained at different depths were chosen. The processed profile is formed by 5 identical grooves in axial section to the one of the ISO metric thread M20x2 and Tr20, their geometry being presented in figure 5.



a) b)
Fig. 5. Geometry of studied profiles

2.4 Experiment plans used

For profile M20 six experiments were performed for each processed material by varying process parameters on 2 and 3 levels, respectively, following geometric progressions in order to be able to linearize the model with logarithms:
-feed, sr = 0.1 / 0.2 / 0.4, [mm/rot];
-processing depth, h1 = 0.3 / 0.5, [mm].
For profile Tr20 nine experiments were performed for each processed material by varying process parameters on 3 levels following geometric progressions:
-feed, sr = 0.1 / 0.2 / 0.4, [mm/rot];
-processing depth, h_1 = 0.3 / 0.5 / 0.7, [mm].

3. NUMERICAL PROCEDURE

3.1 Kinematics of model

One model was developed and used in simulations to accurately describe the rolling process through intermittent blow performed experimentally. The tools were modelled as shell rigid elements. The semi product had small dimensions, a cuboids shape.
The calculating time with this model was of about 90 h and due to the fact that the process took place quickly the frequency of acquiring rolling forces was not enough.
The kinematics used in model describes the experimental conditions. The semi product is deformable and has a cuboids shape. It has small dimensions (10mm x 5mm x 6mm), in order to be meshed into small finite elements, but few overall, to reduce the calculating time.
The rolling head has three rollers and rotates with the speed n_c and the piece moves tangential to the rolling head with feed s, figure 6. The rollers rotate freely around their own axes.

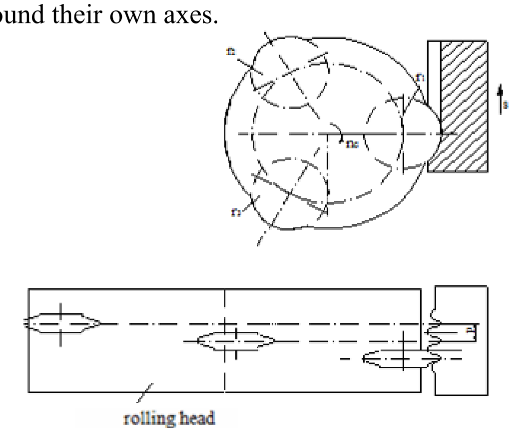


Fig. 6. Kinematics of model

3.2 Constructing numerical model

The semi product is deformable and has a cuboids shape of small dimensions (10 mm x 5 mm x 6 mm) to reduce the calculating time, (Boicea, 2011)
"Shell" type of tools is modelled with the help of rigid elements and have the profile combined with the one to achieve and the exterior diameter has 40 mm, figure 7.

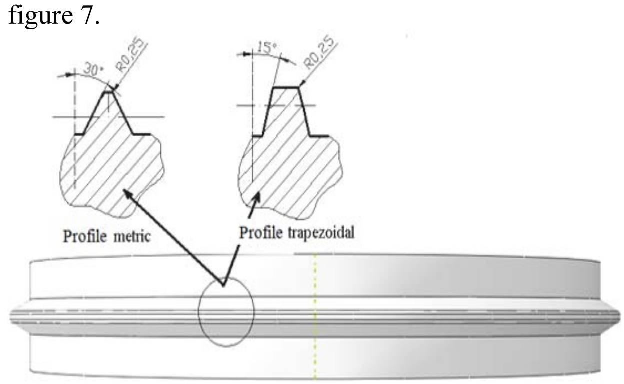
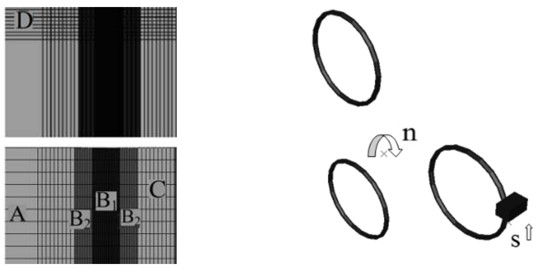


Fig. 7. Profile of the tools used

The mesh of the semi product was performed by dividing areas specific to the degree of deformation, figure 8.



a) b)

Fig. 8. Numerical model
a)semi product mesh; b) model kinematics

For all areas A, B, C and D hexahedral solid elements with 8 nodes and reduced integration – C3D8R are used.

The parameters of the rolling head are introduced in the model by establishing limit conditions, fig.8.b:

- the tools rotate around the central axes system, n=475 rot/min;
- the semi product moves with the same feed as the experimental one (s = 0.1 mm/rot, s = 0.2 mm/rot, s=0.4 mm/rot etc.).

The contact between surfaces is of the type "surface-to-surface", the friction coefficient between the tools and the semi product is 0. (Boicea, 2011)

3.3 Behaviour laws of materials used for plastic deformation

The behaviour laws of materials at plastic deformation used where those established and used in paper (Marincei 2010) for radial rolling with disk rollers.

In this paper the behaviour of materials was defined as follows:

- in the elastic domain by Young's modulus Young E = 210GPa and Poisson's coefficient ν = 0,3;
- in the plastic domain by the behaviour law combining Hollomon and Voce's laws.

This law was validated by the results obtained at the simulation of the radial rolling process (Marincei 2010). The coefficients of these laws were determined experimentally using the compression test at low speeds for steels AISI1015 and AISI10:

$$\sigma_{AISI1015} = \left[542{,}5 \cdot \varepsilon^{0.135} + 217{,}6(1 - 0{,}99\exp(-9{,}91 \cdot \varepsilon))\right] \quad (1)$$

$$\sigma_{AISI1040} = \left[673{,}8 \cdot \varepsilon^{0.022} + 371{,}8(1 - 0{,}99\exp(-15{,}61 \cdot \varepsilon))\right] \quad (2)$$

4.SIMULATIONS TO VALIDATE THE MODEL

4.1 Objective of simulations and simulation plan

The main objective of the simulations was to validate the numerical model achieved. For the validation of the numerical model achieved it is required to compare the entire assembly of results obtained through numerical simulation to those obtained experimentally. For the comparison there were taken into consideration: the values of the rolling forces; the level of equivalent deformations at the end of the process, of other parameters which can be deduced from these deformations and the behaviour laws of the materials deformed.

When the simulation plan was established, mainly, it was taken into consideration the plan used in the experimental research of the process. In order to have the data necessary to validate the model achieved.

Table 2. The simulation plan

No. of sample simulated	Material of the piece	Type of profile	The experimental parameters		
			n [rot/min]	s [mm/rot]]	h [mm]
1	OLC15	M20	235	0,1	0,5
2	OLC15	Tr20	235	0,1	0,5
3	OLC15	Tr20	235	0,1	0,7
4	40Cr10	M20	235	0,4	0,5
5	40Cr10	Tr20	235	0,4	0, 5
6	40Cr10	Tr20	235	0,4	0,7

4.2 Results obtained at simulations with numerical model

The 6 samples, 1, 2, 3, 4, 5, 6, were simulated with the numerical model for the friction coefficient μ = 0, coefficient which turned to be correct.

The values of the maximum forces obtained experimentally, through simulation with model, for samples 1, 2, 3, 4, 5 and 6 are presented in table 3.

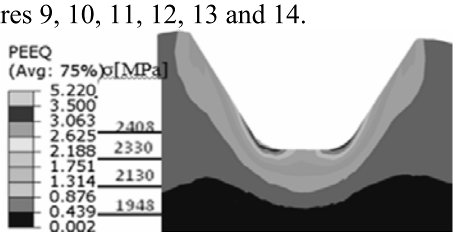
Table 3. Maximum forces obtained experimentally, through simulation

No. of sample	Material of the piece	Type of profile	Depth, mm	Fmax [KN] exp.	Fmax [KN] sim.	Error, [%]
1	OLC15	M20	0,5	3,36	3,95	17,56
2	OLC15	Tr20	0,5	2,98	2,85	4,36
3	OLC15	Tr20	0,7	3,27	3,4	3,98
4	40Cr10	M20	0,5	7,54	7,4	1,86
5	40Cr10	Tr20	0,5	6,52	7,79	19,47
6	40Cr10	Tr20	0,7	7,55	9,2	21,85

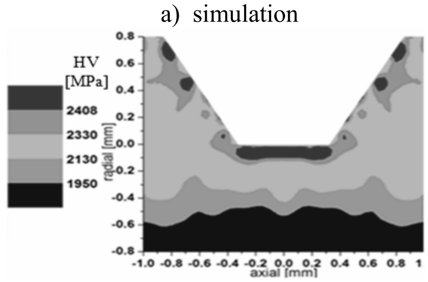
Considering the fact that the errors between the maximum values of the forces obtained by simulation with the model and experimentally vary between 1,86% and 21,85% it can be noted that the model can be validated.

The second parameter used to validate the numerical model was the one based on the analysis of the degree and manner of strain hardening of the deformed layer. For this purpose there were used, on the one hand, the experimental values of the micro hardness of the strain hardened layer measured in the axial section of the profile and on the other hand, the values of the equivalent deformations $\bar{\varepsilon}$ (PEEQ) in the same area of the profile, obtained through simulation. The two values (HV and $\bar{\varepsilon}$) were transformed based on some hypotheses (Tabor 1951) into values directly comparable, into tensions respectively, expressed by the same measuring unit [MPa]. The 6 profiles chosen for the study of micro-hardness in the section of profiles correspond to the conditions considered to be extreme from the point of view of material characteristics and process parameters. The limited number of samples was also determined by the sheer volume of work for this type of measurements. This did not prevent reaching the objectives set.

To point out the way the material of strain hardened, level maps of the micro-hardness were made, in OriginLab8 program, by taking into consideration five levels of values for the micro-hardness measured in the section of profiles. The distributions of equivalent deformations obtained through simulation and experimentally for the 6 sample 2 are presented in figures 9, 10, 11, 12, 13 and 14.

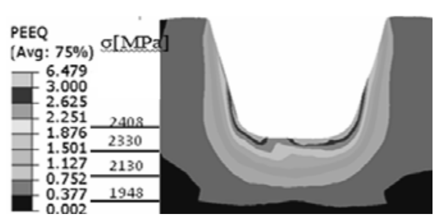


a) simulation

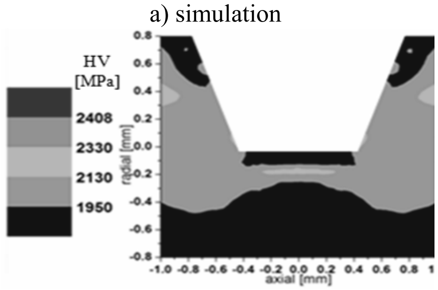


b) experimentally

Fig. 9. Distributions of equivalent deformations obtained through simulation and experimentally for sample 1

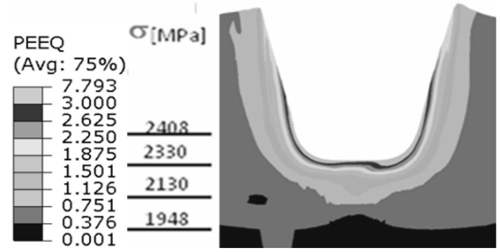


a) simulation

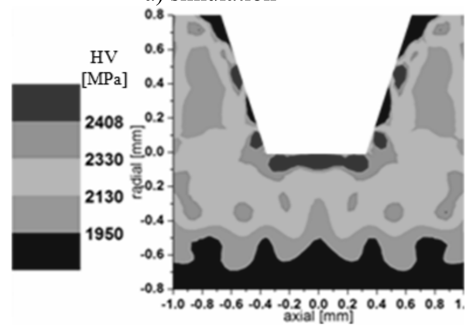


b) experimentally

Fig. 10. Distributions of equivalent deformations obtained through simulation and experimentally for sample 2

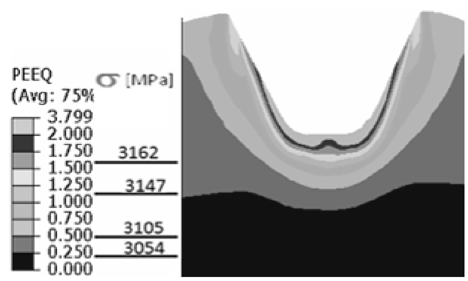


a) simulation

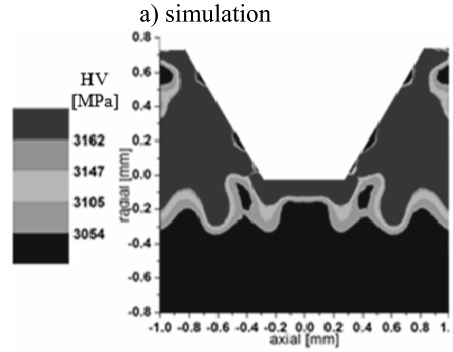


b) experimentally

Fig. 11. Distributions of equivalent deformations obtained through simulation and experimentally for sample 3

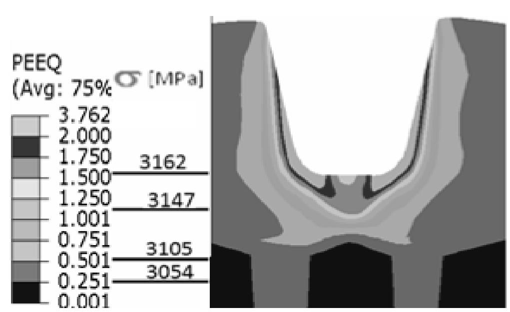


a) simulation

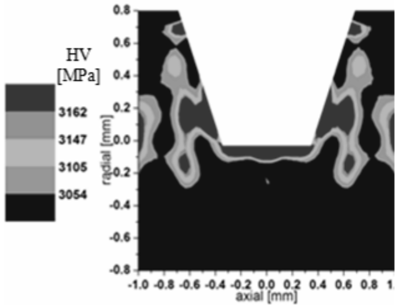


b) experimentally

Fig. 12. Distributions of equivalent deformations obtained through simulation and experimentally for sample 4

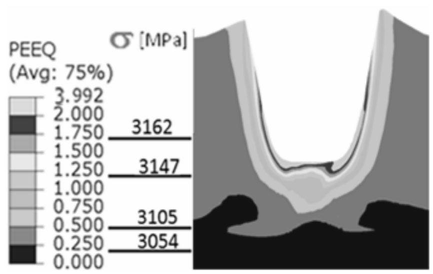


a) simulation

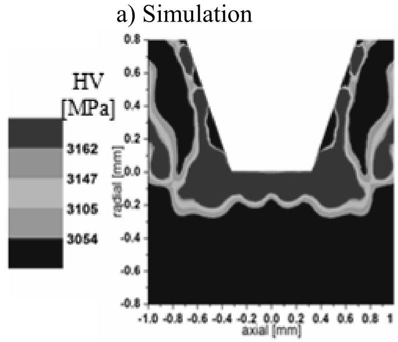


b) experimentally

Fig. 13. Distributions of equivalent deformations obtained through simulation and experimentally for sample 5



a) Simulation



b) Experimentally

Fig. 14. Distributions of equivalent deformations obtained through simulation and experimentally for sample 6

General shape of the deformation field obtained on the metric profile is comparable to the one obtained on the trapezoidal profile. Compared to profile M20 processed on the same material and under the same technological conditions it is pointed out by a higher strain hardening of the gap and base flank of the profile and by a lower strain hardening of the central area of the tooth, aspect found in experiments as well.

5. CONCLUSIONS

The main objective of simulations was to validate the numerical model achieved by comparing the results obtained through numerical simulation to those obtained experimentally. The comparisons concerned two important process parameters: values of the rolling forces, and the level of equivalent deformations at the end of the process, of other parameters which can be deduced from these deformations and the behaviour laws of the materials to be deformed.

By overlapping the forces recorded experimentally for depths of 0.3 mm, 0.5 mm, and 0.7mm, when $\mu=0$, very good correspondence is obtained between the forces obtained experimentally and those obtained through simulation.

The second parameter used to validate the numerical model was based on the analysis of the degree and manner of strain hardening of the deformed layer. For this purpose, there were used, on the one hand, the experimental values of the micro hardness of the strain hardened layer measured in the profile flank and in the axial section of the profile and on the other hand the values of equivalent deformations (PEEQ) in the same area of the profile, obtained through simulation. The simulations plan was wide enough. It concerned samples for materials with extreme characteristics (AISI 1015 and AISI 1040), on two profiles, metric and trapezoidal, different values of working feed and depths of profile penetration.

The comparison of the results obtained through simulation, connected to the forces, deformations and tensions to those obtained experimentally, show that the model give results accurate enough at the simulation of the process.

6. REFERENCES

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