Computational analysis of contact forces influence on cold forming processes in the dies with complex surfaces

D Dragnea¹, P Lixandru², T Chereches³, St Velicu⁴
¹,²,³ SC UPS PILOT ARM SRL, Dragomiresti, 137210, Romania
⁴ Polytechnic University of Bucharest, IMST Faculty, Splaiul Independentei 313, sector 6, 060042, Bucharest, Corp CD 003, Romania
E-mail: danieldrg2003@yahoo.com

Abstract. Interaction forces between the workpiece and the die appear during the cold forming process of metals in dies. Surface forces of high-intensity influence the mesh structure and internal structure of the finished piece by mechanical action. Frictional forces hinder the flow of the material in contact with the die walls, especially on surfaces of complex shape. Under certain conditions, the material can adhere to the wall of the die, leading to the blocking of the cold forming process. In order to highlight the influence of contact forces on cold forming processes in dies with complex surfaces there were used numerical simulation methods with finite elements. Numerical simulations of the process of axial cold forming in the die were carried out for analysis data acquisition necessary, in order to achieve HTD pulleys, for an ordinary range of friction coefficients. The analysis was directed to the gearing area of the HTD pulleys (head, flank and base of the tooth). The analysis highlighted the negative effects of friction forces on the shape and quality of the products and the need to use quality lubricants. Also, using the cold forming process they can be achieved substantial savings by redistribution of the material without removing it.

1. Introduction
The achievement of the timing pulleys through conventional processes (gear cutting) requires a wide variety of mechanical processing and other processing and equipment either alone or in combinations. Timing pulleys do not need hardened teeth such as are practiced in the spur gears and for this reason the manufacturing process of these gears is easier. Currently the timing pulleys are made of metallic materials (steel, cast iron), non-ferrous alloys that include aluminium alloys and non-metallic materials such as PA, PE and POM. Die-casting process of the non-metallic materials such as the zinc and the aluminium alloys as well as the plastic injection moulding are considered by the designers like processes that ensure sufficient quantities (timing belt pulleys) for mass production. Another method of mass production is the process of isostatic pressing and sintering of the timing pulleys, using powder metallurgy. The process is very attractive due to high productivity and is mainly used in the automotive industry. These methods eliminate machining by cutting of the teeth of the timing belt pulleys [1]. The numerical simulations from the paper are based on the method of gears processing by axial cold forming in the die, which completes the mass production processes mentioned above. Lately, in addition to the further improvement of classical gear cutting processes, it was found out a general interest for the application of cold forming processes. Application on a larger scale of the cold working is justified by the following:

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
The generation of a deformation structure by changing crystals shape and the orientation of the grains due to proper distribution of compressive stresses;
- favourable fibrous structure of the material, reoriented as a result of the plastic strain;
- the hardening of the material;
- improvement of mechanical properties by increasing of the yield strength, resistance to fatigue, wear resistance;
- material savings, the processing taking place with redistribution of the material without removing it;
- improved surface quality in terms of roughness;
- High productivity by automating the process.

2. Numerical simulations objective
Numerical simulations objective is to highlight the influence of the contact forces concerning the axial cold forming processes in the dies with complex surfaces using an analysis with finite element. Numerical simulations of the process of axial cold forming in the die for the achievement of a timing belt pulley with 24 teeth, with HTD type tooth profile and the pitch 5 mm, as a particular case, were carried out for the data acquisition necessary for the analysis. The analysis was directed to the gearing area of the HTD pulleys (head, flank and base of the tooth). There were monitored especially: the distorted mesh; effective plastic strain and Von Mises effective stress, in longitudinal section and in the cross sections of teeth area; the resultant displacement in XZ plan of three control nodes; evolution of the actuation force on the die punch, depending on the friction coefficient, throughout the entire process and at different times.

3. Simulation procedure
The numerical simulations follow a procedure that consists of the following steps:
- Stage 1 - The achievement of the physical model;
- Stage 2 - Mathematical model;
- Stage 3 - The achievement of the discretized model;
- Stage 4 - Coding;
- Stage 5 – Numerical solving.

3.1. Achieving the physical model
The physical model of the die for the manufacturing of the timing pulleys with 24 teeth, with HTD profile of the tooth and the pitch of teeth 5 mm through axial cold forming is shown in Figure 1. The physical model is a simplified one if we compare it to the real model of the die but this does not negatively influence the performance of numerical simulations, but on the contrary, decreases the working effort from the solving stage by reducing significantly the number of the elements. For reasons of symmetry of the physical model related to the two axes X and Y, it was chosen the quarter model (1/4). This fact resulted in lowering the computational effort from the solving stage, for the same reasons stated above. For materials involved in the physical model, representing the component parts of the die except the “punch plate”, it was adopted the linear-elastic material model that is governed by the law of Hooke. A rigid material model is adopted for the "punch plate" part. A good solution for simulation process by axial cold forming in the die is obtained only when the workpiece material properties are correctly established for all states of deformation until its failure. In order to establish these features, there are necessary tensile tests and compression tests on a testing universal machine, with standardized test samples of the workpiece material - aluminum alloy EN AW 6082 in its natural state T0. In order to achieve the numerical simulations, a characteristic curve of plasticity for the workpiece material was used, carried out following laboratory tests [2]. The workpiece from
aluminum alloy EN AW 6082, used for numerical simulations, has dimensions $\Phi_e \times H / \Phi_i = 32.6 \times 13 / 6.8$ mm.

3.2. Mathematical model
The mathematical model is established based on the laws that govern the physical model - in this case, the theory of plasticity. The objective of the theory of plasticity is the mathematical study of the states of stress and of the strains in the plastic domain and the connection between the two states. The mathematical model is generally expressed under the form of governing equations and of boundary and initial conditions [3].

![Figure 1. The physical model of the die.](image1)

![Figure 2. Discretized model of the die.](image2)

3.3. The achievement of the discretized model
The analysis method used was the mesh method (Lagrange) or finite element method. According to the procedure mentioned in chapter 3, to achieve numerical simulations of the axial cold forming process in the die of the HTD timing belt pulleys it is necessary to realize a meshed model of the die and of the workpiece in accordance with the intended aim (Figure 2). The meshing of the physical model has been realized with different densities of the pitch of the mesh, depending on the place and importance of each component piece in the process. A judicious mesh provides a greater density of elements in the regions with large gradients of the plastic strain field. For example the punch die, the lower part of the die, the upper part of the die in the contact area with the workpiece were discretized with a fine pitch of the mesh. The workpiece submitted to large plastic strain was also discretized with a fine pitch of the mesh.

3.4. The coding
Numerical simulation coding consists of passing the discretized model and the calculation algorithms into computer code by using a programming language.

3.5. Numerical solving
The numerical solution is obtained by using the module of solving - SOLVER which results in an output data set. In addition to this data set obtained, the solution of the problem can be also presented
under graphical form in fields (maps) of color or as diagrams. The numerical simulations performed in the paper highlight the axial cold forming processes in die of the metallic materials, using finite element methods. The material mesh used - Lagrange type - is a mesh linked to the bodies and deforms together with these ones.

4. Numerical simulations of the process of axial cold forming in the die

4.1. Conditions for numerical simulations

After meshing of the die and of the workpiece physical model as well and after assigning the mathematical model [3] there were put the necessary conditions for numerical simulations:

- The punch moves according to a linear time law;
- The working speed of the punch – 1 m/s;
- Duration of plastic deformation process in the die– $1.68 \times 10^{-2}$ s;
- The imposed tie increment $\Delta t = 5 \times 10^{-5}$ s, in quasi-static conditions [4].

The working regime is justified for the axial cold forming in the die because the inertial forces, the viscosity and heat are negligible at the speed of 1 m/s. The problem may be considered as a quasi-static problem, in which the time plays an insignificant role.

4.2. Results obtained at the numerical simulations

4.2.1. Deformed structure of the nodal mesh

There were performed five numerical simulations of the process of axial cold forming in the die for making a timing pulley with 24 teeth and the pitch of 5 mm for 5 different coefficients of friction ($\mu = 0.06, 0.08, 0.10, 0.12$ and 0.14). In figures 3 and 4 are presented the deformed meshes of a tooth in the areas of interest: the head of the tooth, its base and its flank.

![Figure 3](image)

**Figure 3.** The distorted mesh of the tooth head, for the five studied cases (top view).

During the cold forming, the workpiece material tends to fill the gaps between the teeth of the die. Because of the friction between the workpiece material and the flanks of the die teeth one can observe that the layers close to this area remain behind. At the increase of the friction coefficient, the layers of workpiece material from the area of contact with the die flanks teeth remain behind due to increasing of friction forces - figure 3. Also due to friction, three areas can be distinguished on the mating surfaces of the punch with the workpiece in which appear distortions of the mesh, marked with "A", "B", and "C".
"B" and "C". The mesh distortions are more obvious at the increasing of the friction coefficient. Distorted contact surfaces do not appear in cases $\mu = 0.06$ and 0.08. Figure 4 shows the distorted mesh of the tooth base and of its flank. Due to the fact that the layers of material from the base of the tooth of the timing pulley come into contact with the head of die tooth, very large plastic deformations are produced, which determine a compaction of its layers. The most uniform structures of deformed meshes are obtained for the smallest friction coefficients $\mu = 0.06$ and $\mu = 0.08$ and this corresponds to a better fibrous structure for the material of the finished parts.

![Figure 4](image1)

**Figure 4.** The distorted mesh of the tooth base and flank for the five studied cases (top view).

4.2.2. **Effective plastic strain field**

Figures 5 and 6 present the effective plastic strain fields in longitudinal section and in cross-section respectively at a distance of 7.6 mm from the base of teeth.

![Figure 5](image2)

**Figure 5.** The effective plastic strain in the longitudinal section of the finished part, according to different coefficients of friction.
It is found out that in the contact areas between the profiles of the punch, the lower part of the die and the finished piece appear superficial effective plastic strains with high values, $\varepsilon = 2$ on surfaces (darker areas from figure 5 denoted by the letter "A") that increase with increasing friction coefficient. Otherwise, the distribution of the effective plastic strain has small variations, from one friction coefficient to another. In this analysis, the distribution of the plastic strain fields was also monitored in three cross sections: at 5mm to 7.6 mm and 10 mm from teeth base. It has been found out that they have an identical graphical layout (figure 6), which means that the layout of the effective plastic strain fields is uniform on the entire teeth area. Figure 6 shows the distribution of the effective plastic strains field, in one representative section, that is located approximately at the half of teeth area.

![Figure 6](image)

**Figure 6.** The effective plastic strain in the cross-section through the finished piece (at 7.6 mm from the base of the teeth), according to different coefficients of friction.

![Figure 7](image)

**Figure 7.** Von Mises effective stress in the longitudinal section of the finished piece, according to different coefficients of friction.
4.2.3. Von Mises effective stress field
Figure 7 highlights the field of Von Mises effective stress in a longitudinal section through the finished piece. Von Mises effective stress reaches values of 200 MPa in the areas marked with the letter "B" (darker ones). These surfaces grow with increasing of friction coefficient. Within the analysis it was also monitored the distribution of Von Mises effective stress fields, in three cross sections: at 5mm, 7.6 mm and 10 mm from the teeth base. It has been found out that they have an identical graphical layout (figure 8), which means that the distribution of these fields is uniform on the entire teeth area. Figure 8 presents a distribution of Von Mises effective stress field in one representative section, located at half of teeth area approximately. The Von Mises effective stress in cross sections reaches values similar to the longitudinal section, about 200 MPa.

![Figure 8. Von Mises effective stress in the cross-section through the finished piece (at 7.6 mm from the base of the teeth), according to different coefficients of friction.](image)

4.2.4. The resultant of displacements of some control nodes in XZ plane
Three control nodes were selected within the analysis, located on the outer diameter of the workpiece. It was monitored the evolution of their resultant displacements in XZ plane during the axial cold forming process in the die, according to the five friction coefficients shown in figure 9. As expected, it was found out that the node number 407 146 located on the outside of the workpiece in contact with the die punch is subjected to the displacements with the highest values in the XZ plane.

4.2.5. The evolution of actuation forces on the die punch
It was performed an analysis of the evolution of actuation forces on the die punch both throughout the entire duration of the axial cold forming process and at certain points of time, according to the five friction coefficients, figures 10 and 11. In Figure 10 it is shown a relatively small variation of the actuation forces on the punch depending on the friction coefficient, which is due to the reduced stroke of the punch in the die for achieving the finished part. It can be also observed from the graph that the maximum actuation force tends to the 280 [kN] which means about 28 (tonnes force) [tf]. Given that the physical model of the simulation is on-quarter (1/4), then the necessary force of a press, for realizing an axial cold forming process in the die of the timing pulleys with 24 teeth and step of teeth 5 mm, is $28 \times 4 = 112$ [tf]. In Figure 11 it is noted that the actuation forces are grouped at the moments
t = 0.010, 0.012, and 0.014 [s], their values ranging from 50 ... 80 [kN] for the friction coefficient $\mu = 0.06$ and 60 ... ~ 100 [kN] for friction coefficient $\mu = 0.14$. The increases of the actuation forces are about 20 [kN] for each time point.

Figure 9. The resultant of the displacement in the XZ plane for three control nodes.

Figure 10. The actuation force on the punch according to the friction coefficient $\mu$. 
For time $t = 0.016 \,[\text{s}]$ it has been observed a spectacular increase of the actuation force (the coefficient of friction $\mu = 0.06$) from about 80 \,[\text{kN}] as it was at time $t = 0.014 \,[\text{s}]$ up to 180 \,[\text{kN}] for the same friction coefficient. Due to the small stroke of the axial cold forming in the die, at this moment ($t = 0.016 \,[\text{s}]$) we do not have a significant increase of the actuation force for friction coefficient $\mu = 0.14$. This increase is from 180 \,[\text{kN}] up to about 210 \,[\text{kN}].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Grapdhics of the actuation force on the punch, according to the different coefficients of friction $\mu$, at different time points.}
\end{figure}

5. Conclusions to the numerical simulations
The numerical simulations of the axial cold forming process in the die of a timing pulley with 24 teeth and pitch of 5mm, realized for five friction coefficients ($\mu = 0.06, 0.08, 0.10, 0.12$ and $0.14$) have revealed the following matters:
- the deformed structure of the mesh in the area of interest both to the head and the base of the tooth as well as on its flank is relatively uniform in all five cases; the structures realized for friction coefficients $\mu = 0.06$ and 0.08 are preferable because some distortions of the mesh occur at higher friction coefficients; a uniform mesh structure is the equivalent of a better fibrous structure of the finished piece;
- it was found out that in the contact areas between the profiles of die punch, the lower part of the die and the finished piece, appear superficial effective plastic strains with high values, $\varepsilon = 2$, (darker areas in figure 5, marked with the letter "A"), surfaces that increase with increasing of friction coefficient; otherwise, the effective plastic strain field shows small variations from a coefficient of friction to another;
- the effective plastic strain fields from the cross sections (figure 6) are identical, which means uniformity over the entire length of their teeth; here too there are found out effective plastic strains with high values in the contact areas between the die punch profile and the finite piece also, $\varepsilon = 3$ (the dark areas from the centre of the timing pulley) whose sizes increase with increasing of friction coefficient value;
- The Von Mises effective stress field in the longitudinal section through the finished piece (figure 7) shows maximum values of 200 MPa in the darker areas marked with the letter "B". These areas
increase in size with increasing friction coefficient value. The same conclusions can be drawn for the
case of the cross-sections: there were found out identical shapes of the Von Mises effective stress
fields (figure 8) in the three cross sections, which means that their layout on the entire toothed area is
also uniform;
- at the analysis of the resultant displacements in the XZ plane of the 3 control nodes located on the
outer diameter of the workpiece it was found out that the node with number 407146, placed in contact
with the die punch, as expected, it is subject to displacements with the highest values;
- the actuation force on the die punch increases pretty little, for the maximum friction coefficient $\mu = 0.14$, due to the small stroke of the punch; the maximum actuation force is somewhere at 280 [kN],
that means 28 [tf] because the physical model is on quarter (1/4) it results an actuation force of 112 [tf]
for the entire piece; at time $t = 0.016$ [s] it is observed a spectacular increase of the actuation force (the
friction coefficient $\mu = 0.06$) from about 80 [kN] as it was at time $t = 0.014$ [s] up to 180 kN for the
same friction coefficient (Figure 11);
- It is preferable to realize an axial cold forming in the die at the low friction coefficients ($\mu = 0.06$
or 0.08) because the surface quality and the fibrous structure of the finished piece are better, this
necessitating a good lubrication during the process.

6. General conclusions
Axial cold forming in the die is a process used mainly for the achievement of the pieces demarcated by
complex borders made of nonferrous alloys (duralumin, copper, bronze etc.). Axial cold forming in the
die presented in the paper has many advantages compared to the gear cutting processes and even to the
processes in which gears are made by rolling, sintering or casting:
- the machining by cutting processes require several preparatory operations for achieving the
workpiece (time consuming) necessary for the gear cutting itself. In the processes for manufacturing
the gears through rolling operations, although they are more productive than gear cutting processes, in
the most cases, the accuracy of the workpiece causes the most problems; compared to these processes,
the process of cold pressing in the die does not require a special machining and the achievement of the
workpiece does not require tight tolerance fields;
- the generation of a deformation structure by modifying the shape of the grains and their
orientation, as a result of the proper distribution of compressive stresses;
- favourable fibrous structure of material, reoriented as a result of the plastic deformation;
- the hardening of the material;
- improvement of the mechanical properties by increasing the yield strength of the material, fatigue
resistance and wear resistance;
- material savings, as the process takes place by redistributing the material without removing it;
- improved surface quality in terms of the roughness;
- high productivity by the automation of the process;
- further improvement of the mechanical characteristics of the finished pieces through heat
treatments, not very demanding.

7. Appendices
7.1. List of abbreviations
HTD – High Torque Drive – is a curvilinear profile of the timing pulley tooth; PA – Polyamide
PE – Polyethylene; POM – Polyacetal; $\Phi_e$ – Outer diameter of the workpiece; $H$ – The height of the
workpiece; $\Phi_i$ – The inner diameter of the workpiece.

References
[1] https://books.google.ro/books?id=ScX-oZ-2NEoC&pg=PA89&lpg=PA89&dq=Timing+pulleys
[2] Chereches T, Lixandru P, Gheorghian S 2012 ModTech International Conference, „Advanced Technology for Manufacture by Plastic Deformation of the Cartridge Case with Pressure Chambers”, 1, pp 217-221

[3] Velicu S and Dragnea D 2014 Proc. In Manufacturing Systems, “Numerical Simulations of Severe Plastic Deformation of a workpiece from EN AW 6082 in the ECAP die with low friction”, 9, pp 193-198

[4] Dragnea D and Velicu S 2015 Conf. Proc. of the Academy of Romanian Scientists, „Analysis of some influence factors of the quality of finished pieces produced by SPD – method ECAE – by numerical simulations”, 7, Academy of Romanian Scientists, Bucharest, pp 303-314

[5] Cook R D, Malkus D S, Plesha M E, Witt R J 2002 Concepts and Applications of Finite Element Analysis, John Wiley and Sons, Inc., University of Wisconsin

[6] K. J. Bathe, 2007 Finite Element Procedures, Prentice-Hall Inc.