A Finite Element simulation of the hot forging process

J. de Arizon [1], E. Filippi [1], J. Barboza [2], L. D'Alvise [2]
[1]Faculté Polytechnique de Mons, Service de Génie Mécanique
Rue du Joncquois 53, 7000 Mons, Belgium
[2]Cenaero, Virtual Manufacturing group
Avenue Jean Mermoz 30, 6041 Gosselies, Belgium
email: jacques.dearizon@fpms.ac.be,enrico.filippi@fpms.ac.be,josue.barboza@cenaero.be,laurent.dalvise@cenaero.be

Abstract—
Hot forging process currently requires a succession of preforming operations to target the final form. The shape of each preform is based on how the workpiece material must be distributed for most effective forging in the next impression. The number of preform impressions is difficult to determine for forgings characterized by irregular shape and a length somewhat greater than the other dimensions. The manufacturing of the forging tools and their adjustment, is most cases a result from forger's experience and from a series of experiments. These tools development will affect the time to manufacturing and the profitability of the manufacturing.

Thanks to the finite element method and prediction of the material constitutive laws, these expensive operations can be reduced extensively by adding results of a numerical approach to the forger experience. However, finite element modeling of the hot forging process constitutes complex computations that require the knowledge of different process characteristics and accurate numerical methods. This paper presents a virtual manufacturing of an industrial workpiece (from the FCC-MSI5 company) performed with Morfeo. This new code is specially dedicated to the simulation of material forming processes and is currently developed within Cenaero. Morfeo has been enhanced with special features in order to simulate the forging process.

The forging process is carried out in two steps:
- **the forming of cylindrical billet by crushing a cylindrical slab between two plane tools on a mechanical press.**
- **the final workpiece forming with a hammer. Three to four punches may be done to obtain the final part.**

Keywords—**Forging simulation, virtual manufacturing, hot forging, finite element.**

I. Introduction

THE manufacturing of machine elements by hot or cold plastic deformation is one of the oldest metalworking operations. The forging term is related to a family of processes in which the deformation of the product is carried out by compression.

In particular, the process of hot forging consists of heating at high temperature ($\geq 0.6 \cdot T_{fusion}$) a semi-finished product, called workpiece, which will be deformed between two dies. The negative of the form of the workpiece is then reproduced in the dies. In order to allow a sufficient filling of the die cavity and a limitation of the compressive forces, an additional volume will be created in the dies allowing the formation of a flash. The product obtained will then be trimmed and, in most cases, will be machined.

From their characteristics in terms of the plastic deformation, metals adapt particularly well to this mode of deformation. The process is adapted as well to small as to big series, and allows the manufacturing of parts going from a few grams to a few tons. This great flexibility enables the forging process to have applications in multiple and varied fields (e.g. transport, aeronautics, spatial).

Compared to the traditional and competitor processes of metalworking such as the foundry and machining, hot forging confers to the parts manufactured high mechanical properties thanks to the material hardening during deformation and the lack of porosity.

In spite of the emergence of new means of manufacturing, the traditional forging process remains advantageous and needs continuous developments especially in precision forging.

Thanks to the progress carried out in the numerical methods and in the prediction of the behavior of materials, a new door is opened for the improvement of the hot forging process.

A. Importance of the numerical simulation in the improvement of the process

The manufacturing of a part per forging requires in most cases the realization of various stages of preforming operations, each of these stages making it possible, to approach the desired final form.

These stages require the manufacturing of engravings or the modification (by matter addition-withdrawal) of the existing dies. The experiment of the blacksmith will lead more or less quickly to the adopted solution.

It is obvious that the more important these operations of development will be, the more the profitability of the industrial will be penalized.

The purpose of the simulation of the process is, not to replace the blacksmith in the development of its tools and dies, but to bring a support to it and to visualize the material flow before any manufacturing of the tools.

B. Important aspects of modeling the hot forging process

A reliable hot forging simulation tool should allow the treatment of the following aspects:
- the viscoplastic behavior of the material at high temperatures and the dependence of the material law to strain rate;
- the influence of the thermal exchanges on the temperature distribution and so on the mechanical properties;
- the influence of the mechanical strain on the thermal history of the workpiece and on the boundary conditions;
- the influence of the creep forces on the strain and on the thermal behavior;
- the important deformations occurring during the process;
- the influence of the tool velocity profile on the deformation history.

The treatment of all these aspects will require the knowledge of different process characteristics and accurate numerical methods.

Some of these characteristics are cited by Staub [5]:

- the mechanical properties of the materials to be deformed (e.g parameters of the viscoplastic law);
- the thermal properties of the materials, coefficients of exchange and temperature of deformation;
- the tribological properties of the tool-workpiece interface;
- the initial shape of the workpiece;
- the geometry of the tools;
- the speed of the tools;
- the supplied energy for the deformation (e.g. the number of impacts necessary to deform the workpiece properly);

II. Conservative equations and finite element formulation

The deformation of a solid must respect the fundamental laws of Physics such as the law of conservation of the mass and the law of conservation of the momentum. According to the studied system, simplifications of these laws are allowed to simplify the problem and its numerical processing.

These two laws of conservation and the simplifications brought within the framework of the simulation of the hot forging are stated hereafter.

A. *Conservation of the mass*

The conservation equation of the mass is written:

$$\frac{\delta \rho}{\delta t} + \mathrm{div}\left(\rho \cdot \mathrm{v}\right) = 0 \tag{1}$$

with:

- ρ : the density of the material;
- t : the time;
- v : the velocity field.

This equation will be transformed, in the majority of the cases of manufacturing of metals with plastic deformation, in the equation 2,

$$\mathrm{div}\left(\mathrm{v}\right) = 0 \tag{2}$$

since one can assume the incompressibility of the material at the time of the deformation.

B. *Conservation of the momentum*

The law of conservation of the momentum must be checked in all the material. The general expression of this conservation equation is given by the equation 3.

$$\rho \cdot \gamma = \mathrm{div}\left(\sigma\right) + \rho \cdot \mathrm{g} \tag{3}$$

with:

- γ : reactions of inertia;
- g : the acceleration of gravity.

In practice, the physics of the process will make possible to simplify the problem by neglecting the terms of inertia as well as the volume forces of gravity [7]. The equation 3 becomes :

$$\mathrm{div}\left(\sigma\right) = 0 \tag{4}$$

III. The finite element method for manufacturing operations

The finite element method is among the most used numerical methods to model the forging process. Its principle, based on a decomposition of the system in elements allows the study of complex phenomena and geometries.

A. *Displacement and speed-pressure finite element formulation*

The local equilibrium resulting from the conservation equation of momentum is written according to the equation:

$$\mathrm{div}\left(\sigma\right) = 0 \tag{5}$$

The resolution of the problem by finite elements generally privileges a similar formulation of the problem, based on the principle of virtual work.

It results from this, the following equation :

$$\int_{\Omega} \sigma : \epsilon^{*} dV = \int_{\delta\Omega} T \cdot u^{*} dS \tag{6}$$

with:

- ϵ^* : the virtual strain tensor ;
- u^* : the virtual displacement;
- Ω : the system domain;
- $\delta\Omega$: the surface of the Ω domain;
- T : the vector of the external forces applied on $\delta\Omega$ (applied forces, contact conditions,...).

Under this form, the solution of the problem is the displacement of the nodes of the discretized system.

However, the nature of the hot forging problem and the viscoplastic nature of the workpiece material at high temperature privileges an other formulation of the problem : the velocity-pressure formulation.

In this formulation, the unknown factor of the problem is not the displacement at nodes any more but the velocity and pressure fields.

This formulation, which supposes that the behavior of the material approaches more the behavior of a fluid than those of a solid, is governed by the equations 7.

$$\int_{\Omega} \sigma : \dot{\epsilon}^{*} dV = \int_{\delta\Omega} T \cdot v^{*} dS \tag{7}$$

with:

- $\dot{\epsilon}^*$: the virtual strain rates tensor;
- v^* : the virtual speed.

If the condition of incompressibility is extracted starting from 7, the system of equations below is obtained

$$\left\{ \begin{array}{c} \int_{\Omega} s : \dot{\epsilon}^{*} dV - \int_{\Omega} p \cdot \mathrm{div}\left(\mathrm{v}^{*}\right) \mathrm{dV} - \int_{\delta\Omega} \mathrm{T} \cdot \mathrm{v}^{*} \mathrm{dS} = 0 \\ - \int_{\Omega} p \cdot \mathrm{div}\left(\mathrm{v}^{*}\right) \mathrm{dV} = 0 \end{array} \right\}$$

with:

- s : the stress deviator;
- p : the hydrostatic pressure.

B. *Constitutive law*

The resolution of the previous system needs an expression relating the stress deviator to the strain rate tensor. Norton-Hoff law has been implemented with a non-linear viscoplastic behavior and thermal dependency. This model relates the stress deviator to the strain rate tensor (equation 8).

$$s = 2 \cdot K\left(T, \epsilon, ...\right) \cdot \left(\sqrt{3} \cdot \dot{\bar{\epsilon}}\right)^{m-1} \cdot \dot{\epsilon} \tag{8}$$

with:

- s : the stress deviator such as $\sigma = -\left(p\right) \cdot I + s$
- p : the hydrostatic pressure such as $p = -\frac{\sigma_{11}+\sigma_{22}+\sigma_{33}}{3}$
- $K\left(T, \epsilon, > ...\right)$: the consistency;
- m : the sensitivity.
- $\bar{\epsilon}$: the effective strain equal to equation 9

$$\bar{\epsilon} = \sqrt{\frac{2}{3} \cdot \sum_{i,j} \dot{\epsilon}_{i,j}} \tag{9}$$

The expression of the consistency of the material makes it possible to take into account various types of behaviors. For example:

- law by work hardening of power:

$$K\left(T, \epsilon\right) = K_0 \cdot \left(\epsilon + \epsilon_0\right)^n \cdot e^{\frac{\beta}{T}}; \tag{10}$$

- linear law of work hardening:

$$K\left(T, \epsilon\right) = K_0 \cdot \left(1 + a \cdot \epsilon\right) \cdot e^{\frac{\beta}{T}} \tag{11}$$

with:

- K_0: a constant term;
- ϵ_0: the regularization of work hardening term;
- n : the sensitivity to work hardening coefficient;
- β: the temperature term ;
- a : the work hardening term.

Another form using directly the stress tensor is given to the equation 12.

$$\bar{\sigma} = K \cdot \left(\sqrt{3}\right)^{m+1} \cdot \dot{\bar{\epsilon}}^m \tag{12}$$

IV. MECHANICAL BOUNDARY CONDITIONS

A. *Contact modeling*

The software designed to model the forging process must be able to simulate

- the contact die-workpiece;
- the contact workpiece-workpiece.

In each case, the friction will have to be accounted for. This friction will indeed create a tangential stress at the interface, which will restrict the movement of the matter and will increase the effort of compression. The best example of the influence of friction is the barreling effect that occurs when upsetting a cylindrical billet. The methods the most often used for the modeling of the contact are the method of the multipliers of Lagrange and the penalization method. Various methods make it possible to take into account friction (see [1] & [9]): The introduction of a component of friction will change the equation 7 to 13

$$\int_{\Omega} \sigma : \dot{\epsilon}^* dV - \int_{\delta\Omega} T \cdot v^* dS + \int_{\delta\Omega_f} \tau \cdot v^* dS = 0 \tag{13}$$

with:

$$\tau = -\alpha\left(\Delta v, \sigma_n\right) \cdot \frac{\Delta v}{\|\Delta v\|} \tag{14}$$

and α an expression depending on the model used for friction.

B. *Forging tool modeling*

The hot forging involves a viscoplastic behavior of the deformed material because of the temperature effects. This viscous behavior is different from the elastoplastic behaviors characterizing cold metals by the influence of the strain rate $\dot{\epsilon}$ (see 12).

Because of this dependency, it is important to model the velocity profile of the tools in order to be able to impose correct boundary conditions close to those observed in the reality.

The tools generally used in hot forging are:

- hammers, characterized by the fall of a mass (by gravity or by the action of a compressed gaz) on the workpiece;
- mechanical presses, for which the tool has a movement of a slider-crank mechanism;
- hydraulic presses, characterized by a constant profile speed.

B.1 Hammers

Hammers are the most versatile and least expensive type of forging equipment;they are often used for the final stage of deformation during the forging.

Their movement is characterized by the following stages during the deformation:

- falling and acceleration of the mass by gravity according to a uniformly accelerated rectilinear movement with or without initial speed. This velocity evolution is characterized by the equations 15 & 16;

$$x_t = \frac{1}{2} \cdot a \cdot \left(t - t_0\right) + V_{t_0} \cdot \left(t - t_0\right) + x_{t_0} \tag{15}$$

$$v_t = a \cdot \left(t - t_0\right) + v_{t_0} \tag{16}$$

with

- t : the current time of simulation;
- t_0 : the initial time;
- x_t : the position of the tool at time t;
- x_{t_0} : the position of the tool at initial time ;
- a : the acceleration (e.g the acceleration of gravity in the case of a drop hammer);
- v_t : the tool speed at time t
- v_{t_0} : the tool speed at initial time

- contact between the workpiece and the die;
- deceleration of the mass and deformation of the workpiece;
- come back to the initial state when all the energy of the mass is dissipated.

Once the deformation of the workpiece is started, if the reactions of inertia are neglected (the forging process is considered here as a quasi-static process) the speed of the die is at every moment determined starting from its residual kinetic energy. This residual kinetic energy is given starting from the equation 17

$$E_{tot} = E_P + E_C + \Omega_{def} \tag{17}$$

with:

- E_{tot} : the total energy the mass holds, before the beginning of the forging operation;
- E_P : the potential energy of the mass calculated starting from the mass, the current height and the acceleration of gravity (see equation 18);

$$E_P = M \cdot g \cdot h \tag{18}$$

- E_C : the residual kinetic energy allowing the determination the speed of the tool thanks to the equation 19;

$$V = \sqrt{\frac{2 \cdot E_c}{M}} \tag{19}$$

- Ω_{def} : the work of deformation of the workpiece. This last quantity can be expressed starting from the efforts of contact between the die and the workpiece. For each increment of time, the additional work of deformation is calculated according to the formula $\delta F \cdot \delta d$ with F the contact forces and d the displacement of the tool during the increment.

An other way to determine the deformation work is to compute directly the deformation power in the billet by evaluation of the internal state(since the billet is considered at each step in equilibrium) .

B.2 Mechanical press

Mechanical presses are made of a table driven by a slider-crank mechanism which speeds vary from a maximum at the center of the stroke to zero at the bottom of the stroke. The crank is driven by a flywheel powered by an electric motor. At each blow, a clutch engages the flywheel to the crank and the energy necessary for the deformation is borrowed from the wheel of inertia.

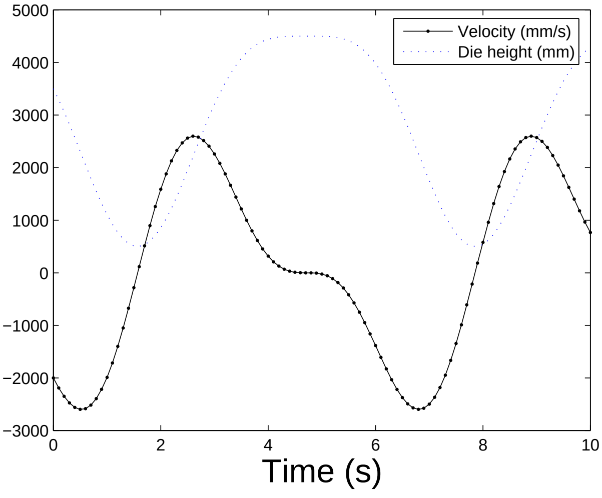

Fig. 1. Mechanical press velocity and height profile

The movement of a mechanical (see figure 1) tool can be expressed by the equations 20 and 21

$$V_t = -R \cdot \omega \cdot \cos(\omega \cdot t) \left(1 + \frac{R}{L} \cdot \sin(\omega \cdot t)\right) \tag{20}$$

$$h_t = h_f + R \cdot \left(1 - \sin(\omega \cdot t) + \frac{R}{2 \cdot L} \cos^2(\omega \cdot t)\right) \tag{21}$$

with:

- V_t : the instantaneous speed of the die;
- h_t : the instantaneous height of the die;
- h_f : the final height of the die;
- R : the crank radius;
- L : the length of the connecting rod;
- ω : the angular velocity of the crank;
- t: the time of working.

B.3 Hydraulic press

Hydraulic presses operate by the descent of a sliding piston in a cylindrical room. Whatever the size of the press, the movement of the anvils is achieved slowly and the workpiece may cool too much rapidly. So the use of the hydraulic presses is usually reserved, for the production of large parts or for the forging of light alloys, in particular those which require a slow deformation and law temperatures. These conditions prohibit its use to forge steel in most cases.

V. THERMAL PROBLEM

The process of hot forging requires the heating of the workpiece at a high temperature allowing the reduction of the compression efforts during the process. The temperature will strongly influence the characteristics of the material and thus the profile of deformation.

Table I lists the ranges of usual temperatures during hot forging operations for various metals.

TABLE I
USUAL TEMPERATURES IN HOT FORGING

Metal	Temperature in ℃
Aluminium alloys	400-550
Copper alloys	625-950
Nickel alloys	870-1230
Steel	925-1260
Titanium alloys	750-950

In hot forging, the dies are usually preheated (200-500 ℃) in order to decrease the thermal shocks and the risk of cracking during the upsetting.

These important variations in temperature within the die-workpiece-environment will cause important heat transfers. Those will follow the three fundamental modes of thermal exchange :

- conduction (within the bodies themselves but also with the interface between two bodies);

- convection (respectively between the free edge of the die and environment between the free edge of the tool-workpiece and environment);
- radiation (between all the free faces with the environment as well).

A. Modeling of the thermal effects

The distribution of temperature within the workpiece is described by the law of Fourier-Kirchoff taking into account the boundary conditions with the interface of the workpiece.

This equation is written as follow :

$$\rho \cdot c \cdot \dot{T} = \lambda \nabla^2 T + \dot{q} \tag{22}$$

with:

- T : the temperature;
- ρ : the density;
- c : the specific heat in $\frac{J}{kg \cdot C^\circ}$;
- $\dot{q}$: the heat internal generation per unit of volume in $\frac{W}{m^3}$.

The heat internal generation comes from the combination of two effects:

- the heat generation due to the plastic deformation. According to [8] and [6], the fraction of the deformation energy transformed into heat would be equivalent to 90 % of the deformation energy (k=0.9). In this case, the internal generation of heat takes the expression given in equation 23:

$$\dot{q} = k \cdot \sigma \cdot \dot{\epsilon} \tag{23}$$

- the heat generation due to friction between the workpiece and the die.

The solution of equation 22 requires the expression of the boundary conditions of the body considered.

Two cases of Fourier's boundary conditions are usually considered , according to whether one treats the exchanges by convection between the workpiece and the ambient air (see equation 24) or exchanges by radiation between the bodies (see equation 25)

$$-\lambda \cdot \frac{\delta T}{\delta n} = K \cdot (T - T_{ext}) \tag{24}$$

$$-\lambda \cdot \frac{\delta T}{\delta n} = \epsilon_r \cdot \sigma_r \cdot \left(T^4 - T_{ext}^4\right) \tag{25}$$

with:

- K : the coefficient of exchange in $\frac{w}{m^2 \cdot K}$;
- ϵ_r : the emissivity of surfaces;
- σ_r : the constant of Stefan Botlzmann;
- T_{ext} : the outside temperature.

One can remark that for the sake of simplifications, the radiation will be in most of cases linearized and treated like a convective exchange.

In addition to these thermal phenomena, the conduction that occurs between the dies and the workpiece has to be modeled in forging operations. This exchange mode will be of prime importance once the bodies will be in contact.

When two solids are in contact, because of their roughness, the contact zones are never situated on all apparent surfaces, but only in certain zones of very small extent. According to [2], thermal conduction will only occur on 1 % of the apparent contact surface (before the application of the contact pressure).

This reduction of the contact zone can be represented by the introduction of thermal contact resistance that will reduce the the heat flux between the contacting bodies (see figure 2). These contact resistance can be expressed as follows :

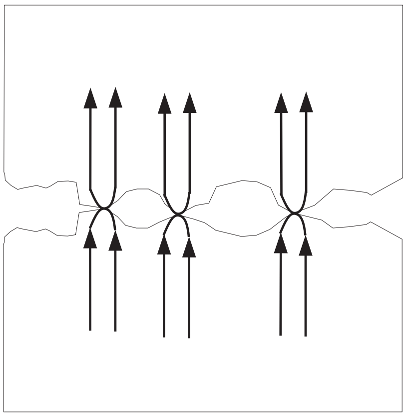

Fig. 2. Heat exchange between asperities

$$R_c = \frac{T_{c_1} - T_{c_2}}{\phi} \tag{26}$$

with:

- R_c : the resistance of contact;
- T_{c_1} : the temperature with the interface of body 1;
- T_{c_2} : the temperature with the interface of body 2;
- ϕ : the heat density through the contact zone.

Marchand [2] reviews a bibliography gathering the various assumptions of measurement of the thermal resistances of contact.

In [3] and [4] Bourouga et al. highlight various parameters influencing the resistance. The dependence of the thermal resistance with respect to the contact pressure and to the deformation (behavior law) is highlighted. It can be easily understood that the more the contact pressure will be important, the more the resistance will be low.

VI. MORFEO

Morfeo (Manufacturing ORiented Finite Element tOol) is a code developed within the research center Cenaero(Belgium). As its name indicates, Morfeo's principal applications are the manufacturing processes. Initially developed for the simulation of machining and welding processes, its features appeared to completely satisfy the forging simulation needs. They can be summarized as:

- displacement and velocity-pressure formulation;
- thermo-mechanical coupling;
- Norton-Hoff constitutive law;
- Lagrangian and penalized multi-bodies contact;
- parallelization;
- coupling with an optimization software using genetic algorithm (Cenaero in-house code MAX).

The code is validated by performing analysis whose analytical solution are known. One of these corresponding to the upsetting of a rectangular workpiece is stated

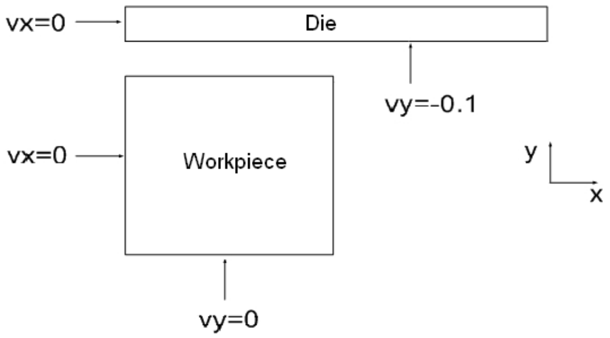

Fig. 3. Validation test case

hereafter (see figure 3). The analytical solutions of the problem described on figure 3 is written as :

$$v_x = -v_{tool} \cdot \frac{a}{b} \qquad (27)$$

with:

- v_{tool} : the value of tool velocity;
- a : the length of the billet;
- b : the height of the billet;

Comparison results are given on figure 4.

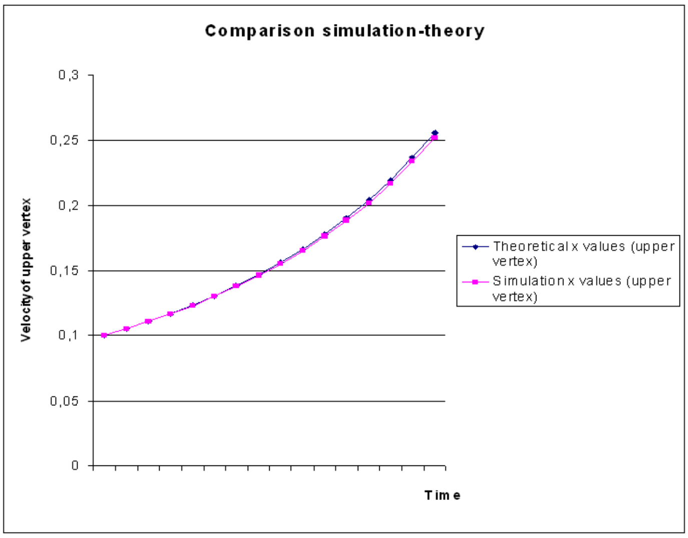

Fig. 4. Comparison of analytical and simulation results

These results show the good agreement between simulation and analytical results in a simple forging case and validate the Morfeo code.

VII. Industrial test case

The industrial test case here presented, is a compressor part built at the Belgian forge called FCC-MSI5. A 3D representation of the part to obtain is presented on figure 5. Different forging operations are needed for the manufacturing of this part:

- a first compression (called upsetting) performed on a mechanical press in order to bust and remove the scale,to break down the workpiece and to change its microstructure.

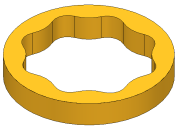

Fig. 5. Piece

- a second compression stage where preform is deformed between finishing closed dies moved by drop hammer.
- a trimming to eliminate the flash and to pierce to workpiece

Machining operations are then necessary to finish the workpiece. A CAD representation of these different stages is presented on figure 6

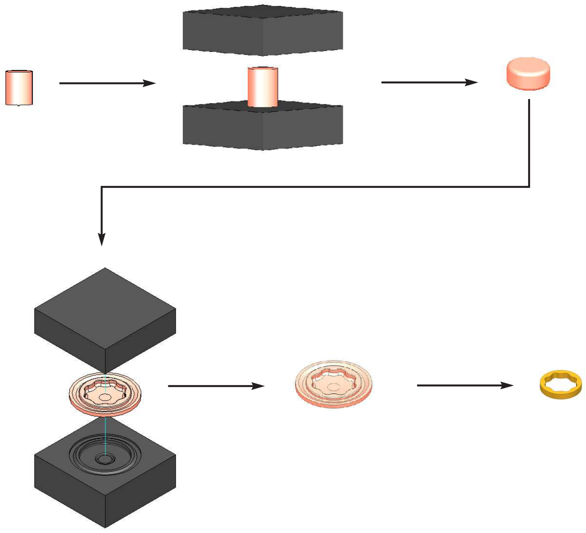

Fig. 6. Forging operations

A. *Model description*

As an attempt to model the forging of the test case presented on figure 6, a first simplified modeling was realized.

The simplifications hypothesis lies in the fact that the problem was considered as axisymetric (which is not the case regarding figure 5). This was assumed in this paper in order to validate first the developments of the 2D model, before the true 3D one. The resulting meshes are therefore presented on figures 7 & 8 .

A.1 Boundary conditions and assumptions

The simulated problem assumes that:

- the contact between the dies and the workpiece is frictionless;
- the simulation is isothermal;
- the material is steel warmed at high temperature;
- the parameters of the mechanical press are :
  - R= 1000 mm;

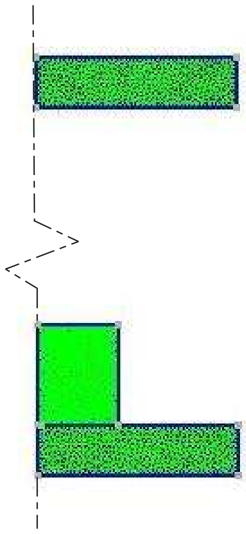

Fig. 7. Mesh of the axisymmetric modeling of the preforming dies

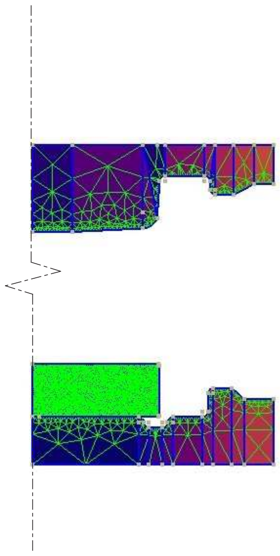

Fig. 8. Mesh of the axisymmetric modeling of the finishing dies

  - $L=$ 2000 mm;
  - $w=$ 1.0 $\frac{rad}{s}$;
- the deformation obtained after the first stage reaches 50% of height reduction in order to change microstructure and to insure a sufficient material hardening of the piece and acceptable mechanical characteristics.
- only the geometrical state of the deformed piece after the first stage is transported to the second stage; no residual stress is considered at this stage;
- the parameters of the hammer are chosen such as
  - the mass of the hammer is equal to $M = 1000kg$;
  - the initial height of the mass is equal to $h_i = 0.1$ m;

B. *Results interpretation*

Figure 9 shows the evolution of the velocity profile within the workpiece for different times of deformation. The first stage allows a first deformation of the workpiece, necessary to avoid too important compression efforts on the finishing dies. By decreasing the number of blows managed by the hammer, an increase of the finishing tool life will be observed. Since these finishing tools have generally complex shapes,they represent the biggest part of the tools costs and a special attention must be paid to the reduction of their wear.

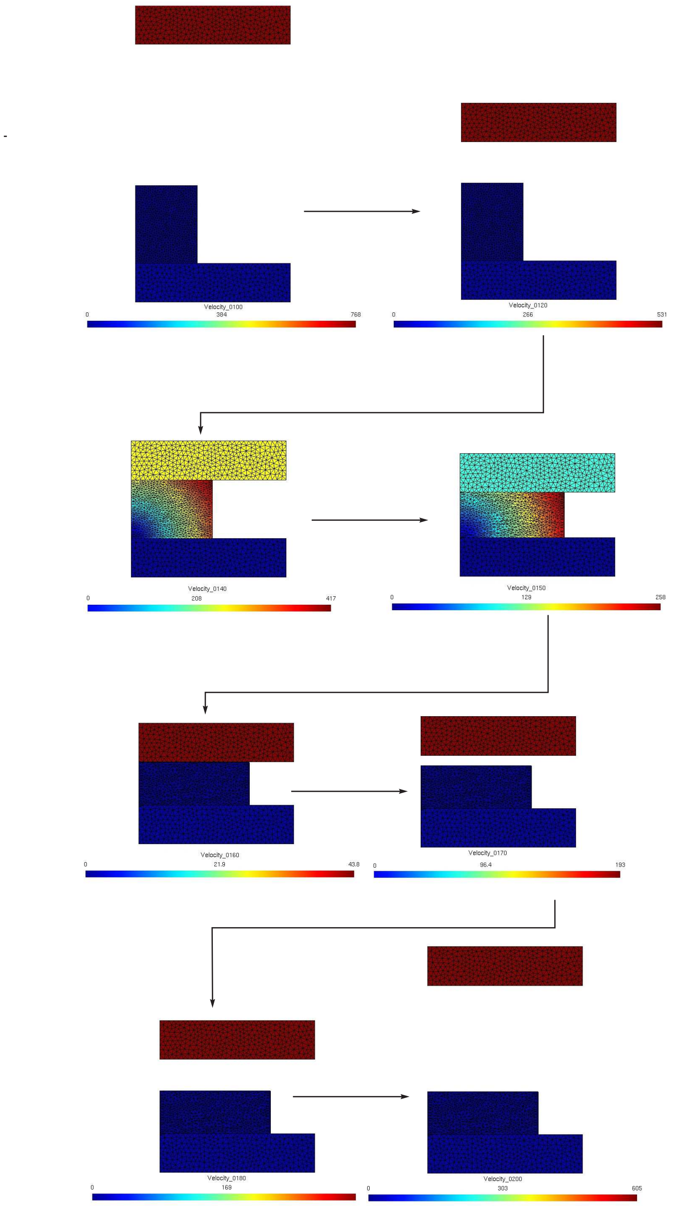

Fig. 9. Velocities for the first stage of deformation

Figure 10 shows the evolution of the velocity profile within the workpiece for different times of deformation and for the last stage of deformation performed with a hammer. For the last steps of deformation, the apparition of a flash that will be later machined can be seen. Three blows of

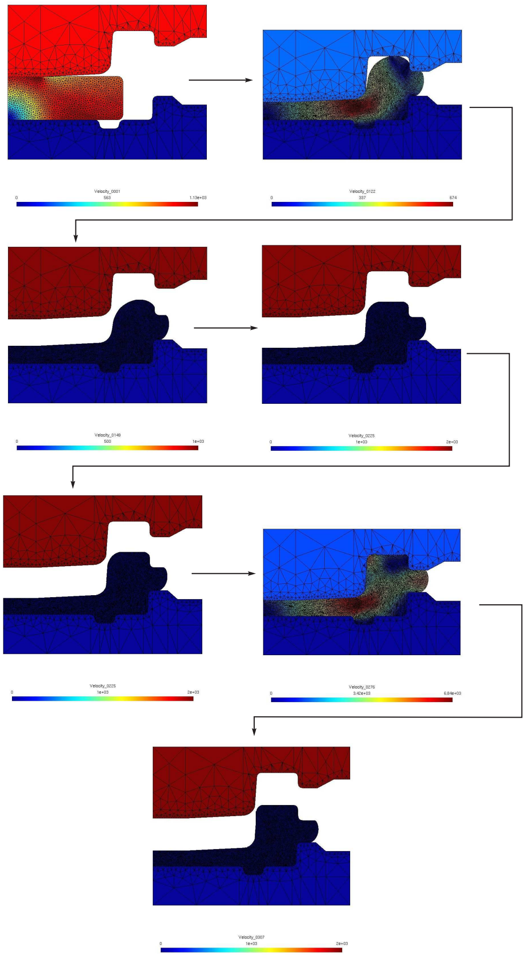

Fig. 10. Velocities for the second stage of deformation

the hammer are needed to completely fill the dies. More blows could have been performed in order to reduce the volume of the internal flash, that will be trimmed just after the last forging operation, the forger taking advantage of the residual heat of the workpiece. Moreover,the internal volume to be removed will be low, the more the geometrical tolerances, imposed by the forger's custommer, will be respected.

The determination of the number of blows, the forging parameters, and the different deformation stages, will be therefore a combination of every manufacturing stages best solutions.

VIII. CONCLUSIONS AND PERSPECTIVES

A first simulation of the forging of an industrial workpiece produced with Morfeo was presented is this paper. Using a velocity-pressure formulation with Norton-Hoff law, the two stages of deformation used in the industry for the forming of the workpiece were modeled. An important simplification of the system was assumed while considering that the final workpiece and the dies were axisymetric. However a true 3D model is currently under development.

The perspectives of the present work lie in the inclusion of friction effect which can clearly influence the deformation profile even if some lubrication is used to reduce friction in the system. A complete coupling between the two stages of deformations seems important to present accurate simulations of the process.The thermal and mechanical history of the workpiece will influence strongly the behavior during the final stage of deformation.

A tridimensional simulation of the process would allow to suppress all the assumptions induced by the axisymetry. this will be presented in a future paper.

Finally a comparison between experiments and simulations will lead to the validation of the simulation model.

This last step will lead to the optimization of the process in terms of manufacturing costs by coupling the simulations to an optimizer.

REFERENCES

[1] Behrens A. and Schafstall. 2d and 3d simulation of complex multistage forging processes by use of adaptive friction coefficient. *Journal of Materials Processing Technology*, 80-81:298–303, 1998.

[2] Marchand Anne-Sophie. *Etude de la résistance thermique de contact à l'interface de solides déformables en frottement: application aux procédés de forgeage.* PhD thesis, Institut natianal des sciences appliquées de Lyon, 1998.

[3] Bourouga B., Goizet V., and Bardon J.P. Le contact thermique pièce–outil lors d'une opération de forgeage à chaud: Validation de l'hypothèse de résistance thermique de contact et influence de la loi de comportement de la pièce. *Internationnal Journal of Heat and Mass Transfer*, 44:4107–4117, 2001.

[4] Bourouga B., Goizet V., and Bardon J.P. Modèle prédictif de résistance thermique du contact dynamique adapté au cas de l'interface pièce-outil de forgeage. *Internationnal Journal of Heat and Mass Transfer*, 46:565–576, 2003.

[5] Staub Carole. *Modélisation dynamique des procédés de forgeage.* PhD thesis, Ecole doctorale des sciences pour l'ingénieur, 1998.

[6] Castro C.F., Antonio C.A.C., and Sousa L.C. Optimisation of shape and process parameters in metal forging using genetic algorithms. *Journal of Materials processing Technology*, xxx:xxx, 2004.

[7] Boyère E. *Contribution A La Modélisation Numérique Thermo-Mécanique Tridimensionnelle Du Forgeage.* PhD thesis, Ecole Nationale Supérieure Des Mines De Paris, 1999.

[8] Qingbib L., Zengxiang F., He Y., and Shichun W. Coupled thermo-mechanical analysis of the high-speed hot-forging process. *Journal of Materials Processing Technology*, 69:190–197, 1997.

[9] Wagoner R.H. and Chenot J.L. *Metal Forming Analysis.* Cambridge University Press, 2001.