Numerical Simulation using Finite Elements to Develop and Optimize Forging Processes

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Forging is one of the main processes used to manufacture metal components for a broad range of applications. This occurs mainly because forged products are highly reliable and present superior mechanical properties. However, lately the competitiveness of forged products has been threatened, since the difference between their superior performance and the performance resulting from other processes has lessened continuously. This has obliged the forging industry to invest in optimizing its processes, saving in raw materials and energy. In this context, the use of numerical simulation of the forging process has become an increasingly reliable tool in seeking this optimization. This study uses the commercial software *QForm 3D, version 3.2.1.1*, to analyse two forging processes, one by hot forging and one by cold. In the case of hot forging, work on a component with axial symmetry is looked at from which a gear is machined. Currently the part is forged in three stages based on an initial billet with a 7.0 kg mass. Forging is performed in a 40 NM mechanical press with an initial temperature of 1200°C. The hot forging process is optimized and this results in a saving of about 5% in material. In the cold forging case it is shown that the process, as designed, results in laps in the final part, and in possible tool failure due to excess load. In both cases, the material used is DIN 1.7131 (16MnCr5) steel.

Keywords: finite element method, computer simulation, bulk metal forming, hot forging, cold forging, QForm 3D.

Introduction

Forging is a widely used manufacturing process since, depending on the type of process it may generate, a minimum loss of materials, good size precision, and improve the mechanical properties of the forged part. However, designing the production sequence of a new part is not a simple task, and it requires many tests and adjustments until a satisfactory production condition is reached. The "trial and error" method is expensive and takes a lot of time. Beginning in the 1980s, computer simulation became reliable and acceptable as design tool for the development of new forged products. There are different commercial programs available on the market based on different methods to solve or combine them. In the case of simulation of mechanical forming problems, the most used method is definitely the finite elements method (FEM). However, when one wishes to develop a new forging process or improve an already existing one, one should consider the main parameters to be studied and which programs present the best conditions to look at the influence of these parameters. When performing mathematical modeling of the forging process, the most significant problems commonly encountered are: contact, friction, large deformations, changes in mechanical properties of metals, need for a constant volume, heat generation due to mechanical work and thermal exchange between the piece and the environment. These difficulties are the reason for a number of non-linearities that make it difficult to solve the problem by means of mathematical modeling. In the finite elements method, in order to solve a few of the problems related to non-linearity, the piece is divided into a number of elementary volumes, forming a mesh. Load application (or, in this case, tool displacement) is divided into small increments of displacement. Calculations are then performed until reaching a balance between the internal and external forces and after this a new increment of displacement is performed. This procedure is repeated until the end of the simulation. The change in form involved in forging processes generally causes great deformations in the mesh, which becomes too distorted to continue calculating. Thus, it is necessary to change this mesh for a new one. This procedure is called remeshing and may become complex due to the piece geometry and/or if the previous mesh is very distorted. In the case of a simulation that takes into account the influence of temperature on mechanical properties, it is still necessary to perform some type of thermomechanical coupling. One of the great advantages of using a simulation system in the design phase of a forging process is the possibility of verifying defects such as lack of filling of the die, folds, cracks and laps. The simulation programs are also quite useful when it is a matter of studying how different process parameters influence forging and the final resulting properties. For instance, a same piece, presenting the same initial conditions, will have a different temperature distribution if forged slowly in a hydraulic press or at a high speed in a hammer forge or mechanical press. The difference in the temperature distribution influences the total forging force, in the requirements in the dies, in the microstructure and the final properties of the piece. Another major use of simulation systems is the determination of forging stages. Especially in the case of cold forging, normally constituted by several stages, the process simulation during the design phase may significantly reduce errors, such as the non-filling of tools and die failure [1-4]. Although it presents all these advantages, the use of numerical simulation in the industrial environment and even in academic circles has always been subject to limitations imposed by existing computer resources, where realistic 3D simulations took a long time to be implemented and/or attained mediocre results. Such limitations have been over-

come by the rapid advance of computer technology in recent years. Currently, realistic simulations of 3-dimensional processes are perfectly feasible [5,7].

Theoretical background

Basic equations. In order to obtain realistic results concerning the evolution of the material in mechanical forming operations, the formulation should take into account the large plastic deformations that occur in the process, the incompressibility of material, the contact between the part and the die, and the effects of temperature when it is the simulation of a hot forming process. In order to discretize a 3-dimensional piece the finite elements programs use hexagonal or tetragonal elements. Although hexagonal elements perform better than tetragonal elements [6] it is quite difficult to generate an irregular mesh using them, that could describe, for instance, the great change in size like the flash in closed-die forging process. Tetragonal elements are more flexible to represent a complex geometry or generate an adaptive mesh. Depending on the type of element, formulations based on solving nodal velocities as primary variables or based on the solution of velocity and pressures may be used. The basic equations to be solved are the equilibrium equation, the incompressibility condition and the constitutive equation of material. In order to solve the nodal velocities as primary variables, a penalty constant which acts directly on the volumetric strain rate so as to force the incompressibility of the material is introduced and the variational equation has the form:

$$\int_v \bar{\sigma} \delta \dot{\bar{\varepsilon}} \ dV + K \int_v \dot{\varepsilon} \delta \dot{\varepsilon}_v \ dV - \int_S F_i \delta v_i \ dS = 0 \quad (1)$$

where $\bar{\sigma}$, $\dot{\bar{\varepsilon}}$, $\dot{\varepsilon}_v$, and δv_i are, respectively, the effective stress, the effective strain rate, the volumetric strain rate and an arbitrary variation of the velocity field, K is the penalty constant and V and S are the volume and surface of the part [6, 8-10].

If a mixed formulation is used with the solution of velocity and pressure using primary variables, the variational equation has the form:

$$\int_v \bar{\sigma} \delta \dot{\bar{\varepsilon}} \ dV + \int_v p \delta \dot{\varepsilon}_v \ dV + \int_v \dot{\varepsilon}_v \delta p - \int_s F_i \delta v_i \ dS = 0 \quad (2)$$

where p is the pressure and the other terms have already been defined previously [6]. In order to solve the problem, equations (1) or (2) are converted into a set of algebraic equations using finite element discretization procedures. In view of the non-linearities of the material of the piece and/or the die and the friction conditions in the contact between the piece and the die, the solution is obtained by iteration. After the nodal velocities have been calculated for a given time step, the deformed configuration may be obtained updating the nodal coordinates.

In the case of hot forming processes, the distribution of temperatures in the piece and/or in the dies may be achieved by the equilibrium equation in the form:

$$\int_v kT_{,j} \delta T_{,j} \ dV + \int_v \rho c \dot{T} \delta T \ dV - \int_v \alpha \bar{\sigma} \dot{\bar{\varepsilon}} \delta T \ dV =$$
$$= \int_S q_n \delta T \ dS \quad (3)$$

where k is the thermal conductivity, T the temperature, ρ the density, c the specific heat, α the fraction of deformation energy converted into heat and q_n the heat flow normal to the boundary, including the loss into the environment and the heat generated by friction between the piece and the die. Applying finite element discretization methods, equation (3) can also be converted into a system of algebraic systems and solved [6-8].

Formulation and integration. In order to achieve the geometric evolution of the part as a function of time, the code of finite elements may use a Lagrangian ou Eulerian formulation, with the explicit or implicit integration method. In the implicit method, integration is performed at instant $t+\Delta t$, and at instant t for the explicit method. The kinematic description of the coordinates may be Lagrangian or Eulerian. In the Lagrangian description, it is considered that the material position of a point is related to the original position of the same point, i.e., $x=X(x,t)$ where x is the current position and X the position of reference for instant $t=0$. In the Eulerian description, it is considered that the position of reference is a function of the current position, i.e., $X=X(x,t)$, in which the positions at the current instant and the initial instant are independent variables. Thus, in the Lagrangian description, the system of coordinates is fixed for a given body and its movement at any instant is a function of the coordinates of the material. In the Eulerian description the coordinates system is fixed in space and the movement of the particles of material goes through a fixed region of space. Since it is connected to the material, the Lagrangian formulation is more appropriate to the description of the non-stationary processes, such as forging, in which it is desired to obtain precise forecasts of the flow of material on free surfaces. The disadvantage of this method is that the elements easily degenerate when large deformations or sudden changes of shape occur during the process. In this case, in order to be able to continue the analysis, the mesh of degenerated elements must be substituted by a new one. This process is known as remeshing, and it may be necessary to perform it several times while simulating a process such as forging. The Eulerian formulation is more appropriate to model stationary processes such as extrusion and rolling [6].

Materials and boundary conditions

When one wishes to perform the numerical simulation of a mechanical forming process, it is not enough to have the appropriate software and hardware and trained people available. It is also essential to have reliable data to feed the program. Besides the geometrical modeling of the billet and

the dies, the simulation programs must be fed with data concerning the materials and process contour conditions. Among the materials data are the physical properties such as density, specific heat and thermal conductivity, and mechanical properties such as the flow curve, Young's modulus and Poisson's coefficient. The boundary conditions include the realistic description of friction on the piece/die interface and parameters for heat exchange between the piece and the environment, piece and die and die and environment.

Flow curves. In modeling using finite elements the material of the part is usually described by rigid-plastic or rigid-visco-plastic constitutive equations. In the rigid-plastic model, the flow stress is a function of strain and temperature. On the other hand, in the rigid-visco-plastic model, the flow stress is a function of strain, strain rate and temperature. In the case of the forging process, especially those performed at high temperatures, where elastic strain is negligible, these models are perfectly acceptable [6, 8]. When it is important to know residual stresses or elastic spring-back at ambient temperature, it is necessary to use an elasto-rigid-plastic or elasto-rigid-visco-plastic model. In such cases the elastic part of deformation is described by Hooke's law.

$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij} \tag{4}$$

where E and ν are, respectively, Young's modulus and Poisson's coefficient [11]. The flow curve of a metal or alloy is strongly influenced by temperature, and it also depends on strain, on strain rate, state of stresses and several other parameters. Therefore, it is important that curves introduced in the program to perform a given simulation have been obtained under conditions as similar as possible to the conditions of the process to be simulated. The curves used in the simulations presented in this study were obtained for 16MnCr5 steel, cold and at temperatures of 800, 900, 1000, 1100 and 1200°C, at constant strain rates equal to 0.1 , 1.0 and 10.0/s. The method to obtain these was the compression test a cylindrical work-pieces, 20mm in diameters and 30 mm high. **Figure 1** shows the curves obtained cold, whereas **figure 2** shows the curves at a high temperature.

Elastic properties. In the simulations, the elastic part of the piece deformation was ignored, and thus it was not necessary to introduce the elastic properties of the piece material. However, since one of the objectives of the cold forging case studied here is the analysis of stresses developing in the tools, it became necessary to introduce the elastic properties of the die. The elastic properties used were obtained in the literature [12, 13].

Friction factor. Although there are different models to describe friction, the software used here for simulation only works with the model of the constant friction factor. According to this model

$$\tau = m\,k \tag{5}$$

where τ is the friction stress on the piece/die interface, m is the friction factor ($0<m\leq1$) and k is the yield stress in pure shear. The main process parameters that influence the value of m are temperature, surface characteristics of the piece and the die and the lubricant used. Like the flow curve, m must be determined for each case under conditions as close as possible to those of the process one wishes to simulate. The most widely used method to determine m is the ring compression test, where experimental data are compared
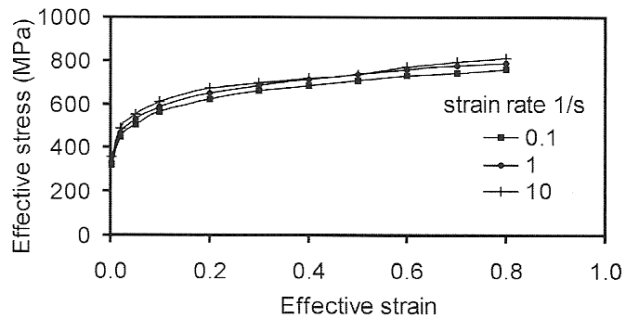

Figure 1. Flow curves obtained to 16 MnCr5 steel at 25°C, with different strain rates.
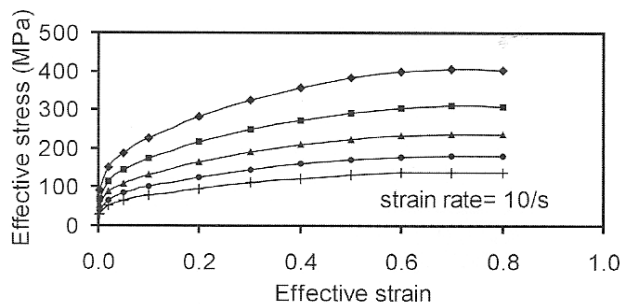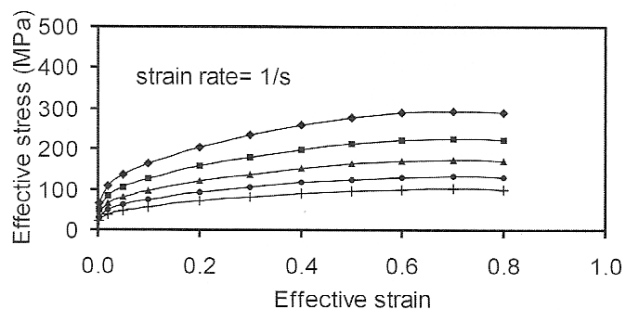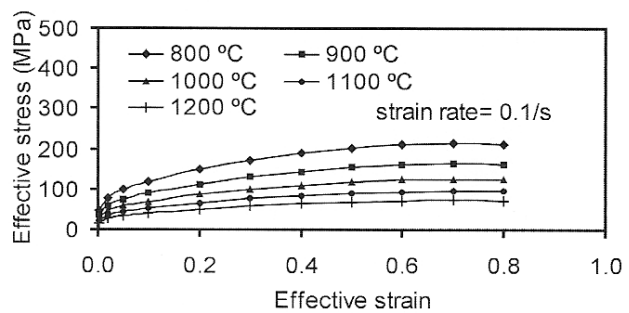

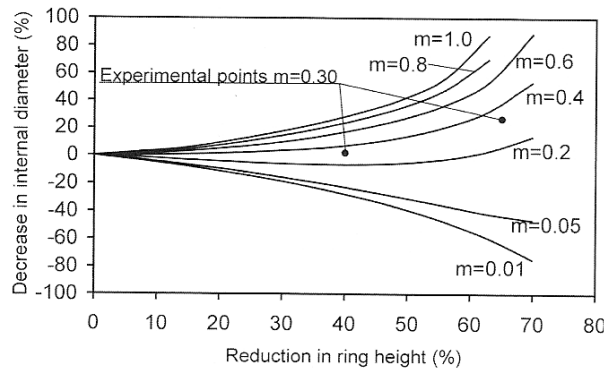**Figure 2.** Flow curves obtained to 16MnCr5 steel at different temperatures and strain rates.

Figure 3. Calibration curves for constant values of the friction factor, *m,* and experimental values in the ring test.
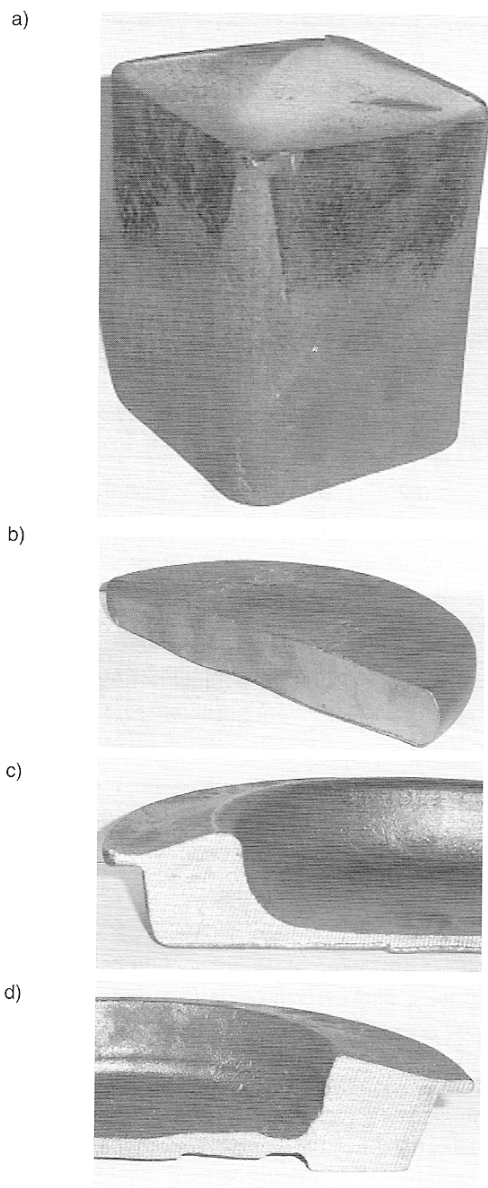
a)

b)

c)

d)

Figure 4. Steps of the process: (a) initial billet; (b) upsetting operation; (c) preform; (d) final form.

with calibration curves obtained by simulating the test to different constant values of *m*. Kudo [14, 15] pioneered the mathematical treatment of the test using the upper bound theory for the friction factor, and several other authors also gave their contribution [16, 17]. In this study ring tests were performed at ambient temperature and at 1200°C with a graphite-water lubricant. In the case of the rings warmed at 1200°C the dies were heated and kept at 200°C. **Figure 3** shows the curves *relative variation of the internal radius versus relative variation of the height* for constant values of the friction factor, obtained using simulation software for 1200°C. In the same graph are the experimental points, indicating a friction of about *m*=0.30 for the hot process. Using the same methodology *m*=0.15 was determined for the cold process.

Thermal parameters. The thermal properties of the materials of the piece and the die, and the heat exchange coefficients were used in the simulations and obtained in the literature [12, 13] and from the data base of the software itself and are shown in **table 1**. In the case of hot forging AISI

Table 1. Thermal properties and heat exchange coefficients used in simulation [12, 13, *QForm 3D* data base].

Parameter	DIN 1.7131	AISI H13	AISI M2
Density (kg/m^3)	7850	7850	8150
Specific heat (J/kg K)	461 (20°C) 533 (200°C) 611 (400°C) 778 (600°C)	460	420
Thermal conductivity (W/m K)	42 (20°C) 41 (200°C) 38 (400°C) 32 (600°C)	24.6	46
Piece/die heat exchange coefficient (W/m^2 K); cold forging			9000
Piece/environment heat exchange coefficient (W/m^2 K); cold forging			10.90
Piece/die heat exchange coefficient (W/m^2 K); hot forging			6000
Piece/environment heat exchange coefficient (W/m^2 K); hot forging			17.54
Emissivity			0.4

Table 2. Force and maximum stress values in the dies at the different steps of the current and proposed process.

Parameter	Current Process	Proposed Process
Upsetting force (MN)	0.27	0.27
Preforming force (MN)	7.2	2.7
Final forming force (MN)	2.8	2.9
Maximum stress in the preform die (MPa)	1194	668
Maximum stress in the final form die (MPa)	516	712

H13 steel dies are used. For cold forging the dies are made of a AISI M2 steel.

Forging simulation

Next, two cases are presented, one of hot forging and one of cold forging, in which the software *QForm 3D* was used to optimize the processes.

Hot die forging. Currently the part is forged in three stages based on an initial billet with a mass equal to 7.0 kg, a square section with a side measuring 85 mm, and corner radii of 10 mm and 125 mm high. The forging is performed in a 40 MN mechanical press. The initial temperature is 1200°C. The material used is DIN 1.7131 (16MnCr5) steel. **Figure 4** shows the stages of the process: the billet (a) is initially upset to a height of 25 mm , taking on an approximately round form (b) about 210 mm in diameter. Next a preform is forged (c) and then the final form (d).

Before beginning to study, by means of simulation, the development of an alternative process aiming at reducing the material, the current process was simulated for the purpose of calibrating and verifying the precision of the simulation system. **Figure 5** shows the results obtained, by simulation, for the upsetting operation (a) and for the preform (b) and final form (c) forging operations. The figure shows the distribution of the effective stress. The excellent correlation between the real process and the simulation results is seen comparing figures 4 and 5. This occurs both in terms of geometry and in terms of force, as can be seen in table 2. This table also shows the maximum stress values calculated for the tools in the preform and final form forging operations.

Once the precision of the simulation software had been confirmed, a new forging process was developed, empha-
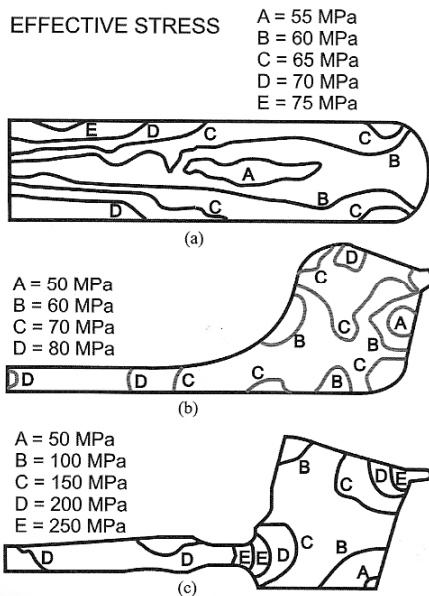

Figure 6. Distribution of effective stress at the end of each stage in the new process: (a) upsetting operation; (b) preform; (c) final form.

Figure 5. Distribution of the effective stress at the end of each step in the current process: (a) upsetting operation; (b) preform; (c) final form.
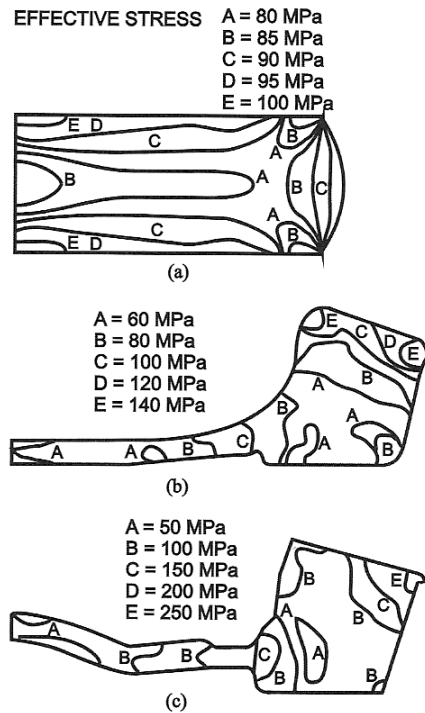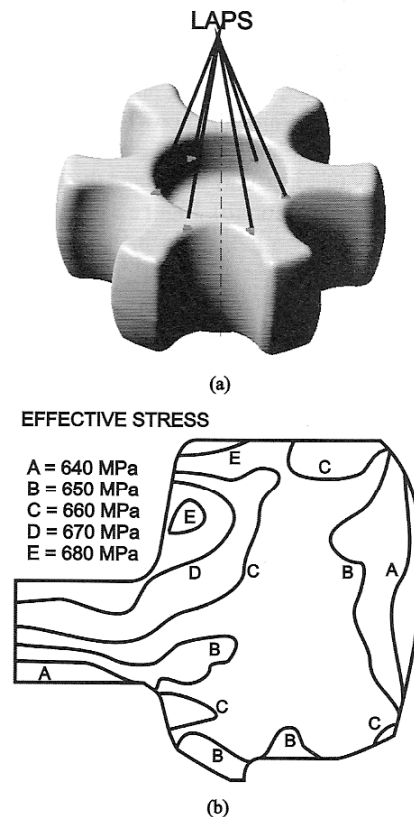

Figure 7. Indications of laps (a) and distribution of effective stress (b) at the end of the process.

EFFECTIVE STRESS

A = 600 MPa
B = 800 MPa
C = 1000 MPa
D = 1200 MPa
E = 1400 MPa
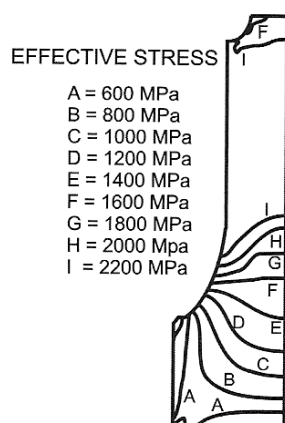F = 1600 MPa
G = 1800 MPa
H = 2000 Mpa
I = 2200 MPa

Figure 8. Distribution of effective stress in the punch.

sizing the saving of material. In the new process the raw material consists of a cylindrical billet with a radius of 50.8 mm and 104.84 mm high, which results in a mass of 6.671 kg. The billet is initially upset to a height of 37 mm. Next a preform is forged and then the final shape. **Figure 6** shows the effective stress at the end of each stage of the new process. In **table 2** are seen the force and stress values in the dies calculated for the stages of both process.

Cold die forging. The cold forming case studied involved an inner ring of a constant velocity joint. In this case it was only sought to validate the software testing whether it reproduced a lap found in practice. The stresses that appeared in the tool were also calculated, since during the industrial process it was found that the lower punch, made from AISI M2 steel, had broken. **Figure 7** shows the part (a) at the end of the process with points where the software indicates a great probability that laps may occur and the distribution of effective stress in a section (b). **Figure 8** exhibits the distribution of effective stress in the punch.

Conclusions

In both processes analysed the results of simulation showed an excellent correlation with the industrial results.

In the case of hot forging, the simulation results demonstrate that it is possible to forge the component without flash, without a significant increase in the force needed and stresses in the dies, and the material saved in the process without flash is about 0.33 kg per piece, which, depending on production, may be a very significant saving.

In the cold forging process, siulation reproduced the location of the lap found in practice. It also shows that the stress peak in the lower punch is 2350 MPa, i.e., higher than the flow stress of the AISI M2 (2100 MPa) steel [13].

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References

[1] L. Schaeffer, A. M. G. Brito: Metalurgia & Materiais, 60 (2004), No. 542, 104/109.

[2] A.M.G. Brito, L. Schaeffer, J. M. C. Rodrigues, P. A. F. Martins: Simulação termo-mecânica de componentes forjados: reflexões em torno de um caso concreto, Proc. VI Int. Conf. on Forging, 2002, Porto Alegre, Brazil, p. 139/154.

[3] L. A. Koller, L. Schaeffer: Características de três dife-rentes programas de simulação numérica de forjamento. Proc. IV Int. Conf. on Forging, 2000, Porto Alegre, Brazil, p. 30/40.

[4] N Biba: Qform3D – efficient and easy-to-use software for bulk metal forming simulation, VII Int. Conf. on Forging, 2003, Porto Alegre, Brazil, p. 142/150.

[5] X. Zuo,Y. Wei, J. Chen, L. Zeng, X. Ruan: Journal of Materials Processing Technology, 91 (1999), p. 191/195.

[6] G. Li, J. T. Jinn, W. T. Wu, S. I. Oh: Journal of Materials Processing Technology, 113 (2001), p. 40/45.

[7] M. B. Silva: A aplicação de prototipagem virtual à análise do processo de enformação plática de chapa fina, M.Sc. Thesis, Lisbon, 2003.

[8] A.M.G. Brito, L. Schaeffer, J. M. C. Rodrigues, P. A. F. Martins: Utilização de simulações numéricas termo-mecânicas no estudo de componentes forjados, Proc. V Congreso de Métodos Numéricos en Ingenieria, 2002, Madrid, Spain.

[9] M. L. Alves: Modelação numérica e análise experimental de operações de forjamento, Dr.-Ing. thesis, Lisbon, 2004.

[10] M. L. Alves, J. M. C. Rodrigues and P. A. F. Martins: Finite Elements in Analysis and Design, 37 (2001), 549/558.

[11] J. Betten: Elastizitäts- und Plastizitätslehre, Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Aachen,1986.

[12] http://www.matweb.com.

[13] H. Tschätsch HandbuchUmformtechnik, 3. Auflage, Hoppenstedt Technik Tabellen Verlag, Darmstadt, 1990.

[14] H. Kudo: International Journal of Mechanical Sciences, 2 (1960), 102/127.

[15] H. Kudo: International Journal of Mechanical Sciences, 3 (1961), 91/106.

[17] A. T. Male, V. DePierre: Journal of Lubrication Technology, 92 (1970), 389/397.

[18] J. B. Hawkyard, W. Johnson: International Journal of Mechanical Sciences, 9 (1967), 163/182.