Simulation of microstructure of nickel base alloy 706 in production of power generation turbine discs.

J. Huez, J-F. Uginet

FORTECH
BP 173 – 09102 PAMIERS cedex - FRANCE

Abstract

die forging the conditions of strain and of the subsequent heat cycle have a significant influence on the structure and operties of the final product, that is why the determination and modelling of grain size development during and after :formation is of primary interest.
this paper we present the simulation procedure and the methodology used to develop a model which can predict icrostructural changes in alloy 706 during hot forming.
igh temperature compression test samples were used to develop a constitutive equation for the alloy 706 which was then ıplied via a finite element model to firstly simulate industrial forging process and finally optimize it.
ıportant parameters such as critical deformation to initiate recrystallization have been determined.
ıe model was found to accurately predict the recrystallized grain size and the percentage of recrystallization on compression st samples as well as on industrial parts.

Superalloys 2000
Edited by T.M. Pollock, R.D. Kissinger, R.R. Bowman,
K.A. Green, M. McLean, S. Olson, and J.J. Schirra
TMS (The Minerals, Metals & Materials Society), 2000

Introduction

nperature nickel base alloy 706 is used for power on applications requiring excellent mechanical es at elevated temperatures.

roperties, principally high strength and good low itigue resistance, necessitate the process being ed accurately to obtain the necessary uctures and to ensure similar mechanical properties y forging.

progress in high pressure turbine discs is measured in technical terms (mechanical properties, parts nd size) but also in economical terms (input , manufacturing cycles, press power).

context, numerical simulation becomes an essential nprove product quality and process efficiency.

te element method, used in Forge2® [1], gives the nd thermal parameters of each instant of the n. Through the analysis of these results it is to determine the evolution of the microstructure in y simple cases, but for more complex ones, g re-heating and cooling sequences, it would appear need to control the prediction of the microstructure. o the only way to optimize a microstructure and process.

ı of this work is to present the simulation results l with a model which incorporates microstructural ena taking place during hot forging of alloy 706.

Material

emical composition of alloy 706 used in this ation is given in Table I.

crostructure of alloy 706 is governed by the fcc of the γ matrix associated with characteristic ates such as the aluminum rich fcc γ' phase. The e of this precipitate is the essential strengthening ism in this alloy. γ' will transform to a stable ıal η phase during elevated temperature exposure. lvus temperature of the η phase in the present l is ~ 954°C (1750°F).

: I Chemistry of alloy 706 used. Weight Percentage.

Fe	Cr	Nb	Ti	Al	Mn	C	Si	S
38.74	15.83	2.84	1.71	.18	.14	.034	.03	.006

ıin steps of the processing route of alloy 706, have tensively describe elsewhere [2], we will summarize e essential elements.

loy 706 is triple melted: the primary melting is a n Induction Melting (VIM), followed by an Electro emelting (ESR) , and a final Vacuum Arc Remelting

An upsetting and drawing of the ingot is carried out well above the recrystallization temperature before the close die forging. Generating a uniform level of strain throughout the workpiece is key to producing a uniform microstructure .
Grain size of ASTM 0-1 is obtained after billetizing (see figure 1).

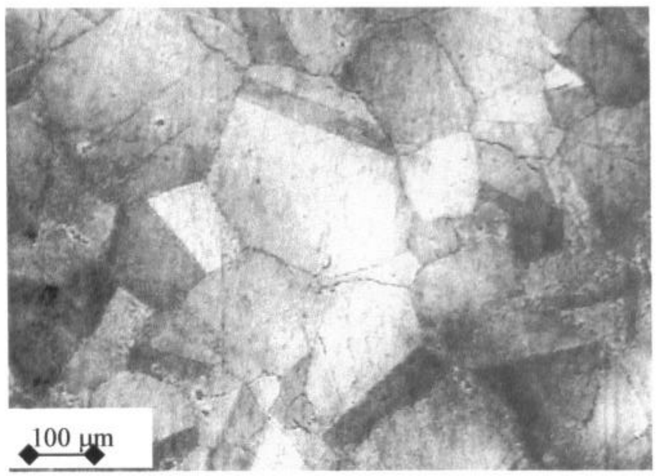


Figure 1 : billet microstructure

Modelling

By the use of the finite element method the prediction of mechanical, thermal and structural conditions is possible but material data has first to be well known.
Knowledge of both the thermomechanical behavior and thermophysical properties of the material as well as that of the kinetic tools is essential to give an accurate description of the deformation process.

The constitutive law

In the first phase, a rheological model of the material was defined through high temperature compression tests.
Typical flow curves were obtained and analyzed.
The constitutive law used is the Norton-Hoff model, expressed as follow :

$$\sigma = \sqrt{3}^{m+1} K(T) \dot{\varepsilon}^{m} \left(\varepsilon_0 + \varepsilon\right)^n$$

with σ the stress flow
$K(T)=K_0 \exp(Q/RT)$ the strength constant of the material,
ε the strain
ε_0 the strain hardening regularization term
$\dot{\varepsilon}$ the strain rate
n the strain hardening coefficient
m the strain rate hardening coefficient

The temperature is not only studied within the range of the forging window but also until the ambient temperature, to simulate correctly the heat treatment.

:ial and thermophysical properties of alloy 706

:sts are performed to reach a compromise between reduction and thermal insulation but, above all to ;ood, effective Coulomb friction coefficient for the tion. The knowledge of the influence of the friction ient on the deformation process permits the increase decrease of the minimum strain in the workpiece is a very important parameter leading to the ructure and to partial recrystallization.
:rmal constants are also determined such as calorific y, thermal conductivity, emissivity, and global r coefficient : heat transfer coefficient between die orkpiece and exterior area interface. So losses by on and convection are taken into account as are tion effects and adiabatic heating produced during ation.

ıetic tools

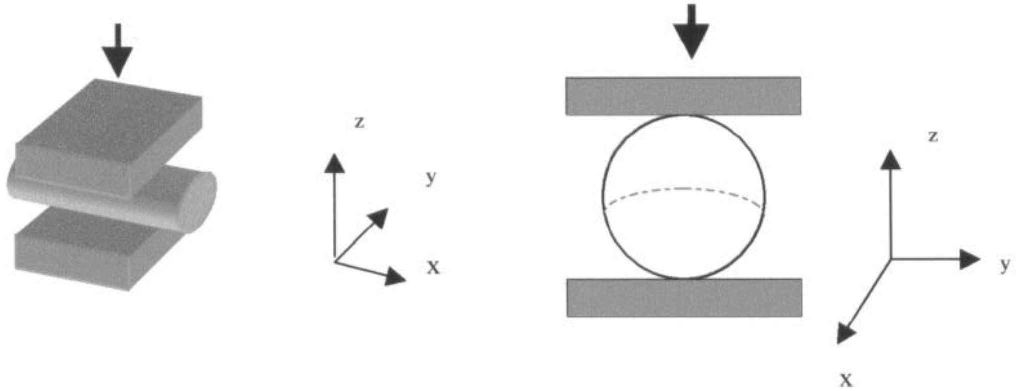
st approach it can be considered a constant velocity the simulation, but in reality the press velocity ses when a force limit and/or power limit is reached.

Thus for an accurate calculation, we are taking into account a driving velocity application simulating hydraulic press.

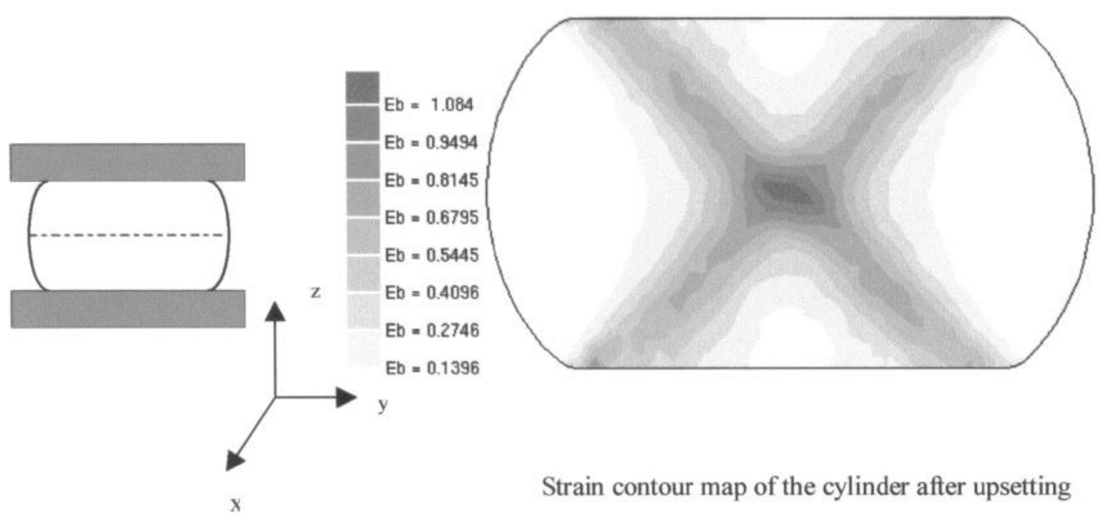
Microstructure evolutions

To take full advantage of controlled deformation processes it is necessary to understand the interactions of the forging parameters with the microstructure developed.
Thus the effects on microstructure of strain, strain rate and temperature during forging and after heat treatment have been studied in details by Plisson [3]. The aim of his study was to find a semi empirical equation describing the microstructural evolution, essentially the grain size and the recrystallized fraction evolutions, of alloy 706.
Recrystallization has been studied through compression tests : miniature cylinders of 80 mm in diameter and in length are tested in compression along their axial direction, in different conditions of strain rate and temperature, so that nominal strain varying between 0.1 and 1.2 is obtained (see figure 2). It appears from Plisson studies that in alloy 706 dynamic recystallization does not take place in that strain domain and that the evolution of microstructure is essentially governed by static recrystallization and grain growth phenomena.

(1)



(2)



Strain contour map of the cylinder after upsetting

;ure 2 : Compression test on cylinder of 80 mm in diameter and in length. Strain rate, temperature and forging ratio varying.

Concerning the static recrystallization, an Avrami-Sellars [4,5,6,7] analysis allowed the establishment of the equation of the kinetic evolution which after discretization [8], is directly usable by numerical simulation. The expression of the recrystallized fraction and of the grain size after static recrystallization are :

$$X = 1 - \exp\left[\ln(0.5).\left(\frac{t}{t_{0.5}}\right)^k\right]$$

were X is the recrystallized fraction, t the time, $t_{0.5}$ the necessary time to have 50% of the structure recrystallized and k the Avrami exponent.

$$t_{0.5} = \alpha \varepsilon^a Z^b D_0^c.\exp\left(\frac{Q_{rex}}{RT_{rex}}\right)$$ and

$$Z = \dot{\varepsilon}.\exp\left(\frac{Q_{def}}{RT_{def}}\right)$$

$$d_{rex} = \beta \varepsilon^n D_0^m Z^l$$

with Z the Zener-Hollomon parameter, R the universal gas constant, D_0 and d_{rex} respectively the initial and the final recrystallized grain size (in mm), Q_{def} the activation energy for hot deformation, Q_{rex} the activation energy for static recrystallization, T_{def} the temperature of deformation and T_{rex}, the temperature of subsequent annealing. α, β, a, b, c, n, m, and l are constant.

Concerning the grain growth mechanism, the experimental results allow finding the parameters of the expression

$$A^n = A_0^n + B.\exp\left(\frac{Q_{gg}}{RT}\right).t$$

with A the mean area of the grain at t, A_0 the mean area of the initial grain (in mm^2), Q_{gg} the activation energy for grain growth, B a constant.

The experimental study shows that the recrystallization is static and that the dynamic recrystallization is not significant in the industrial shaping process of alloy 706. Thus microstructure evolutions will be calculate separately from the thermomechanical calculation.

The simulation starts by a mechanical calculation which gives strain, stress, strain rate and temperature, these last two being averaged on the calculation time. The temperature distribution at the end of the mechanical calculation initializes the thermal calculation which will follow.

All these values are re-entered at the beginning of the thermal calculation. For a given node, the material is divided in several microstructural elements, to take into account the structure heterogeneity. If it is the first thermal calculation, the microstructural values such as grains size are initialized. If not, the program reads in a file the characteristics of each microstructural element (recrystallized fraction, mean grain size in the recrystallized and in the worked part of the disc).

For each step of the thermal calculation, recrystallized fraction at each point increases. If the material does not reach the critical strain needed to recrystallize, the grain growth mechanism is applied to the worked grains. As soon as all the material is recrystallized the grain growth law is brought into action.

Each mechanism is limited by a value experimentally determined:

- no microstructural evolution starts until a minimum temperature T_{min} is reached
- recrystallization starts only if the critical strain (ε_c) is reached . The value of ε_c depends on the deformation temperature.
- the recrystallization is considered to be finished, when 95% of the structure is recrystallized and when the grain growth can take place. Then the recrystallized fraction appears to be 100%.

The microstructure parameters are calculated assembling the information of the totality of the microstructure elements of each node. So the recrystallized fraction, the mean grain size, the standard deviation between grain size and the maximal grain size are estimated; these two last parameters permit the estimation of the heterogeneity of the microstructure.

To validate the calculation development, forging tests have been carried out on identical cylinders as those described before. Figure 3 presents one of these results.

The predicted grain size differs from experimentation by only half a unit on the ASTM grade, while predicted recrystallized volume fraction differs from experimentation by 5 %.

Finally, the variety of the microstructure (deformed grains and recrystallized grains) is also accurately predicted : the center of the material has a slightly coarser grain size than that near the surface. This is a result of the non uniform deformation but also of the relative difference in heating rates between center and surface location.

A good match exists between predicted and actual values, confirming the correspondence between the parameters and the analytical description of the evolution of the microstructure introduced in the Forge2® software.

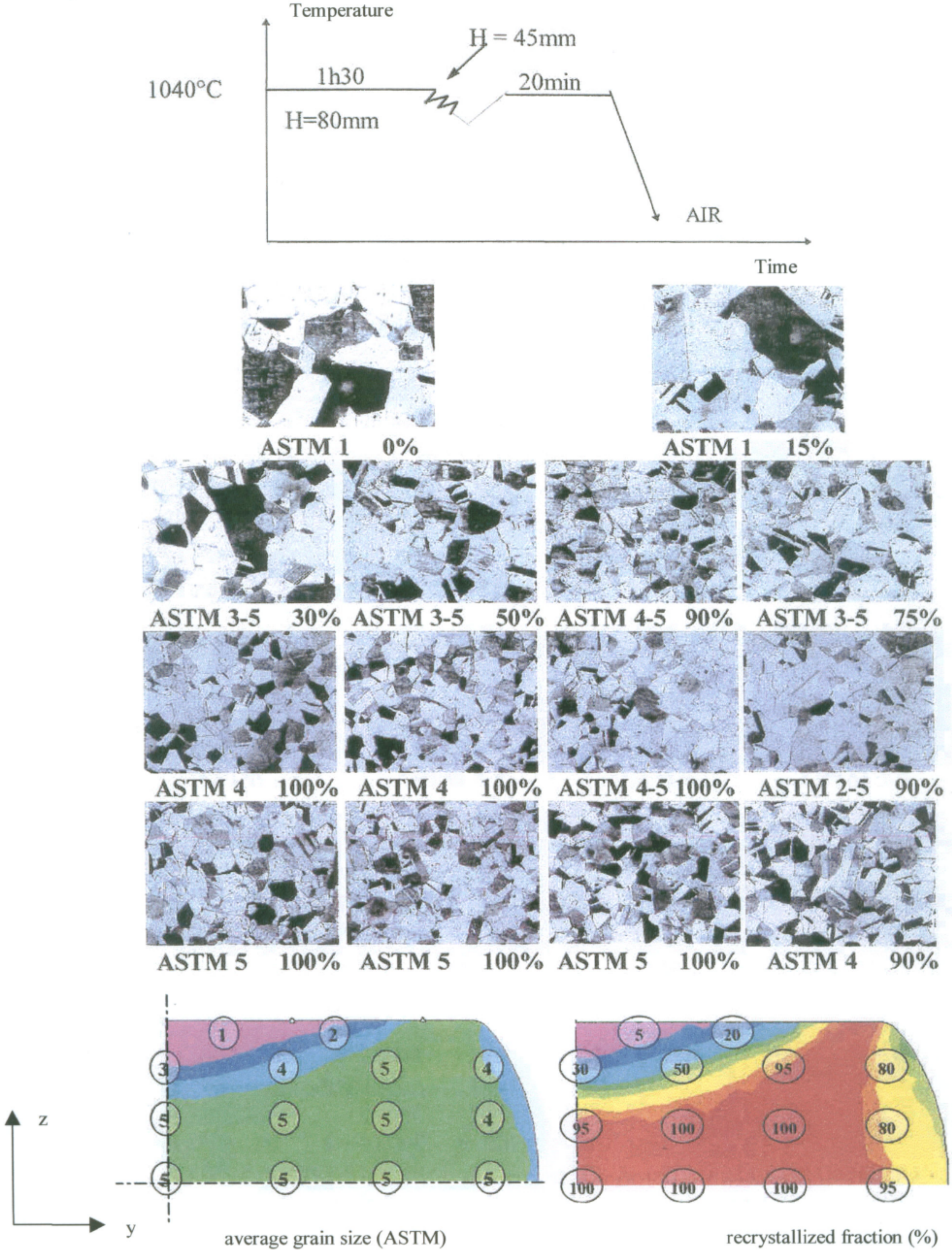


Figure 3 : Numerical results

Industrial application

ıese positive results, the model was used for the l production of gas turbine discs.
ɔllowing, results of the improvement and of the tion of a die forging process are presented. Figure the scheme of the thermomechanical process ınd simulated. The dimensions of the billet are in to 0.9 m range concerning the diameter, with a diameter ratio of approximately two.
ı00 tonnes press at Interforge adequately meets ıents necessary to optimize both ure/reduction rate parameters. At this step of the t is important to know the strain distribution in the as achieving uniform recrystallization is also ıt upon generating sufficient strain throughout the

forging process consists of an upsetting followed hing and then die forging. The simulation of this ;hows a lack of strain just below the surface of the ıdeed, during the first heat, the work does not ; efficiently from surface to mid-length of the part. lequate strain is not achieved, which results in a ecrystallization, with negative effect on the final ;s of the product. To avoid the problem of die-lock ɔunching operation was added. Figure 5 shows the ıe recrystallized fraction and the average grain size

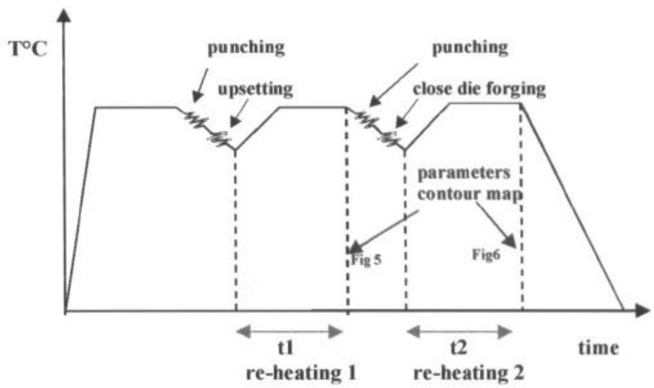
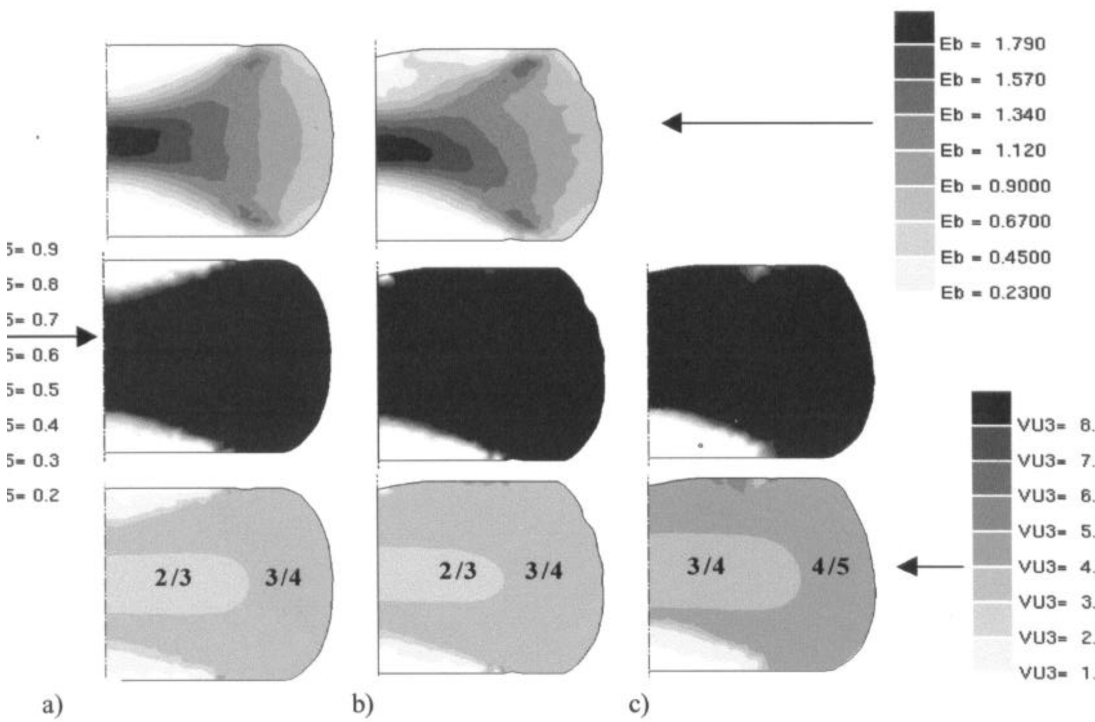


Figure 4 : Scheme of the industrial process studied and simulated

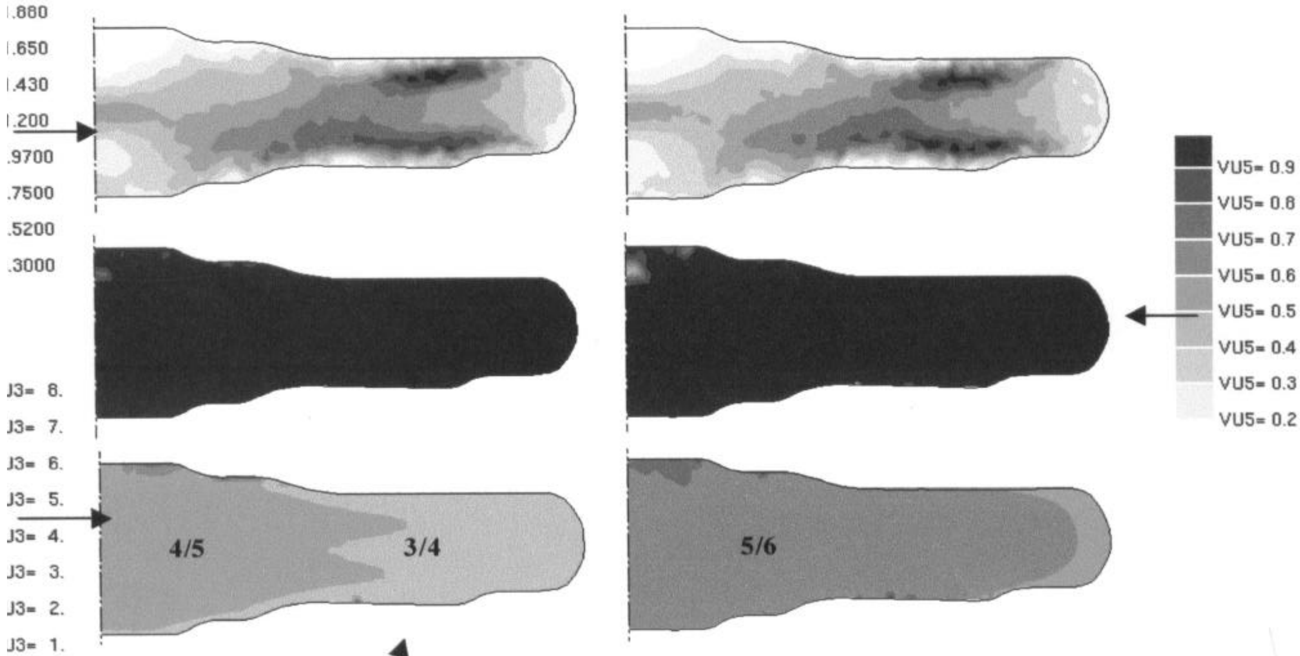
contour map inside the preform resulting from an upsetting plus a re-heating (a) and from a punching followed by an upsetting plus re-heating (b), to reach the same thickness.
The stored energy of deformation during the punching allows recrystallization to take place during thermo-mechanical processing, which follows : upsetting to thickness H followed by re-heating 1 at temperature T (°C) during a time t1.

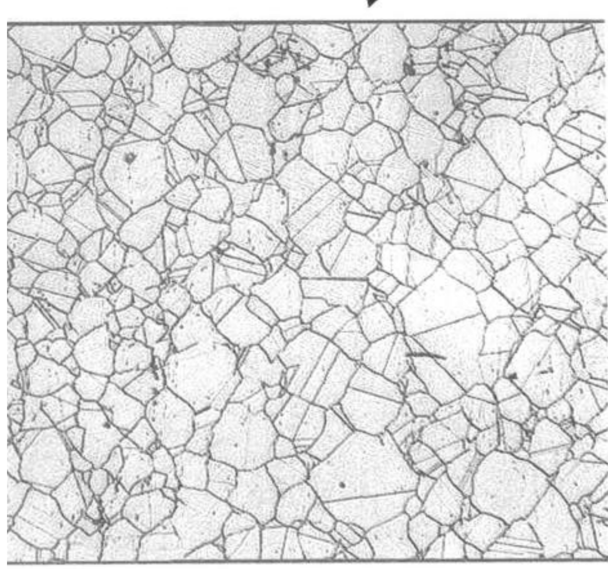


; : First heat . Strain (top), recrystallized fraction in percent (center) and average grain size in ASTM grades (bottom)
d after (a) an upsetting to H followed by a re-heating during a time t1
(b) a punching plus an upsetting to H followed by a re-heating during a time t1
(c) a punching plus an upsetting to H followed by a re-heating during a time t1'

ıe operation, punching, is repeated on the other face part, before the final close die forging and a re- (2) followed by air cooling.
d inverting the mesh in the simulation, the second ıg is made on the bottom face. Thus on the final product contour maps, the real top face is at the bottom and vice et versa.

The industrial production process, subdivided into forging a preform and finish close die forging, is simulated. Figure 6 shows the final microstructure obtained, which corresponds to that observed on the workpiece.





	Actual process (b)	Optimized process (c)
Average grain size after re-heating 1 (ASTM grades)	**3-4 + 2-3 in the center**	**4-5 + 3-4 in the center**
Average grain size after re-heating 2 (ASTM grades)	**3.5 - 4.5**	**4.5 – 5.5**

a)
200 µm

6 : Second heat. Strain (top), recrystallized fraction in percent (center) and average grain size in ASTM grades n) predicted on the final product after a re-heating during the time t2 (b) and t2' (c). (a) microstructure observed on the roduct.

ıe simulation gives, at each step of the process, similar ain size and morphology (deformed or recrystallized) to ɔse obtained on the workpiece. Once again, these results monstrate that the laws which govern the physical enomena surrounding alloy 706 are well identified.
ıus, by varying the re-heating time between two forging ps and/or the temperature of the heat treatment, the timization of the forging procedure can be obtained rough computer techniques of modelling.
ıe present study also investigated an alternative oduction route, consisting of reducing the re-heating time tween two forging steps. The same simulation was rried out with t1 and t2 reduced. Below we will speaking out an actual production process (time t1 and t2) and the timized process (reduced time t1' and t2').
ıe different strain, grain size and recrystallized fraction ntour map for both process are summarized in figures 5 d 6.
ıe microstructure obtained after the re-heating 1, presents ı average grain size of 4-5 and of 3-4 ASTM grade spectively for the actual process and the optimized one. A arser grain 1 to 2 ASTM grades larger is observed in the nter of the part because the strain and the temperature vels and thus the adiabatic heating leads to a rapid crystallization followed by the grain growth. The finer ructure predicted by the simulation for the optimized ocess is due to shorter time for grain growth before the ıbsequent forging step is applied. The recrystallized ɔlume fraction remains unchanged.
he microstructure predicted by simulation on the final oduct, still has the difference of 1 to 2 ASTM grades on ıe grain size, for the same fraction of recrystallized grains.
he difference between the two processes of final average rain size has no significant influence on the mechanical roperties, a good recrystallization is also achieved in both ases. So the reduction of the re-heating time leads to a duction of cost and increase of press availability.
imulation allows to correctly adapt initial and finished ıapes to ensure to have sufficient strain in all of the disc ıd associated to the close-die forging procedure with a recise time and temperature sequence, it leads to a ɔntrolled microstructure and to the required mechanical roperties.

Conclusion

Jsing compression test samples, the microstructural volutions and especially static recrystallization and grain rowth of alloy 706 have been identified and introduced ıto 2D modelling software. The model has been validated nd is now used for industrial process optimization. This tudy illustrates that now the finite element model is not nly used to correctly predict the material flow occurring in ıe part but today numerical simulation has become an ssential tool for process optimization and improvement of ıicrostructure.

The knowledge of constitutive equations that involve microstructural parameters and allow to predict microstructural evolution during forging are of first importance.
Of course the identification of the laws which governs the microstructure evolution is not easy especially when there is not only static recrystallization but also dynamic one, but it is the next step in pushing back the blacksmiths' boundaries and to decrease the cost and manufacturing cycles.

[1] Forge2®, a modelling software for the shaping of axisymmetrical and /or two-dimensional parts, Transvalor, BP037, 06901 Sophia Antipolis Cedex - France.

[2] D. Rayne, J.F. Uginet, " Fabrication of large components in 706 Alloy for gas turbine application ", 11th International Forgemasters Meeting Terni /Spoleto, Italy, 1991.

[3] C.Plisson, " Mise en forme du superalliage base nickel 706 ", (Internal Report 1997).

[4] Avrami, " Kinetics of phase change I, general theory ", Journal of Chemical Physics, vol. 7, (1939).

[5] Avrami, " Kinetics of phase change II, transformation-time relations for random distribution of nuclei ", Journal of Chemical Physics, vol. 8, (1940).

[6] Avrami, " Kinetics of phase change III, granulation, phase change and microstructure ", Journal of Chemical Physics, vol. 7, (1939).

[7] Glovers,. Sellars, " Static recrystallisation after hot deformation in alpha-iron ", Metallurgical Transactions A, vol. 3, (1972).

[8] P.Audrerie, "Etude du comportement rhéologique au cours de traitements thermomécaniques d'alliages de titane", (Ph. D., Ecole Nationale Supérieure des Mines de Paris, 1993).