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Numerical Prediction of Biphasic Titanium Alloys Microstructure in Hot Forging Operations

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Abstract. Modern transportation industries shall comply with two demanding requirements: reducing operational consumption together with production costs coming from materials and labour. Current trend of engineering is oriented to meet both requirements increasing the rate of polymer matrix composites which implies association with structures made of titanium alloys. Hot forming can be used to reduce the production costs of titanium components: forging in closed dies of billets or semi finished form, in the temperature range where the Beta phase of titanium is stable, grants an adequate plasticity of the Ti-6Al-4V alloy, the most commercially used, allowing production of complex shapes with limited amount of edge trim removal and machining rework after forging. Unfortunately, as far as Ti6Al4V titanium alloy is regarded, several material peculiarities have to be properly taken into account. In the paper, a numerical model is presented for hot forging of Ti-6Al-4V titanium alloy. Once set up, the model was tested through comparison with experimental data found in literature. A good agreement between the numerically calculated and the experimentally measured data was observed, indicating that the model can be utilized as a design tool in complex hot forging processes of titanium alloys.

Keywords: Titanium alloys, microstructure, FEM model.

1. INTRODUCTION

Titanium alloys are desirable and, sometimes, indispensable materials for several aerospace and aeronautical applications due to their combination of mechanical properties and corrosion resistance. In particular the mechanical properties depend on microstructure in terms of phases composition, distribution and grain size. In turn, these features depend by thermo-mechanical treatment and processing history; besides, it is necessary to know the laws that govern the thermo-mechanics and the kinetics of phase transformations during the process. Although some of these aspects are well studied, the complete knowledge of the transformations kinetics is still under development.

In this paper a FEM model is developed to simulate the phase transformation of the Ti-6Al-4V titanium alloy to study the beta to alpha+beta transformation during hot forging operations. The model was developed using DEFORM™ [1] software and calibrated and validated with parameters of a real case study developed by Malinov, Markovsky, Sha and Guo [2]. The first alpha to beta phase transformation is carried out using a simplified form of the Avrami model [2] available in the Deform code while the final beta to mixed alpha+beta phase transformation is developed using the TTT curves for the considered alloy. Finally, the model was used to analyse the hot forging process of a prismatic billet. It should be observed that the model does not consider the diffusional phenomenon and its contribution to microstructural evolution of material but only the thermo-mechanical aspect of the transformation.

2. EXISTING FEM MODELS

A few numerical models have been developed to calculate the phase evolution during a thermo-meccanical process and to predict the grain size into the microstructure at the end of a forming process.

Katzarov, Malinov and Sha [3] proposed a model for the analysis of the beta to alpha transformation for a Ti-6Al-4V alloy based on an implicit time-stepping technique that resolves a diffusion equation as function of the volume occupied by the beta phase in a space-time domain. This volume was approximated with a set of four nodes elements in a 2D space. These elements were considered as the bases of prisms in a 3D space. This subdivision allowed to calculate the values of concentration of the phases just at the nodes of the elements.

Z.M. Hu, J.W. Brooks and T.A. Dean [4] proposed a 2D thermo-plastic model to study the hot die forging of titanium alloy aerofoil sections based on compression tests and analysis of microstructure of forged pieces. This model was developed using the Abaqus/Standard software with a 2-D mesh for the transverse and longitudinal sections of the aerofoil. The constitutive relationships were determined from compression tests and analysis of the forged parts while the boundary conditions were determined from various tests on hot forging of titanium alloys. The simulation was divided into three steps as the real forging process.

R. Ding and Z.X. Guo [5] proposed a 2D model joining the physical laws of dynamic recrystallization (DRX) with the cellular automatation method that is an algorithm describing the spatial and temporal evolution in a physical system using deterministic/probabilistic rules. This model was used to simulate the DRX process of the Ti–6Al–4V alloy and to calculate the characteristics of DRX. The initial orientation of grains was set randomly and was represented by a random integer in the range of 1–180.

A. Suárez, M.J. Tobar, A. Yáñez, I. Pérez, J. Sampedro, V. Amigó and J. J. Candel [6] used a FEM model to study the phase transformation of titanium Ti-6Al-4V alloy during a laser cladding process. It was implemented into the ANSYS software using a subroutine that allows to calculate the phase transformation during the on-going transient. Each step of the simulation was solved by a staggered approach of a thermal analysis and a metallurgical analysis. The main subroutine controls the transition between the different regions containing the different phases, according to the temperature range of each region and the element‘s temperature. The transformation history of phases and all information about it were calculated and stored, during the transient analysis, into several vectors related to each one of the elements. All these vectors were stored in a matrix in which each row corresponded to one element of the model. It should be observed that a growing interest is developing in the scientific community regarding the set up of numerical models taking into account simultaneously mechanical, thermal and metallurgical effects.

3. THE NUMERICAL MODEL

3.1. Model tuning and calibration

DEFORM™ software [1] was used to carry out the model of the phase transformation of Ti-6Al-4V. It is a FEM implicit code particularly used to conduct coupled thermo-mechanical simulations about heat-treatment and hot-working process. The code has a large material library that includes several information about the thermo-mechanical characteristics of several kind of titanium, aluminium alloys and steels. The code can calculate phase transformations and the grain size as function of the evolution undegone by the material. It is possible to calculate the metallurgical evolution of a processed material using several relationships to adapt the model to various type of alloy. However the user can manually insert additional data he found during his research to make the database more complete. The code also allows the user to insert new relationships as subroutines as integration to the existing equations. In this case the authors conducted a literature research to collect much information about the flow stress laws of the material as function of temperature and strain rate.

The model was tuned on the basis of the results of an experimental study by Malinov and Sha [2]. The latter consists of the analysis of a sheet metal titanium Ti-6Al-4V alloy of 60x3x1.5 dimensions (figure 1) heated from room temperature to beta zone.

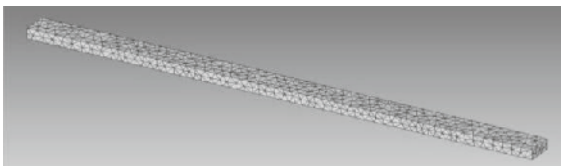

Figure 1. 3D view of the workpiece.

This limit allows an almost complete transformation of the alpha phase to beta phase. Then the workpiece was cooled with different cooling rates and it was finally quenched by water to room temperature again (figure 2). During the process the evolution of the mixed alpha+beta phase was studied and plotted on a graph.

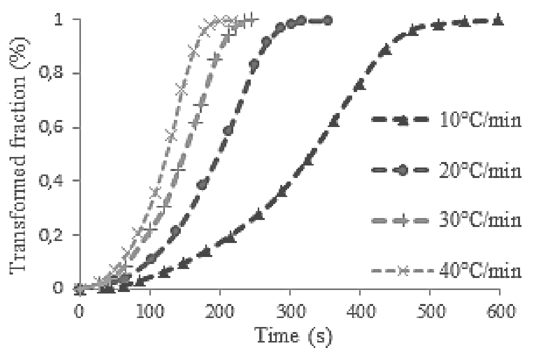

Figure 2. Alpha+beta phase evolution at different cooling rates [2].

A set of 178 flow stress curves were collected from literature and inserted into the software to manage the thermo-mechanics evolution of the material into a great range of temperatures and strain rates to can simulate a great variety of conditions. These data have been found on JMatPro [7] database and further literature [8-12]. The demo version of this software contains several information about various alloy including titanium Ti-6Al-4V alloy.

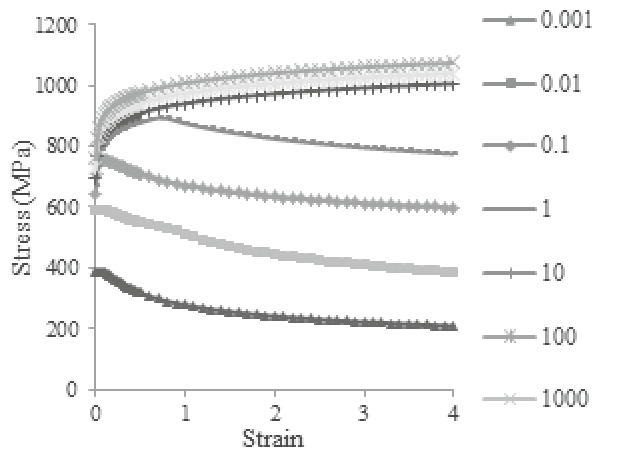

Figure 3. Example of a flow stress curve at 600° C and various strain rates.

Furthermore the TTT curves for Ti-6Al-4V to calculate the beta to alpha+beta transformation and the curves for alpha to beta phase transformation during heating [7] were considered. It should be observed that such information is also included into ther JMatPro database. In order to model the alpha to beta phase transformation during heating the Avrami simplified model included into DEFORM™ code, was used, as follows

$$\boldsymbol{\vartheta_v = 1 - e^{\left\{A\left(\frac{T-T_s}{T_B-T_s}\right)^D\right\}}} \qquad (1)$$

where A and D are material parameters, T is the actual temperature, T_s is the phase transformation starting temperature and T_e is the phase transformation ending temperature.

The material parameters were determined through an inverse approach starting from the experimental data (figure 4).

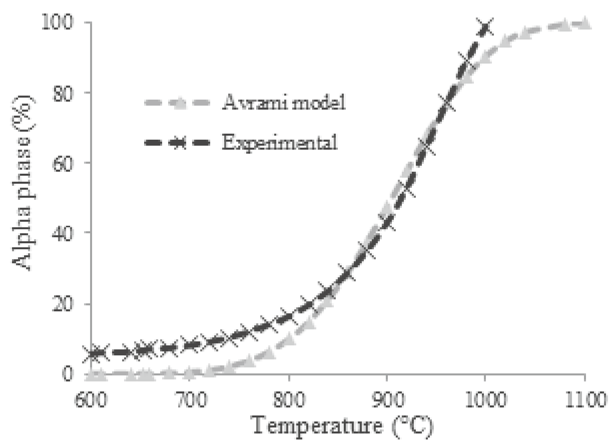

Figure 4. Comparison between experimental data and Avrami simplified model.

At the end of the processing the optimizing values for A and D coefficients were found as follows:

- A = -1.87
- D = 4.32

The used analytical expression results very simple to be used due to its dependence on temperature only. The used coefficients create a temperature gap of about 50°C to get the total transformation during the heating process. This difference does not represent a problem as the most of hot-working processes is done at temperatures above the beta transus.

After setting the transformation from alpha to beta phase as already mentioned the TTT curves for Ti-6Al-4V were implemented to simulate the real beta to alpha+beta transformation of the alloy during cooling process as showed in figure 5.

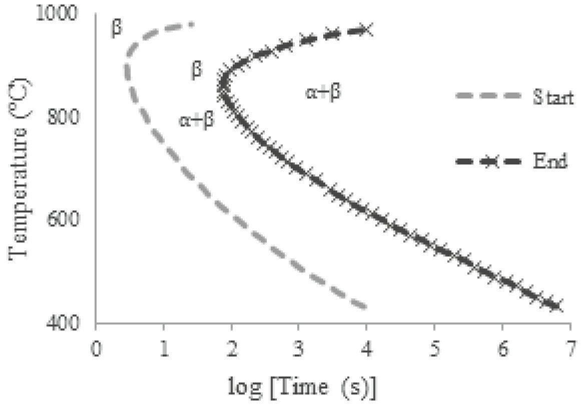

Figure 5. TTT curves for Ti-6Al-4V [7].

The analysis of the heat treatment of the workpiece was conducted using a mesh with 1600 tetrahedral elements and a time step of 0.5s. The heating phase was simulated by boundary conditions for temperature at external nodes because the part geometry shows a nearly isothermal behaviour. At the start of simulation the material was set with his real composition at room temperature namely 91% of alpha pase and 9% of beta phase. After the workpiece is conducted above the beta transus zone the initial alpha phase content was converted to beta phase and it was added to initial beta phase content. Then the part was cooled down using four different cooling rates: 10, 20, 30 and 40 °C/min to a common temperature of 800° C. At the end of such preliminary cooling phase a quenching by water to room temperature was simulated. The latter issue does not represent any relevant aspect for the considered analyses due to the actual thermal behaviour of the material. In other words the full alpha+beta transformation is already obtained at 800° and the quenching does not determine any further transformation. The next figure 6 shows the overlap level between the experimental data and the numerical results of the fem model of a middle point of the workpiece. The latter image shows how the model is able to predict the trends of the beta to alpha+beta phase evolution during the cooling rounds.

The next figure 7 shows the TTT and cooling curves highlighting the thermal course followed in the considered tests. All cooling time analysis start with a 100% content of beta phase and enter into the partial alpha+beta transformation zone to end into the alpha+beta zone with different speeds. The considered graphs show that the model is coherent because it follows all inserted relationships to calculate the phase transformation during the thermo-mechanical process as function of thermal conditions and thermal history.

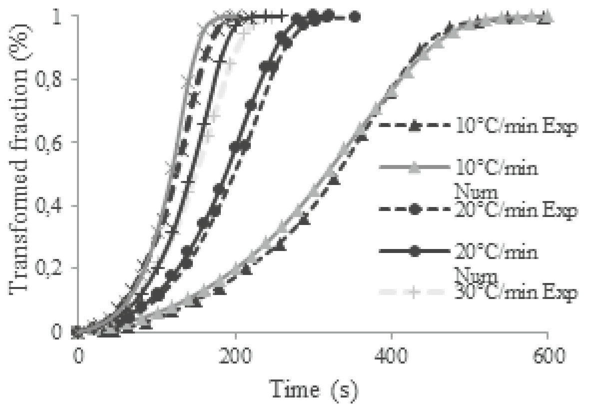

Figure 6. Comparison between experimental and numerical results at various cooling rates.

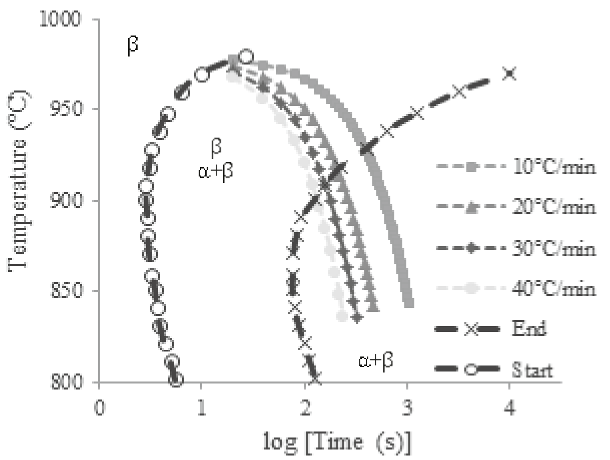

Figure 7. TTT and cooling curves at various cooling rates.

3.2. Model application

After that the model was verified, it was used it to conduct a simulation of another study case about an hot-forging process of a billet. This analysis was done using DEFORM2D™ because the workpiece was considered in plane strain conditions. In this way the computational cost was reduced significantly.

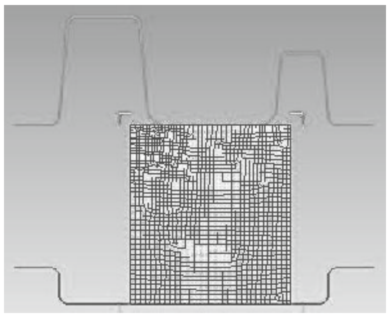

Figure 8. Geometry of workpiece and dies at the start of simulation.

The simulation parameters were chosen from typical real hot-forging titanium alloy processes:

- Workpiece temperature: 1050° C;
- Die temperature: 600° C;
- Die speed: 1mm/s.

The next image composition (figure 9) shows the comparison between the thermal distribution and the alpha+beta phase distribution into the workpiece as undeformed (namely after heating), at the end of the forging stage and after the cooling.

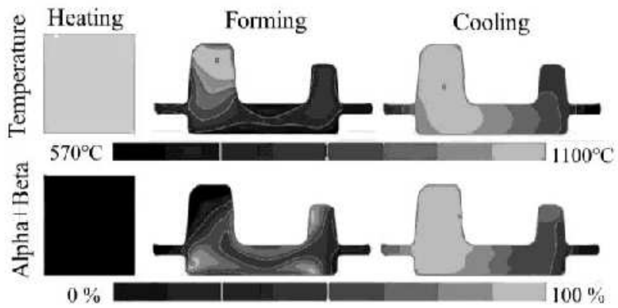

Figure 9. Evolution of the temperature and alpha+beta phase during the process.

While the next figures 10 and 11 show a point tracking of a middle point of the left rib of the part with all phase evolutions.

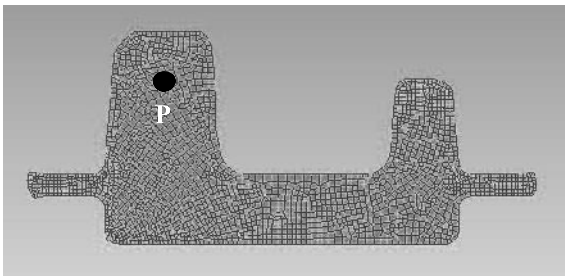

Figure 10. Point tracking of the workpiece.

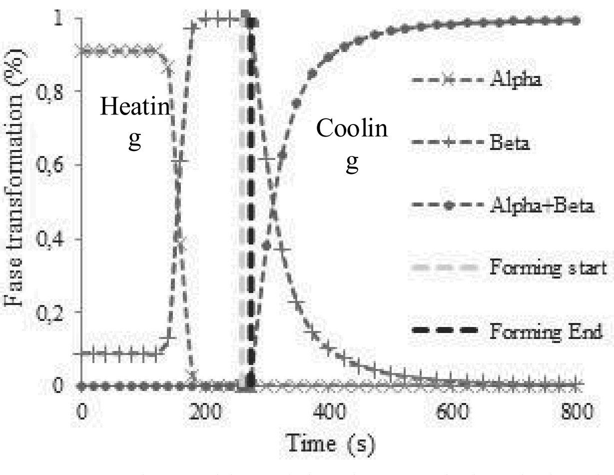

Figure 11. Point tracking of the phase evolution during the simulation.

The previous diagram (figure 11) shows how the model is coherent during the singles phase calculation since the total content of phase is instantaneously equal to 100%. This is an important datum attesting all transformations of the phases is correct and mutually related. Otherwise it would be possible to obtain some zone of workpiece with an incorrect and unjustified phase content.

4. CONCLUSION

The developed model was able to provide good phases distribution prediction, for the tested alloy, under varying temperature conditions.

However, it has great possibility for improvement as most of the used data are the result of literature reconstructions. The difference between the experimental data and the model output can be reduced by doing various simulations of real study cases and comparing the obtained results with the experimental data.

Another way to optimize the model can be using time depending relationships to analyse the phase transformations during the heating process as function of temperature and time. The limit of current used equation is to not consider the time influence for a phase transformation. However it is possible improving this kind of relationship into the model to allow calculating the phase content as function of time at isothermal condition as proposed by literature.

Another considered aspect is the computation cost of the model. The authors did not record increases in the computational cost with respect to conventional thermo-mechanical analysis conducted in the absence of phase transformation prediction. This results were confirmed both with 2D and 3D model.

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