Modelling of the Transformation of Coarse Grained Microstructure of α+β Titanium Alloys Along with FEM Simulation of Hot Forming Processes

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Abstract

It is well known that fine grained titanium alloys are characterized by very promising properties, but the process of obtaining such materials is normally quite costly and time consuming. To reduce the cost of manufacturing an attempt can be made to refine the initial coarse grained microstructure directly in the process of hot working. Various experiments conducted by the authors as well as work carried out by other researchers indicate that this is possible. The main complexity in the implementation of this idea into real technological processes is related to the high non-uniformity of the strains, strain rates and temperatures in the deformed workpiece and the sensitivity of microstructural transformation to these parameters. To approach this problem the capability of modelling the microstructure transformation along with the finite element (FEM) simulation of the deformation process is required. In this work a simple constitutive model coupled with the microstructure transformation is programmed into the FEM software, QForm, and used to investigate the perspectives of hot forging of the coarse grained two-phase titanium alloy.

Keywords: Superplasticity, complex loading, α+β Ti alloys, constitutive modeling, FEM simulation

1. Introduction

Titanium alloys are widely used in many industries including aerospace, automobile and biomedicine due to their high strength to weight ratio, excellent creep and corrosion resistance, good biocompatibility etc. But almost all widely used titanium alloys, especially the family of α+β alloys, which are discussed in this paper, exhibit poor formability at room temperature. These alloys have a high yield stress of about 1GPa and relatively low ductility at room temperature. However, manufacturers are interested in producing complex shaped products out of these materials in a limited number of mechanical steps. The possibility of near net-shape hot forming can be linked to a phenomenon known as superplasticity (SP), which takes place at certain thermo-mechanical conditions (temperature T>0.5Tₘ, strain rate of about 10⁻⁴ to 10⁻² s⁻¹) and fine-grained microstructure (grain sizes d≤10 µm), as shown by Padmanabhan and Davies(1980) also Padmanabhan, K.A. et al.(2001). This latter aspect is of significance because the smaller the grain size the more
similar to the flow of viscous liquid is the mechanical behaviour of the material. Unfortunately, the production of ultra-fine grained (UFG) titanium alloys is costly and the availability of UFG material in sheet form typically used for superplastic forming is still somewhat limited.

Superplastic forming relies on a fine grain structure however this feature is not always needed. The majority of manufacturing processes require not more than 100-200% deformation. The fine grained structure is not always optimal for in-service properties, for example it was shown by Nalla et al (2002) that a coarse-grained lamellar microstructure has better resistance for the propagation of fatigue cracks.

This generates the concept of investigating the possibility of widening the range of near-net shaping processes by using initially coarse grained materials. These materials due to their microstructure cannot provide deformation driven mainly by the grain boundary sliding mechanism assumed to be typical for SP deformation, Anoshkin et al. (1980). As the result the strain rate sensitivity in this case is lower than in case of SP. The material can demonstrate deformation softening and the microstructure can undergo transformation during deformation. However experimental work done by Korshunov et al.(1996), Seshacharyulu et al.(2002), Venugopal et al. (2005), Bhattacharia et al.(2009) show that in such kinds of processes, which can be termed “near-to-superplastic” forming, refinement and globularisation take place and relatively high deformations of 100-300% nevertheless can be reachable.

In this way the transformation of a coarse microstructure in principle could be at least partly integrated directly into the process of hot forming. At the first stage of the hot forming the microstructure would undergo some necessary refinement and then at the second stage material will flow in a regular way to fit all complexities of the geometry of the die. The idea that forming process can be multistage, and actual superplastic conditions are required only at its final stage, was proposed and studied by O.V.Sosnin et al. (1993) and his colleagues. The main difficulty of such an approach is in the development of the first part of the deformation process. On the one hand at this stage the microstructure should get processed enough for further superplastic flow, but on the other hand there should not occur any flow localization or damage (cracking, void formation) of the material. To resolve this problem some experience of the severe plastic deformation process used for producing UFG microstructure can be utilized.

To investigate the possibility of such an approach some experiments on near-to-superplastic deforming of α+β titanium alloy VT9 were conducted and analyzed. On the basis of the observations obtained a microstructurally coupled constitutive model was developed and programmed as a user function into commercial metal forming software, QForm. One trial model problem of hot forming of an automobile wheel using coarse grained α+β titanium alloy was simulated and analyzed.

2. Experimental Procedure

A significant number of standard tensile and compressive tests have been performed with the coarse grained α+β titanium alloys at conditions close to SP, e.g. by Seshacharyulu et al. (2002). All of them witness that very significant refinement and globularisation of the microstructure can be achieved. The main problem with obtaining really large deformations in these kind of tests is related with the fact that at a time when the microstructure is sufficiently refined to support SP deformation, the specimen itself loses its uniformity due to prior flow localization.

To avoid this, two main approaches normally used in the Severe Plastic Deformation techniques could be exploited. Large deformations without early localization can be obtained either by adding hydrostatic pressure (which helps in partial healing of the accumulated damages) or by some complex loading (when large deformation is accumulated). The behavior of the material under one variant of such complex loading which gives the ability to accumulate large effective plastic strain (Ouquist parameter) under a relatively low strain intensity was studied experimentally and compared to the standard simple modes of deformation.

Two-phase (α+β) titanium alloy VT9 (Ti-6.5Al-3.5Mo-1.6Zr-0.27Si) with lamellar (Widmanstätten) microstructure was tested with primary transformed β-grains of about 250µm, and mean length of α-plates of about 21µm and thickness ~ 2µm by Bylja et al.(1997).

The mechanical tests were conducted under isothermal conditions at a temperature 970±5°C on a testing machine of kinematic type at constant cross-head velocity and constant angular velocity of the specimen’s grip. The strain rate was 1 × 10⁻³s⁻¹. Cylindrical specimens with ratio of height to diameter equal to 2 were used for tests on compression with shear, and cylindrical samples 8mm diameter and 30 mm of gauge length with threaded ends and slots on the heads were used for other tests. After unloading the specimens were quenched into water.

![Figure1: Deformation paths used in experiments: 1. Compression with shear; 2. Tension; 3. Torsion; 4. Tension with cyclic torsion](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Loading</th>
<th>Effective strain</th>
<th>Strain intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No load, only temperature</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Compression with shear</td>
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<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>Tension</td>
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</tr>
<tr>
<td>3</td>
<td>Torsion</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>Tension with cyclic torsion</td>
<td>1.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table1: Characteristics of loading
The specimens were subjected to four different types of loading, deformation paths of which are shown in the Figure 1. Simple monotonic loading was represented by tension (2) and torsion (3). Proportional two-component deformation was studied in compression with shear (1). Two-component complex loading with a poly-line deformation path was done by tension with subsequent cyclic torsion (4). In the last type of tests the specimen was first stretched up to elongation of about 14 mm (gauge length 30 mm) and then subjected to cyclic torsion with a twist angle of about $\gamma \approx \pm 0.6\pi$. The values of the effective strains (Odquist parameter) and strain intensities are given in the Table 1.

To exclude the effect of temperature, in all microstructural analyses the comparison was done with respect to the microstructure of special “witness” samples.

These experiments have shown that after 2.5 cycles of cyclic torsion the microstructure of the specimens subjected to the complex loading undergo significant transformation, Fig. 2.4 (though some non-uniformity along the radius was observed due to the character of torsion loading). The grain-boundary primary $\alpha$-grains, visible in the “witness” specimen (see Fig. 2.0.) got completely globularized and randomized as well as the colonies of the primary Widmanstätten $\alpha$-laths. The mean value of the non-equiaxiality factor for the $\alpha$-phase grains has decreased from about 6-7 in the undeformed sample to about value of 3. The percentage of globular has increased from about 10% to more than 50%. It has to be mentioned, that these results are significantly better than the same for simple loadings (with the same values of strain intensity) including pure torsion, Fig. 2.1-2.3.

### 3. Model Description

The main trends observed in these experiments were used for development of the phenomenological model. The microstructure of $\alpha+\beta$ titanium alloys can have a wide range of different morphologies and due to the relatively close specific volume of the crystal cells of $\alpha$ and $\beta$ phase (0.17%, about 20 times less than for iron as shown by Anoshkin et al. (1980)) its transformations during deformation can be very complicated. Detailed modeling of these processes is not trivial and is the task of a separate investigation. The aim of this work was to use a simple internal variable model to assess the possibility of using a multi-stage production process to generate a controlled refinement of microstructure. For this purpose this analysis was limited with the only single internal parameter - effective grain size. This parameter represents rather the class of the microstructures i.e. a representative volume, than some real average microstructural value. The kinetics of microstructure transformation are also simplified and represented with only three basic modes – temperature activated grain growth, deformation induced grain growth and net grain refinement (due to all acting mechanisms). The active mode is assumed to depend on the current effective grain size and the accumulated distortion energy. The model is valid for deformation in the $\alpha+\beta$ field only (below $\beta$-transus). Mathematically it is expressed in the form of the following set of equations:
\[
\sigma = A \dot{\varepsilon}^m \exp \left( \frac{Q}{RT} \right) \left( \frac{D}{d_0} \right)^k \quad (1)
\]

\[
D = \begin{cases} 
\left( \frac{\sigma}{D} + \tau \right) \exp \left( -\frac{Q}{RT} \right) & \text{if } D \leq D_s, \\
0 \quad \text{if } D = 0.7 \quad D_s, & \text{if } D \geq D_s 
\end{cases}
\quad (2)
\]

\[
D_{gr} = D_t + D_{cr} \exp \left( -B_1 \int \sigma \cdot \dot{\varepsilon} \cdot dt \right) \quad (3)
\]

In these equations \( \sigma \) is effective stress, \( \dot{\varepsilon} \) is effective strain rate, \( T \)- temperature, \( R \)- the gas constant, \( D \) – effective grain size, \( d_0 \) initial grain size of the material used in the basic calibration experiments (normally 5-8 \( \mu m \)). Parameters \( A, m, Q \) and \( k \) are not constants, they depend on the temperature and strain rate. Their values are found from the experimental data for the different testing regimes and then interpolated. This approach gives the ability to take into account different microstructural mechanisms acting at different conditions as well as partial \( \alpha \) to \( \beta \) transformation that takes place at elevated temperatures. Parameters \( \tau, \tau_0, c, D_m, D_t, D_{cr0} \) and \( B_1 \) are constants having empirical values found from the experimental data.

The proposed model was programmed as a user subroutine via the facilities of the QForm 7 FE metal forming simulation code and used for the simulation of the behaviour of the coarse grained Ti-6Al-4V in the process of hot forming. This alloy exhibits similar behaviour to that described above for VT9.

### 4. FEM Simulation Of Hot Forming

To illustrate the idea of widening the range of manufacturing processes by using an unprepared microstructure the problem of hot forging of automobile wheel was chosen. This problem is to some extent imaginary; in practice wheels of this type are generally formed using aluminum alloys at quite different temperatures. One example of such a problem was simulated by Stebunov et al. (2007) and was used as the source of information about the forging sequence and geometry of the forged part. However the aim of the simulation described in this paper is different. It is not a question of development of a new technological process or verification of the accuracy of the model. The main purpose is to simulate and observe the main trends of predicted mechanical and microstructural behavior of the material during this sequence and to conclude whether the idea of hot forming of coarse grained material has any promising perspectives.

![Figure 3: The sequence of the technological operations used for the hot forming of the automobile wheel: a) initial billet, b) initial upset, c) primary die forming c) final die forming, Stebunov et al.](image)

The simulated process has three consecutive technological operations, shown in the Figure 3 – initial upset of the billet, primary and then final die forming. For simplicity all operations were simulated as isothermal (\( T=900\text{C} \)) with uniform friction at the contact surfaces with friction coefficient of 0.5 and Levanov coefficient of 1.25, which is representative of the standard graphite lubricant. However particular loading, thermal and friction conditions are not that much important for the current assessment study and would need to be specially analyzed in the case of development of this process for actual production.
The results of numerical simulation are shown in Figures 4 and 5. It can be seen in Fig.4 that after the first operation – a so-called “dead zone” exists (marked A) in which little refinement is predicted to occur. At the same time part B of the workpiece; that part of the material which will be shaped into the rim during the next stages, would see the refinement of the grains from about 80 to 40-50 µm. The main risk of this operation is related with the possibility of appearance of cracks at the surface of the workpiece where the mean stress is positive, (i.e. hydrostatic tension) but the plastic strain there is only about 0.5 which gives a good chance for safe deformation, otherwise this problem can be solved by changing the preform geometry and/or the temperature of the first operation.

Both operations of the die forming (Fig.5) are interesting from the viewpoint of the shaping the rim. As can be seen, the accumulated plastic strains in this area are quite high, about 300-400%, at the end of the second operation and more than 450% (at a few points even above 500%). Even though, due to the deformation, the microstructure was simultaneously refining down to 30-35 µm at the end of second operation and to 20-25 µm close to the end, specimens with such microstructure being tested in tension will hardly demonstrate 400-500% elongation. However the solution in this situation is given by the experience of Severe Plastic Deformation Processing, in which to achieve large deformations without fracture hydrostatic pressure is utilized. In the simulated case it can be observed that at all critical regions of the formed part the mean stress is negative (i.e. hydrostatic compression), which means that the tendency for crack or void formation would be inhibited.

5. Conclusion

The final microstructure distribution in the disk is shown in the Figure 6. It can be seen that it is quite non-uniform, varying from coarse-grained (50-60 µm) at the hub part and fine (30-35 µm in bulk and 20-25 µm at some surfaces) at the rim part. The question whether this is useful or otherwise from the viewpoint of operational properties would need a separate investigation. The list of various operational characteristics is quite long and their dependence on the morphology of the microstructure is sometimes not well established and in some cases even contradictive.

It may be that careful control of processing can be used to tailor properties to best effect. For example, a fine-grained microstructure in the rim can provide a higher strength and higher resilience which is important for this part of the wheel due to dynamic loading. At the same time the hub part of the wheel would normally be subject to fatigue damage. As was mentioned in investigations of Anoshkin *et al.* (1980)
and Nalla et al.(2002) a coarse grained microstructure can be suitable for slowing fatigue crack propagation. A lamellar structure also has a higher threshold stress for the initiation of crack propagation (e.g. for Ti-6Al-4V it is 260 MPa·mm^{0.5} for globular and 360 MPa·mm^{0.5} for lamellar structure Anoshkin et al. (1980)).

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References


