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Calvert, E., Pollard, J., Jackson, M. et al. (2 more authors) (2015) Determining a Flow Stress Model for High Temperature Deformation of Ti-6Al-4V. Materials Science Forum, 828-9. pp. 441-446. ISSN 0255-5476

https://doi.org/10.4028/www.scientific.net/MSF.828-829.441

Determining a flow stress model for high temperature deformation of Ti-6Al-4V

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Keywords: extrusion, titanium, modeling, thermomechanical processing, flow stress

Abstract

In some commercial titanium extrusion practices, twisting of the extrudate can occur, which can result in the need to crop the back and front end of the extruded material, thereby reducing yield and increasing material losses. Understanding more about the behaviour of material during the extrusion process, and investigating the cause of defects such as twisting by use of finite element (FE) modelling techniques could help to reduce these losses, improve the productivity of the extrusion process, and the overall quality of the material produced.

One of the most important components of FE techniques for hot deformation is the type of flow stress model that is used in the simulations. In this investigation isothermal uniaxial compression testing was performed on cylindrical specimens of Ti-6Al-4V at temperatures ranging from 950 °C to 1200°C and strain rates of 0.1 s^{-1} to 50 s^{-1}, to produce true stress against true strain and load against die travel curves which were subsequently used to develop a new specific flow stress model for use in hot deformation above the beta transus, which can ultimately be applied to the hot extrusion of Ti-6Al-4V.

From analysis of this data it was concluded that flow softening and work hardening do not occur during deformation, and that low friction conditions exist between the material and the tooling. The activation energy for deformation was found to be 193178 $J.mol^{-1}$, and the flow stress model was shown to give a good fit to the raw data at low strain rates, but this relationship broke down at higher strain rates. Finally the importance of generating a flow stress model specific to a particular operation, and set of experimental data, rather than relying on existing data available in the literature is demonstrated.

Introduction

Ti-6Al-4V is the most widely used alpha plus beta titanium alloy, with the largest end user being the aerospace sector. The alloy exhibits an optimum balance of properties, with good tensile strength, ductility, low cycle fatigue (LCF) resistance and adequate fracture toughness, and shows good workability. These properties make the alloy an ideal choice for aerospace components which require high strength and low weight, and which operate at low to moderate temperatures. The flow stress behaviour in Ti-6Al-4V below the beta transus, i.e. in the alpha plus beta region, is relatively high due to the content of the alpha phase, which has few slip systems and therefore requires more force to deform it. However, above the beta transus only the beta phase exists, which has more slip systems than the alpha phase and therefore requires less force to deform it, resulting in a lower flow stress [1]. Extrusion of Ti-6Al-4V is carried out above the beta transus, which for this alloy is around 995°C.

As Ti-6Al-4V is rarely hot worked above the beta transus, there are relatively few flow stress models that exist for hot working at these temperatures. The few that do exist are based on the Zener-Hollomon, Sellars and Tegart, and Johnson-Cook equations. Sheppard et al. [2] used the Zener-Hollomon equation to describe the behaviour of the flow stress above and below the beta transus. Braga et al. [3] used a slightly modified version of the Zener Hollomon equation to describe the behaviour of Ti-6Al-4V below the beta transus, and for pure titanium in the alpha and beta phase. Tello et al. [4] used the Sellars and Tegart equation to describe the behaviour of the alloy above the beta transus, whilst Seo et al. [5] used the Johnson-Cook equation to describe behaviour below and slightly above the beta transus.

Analysis of the methodology and experimental techniques used to generate the data from these studies show that despite the same overall form of equation used, and similar values for the parameters used, there are major differences between the flow stresses that are predicted. For example, predictions of flow stress from the Tello et al. study are three times higher than the flow stresses predicted by Braga et al. These large differences in the predictions for the flow stress illustrate how important it is to develop an accurate flow stress model, which agrees with the data gathered from whichever physical testing method is employed.

Experimental Procedure

In order to develop a high temperature flow stress model for the Ti-6Al-4V used in the extrusion process, hot isothermal axisymmetric compression testing was performed at temperatures ranging from 950°C and 1200°C, and strain rates of between 0.1 and $50 s^{-1}$ on small cylinders of the alloy in a Servotest Thermo-Mechanical Treatment Simulator (TMTS). Following deformation, the specimens were water quenched to preserve the as-deformed microstructure for further analysis.
The specimens were deformed to a strain of 0.8 to ensure deformation was at least to half the original height. The data obtained were then analysed and corrected according to the axisymmetric compression testing good practice guide [6]. A moving-average correction technique was used to filter out the effects of the velocity variation on all the specimens deformed at a strain rate of $50\ s^{-1}$. In this way, both load vs die travel and true stress vs true strain curves were generated

Results and Discussion

The true stress values calculated during analysis of the TMTS data were used to determine a flow stress model for this material, which involved obtaining values for the activation energy, Q, and other stress and temperature independent constants, A, n and α. Full details of the methodology used to do this can be found in Davenport et al. [7]. In order to calculate the activation energy, the true stress values at each strain rate and temperature for a set strain were required. For the calculation of the activation energy at a particular strain, it is necessary to fix the stress in order to create an equation in which there are only two variables, $\dot{\varepsilon}$ and T. The equation used to do this, equation 1, is a combination of the Zener-Hollomon parameter (used to relate the strain rate to the thermal activation energy) and an equation used to relate the stress to the strain rate. It was rearranged to give an equation for a straight line, which could be used to calculate the activation energy (as the activation energy is part of the gradient), equation 2

$$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n e^{-\frac{Q}{RT}} \qquad \text{Eq 1}$$

$$\ln\dot{\varepsilon}=\ln A+n\ln[\sinh(\alpha\sigma)]-\frac{Q}{RT} \qquad \text{Eq.2}$$

Where $\dot{\varepsilon}$ is the strain rate, R is the universal gas constant, 8.31, and the values A, n, α and σ are all constant. Therefore a straight line where $\ln\dot{\varepsilon}$ is on the y-axis and $\frac{1}{T}$ is along the x axis would yield a gradient of $-\frac{Q}{R}$ and a y intercept of $\ln A+n\ln[\sinh(\alpha\sigma)]$. In this way, Q can be calculated for each of the strains used in this study. In order to make the calculation of the activation energy as accurate as possible, the temperatures measured by the TMTS during deformation were averaged for each strain rate and used in the $\frac{1}{T}$ calculation.

This methodology used to calculate the activation energies at strains up to 0.8 resulted in an average activation energy for deformation over all the strain of 193178 $Jmol^{-1}$. The activation energy for self diffusion in the beta phase is given to be 152818 $Jmol^{-1}$ [2]. There is obviously a discrepancy in this value with the value measured in this report. This is likely to be due to alloying additions in the alloy which will inhibit self-diffusion, and may also be due to a change in deformation mechanism at high temperature, as the thermal energy will allow dislocations to glide and climb as well as slip.

The maximum and minimum values measured in the calculations described above for the activation energy were 301354 and 89407 $Jmol^{-1}$, which shows the extent of the variation between the activation energy for different strains and constant stress values. This highlights the need for further testing to be performed to ensure the value for the activation energy is as accurate as possible.

Calculation of additional flow stress model parameters

The value calculated for the average activation energy could then be used to calculate the values of the other parameters which make up the flow stress model: A, n and α.

The general function of the Zener-Hollomon parameter is given in equation 3

$Z=\dot{\varepsilon}e^{\frac{Q}{RT}}$ Eq.3

This can be related to the flow stress, as shown in equation 4

$Z=\dot{\varepsilon}e^{\frac{Q}{RT}}=Af(\sigma)$ Eq.4

Where A is a constant and f(σ) is a function of the flow stress, which is given by equations 5-7

$f(\sigma)=\sigma^n$ for $\alpha\sigma<0.8$ Eq.5
$f(\sigma)=e^{(\beta\sigma)}$ for $\alpha\sigma>1.2$ Eq.6
$f(\sigma)=[\sinh(\alpha\sigma)]^n$ for all values of σ Eq.7

Where β is another constant given by α/n.
The results of these calculations are shown below in Table 1

Table 1 Summary of the flow stress parameters calculated using equations 4 -7

Q / $Jmol^{-1}$	α / MPa^{-1}	n	A / s^{-1}	β
193178	0.01835	5.1214	4.768×10^7	0.094

Flow stress comparisons

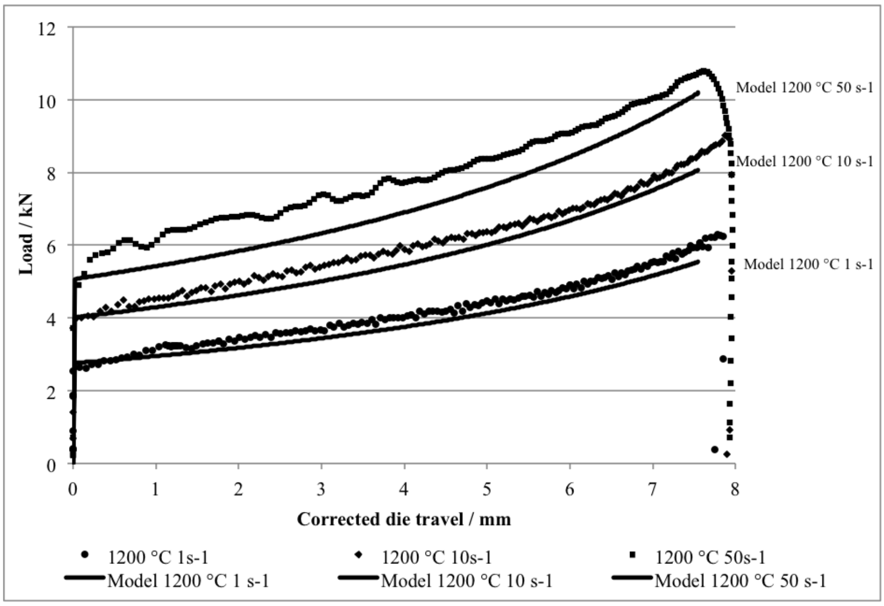

Figure 1. Graph to show the comparison between the experimental load against die travel data and the flow stress model developed in this study for a temperature of 1200°C

The flow stress model developed in this study was input into DEFORM using equation 8 below, with the values for A, α, n and ΔH being taken from Table 1

$$\dot{\bar{\varepsilon}}=A[\sinh(\alpha\bar{\sigma})]^n e^{\left(\frac{-\Delta H}{RT_{abs}}\right)} \qquad \text{Eq.8}$$

Figure 1 shows the difference between the raw data for the load against the die travel, and the load against the stroke data predicted by the flow stress model for 1200°C. The model and the raw data have good agreement at strain rates 1 s^{-1} and 10 s^{-1}, but the agreement is worse at 50 s^{-1}, with some values approximately 1 kN away from the raw data. This pattern was repeated at the other two testing temperatures, good agreement at low strain rates, and less agreement at the higher strain rates.

Overall, the flow stress model developed from the raw TMTS data appears not to correspond very well to the raw TMTS data when the model is input into a DEFORM isothermal axisymmetric compression test. This may be due to error in the activation energy value used, which was an average over all strains for all constant stress values, and could therefore have a large degree of error. The DEFORM simulation also assumed zero friction conditions, which is very unlikely to be the case in the TMTS compression testing as the Boron Nitride lubricant had quite a high friction coefficient. One final issue is that some of the data used in the flow stress model was taken at 1000 °C, which, although it may contain enough of the beta phase to have a similar flow stress to the beta phase, will not be the same and therefore introduces a level of error in the model.

Flow stress model comparison with existing literature

The flow stress model developed in this report and the flow stress previously developed for above the beta transus found in literature are shown in Table 2.

Table 1: Comparison of parameters for three of the flow stress equations above the beta transus in literature and the flow stress model developed in this report (for Tello, Gerlich and Mendez, the α value was given instead of σ_R to allow for comparison, as α is $1/\sigma_R$) [2] [3] [4]

	Model used	A / s^{-1}	ΔH or Q / $Jmol^{-1}$	n	α / MPa^{-1}
Sheppard and Norley	Zener-Hollomon	3.982×10^7	169962	4.29	0.0186
Braga, Barbosa and Breme	Zener-Hollomon	4.40×10^7	179000	4.9	0.0480
Tello, Gerlich and Mendez	Sellars-Tegart	3.92×10^6	176000	3.6	0.0213 (=1/46.9)
This model	Zener-Hollomon	4.768×10^7	193178	5.1214	0.01835

There are clear similarities in some of the values between the different papers and the flow stress model developed; the n, A and Q values are most similar to Braga, Barbosa and Breme's values but the α value is most similar to Sheppard and Norley's. This suggests that the model developed by Braga, Barbosa and Breme is the closest to the flow stress model developed in this paper.

To compare the performance of these different models in terms of flow stress against strain curves, the models were input into an isothermal axisymmetric compression DEFORM simulation using equation 8 with the values for A, α, n and ΔH being taken from Table 1.

The data for the flow stress and strain were extracted from the DEFORM load against stroke graphs, and graphs illustrating the model comparisons at 1100°C and a strain rate of 0.1 and $1s^{-1}$ are given in figure 2 below

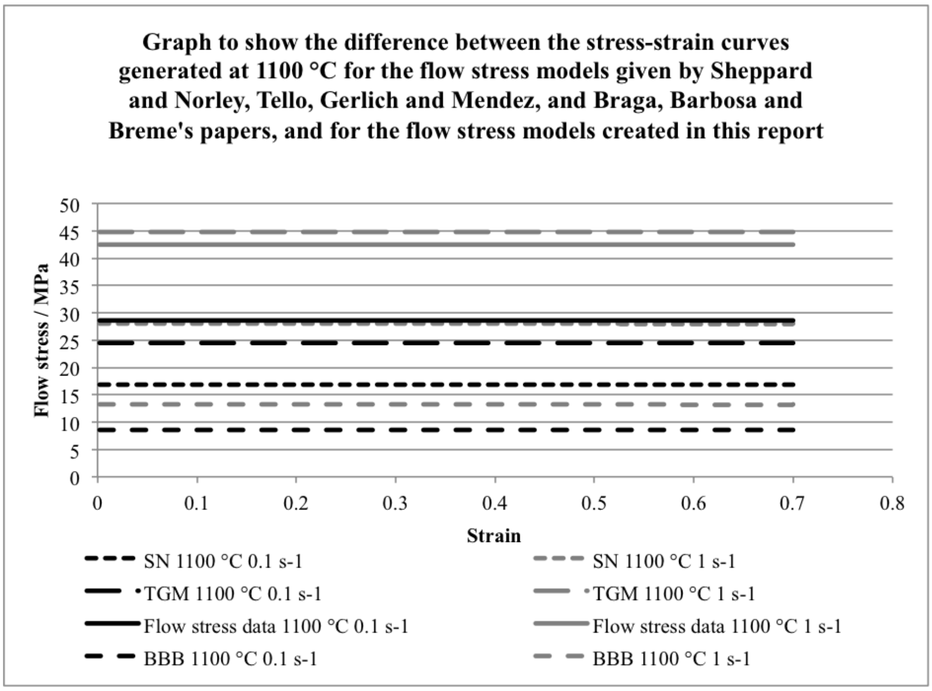

Figure 2. Graph to show the difference between the stress strain curves generated at 1100°C for the flow stress models given by Sheppard et al [2], Tello et al [4] and Braga et al [3] for the flow stress model created in this study

The data from the flow stress model generated in this report is shown by the solid lines, and is clearly closest to the model produced by Tello, Gerlich and Mendez. Although the flow stress model parameters generated in this report were very similar to the parameters generated by Braga, Barbosa and Breme, the flow stress against strain curves on the graph are very different. This may be due to the large difference in the alpha value, and illustrates how sensitive the flow stress against strain curves are to a change in only one parameter.

A similar analysis was carried out for strain rates of 10 and $50s^{-1}$. It was seem that the flow stress model generated in this report is closest to the model produced by Sheppard and Norley. Again Braga, Barbosa and Breme's model produces very different flow stress against strain curves to the curves produced by the flow stress model generated in this paper. The differences between the flow stress models in literature and the flow stress model generated in this report relate back to the specific nature of the generation of the flow stress models. The models in literature vary in terms of the test method, i.e. whether tension or compression testing was performed, and the temperatures and strain rates that the tests were performed at, and will therefore generate different flow stress models specific to their data. Although the flow stress model generated in this report does not fit the raw data as well as it could, the tests can be re-done multiple times to develop a more accurate model, which will be better than relying on other flow stress models which are not specific to the conditions experienced during this particular extrusion process with this particular alloy.

Conclusions

1. Isothermal uniaxial compression tests were performed on cylindrical specimens of Ti-6Al-4V over a range of temperatures to produce true stress against true strain curves. From this data a flow stress model for deformation above the beta transus temperature was developed
2. The activation energy for deformation of this material was found to be higher than the value for self diffusion in pure titanium beta phase. This discrepancy may be due to alloying elements and/or a change in deformation mechanism at high temperatures
3. The flow stress model generated a good fit for the raw data at lower strain rates but was less accurate at higher strain rates. This may be due to inaccuracies in the activation energy used, the frictional conditions used in the simulations, and complications arising from the use of 1000°C as a test temperature when this temperature may be below the beta transus
4. The flow stress model parameters were similar to those found in the literature, but when true stress and true strain values from these models generated by DEFORM were compared, there were large differences. This illustrates the importance of generating a flow stress model specific to the conditions used in this industrial extrusion operation, and this is where the next stage of the work will be focussed

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