Numerical simulation of the change characteristics of power dissipation coefficient of Ti-24Al-15Nb alloy in hot deformation

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Abstract. The power dissipation maps of Ti-25Al-15Nb alloy were constructed by using the compression test data. A method is proposed to predict the distribution and variation of power dissipation coefficient in hot forging process using both the dynamic material model and finite element simulation. Using the proposed method, the change characteristics of the power dissipation coefficient are simulated and predicted. The effectiveness of the proposed method was verified by comparing the simulation results with the physical experimental results.

1. Introduction

Ti-24Al-15Nb alloy have many advantages, such as low density, good oxidation resistance and high temperature performance. The material is considered to be an ideal lightweight high temperature structural material [1]. However, the structure and performance of Ti-24Al-15Nb alloy are sensitive to the hot working conditions, so it is very important to select the suitable parameters for the hot working process [2].

Dynamic material model (DMM) is an effective method to optimize material deformation process parameters, which is based on the theory of continuum mechanics, irreversible thermodynamics and physical model [3]. The dynamic material model introduces a dimensionless parameter - power dissipation coefficient. This dimensionless parameter is considered to reflect the deformation mechanism of the material [4].

The purpose of this research is to analyze the forming behavior of Ti-24Al-15Nb alloy by means of dynamic material model and numerical simulation. The power dissipation coefficient was computed based on the stress data of the tested alloy. The power dissipation maps at different strains were drawn. Then the different thermomechanical parameter regions of power dissipation coefficient are determined. The tailor-made FE codes on the top of a commercial FE software system are developed so that the thermomechanical parameter regions are built into the FE software system for simulation of the entire forming process.

2. Theory of DMM and power dissipation map

Prasad et al. assumed additionally, that the system input energy $P$ at a given temperature $T$ and strain $\varepsilon$ can be separated into two contributions: $G$, the power dissipated by temperature rise and $J$, the power dissipated by structure evolution. In the DMM, this separation can be described as [5]:

$$ P = G + J $$

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\[ P = \bar{\sigma} \bar{\varepsilon} = G + J = \int_0^\sigma \bar{\sigma} \, d\bar{\varepsilon} + \int_0^{\bar{\sigma}} \bar{\varepsilon} \, d\bar{\sigma} \]  

(1)

\( \bar{\sigma} \) and \( \bar{\varepsilon} \) are the true stress and strain rate.

The power dissipation coefficient, \( \eta \), is defined as the ratio of \( J \) and maximal \( J \), given by a linear dissipator [6]:

\[ \eta = \frac{J}{J_{\text{max}}} = \frac{2m}{1 + m} \]  

(2)

According to the change rule of \( \eta \) with temperature and strain rate, power dissipation map can be obtained. It is generally believed that the regions with high \( \eta \) often correspond to the beneficial deformation mechanisms.

3. Experimental

The nominal component of the experimental alloy is Ti-24Al-15Nb. Its \( \beta \) transus temperature is 1100 °C. The original microstructure is a mixed microstructure of \( \alpha + \beta + \gamma \) and shown in Fig. 1.

![Figure 1. The original structure of the experiment alloy](image)

The size of the compressed sample is \( \Phi 8 \times 12 \text{mm} \). The compression test was carried out by Thermecmaster-Z thermal simulator. The deforming temperature and strain rate range are 950-1350 °C and 0.001-10 s\(^{-1}\), respectively. Graphite sheets are placed at both ends of the cylindrical sample to reduce the friction coefficient. The sample is heated to the set deformation temperature, heat preservation 300s, and then deformed. The specimen after the deformation was immediately cooled to room temperature by helium quenching. All the samples were processed into metallographic samples, and then etched with a metallographic corrosion solution of 7% HF+10% HNO\(_3\)+83% H\(_2\)O.

4. Results and discussion

4.1. Flow stress behavior

Fig. 2 is the stress-strain curves of the experiment alloy under different conditions. It can be seen from Fig. 2, the true stress of Ti-24Al-15Nb alloy increases rapidly with the increase of strain at the initial stage of deformation. The main reason is that the dislocation density increases rapidly with the increase of strain at this stage. When the deformation temperature is low or the strain rate is high, the true stress decreases with the further increase of strain. It is generally believed that the flow softening is mainly caused by dynamic recrystallization, adiabatic shear or flow location. On the contrary, when the deforming temperature is high or the strain rate is low, the change of flow stress is very small. The main reason is that the processing hardening makes the material in the unstable state. It provides a driving force for dislocation movement, some dislocations disappearing and rearranging, which can offset part of the work hardening. When the strain reaches a certain value, the working hardening and flow softening reach a dynamic equilibrium, and the flow stress curve tends to be stable.
Figure 2. Stress-strain curves of Ti-24Al-15Nb alloy at strain rates of: (a) 0.01 s\(^{-1}\), and (b) 10.0 s\(^{-1}\)

4.2. Power dissipation maps
According to Eq.2, the η value at different strain, strain rate and temperature is calculated. And the power dissipation map of Ti-24Al-15Nb alloy at strains of 0.6 and 1.2 was obtained, as shown in Fig.3. The curve in Fig. 3 is the contour line of the power dissipation coefficient, and the value is the power dissipation coefficient.

As can be seen from Fig.3, the shape features of the power dissipation map are approximately similar under different strain. With the increase of strain rate and deforming temperature decreased, the η value decreases gradually. The results demonstrate that the high strain rate and low deformation temperature will lead to the deterioration of the hot workability.

The power dissipation map ((Fig.3(b)) for Ti-24Al-15Nb alloy exhibits three peak regions at the strain of 1.2: (1) The first region occurs in the temperature range 970-1010 °C and strain rate range 0.001-0.025 s\(^{-1}\) with a peak η value of 0.6 occurring at 990 °C and 0.001 s\(^{-1}\). (2) The second region occurs in 1120-1170 °C and 0.001-0.159 s\(^{-1}\) with a peak η value of 0.6 occurring at 1150 °C and 0.021 s\(^{-1}\). (3) The third region occurs in 1300-1350 °C and 0.06-1.78 s\(^{-1}\) with a peak η value of 0.65 occurring at 1350 °C and 0.167 s\(^{-1}\). It can be roughly considered that the three peak areas were the most suitable process parameters range for Ti-24Al-15Nb alloy.

Figure 3. Power dissipation maps of Ti-24Al-15Nb alloy at a strain of: (a) ε=0.6, and (b) ε=1.2

4.3. Numerical simulation and prediction of power dissipation coefficient in hot compression process
According to the flow stress data of hot compression of Ti-24Al-15Nb alloy, the power dissipation coefficient under different deformation conditions was calculated. It was developed by using Deform
3D software as a second development platform, and the thermal parameter window conditions corresponding to different power dissipation coefficient were introduced into the finite element model.

The variation and distribution of the power dissipation coefficient of Ti-24Al-15Nb alloy during hot compression are shown in Fig. 4. The upper numbers are the height reduction of the specimens. P1, P2, P3 and P4 are the identified points for the analysis of plastic deformation mechanisms at the different zones in the specimen. It can be observed from Fig. 4 that the change of \( \eta \) value is small in different regions under the same deformation condition. The power dissipation coefficient varies greatly under different process conditions.

It can be seen from Fig. 4 (a) that when the deformation condition of \((1000 \, ^\circ C, \, 1 \, s^{-1})\) and the height reduction from 17% to 70%, the change range of \( \eta \) value is 0.14-0.29. With the increase of true strain, the change of \( \eta \) value of point P3 is the most obvious. When the height reduction is 70%, the \( \eta \) value of points P2, P3 and P4 are 0.26, 0.24 and 0.27 respectively. From Fig. 4(b), it can be observed that when the specimen is compressed at \((1150 \, ^\circ C, \, 0.01 \, s^{-1})\), the change range of \( \eta \) value is about 0.38-0.70. With the increase of the height reduction, the power dissipation coefficient of the samples increases at different positions, and the increase of the points P1 and P3 is more obvious. According to the variation rule of \( \eta \) value under different thermal parameters, it can be roughly judged that the more suitable process parameter for Ti-24Al-15Nb alloy is \((1150 \, ^\circ C, \, 0.01 \, s^{-1})\) rather than \((1000 \, ^\circ C, \, 1 \, s^{-1})\).

![Figure 4](image-url)

**Figure 4.** Numerical simulation of power dissipation coefficient of Ti-24Al-15Nb alloy at different process parameters: (a) 1000 °C, 1 s⁻¹, and (b) 1150 °C, 0.01 s⁻¹.

### 4.4. Microstructures observation and verification

To verify the simulation results, optical microscopy observation was conducted on specimens compressed at different deformation condition. The results are shown in Fig. 5. When the process parameters of \((1000 \, ^\circ C, \, 1 \, s^{-1})\), the deformation microstructure of the P3 region is shown in Fig. 5(a). It is found that the microstructure is compressed along the main deformation direction and the flow localization can be observed. Fig. 5(b) is the deformation microstructure of the P3 region at a process temperature of 1150 °C and strain rate of 0.01 s⁻¹. The more subgrains can be observed in the original \( \beta \) grain under this deformation condition. This is a beneficial plastic deformation mechanism. As
shown in Fig. 3, when the deformation thermodynamic parameters are (1000 °C, 1 s−1) and (1150 °C, 0.01 s−1), the corresponding power dissipation coefficient is 0.24 and 0.66, respectively. The higher power dissipation coefficient corresponds to the suitable plastic deformation mechanism.

![Figure 5. Microstructures at central zone of specimens compressed at different process parameters: (a) 1000 °C, 1 s−1, and (b) 1150 °C, 0.01 s−1](image)

5. Conclusions
1) A method to predict the power dissipation coefficient in hot forging process is proposed using FE simulation with the built-in thermomechanical parameter windows of the different power dissipation coefficient zones determined by power dissipation maps.

2) Using the proposed method, the distribution and variation of the η value in compression of Ti–24Al–15Nb alloy is simulated at deformation conditions of (1000 °C, 1s−1) and (1150 °C, 0.01 s−1).

3) Microstructure verification showed that the results of FE simulation have a good agreement with experiments.

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