Constitutive equation and hot processing map of TA15 titanium alloy

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Abstract
The stress-strain curves of TA15 titanium alloy at 750 °C and 0.001 ~ 1 s⁻¹ were obtained by hot compression with Gleeble-1500D. Based on the compression experimental data of TA15 titanium alloy, the Johnson-Cook high temperature thermal deformation constitutive equation was established. By calculating the constitutive equation, the flow stress was compared with the measured stress-strain curve, and the accuracy of the equation was verified. Then, based on the theory of hot processing map of dynamic materials, the hot processing map is drawn when the strain is 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6. The reasonable range of hot processing map of TA15 titanium alloy was determined. When the temperature is between 750 °C–875 °C, the power dissipation factor decreases with increasing strain rate. The maximum power dissipation is distributed between 825 °C–950 °C. This indicates that recrystallization occurred within this range. The safe zone is mainly concentrated in the temperature range of 885 °C–950 °C, the strain rate is less than 0.1 s⁻¹. It can be seen that instability does not occur in the high temperature and low strain region. Therefore, at 885 °C ≤ T ≤ 950 °C, 0.001 ≤ ε ≤ 0.1 s⁻¹ or 800 °C ≤ T ≤ 875 °C, 0.001 ≤ ε ≤ 0.002 s⁻¹, it is reasonable to perform high temperature deformation on TA15 titanium alloy.

1. Introduction

TA15 titanium alloy belongs to high aluminum equivalent near α titanium alloy [1]. With the characteristics of high specific strength, low density, strong corrosion resistance and good welding performance, it was widely used in the manufacturing of wall panels, spacer frames, thin webs and other structures with complex stress in the aviation field [2]. Thus, many studies were carried out regarding the dynamic behavior of different titanium alloys [3–6]. These alloys are classified into three groups based on their phases: α, β, and α+β titanium. The α phase possesses hexagonal closed packed crystal structure. This phase is also stable at room temperature and transformed to the body-centred cubic phase, which is called β phase, at above the β transition temperature. The existence of two different crystal structures results in a wide variety of titanium alloy properties. According to processing condition, different grain sizes and morphologies of this alloy can be achieved. However, TA15 titanium alloy is sensitive to deformation temperature and strain rate in the process of forming, because the production conditions are not easy to control and there are some differences in the production result, resulting in some differences in its initial structure and mechanical properties. Gao et al [7–9] investigated the microstructure evolution (mainly including the DRX and globalization behavior) and relationship with the final tensile properties of TA15 alloy under multi-pass hot deformation. Zhang et al [10]. Studied the microstructure of hot extrusion of TA15 titanium alloy extruded tube in two different heating areas at 950 °C and 1050 °C, analyzed the influence of two different morphologies on its mechanical properties at high temperature; Yao et al [11]. Used the binary phase diagram calculation method and differential scanning calorimetry (DSC) to accurately determine the phase transition point of TA15 titanium alloy, Thermal simulation compression
The experimental material is a forged and annealed TA15 titanium alloy. Thermal simulation compression experiments, optical microscopy (OM), and quantitative analysis were used to study the β thermal deformation behavior of TA15 titanium alloy. Thermal simulation compression experiments, optical microscope (OM), and electronic backscatter diffraction Technology (EBSD) and Quantitative Analysis study the β Hot Deformation Behavior of TA15 Titanium Alloy, analyzed the influence of deformation temperature, strain rate and deformation on its flow stress and microstructure; Xi et al [12]. Studied the evolution of the microstructure of TA15 titanium alloy after superplastic deformation and the effect of deformation conditions on the superplastic deformation behavior; Xu et al [13]. Experimentally studied the compression deformation behavior and microstructure characteristics of TA15 titanium alloy under the conditions of strain rate 0.01 ∼ 20 s⁻¹ and deformation temperature 850 ∼ 1050 °C, TA15 constitutive equation was derived using Arhenius hyperbolic sine function model. Based on the dynamic material model, the hot processing map of the alloy at the true strain of 0.1 ∼ 0.7 was established. The hot processing map is very practical for studying the flow stress of materials and optimizing the parameters of heat treatment, and its practicality has been in Bstmuf601 superalloy [14], medium and high carbon high silicon bainite steel [15], as-cast 6Mo super austenitic stainless [16], S3508-Iv steel [17], 34CrNiMo6 steel [18], Fe-Mn-Al-C steel [19] and other materials have been proven.

Constitutive model is the key to the relationship between reaction rheological behavior and metal and alloy parameters [20–23]. Therefore, the flow stress, constitutive equation, hot processing map and thermal deformation structure of TA15 material under high temperature conditions should be studied. In this paper, the stress-strain experimental data of TA15 titanium alloy are obtained by hot compression experimental. Based on the experimental data, the constitutive equation and hot processing map are established. The hot deformation structure of TA15 titanium alloy is analyzed by combining with the hot processing map, which provides the basis for the research of high temperature hot deformation of TA15 titanium alloy. In general, the ideal model should be able to describe the plastic behavior of the material, such as strain rate correlation, temperature correlation, historical strain and strain rate correlation, work hardening or strain hardening behavior. However, it is extremely difficult or even impossible to fully describe all these phenomena. Therefore, many scholars introduced the necessary assumptions and tried to describe the deformation behavior as accurately as possible in a large range of strain rates and temperatures. At present, many phenomenon constitutive models have been proposed that can well represent the plastic deformation behavior of materials in a certain range. For example, Johnson–Cook (J-C) model [24], Zerilli-Armstrong model [25], Bodner-Partom model [26] and Khan-Huang model [27]. In particular, the J-C constitutive model has been widely used due to its simplicity and versatility [28–30]. In the past few decades, many scholars at home and abroad have done a lot of studies on the constitutive models of different materials. The J-C model is the first used to predict the σ of metals due to its simple form, small amount of calculation and significant reduction in the number of experiments [31–35]. However, there is a large error in the low strain rate, so Lin et al [34] used the modified J-C constitutive model to analyze the tensile stress curve of 42CrMo high-strength alloy steel under the condition of strain rate of 0.0001 ∼ 0.01 s⁻¹, and obtained satisfactory results. The maximum absolute error is only ∼ 5.15%. Tanetal [35]. The J-C model and the improved J-C model were used to observe the mechanical behavior of 7050-T7451 aluminum alloy. Two models were used to predict the stress of 7050-T7451 aluminum alloy. The prediction results show that the accuracy of the improved J-C model is significantly improved. Wang et al [36]. Investigated the dynamic behavior of Inconel 718, established σ-ε to modify the model data, and verified the accuracy of the prediction. Bobbili et al [37] respectively studied the J-C model, Khan-Huang-Liang (KHL) model and artificial neural network (ANN) model of Ti-13Nb-13Zr alloy. In order to accurately calculate the stress-strain response of materials under high temperature and large load and improve the accuracy of numerical simulation of thermal deformation process, it is necessary to seek an accurate and reasonable constitutive model of thermal deformation process [38].

In this paper, the stress-strain experimental data of TA15 titanium alloy are obtained by hot compression experimental. Based on the experimental data, the modified JC constitutive equation and hot processing map of TA15 titanium alloy are established, and the constitutive equation is verified. It provides the theoretical basis for the numerical simulation of high temperature forging and rolling process of TA15 titanium alloy.

2. Experiment

The experimental material is a forged and annealed TA15 titanium alloy. The structure of the alloy is shown in figure 1 which composed of two phases of α phase (dark area) and β phase (bright area) and the α is the main phase area. The size of the experimental material TA15 is 68 x 15, and its specifications are shown in figure 2. The main ingredients are shown in table 1. TA15 titanium alloy thermal compression experiment process flow shown in figure 3. Compression experiments on a Gleeble-1500D thermal simulator (figure 4). In order to reduce the impact of friction on the specimen during thermal compression deformation, and ensure that it can deform uniformly, paste lubricating sheets on both ends of the specimen. First, the experimental piece is heated
to a predetermined target temperature at a heating rate of 10 °C s\(^{-1}\) and held for 3 min to make the internal temperature of the TA15 experimental piece uniform, ensuring its complete austenitization. Then, perform compression experiments at the set strain rate. When the thermal compression test is completed, the high temperature test piece is cooled and quenched in water to maintain its deformed microstructure \[39, 40\]. The computer will automatically record the load and strain of the material during the experiment. Finally, Cut the sample into two halves along the longitudinal direction, and select the better 1/2 sample for mounting. Grinding on metallographic pre-grinding machine and polishing machine to prepare samples. The specific thermal simulation experimental scheme is: deformation temperature: 750, 800, 850, 900, 950 °C; degree of deformation 50%; strain rate: 0.001, 0.01, 0.1, 1 s\(^{-1}\). Use corrosive solution (HF: HNO₃: H₂O = 1: 2: 50) to corrode the sample section and observe the structure of the sample, which was examined by optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy dispersive spectrometry (EDS) operated under high vacuum condition.

Table 1. Chemical composition of TA15 titanium alloy.

| Component | Ti   | Al  | V   | Mo  | Zr  | Fe | Si  | C   | N   | H   | O  |
|-----------|------|-----|-----|-----|-----|----|-----|-----|-----|-----|----|
| W%        | allowance | 6.8 | 2.2 | 1.7 | 2.0 | 0.07 | <0.04 | 0.01 | 0.001 | 0.002 | 0.13 |

Figure 1. TA15 titanium alloy original structure.

Figure 2. Experimental material specifications.
3. Result and discussion

3.1. Stress-strain curves

3.1.1. Effect of strain rate on flow stress

Figure 5 shows the true stress-strain curves of TA15 titanium alloy at different hot deformation temperatures $T$ (750, 800, 850, 900, 950 °C). According to the experimental data, when the deformation temperature is constant, the peak stress will gradually increase with the increase of strain rate. Mainly due to the increase of the strain rate, the $\alpha$ phase dynamic recrystallization cannot be performed sufficiently, which results in an increase in the deformation resistance of the compressed specimen. At $750 \leq T \leq 900$ °C, as the strain rate decreases, the stress in the graph gradually becomes stable after reaching the peak. The main reason is that at the same deformation temperature, the decrease of thermal deformation rate leads to the increase of deformation time. Distortion and dynamic recrystallization of $\alpha$ phase after fragmentation become sufficient, more dynamic recrystallization $\alpha$ phases replace the original broken $\alpha$ phase and the $\alpha$ phase with higher dislocation density. Thus, the stress in the graph becomes more stable after thermal compression, as shown in figures 5(a)–(d). When $\varepsilon = 1$ $s^{-1}$ and $T = 950$ °C, the stress in the curve tends to be stable after reaching the peak value, It is mainly that the softening effect of $\alpha$ phase at this time is equivalent to that of work hardening, as shown in (e) in figure 5. With the increase
of temperature, the flow stress changes little, which indicates that the sensitivity of flow stress to temperature decreases.

3.1.2. Effect of deformation temperature on flow stress

When the strain rate is constant, the gradual decrease of the peak stress is related to the increase of the thermal deformation temperature of TA15 (figure 6). Mainly due to the increase in deformation temperature, more fragmented and distorted α phase reached dynamic recrystallization nucleation conditions at this time. Therefore, the α phase undergoes more sufficient dynamic recrystallization at high temperatures, which results in a reduction in the peak stress of TA15 thermal deformation. When \(0.001 \leq \varepsilon \leq 0.1 \text{s}^{-1}\), with the increase of deformation temperature, the stress gradually becomes stable after reaching the peak value. This is mainly due to the increase of deformation temperature, the dynamic recrystallization of α phase is more likely to occur at

![Figure 5. True stress-true strain curves of TA15 titanium alloy at different strain rates.](image)
higher temperature, which makes the dynamic recrystallization of α phase more sufficient at high temperature. When ε = 1 s⁻¹, 750 °C ≤ T ≤ 950 °C, with the increase of deformation temperature, the stress tends to be stable after reaching the peak value. Related research shows that the deformation resistance of TA15 titanium alloy β is smaller than that of α phase [41]. In the range of 750 °C–900 °C, there is more α phase content, and the α phase is a close-packed hexagonal lattice. Its performance is sensitive to the orientation, so the range of the flow stress value fluctuates widely, and the stress is more sensitive to the influence of temperature; Because the deformation resistance at low temperature is greater than that at high temperature, under the same strain, the deformation heat generated by low temperature deformation is higher than that generated by high temperature deformation. This is one of the reasons why the degree of softening at low temperature deformation is greater than that at high temperature deformation.

Considering that the material has different compression ratios under different experimental conditions and the applicable range of the model, the strain range used in this paper is the data of the plastic deformation and deformation stage, without considering the effect of work hardening.

### 3.2. Johnson-Cook model

#### 3.2.1. The establishment of J-C constitutive model

J-C constitutive model [42] considers the influence of large strain, strain rate and temperature on the material, and its constitutive model expression is as follows:

\[
    \sigma = A + B \varepsilon^p (1 + C \ln \dot{\varepsilon}^p)[1 - (T/T_m)\alpha]
\]  

In the equation: \(\sigma\)-flow stress (MPa); \(\varepsilon\)-true strain; \(\dot{\varepsilon}^p\)-Dimensionless strain rate parameters; \(\dot{\varepsilon}\)-strain rate (s⁻¹); \(T^*\)-relative reference temperature, \(T^* = (T - T_r)/(T_m - T_r); T_m\)-melting point of the metal; \(T_r\)-reference temperature; A, B, C, n, m-material parameters to be determined.

Select 750 °C as the reference temperature and 0.001 s⁻¹ as the reference strain rate. When the deformation temperature and strain rate are the reference temperature and the reference strain rate. The value of the last two terms in equation (1) is 1, which can be summarized as:
In the equation: A is the initial yield stress under the condition of reference temperature and reference strain rate, which can be read directly from the real stress-strain curve of quasi-static compression experimental in the experimental data, $A = 195.79 \text{MPa}$, and then take the data of strengthening section, and transform the equation (2) into the form of equation (3), equation (3) can be regarded as a straight line with slope of n and intercept of lnB. According to figure 7. Fitting the data of the enhanced segment can get: $n = -1.5645$, $B = 3.8908 \text{ MPa}$.

$$
\ln(\sigma - A) = \ln B + \ln e^n
$$

(3)

When the deformation temperature is the reference temperature, equation (1) can be rewritten as:

$$
\sigma = A + Be^n + C\ln e^n
$$

(4)

Collate available:

$$
\frac{\sigma}{(A + Be^n)} = 1 + C\ln e^n
$$

(5)

Equation (5) can be regarded as a linear equation with a slope of C and an intercept of 1. It can be seen from figure 8 that C = 0.1518 can be obtained through data fitting.

In order to further determine the size of coefficient m. Take compression data at the same strain rate and different temperatures to fit the material stress data at different temperatures. Equation (1) can be rewritten as:

$$
\ln \left[ 1 - \frac{\sigma}{(A + Be^n)(1 + C\ln e^n)} \right] = m\ln T^*
$$

(6)

As can be seen in figure 9, $m = 0.206$ can be obtained by data fitting.
By substituting the fitted $A$, $B$, $C$, $n$, $m$ into equation (1), Table 2 shows the corresponding parameters obtained of J-C constitutive model. The J-C constitutive model of the material at high temperature can be obtained:

$$
\sigma = (195.79 + 3.8908e^{-1.5645}) (1 + 0.1518 \ln \dot{\varepsilon}^*) (1 - T^{-0.206})
$$

3.2.2. Verification of J-C constitutive equation

Figure 10 shows the comparison between the calculated results of the established J-C model and the experimental results. By comparing the predicted values of the J-C model with the experimental true stress-strain curves, it is found that the established J-C model cannot well predict the flow stress of the material. Therefore, revise the established J-C model.

3.2.3. J-C model modification

The modified J-C model is shown in equation (7):

$$
\sigma = (A + B_1 \varepsilon + B_2 \varepsilon^2)(1 + \text{Cln} \varepsilon^*) \exp [(\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*) T^*]
$$

In the equation: $T^* = T - T_{\text{ref}}$, $T$-Deformation temperature; $T_{\text{ref}}$-Reference deformation temperature; $A$, $B_1$, $B_2$, $C$, $\lambda_1$, $\lambda_2$ - parameters of the material.

As the J-C model without modification, 750 °C was selected as the reference temperature and 0.001 s$^{-1}$ as the reference reaction rate. When the deformation temperature and strain rate are reference temperature and reaction rate, equation (7) is rewritten as:

$$
\sigma = A + B_1 \varepsilon + B_2 \varepsilon^2
$$

Figure 11 shows the curve of $\sigma$ with $\varepsilon$. The corresponding values of $A$, $B_1$ and $B_2$ can be obtained by parabola fitting. $A = 279.579$, $B_1 = -122.155$, $B_2 = -14.103$.

When the deformation temperature is the reference temperature, the equation (7) can obtain:

$$
\frac{\sigma}{A + B_1 \varepsilon + B_2 \varepsilon^2} = 1 + \text{Cln} \dot{\varepsilon}^*
$$

According to equation (9), $C$ is the slope, which can be obtained by fitting. As shown in figure 12, it can be concluded that $C = 0.152$.

Introduce a new parameter $\lambda$:

$$
\lambda = \lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*
$$

| A    | B    | C    | n    | m    |
|------|------|------|------|------|
| 195.79 | 3.8908 | 0.1518 | -1.5645 | 0.206 |
Rewrite equation (7) and sort it out to obtain:

\[
\ln \left[ \frac{\sigma}{(A + B_1 \varepsilon + B_2 \varepsilon^2) (1 + C \ln \varepsilon^* \varepsilon^*)} \right] = \lambda T^* \tag{11}
\]

Figure 13 is the change rule of \( \ln \left[ \frac{\sigma}{(A + B_1 \varepsilon + B_2 \varepsilon^2) (1 + C \ln \varepsilon^* \varepsilon^*)} \right] \) and \( T^* \). Take the average of the slope of the fitted straight line under different strain conditions to calculate the corresponding \( \lambda \) value. Then, the change curve of \( \lambda = \ln \varepsilon^* \) is fitted by linear regression, where \( \lambda_1 \) is intercept and \( \lambda_2 \) is slope. We can get the corresponding \( \lambda_1 \) and \( \lambda_2 \), \( \lambda_1 = -0.011, \lambda_2 = 0.001 \), as shown in figure 14. Table 3 shows the corresponding parameters obtained.
Therefore, the modified J-C constitutive equation of TA15 titanium alloy is:

\[
\sigma = (279.579 - 122.155\varepsilon - 14.103\varepsilon^2)(1 + 0.152 \ln \varepsilon^*) \exp \left[\left( -0.011 + 0.001 \ln \varepsilon^* \right)T^* \right]
\]

### 3.2.4. Verification of modified J-C constitutive equation

Figure 15 shows the comparison between the calculated results of the established modified J-C model and the experimental results. The flow stress determined by the modified J-C constitutive model is in good agreement with the experimental data. It is just that the calculation results are different from the actual data under some deformation conditions.

In order to more accurately measure the consistency between the modified J-C constitutive model and the experimental data, the correlation coefficient R and the average relative error AARE are introduced for error analysis. Correlation coefficient is a common statistical method, which is generally used to express the degree of agreement between the calculated value and the experimental value. Its mathematical expression is [43]:

\[
R = \frac{\sum_{i=1}^{N}(E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 \sum_{i=1}^{N}(P_i - \bar{P})^2}}
\]

\[
AARE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - P_i}{E_i} \right| \times 100\%
\]

In the equation: \(E_i\)—Experimental flow stress value (MPa); \(\bar{E}\)—Average value of experimental flow stress (MPa); \(P_i\)—Predicted flow stress value (MPa); \(\bar{P}\)—Predicted mean flow stress(MPa); \(N\)—number of data; The correlation coefficient R is a statistical parameter used to characterize the linear correlation between the predicted data and the experimental data. Its value varies from 0 to 1. AARE is an unbiased statistical parameter,
Table 3. Modified J-C constitutive model parameters of TA15 titanium alloy.

| $\lambda$ | $B_1$  | $B_2$  | $C$  | $\lambda_1$ | $\lambda_2$ |
|-----------|--------|--------|------|--------------|--------------|
| 279.379   | -122.155 | -14.103 | 0.152 | -0.011       | 0.001        |
which can be used to accurately measure the accuracy of constitutive equation. The error analysis results show that the correlation R between the calculated value of the flow stress model and the experimental data is 0.984, as shown in figure 16. AARE is 7.33%. Therefore, the modified J-C constitutive model established in this paper can accurately describe the rheological behavior of TA15 Titanium Alloy during hot deformation.

3.3. Hot processing map of TA15 titanium alloy
Prasad et al [44] based on the dynamic material model, the material hot processing map can directly reflect the deformation law of materials under different temperatures and strain rates, and has been successfully used in a variety of alloys [45–47]. The metal plastic deformation process contains energy storage and dissipation. The deformed workpiece can be regarded as a non-linear energy dissipator [48–50]. The model treats the afterburner equipment, mold and workpiece as a thermodynamic closed system, and considers that the energy P input to the workpiece during the process of deformation is converted into two parts: the amount of dissipation (G) and the

Figure 15. Comparison of flow stress calculation results and experimental data of TA15 titanium alloy at different temperatures.
amount of dissipation (J). Most of the dissipation (G) is converted into thermal energy, and the rest becomes lattice defect energy. The dissipation covariance (J) is the energy consumed in the process of material structure evolution. The proportion of the two can be expressed by strain rate sensitivity index m [51].

\[ m = \frac{df}{dG} = \frac{\dot{\varepsilon} d\sigma}{\sigma d\dot{\varepsilon}} = \frac{d \ln \sigma}{d \ln \dot{\varepsilon}} \]  

(14)

m = 1 represents completely linear dissipation, at which time J will obtain the maximum value \( J_{\text{max}} = P/2 \); and in the case of non-linear dissipation, a dimensionless parameter \( \eta \) is used to express the power of tissue evolution and dissipation, see the equation (15). The larger the value of \( \eta \), the larger the value of J, which means that the organization has evolved more violently; when the value of \( \eta \) is negative, the transformation of the organization has become unstable.

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

(15)

According to the extreme value principle of irreversible mechanics, if the dissipation function \( D(\dot{\varepsilon}) \) and strain rate \( \dot{\varepsilon} \) satisfy the inequality \( \frac{dD}{d\dot{\varepsilon}} \leq \frac{2}{\xi} \), then the system is unstable. A dimensionless parameter \( \xi (\dot{\varepsilon}) \) is used to represent the continuous instability criterion in large plastic deformation, as shown in equation (16).

\[ \xi (\dot{\varepsilon}) = \frac{\partial \ln \left( \frac{m}{m+1} \right)}{\partial \ln \dot{\varepsilon}} + m \]  

(16)

3.3.1. Strain rate sensitivity index m

First, \( \lg \sigma \) is expressed as a polynomial of \( \lg \dot{\varepsilon} \) (equation (17)), and then equation (18) is obtained from equation (14).

\[ \lg \sigma = a + b \lg \dot{\varepsilon} + c (\lg \dot{\varepsilon})^2 + d (\lg \dot{\varepsilon})^3 \]  

(17)

\[ m = b + 2c (\lg \dot{\varepsilon}) + 3d (\lg \dot{\varepsilon})^2 \]  

(18)

Where, a, b, c, d are the coefficients in the fitted polynomial.

Fit the third-order nonlinear relationship between stress and strain rate under different strain (0.1, 0.2, 0.3, 0.4, 0.5, 0.6) and different temperature (750, 800, 850, 900, 950 °C) in logarithmic operation (equation (17)), after the cubic spline curve is obtained, the slope at different points on the curve is solved to obtain the response surface of m value to deformation temperature, strain rate and strain response surface as shown in figure 17. It can be seen from figure 17 that the response surface under different strain conditions has undulating fluctuations, indicating the complexity of the internal deformation mechanism conversion. The change in m value may be caused by many factors. For example, during the plastic deformation of TA15 titanium alloy, various deformation mechanisms such as base slip, cylindrical slip, cone slip, and deformation twin will affect the change of m value. Therefore, the value of m cannot be used to determine the non-stable deformation area, and it needs to be further identified by combining the power dissipation coefficient and the instability criterion.

Figure 16. Correlation between predicted flow stress and experimental data by constitutive equation
3.3.2. Power dissipation coefficient $\eta$

Figure 18 shows the equivalent curve of the power dissipation coefficient $\eta$ as a function of strain, deformation temperature, and strain rate, as well as the power dissipation map, calculated using equation (14). It can be seen

Figure 17. 3D response of m value to temperature and strain rate under different strains (a) $\varepsilon = 0.1$ (b) $\varepsilon = 0.2$ (c) $\varepsilon = 0.3$ (d) $\varepsilon = 0.4$ (e) $\varepsilon = 0.5$ (f) $\varepsilon = 0.6$. 
from figure 18 that the power loss efficiency of the alloy is greatly affected by temperature and strain rate. The power dissipation coefficient is basically between 2%–54%, and the range of variation is relatively wide. When the temperature is 825 °C–900 °C, the strain rate is lower than 0.003 s⁻¹ and the temperature is 900 °C–1950 °C, the strain rate is lower than 0.1 s⁻¹ and higher than 0.01 s⁻¹, the value of η is at a higher level. When the temperature is 750 °C–875 °C, the strain rate is 0.01 s⁻¹–1 s⁻¹, the η value is mostly at a low level, and all values are less than 0.3. When the strain rate is less than 0.01 s⁻¹, the η values are all greater than 0.3. There are many reasons for the increase of η value, such as dynamic recovery, dynamic recrystallization, wedge cracking at high temperature and so on. Wedge cracking also leads to increase in power dissipation efficiency during high
temperature deformation [52]. So, the safety area cannot be determined only by the higher $\eta$ value, which needs to be further analyzed in combination with the instability criterion $\xi (\dot{\varepsilon})$ [53, 54].

### 3.3.3. Instability criterion $\xi (\dot{\varepsilon})$

Figure 19 shows the contours of the instability criterion $\xi (\dot{\varepsilon})$ values on the T and $\log(\dot{\varepsilon})$ planes, which are the instability map, calculated under equation (16) under different strains. In figure 19, the green area $\xi (\dot{\varepsilon})$ value is less than zero, which belongs to the rheological instability area, and the white area is the safety area. It can be seen from figure 19 that when the deformation temperature is 750 °C—850 °C, and the strain rate is between 0.01–0.1 s$^{-1}$, most of them are rheological instability areas. The safety area is generally concentrated in the low
strain rate area (\(<0.1\ \text{s}^{-1}\)) and the high temperature (875 °C–950 °C). The temperature is 900 °C–945 °C, the strain rate is greater than 0.1 s\(^{-1}\), they are all in the instability region.

3.3.4. Establishment of hot processing map

The hot processing map of TA15 titanium alloy with strain of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 is obtained by superposing the power dissipation map and instability map, as shown in figure 20. The region in the hot working drawing is divided into unstable region and safe region, in which the unstable region is the green shadow part, and the region outside the unstable region is the safe region [35].

**Figure 20.** Hot processing map of TA15 titanium alloy under different strain conditions (a) \(\varepsilon = 0.1\) (b) \(\varepsilon = 0.2\) (c) \(\varepsilon = 0.3\) (d) \(\varepsilon = 0.4\) (e) \(\varepsilon = 0.5\) (f) \(\varepsilon = 0.6\).
The power dissipation coefficient of TA15 titanium alloy in the process of hot deformation is expressed by the numerical value of isoline in its hot processing map. In the hot processing map, the region with the power dissipation coefficient $\eta$ higher than 0.3 is usually regarded as the high power dissipation region, and the region is regarded as the region with the best thermal deformation performance of metal materials \[56\]. When $0.3 \leq \eta \leq 0.6$, it belongs to the typical dynamic recrystallization region of TA15 \[57\]. The energy dissipation efficiency of TA15 is positively correlated with deformation temperature and inversely correlated with strain rate. Choose to deform TA15 in higher power dissipation region to improve its thermal deformation performance. When the strain of TA15 thermal deformation increases, the increase of strain has little effect on its power dissipation coefficient. When the temperature is between 750 °C–875 °C, the power dissipation factor decreases with increasing strain rate. The maximum power dissipation is distributed between 825 °C–950 °C. This indicates that recrystallization occurred within this range. As can be seen in figure 20. The safe zone is mainly concentrated in the temperature range of 885 °C–950 °C, the strain rate is less than 0.1 s⁻¹. It can be seen that instability does not occur in the high temperature and low strain region. The maximum value of $\eta$ in this region is 0.46. As shown in figure 20(d). When the strain is 0.1, the temperature is 800 °C–875 °C, and when the strain rate is less than 0.002 s⁻¹, the processing is also in a safe area, and the maximum value of $\eta$ reaches 0.58, as shown in figure 20(a). Therefore, at $885 \leq T \leq 950$ °C, $0.001 \leq \dot{\varepsilon} \leq 0.1$ s⁻¹ or $800 \leq T \leq 875$ °C, $0.001 \leq \dot{\varepsilon} \leq 0.002$ s⁻¹, it is reasonable to perform high temperature deformation on TA15 titanium alloy. Instable phenomena such as adiabatic shear bands are difficult to discern by tissue observation and low reliability of instability judged by organizational characteristics. However, if the alloy deformed in the safety area has unstable structure characteristics, the hot processing map is not correct. Therefore, in order to verify the rationality of the

Figure 21. $\dot{\varepsilon} = 0.01$ s⁻¹ metallographic structure of TA15 titanium alloy.
safety area of the hot processing map, this experiment selects the deformed alloy samples under the safe condition of hot processing to carry out the organization analysis.

3.4. Evolution of hot deformed microstructure of TA15 titanium alloy

3.4.1. Effect of deformation temperature on TA15 microstructure

The influence of deformation temperature on the microstructure must be discussed from two aspects: one is the influence of deformation temperature on the driving force for recrystallization. The increase in deformation temperature promotes the migration and diffusion of atoms, the recovery degree increases, the distortion energy stored in the metal decreases, and the driving force for recrystallization decreases; the second is the effect of deformation temperature on the recrystallization rate. The increase of deformation temperature promotes the enhancement of grain boundary migration ability, which shortens the recrystallization time, which accelerates the renucleation rate and growth \[58\].

In the hot processing map of TA15 titanium alloy, the microstructure of different deformation areas is different, so it is necessary to study the microstructure of different deformation areas. Analyze the microstructure evolution law of the sample with TA15 titanium alloy with 0.5 strain as an example. When the deformation temperature of the titanium alloy is 850 °C and the reaction rate is 0.01 s\(^{-1}\), the power dissipation coefficient is 0.24 ∼ 0.3, and in an area of instability, the primary \(\alpha\)-phase grains mainly appear in an equiaxed shape, and a small amount is elongated (figure 21(a)). When the deformation temperature is 950 °C, the power dissipation coefficient is 0.34 ∼ 0.44, the broken \(\alpha\) dynamic recrystallization is more obvious than that at 850 °C, and many broken \(\alpha\) phases form fine new \(\alpha\) phase through dynamic recrystallization (figure 21(b)). The reason for this is that during deformation at \(T = 950\ \degree\text{C}\), the nucleation rate of the \(\alpha\) phase undergoes dynamic recrystallization, and many small new \(\alpha\) phases appear on the initial \(\alpha\) phase grain boundaries. Since the subcrystals generated by the dynamic recovery tend to grow at a lower strain rate, the dynamic recovery is the most important softening mechanism.

3.4.2. Effect of deformation rate on TA15 microstructure

Figure 22 is a metallographic photograph of a TA15 alloy pattern after a hot compression experimental at a temperature of 950 °C. When the strain rate is 0.1 s\(^{-1}\), the power loss coefficient is at 0.36 ∼ 0.43. It belongs to the typical recrystallized area. It can be seen from figure 22 that the \(\alpha\)-phase grains have a significant growth trend when the strain rate decreases. This is mainly because the distortion energy increases faster when deformed at a larger strain rate, the energy required for dynamic recrystallization is sufficient, and grain refinement and equiaxion are easier to achieve. If the deformation is slow, the crystal grains tend to grow easily due to the long deformation time.

From the above analysis, it can be concluded that the hot processing map of TA15 titanium alloy plays an important role in predicting its hot deformation structure.

4. Conclusion

In this paper, the true stress-strain data of TA15 titanium alloy at temperatures of 750 ∼ 950 °C and a strain rate of 0.001 ∼ 1 s\(^{-1}\) were obtained by hot compression experimental. The Johnson-Cook constitutive model of...
TA15 titanium alloy was constructed after analysis and processing. Equation, and based on the dynamic material model, the hot processing maps of TA15 titanium alloy with strains of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 were drawn. The results show:

(1) When the temperature is within 750 ∼ 900 °C, before the peak strain is reached, as the strain increases, the stress increases rapidly; After reaching the peak strain, as the strain increases, the stress drops sharply and eventually flattens. With the increase of temperature, the flow stress decreases obviously, that is to say, the flow stress is sensitive to the temperature in this temperature range. When the temperature is 950 °C, after the peak strain is reached, there is almost no obvious downward trend in the curve, and then it enters into a gentle state. With the increase of temperature, the flow stress changes little, that is, the sensitivity of flow stress to temperature decreases. At the same strain rate, the gradual decrease of peak stress is related to the increase of hot deformation temperature of TA15, mainly due to the increase of deformation temperature, which makes more broken and distorted α phase reach the dynamic recrystallization nucleation condition at this time.

(2) Based on the results of the thermal simulation compression experimental of TA15 titanium alloy, a modified J-C constitutive model of TA15 titanium alloy is established. The flow stress calculated using the constitutive equation is compared with the experimental results, the correlation coefficient R and the average relative error AARE are introduced to analyze the modified J-C constitutive model. The correlation R between the calculated value of flow stress model and the experimental data is 0.984, and AARE is 7.33%. Therefore, the modified J-C constitutive model can accurately predict the flow stress of TA15 titanium alloy at high temperature.

(3) When the temperature is between 750 °C–875 °C, the power dissipation factor decreases with increasing strain rate. The maximum power dissipation is distributed between 825 °C–950 °C. This indicates that recrystallization occurred within this range. The safe zone is mainly concentrated in the temperature range of 885 °C–950 °C, the strain rate is less than 0.1 s⁻¹. It can be seen that instability does not occur in the high temperature and low strain region. Therefore, at 885 ≤ T ≤ 950 °C, 0.001 ≤ ̇ε ≤ 0.1 s⁻¹ or 800 ≤ T ≤ 875 °C, 0.001 ≤ ̇ε ≤ 0.002 s⁻¹, it is reasonable to perform high temperature deformation on TA15 titanium alloy.

(4) When TA15 titanium alloy is at T = 950 °C, ̇ε = 0.001 s⁻¹ and ̇ε = 0.5, the α phase undergoes dynamic recrystallization, and a small new α phase appears in the pattern structure. The nucleation rate of the α phase increases during dynamic recrystallization, and many small new α phases appear on the initial α phase grain boundaries.

Acknowledgments

This work is supported by the Project funded by China Postdoctoral Science Foundation (Grant No. 2018M641186) and also supported by the Hebei Provincial Department of Education Youth Talents Project (BJ2019010). This work is also supported by Major scientific and technological achievements into the project of Hebei province (Grant No.19012204Z)

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