A Comparative Study of Various Flow Instability Criteria in Processing Map of Superalloy GH4742

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Hot compression tests were conducted on a Gleeble-1500D thermal simulating tester. Based on the deformation behavior and microstructural evolution of superalloy GH4742, different types of instability criteria of Prasad, Gegel, Malas, Murty and Semiatin were compared, and the physical significance of parameters was analyzed. Meanwhile, the processing maps with different instability criteria were obtained. It was shown that instability did not occur when average power dissipation rate was larger than 50% in the temperature range of 1020–1130 °C, corresponding to the strain rate range of 5 × 10⁻³–3.2 × 10⁻¹ s⁻¹. The domain is appropriate for the processing deformation of superalloy GH4742.

KEY WORDS: GH4742 superalloy; Hot compression tests; Flow instability criterion; Processing map

1. Introduction

GH4742 is a typical γ⁻hardened nickel-based superalloy. In the GH4742 superalloy, total content of solution strengthening elements such as the Co, Mo, Cr is 28.63% (wt%) and total content of aging strengthening elements such as the Al, Ti, Nb is 7.63% (wt%). This alloy possesses high thermal strengthening properties and integrative properties, and has long-term working stability and excellent service performance. However, the increase of strengthening elements will lead to the increase of recrystallization temperature. Very narrow available deformation temperature range, high resistance to deformation and poor ductility are the main obstacles that restrict hot workability of the GH4742 superalloy which usually is difficult in deformation[1-4].

Processing map is a powerful tool in the design and optimization of metallic forming process. Processing map not only describes the deformation mechanisms of specific microstructures in deterministic regions but also describes the instability flow regions that should be avoided during forming process. In the meantime, optimized forming temperature and strain rates can be obtained by using the processing map. Therefore, the processing maps have been used in more than 200 alloys[5-10].

In the present work, based on the concepts of dynamic material model (DMM) proposed by Prasad[11], Gegel[12], Malas[13], Murty[14] and Semiatin[15], of which the Prasad’s criterion is derived carefully by the maximum entropy generation rate principle and big plastic deformation. However, when this criterion is put into application, it is needed that the established constitutive equation during high temperature compression deformation meets the three-order derivability of the strain rate i. Malas’s and Gegel’s criterion is derived on the basis of thermodynamics theorem and its theoretical basis is strict. However, as compared with the requirements of Gegel’s criterion in which the strain rate sensitivity exponent (m) value is a constant parameter, Malas’s criterion needs not considering m value as a constant. Entire derivation process of Murty’s criterion does not involve the problem that whether or not m value is a constant, the application scope of this criterion is the most expansive. However, during calculating power dissipation rate (η) value, the definition formula of η value must be used to solve and the calculation process is cockamamie. Semiatin’s criterion is an empirical formula derived on the basis of microstructure observation of titanium and its alloys. But as compared with other several criterions, this criterion does not take strict theoretical derivation as the basis.

In the present study, a comparison of five plastic instability criteria (including Prasad, Murty, Gegel, Malas and Semiatin) was carried out based on the hot compression experiment data of GH4742 superalloy which have important significances for the
determination and optimization of process parameters during practical production and processing of GH4742 superalloy.

2. Experimental

The chemical composition (wt%) of the GH4742 superalloy in this investigation was as follows: 0.053 C, 13.83 Cr, 9.96 Co, 4.84 Mo, 2.67 Al, 2.52 Ti, 2.44 Nb, 0.0036 B, 0.005 V, 0.20 Fe, 0.002 La, 0.0038 Ce, 0.001 S, 0.005 P and balanced Ni. Hot compression tests were performed on a Gleeble-1500D thermal simulating tester for GH4742 superalloy specimen whose dimension is Ø8 mm × 12 mm. The test temperature was in the range from 900 to 1150 °C with a temperature interval of 50 °C. The strain rate was in the range from 5 × 10⁻⁴–10 s⁻¹. The heating rate was 10 °C/s and the holding time was 3 min, and then the specimens were deformed to a true strain of 0.6 and the specimens were immediately water-cooled to room temperature after deformation ends.

The deformed specimens were sectioned parallel to the compression axis and the cutting surfaces were prepared for microstructure observation. The metallographic specimens were etched by using a solution of CuSO₄ (1.5 g) + HCl (40 ml) + C₆H₅OH (20 ml). The microstructures of the specimens were investigated by optical microscopy (OM) with OLYMPUS GX51 microscope.

3. Result and Discussion

3.1. Process map theory based on DMM

According to the theory of dissipative structures, Prasad et al. [16] believed that the energy of input system, P, can be divided into dissipative magnitude, G, and dissipative coordination magnitude, J. Its mathematical definition is as follows:

\[ P = \sigma \dot{\varepsilon} = G + J = \int_{0}^{\sigma} \delta d\varepsilon + \int_{0}^{\sigma} \dot{\varepsilon} d\sigma \]  
(1)

where G is the energy consumed by the plastic deformation of materials among which a majority of energy is turned into thermal energy and small amount of energy is stored in crystal defect energy. J is the energy dissipated during the microstructure evolution of material deformation. The proportion of two energies is determined by the strain rate sensitivity exponent, m, of forming component under definite stress:

\[ m = \partial J / \partial G = \dot{\varepsilon} d\sigma / \partial \sigma \dot{\varepsilon} = \partial \ln G / \partial \ln \dot{\varepsilon} \]  
(2)

The physical meaning of partition rate of system energy can be elucidated clearly from the viewpoint of atomic movement. The dissipation of material energy can be divided into potential energy and kinetic energy. Potential energy is related to the relative positions among atoms. The variation of microstructure will result in the variation of atomic potential energy and hence corresponds to the dissipative coordination magnitude, J. Kinetic energy is related to the movement of atoms, i.e., the movement of dislocations. Kinetic energy conversion is dissipated in the form of thermal energy and hence corresponds to dissipative magnitude, G. Differential calculus of dissipative coordination magnitude J is expressed as:

\[ dJ = i d\sigma \]  
(3)

Presuming that material conforms to constitutive relation:

\[ \sigma = C \dot{\varepsilon} \]  
(4)

Then, J is expressed as:

\[ J = \int_{0}^{\sigma} \dot{\varepsilon} d\varepsilon = m/(m + 1) \sigma \dot{\varepsilon} \]  
(5)

When \( m = 1 \), material is in an ideal linear dissipation state. Dissipative coordination magnitude J reaches the maximum value \( J_{\text{max}} \), i.e.,

\[ J_{\text{max}} = \sigma \dot{\varepsilon} / 2 \]  
(6)

A dimensionless parameter value \( \eta \) which is the power dissipation rate can be obtained by formulas (5) and (6). Its physical meaning is to elucidate the proportion relation of energy dissipated by microstructure evolution to linear dissipation energy during material forming. Its value is:

\[ \eta = J / J_{\text{max}} = 2m/(m + 1) \]  
(7)

The flow stresses at different strain rates and temperatures with a strain of 0.6 were obtained by thermal simulation compression test and the power dissipation rate map was obtained, as shown in Fig. 1.

It can be seen from Fig. 1 that when hot forming is performed in region I (temperature of 1080–1150 °C and strain rate of \( 5 \times 10^{-4}–10^{-3} \) s⁻¹), region II (temperature of 1020–1080 °C and strain rate of \( 5 \times 10^{-4}–3.2 \times 10^{-3} \) s⁻¹), the mean value of power dissipation rate of GH4742 superalloy is 54%. The maximum value is 56%.

3.2. Analysis and application of different instability criterions for GH4742 superalloy

3.2.1. Gegel’s instability criterion. Based on the second law of thermodynamics, Gegel et al. [11] found that flow instability is related to the temperature sensitivity parameter, S. The definition of S is as follows:

![Fig. 1 Power dissipation rate (η) map at different strain rates (i) and temperatures with a strain of 0.6.](image-url)
The processing map on Gegel’s instability criterion of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 2. The map is clearly classified into two domains, e.g. the stability deformation domain and instability deformation domain, the latter being the shaded part in Fig. 2.

3.2.2. Malas’s instability criterion. When Malas et al.\textsuperscript{[13]} investigated Ti–49.5Al–2.5Nb–1.1Mn alloy, they used Lyapunov function $L(\eta, s)$ and meantime replaced $\eta$ with $m$. They proposed Malas’s instability criterion on the basis of Gegel’s criterion:

$$\frac{\partial m}{\partial \ln \dot{\varepsilon}} > 0, \quad \frac{\partial m}{\partial \ln T} < 0$$  \hspace{1cm} (11)

The processing map on Malas’s instability criterion of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 3.

3.2.3. Prasad’s instability criterion. At present, when DMM method is used to solve hot working problem, Gegel’s and Malas’s instability criterions have been rarely used. Many scholars used the instability criterion established by Prasad\textsuperscript{[17]}. This kind of criterion takes the extremum principle of irreversible thermodynamics of big plastic flow and satisfies the following relation when flow instability occurs:

$$\frac{\partial D}{\partial R} < \frac{D}{R}$$  \hspace{1cm} (12)

As dissipation coordination magnitude is relevant to the microstructure evolution of metallurgical process, Prasad replaced $D$ with $J$ and got:

$$\frac{\partial J}{\partial \dot{\varepsilon}} < \frac{J}{\dot{\varepsilon}}$$  \hspace{1cm} (13)

$$\frac{\partial \ln J}{\partial \ln \dot{\varepsilon}} < 1$$  \hspace{1cm} (14)

Take logarithm on both sides of formula (5) and seek local derivation for $\ln \dot{\varepsilon}$, one gets:

$$\frac{\partial \ln J}{\partial \ln \dot{\varepsilon}} = \frac{\partial \ln (m/(m + 1))}{\partial \ln \dot{\varepsilon}} + \frac{\partial m}{\partial \ln \dot{\varepsilon}} = 1$$  \hspace{1cm} (15)

Integrating formulas (5), (14) and (15), one gets Prasad’s instability criterion:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln (m/(m + 1))}{\partial \ln \dot{\varepsilon}} + m < 0$$  \hspace{1cm} (16)

The processing map on Prasad’s instability criterion of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 4.

3.2.4. Murty’s instability criterion. It is believed that $m$ value in formula (4) of Prasad’s criterion is constant. But Indian scholar Murty et al.\textsuperscript{[18–23]} and Italian scholar Spigarelli et al.\textsuperscript{[24]} believed that for pure metal and alloy with low alloying elements, $m$ could be considered simply a constant value; while $m$ is not constant for complex alloy system. Based on this situation,

$$\frac{\partial D}{\partial R} < \frac{D}{R}$$  \hspace{1cm} (12)
Murty et al.\cite{18} derived an instability region criterion that is suitable for any stress and strain rate curve. According to the definition of \( J \) and \( \eta \):

\[
J = \int_0^\varepsilon \sigma \dot{\varepsilon} \, \mathrm{d}\varepsilon = \int_0^\varepsilon \frac{\partial\sigma}{\partial\varepsilon} \, \mathrm{d}\varepsilon = \sigma \frac{\partial\ln\sigma}{\partial\ln\varepsilon} = n\sigma
\]

(17)

\[
\eta = \frac{J}{J\text{max}} = 2\frac{J}{(\sigma\dot{\varepsilon})\text{max}} = J = \eta\sigma/2
\]

(18)

According to formula (13), one gets Murty’s instability criterion:

\[
2m < \eta
\]

(19)

The processing map on Murty’s instability criterion of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 5.

3.2.5. Semiatin’s instability criterion. Semiatin and Jonas\cite{15} put forwards the relationship of flow softening with material parameter \( \alpha, \alpha = -\gamma/m \), where \( \gamma \) is flow softening rate \( \gamma = \partial\ln\sigma/\partial\varepsilon \). The Semiatin’s flow localization criterion becomes:

\[
\alpha > 5
\]

(20)

The processing map on Semiatin’s instability criterion of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 6.

3.3. Analysis of the hot forming properties for GH4742 superalloy

The processing map on different instability criterions of the GH4742 superalloy generated at the strain of 0.6 is shown in Fig. 7.

I, II, III, IV and V five regions in Fig. 7 represent the flow instability domains under Gegel, Malas, Prasad, Murty and Semiatin five different instability criterions, respectively. It can be seen from Fig. 7 that the superposition of five flow instability criterions appears in upper left corner and lower right corner domains which are in the temperature range from 900 to 950 °C over a strain rate range from 1 to 10 s\(^{-1}\); and in the temperature range from 1130 to 1150 °C over a strain rate range from 5 \times 10\(^{-4}\) to 1.8 \times 10\(^{-2}\) s\(^{-1}\), indicating that working instability phenomenon appears in above forming domains and should be avoided during practical forming process. Flow instability phenomenon probably appears in the instability domains with less superposition of flow instability criterions. The domains with high power dissipation rate and no flow instability are appropriate for the forming.

It can be seen from Fig. 7 that the instability domains obtained by different instability criterions are different. Intersection and supplement occur among the instability domains. Therefore, when hot forming workability of GH4742 superalloy is analyzed, different instability criterions, had better be considered integratively. The instability domains of hot forming can be judged correctly by using integrative criterion.

Gegel’s criterion is derived on the basis of thermodynamics theorem and its theoretical basis is strict. Malas’s criterion is obtained by replacing \( \eta \) with \( m \) on the basis of Gegel’s criterion. It can be seen from Fig. 7 that the instability regions of these two instability criterion are basically the same. However, as compared with the requirements of Gegel’s criterion that \( m \) value is a constant parameter, Malas’s criterion needs not considering \( m \) value as a constant. Therefore, Malas’s criterion is more expansive than Gegel’s criterion. Prasad’s criterion is derived carefully by the maximum entropy generation rate principle and big plastic deformation, as compared with other criterions, the scope of instability region is the smallest, as shown in Fig. 7. As entire derivation process of Murty’s criterion does not involve
the problem that whether or not $m$ value is a constant, the application scope of this criterion is the most expansive. However, during calculating $\eta$ value, the definition formula of $\eta$ value must be used for solving and the calculation process is cockamamie. Semiatin’s criterion is an empirical formula derived on the basis of microstructure observation of titanium and its alloys. But as compared with other several criterions, this criterion does not take strict theoretical derivation as the basis, thus its scope of application is restricted greatly.

3.4. Microstructures of GH4742 alloy during hot deformation

The microstructural evolution during deformation of GH4742 superalloy is shown in Fig. 8. Fig. 8(a) shows the metallograph at a temperature of 900 °C and a strain rate of 10 s$^{-1}$. It can be seen that obvious cracks appear between $\gamma$ and $\gamma'$ phase, indicating that flow instability will appear at cracks during deformation. Fig. 8(b) shows the metallograph at a temperature of 1150 °C and a strain rate of 5 × 10$^{-3}$ s$^{-1}$. It can be seen that cracks appear at triple junction of grain boundaries. The reason is that when deformation temperature is high and strain rate is low, it is difficult for grains at grain boundary to slide during deformation. Thus stress concentration is formed at triple junction of grain boundaries. Dynamic recrystallization cannot proceed fully at 900 °C and hence the stress concentration formed at triple junction of grain boundary cannot be relaxed under high strain rate. Therefore, cracks at triple junction of grain boundary appear at high strain rate and hence flow instability appears. This phenomenon corresponds to the upper left corner and lower right corner in Fig. 7 which is the superposition of five flow instability criterions. Fig. 8(c) shows the metallograph at a temperature of 1050 °C and at a strain rate of 5 × 10$^{-2}$ s$^{-1}$. It can be seen that fine equiaxed grains exist and dynamic recrystallization occurs in this condition. The progression of dynamic recrystallization relaxes the stress concentration effectively at triple junction of grain boundary and adiabatic shear crack does not appear. The microstructure in Fig. 8(c) corresponds to the region (temperature of 1020–1130 °C and strain rate of 5 × 10$^{-4}$–3.2 × 10$^{-3}$ s$^{-1}$) and the peak value of power dissipation rate of GH4742 superalloy in Fig. 7. Thus GH4742 alloy has excellent hot forming performance under this deformation condition.

3.5. Kinetic analysis of GH4742 superalloy during hot deformation

During hot deformation, it is well accepted that the relationship between the steady-state flow stress ($\sigma$), strain rate ($\dot{\varepsilon}$) and temperature ($T$) is generally expressed in the form of an Arrhenius type rate equation:

$$\dot{\varepsilon} = A\sigma^n \exp\left(\frac{-Q}{RT}\right)$$  \hspace{1cm} (21)

where $A$ is a constant, $\sigma$ is the flow stress, $\dot{\varepsilon}$ is the strain rate, $n$ is the hardening exponent ($n = 1/m$, $m$ is the strain rate sensitivity), $Q$ is the deformation activation energy, $R$ is the gas constant, $T$ is the deformation temperature. On the basis of the stress exponent and activation energy values, the deformation mechanisms for microstructure development during deformation are identified. For this model, steady-state flow stress ($\sigma$) data at different temperatures ($T$) and strain rates ($\dot{\varepsilon}$) at a true strain of 0.6 have been used. A plot of ln$\sigma$ vs ln$\dot{\varepsilon}$ for different temperatures is shown in Fig. 9. The value of $n$ is the inverse of the slope of the line. The Arrhenius plot obtained between ln$\sigma$ and 1/$T$ for different strain rates is shown in Fig. 10. The slope of the curves and the corresponding activation energy values were
obtained from the figure and the activation energy are reported in Table 1. Based on these results, when hot forming is performed in region I (temperature of 1080–1125 °C and strain rate of 5 × 10⁻⁸–10⁻² s⁻¹) and region II (temperature of 1020–1080 °C and strain rate of 5 × 10⁻³–3.2 × 10⁻³ s⁻¹), the mean value of deformation activation energy for GH4742 superalloy is lesser, thus the alloy has excellent forming performance. The superposition of flow instability criterions, the mean value of deformation activation energy is bigger, thus the alloy has poor forming performance. The result corresponds to comparative study of various flow instability criteria in processing map of GH4742 superalloy in Fig. 7.

4. Conclusions

(1) According to power dissipation rate maps integrating several different instability criterions, appropriate forming domains of GH4742 superalloy are in the temperature range of 950–975 °C and strain rate range of 5 × 10⁻²–10⁻¹ s⁻¹, in the temperature range of 975–1125 °C and strain rate range of 5 × 10⁻³–10⁻¹ s⁻¹ and in the temperature range of 1125–1150 °C and strain rate range of 1–10 s⁻¹. Ave rage power dissipation rate in the domain (temperature range of 1020–1130 °C corresponding to the strain rate range of 5 × 10⁻²–3.2 × 10⁻³ s⁻¹) is larger than 50%.

(2) Flow instability phenomenon appears in low temperature and high strain rate domain and high temperature and low strain rate domain for the forming of GH4742. The reason is that adiabatic shear crack appears due to the stress concentr ation at triple junction of grain boundaries and excessively high temperature. Dynamic recrystallization takes place in appropriate domains and relaxes the stress concentration at triple junction of grain boundaries. Thus the alloy has excel lent forming performance in this region.

(3) Analysis and comparison of different instability criterions of GH4742 superalloy reveal that the instability domains of this alloy under different instability criterions are different. Intersection and supplement occur among the instability domains. Based on the analysis and comparison for above five types of instability criterions, computational process, and cope of application, it is recommended to use MURTY instability criterion.

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