A Comparative Study of Various Flow Instability Criteria in Processing Map of TC21 Alloy

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Hot compression tests were conducted on the Gleeble-1500D thermal simulating tester. Based on deformation behaviors and microstructural evolutions, different instability critical types of Prasad, Gogel, Malas, Murty and Semiatin were compared, and the physical significance of parameters was analyzed in this paper. Meanwhile, the obtained processing map of different instability critical. It can be got that instability critical did not occur and average power dissipation rate was larger than 50% at the temperature of 830~910°C and 850~1010°C, corresponding the strain rate of $5 \times 10^{-4} s^{-1}$ to $10^{-2} s^{-1}$ and $5 \times 10^{-4} s^{-1}$ to $10^{-2} s^{-1}$, respectively. The two areas are appropriate for the processing deformation of TC21 alloy.

Keywords: TC21 alloy, hot compression tests, flow instability criterion, processing map, dynamic recrystallization

1. Introduction

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. Meantime, optimized forming temperature and strain rates can be obtained by processing map. Therefore, the processing maps have been used in more than 200 alloys[1-5]. At present, domestic and foreign researchers only consider a instability criterion during the determination of working process. There appears little information about the workability available analyzing by combining other instability criterions.

For specific alloy, processing map theory can not only determine different deformation mechanisms in working regions but also can avoid the instability deformation regions, obtain required microstructures and properties, realize the control of microstructure and properties and hence optimize forming process parameters. When forming process parameters are optimized, it is particularly important to determine the instability region. In the present work, based on the concepts of dynamic material model (DMM) proposed by Gogel, different instability criterions of Prasad[5-9], Malas[10], Murty[11] and Semiatin[12], are applied to study on the hot compression deformation of TC21 alloy and valuable conclusions are arrived at by analyzing and comparison above instability criterions, which have important significances for the determination and optimization of process parameters during practical production and processing of TC21 alloy.

2. Processing Map Theory Based on DMM

According to theory of dissipative structures, Prasad et al[13] believed that the energy of input system $P$, can be divided into dissipative magnitude $G$, and dissipative coordination magnitude $J$. Its mathematical definition is:

$$ P = \sigma \varepsilon = G + J = \int_{\sigma}^{\sigma} \sigma d\varepsilon + \int_{\sigma}^{\sigma} \varepsilon d\sigma $$  (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,

$$ m = \frac{\partial J}{\partial G} = \frac{\partial}{\partial \sigma} \frac{\partial \varepsilon}{\partial \sigma} = \frac{\partial (\ln \varepsilon)}{\partial (\ln \sigma)} $$  (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:

$$ dJ = \varepsilon d\sigma $$  (3)

Presuming that material conforms to constitutive relation:

$$ \varepsilon = C \sigma^m $$  (4)

Then, $J$ is expressed as:

$$ J = \int_{\sigma}^{\sigma} \sigma d\varepsilon = m/(m+1) \sigma $$  (5)

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

$$ J_{max} = \sigma /2 $$  (6)

A dimensionless parameter value $\eta$ which is the power dissipation rate can be obtained by formulae (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:
\[ \eta = \frac{J}{J_{\text{max}}} = \frac{2m}{(m + 1)} \]  
(7)

The power dissipation rate maps are obtained by investigating the variation in power dissipation efficiency factor with temperature and strain rate. Because various damages such as cavity formation and wedge crack or metallurgical variation such as dynamic recovery and dynamic recrystallization during plastic deformation dissipate energy, the power dissipation map can be used to analyze the deformation mechanisms in different regions.

3. Experimental Materials and Method

Raw material was two-phase TC21 alloy which is a high strength high ductility damage tolerance type TiAl-Sn-Zr-Mo-Cr-Nb(-Ni-Si) alloy developed by Northwest Nonferrous Metallic Research Institute. Thermal simulating test was performed on Gleeble-1500D thermal-force simulation testing machine for TC21 alloy specimen whose dimension is 68mm×12mm. The test temperature was in the range from 830°C to 1010°C with a temperature interval of 30°C. The strain rate was in the range from 5×10^{-4} \text{s}^{-1} to 10s^{-1}. The heating velocity was 10°C/s and holding time was 3 min.

4. Instability Analysis of Processing Map

4.1 Power Dissipation Map of TC21 Alloy

The flow stresses at different strain rates and temperatures with a strain of 0.5 obtained by thermal simulation compression test on Gleeble-1500D thermal-force simulating testing machine were analyzed and calculated and the power dissipation map is obtained, as shown in Figure 1.

![Figure 1. Power dissipation rate map at different strain rates and temperatures with a strain of 0.5.](image)

It can be seen from Figure 1 that when hot forming is performed in region I (temperature of 830°C~930°C and strain rate of 5×10^{-4}~10^{-2} \text{s}^{-1}), region II (temperature of 980~1010°C and strain rate of 5×10^{-4}~10^{-3} \text{s}^{-1}), and region III (temperature of 950°C~990°C and strain rate of 1.5~10^{-1} \text{s}^{-1}), the mean value of power dissipation rate of TC21 alloy is 52%. The maximum value is 67%. It was reported that dynamic recrystallization would occur in the alloy when the power dissipation rate value exceeds 45%. Thus the hot deformation mechanism of this alloy in above three regions is dynamic recrystallization. Dynamic recrystallization results in grain refinement and improves greatly the plastic forming capability of this alloy. However, it is not enough only to consider power dissipation rate when plastic forming capability of this alloy is considered. The instability state of this alloy during deformation should be analyzed fully. When temperature is 950°C, the equivalent contour curves of power dissipation rate in Figure 1 vary and obvious inflection point of power dissipation rate appears. The temperature corresponding to the inflection point is just the phase transformation point of TC21 alloy. Therefore, the phase transformation point of the alloy can be judged by the power dissipation rate map.

4.2 Analysis and Application of Different Instability Criteria for TC21 Alloy

Based on the second law of thermodynamics, Glegg et al. found that flow instability is related to the temperature sensitivity parameter, s. The definition of s is as follows:
\[ S = (1/T)(\partial \ln \sigma / \partial (1/T)) = -\partial \ln \sigma / \partial \ln T \]  
(8)
Meantime, Glegg used Lyapunov function L(\eta,s). He believed that the flow stress curve is up-convex when stable flow occurs in the material. Flow stress decreases with increasing temperature, s decreases with increasing T.
\[ \partial s / \partial (\ln \eta) = -\partial (\sigma/\eta) / \partial (\ln T) \partial (\ln \eta) ) \]
\[ = -\partial m / \partial (\ln T) > 0 \rightarrow \partial m / \partial (\ln T) < 0 \]  
(9)
Thus, Glegg’s instability criterion becomes:
\[ \partial \eta / \partial (\ln \eta) > 0, \quad \partial m / \partial (\ln T) < 0 \]  
(10)
When Malas et al. investigated Ti-49, 5Al-2, 5Nb-1, 1Mn alloy, they used Lyapunov function L(\eta,s) and meantime replace \eta with m. They proposed Malas’s instability criterion on the basis of Glegg’s criterion:
\[ \partial m / \partial (\ln \eta) > 0, \quad \partial m / \partial (\ln T) < 0 \]  
(11)
At present, when DMM method is used to solve hot working problem, little use is for Glegg’s and Malas’s instability criteria. Many scholars used the instability criterion established by Prasad. This kind of criterion takes the extremum principle of irreversible thermodynamics of big plastic flow and satisfies following relation when flow instability occurs:
\[ \partial D / \partial R < D / R \]  
(12)
As dissipation coordination magnitude is relevant to the macrostructure evolution of metallurgical process, Prasad replaced D with J and got:
\[ \partial J / \partial \eta < J / \varepsilon \]  
(13)
\[ \partial (\ln J) / \partial (\ln \eta) < 1 \]  
(14)
Take logarithm on both sides of formula (5) and seek local derivation for \ln \eta, one gets:
\[ \frac{\partial (\ln \gamma)}{\partial (\ln \epsilon)} = \frac{\partial n (n/m + 1)}{\partial (\ln \epsilon)} + \frac{\partial n}{\partial (\ln \epsilon)} + 1 \]  
\[ (15) \]

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

\[ \xi = \frac{\partial n (n/m + 1)}{\partial (\ln \epsilon)} + m < 0 \]  
\[ (16) \]

It is believed that m value in formula (4) of Prasad’s criterion is constant. But Indian scholar Murty et al. [13] and Italian scholar Spigarelli et al. [19] believed that for pure metal and alloy with low alloying, m is considered simply a constant value but m is not constant for complex alloy system. Based on this situation, Murty et al. [20] derived a instability region criterion that is suitable for any stress and strain rate curve. According to the definition of J and η:

\[ J = \int_0^2 \tilde{\alpha} \, d\tilde{\alpha} \Rightarrow J/\tilde{\alpha} = \dot{\epsilon} + \alpha \partial \ln \eta/\partial \alpha \]  
\[ (17) \]

\[ \eta = J/J_{\text{max}} = 2J/(\alpha \ln \eta) \Rightarrow J/\dot{\epsilon} = \eta \alpha/2 \]  
\[ (18) \]

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

\[ 2m < \eta \]  
\[ (19) \]

Semiatin and Jonas’ put forwards the relationship of flow softening with material parameter \( \alpha \cdot \alpha = -\gamma/\eta \), where \( \gamma \) is flow softening rate \( \gamma = \partial (\ln \gamma)/\partial \eta \). The Semiatin’s flow localization criterion becomes:

\[ \alpha > 5 \]  
\[ (20) \]

Gegel, Malas, Prasad, Murty and Semiatin’s instability criterion maps are shown in Figure 2. The shadow part is flow instability region.

**Figure 2.** Instability maps through different instability criterions for TC21 alloy, \( \epsilon_0 = 0.5 \), (a) Gegel’s instability criterion; (b) Malas’s instability criterion; (c) Prasad’s instability criterion; (d) Murty’s instability criterion; (e) Semiatin’s instability criterion.

It can be seen from Figure 2 that the instability regions obtained by different instability criterions are different. Intersection and supplement occur among the instability regions. Therefore, when hot forming workability of TC21 alloy is analyzed, different instability criterions should be considered integratively. The instability regions of hot forming can be judged correctly 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 \( \gamma \) with \( m \) on the basis of Gegel’s criterion. It can be seen from Figure 2(a, b) that the instability regions of these two in-
stability criterion are basically the same. However, as compared with the requirements of Gogel’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 expensive than Gogel’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 Figure 2(c). 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 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. This criterion is very accurate when used for TC21 alloy. 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.

4.3 Microstructures of TC21 Alloy during Deformation

The optical micrographs during this process are shown in Figure 3. It can be seen from Figure 3(a-b) that the microstructure consists of \( \alpha \) phase and \( \beta \) phase. The particulate grains are equiaxed \( \alpha \) grains and the matrix is \( \beta \) phase. When amount of deformation continues to increase and reach to a certain extent, distortion energy caused by the metallic dislocation stress field accumulates to reach the energy required by dynamic recrystallization. New and small recrystallization nucleus are formed at primary grain boundary and dynamic recrystallization begins (Figure 3(a-b)). The nucleation and growth process of recrystallization are with the occurrence of plastic deformation. When dislocation density increases to a certain extent, polygonal dynamic recrystallized grains tangled by dislocations inside the deformation matrix, new dynamic recrystallization begins. With the rise of temperature, the recrystallized grain size tends to grow, \( \alpha \) phase congregates. Macroskopically, entire grain sizes increase. The higher the deformation temperature is, the more obvious the grain growth (Figure 3(c-d)).

With the rise of temperature from 830°C to 920°C, due to the existence of \( \alpha \rightarrow \beta \) phase transformation, the rise of temperature results in the increase of \( \beta \) phase. Moreover, due to the atomic diffusion, dissolution, precipitate-out and congregation of phase during phase transformation, elongated \( \beta \) phase due to deformation gradually turns into small islands distributed around \( \alpha \) grains. When temperature is high, the proportion of \( \beta \) phase increases and \( \beta \) phase becomes the matrix. Because \( \beta \) phase with body-centered crystal structure has more slip systems than \( \alpha \) phase with hexagonal centered crystal structure, some \( \alpha \) phase turns into \( \beta \) phase during deformation within the temperature range from 830°C to 920°C and \( \alpha + \beta \) two-phase alloy is formed, which plays active role in improving the plasticity of this alloy.

5. Conclusions

5.1 According to power dissipation rate maps integrating several different instability criterions, appro-
private forming regions of TC21 are temperature of 830°C ~ 910°C and strain rate of $5 \times 10^{-4} - 10^{-2}$ s$^{-1}$ and temperature of 950 ~ 1010°C and strain rate of $5 \times 10^{-4} - 10^{-3}$ s$^{-1}$.

2) The analyzing results of the hot deformation behavior and microstructure evolution of TC21 alloy reveal that dynamic recrystallization occurs in the temperature range from 830°C to 920°C over the strain rate from $5 \times 10^{-4}$ to $10^{-2}$ s$^{-1}$. Meantime, phase transformation of $\alpha$→$\beta$ occurs. Moreover, with the increase of temperature, grains grow.

3) The conclusion can be arrived at through analysis and comparison of different instability criterions of TC21 alloy that the instability regions of this alloy under different instability criterions are different. Therefore, when the workability of an alloy, especially the forming instability performance, is investigated, the integrative action of different instability criterions should be considered.

REFERENCES