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Fracture criterion for predicting surface cracking of Ti40 alloy in hot forming processes

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Abstract: Hot compression tests were conducted on Ti40 burn resistant titanium alloy in the temperature range of 900−1 100 ℃ and strain rate range of 0.01−10 s^{-1} to investigate its fracture behavior and critical fracture conditions in hot forming. It was observed that the failure of Ti40 alloy is attributed to longitudinal surface cracking due to severe oxidation of element V and the secondary tensile stresses. The critical fracture strain increases with increasing temperature and decreasing strain rate. From these observations and parallel FEM simulations, it was concluded that the critical fracture strain is a function of a single argument Zener-Hollomon parameter, and there is a linear relationship between them. An Oyane criterion successfully predicted the location of crack initiation. The critical fracture values also exhibit a liner relationship with ln$Z$. Based on these results, a new fracture criterion of Ti40 alloy based on Zener-Hollomon parameter was established.

Key words: Ti40 alloy; ductile fracture; Zener-Hollomon parameter; Oyane criterion; critical fracture value

1 Introduction

Burn resistant titanium alloy has been developed to meet the requirements of high performance gas turbines that need not only excellent mechanical properties but also good burn resistance for some key parts. Ti40 (Ti-25V-15Cr-0.2Si) alloy, a Ti-V-Cr series burn resistant titanium alloy, was developed by Northwest Institute for Nonferrous Metal Research of China in 1996[1]. Compared with other burn resistant titanium alloys, Ti40 alloy possesses better burn resistant and mechanical properties[2]. However, it is difficult to work in hot forming processes due to extensive surface and edge cracking[3]. Therefore, it is necessary to study the fracture behavior of Ti40 alloy and establish a reasonable fracture criterion to predict the crack initiation in the design stage of the process.

In the past, many fracture criteria have been developed to predict the initiation of ductile fracture. They can be broadly classified as empirical and semi-empirical criteria. The empirical criteria can either be strain based[4] which defined a fracture locus, or stress based[5−6] defined in terms of the stress formability index. The semi-empirical criteria were classified into two types: cumulative plastic energy models and void coalescence models. Some researchers treated ductile fracture from a macro-mechanical perspective, and devised some widely used failure criteria[7]. Other researchers, such as MCCLINTOCK[8] and OYANE et al[9], examined the ductile fracture through void growth phenomenon and proposed correlative failure criteria.

The criteria aforementioned have been successfully used in some cold metal forming processes. However, the extension of the fracture criteria to hot forming processes is difficult because ductile fracture is a complicated phenomenon that is dependent upon process parameters, such as stress, strain, stress states, strain rate and, particularly forming temperature. Therefore, for hot forming processes, a reliable fracture criterion should at least account for temperature and strain rate.

The objective of the present work was to establish a fracture criterion of Ti40 alloy in hot forming which may be used to predict the fracture initiation and to optimize the processing parameters. For this purpose, hot compression tests were conducted over a wide range of

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process conditions to study the fracture behavior of Ti40 alloy at a high temperature in conjunction with FEM simulation. The Zener-Hollomon parameter accounting for the combined effect of temperature and strain rate was introduced into the fracture criterion.

2 Experimental

2.1 Experimental procedures

A 40 kg Ti40 alloy ingot with a diameter of 140 mm was used in this study. Its nominal chemical composition was Ti-25V-15Cr-0.2Si. Cylindrical specimens of Ti40 alloy with 8 mm in diameter and 12 mm in length were machined from the cast ingot. Compression tests at temperatures of 900, 950, 1 000, 1 050, 1 100 ℃ and strain rates of 0.01, 0.1, 1, 10 s^{-1} have been performed on Gleeble−1500 thermo-simulator. The high strain rate (10 s^{-1}) was chosen to determine the fracture conditions in the rapid forming processes and to compare with the results from the lower strain rates. Samples were held at the test temperature for 5 min and upset to a reduction in height between 10% and 70%. Following the hot compression tests, each sample was air cooled, cleaned, measured, and visually inspected to determine the occurrence of fracture on the free surface.

2.2 Finite element analysis

Finite element method(FEM) simulations were conducted for each compression test to determine the local stress—strain history and various damage parameters. The computations were realized on IBM workstation, using the university version of commercial explicit finite element code DEFORM-3D. In simulations, flow stress data (corrected for deformation heating) were obtained from the previous investigation of hot compression behavior of Ti40 alloy and the thermophysical properties were also obtained[10].

After appropriate tuning of all the relevant input data, the computational results show a satisfactory agreement with the experiments. Subsequently, damage- parameter calculations, based on the Oyane criterion[9], were employed for free surface cracking.

3 Results and discussion

The results of this research relate to fracture observations and mechanism, critical fracture strain, the application of the conventional Oyane criterion[9] and the establishment of a new criterion for hot forming. The findings in each of these areas were discussed.

3.1 Fracture observations and mechanism

Macroscopic observations for Ti40 alloy forging trials revealed that the crack usually occurred on the free surface under the condition of faster strain rate and lower temperature. The common form is longitudinal cracking (Fig.1(a)) due to the development of circumferential stresses caused by barreling. It also exhibits "bean-curd-refuse like" cracking (Fig.1(b)) in specimen deformed at 1 100 ℃, 10 s^{-1} and 70% height reduction, indicating severe oxidation and poor workability. It is believed that the cracking of Ti40 alloy in hot forging is attributed to the oxidation of element V. ZHAO et al[11] found that the V_2O_5 would evaporate over 700 ℃ and the pores that were the results of the vaporization of V_2O_5 would be the preferred sites for crack initiation, leading to premature fracture in the ingot breakdown processes.

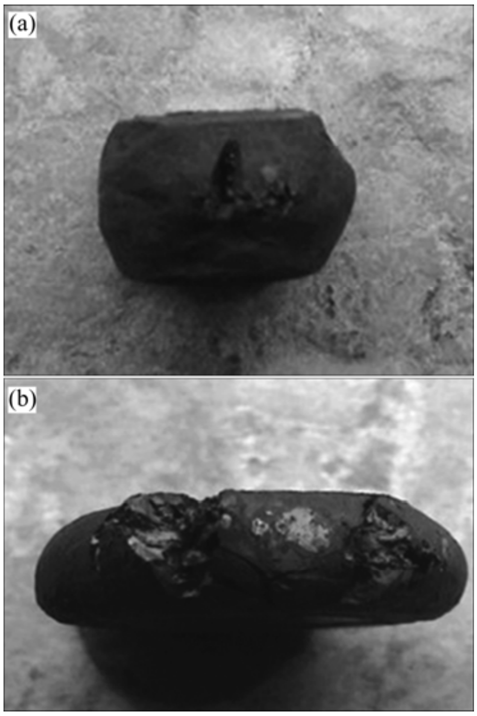

Fig.1 Cracking of Ti40 alloy in hot compression tests: (a) Longitudinal cracking, occurring at 1 050 ℃, 10 s^{-1} and 50% height reduction; (b) "Bean-curd-refuse like" cracking, occurring at 1 100 ℃, 10 s^{-1} and 70% height reduction

Therefore, it is important to prevent oxidation during the high temperature heating (e.g. plasma spraying on the surface[12]) and to reduce the circumferential stresses (e.g. extrusion and canned forging[13]) to avoid the cracking of Ti40 alloy.

3.2 Critical fracture strain in compression tests

Visual inspection of upset samples also revealed a noticeable dependence of cracking of the barreled free surface on deformed temperature, strain rate and height reduction. The critical fracture strain (ε_f), which is defined as the maximum height reduction that can be achieved in a particular metalworking process without cracking, was plotted as a function of temperature and strain rate in Fig.2. It can be seen that the critical fracture strain increases with increasing temperature and decreasing strain rate. At the nominal axial strain rates of 0.1 and 0.01 s^{-1}, all the critical fracture strains were beyond 50% and a higher strain is indicated at higher temperature. The critical fracture strain was about 70% at 1 100 ℃ and 0.01 s^{-1}. However, the critical fracture strain decreases dramatically at the higher strain rate of 10 s^{-1}.

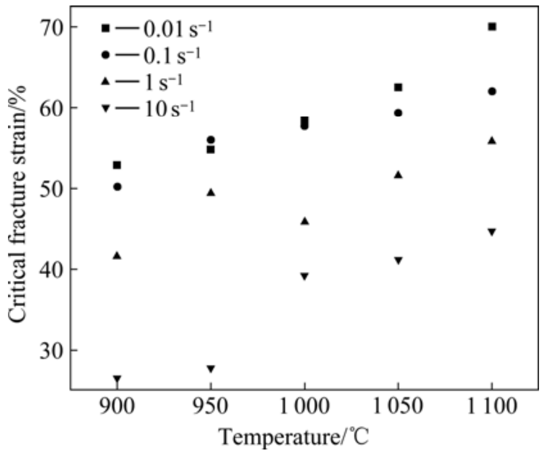

Fig.2 Fracture strain as function of temperature and strain rate

Since the Zener-Hollomom parameter(Z) accounts for a combined effect of strain rate and temperature, it was introduced to replace the two parameters. The parameter Z is defined by

$$Z=\dot{\varepsilon}\exp[Q/(RT)] \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, s^{-1}; R is the molar gas constant; Q is the activation energy; T is the absolute temperature. Since Q/R is known for each alloy[9], using Fig.2 and Eq.(1), the fracture strain may be plotted against ln Z (Fig.3). The data appear in a linear relationship, meaning that fracture is mainly controlled by ln Z rather than by temperature and strain rate separately and this observation may be useful in the computational analysis. Moreover, this linear relationship, if verified for other stress states, may significantly reduce the number of experiments needed to develop a fracture criterion. Such verification have been carried out using tension and torsion tests data on Al alloy in hot forming[14].

The fact that fracture strain is sensitive to $\ln Z$ is important for both the interpretation of experimental results and their application to simulation of metal forming processes. Nevertheless, the critical fracture strain and the relationship between fracture strain and $\ln Z$ obtained by upset tests cannot be used in other stress states directly. Therefore, fracture criteria were developed to assess ductile fracture under arbitrary stress states[15].

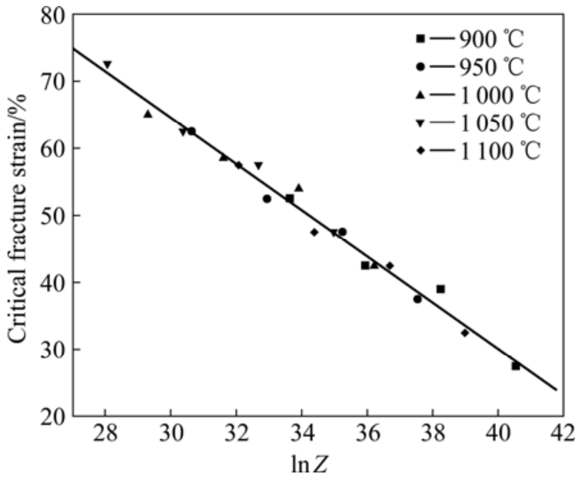

Fig.3 Fracture strain as function of $\ln Z$ and temperature

3.3 Application of Oyane criterion in hot forming

Due to the different principles and applications of various fracture criteria, it is necessary to compare their validity and make a reasonable choice. In Ref.[16], the authors performed a comprehensive theoretical and experimental analysis of the six typical fracture criteria. The conclusion was that Oyane criterion (Eq.(2)) based on the void coalescence model could be applied to compression deformation of Ti40 alloy in hot forming. It has also been successfully applied for different materials [17].

$$\int_0^{\bar{\varepsilon}_f}\left(1+\frac{\sigma_H}{A\bar{\sigma}}\right)d\bar{\varepsilon}=C \tag{2}$$

where σ_H is the hydrostatic stress; $\bar{\sigma}$ is the equivalent stress; $\bar{\varepsilon}$ is the effective strain; A=2/3[9] under the compression tests and it is the mean of 1/3 and 1 (between uniaxial and triaxial stress states). The variation of σ_H and $\bar{\sigma}$ with the effective strain $\bar{\varepsilon}$ in the complete range of upset tests was obtained by FEM simulation using DEFORM-3D.

Numerical simulation produces local values of the stress and strain components during the whole history of the deformation process. The damage value (C) of any point on the specimen can be calculated using Eq.(2) and the point with the maximum value is usually the fracture initiation site. In order to confirm the fracture initiation sites predicted by Oyane criterion, the positions of selected points for calculating the damage value are shown in Fig.4. And evaluation of the Oyane integral at various locations on the equatorial plane was performed using DEFORM-3D simulations (Fig.5). It must be noticed that the maximum occurred at the midheight of the exterior surface, which indicates that Oyane criterion can successfully predict the fracture initiation sites on the free surface, in close agreement with our experimental observations. Although some researchers suggested that fracture initiation depends upon the level of the largest principal stress (σ_1), rather than on the hydrostatic stress (σ_H), this distinction is not very important for characterizing free surface cracking, since σ_1 and σ_H usually increase or decrease simultaneously.

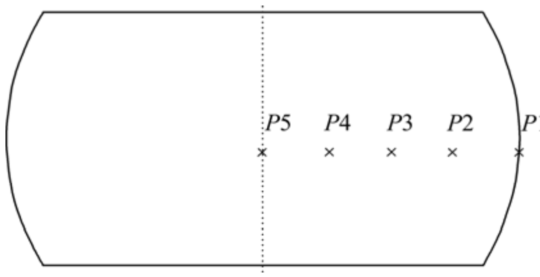

Fig.4 Schematic diagram showing positions of selected points for calculating damage value(C) using Oyane criterion

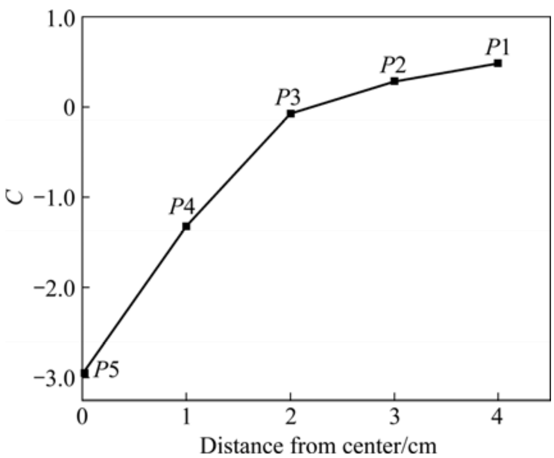

Fig.5 Distribution of damage value(C) from free surface to center of sample

The damage value obtained by Oyane criterion in cold metal forming is usually a constant. However, for hot metal forming processes, the critical fracture values increase with increasing temperature and decreasing strain rate, showing a strong dependence on compression test conditions, as shown in Fig.6. The prediction of surface cracking of Ti40 alloy by critical value (C_f) is difficult because the critical fracture value is a complex function of temperature and strain rate. Therefore, it is necessary to establish a criterion that involves temperature and strain rate at least and could easily predict the crack initiation for hot forming processes.

3.4 New fracture criterion of Ti40 alloy based on Zener-Hollomon parameter for hot forming

Similar to the analysis abovementioned, the influence of deforming temperature and strain rate on critical fracture value can also be replaced with $\ln Z$. It can be seen from Fig.7 that a linear relationship is obeyed between C_f and $\ln Z$. Its regression equation is

$$C_f=2.227-0.049\ 3\ \ln Z \tag{3}$$

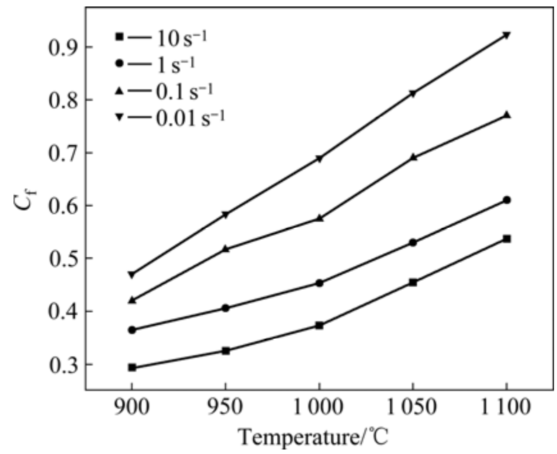

Fig.6 Critical fracture value (C_f) obtained by Oyane criterion as function of temperature and strain rate

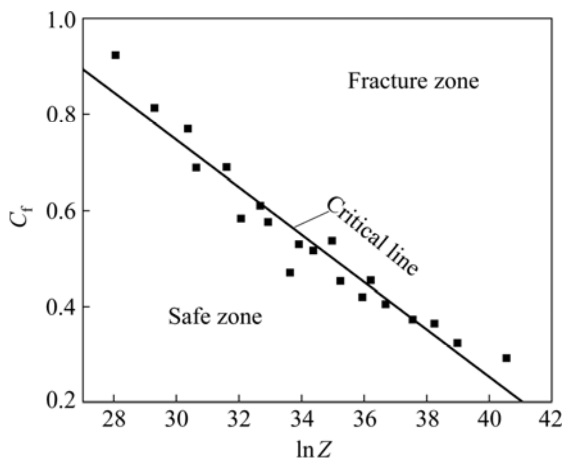

Fig.7 Relationship between $\ln Z$ and critical fracture value (C_f) of Oyane criterion

The correlation coefficient is 0.967 72 and the confidence level is high. This regression line marks the boundary between the fracture zone and the safe zone. If the damage value, obtained by FEM simulation under arbitrary deformation conditions, drops into the safe zone in the lower left quadrant, a sound product without failure will be obtained.

As a result, the Oyane criterion can be written in the form:

$$C>C_f \tag{4}$$

Viz.

$$\int_0^{\bar{\varepsilon}}\left(1+\frac{\sigma_H}{A\bar{\sigma}}\right)\mathrm{d}\bar{\varepsilon}>2.227-0.049\ 3\ln Z \tag{5}$$

Eq.(5) is the fracture criterion of Ti40 alloy in hot forming. The integration of the left-hand side is the damage that the material suffers during the plastic deformation, and the right-hand side is the critical fracture value (C_f). This criterion implies that ductile fracture is dependent not only on the stresses and the strains imposed, but also on the combined effect of temperature and strain rate in hot forming.

As we known, ductile fracture in hot forming depends on the local conditions of stress, strain, strain rate and temperature as well as processing methods, such as compression, tension, torsion, and extrusion. However, these processes can be expressed as a function of stress and strain that are the thermodynamics parameters. Therefore, the critical fracture value (C_f), obtained by simple hot compression tests, can be used to predict the facture initiation during other complex processes comparatively by FEM simulation. The introduction of such a strategy will dramatically reduce the number of experimental tests that have to be done in order to calibrate the critical values of workability models. However, this calculation is on the assumption that the critical value (C_f) is independent on the stress states. GOUVEIA et al[17] conducted upset tests for cylindrical specimens of different aspect ratios, rings, tapered, flanged and pure tension on a UNS L52905 Pd alloy at room temperature. It was found that the critical value exhibits a good correlation, with an error remaining lower than 20% for the complete set of experiments, indicating the independence of the critical fracture values on stress states. Nevertheless, further experiments are required to confirm the independence between critical fracture value and stress state in hot forming.

4 Conclusions

1) The critical fracture strain ε_f of Ti40 alloy increases with increasing temperature and decreasing stain rate. The temperature and the strain rate can be replaced by a single argument Zener-Hollomon parameter that accounts for a combined effect of them. And a linear relationship is obeyed between ε_f and $\ln Z$, therefore the number of the required experiments may be significantly reduced.

2) The Oyane criterion can successfully predict the fracture initiation sites at the midheight of the exterior surface, in good accordance with experimental observation.

3) The critical fracture value (C_f) calculated by Oyane criterion increases with increasing temperature and decreasing strain rate, and C_f and $\ln Z$ also exhibit a linear relationship. Eventually, the fracture criterion of Ti40 alloy in hot forming is

$$\int_0^{\bar{\varepsilon}} \left(1 + \frac{\sigma_H}{A\bar{\sigma}}\right) d\bar{\varepsilon} > 2.227 - 0.049\,3 \ln Z.$$

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