JOURNAL OF MATERIALS SCIENCE **29** (1994) 1217–1221

Types of superplastic m–δ curves of Ti–6Al–4V alloy and their intertransformation

CHIN LIU, DI CHANG
Department of Materials Science, Shanghai Jiaotong University, Shanghai 200030, People's Republic of China

HUANG LI-PING
Shanghai Research Institute of Iron and Steel, Shanghai 200940, People's Republic of China

The superplastic m–δ curves of Ti–6Al–4 alloy have been determined at different temperatures and strain rates; all were of the $m_L = m_{max}$ type, and were of either fundamental, descending or ascending types. The latter two types were transformed from the former through the processes of $m_L \rightarrow m_O$, $\delta_L \rightarrow \delta_O$ and $m_L \rightarrow m_F$, $\delta_L \rightarrow \delta_F$, respectively. The highest total elongation, δ_F, was 1150% obtained at 950 °C and $1.55 \times 10^{-3}\ s^{-1}$. The Chin Liu equation has been applied to all types of m–δ curves. The parameters characteristic of all types of m–δ curves have been obtained and were found to vary with temperature and strain rate. The total elongation, δ_F, is determined by the resultant effects of all other parameters, not by a single m value, theoretically considered to be constant and determined practically by a tensile strain of about 30%–50% ($m_{30\%-50\%}$) as usual.

1. Nomenclature

C	($= k/k_O$) the normalized slope of m–δ curve corresponding to δ
k	a material constant corresponding to δ
m	strain-rate sensitivity index corresponding to δ
m_{max}	maximum on the m–δ curve corresponding to δ_L
m_{min}	minimum on the m–δ curve corresponding to δ_L
v	crosshead speed during the tensile test
δ	the strain of the entire stretching process (has same significance as ordinarily adopted ε)
δ_F	total elongation at fracture chosen for the present work
δ_I	intermediate strains including δ_{I1}, δ_{I2}, δ_{I3}, ..., $\delta_{I(i-1)}$, δ_{Ii}, $\delta_{I(i+1)}$, ..., chosen for the present work
δ_L	"limit" strain separating m–δ curves into sections
δ_O	($= 0$) starting strain
$\dot{\varepsilon}$	strain rate
σ	flow stress

2. Introduction

With high strength, low specific gravity, high temperature and corrosion resistance, the Ti–6Al–4V alloy is an important material widely used in the aeronautical industry. Unfortunately, it is very hard to form owing to its poor plasticity. Therefore, development of its superplasticity has been an interesting topic for superplastic research.

The superplastic total elongation, δ_F, of Ti–6Al–4V alloy determined was 1000% in certain cases, and 2000% in others [1, 2]. However, the strain-rate sensitivity index of flow stress, m, varied from 0.46–0.88 according to the tensile testing strains adopted. Evidently, it is impossible to relate them to the total elongation, δ_F [3].

On the other hand, Boyer and Magnuson [4] also found that the value of m of Ti–6Al–4V alloy was strain-dependent. Two examples were given in their paper. One showed that m decreased from 0.74 to 0.7 with increase in strain from 10.52% to 111.7% and a descending type of m–δ curve was formed. The other example showed that m increased from 0.35 to 0.55 with increase in strain from 16.183% to 285.74% and an ascending type of m–δ curve was formed [4].

It is predictable that the superplastic m–δ curves should also be of different types under different conditions and can be classified according to the Chin Liu classification [5, 6]. The Chin Liu classification of m–δ curves and their intertransformation is shown in Fig. 1. They can all be expressed by the following Chin Liu equation [5–8]

$$\delta = [C\dot{\varepsilon}^{(m-m_O)} - 1] \times 100\% \tag{1}$$

which can be rearranged for calculating C values as follows

$$C_O = (0.01\ \delta_O + 1)\ \dot{\varepsilon}^{(m_C - m_O)} = 1 \tag{2a}$$

$$C_L = (0.01\ \delta_L + 1)\ \dot{\varepsilon}^{(m_O - m_L)} \tag{2b}$$

$$C_F = (0.01\ \delta_F + 1)\ \dot{\varepsilon}^{(m_C - m_F)} \tag{2c}$$

0022-2461 © *1994 Chapman & Hall*

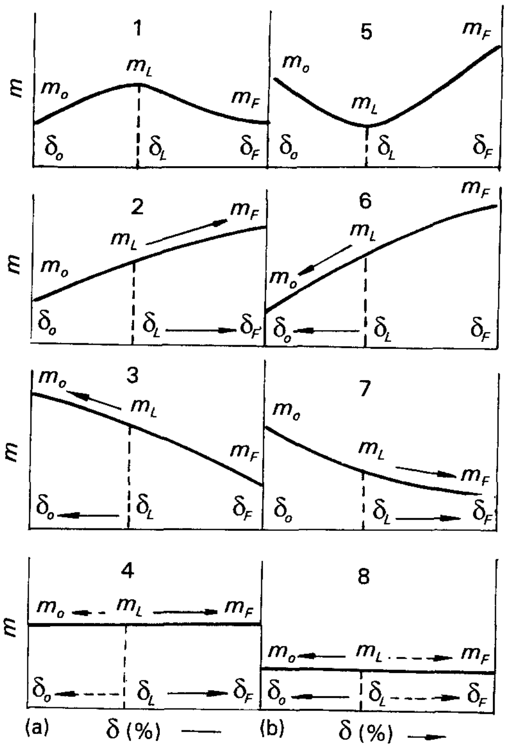

Figure 1 Chin Liu classification of superplastic m–δ curves. (a) $m_L = m_{max}$ type. (b) $M_L = M_{min}$ type.

Finally, all the parameters characteristic of the m–δ curves can be obtained as follows.

1. The fundamental type: δ_F, δ_F, m_F, m_L, m_O, C_F ($= k_F/k_O$) and C_L ($= k_L/k_O$): the m_L value is maximum or minimum among the three m values, depending upon the type of curve they belong to.
2. The ascending type: δ_F, m_F, m_O and C_F ($= k_F/k_O$), ($m_O < m_F$).
3. The descending type: δ_F, m_F, m_O and C_F ($= k_F/k_O$), ($m_O > m_F$).
4. The horizontal type: δ_F, m_F, (or m_O) and C_F ($= k_F/k_O$).

It can be seen that the m_O, m_L, m_F, C_L and C_F values should be representative of the m and k values characteristics of the fundamental equation, $\sigma = k\dot{\varepsilon}^m$. The δ_L value can affect these two values and its effects are indirect.

The static (or indirect) and dynamic (or direct) effects of both m and k values on the superplastic total elongation, δ_F, have been discussed in detail and need not be repeated here [6]. The total elongation, δ_F, should be determined by the resultant effects of all other parameters characteristic of the m–δ curves or the m and k values, but *not* by a single m value theoretically considered to be a constant and determined practically with a tensile strain of about 30%–50% ($m_{30\%-50\%}$) as is usual [9].

It has been explained that the individual effects exerted by the parameters characteristic of the m–δ curve or the m and k values may be favourable or unfavourable (strain-rate softening or hardening effect). The very high total elongation can be obtained because of the fact that the favourable effects must be very prominent.

The purposes of this research were to determine the m–δ curves of Ti–6Al–4V alloy under different conditions and to understand their intertransformation. The Chin Liu equation was applied to the curves so that all the parameters characteristic of the m–δ curves determined could be obtained. Therefore, the same conclusion can then be drawn for the Ti–6Al–4V alloy as for other materials [6, 10–14].

3. Experimental procedure

3.1. Material

The test material contained 5.8% Al, 4.10% V, 0.143% O, 0.01% N, 0.02% C, 0.22% Fe and the balance titanium. It was preliminarily hot-rolled at 930 °C and further rolled to 19 mm rod at 750–800 °C. The tensile specimen is shown in Fig. 2. The microstructure is composed of α and β phases with a grain size of 92 μm which is known to be suitable for producing superplasticity in this material.

3.2. Determination of m–δ curves

On the tensile testing machine, a series of $m(m_I)$ values, corresponding to a series of strains, δ (δ_I), were determined by the velocity change method developed by Backofen *et al.* [15]. Then an m–δ curve could be constructed. The M_O values could only be determined by the extrapolation method from the experimental m–δ curve, as were the m_F values, because it was very difficult to change the velocity when the specimen was stretched nearly to fracture.

On the testing machine, only a constant cross-head speed, v, could be maintained; however, for the following experiments it was necessary to have a constant strain rate, $\dot{\varepsilon}$. Therefore, some remedial measures were adopted with very satisfactory results [5, 8]. In this research, the mean value method was adopted.

4. m–δ curves, their intertransformation and the application of the Chin Liu equation

All m–δ curves determined were of the $m = m_{max}$ type and could be fundamental, ascending or descending types, depending upon the experimental conditions adopted. The latter two were transformed from the first one according to the definite rule mentioned above. The Chin Liu equation was applied to the curves to calculate the C values.

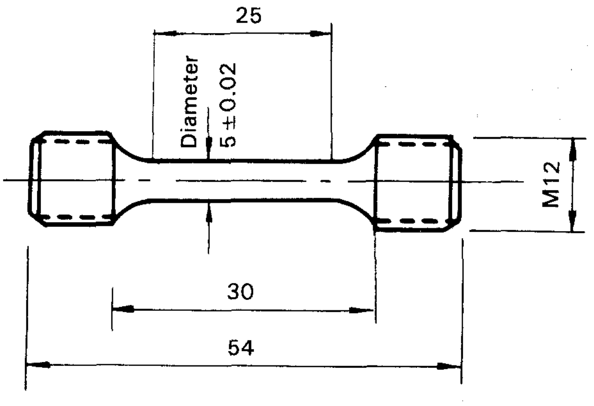

Figure 2 The specimen

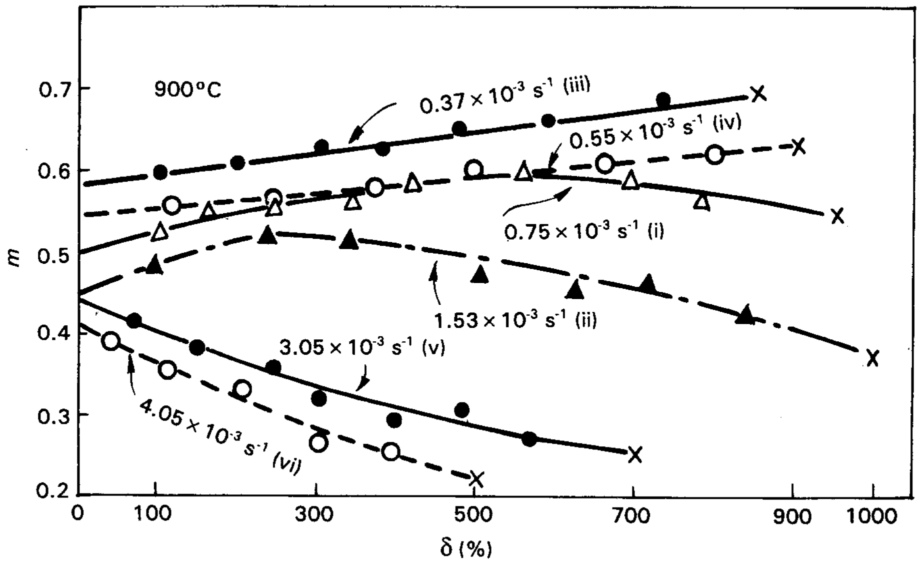

Figure 3 Effect of strain rate on the superplastic *m* curves of Ti–6Al–4V alloy.

(a) At $T = 900\,^\circ\text{C}$ and $\dot{\varepsilon} = 0.37 \times 10^{-3}$–$4.05 \times 10^{-3}\,\text{s}^{-1}$, six m–δ curves (i–vi) were determined as follows (Fig. 3).

1. When intermediate strain rates were used, the curves were of the fundamental type with $m_\text{L} = m_\text{max}$.

(i) At $\dot{\varepsilon} = 0.75 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.50) < m_\text{L}(=m_\text{max}=0.6) > m_\text{F}(=0.55) \tag{3a}$$

$$\delta_\text{O}(=0) < \delta_\text{L}(=560\%) < \delta_\text{F}(=950\%) \tag{3b}$$

$$C_\text{O}(=1) < C_\text{L}(=14.56) < C_\text{F}(=15.05) \tag{3c}$$

(ii) At $\dot{\varepsilon} = 1.55 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.45) < m_\text{L}(=m_\text{max}=0.53) > m_\text{F}(=0.38) \tag{4a}$$

$$\delta_\text{O}(=0) < \delta_\text{L}(=240\%) < \delta_\text{F}(=1000\%) \tag{4b}$$

$$C_\text{O}(=1) < C_\text{L}(=5.71) < C_\text{F}(=6.69) \tag{4c}$$

We can see that the position of the curve is raised and the values of m_L and δ_L are increased with decrease in strain rate.

2. When the strain rates were lower than $0.75 \times 10^{-3}\,\text{s}^{-1}$, the curves were of the ascending type with $m_\text{L} = m_\text{max}$.

(iii) At $\dot{\varepsilon} = 0.37 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.59) < m_\text{L}(=m_\text{max}) \rightarrow m_\text{F}(=0.7) \tag{5a}$$

$$\delta_\text{O}(=0) < \delta_\text{L} \rightarrow \delta_\text{F}(=850\%) \tag{5b}$$

$$C_\text{C}(=1) < C_\text{L} \rightarrow C_\text{F}(=22.66) \tag{5c}$$

(iv) At $\dot{\varepsilon} = 0.55 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.55) < m_\text{L}(=m_\text{max}) \rightarrow m_\text{F}(=0.63) \tag{6a}$$

$$\delta_\text{O}(=0) < \delta_\text{L} \rightarrow \delta_\text{F}(=900\%) \tag{6b}$$

$$C_\text{O}(=1) < C_\text{L} \rightarrow C_\text{F}(=18.23) \tag{6c}$$

They were formed due to the decrease in strain rates from the processes of $m_\text{L} \rightarrow m_\text{F}$ and $\delta_\text{L} \rightarrow \delta_\text{F}$. The position of the curve with lower strain rate is higher than that with higher strain rate. This is in accordance with the results obtained above.

3. When the strain rates were higher than $1.55 \times 10^{-3}\,\text{s}^{-1}$, the curves were of the descending type with $m_\text{L} = m_\text{max}$.

(v) At $\dot{\varepsilon} = 3.05 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.44) \leftarrow m_\text{L}(=m_\text{max}) > m_\text{F}(=0.25) \tag{7a}$$

$$\delta_\text{O}(=0) \leftarrow \delta_\text{L} < \delta_\text{F}(=700\%) \tag{7b}$$

$$C_\text{O}(=1) \leftarrow C_\text{L} < C_\text{F}(=2.66) \tag{7c}$$

(vi) At $\dot{\varepsilon} = 4.05 \times 10^{-3}\,\text{s}^{-1}$

$$m_\text{O}(=0.41) \leftarrow m_\text{L}(=m_\text{max}) > m_\text{F}(=0.22) \tag{8a}$$

$$\delta_\text{O}(=0) \leftarrow \delta_\text{L} < \delta_\text{F}(=500\%) \tag{8b}$$

$$C_\text{O}(=1) \leftarrow C_\text{L} < C_\text{F}(=2.11) \tag{8c}$$

They were formed due to the increase in strain rates from the processes of $m_\text{L} \rightarrow m_\text{O}$ and $\delta_\text{L} \rightarrow \delta_\text{O}$ of the fundamental type of curve. Similarly, the position of the curve with lower strain rate is higher than that with higher strain rate. This is again in accordance with the results obtained above.

(b) At $\dot{\varepsilon} = 1.55 \times 10^{-3}\,\text{s}^{-1}$ and $T = 750$–$950\,^\circ\text{C}$, five curves have been determined (Fig. 4).

1. When the intermediate temperatures were used, the curves were of the fundamental type with $m_\text{L} = m_\text{max}$.

At $T = 800\,^\circ\text{C}$

$$m_\text{O}(=0.38) < m_\text{L}(=m_\text{max}=0.5) > m_\text{F}(=0.28) \tag{9a}$$

$$\delta_\text{O}(=0) < \delta_\text{L}(=150\%) < \delta_\text{F}(=850\%) \tag{9b}$$

$$C_\text{O}(=1) < C_\text{L}(=5.43) > C_\text{F}(=4.97) \tag{9c}$$

At $T = 850\,^\circ\text{C}$

$$m_\text{O}(=0.46) < m_\text{L}(=m_\text{max}=0.55) > m_\text{F}(=0.28) \tag{10a}$$

$$\delta_\text{O}(=0) < \delta_\text{L}(=390\%) < \delta_\text{F}(=900\%) \tag{10b}$$

$$C_\text{O}(=1) < C_\text{L}(=8.77) > C_\text{F}(=4.02) \tag{10c}$$

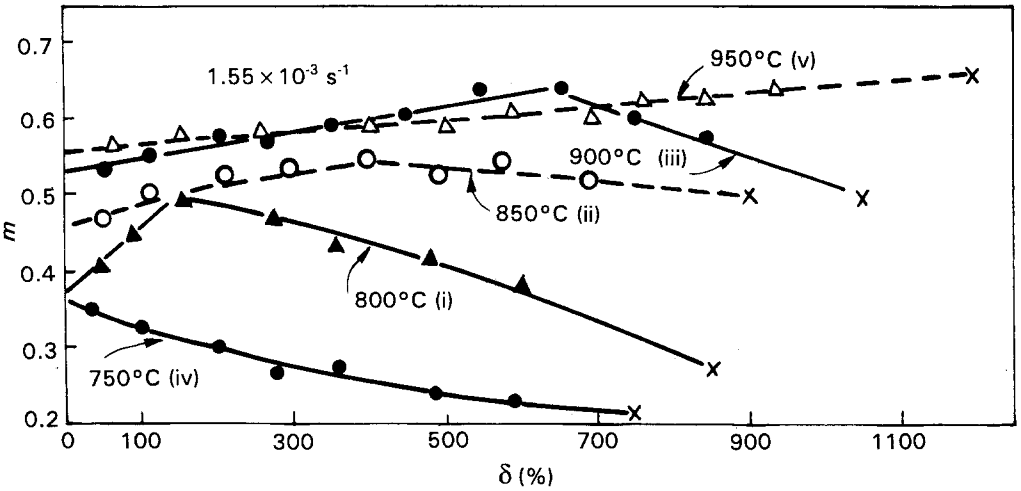

Figure 4 Effect of temperature on the superplastic m–δ curves of Ti–6Al–4V alloy.

At $T = 900\,°\mathrm{C}$

$$m_O(=0.54) < m_L(=m_{\max}=0.64) > m_F(=0.50) \qquad (11a)$$

$$\delta_O(=0) < \delta_L(=650\%) < \delta_F(=1050\%) \qquad (11b)$$

$$C_O(=1) < C_L(=14.32)\ C_F(=8.88) \qquad (11c)$$

We can see that the position of the curve is raised and the values of m_L and δ_L are increased due to the increase in temperature.

2. When the temperature was at the lower limit of the above range (750 °C), the curve was of the descending type with $m_L = m_{\max}$

$$m_O(=0.36) \leftarrow m_L(=m_{\max}) > m_F(=0.22) \qquad (12a)$$

$$\delta_O(=0) \leftarrow \delta_L \dot{<} \delta_F(=750\%) \qquad (12b)$$

$$C_O(=1) \leftarrow C_L < C_F(=3.44) \qquad (12c)$$

which was formed from the processes of $m_L \rightarrow m_O$ and $\delta_L \rightarrow \delta_O$ of the fundamental type of curve.

3. When the temperature was at the upper limit of the above range (950 °C)

$$m_O(=0.56) < m_L(=m_{\max}) \rightarrow m_F(=0.67) \qquad (13a)$$

$$\delta_O(=0) < \delta_L \rightarrow \delta_F(=1150\%) \qquad (13b)$$

$$C_O(=1) < C_L \rightarrow C_F(=25.47) \qquad (13c)$$

which was formed from the processes of $m_L \rightarrow m_F$ and $\delta_L \rightarrow \delta_F$ of the fundamental type of curve.

The magnitude of C_F can then be discussed as follows. From Equations 2a–c, we can see that the higher the δ_F value, the higher will be the C_F value. In the case of the ascending type of m–δ curve, the value of $(m_F - m_O)$ is positive, thus the higher the m_F value, the higher will be the C_F value. Therefore, we can only have

$$C_F(=k_F/k_O) \gg C_O(=k_O/k_O=1) \qquad (14)$$

In the case of the descending m–δ curve, the value of $(m_F - m_o)$ is negative, then the lower the m_F value, the lower will be the C_F value. Therefore, we can have

$$C_F(=k_F/k_O) > C_O(=k_O/k_O=1) \qquad (15a)$$

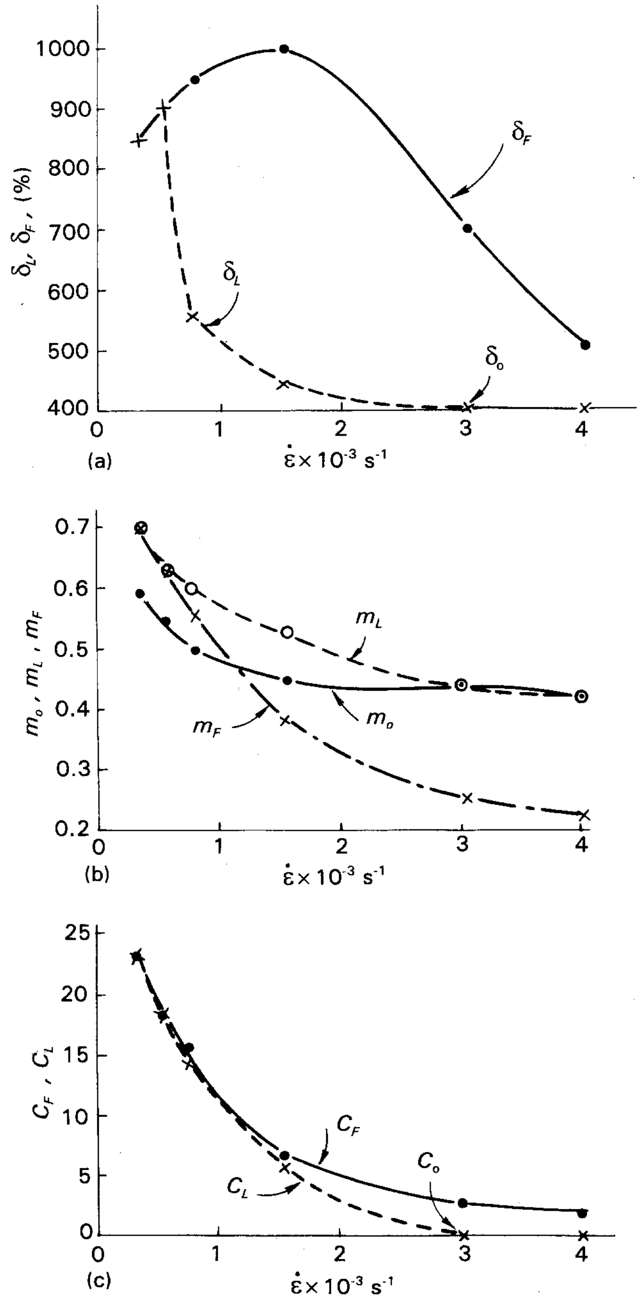

Figure 5 Effect of strain rate on the parameters characteristic of m–δ curves at 900 °C. (a) δ (δ_L, δ_F)–$\dot{\varepsilon}$ curves; (b) m (m_O, m_L, m_F)–$\dot{\varepsilon}$ curves; (c) C (C_L, C_F)–$\dot{\varepsilon}$ curves.

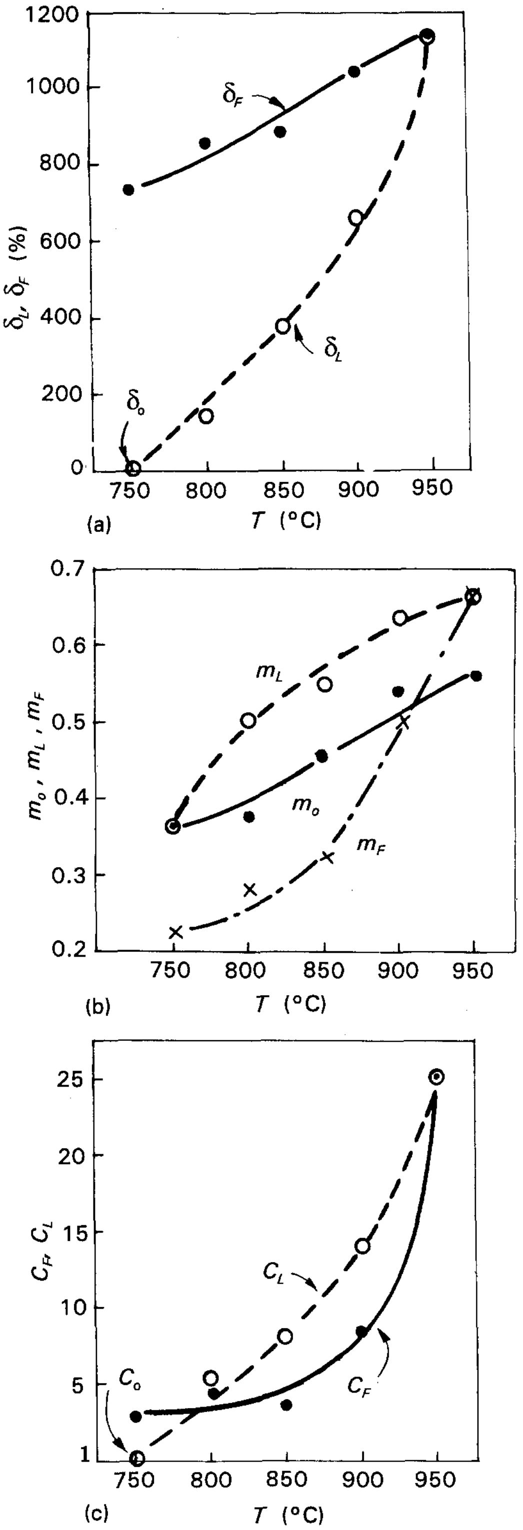

Figure 6 Effect of temperature on the parameters characteristic of m–δ curves at $\dot{\varepsilon} = 1.55 \times 10^{-3}\,\mathrm{s}^{-1}$. (a) $\delta(\delta_L, \delta_F)$–$T$ curves; (b) $m(m_O, m_L, m_F)$–T curves; (c) $C(C_L, C_F)$–T curves.

and possibly

$$C_F(=k_F/k_O) \rightarrow C_O(=k_O/k_O = 1) \qquad (15b)$$

In the case of the fundamental type of curve, the C_F value is determined by the resultant effects of its two sections separated by the limit strain, δ_L.

k_O value can be obtained from the σ–$\dot{\varepsilon}$ curve by the extrapolation method. With $C_F(=k_F/k_O)$ known, k_F can be calculated.

In Figs 5 and 6, the effects of strain rate and temperature on all the parameters characteristic of the m–δ curves are shown. From them, we can clearly understand the effects of these two factors on the hinges of the m–δ curves or the superplastic flow process behaviour of Ti–6Al–4V alloy tested.

5. Conclusions

1. The superplastic total elongation, δ_F was 500%–1000% at $T = 900\,°\mathrm{C}$ with $\dot{\varepsilon} = 0.37 \times 10^{-3}$–$4.05 \times 10^{-3}\,\mathrm{s}^{-1}$ and were 750%–1150% with $\dot{\varepsilon} = 1.55 \times 10^{-3}\,\mathrm{s}^{-1}$ at $T = 750$–$950\,°\mathrm{C}$.
2. The superplastic m–δ curves were all of the $m_L = m_{max}$ type including the fundamental, ascending and descending types. The latter two types were formed from the processes of $m_L \rightarrow m_F$ and $\delta_L \rightarrow \delta_F$ or $m_L \rightarrow m_O$ and $\delta_L \rightarrow \delta_O$ of the fundamental type.
3. The Chin Liu equation has been applied to all types of m–δ curves determined. All or some of δ_F, δ_L, m_F, m_L, m_O, C_F, and C_L were obtained for a m–δ curve depending upon the types of m–δ curves determined.
4. The superplastic total elongation, δ_F, of Ti–6Al–4V alloy should also be determined by the resultant effects of all other parameters characteristic of the m–δ curve, not by a single m value theoretically considered to be constant and determined practically with a tensile strain of about 30%–50% as is usual.

Acknowledgements

The authors thank the National Natural Science Foundation for the financial support with grant 58971054.

References

1. D. LEE and W. A. BACKOFEN, *Trans. AIME* **239** (1967) 1034.
2. J. E. LYTTLE, G. FISHER and A. R. MARDER, *J. Metals* **17** (1965) 1055.
3. CHANG ZHI-SHING and CHENG CHU-HENG,"The Strain Rate Sensitivity Index of Flow Stress of α + β Titanium Alloy And Its Measurements", Shanghai Research Institute of Iron and Steel, January 1983.
4. RODNEY R. BOYER and JOEL E. MAGNUSON, *Metall. Trans.* **10A** 8 (1979) 1991.
5. CHIN LIU, *ibid.* **17A** (1986) 679.
6. CHIN LIU and YI SHI-GONG, *Mater. Sci. Technol.* **6** (1880) 141.
7. CHIN LIU, *Plasticity Working* **24** (270) (1983-7) 692.
8. CHIN LIU, "Superplasticity of metals" (Shanghai Jiaotong University Press, Shanghai 1989)
9. *Idem.. Metall. Trans.* **17A** (1986) 685.
10. CHIN LIU, WONG WEI and LIU WAN-FU, in "Materials Research Society Symposium Proceedings of An International Conference On Superplasticity in Metals, Intermetallics and Ceramics", San Francisco, CA, 16–19 April 1990, p 239.
11. CHIN LIU and TAO JING, *ibid.*, p. 271.
12. CHIN LIU, DI CHANG, CHUNFU LIANG and ZHUMING SHEN, in "Proceedings of An International Conference. On Superplasticity in Advanced Materials", Osaka, Japan, 3-6 June 1991, p. 87.
13. CHIN LIU, DI CHANG, CHUNFU LIANG and JIE LIU, *ibid.*, p. 81.
14. CHIN LIU, PENCHANG SI, DI CHANG and JUN WONG, *ibid.* p. 75.
15. W. A. BACKOFEN, I. R. TURNER and D. H. AVERY, *Trans. Q. ASM* **57** (1964) 980.

Received 30 July 1992
and accepted 10 August 1993