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Scripta Materialia 45 (2001) 631–638



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# Load transfer during transformation superplasticity of Ti–6Al–4V/TiB whisker-reinforced composites

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Received 6 March 2001; accepted 3 May 2001

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## Abstract

Superplastic deformation is investigated during thermal cycling through the  $\alpha/\beta$  transformation of Ti–6Al–4V containing 5 vol% TiB whiskers. The measured constitutive behavior is compared with existing data for 0 and 10 vol% composites, and the observed trends are discussed in terms of load transfer from matrix to whiskers. © 2001 Acta Materialia Inc. Published by Elsevier Science Ltd. All rights reserved.

*Keywords:* Superplasticity; Metal matrix composites; Titanium alloys; Phase transformation

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## Introduction

Transformation superplasticity, in which an external biasing stress is superimposed upon internal mismatch stresses from a polymorphic transformation, is a grain-size independent Newtonian deformation mechanism. It is typically induced by thermal cycling through the polymorphic transformation range, which continuously regenerates the internal mismatch stresses driving Newtonian flow [1]. As reviewed in Refs. [2,3], transformation superplasticity has produced tensile elongations in excess of 100% in iron, zirconium, titanium, as well as alloys and composites of these materials. Thus, this mechanism is of potential shape-forming interest for, e.g., titanium-matrix composites that are otherwise very difficult to form.

In a recent publication [4], we have reported the first observation of transformation superplasticity in a whisker-reinforced metal matrix composite (Ti–6Al–4V/10 vol% TiB). In that work, we demonstrated: (i) Newtonian flow characteristics during thermal cycling through the matrix  $\alpha/\beta$  phase transformation and (ii) a tensile elongation of 260% after several hundred thermal cycles under an applied stress of  $\sigma = 4.5$  MPa. In

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addition, we found that the reinforcing whiskers aligned along the tension axis during superplastic flow, and caused an apparent strain hardening over the course of deformation.

In the present work, we extend our previous study to examine the effect of whisker volume fraction on transformation superplasticity of Ti–6Al–4V/TiB composites. We report new data for 5 vol% TiB for comparison with our original data for 0 and 10 vol% whiskers [4]. We also explain the observed trends in terms of load transfer from matrix to whiskers during deformation, using existing theories for the rheology of whisker-reinforced metals.

## Experimental procedures

Billets of Ti–6Al–4V/5 vol% TiB were supplied by Dynamet Technology (Burlington, MA), the same supplier for the unreinforced Ti–6Al–4V and Ti–6Al–4V/10 vol% TiB composites examined in our earlier work [4]. The materials were fabricated by a powder metallurgy technique which involves powder blending (Ti, Al–V master alloy, and TiB<sub>2</sub> powders), cold isostatic pressing, vacuum sintering, and containerless hot isostatic pressing. During the latter two high-temperature steps, the TiB<sub>2</sub> phase dissolves and reprecipitates as randomly oriented TiB whiskers, with aspect ratios of 15–20 and length  $\sim 80$   $\mu\text{m}$ . Typical microstructures of such composites are available in Refs. [4–6], for higher volume fractions than used in this work.

Cylindrical tensile specimens (20 mm gauge length with 5 mm diameter) were machined from the billets, and tested under an atmosphere of high-purity argon in a custom thermal-cycling creep frame described in detail in Ref. [7]. The thermal cycles were symmetric triangles of 8-min duration, between 840°C and 1030°C. This cycle profile was chosen to maximize the amount of transformation product ( $\sim 75\%$ ), while providing ample time for the kinetics of the diffusional transformation. Two types of experiments were performed. First, stress change experiments were used to determine the flow law during thermal cycling. The strain increment  $\Delta\epsilon$  after each thermal cycle was determined as a function of the applied uniaxial tensile stress,  $\sigma$ ; reported values are averages over four or more consecutive thermal cycles. For these experiments, the total engineering strain of the specimen was maintained below 11%, to avoid substantial reorientation of the TiB whiskers. Second, a single specimen was deformed to fracture at an applied true stress of  $\sigma = 2.5 \pm 0.1$  MPa, accounting for the cross-section reduction by assuming constant volume and uniform elongation.

## Results and discussion

The superplastic strain increment  $\Delta\epsilon$  after each thermal cycle of Ti–6Al–4V/5 vol% TiB is shown in Fig. 1 as a function of the applied tensile stress. The relationship is linear, in agreement with the prevailing theory of transformation superplasticity by Greenwood and Johnson [1]:

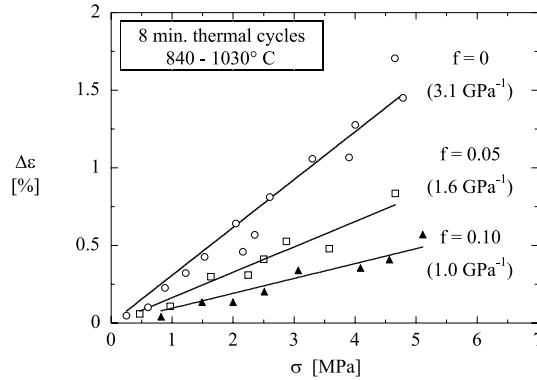


Fig. 1. Strain increment  $\Delta\varepsilon$  accumulated after each thermal cycle, as a function of the applied uniaxial tensile stress  $\sigma$ , for three whisker volume fractions,  $f$ .

$$\Delta\varepsilon \approx \frac{4}{3} \frac{\Delta V}{V} \frac{5n}{4n+1} \frac{\sigma}{\sigma_0} \quad (1)$$

in which  $\Delta V/V$  is the volume mismatch between the polymorphic phases,  $n$  is the creep stress exponent of the phase which accommodates the mismatch strain, and  $\sigma_0$  is the time- and volume-averaged internal equivalent stress during the phase transformation. Although Eq. (1) was derived for an isothermal phase transformation (as for a pure allotropic metal), the linear result holds for alloys which transform over a range of temperatures, such as Ti–6Al–4V [8]. Furthermore, the internal strain due to thermal expansion-mismatch between matrix and TiB reinforcements is small compared to  $\Delta V/V$ . For comparison with the 5 vol% composite, our data from Ref. [4] are shown for unreinforced Ti–6Al–4V and Ti–6Al–4V/10 vol% TiB composites. The superplastic slope  $d(\Delta\varepsilon)/d\sigma$  decreases monotonically with the volume fraction of reinforcement.

In Fig. 2, the strain increment history is shown for the specimen deformed to failure at  $\sigma = 2.5$  MPa, normalized by the instantaneous true stress. For an unreinforced material deforming by transformation superplasticity, Eq. (1) indicates that  $\Delta\varepsilon/\sigma$  should be a constant, independent of the test history; this theoretical expectation has been borne out experimentally for unreinforced Ti–6Al–4V [4]. However, the strain increment history in Fig. 2 shows a significant apparent strain hardening (by about a factor of three) over the course of the experiment. Such strain hardening has been observed previously during transformation superplasticity of Ti–6Al–4V/10 vol% TiB composites, and correlated with the alignment of the whiskers along the axis of the flow [4]. In that work, we measured the angular distribution of the whiskers as a function of the superplastic strain, and used a simple mechanical calculation of elastic load transfer to rationalize the decrease in the strain increment  $\Delta\varepsilon$ . As the whiskers align with superplastic extension, they bear a greater fraction of the applied load, relieving the deforming matrix of the biasing stress which controls transformation superplasticity (i.e., decreasing  $\sigma$  in Eq. (1)), and thereby reducing the rate of matrix deformation. We also

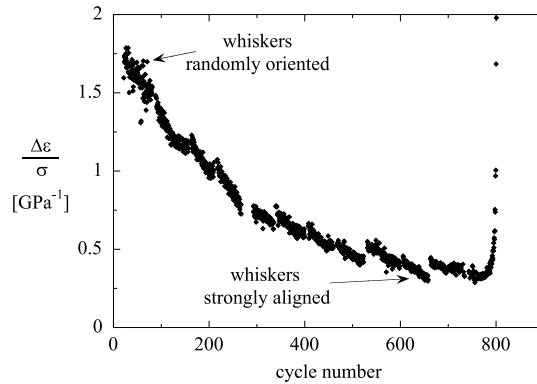


Fig. 2. Strain increment history for a specimen deformed to failure at  $\sigma = 2.5$  MPa. The final engineering strain was 390%.

note that the length of the tertiary stage shown in Fig. 2 for Ti-6Al-4V/5 vol% TiB is somewhat less than for either the 0% or 10% composites, as reported in Ref. [4].

As shown in Fig. 2, the composite failed at an engineering strain of 390% with an applied stress of  $\sigma = 2.5$  MPa. Combined with our previous results for different volume fractions,  $f$ , of reinforcement, this result is shown in Fig. 3. Under identical thermal cycling conditions and the same applied stress, the addition of 5 vol% TiB only slightly reduces the achievable superplastic elongation of Ti-6Al-4V (from 398% to 390%). Although the tensile ductility of these composites is substantial under thermal cycling conditions, the whisker addition significantly reduces the deformation rate; the composite with 5 vol.% whiskers required about 800 thermal cycles (107 h) to reach failure, compared with only 135 cycles (18 h) for unreinforced Ti-6Al-4V to reach the same

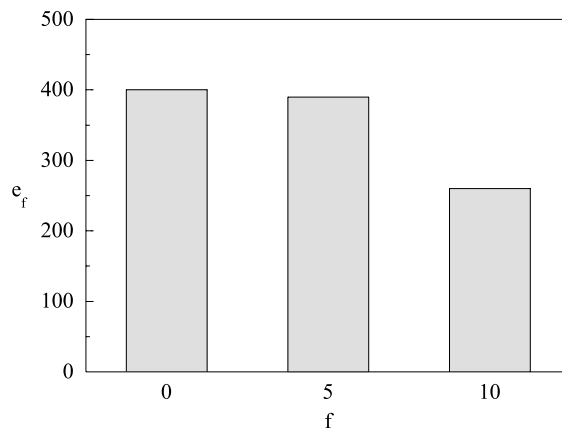


Fig. 3. Effect of volume fraction  $f$  of reinforcing whiskers on elongation to failure ( $e_f$ ) of Ti-6Al-4V/TiB composites, deformed during thermal cycling with applied stress  $\sigma = 2.5$  MPa.

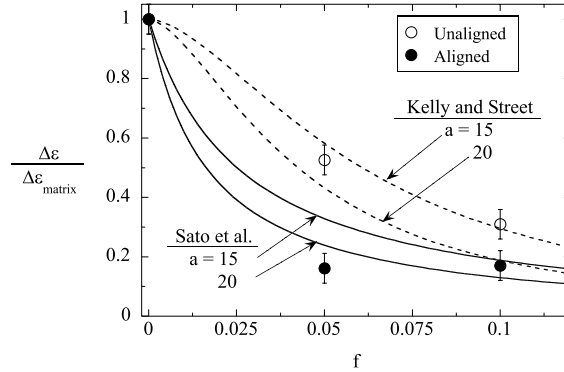


Fig. 4. Reduction in the superplastic strain increment  $\Delta\varepsilon/\Delta\varepsilon_{\text{matrix}}$  due to volume fraction  $f$  of reinforcing whiskers, at early stages of straining (i.e., with unaligned whiskers) and after superplastic straining (i.e., with strongly aligned whiskers). The analytical model predictions of Kelly and Street [11] and Sato et al. [12] (both for fully aligned whiskers) are also shown, for whisker aspect ratios  $a = 15$  and  $20$ .

strain [4]. The addition of 10 vol% whiskers has a greater impact on the tensile ductility, reducing the elongation to failure by a factor of 1.5.

The effect of TiB whisker reinforcement on transformation superplasticity of Ti–6Al–4V is summarized in Fig. 4, which shows the superplastic slope ( $d(\Delta\varepsilon)/d\sigma$ , equal to the inverse of viscosity for a Newtonian flow) as a function of the volume fraction of TiB, and normalized by the superplastic slope of the unreinforced matrix material,  $d(\Delta\varepsilon_{\text{matrix}})/d\sigma = 3.1 \text{ GPa}^{-1}$ . The slope measured at early stages of straining (Fig. 1), when the whiskers are randomly oriented, is shown, as well as the value obtained after superplastic elongation, when the whiskers are strongly aligned. Fig. 4 shows that the superplastic strain increments decrease with the reinforcement volume fraction, though this effect is more pronounced from 0 to 5 vol% than from 5 to 10 vol% TiB. In what follows, we consider the data in Fig. 4 in terms of existing models for creep of whisker-reinforced composites, which specifically consider the effect of load transfer.

Although the high-temperature creep of composites has been widely studied (see e.g., Refs. [9,10] for an overview), there is no simple theoretical description for a power-law creeping matrix around large, rigid particles or whiskers. In the simpler case of a linear (Newtonian) matrix creeping around a rigid reinforcement, analytical solutions are possible, although they have little relevance to technologically important composites, which exhibit power-law creep behavior. Thus, transformation superplasticity represents a unique test case for the latter type of analytical model, because the matrix deforms according to a linear constitutive law, and the reinforcement particles can be reasonably assumed rigid.

One such model for creep of a whisker-reinforced metal is due to Kelly and Street [11]. These authors used a shear-lag mechanics approach, in which the whiskers are assumed aligned with the tension axis, and load transfer is assumed to occur only due to shear strain mismatch at the longitudinal matrix/whisker interfaces. For rigid fibers of

aspect ratio  $a$  which are perfectly bonded to the matrix, these authors derived a closed-form solution for the steady-state creep rate of the composite, which, for the case of transformation superplasticity (i.e., Newtonian flow), reduces to:

$$\frac{(d(\Delta\varepsilon)/d\sigma)}{(d(\Delta\varepsilon)/d\sigma)_{\text{matrix}}} = \frac{1}{1 - f + fa^2S_1} \quad (2)$$

where the load transfer parameter  $S_1$  is given by:

$$S_1 = \frac{2}{9} \left[ \left( \left( \frac{2\sqrt{3}}{\pi} f \right)^{-1/2} - 1 \right) \right]^{-1} \quad (3)$$

A second model for creep of a Newtonian matrix containing ellipsoidal particles is given by Sato et al. [12], who use the Eshelby equivalent inclusion method [13]. Assuming that the ellipsoids are rigid and have their major axes aligned with the uniaxial applied stress, these authors derive the following expression, written here in terms of the superplastic slope:

$$\frac{(d(\Delta\varepsilon)/d\sigma)}{(d(\Delta\varepsilon)/d\sigma)_{\text{matrix}}} = \frac{1 - f}{1 - f + f/S_2} \quad (4)$$

in which

$$S_2 = \frac{-9a^2}{2(a^2 - 1)^2} + \frac{3a(a^2 + 1/2)}{(a^2 - 1)^{5/2}} \text{arccosh}(a) \quad (5)$$

In Fig. 4 the predictions of these two models (Eqs. (2) and (4)) are shown as a function of the volume fraction of TiB, assuming an aspect ratio of  $a = 15$  or  $20$  [4,6]. Both models predict significant decreases in the superplastic deformation rate with increasing TiB content. Moreover, both models predict a larger strengthening effect at lower volume fractions, and a gradual plateau at larger values of  $f$ , as exhibited by the experimental data.

Because both of the above models are formulated under the assumption of perfectly aligned whiskers, it is appropriate to compare their predictions with the solid points in Fig. 4, which represent superplastically deformed Ti-6Al-4V composite specimens with strongly aligned reinforcements. The model of Sato et al. [12] is very close to the experimental data after whisker alignment, while the shear-lag-based model of Kelly and Street [11] tends to underpredict the strengthening effect of the reinforcing whisker phase. However, Kelly and Street [11] have in fact noted that their model is expected to be most accurate for power-law creeping materials with stress exponents larger than unity.

Finally, we note that all of the observed strengthening effects due to reinforcing TiB during transformation superplasticity of Ti-6Al-4V can be fully accounted for through considerations of load transfer. In Ref. [4] we explained the apparent strain hardening during superplastic elongation (e.g., Fig. 2 in this work or Fig. 4(b) in Ref. [4]) by

considering the effect of whisker alignment upon elastic load transfer. Although these changes in elastic load transfer could fully explain the loss of steady-state deformation, the effect of elastic load transfer was not large enough to explain the significant reduction in the superplastic slope upon addition of TiB (e.g., the lower slope for the composites in Fig. 1). Here, we have shown that the inherent strengthening effect of 5 or 10 vol% reinforcing TiB can be explained with the mechanical models of Sato et al. [12] or Kelly and Street [11], which consider plastic mismatch during Newtonian flow around reinforcements.

## Conclusions

We report experimental data on transformation superplasticity of Ti–6Al–4V/5 vol% TiB whisker reinforced composites, for comparison with our earlier works on unreinforced Ti–6Al–4V and Ti–6Al–4V/10 vol% TiB composites [4]. Newtonian flow (and superplastic elongation) are achieved by thermally cycling through the  $\alpha/\beta$  transformation range of the matrix, giving rise to transformation superplasticity. We show that the deformation rate and achievable superplastic elongation decrease as the volume fraction of reinforcement increases, and discuss the effect of whisker alignment on superplastic flow. Additionally, we compare the experimental results to two existing models for Newtonian creep around whisker reinforcements, and demonstrate that the experiments can be explained by load transfer from matrix to particle during deformation.

## Acknowledgements

This work was funded by NSF (SBIR grant #9901850 through a subcontract from Dynamet Technology, Burlington, MA) and the US DOD (through a National Defense Science and Engineering Graduate Fellowship for CS). We also would like to thank Mr. W. Zimmer (of Dynamet Technology) and Prof. E. Sato (of the Institute of Space and Astronautical Science, Japan) for useful discussions.

## References

- [1] Greenwood, G. W., & Johnson, R. H. (1965). *Proc Roy Soc Lond* 283A, 403–422.
- [2] Nieh, T. G., Wadsworth, J., & Sherby, O. D. (1997). *Superplasticity in metals and ceramics*. Cambridge: Cambridge University Press.
- [3] Dunand, D. C. In T. Chandra & T. Sakai (Eds.), *International Conference on Thermomechanical Processing of Steels and Other Materials*. TMS, 1997, pp. 1821–1830.
- [4] Schuh, C., & Dunand, D. C. (2001). *Int J Plastic* 17, 317–340.
- [5] Abkowitz, S., Weihrauch, P. F., & Abkowitz, S. M. (1993). *Ind Heating* 12, 32–37.
- [6] Saito, T., Furuta, T., & Yamaguchi, T. (1994). In S. Fujishiro, D. Eylon & T. Kishi (Eds.), *Metallurgy and technology of practical titanium alloys* (pp. 351–362). TMS.
- [7] Zwigl, P., & Dunand, D. C. (1998). *Metall Mater Trans* 29A, 2571–2581.

- [8] Schuh, C., & Dunand, D. C. (2001). *Acta Mater* 49, 199–210.
- [9] Dunand, D. C., & Derby B. (1993). In S. Suresh, A. Mortensen & A. Needleman (Eds.), *Fundamentals of metal matrix composites* (pp. 191–214). Boston, MA: Butterworth-Heinemann.
- [10] Clyne, T. W., & Withers, P. J. (1993). *An introduction to metal matrix composites*. Cambridge: Cambridge University Press.
- [11] Kelly, A., & Street, K. N. (1972). *Proc Roy Soc Lond A* 328, 283–293.
- [12] Sato, E., Ookawara, T., Kuribayashi, K., & Kodama, S. (1998). *Acta Mater* 46, 4153–4159.
- [13] Eshelby, J. D. (1957). *Proc Roy Soc Lond A* 241, 376–396.