Progress Report:

BES Grant DE-FG03-99ER-45768
"Rate Controlling Processes for Five Power Law Creep"

A. Research Summary

The initial grant emphasized the rate-controlling processes for five power-law creep. The effort has six aspects:

1. Theory of Taylor hardening from the Frank dislocation network in five power law substructures.

2. The dual dynamical and hardening nature of dislocations in five power law substructures.

3. Determination of the existence of long-range internal stress in five-power law creep dislocation substructures.

4. Dynamic recovery mechanisms associated with dislocation heterogeneities during five power law creep.

5. Versatility of five power law creep concept to other (hcp) crystal structures.

6. Writing of a book on "Fundamental of Creep in Metals and Alloys" by M.E. Kassner and Maria-Teresa Perez-Prado (postdoctoral scholar, funded by this project) Elsevier Press, 2004, in press.

These areas are consistent with the original goals of this project as delineated in the original proposal to Basic Energy Sciences. The progress in each of these areas will be discussed separately and there will be an attempt to tie each aspect together so as to allow a summary regarding the conclusions with respect to the rate-controlling mechanisms of five power-law creep.

1 <u>Theory of Taylor hardening from the Frank dislocation network in five power law substructures</u>

and

2. <u>The dual dynamical and hardening nature of dislocations in five power law substructures</u>

Previous work on stainless steel by the PI showed that the density of dislocations within the subgrain interior (or the network dislocations) are associated with the rate-controlling process for five-power-law creep-plasticity. The hardening in stainless stress was shown to be consistent with the Taylor relation if a linear superposition of "lattice" hardening (τ_o, or the stress necessary to cause dislocation motion in the absence of a dislocation substructure) and the dislocation hardening ($\alpha MGb\rho^{1/2}$) is assumed, i.e.,

$$\tau = \tau_0 + MGb\sqrt{\rho} \tag{1}$$

It was shown in this grant period that the same relationship appears valid for high purity aluminum with the *same* values of α observed in other metals, such as 304 stainless steel, where dislocation hardening is established. It appears that the constant, α, is temperature independent and, thus, the dislocation hardening is nearly athermal as theoretically expected.

It has often been argued that dislocations cannot be the basis for elevated temperature hardening, such as by Eq. (1), since during constant-stress creep, ρ, decreases during the hardening stage. This was considered an important apparent contradiction to resolve in this research. It is also shown that constant-stress creep behavior, where the *total* interior dislocation decreases during primary (hardening stage) creep, is consistent with Taylor hardening. The results of this work are detailed in the very recent publication by the PI [9,16]. Under constant stress conditions,

$$\dot{\varepsilon} = (b/M)\rho_m v \tag{2}$$

where ρ_m is the mobile dislocation density and v is the dislocation velocity. Equation (1) considered ρ as an immobile dislocation density with a fixed ρ_m. It was demonstrated that

$$\dot{\varepsilon}_{\varepsilon_p \cong 0} / \dot{\varepsilon}_{ss} = \left(\frac{f_m^p}{f_m^o}\right) 3\rho_p / \rho_{ss} \tag{3}$$

where f_m^p is the fraction of dislocations that are mobile at the peak (total) dislocation density ρ_p. ρ_{ss} is the steady-state dislocation density, and f_m^o is the fraction of dislocations in the annealed metal that are mobile at yielding. Equation (3) assumes Taylor (Eq. (1) hardening. Figure 1 shows the predicted dislocation density in the subgrain interior against the strain in aluminum deforming under constant-stress conditions. The predicted dislocation density is based on Eq. (3). Thus, the constant-stress creep behavior, in which the total dislocation density (ρ) decreases during primary (hardening stage) creep, is actually consistent with Taylor hardening (Eq. (1)). The increase in total dislocation density simply reflects the high initial strain-rates in a constant-stress tests. The obstacles for dislocation motion in this case are still the Frank-network dislocations.

3. Determination of the existence of long-range internal stress (LRIS) in five-power law creep dislocation substructures

Creep experiments were conducted on aluminum single crystals and copper polycrystals deformed within the five-power-law regime. The dislocation structure of copper, which has not been extensively characterized in the past, consists of less well-defined subgrain walls of relatively low-misorientation, typically between 0.1 and 0.3°, with a Frank network of dislocations within the subgrains. The aluminum, as expected, consisted of well-defined subgrain boundaries with a typical misorientation between 0.5 and 2.0°. The subgrains were probed from one boundary to another in copper and aluminum using convergent beam electron diffraction (CBED). This allowed a determination of any changes in the lattice parameter which would

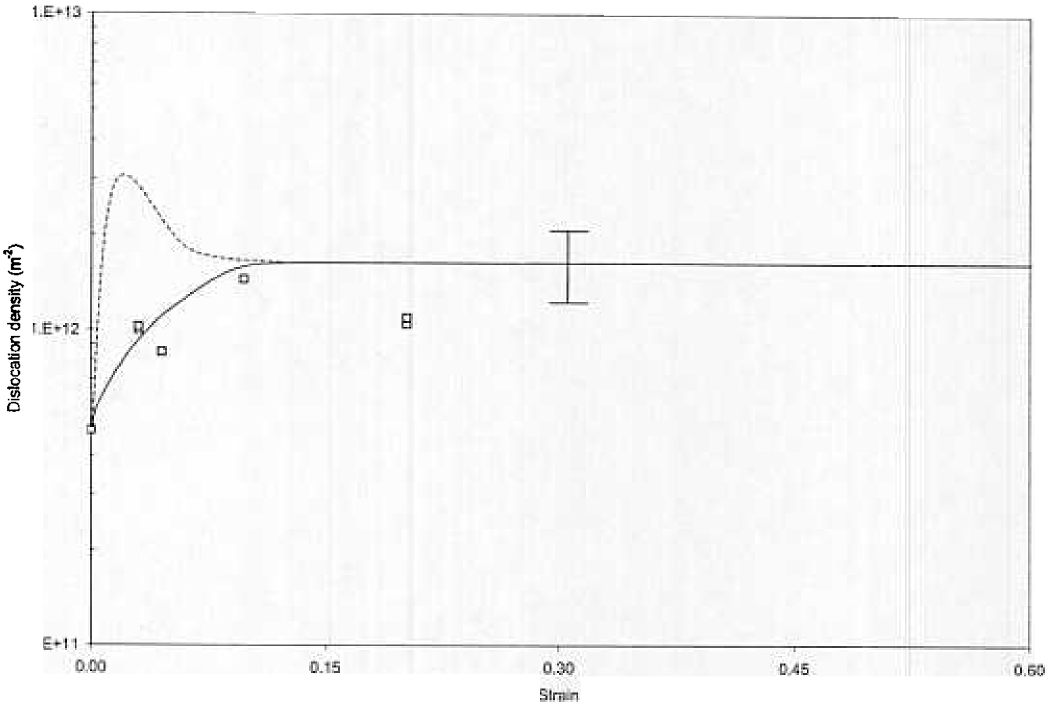

Figure 1 The predicted dislocation density (— — —) in the subgrain interior against strain for aluminum deforming under constant-stress conditions is compared with that for constant strain-rate conditions (——). The predicted dislocation density is based on Eq. (3) which assumes Taylor hardening.

indicate the presence of any internal stresses. Earlier investigations by others suggested that internal stresses may be high in the vicinity of the "hard" subgrain boundaries in both loaded and unloaded specimens based on a variety of techniques, including x-ray diffraction, stress-dip tests as well as some preliminary CBED. It was determined in this work that the lattice parameter was unchanged at the equilibrium or stress-free value within the interior of the subgrains and along (within one beam diameter) the subgrain boundaries. The results of this work are detailed in the very recent publication by the PI [3,4,17]. Thus, LRIS need not be considered in any (constitutive) descriptions of creep, as commonly done in the past.

4. Dynamic recovery mechanisms associated with dislocation heterogeneities during five power law creep

Pure aluminum deformed in pure shear at elevated temperature reaches a broad "peak" stress and then undergoes about a 17% decrease in flow stress with deformation to roughly 1-2 equivalent uniaxial strain. The flow stress is approximately constant beyond this strain. The sources for this softening are unclear. The suggested basis includes texture softening, microstructural softening, and enhanced dynamic recovery. This latter contention is important as it implies an important recovery role for dislocation heterogeneities during five-power-law (steady-state) creep. Experiments were performed where specimens were deformed in torsion to various strains within the softening regime followed by compression tests at ambient and elevated temperature. Analysis of the compressive yield strengths indicate that the softening is at least substantially explained by a decrease in the average Taylor factor. Orientation Image Microscopy measurements suggest that only small effects with increased high angle boundary area with strain and this is consistent with the texture explanation. These are discussed in detail in [6,12,13,14] by the PI and coworkers.

5. <u>Versatility of five power law creep</u>

The applicability of five power law creep to "non-traditional" metallic systems was tested. In particular, the applicability of the appropriate stress exponent (4-7) and proper correlation of the activation energy of creep to that of dislocation climb (typically lattice self-diffusion) was examined. Earlier work suggested that other mechanisms such as glide control may actually apply to this hcp metal. This study confirmed the applicability of five-power-law climb control with an activation energy equal to that of self-diffusion, if impurity effects are considered. The results are discussed in [5,11,15], by the PI and coworkers.

6. <u>Writing and publishing of a book on "Fundamental of Creep in Metals and Alloys"</u>

This book [1] is complete and is now in press. It is an advanced text for graduate students and researchers in the field. This book was written by M.E. Kassner, the PI, and Maria-Teresa Perez-Prado (postdoctoral scholar, funded by this project). The book is being published by Elsevier Press, and will be available in early 2004. This book included the extensive reviews supported by this grant [2,17]. BES is exclusively acknowledged.

B. Progress Report References

1 M.E. Kassner and M.-T. Perez-Prado, *Fundamentals of Creep in Metals and Alloys,* Elsevier, 2004, in press.

2. M.E. Kassner and M.-T. Perez-Prado, "Five-Power-Law Creep in Single Phase Metals," *Progress. Mater. Sci.*, 45, 2000, pp. 1-102.

3. M.E. Kassner, M.-T. Perez-Prado, and K.S. Vecchio, "Internal Stress Measurements by Convergent Beam Electron Diffraction on Creep Deformed Al Single Crystals," *Mater. Sci. and Eng.*, A319-321, 2001, pp. 730-734.

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6. M.E. Kassner, M.Z. Wang, M.-T. Perez-Prado, and S. Alhajeri, "Large-Strain Softening of Aluminum in Shear at Elevated Temperatures," *Metall. Mater. Trans.*, 33A, 2002, pp. 3145-3154.

7 M.E. Kassner and T.A. Hayes, "Creep Cavitation in Metals," *Int. Jour. Plasticity*, 17, 2003. pp. 1715-1748.

8. H.J. McQueen and M.E. Kassner, "Comments on 'A Model of Continuous Recyrstallization Critique of Continuous Dynamic Recrystallization Model for Aluminum'", Scripta, Mater, submitted.

9. M.E. Kassner, "Taylor Hardening in Five Power Law Creep of Metals and Class M Alloys", *Acta Mater.,* in press.

10. M.E. Kassner and T.A. Hayes, "Subgrain Strengthening Revisited II," *Deformation, Processing and Properties of Structural Materials*, A Symposium Honoring Prof. O.D. Sherby, E.M. Taleff, C.K. Syn, and D.R. Lesuer, eds., TMS, Warrendale, PA, 2000, pp. 121-130 (invited).

11 M.E. Kassner, M.-T. Perez-Prado, R.S. Rosen, and S.C. Bergsma, "Recent Developments in Understanding Five Power Law Creep in Metals," *Plastic and Viscoplastic Response of Materials and Metal Forming*, A.S. Khan, H. Zhang, and Y. Yuen, eds., Neat Press, Fulton, MD, 2000, pp. 351-353.

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13. H.J. McQueen and M.E. Kassner, "Hot Deformation Mode and TMP in Aluminum Alloys," *Lightweight Alloys for Aerospace Applications IV* (PDF Edition), K. Jata, E.W. Lee,W. Frazier, and N.J. Kim, eds., TMS, Warrendale, PA, 2001, pp. 63-76.

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15. S. Barrabes, C. Daraio, M.E. Kassner, T.A. Hayes, and M.Z. Wang, "Dynamic Restoration Mechanisms and Discontinuous Dynamic Recrystallization in α-Zirconium," *Light Metals 2002*, T. Lewis, ed., Canadian Inst. Mining, Metall. and Petrol., Montreal, 2002, pp. 825-839.

16. M.E. Kassner and K. Kyle, "Taylor Hardening in Five Power Law Creep of Metals and Class M Alloys," *Proc. of the Symposium to Honor Gareth Thomas*, TMS, Columbus, OH, 2002.

17. M.A. Delos-Reyes, M.E. Kassner and L.A. Levine, "X-Ray Diffraction and the Existence of Long-Range Internal Stresses," *Dislocations, Plasticity and Metal Forming*, A.S. Kahn, R. Kazmi and J. Zhou eds.,Neat Press, 2003, pp. 262-264.

C. Publications Resulting from the Initial BES Grant, Where BES is Specifically (and Generally Exclusively) Acknowledged

Books

M.E. Kassner and M.-T. Perez-Prado, *Fundamentals of Creep in Metals and Alloys,* Elsevier, 2004, in press.

Journal Articles

2. M.E. Kassner and M.-T. Perez-Prado, "Five-Power-Law Creep in Single Phase Metals," *Progress. Mater. Sci.*, 45, 2000, pp. 1-102.

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Conference Proceedings

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and Viscoplastic Response of Materials and Metal Forming, A.S. Khan, H. Zhang, and Y. Yuen, eds., Neat Press, Fulton, MD, 2000, pp. 351-353.

12. M.E. Kassner, "Elevated Temperature Large-Strain Softening of Aluminum in Pure Shear," *Light Metals 2000*, J. Kazadi and J. Masounave, eds., Canadian Inst. of Mining, Metallurgy and Petrol., Montreal, 2000, pp. 431-438.

13 H.J. McQueen and M.E. Kassner, "Hot Deformation Mode and TMP in Aluminum Alloys," *Lightweight Alloys for Aerospace Applications IV* (PDF Edition), K. Jata, E.W. Lee,W. Frazier, and N.J. Kim, eds., TMS, Warrendale, PA, 2001, pp. 63-76.

14. M.E. Kassner, M.Z. Wang, and S.C. Bergsma, "Large-Strain Softening of Aluminum in Shear at Elevated Temperature," *Creep Deformation: Fundamentals and Applications*, R.S. Mishra, J.C. Earthman, and S.V. Raj, eds., TMS, Warrendale, 2002, pp. 61-70.

15. S. Barrabes, C. Daraio, M.E. Kassner, T.A. Hayes, and M.Z. Wang, "Dynamic Restoration Mechanisms and Discontinuous Dynamic Recrystallization in α-Zirconium," *Light Metals 2002*, T. Lewis, ed., Canadian Inst. Mining, Metall. and Petrol., Montreal, 2002, pp. 825-839.

16. M.E. Kassner and K. Kyle, "Taylor Hardening in Five Power Law Creep of Metals and Class M Alloys," *Proc. of the Symposium to Honor Gareth Thomas*, TMS, Columbus, OH, 2002, in press.

17 M.A. Delos-Reyes, M.E. Kassner and L.A. Levine, "X-Ray Diffraction and the Existence of Long-Range Internal Stresses," *Dislocations, Plasticity and Metal Forming*, A.S. Kahn, R. Kazmi and J. Zhou eds.,Neat Press, 2003, pp. 262-264.

D. Students and Postdoctoral Scholars supported by this Grant

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Troy Hayes: current PhD student, expected date of graduation June 2004
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