FACTORS INFLUENCING THE FLOW AND FRACTURE OF SUPERPLASTIC CERAMICS

FINAL TECHNICAL REPORT

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Introduction

This research program was initiated with the objective of obtaining a better understanding of the flow, and especially the superplastic flow, of representative ceramics. Detailed experiments were undertaken on the yttria-stabilized tetragonal zirconia (Y-TZP) and on various composite materials containing Y-TZP and Al_2O_3 . In addition, a comprehensive theoretical interpretation was developed which showed, for the first time, that the superplasticity of ceramic materials has very significant differences from the conventional superplastic flow in metals.

Achievements in this research program

The most significant achievement in this program was the development of a new model for the flow of superplastic ceramics (Berbon and Langdon, *Acta Mater.* 47, 2485, 1999). This model built on several early successes in this DOE program. For example, our early work showed there were numerous similarities between the superplastic behavior of Y-TZP and metallic alloys (Ma and Langdon, *Acta Metall. Mater.* 42, 2753, 1994; Ma and Langdon, *Metall. Mater. Trans. A* 27A, 873, 1996). On the other hand, we were able to use high-resolution electron microscopy to demonstrate that, contrary to current thinking at that time, the Y-TZP ceramic does not contain an amorphous layer at the grain boundaries (Primdahl *et al.*, *Acta Metall. Mater.* 43, 1211, 1995). We showed, however, that there was some segregation of yttria to the boundaries. This result has been confirmed in more recent work by other researchers and the conclusions are now generally accepted by all workers in the field.

Based on these results, we developed a new model for flow in which we proposed that flow occurs through Coble diffusion creep controlled by movement of the Zr^{4+} ions. In addition, we suggested that, as a consequence of the exceptionally small grain sizes in the Y-TZP ceramics ($<1\ \mu m$), the creep rates will be reduced through an interface-controlled diffusion creep at very low stress levels. A full description of this approach is given in our publication and the approach has been verified in several independent studies published over the last two years. We showed also that the model is in excellent agreement with the available experimental evidence.

A second theoretical approach was devoted to examining the potential for intragranular movement occurring in superplastic deformation. Many researchers have proposed that superplasticity occurs in these materials through conventional grain boundary sliding but we noted in several papers that sliding will require an additional accommodation mechanism in the form of some intragranular dislocation slip (Langdon, *Mater. Sci. Eng.* A283, 266, 2000; Langdon, *Metall. Mater. Trans. A* 33A, 249, 2002). We showed by calculation that the stresses in the Y-TZP samples are too low to initiate intragranular slip and we proposed instead that the sliding is a consequence of the movement of grains in diffusion creep (Balasubramanian and Langdon, *Scripta Mater.* 48, 599, 2003).

An important additional thrust in this research program was the collection and analysis of experimental data which we obtained by conducting high-temperature tensile tests under conditions of both constant strain rate and constant stress (creep). These results confirmed the validity of the theoretical model and they provide additional evidence that superplasticity in ceramics has important differences by comparison with conventional superplastic metals.

Conclusions

This has been an exceptionally productive program, aided by the continuous support received over a number of years. This long-term support from DOE provided an opportunity to make a very significant contribution to the current understanding of the superplasticity of ceramics to the extent that the current theory for superplastic flow is based on the research conducted on this DOE program.

Personnel associated with this program:

Dr. B.Q. Han (Postdoc at USC - now at University of California, Irvine)

Dr. S.S. Sosa (female Hispanic Ph.D. candidate at USC – now at Southern California Gas Company, Los Angeles, CA)

Dr. M.Z. Berbon (female Ph.D. candidate at USC – now at Rockwell Science Center, Thousand Oaks, CA)

Dr. N. Balasubramanian (Visiting Scholar at USC – now returned to India)

Publications on this program

(For convenience, this report lists only the more recent publications since 1999: all of the early publications on this program are listed in earlier Technical Reports)

1. T.G. Langdon, "Creep Behavior of Ceramics and Geological Materials at Low Stress Levels," Key Engineering Materials **166**, 81-86 (1999).
2. M.Z. Berbon and T.G. Langdon, "An Examination of the Flow Process in Superplastic Yttria-Stabilized Tetragonal Zirconia," Acta Materialia **47**, 2485-2495 (1999).
3. M.Z. Berbon and T.G. Langdon, "Superplasticity in Tetragonal Zirconia Stabilized with 3 mol % of Yttria: An Examination of the Flow Mechanisms," Proceedings of the First China International Conference on High-Performance Ceramics (D.S. Yan and Z.D. Guan, eds.), pp. 664-668. Tsinghua University Press, Beijing, China (1999).
4. S.S. Sosa and T.G. Langdon, "The Role of Diffusion in Superplastic Deformation," Metals, Materials and Processes **11**, 247-258 (1999).
5. T.G. Langdon, "The Significance of Diffusion Creep and Harper-Dorn Creep at Low Stresses," Key Engineering Materials **171-174**, 205-212 (2000).
6. T.G. Langdon, "The Interpretation of Creep Mechanisms in High Temperature Flow," Deformation, Processing, and Properties of Structural Materials (E.M. Taleff, C.K. Syn and D.R. Leseur, eds.), pp. 109-120. The Minerals, Metals and Materials Society, Warrendale, PA (2000).
7. T.G. Langdon, "Identifying Creep Mechanisms at Low Stresses," Materials Science and Engineering A283, 266-273 (2000).
8. M.Z. Berbon and T.G. Langdon, "A Discussion of Flow Mechanisms in Superplastic Yttria-Stabilized Tetragonal Zirconia," Materials Research Society Symposium Proceedings **601**, 105-110 (2000).
9. S.S. Sosa and T.G. Langdon, "Creep Behavior of a Superplastic Y-TZP/ Al_2O_3 Composite: An Examination of the Possibility of Diffusion Creep," Materials Research Society Symposium Proceedings **601**, 111-116 (2000).
10. S.S. Sosa and T.G. Langdon, "Deformation Characteristics of a 3Y-TZP/20% Al_2O_3 Composite in Tensile Creep," Materials Science Forum **357-359**, 135-140 (2001).
11. B.Q. Han and T.G. Langdon, "Factors Contributing to Creep Strengthening in Discontinuously Reinforced Materials," Materials Science and Engineering A322, 73-78 (2002).
12. T.G. Langdon, "Creep at Low Stresses: An Evaluation of Diffusion Creep and Harper-Dorn Creep as Viable Creep Mechanisms," Metallurgical and Materials Transactions A **33A**, 249-259 (2002).
13. T.G. Langdon, "The Role of Grain Boundary Sliding in Superplastic Metals and Ceramics," Proceedings of Iwasaki Workshop on Superplasticity (H. Iwasaki, ed.), pp. 25-42. Himeji Institute of technology, Himeji, Japan (2003).
14. N. Balasubramanian and T.G. Langdon, "Comment on the Role of Intragranular Dislocations in Superplastic Yttria-Stabilized Zirconia," Scripta Materialia **48**, 599-604 (2003).