[3] W. B. Gauster, "Ultrasonic Measurement of the Nonlinearity Parameters of Copper Single Crystals"; Ph.D. Thesis, University of Tennessee, Knoxville, 1966; *Dissertation Abstr.* B, **27** [9] 3245 (1967); *Univ. Microfilms* (Ann Arbor, Mich.), *Order No.* **67-1363**, 106 pp.

[4] D. O. Thompson, M. A. Breazeale, and W. B. Gauster, "A Capacity Microphone for Ultrasonic Measurements at Megacycle Frequencies"; paper presented at Conference on Acoustics of Solid Matter, Warsaw, Poland, 1964.

[5] A. L. Stanford, Jr., and S. P. Zehner, "Third-Order Elastic Constant c_{111} in NaCl and KCl," *Phys. Rev.*, **153** [3] 1025 (1967).

[6] M. A. Breazeale and Joseph Ford, "Ultrasonic Studies of the Nonlinear Behavior of Solids," *J. Appl. Phys.*, **36** [11] 3486 (1965).

[7] J. Hoerni and W. A. Wooster, "Determination of Elastic Constants of Lithium Fluoride from Photographs of Diffuse Reflections of X-Rays," *Acta Cryst.*, **5**, 386–88 (1952).

Effect of Particle Shape on the Kinetics of Sintering of Glass

IVAN B. CUTLER and ROY E. HENRICHSEN

FRENKEL[1] proposed sintering equations based on viscous deformation. A slight numerical error in Frenkel's equations was corrected by Eshelby.[2] The Frenkel mathematical model was used by Kuczynski[3] and by Kingery and Berg[4] in their studies of neck growth between spherical glass particles. Kuczynski and Zaplatynskyj[5] and Oel[6] measured the shrinkage of glass capillaries and confirmed the theory of Frenkel. Oel also measured the shrinkage of angular glass powder compacts. Henrichsen and Cutler[7] measured the shrinkage of spherical glass powder compacts. Each of the investigators obtained agreement between the experimental data and the form of the theoretical equations proposed by Frenkel. Oel obtained exact agreement between the viscosity of glass measured by more traditional methods and the shrinkage of glass capillaries.

The objective of the present experiments was to investigate the effect of particle shape on the rate of shrinkage of powder compacts. Shrinkage measurements were selected because of their sensitivity, ease with which the data may be accumulated, and the availability of a theoretical model for correlating the results.

The Frenkel equation predicts that the shrinkage of a compact of spherical powder will be linear with time. This may be expressed as:

$$\Delta L/L_0 = \gamma t/2a\eta \qquad (1)$$

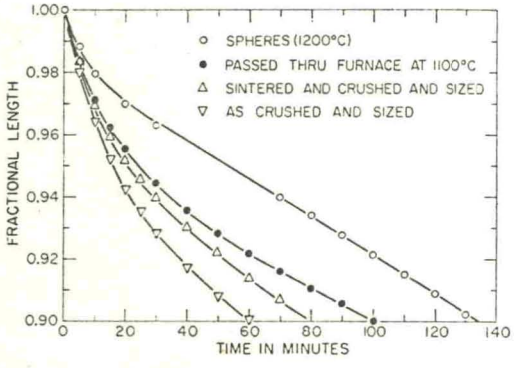

Fig. 1. Isothermal shrinkage of −140 +170 mesh Pennvernon glass sintered at 672°C. Spheres were made by dropping crushed glass through a furnace tube at 1200°C.

where $\Delta L/L_0 = (L_0 - L)/L_0$, L is the length at any time t, L_0 the original length, γ the surface tension, a the average radius of the spherical particles, and η the viscosity.

Powder compacts were prepared from two commercially available soda-lime glasses, one designated as Pennvernon sheet glass* and the other as R-6.† Various size fractions of crushed glass were obtained by sieving through standard sieves using methanol to aid in the size separation. Selected size fractions were spheroidized by feeding powders slowly through a vertical tube furnace. Since the spheroidizing operation tended to form some clusters, resieving of the particles was necessary. Also, spheroidizing produced undersized as well as oversized fractions. Temperature measurements were corrected with calibrated thermocouples. Shrinkage was measured on powder compacts 1 by 1 by 0.25 in. held together with a very dilute solution of polyvinyl alcohol. The apparatus for measuring shrinkage was previously described.[7] Time zero was taken as the time when the powder compact reached temperature after it was inserted in the furnace. This was easily observed as the time at which shrinkage was first observed.

Figure 1 shows the isothermal shrinkage of the Pennvernon glass. The crushed glass sinters much more rapidly than the spherical glass. The degree of sphericity of glass is best judged under a microscope. Figure 2 shows the four glass powders for which data are given in Fig. 1.

Because the glass powder may lose sodium oxide by evaporation when falling through the hot zone of the furnace and increase in viscosity, this hypothesis was tested by several experiments and chemical analyses. No evidence of loss of sodium oxide was observed.

The data show that crushed glass shrinks much more rapidly than spherical glass. The rate of shrinkage is not only a measure of viscosity, which should be identical for each of the samples in Fig. 1, but it is also inversely proportional to the radius of the

---

Presented at the Seventieth Annual Meeting, The American Ceramic Society, Chicago, Ill., April 23, 1968 (Basic Science Division, No. 34-B-68). Received April 17, 1968; revised copy received July 24, 1968.

This work was supported by the Materials Research Laboratory, University of Illinois under ARPA Contract SD-131 and Contract AEC-AT(11-1)-1122, University of Utah.

At the time this work was done the writers were, respectively, visiting professor and graduate student, Department of Ceramic Engineering, University of Illinois, Urbana, Illinois 61801. I. B. Cutler is now professor, Division of Materials Science and Engineering, College of Engineering, University of Utah, Salt Lake City, Utah 84112.

[1] Ya. I. Frenkel, "Viscous Flow of Crystalline Bodies Under Action of Surface Tension," *J. Phys. (USSR)*, **9** [5] 385–91 (1945) (in English).

[2] J. D. Eshelby, "Discussion of Paper by A. J. Shaler," *Trans. AIME*, **185** [11] 806 (1949).

[3] G. C. Kuczynski, "Study of Sintering of Glass," *J. Appl. Phys.*, **20** [12] 1160–63 (1949).

[4] W. D. Kingery and M. Berg, "Studies of Initial Stages of Sintering Solids by Viscous Flow, Evaporation-Condensation and Self-Diffusion," *ibid.*, **26** [10] 1205–12 (1955).

[5] G. C. Kuczynski and I. Zaplatynskyj, "Sintering of Glass," *J. Am. Ceram. Soc.*, **39** [10] 349–50 (1956).

[6] H. J. Oel; pp. 473–79 in Transactions of the VIIth International Ceramic Congress, London, 1960. The British Ceramic Society, Stoke-on-Trent, 1961.

[7] R. E. Henrichsen and I. B. Cutler, "Isothermal Shrinkage of Glass Powders Sintered by Viscous Deformation"; to be published in the *Proceedings of the British Ceramic Society*, No. 12.

* PPG Industries, Glass Division, Pittsburgh, Pa.

† Owens-Illinois, Inc., Toledo, Ohio