Table II. Calculated Value of $S/Ea$ for $(0.65Zn,0.35Mg)_2SiO_4$ and Other Oxides* During Cooling to 25°C

| Temp. (°C) | Willemite(ss) | Magnesium dititanate | Aluminum titanate | Cordierite | $Al_2O_3$ | BeO | MgO |
|---|---|---|---|---|---|---|---|
| 1000 | 345 | 90 | 123 | 330 | 50 | 23 | 41 |
| 800 | 230 | 40 | 330 | 358 | | | |
| 600 | 285 | 1000 | | 384 | | | |
| 400 | 360 | 320 | | 470 | 45 | 50 | 37 |
| 200 | 490 | 430 | | | | | |

* From Refs. 2 and 10.

(2) Calculated $S/Ea$ values and cyclic temperature tests indicate that the willemite solid solution has very good thermal shock resistance between room temperature and 1000°C.

### References


[1] Pu-Yi Wen, J. J. Brown, and F. A. Hummel, "Dilatometer and X-Ray Data for Zinc Compounds: I," *Trans. Brit. Ceram. Soc.*, **63** [9] 501–508 (1964).

[2] E. A. Bush, "Influence of Crystal Anisotropy on the Mechanical Properties of Single-Phase Ceramic Materials"; Ph.D. Thesis, The Pennsylvania State University, 1958; *Univ. Microfilms* (Ann Arbor, Mich.), *L. C. Card No.* **Mic 58–7266,** 161 pp.; *Dissertation Abstr.*, **19,** 1313 (1958).

[3] W. R. Buessem; pp. 127–48 in Mechanical Properties of Engineering Ceramics. Edited by W. W. Kriegel and Hayne Palmour III. Interscience Publishers, Inc., New York, 1961.

[4] E. A. Bush and F. A. Hummel, "High-Temperature Mechanical Properties of Ceramic Materials: I," *J. Am. Ceram. Soc.*, **41** [6] 189–95 (1958).

[5] F. H. Gillery and E. A. Bush, "Thermal Contraction of β-Eucryptite ($Li_2O \cdot Al_2O_3 \cdot 2SiO_2$) by X-Ray and Dilatometer Methods," *ibid.*, **42** [4] 175–77 (1959).

[6] J. F. Sarver and F. A. Hummel, "Solid Solubility and Eutectic Temperature in the System $Zn_2SiO_4$-$Mg_2SiO_4$," *ibid.*, **45** [6] 304 (1962).

[7] E. R. Segnit and A. E. Holland, "The System MgO-ZnO-$SiO_2$," *ibid.*, **48** [8] 409–13 (1965).

[8] H. E. Swanson, N. T. Gilfrich, and M. I. Cook, "Standard X-Ray Diffraction Powder Patterns, Vol. 7," *Natl. Bur. Std. (U. S.) Circ.* No. **539,** pp. 62–64 (1957).

[9] G. K. Dunsmore, "High-Temperature Mechanical Properties of Vitrified Porcelain Bodies"; M.S. Thesis, The Pennsylvania State University, 1961; Pattee Library, microfilm.

[10] W. D. Kingery, "Factors Affecting Thermal Stress Resistance of Ceramic Materials," *J. Am. Ceram. Soc.*, **38** [1] 3–15 (1955).

[11] F. A. Hummel, "Ceramic Bodies and Their Production," U. S. Pat. 3,169,072, February 9, 1965.


# Discussions and Notes

## Elastic Properties of Silicon Carbide

R. D. CARNAHAN

THIS note reports recent data on the elastic properties of pressure-sintered silicon carbide ranging from near theoretical density to 15% porosity and compares these data with those previously reported.[1–4] The samples used in the present investigation were prepared by hot-pressing in graphite dies using high-purity* SiC powder having a particle size of 7μ. To fabricate very high-density SiC, 1 wt% aluminum powder was dry-blended with some of the SiC to act as a densification aid. An optimum hot-pressing cycle of 6000 psi for 15 min at 2100°C, subsequent removal of pressure, and in situ cooling at a rate of 5°C/min resulted in fabrication of billets having densities as high as 3.2057 g/cm³ or 99.93% of theoretical density (3.208 g/cm³). Although similar compositions were previously referred to as metal bonded,[5] spectrographic analysis showed a residual of only 19 ppm Al in the high-density SiC. This quantity is not considered to be enough to disturb the experimental results. X-ray analysis indicated only the presence of α-SiC.

Samples were prepared from the hot-pressed billets as right circular cylinders 1/4 in. in diameter and 1 to 1 1/2 in. long. Densities were determined relative to a sapphire crystal calibrated as a secondary standard using distilled water for immersion. The Young's modulus and shear modulus of elasticity were then determined by the resonance method. The fundamental and at least the first overtone were determined for each mode of vibration. The experimental data from this investigation are listed in Table I and are plotted in Fig. 1 along with all other known data ob-

Table I. Young's and Shear Moduli of Hot-Pressed SiC

| Density (g/cm³) | $E$ (kbars) | $G$ (kbars) |
|---|---|---|
| 2.7067 | 2406.1 | 999.1 |
| 2.7637 | 2323.9 | 1018.6 |
| 3.0347 | 3628.5 | 1544.8 |
| 3.1413 | 4102.6 | 1748.6 |
| 3.2033 | 4408.9 | 1891.9 |
| 3.2037 | 4438.7 | 1890.0 |
| 3.2057 | 4454.8 | 1899.9 |

NOTE: Kilobars × 14,503.8 = psi.

Received December 6, 1967.

The writer is assistant department head, Metallurgy & Ceramics, Materials Sciences Laboratory, Aerospace Corporation, Los Angeles, California 90045.

* High-purity, 7μ, light, 99% SiC from the Carborundum Company.


[1] S. M. Lang, "Properties of High-Temperature Ceramics and Cermets—Elasticity and Density at Room Temperature," *Natl. Bur. Std. (U. S.) Monograph,* No. **6,** 45 pp. (1960).

[2] J. B. Wachtman, Jr., and D. G. Lam, Jr., "Young's Modulus of Various Refractory Materials as a Function of Temperature," *J. Am. Ceram. Soc.*, **42** [5] 254–60 (1959).

tainable from the literature as a function of porosity, defined as the difference between actual and theoretical densities.

A least-squares analysis of the data plotted in Fig. 1 yielded the following empirical equations for Young's modulus and the shear modulus:

$$E = 4480 \exp^{-4.19P} \text{ kbars} \quad (1)$$

and

$$G = 1920 \exp^{-4.27P} \text{ kbars} \quad (2)$$

where $P$ is the volume fraction of porosity. The slopes, $-4.19$ and $-4.27$, are typical of those for materials containing nonspherical porosity.[6] Using the zero porosity values of 4480 and 1920 kbars, respectively, for Young's and shear moduli, the bulk modulus $K$ was calculated to be 2250 kbars, and Poisson's ratio, $\mu$, 0.168.

These values, except for Poisson's ratio, are slightly lower than the extrapolations reported by Schreiber and Soga[4]; however, their suitability as end-point values for SiC is supported by the closeness of fit of the data from the five independent investigations to the curves predicted by the least-squares analysis.

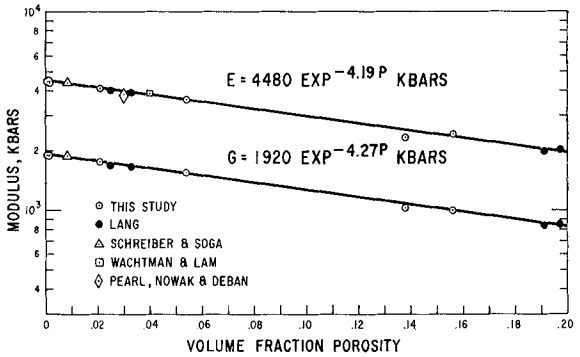


**Fig. 1. Young's and shear moduli as a function of volume fraction porosity (SiC).**

[3] H. A. Pearl, J. M. Nowak, and H. G. DeBan, "Mechanical Properties of Selected Alloys at Elevated Temperatures: II," Tech. Rept. No. WADC-TR-59-702, Pt. II; Contract AF33-(616)-5760, 134 pp., January 1960.

[4] Edward Schreiber and Naohiro Soga, "Elastic Constants of Silicon Carbide," *J. Am. Ceram. Soc.*, **49** [6] 342 (1966).

[5] R. E. Wilson, L. B. Coffin, and J. R. Tinklepaugh, "Metal and Self-Bonded Silicon Carbide," Tech. Rept. No. WADC-TR-54-38, Pt. II; Contract AF33(038)-16190, 40 pp., January 1955.

[6] K. R. Janowski and R. C. Rossi, "Elastic Behavior of MgO Matrix Composites," *J. Am. Ceram. Soc.*, **50** [11] 599-603 (1967)

# Grain Growth During Hot-Pressing of Tantalum Carbide

E. ROEDER and J. HORNSTRA

EARLIER studies of grain growth in hot-pressed tantalum carbide and niobium carbide powders with small additions (up to 1 wt%) of manganese, iron, cobalt, or nickel metal powder revealed a linear relation between mean grain size and hot-pressing time.[1] The growth rate is influenced by the kind and quantity of the additive and by densification temperature and pressure. The time dependence mentioned corresponds to the equation for normal grain growth in a pure system deduced by Burke and Turnbull.[2] The present note deals with observations on the growth kinetics during hot-pressing of tantalum carbide powder in the presence of a small quantity of the liquid grain boundary phase.

Figure 1 shows the microstructure of a tantalum carbide compact containing 1 wt% manganese which was hot-pressed for 80 min at 1800°C under 500 kg/cm² pressure. A cross section was polished with diamond and alumina powder and finally etched for 2 min in a solution of 1 part 40% HF and 3 parts concentrated $HNO_3$. The photomicrograph was made by the interference contrast method.*

Received November 10, 1967.

The writers are research scientists at Philips Zentral-laboratorium GmbH, Aachen, Germany, and Natuur-kundig Laboratorium, N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands, respectively.

[1] B. Lersmacher, E. Roeder, and S. Scholz, "Effect of Small Additions of Mn, Fe, Co, and Ni on the Grain Growth of TaC and NbC," *Naturwissenschaften*, **49** [2] 35 (1962).

[2] (*a*) J. E. Burke and D. Turnbull; pp. 220-92 in Progress in Metal Physics, Vol. III. Edited by Bruce Chalmers. Pergamon Press Ltd., London, 1952.

(*b*) R. L. Coble and J. E. Burke; pp. 197-251 in Progress in Ceramic Science, Vol. 3. Edited by J. E. Burke. Pergamon Press, New York, 1963.

* Universalkamera-Mikroskop MeF with interference contrast attachment after Nomarski, C. Reichert, Vienna, Austria.

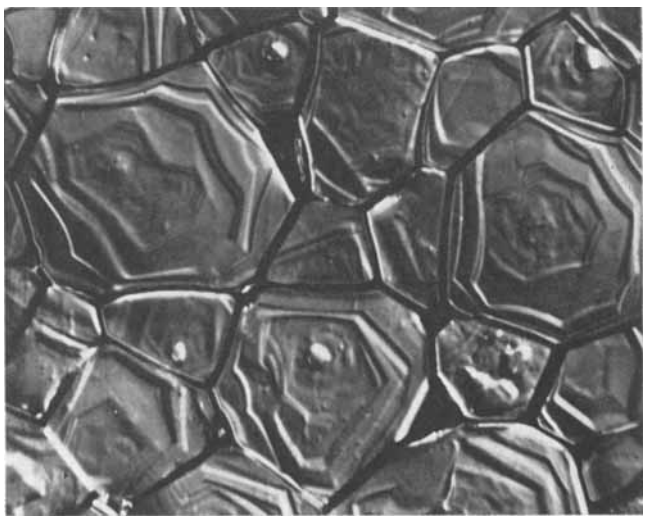

**Fig. 1. Hot-pressed tantalum carbide. (×740.)**

The grains in Fig. 1 clearly show various stages of growth. The "core" of some of the grains is thought to come from an original powder particle. From this core, further growth occurs by a solution and reprecipitation process, because the hot-pressing temperature is above the melting point of the additive. The photomicrograph shows that the grain boundaries move toward their center of curvature. This confirms that, during the later stage of hot-pressing, normal grain growth occurs under the driving force of surface free energy. Thereby, as is also visible, grains with fewer than six sides become smaller and are finally