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John B. Wachtman, Jr.
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Strength of Sapphire in Tension as Measured by Flat Plate Pressure Loading to Burst Tests

CRAIG E. JENSON AND CARL MOUNTEER

Gulton, Servonic Division
A MARK IV COMPANY
Costa Mesa, CA 92627

The design of pressure transducers has required using low hysteresis, high strength materials. Single crystal sapphire was selected based on strength data for filaments and whiskers. Development of fabrication processes providing sapphire parts with strengths approaching filament data has been the focus of activity for developing new transducer technology. Various sapphire material conditions were tested to determine tensile strengths. Crystal orientation, surface finish, and thermal history were independent variables. The objective of the experiments was to determine the design limits for a pressurized flat plate; boundary conditions for the plate were considered. Damaged surfaces produced the lowest strength flat plates, but annealing was determined to restore significant tensile strength. Tensile strengths greater than 1.24 GPa (180 000 psi) were observed.

Introduction

The authors are aware of two uses for sapphire in disk form that require a good understanding of strength in tension. The first is the sapphire window subjected to differential pressure; the second is the use of sapphire as a pressure diaphragm in a pressure measurement transducer. The authors are designing with sapphire as an integral diaphragm for strain gage pressure transducers. During the process of designing and building pressure transducers using sapphire as a diaphragm with integral strain gages made by sputter deposition of platinum alloy, the authors found that tensile strength data for fabricated sapphire are sparse and incomplete. The strain gaged diaphragm itself was seen as an unusually convenient form to measure the strength of sapphire which had been processed in various ways. The results of processing sapphire for maximum tensile strength are reported herein.

Background

The pressure transducer is a Wheatstone Bridge arrangement of 1000 to 2000 ohm resistors with a typical excitation of 10 V dc to make strain measurements. The gage factor of the sputtered, thin film resistors determines output signal levels. Experience shows that the gage factor for noble metal in thin-film form is 2.0. This results in a signal level at a full range strain of 1000 microstrain (micro inch per inch) equal to 2.0 millivolts per volt of excitation. Sapphire, at this strain level and with a modulous of elasticity of 482.63×10^9 Pa (70 000 000 psi) is subjected to a stress of 482.63×10^6 Pa (70 000 psi). Pressure transducers are required to withstand an overpressure of three times full scale. The overload will stress the sapphire to 1.45×10^9 Pa (210 000 psi), well beyond sales literature values of 344.74×10^6 to 482.63×10^6 Pa (50 000 to 70 000 psi). Transducer designers must find ways of treating the sapphire to approach the filament strengths reported to be greater than 1.72×10 Pa (250 000) psi. [1,2]

Experimental Methods and Analyses

Two independent methods are used to determine stress during pressure loading of the sapphire diaphragms. One method is strain measurement. An effective gage factor for sputter deposited, noble metal strain gage has been determined by deflection analysis for a silicon diaphragm pressure sensor. The micromachined silicon diaphragm has three thick sections, called *mesas,* to concentrate strain on the thin sections, called *hinges,* where strain gages have been placed. (See Figure 1*(A)*.) The deflection analysis and gage factor calculation description are presented below.

From Figure 1*B*, the deflection, w, is

$$w = 2R(1-\cos\Theta)+m(\sin\Theta) \tag{1}$$

where R = radius of curvature of strained hinge,
m = width of the outer mesa, and
Θ = angle of repose of the outer mesa
and Θ is defined by:

$$\Theta = s/R \tag{2}$$

where s = hinge width

The strain is defined by assuming a cylindrical deflection shape for the hinge:

$$e = h/2R \tag{3}$$

where h = hinge thickness

A 103.42×10^3 Pa (15 psia) sensor has the following dimensions and deflection:

$s = 203 \times 10^{-6}$ m (0.008 inch)
$m = 914.4 \times 10^{-6}$ m (0.036 inch)
$h = 60.96 \times 10^{-6}$ m (0.0024 inch)
$w = 9.14 \times 10^{-6}$ m (0.00036 inch)

When these dimensions are substituted into Eq. (1) and (2) we can write $0.00036 = (2R)[1 - \cos(0.008/R)] + 0.036 \sin(0.008/R)$. This can be solved iteratively and in so doing we find that $R = 0.978$ in.
Then the strain is $h/2R = 0.0024/2 \times 0.978 = 0.001227$, so, $dL/L = e = 0.001227$.
Data for the barometric sensor show a 2.4 mv/V signal level for a full scale pressure load. Gage factor may be calculated as follows:

$$F = (dR/R)/e = (dV/V)/e \tag{4}$$

where (dR/R) = relative change in resistance due to the strain
(dV/V) = relative change in bridge output voltage due to the strain
$F = 0.0024/0.001227 \approx 2.0$

With the gage factor known, strain measurements may be made and stress levels calculated as shown below:

$$e = (dV/V)/F \tag{5}$$

$$\text{Stress} = Ee \tag{6}$$

where E = modulus of elasticity in tension

Stress = maximum tensile stress on the diaphragm surface

The second method for determining stress is a theoretical calculation based on deflection/stress theory for flat plates. The maximum stress for a uniform, circular flat plate is calculated as shown below.[3,4]

$$\text{Radial Stress} = (3/4)P(a^2/h^2) \tag{7}$$

where p = pressure
a = plate radius
h = plate thickness

The maximum stress is at the edge of the plate on the pressurized surface. The model used must consider the effects of boundary conditions. The ultrasonically machined cavity depth is three-quarters of the total sapphire blank thickness. The sapphire material surrounding the diaphragm is always four times thicker than the diaphragm. Based on this diaphragm to support thickness ratio, a rigidly clamped boundary condition is assumed. Calculation of stress for a given pressure load is possible with a known boundary condition using the references given.

Tensile Strength Testing Results

Tensile strength estimates based on one or both of the methods previously described are shown below in Table I for various types of material. A brief description of each type of sapphire is provided. Differences in raw material and processing make each type of sapphire unique. SEM photographs in Figs. 2 and 3 show the machined cavity and the resulting surface damage for the test specimens. Figure 4 shows the specimen test setup.

Conclusion

The data show the unmachined substrate material is stronger than the ultrasonically machined material with a subsequent 1500°C stress relieve process. The design stress limit for single crystal sapphire is shown to be greater than 1.24 GPa (180 000 psi) with margin bsaed on strain gage data. More testing is required before a thorough error analysis is possible. No conclusion about strength variations due to crystal orientation is possible until additional testing is completed. The pursuit of high tensile strength for crystalline materials in fabricated forms will be a continuing effort for pressure transducer engineers.

References

[1]LaBelle, H. E., Jr., and Mlavsky, A. I., "Growth of Sapphire Filaments from the Melt," *Nature*, **216**, 574–575 (November 11, 1967).

[2]Hurley, G. F., "Short-Term Elevated Temperature Tensile Behaviour in O Sapphire Filament," *Journal of Material Science*, **7** (4), 471–473 (1972).

[3]R. J. Roark, Formulas for Stress and Strain, Pages 216–217, McGraw Hill, 1965.

[4]Timoshenko and Woinowsky-Krieger, Theory of Plates and Shells, pages 55 & 56.

Table I. Sapphire Tensile Strength for Various Fabrication Processes

Sapphire Fabrication Process Description	Stress Measurement Method	Stress Measurement at Failure, MPa (psi)
Union Carbide SOS substrate, 90° crystal orientation, polished side of wafer	Strain gauge data	924.85 MPa (134 138 psi)
	Deflection/stress model	850.38 MPa (123 337 psi)
Union Carbide 90° crystal orientation, ultrasonically machined, 1500°C stress relieve, diamond grit polishing	Deflection/stress model	769.25 MPa (111 570 psi) 916.91 MPa (132 986 psi) 854.72 MPa (123 967 psi)
Union Carbide 90° crystal orientation, ultrasonically machined, no polishing attempted, 1500°C stress relieve	Deflection/stress model	562.52 MPa (81 586 psi) 570.25 MPa 82 708 psi 551.20 MPa (79 945 psi) 562.52 MPa 81 586 psi 562.52 MPa (81 586 psi) 766.88 MPa (111 227 psi) 622.09 MPa (90 227 psi) 622.09 MPa (90 227 psi)
Crystal Systems 90° crystal orientation, heat exchange growth, ultrasonically machined, diamond grit polishing 1500°C stress relieve	Strain gauge data	755.56 MPa (109 585 psi)
	Strain gauge data	783.58 MPa (113 663 psi)
	Deflection/stress model	751.69 MPa (109 024 psi)
	Deflection/stress model	575.86 MPa (83 521 psi)
	Deflection/stress model	565.49 MPa (82 018 psi)
	Deflection/stress model	551.43 MPa (79 978 psi)
Crystal Systems 0° crystal orientation, heat exchange growth, ultrasonic machining, 1950°C anneal	Strain gauge data	1570 MPa (227 500 psi)
	Strain gauge data	1400 MPa (203 000 psi)
	Deflection/stress model	1100 MPa (159 763 psi)
Crystal Systems 90° crystal orientation, heat exchange growth ultrasonic machining, 1950°C anneal	Strain gauge data	972.51 MPa min. (141 050 psia min.) NOTE: Test fixture failed at 10,000 psia before sapphire burst

(A)

(B)

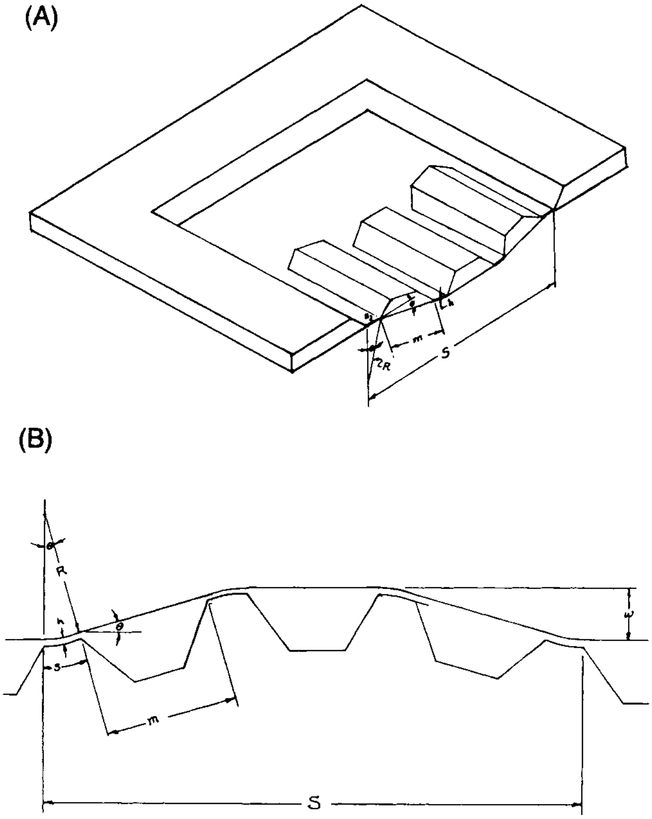

Fig. 1. Silicon diaphragm pressure sensor: (*A*) sectioned diaphragm, (*B*) magnified cross section.

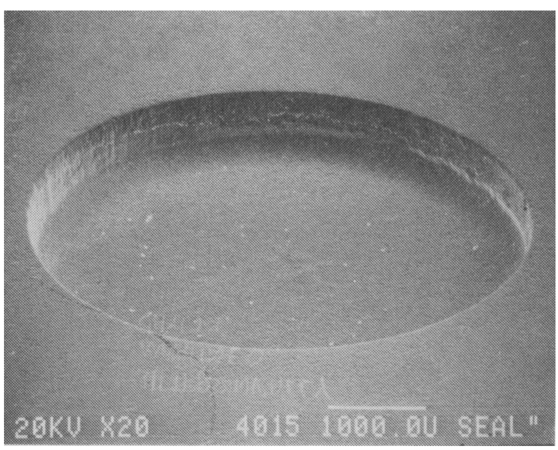

Fig. 2. SEM photo of ultrasonically machined cavity in sapphire to make a rigidly clamped diaphragm for burst testing (magnified 20×).

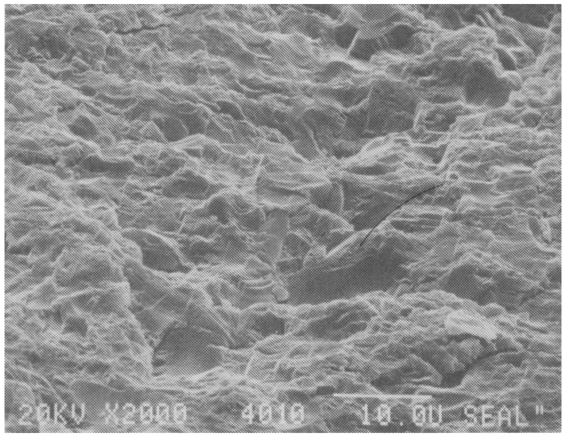

Fig. 3. SEM photo of machining damage to 90° sapphire due to ultrasonic machining of diaphragm surface (2000 ×).

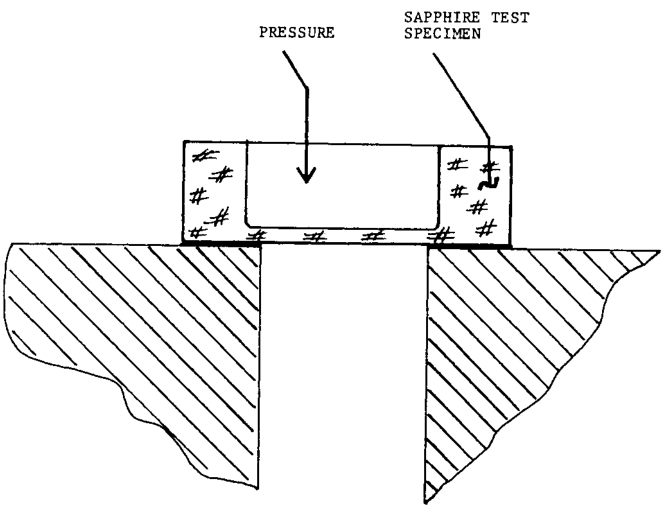

Fig. 4. Sapphire diaphragm burst testing setup.