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TECHNICAL DIVISION
Engineering Development Section

THERMAL STRESSES IN BERYLLIUM

H. C. Savage

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1.0 ABSTRACT

Thermal stresses produced experimentally in various specimens of beryllium cylinders were large enough to cause failure. Experimental results compare with theoretical calculations which may be used to determine expected thermal stresses in beryllium where the heat flow and geometry of the material is similar to the case presented in this report.

2.0 INTRODUCTION

A previous investigation of the thermal stresses in beryllium cylinders (ORNL-73) did not produce stresses large enough to cause failure of the beryllium. In addition no attempt was made to measure the temperature drop through the metal and the physical properties of the pieces tested were not known.

The purpose of the present investigation was to obtain more complete information and to test the pieces to failure. This was accomplished and a theoretical analysis compared with experimental results.

3.0 EXPERIMENTAL PROCEDURE

Beryllium

Samples of both extruded and QM beryllium were tested. The extruded beryllium samples were 1 1/2 inches O.D. cylinders with a 3/16 inch axial

3.0 EXPERIMENTAL PROCEDURE (Con't.)

hole. Two different lengths of 6 inches and 3 inches were used. The outside diameter of the QM beryllium was limited to 1 inch with the present supply of beryllium. The length of the QM beryllium cylinders was 3 inches with a 3/16 inch axial hole.

Tensile test specimens were machined from the same pieces of beryllium from which the test cylinders were taken and tensile tests run.

Procedure

The beryllium cylinders were heated at the outside surfaces by induction. The axial hole surface was water cooled. The water flow and temperature rise of the water were measured for calculation of total heat transfer across the cylinder walls. On several of the cylinders the temperatures near the outside surface and inside surface were measured using iron-constantan thermocouples so that a comparison between the measured and calculated temperature gradient could be made. As long as the thermocouples were a small distance from the outside surface, the induced field had little, if any, affect on the thermocouples.

Induction Heating Equipment

Two induction heating units were used. One was a Lapel, 100 KC induction heating unit with a maximum rated output of 30 KW. The other was a Megatherm Model MI-50-A, 220 KC induction heating unit with a maximum rated output of 50 KW. Because of the small size of the load used the maximum output obtained on either machine was approximately 8 KW.

4.0 CALCULATIONS

Formulae used are those for tubes of infinite length in which the heat is produced at the outer surface and removed from the surface of an axial hole. The maximum stress (tension) occurs at the surface of the axial hole.

Longitudinal and tangential stress at surface of axial hole:

$$\sigma = \frac{E \alpha Q a^2}{8k(1-\nu)} \left[4 P^2 \ln P - 2 P^2 + 2\right] \qquad (1)$$

$$\sigma = - \frac{\Delta T \alpha E}{2(1-\nu)\ln P} \left[\frac{1 - 2 P^2 \ln P}{P^2 - 1}\right] \qquad (2)$$

Longitudinal and tangential stress at outer surface:

$$\sigma = - \frac{E \alpha Q a^2}{8k (1-\nu)} \left[4 \ln P - 2 P^2 + 2\right] \qquad (1)$$

$$\sigma = - \frac{\Delta T E \alpha}{2(1-\nu)\ln P} \left[1 - \frac{2 \ln P}{P^2 - 1}\right] \qquad (2)$$

The equations from references (1) and (2) give the same results.

The value of equations from reference (2) is in calculating stresses using measured or known temperature drops. The calculated temperature gradient, ΔT, is obtained from the relationship

$$T = \frac{H}{2\pi k} \ln r/a = \frac{Q(P^2 - 1)}{2k} a^2 \ln r/a.$$

4.0 CALCULATIONS (Con't.)

Units:

σ = longitudinal and tangential stress, lb/in^2

E = Young's modulus = 40×10^6 lb/in^2

α = coefficient of linear expansion = 13×10^{-6} per ^oC

Q = heat removed, $cal/(cm^3)(sec.)$

a = radius of axial hole, cm.

b = outer radius of cylinder, cm.

k = thermal conductivity = 0.4 $cal/(cm^2)(sec)(^oC/cm)$

ν = Poisson's ratio $\cong$ 0.03

P = b/a

T = temperature difference, $T_b - T_a$, ^oC

H = heat transferred, cal/(sec)(cm. of length)

Then

$$\frac{E\alpha}{8k(1-\nu)} = \frac{40 \times 10^6 \times 13 \times 10^{-6}}{8 \times 0.4 \times 0.97} = \frac{167(lb)(cm)(sec)}{(in^2)(cal)}$$

$$\frac{E\alpha}{2(1-\nu)} = \frac{40 \times 10^6 \times 13 \times 10^{-6}}{2 \times 0.97} = \frac{268(lb)}{(in^2)(^oC)}$$

5.0 EXPERIMENTAL RESULTS

Test work was conducted on six beryllium cylinders as tabulated below:

Cylinder No.	Type Beryllium	Length cm	Outside Diameter cm	Axial Hole Diameter cm
1*	Extruded	15.2	3.8	0.476
2*	Extruded	15.2	3.8	0.476
3**	Extruded	7.6	3.8	0.476
4**	Extruded	7.6	3.8	0.476
5	QM	7.6	2.5	0.476
6	QM	7.6	2.5	0.476

* Longitudinal axis parallel to direction of extruding.

** Longitudinal axis perpendicular to direction of extruding.

Sufficient thermal stress was applied to all samples to cause failure by cracking. For the samples of extruded beryllium failure always occurred first in the direction of minimum physical properties which is transverse to the direction of extruding. The tensile strength of the beryllium tested was measured on tensile samples cut from the same pieces. The compressive strength values were obtained from recent tests conducted by George Adamson of the Metallurgy Division. The results obtained were not consistent. In one case only a minimum compressive strength is shown.

These compressive strengths are included merely to indicate that compressive strengths of beryllium are large in comparison with tensile

5.0 EXPERIMENTAL RESULTS (Con't.)

strengths. The tensile and compressive strength of the material is tabulated below:

Type Beryllium	Tensile Strength psi	Compressive Strength psi
Extruded*	26,600	>120,000
Extruded**	14,000	70,000 - 100,000
QM	28,300	>130,000

* Specimen taken parallel to direction of extruding.
** Specimen taken perpendicular to direction of extruding.

The thermal stress applied during each test is calculated as follows:

For test No. 1, cylinder No. 1

Cooling water flow = 10 lbs./min

Inlet temperature = 17 °C

Outlet temperature = 38 °C

Temperature rise = 21 °C = 37.8 °F

Total heat removed = 10 # H_2O/min x 37.8 °F x 0.0175 $\frac{KW}{BTU/min}$ = 7.0 KW

= 7.0 KW x 238.9 $\frac{cal/sec}{KW}$ = 1670 cal/sec.

Length of specimen = 15.2 cm.

b = 1.90 cm.
a = 0.238 cm.

5.0 EXPERIMENTAL RESULTS (Con't.)

Volume of Specimen = 169 cm^3

$$Q = 9.9 \text{ cal/cm}^3 \text{ sec}$$
$$P = b/a = 8$$

$$T \text{ (measured)} = T_b - T_a = 175^\circ F = 97.5\ ^\circ C$$

$$T \text{ (calc.)} = \frac{Q(P^2-1)a^2}{2k} \ln r/a = 91\ ^\circ C = 163\ ^\circ F$$

$$(4 P^2 \ln P - 2P^2 + 2) = 406$$

$$1 - \frac{2P^2}{P^2 - 1} \ln P = -3.22$$

at surface of axial hole, a

(1) $\text{(calc)} = 167 \times 9.9 \times 406 \times 0.238^2 = 37{,}500$ psi (tension)

(2) $\text{(calc)} = -\frac{268\ (91)\ (-3.22)}{2.08} = 37{,}500$ psi (tension)

(2) $\text{(meas.)} = -\frac{268(97.5)\ (-3.22)}{2.08} = 40{,}000$ psi (tension)

at outer surface, b

$$(4 \ln P - 2 P^2 + 2) = -118$$

$$1 - \frac{2 \ln P}{P^2 - 1} = 0.93$$

(1) $\text{(calc.)} = 167 \times 9.9\ (-118)\ 0.238^2 = -10{,}900$ psi (compression)

(2) $\text{(calc.)} = \frac{-268 \times (91)0.93}{2.08} = -10{,}900$ psi (compression)

(3) $\text{(meas.)} = -268(97.5)(0.93)/2.08 = -11{,}700$ psi (compression)

5.0 EXPERIMENTAL RESULTS (Con't.)

Tabulated results for all tests are given in Table I. Although calculated stresses are given, it should not be inferred that these stresses actually occur in the material. Because some of the stresses where no failure was observed were greater than the ultimate strength of beryllium, it must be assumed that the small amount of material for which the stress was a maximum (at surface of axial hole) underwent some deformation without cracking or that small cracks were not detected. The detection of cracks at the surface of the axial hole was quite difficult and only very pronounced cracks could be seen. Pieces that failed were cross-sectioned and photographs of cracks are included at the end of the report. It will be noted in Table I that 100 thermal cycles at a stress of 37,500 caused failure, one or two initial cycles did not produce a visible failure.

TABLE I

Cylinder No.	Volume cm.3	Heat Removed cal/sec	Q(cal) / cm^3 sec	P	Thermal Cycles	T, °C calc.	T, °C measured
1	169	1670	9.9	8	2	91	97.5
1	169	1800	10.6	8	2	96	96.0
1	169	1800	10.6	8	100	--	---
2	83	1800	21.2	8	2	197	250
3	83	1800	21.2	8	2	---	---
4	83	1800	21.2	8	2	---	---
5	38	1290	34.0	5.3	20	---	---
6	38	1730	45.6	5.3	25	---	---

Cylinder No.	Calculated Stress Outer surface psi	Calculated Stress Axial hole psi	Observations*
1	-10,900	37,500	No cracks
1	-11,700	40,200	No cracks
1	-11,700	40,200	Cracks at surface of axial hole
2	-23,400	80,400	Cracks at surface of axial hole
3	-23,400	80,400	Cracks at surface of axial hole and outer surface
4	-23,400	80,400	Cracks at surface of axial hole and outer surface
5	-15,600	42,700	Small surface cracks at surface of axial hole
6	-20,500	57,200	Small surface cracks at surface of axial hole

*Photographs of cracks in all cylinders are included at the end of the report.

6.0 CONCLUSIONS

All samples in which cracking or failure due to thermal stress occurred were calculated to have stresses well above the measured ultimate for the beryllium as tested. Thus it can be concluded that the formulae given are satisfactory for predicting allowable thermal stresses in beryllium with heat flow patterns and geometries similar to the case presented. Additional formulae are given in reference (1).

The smallest calculated thermal stress at which failure occurred was 37,500 psi. This is well above the measured ultimate strength of 26,600 psi (parallel to the direction of extruding) and 14,000 psi (perpendicular to the direction of extruding) for the extruded beryllium and 28,300 psi for the QM beryllium. Even if a value of Young's modulus for beryllium of 30×10^6 (3) psi were used in the calculations, the minimum calculated stress at failure would be 28,200 psi which is equal to the maximum measured ultimate strength of QM beryllium.

7.0 ACKNOWLEDGMENT

Considerable credit is due Mr. R. B. Briggs of the Design Section for his advice and suggestions pertaining to this investigation.

8.0 REFERENCES

(1) Briggs, R. B., Thermal Stresses in Cylinders, memo to file, December 1, 1947.

(2) Roark, R. J., Formulas for Stress and Strain, page 325, McGraw-Hill, 1943.

(3) Savage, H. C., Measurement of Poisson's Ratio of Beryllium with Electric Strain Gages, Report ORNL-524.

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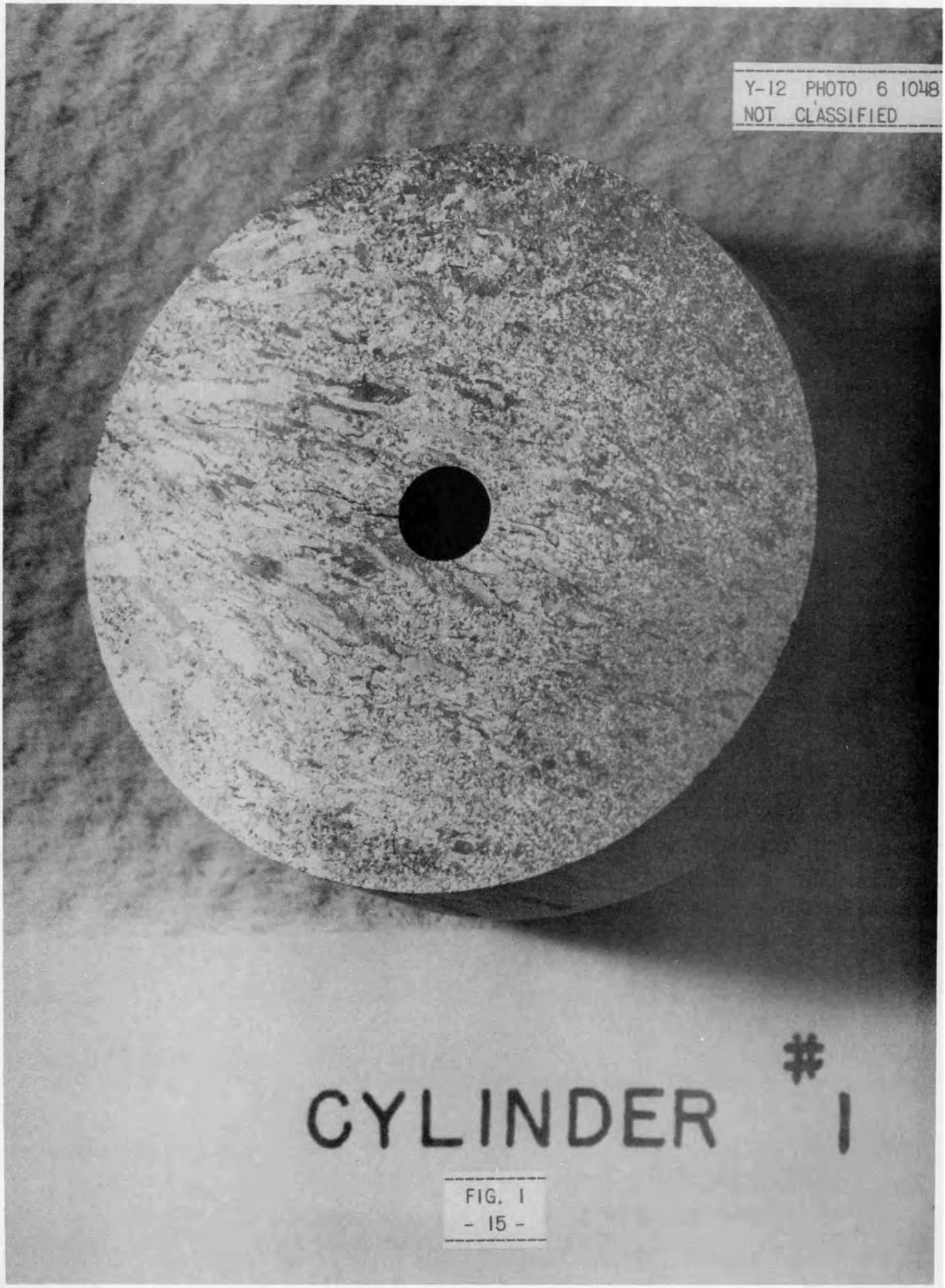


FIG. 1

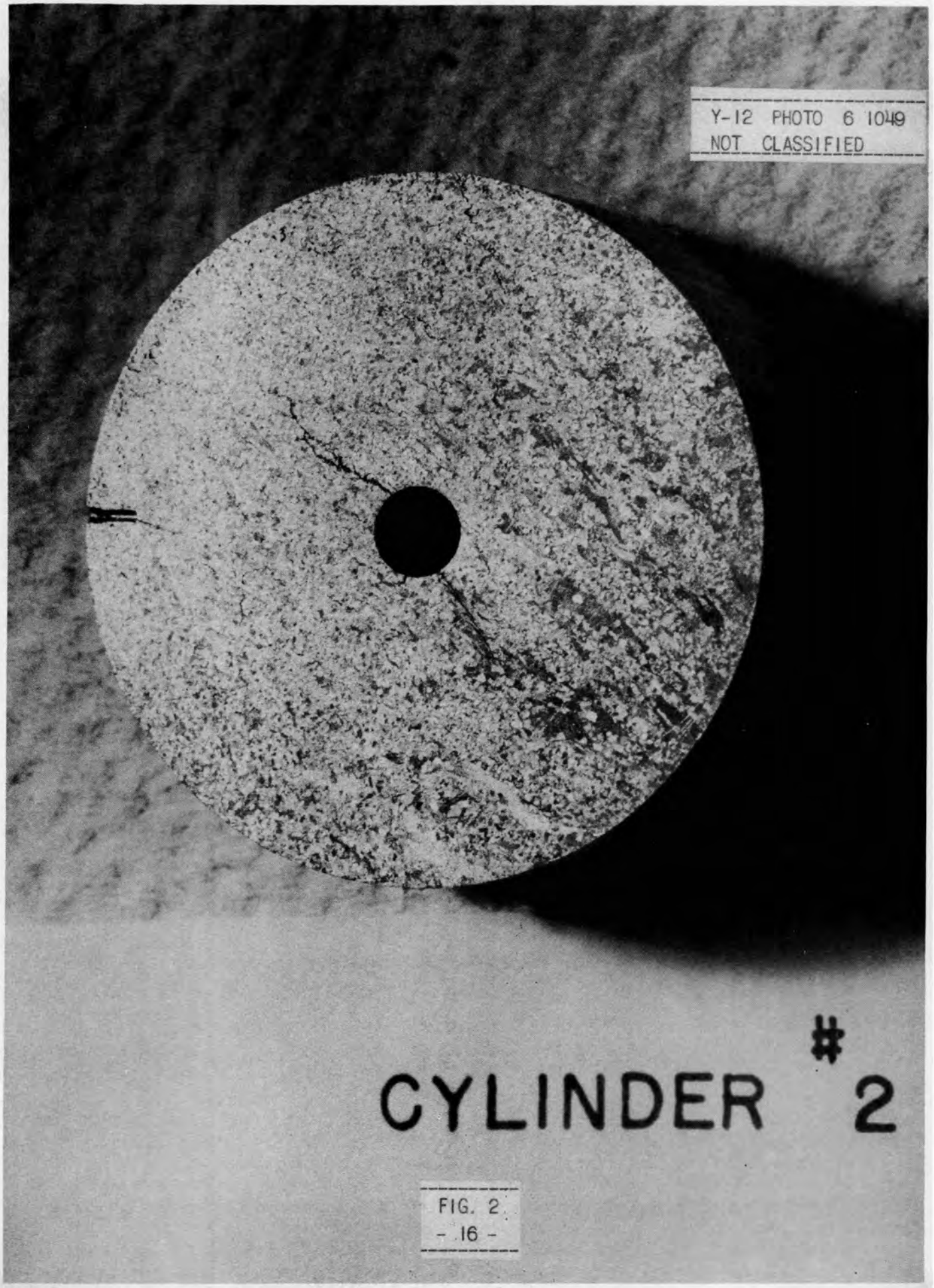
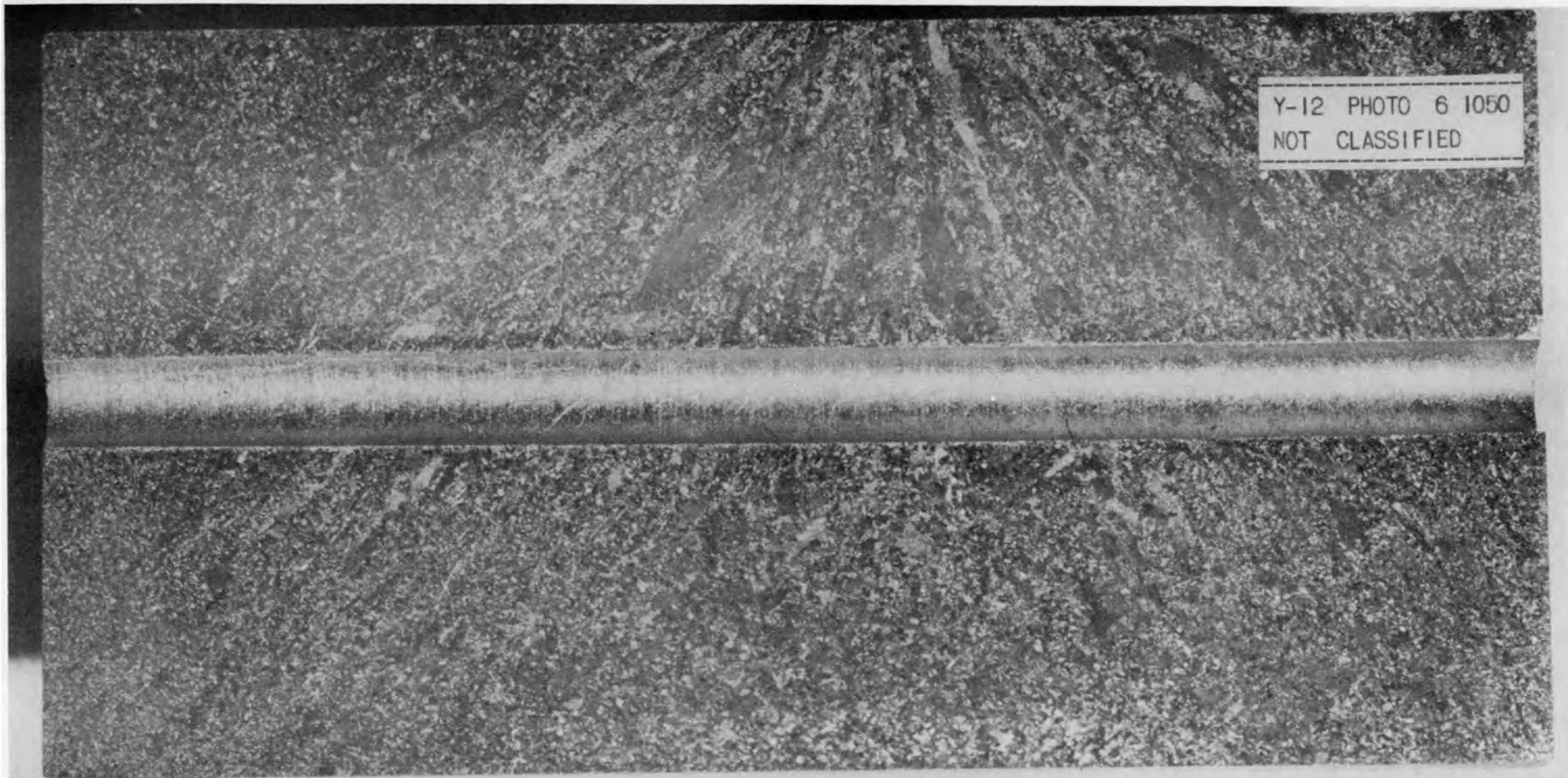
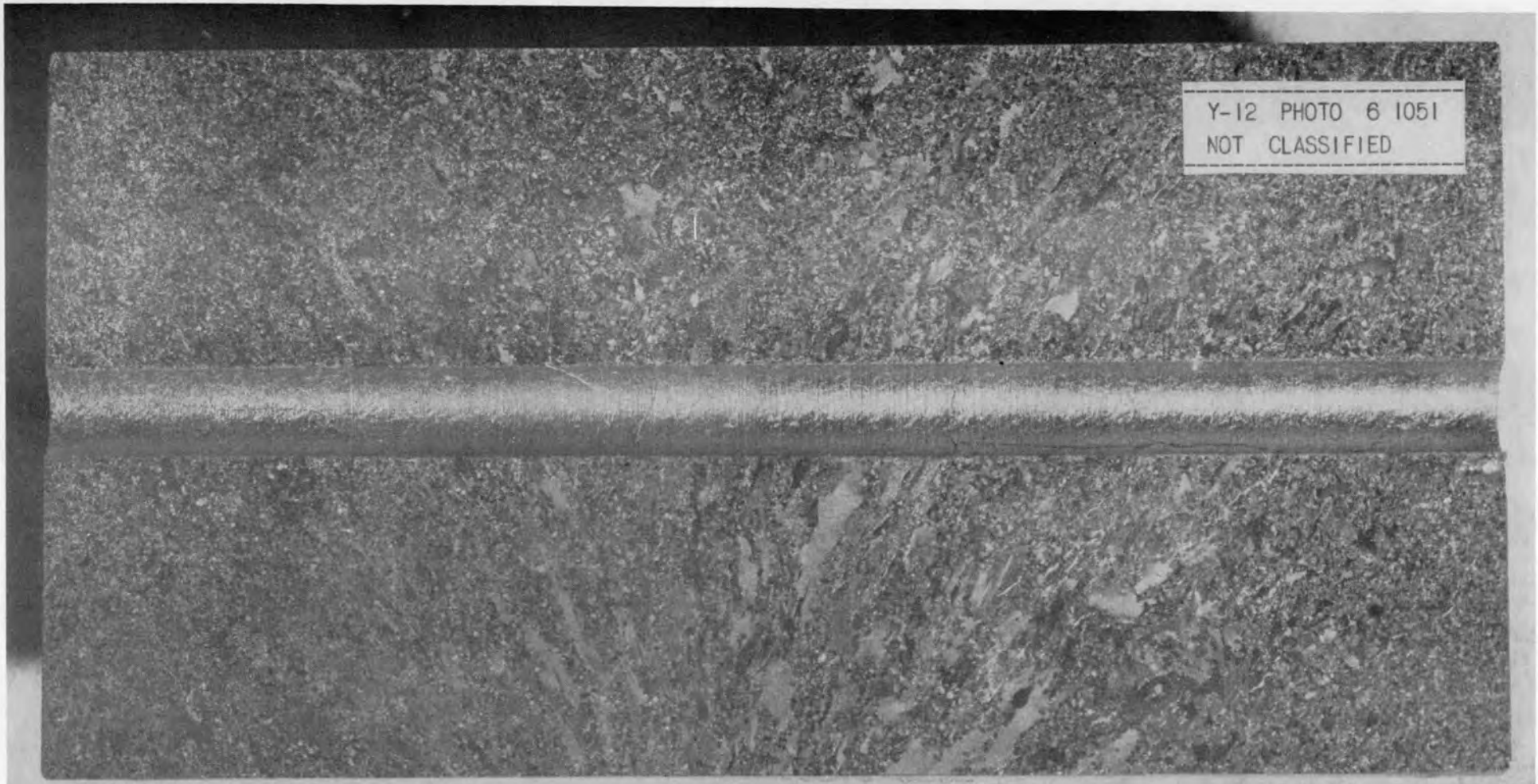


FIG. 2



CYLINDER # 3

FIG. 3



CYLINDER # 4

FIG. 4

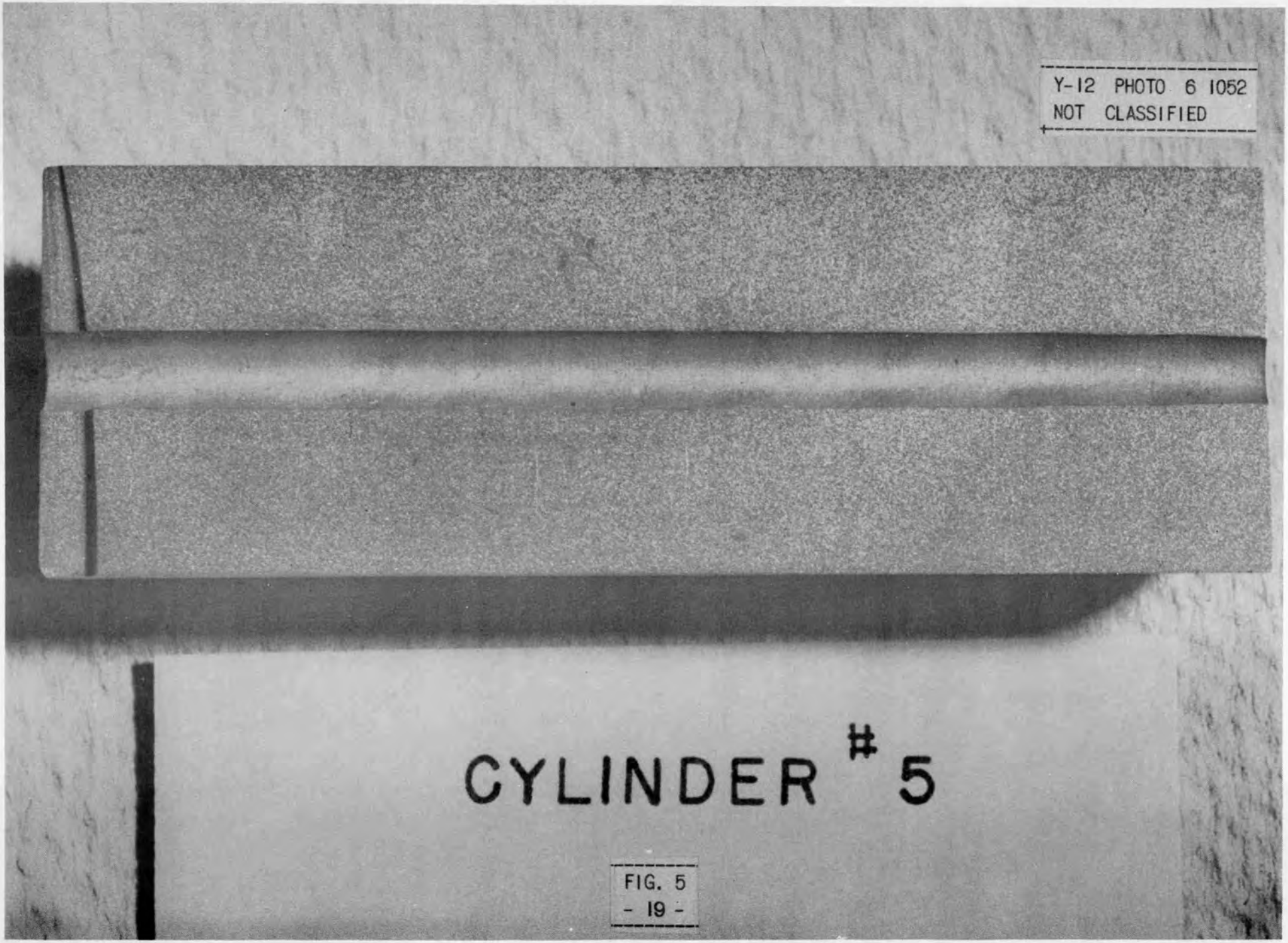


FIG. 5

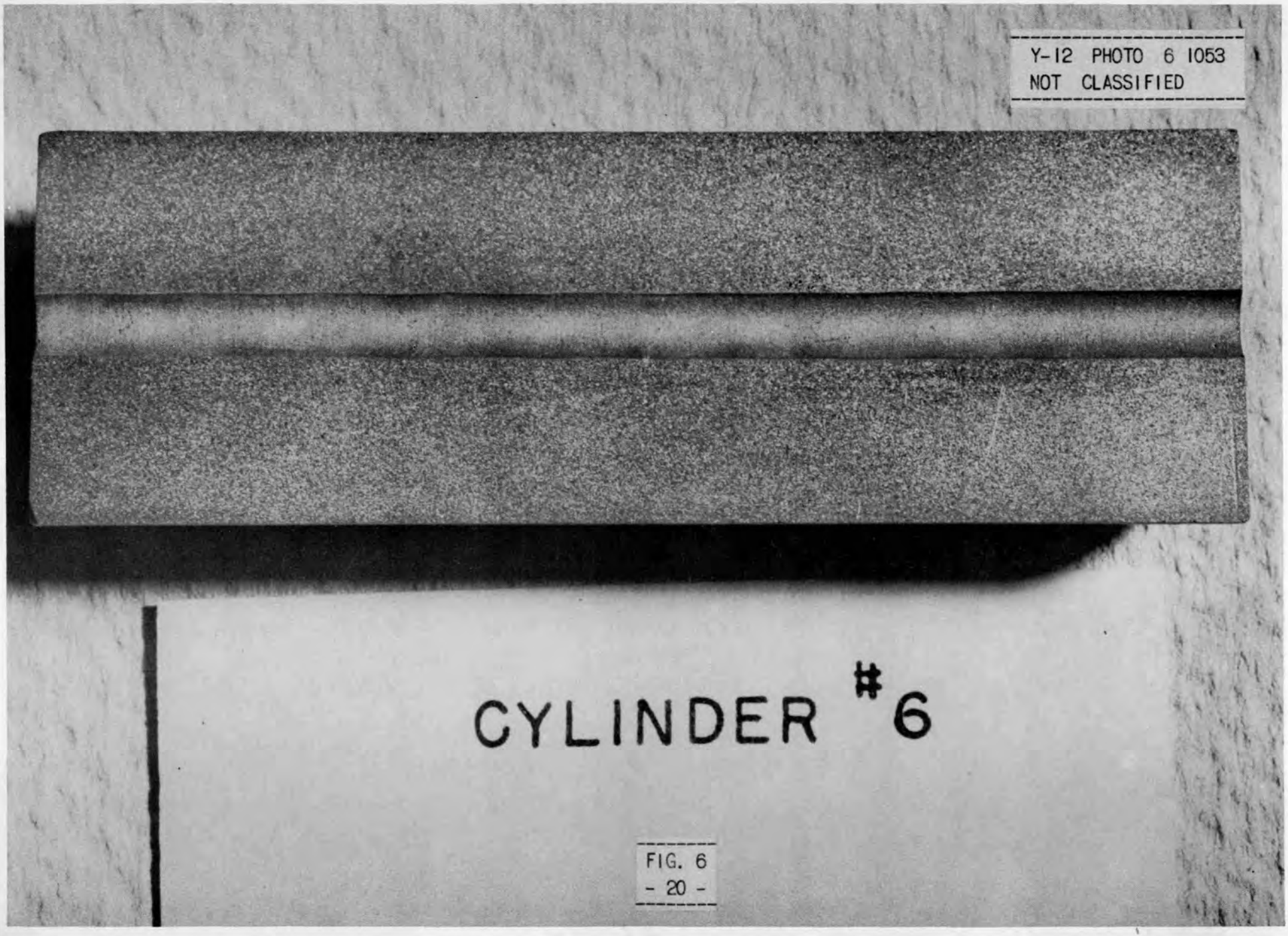


FIG. 6