# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3315

# TENSILE AND COMPRESSIVE STRESS-STRAIN PROPERTIES OF SOME HIGH-STRENGTH SHEET ALLOYS AT ELEVATED TEMPERATURES

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NACA

Washington
November 1954

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## SUMMARY

Results of tensile and compressive stress-strain tests at temperatures up to 1,200° F are presented for SAE 4340, Hy-Tuf, Stainless W, and Inconel X sheet materials which were heat treated to provide ultimate tensile strengths at room temperature in the 170 to 220 ksi range. The materials were exposed to the test temperature for 1/2 hour before loading and were tested at a strain rate of approximately 0.002 per minute.

Representative tensile and compressive stress-strain curves are given for each material at the test temperatures. The variation of the tensile and compressive properties with temperature is shown for specimens tested parallel and transverse to the rolling direction of the materials. Secant and tangent moduli, obtained from the compressive data, are included.

## INTRODUCTION

Missiles and aircraft at supersonic speeds require materials for their construction which can withstand the adverse effects of elevated temperatures. A number of programs have been in progress to supply information on the properties of various ferrous and nonferrous alloys which may be used for this purpose (for example, refs. 1 to 3).

The results of tensile and compressive stress-strain tests of three ferrous alloys, SAE 4340, Hy-Tuf, and Stainless W, and one nickel alloy, Inconel X, are presented herein. The compressive data for these materials, with the exception of Hy-Tuf, were previously used to provide a basis for some structural-efficiency comparisons at elevated temperatures (ref. 4).

Conventional short-time tests were made with the specimens exposed to the test temperature for 1/2 hour prior to loading. Tensile and compressive stress-strain data taken with and transverse to the rolling direction are given for all the materials to 1,000° F. Additional compressive data are given for Stainless W and Inconel X at 1,200° F.

## MATERIALS AND TEST SPECIMENS

The materials used for the tests were received in the annealed condition from various manufacturers. Table 1 gives information on the sheet thicknesses, densities, heat treatments, and suppliers of the materials. The nominal chemical compositions are given in table 2.

The dimensions of the tensile and compressive specimens, which were cut from the sheet both with and transverse to the rolling direction, are shown in figure 1. Specimens were machined from the material in the condition in which it was received and then were heat treated to a room-temperature strength level in the 170 to 220 ksi range. Hardness and tensile stress-strain tests were made on sample specimens to insure uniform properties throughout each heat.

## TEST PROCEDURE

Each specimen was placed in a preheated furnace and kept at the test temperature for 1/2 hour before loading. Throughout the test the strain rate was maintained as closely as possible to 0.002 per minute.

All tensile tests were made in a 100,000-pound-capacity testing machine, and the specimens were loaded through clevises and pins outside of the furnace. Strains were measured over a 1-inch gage length at the center of the specimen by means of two extensometer frames with knife edges which were clamped tightly enough to prevent slipping. Two vertical rods on each side of the specimen, one from the upper frame and one from the lower, transferred the deformation in the gage length to differential-transformer strain gages below the furnace. The tensile equipment is seen in figure 2, in which the furnace is swung back from its normal position to show the specimen with the extensometer frames and transfer rods. Rheostats were used to control the furnace temperature distribution so that a variation in temperature over the gage length of the specimen did not exceed 5° F. Specimen temperatures during the test were constant within ±5° F of the test temperature.

Compressive tests were made in a 120,000-pound-capacity testing machine. Buckling of the specimens was prevented by a grooved-plate compression fixture modified for elevated-temperature use. (For the technique in using this type of fixture at room temperature, see ref. 5.) The equipment is seen in figure 3, in which the furnace is raised to show the specimen, fixture, extensometer, and loading ram. Uniform temperature along the length of the specimen was achieved by independently controlled heating elements in both top and bottom loading rams and in the large cylindrical furnace. Temperatures were measured by thermocouples at top, center, and bottom positions on the face of the specimen inside the supporting fixture. The temperature gradient along the length of the specimen was kept within 5° F, and the temperature change during the test did not exceed ±5° F.

Stress-strain and time-strain records were obtained autographically on a drum-type modified Brown potentiometer for both the tension and the compression tests. A relatively constant strain rate was maintained throughout the test by adjusting the load valve of the testing machine to give an approximately linear time-strain record.

## RESULTS AND DISCUSSION

Results of the tensile and compressive stress-strain tests for SAE 4340, Hy-Tuf, Stainless W, and Inconel X are presented in figures 4 to 21 and tables 3 to 6. The data are for these materials heat-treated to a room-temperature strength level in the 170 to 220 ksi range, one of the many strength ranges possible for each of these materials. The compression tests were made at room temperature and for at least four elevated temperatures with specimens cut both with and transverse to the rolling direction. Tensile tests were made at room temperature and at elevated temperatures selected for comparison with the compression tests.

Tensile and compressive stress-strain curves are presented in figures 4 to 11. Except for Inconel X in compression at 1,000° F and 1,200° F, each curve is representative of the results obtained from two or more tests for a given temperature and material loaded in the rolling direction. Because of the similarity of the stress-strain curves for the specimens tested transverse to the rolling direction and those tested with the rolling direction, only the curves for the specimens tested with the rolling direction are presented. For a given temperature the tensile curves are lower in most cases than the compressive curves but are very similar in shape. The curves are smooth, except those for Inconel X which exhibited unstable plastic flow at 600° F and at 800° F that caused an irregular loading action and an irregular curve having a generally reduced slope (figs. 10 and 11). Such unstable flow has also been found to occur for various combinations of temperature and strain rate for aluminum (ref. 6).

The variation with temperature of yield and ultimate stresses in tension and yield stresses in compression is shown in figures 12 to 15. Generally, the tensile yield stresses are less than the comparable compressive stresses. In the plane of the sheet the materials are apparently isotropic inasmuch as specimens tested transverse to the rolling direction gave essentially the same results as those tested with the rolling direction. The reduction of strength above 800° F is very pronounced for SAE 4340, Hy-Tuf, and Stainless W (figs. 12 to 14). Inconel X, however, shows comparatively little effect of temperature on yield stress and a reduction of only about 35 percent for tensile ultimate stress up to 1,200° F (fig. 15).

The variation of Young's modulus with temperature for the test materials is shown in figures 16 and 17 for tensile and compressive loading for both grain directions. A reduction in modulus for temperatures above about 600° F to 800° F is marked for all the materials except Inconel X which has a relatively high modulus even at 1,200° F. The moduli in tension are consistently less than those in compression for all the materials over the entire temperature range. Values of Young's modulus were difficult to determine in some cases at the higher temperatures because of the reduced elastic range and initial irregularities in the recorded curve. For this reason more scatter is evident in the test results at the higher temperatures (figs. 16 and 17). In the case of Hy-Tuf at 1,000° F in tension, values are omitted because of the excessive scatter.

For convenience in estimating column and plate compressive strengths in the plastic region, the variation of the secant and tangent moduli with stress is given in figures 18 to 21 for each material and temperature in compression. These curves were obtained from the compressive stress-strain curves in figures 5, 7, 9, and 11.

## CONCLUDING REMARKS

The results of the stress-strain tests of SAE 4340, Hy-Tuf, Stainless W, and Inconel X indicate that the properties of any one of the materials are essentially the same either with or transverse to the rolling direction. The tensile curves, however, are slightly lower than the corresponding compressive curves at the same temperature.

The nickel alloy, Inconel X, shows little effect of temperature on tensile and compressive yield stresses and a reduction of only about 35 percent in tensile ultimate stress up to 1,200° F as compared to a large reduction of strength for the other materials above 800° F.

Inconel X, however, does have unstable plastic flow at 600° F and at 800° F which caused an irregular stress-strain curve with a reduced slope.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 26, 1954.

## REFERENCES

1. Seens, W. B., Smith, G. V., et al.: Mechanical Tests of Steels for High Speed Airplane Wings. Rep. No. 588, U. S. Steel Corp., Aug. 1947.

2. Smith, G. V., Seens, W. B., et al.: Strength of Two Hardened Alloy Steels in the Temperature Range 75 to 700 F. Rep. No. 623, U. S. Steel Corp., Aug. 1949.

3. Doerr, D. D.: Determination of Physical Properties of Ferrous and Nonferrous Structural Sheet Materials at Elevated Temperatures. USAF Tech. Rep. No. 6517, Pt. 2, Wright Air Dev. Center, U. S. Air Force, Apr. 1954.

4. Heimerl, George J., and Hughes, Philip J.: Structural Efficiencies of Various Aluminum, Titanium, and Steel Alloys at Elevated Temperatures. NACA TN 2975, 1953.

5. Kotanchik, Joseph N., Woods, Walter, and Weinberger, Robert A.: Investigation of Methods of Supporting Single-Thickness Specimens in a Fixture for Determination of Compressive Stress-Strain Curves. NACA WR L-189, 1945. (Formerly NACA RB L5E15.)

6. McReynolds, Andrew W.: Plastic Deformation Waves in Aluminum. Tenth Quarterly Report to ONR on Deformation of Metals (ONR Contract No. N-6ORI-20-IV, NR 019 302, Ord. Contract No. TB4-2), Inst. for Study of Metals, Univ. Chicago, Aug. 1, 1948 - Oct. 31, 1948, pp. 1-33.

TABLE 1.- DESCRIPTION OF SHEET MATERIALS

| Material | Thickness, in. | Received condition | Additional heat treatment | Source of material | Density, lb/cu in. |
|---|---|---|---|---|---|
| SAE 4340 | 0.064 | Annealed | Heated at 1,525° F for 10 min in controlled atmosphere; air-cooled; tempered at 800° F for 1 hr | Crucible Steel Co. of America | 0.283 |
| Hy-Tuf | .25 | Annealed | Heated at 1,600° F for 25 min; oil-quenched; tempered at 600° F for 1/2 hr | Crucible Steel Co. of America | .281 |
| Stainless W | .064 | Solution-annealed | Precipitation-hardened; heated at 1,000° F for 1/2 hr | U. S. Steel Corp. | .28 |
| Inconel X | .064 | Annealed | Aged at 1,300° F for 20 hr and air-cooled | U. S. Steel Corp. | .30 |

TABLE 2.- NOMINAL CHEMICAL COMPOSITION OF MATERIALS

| Material | C | Mn | P | S | Si | Ni | Cr | Mo | Ti | Cb | Al | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAE 4340 | 0.42 | 0.78 | 0.018 | 0.027 | 0.24 | 1.79 | 0.80 | 0.33 | ---- | --- | --- | Remainder |
| Hy-Tuf | .25 | 1.30 | ----- | 1.5 | ---- | 1.80 | ---- | .40 | ---- | --- | --- | Remainder |
| Stainless W | .05 | .54 | .01 | .006 | .57 | 6.73 | 16.80 | ---- | 0.58 | --- | --- | Remainder |
| Inconel X | .04 | .50 | ----- | ----- | .40 | 73.0 | 15.0 | ---- | 2.5 | 1.0 | 0.7 | 7.0 |

TABLE 3.- MECHANICAL PROPERTIES OF SAE 4340

| Temperature, °F | Compressive properties | | | Tensile properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | Specimen (a) | Yield stress, ksi | Young's modulus, psi | Specimen (a) | Yield stress, ksi | Ultimate stress, ksi | Elongation in 2-inch gage, percent | Young's modulus, psi |
| 80 | 222W | 194.5 | $29.5 \times 10^6$ | 222W | 177.4 | 196.1 | 8.0 | $29.4 \times 10^6$ |
| | 228W | 194.3 | 29.6 | 229W | 182.1 | 200.0 | 6.5 | 30.9 |
| | 222X | 200.8 | 31.2 | | | | | |
| | 223X | 201.0 | 30.6 | | | | | |
| 400 | 229W | 173.2 | 29.0 | | | | | |
| | 2211W | 176.4 | 28.8 | | | | | |
| | 225X | 173.2 | 29.1 | | | | | |
| 600 | 2215W | 157.6 | 26.6 | 224W | 136.6 | 170.0 | 14.0 | 24.5 |
| | 2221W | 157.6 | 27.6 | 225W | 137.2 | 169.0 | ---- | 22.7 |
| | 226X | 161.2 | 28.0 | 226W | 138.1 | 173.8 | ---- | 23.1 |
| 800 | 221W | 118.1 | 24.2 | 227W | 102.0 | 136.0 | ---- | 20.5 |
| | 225W | 118.1 | 25.0 | 228W | 100.6 | 133.1 | ---- | 23.2 |
| | 2210X | 120.0 | 25.5 | | | | | |
| 1,000 | 2210W | 57.8 | 18.7 | 221W | 51.3 | 72.5 | ---- | 17.5 |
| | 2214W | 56.3 | 18.3 | 223W | 50.7 | 76.8 | ---- | 18.1 |
| | 2216W | 57.5 | 20.0 | | | | | |
| | 2211X | 62.8 | 16.8 | | | | | |

[a] W indicates with rolling direction; X indicates transverse to rolling direction.

TABLE 4.- MECHANICAL PROPERTIES OF HY-TUF

| Temperature, °F | Compressive properties | | | Tensile properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | Specimen (a) | Yield stress, ksi | Young's modulus, psi | Specimen (a) | Yield stress, ksi | Ultimate stress, ksi | Elongation in 2-inch gage, percent | Young's modulus, psi |
| 80 | 312W | 199.8 | $31.0 \times 10^6$ | 312W | 181.0 | 222.1 | 10.9 | $27.5 \times 10^6$ |
| | 313W | 200.4 | 30.5 | 313W | 180.0 | 220.7 | 10.2 | 28.2 |
| | 311X | 196.8 | 30.1 | 311X | 181.8 | 219.9 | 11.3 | 28.5 |
| 400 | 314W | 179.5 | 29.9 | | | | | |
| | 315W | 179.6 | 29.5 | | | | | |
| | 312X | 175.8 | 28.4 | | | | | |
| 600 | 316W | 157.9 | 25.2 | 314W | 140.0 | 209.0 | 11.0 | 25.4 |
| | 317W | 156.8 | 25.5 | 315W | 143.8 | 209.0 | ---- | 23.1 |
| | 313X | 159.0 | 26.6 | 317W | 139.2 | ----- | ---- | 23.3 |
| 800 | 318W | 127.6 | 26.6 | | | | | |
| | 319W | 127.6 | 26.0 | | | | | |
| | 314X | 130.6 | 24.0 | | | | | |
| 1,000 | 3111W | 74.4 | 16.7 | 311W | 73.1 | 88.8 | 25.0 | ---- |
| | 3112W | 73.9 | 16.8 | 316W | 70.0 | 88.7 | 25.0 | ---- |
| | 315X | 74.5 | 16.7 | | | | | |

[a] W indicates with rolling direction; X indicates transverse to rolling direction.

TABLE 5.- MECHANICAL PROPERTIES OF STAINLESS W

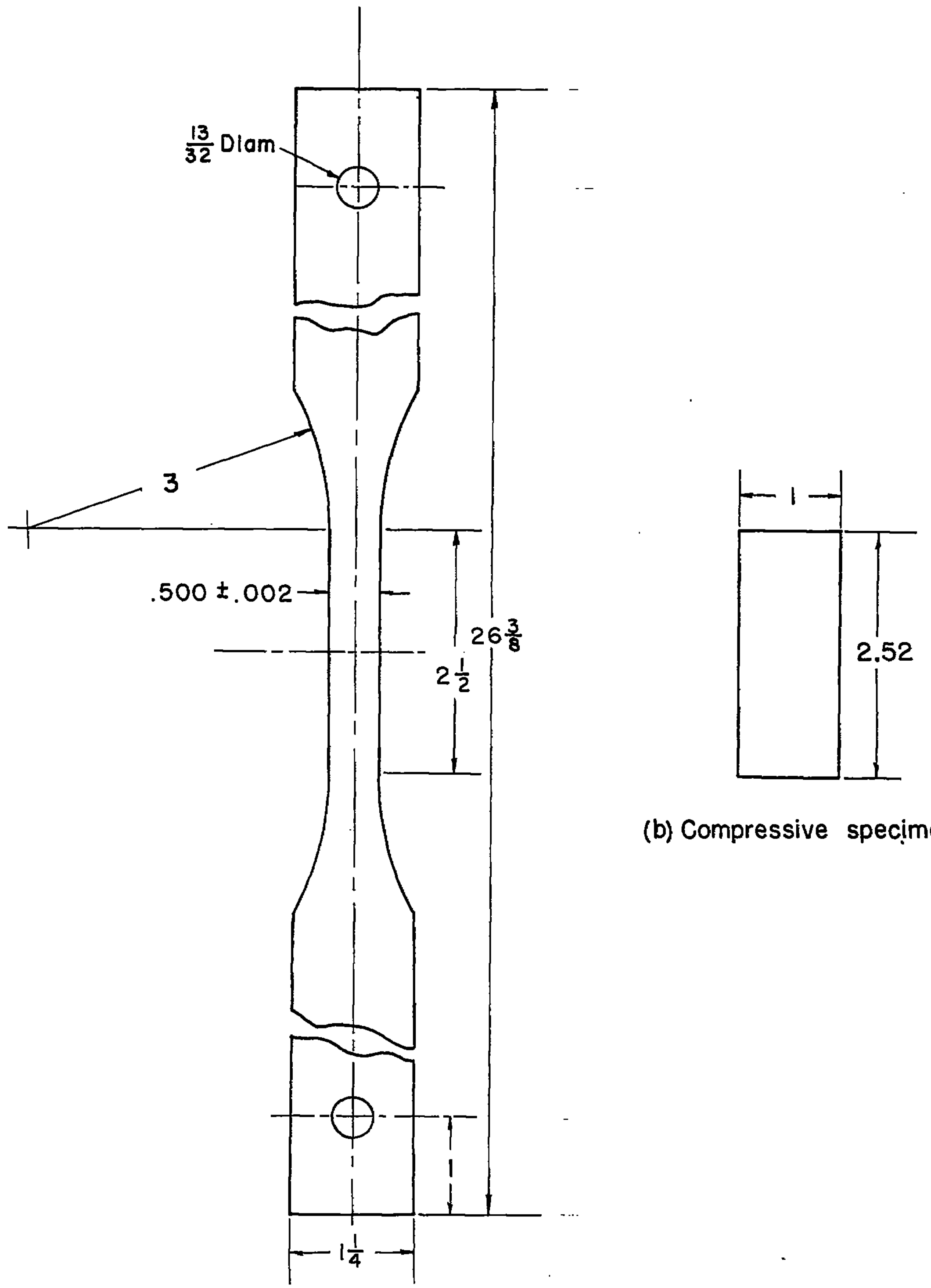
| Temperature, °F | Compressive properties | | | Tensile properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | Specimen (a) | Yield stress, ksi | Young's modulus, psi | Specimen (a) | Yield stress, ksi | Ultimate stress, ksi | Elongation in 2-inch gage, percent | Young's modulus, psi |
| 80 | 1113W | 219.0 | $30.4 \times 10^6$ | 116W | 216.0 | 224.0 | 1.1 | $29.5 \times 10^6$ |
| | 1115W | 220.5 | 30.6 | 118W | 215.0 | 221.2 | 5.3 | 29.1 |
| | 1116W | 220.5 | 30.2 | 112X | 216.2 | 225.2 | 2.3 | 31.9 |
| | 114X | 221.5 | 30.8 | 113X | 219.0 | 225.2 | 1.4 | 30.3 |
| | 115X | 221.5 | 30.9 | | | | | |
| 400 | 113W | 195.1 | 28.8 | | | | | |
| | 114W | 195.2 | 28.6 | | | | | |
| | 117X | 196.2 | 29.8 | | | | | |
| | 118X | 198.0 | 29.8 | | | | | |
| 600 | 119W | 180.1 | 27.8 | 113W | 172.6 | 182.0 | ---- | 26.7 |
| | 1111W | 198.8 | 27.8 | 115W | 175.6 | 186.0 | 3.0 | 26.3 |
| | 119X | 179.0 | 28.2 | 115X | 176.5 | 187.0 | 2.5 | 28.7 |
| | 1110X | 180.7 | 28.4 | 117X | 173.4 | 187.8 | 3.1 | 27.2 |
| 800 | 1118W | 132.2 | 24.8 | | | | | |
| | 1119W | 132.6 | 25.6 | | | | | |
| | 1111X | 134.9 | 25.0 | | | | | |
| 1,000 | 115W | 56.3 | 20.8 | 111W | 50.2 | 75.8 | 47.0 | 16.7 |
| | 116W | 56.5 | 19.0 | 117W | 36.8 | 80.6 | 58.0 | 17.0 |
| | 113X | 52.2 | 20.8 | 113X | 49.3 | 77.7 | 50.0 | 17.2 |
| | 116X | 37.8 | 20.6 | | | | | |
| 1,200 | 117W | 24.0 | 12.9 | | | | | |
| | 118W | 25.4 | 13.2 | | | | | |
| | 112X | 26.5 | 12.2 | | | | | |

[a]W indicates with rolling direction; X indicates transverse to rolling direction.

TABLE 6.- MECHANICAL PROPERTIES OF INCONEL X

| Temperature, °F | Compressive properties | | | Tensile properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | Specimen (a) | Yield stress, ksi | Young's modulus, psi | Specimen (a) | Yield stress, ksi | Ultimate stress, ksi | Elongation in 2-inch gage, percent | Young's modulus, psi |
| 80 | 411W | 112.4 | $31.6 \times 10^6$ | 412W | 109.3 | 170.1 | 31.5 | $31.6 \times 10^6$ |
| | 414W | 114.6 | 32.7 | 414W | 109.7 | 170.8 | 29.0 | 31.9 |
| | 411X | 115.8 | 33.0 | 412X | 108.0 | 168.2 | 30.0 | 32.6 |
| | 412X | 115.4 | 32.7 | 413X | 108.0 | 169.7 | 29.5 | 32.9 |
| 400 | 415W | 106.5 | 30.2 | | | | | |
| | 416W | 107.8 | 30.7 | | | | | |
| | 413X | 106.8 | 31.3 | | | | | |
| 600 | 417W | 105.7 | 31.2 | 415W | 98.7 | 150.3 | ---- | 28.8 |
| | 418W | 107.6 | 30.2 | 417W | 96.8 | 149.5 | ---- | 28.4 |
| | 414X | 107.2 | 30.0 | 414X | 97.7 | 150.5 | 28.0 | 27.7 |
| | 415X | 107.2 | 30.4 | 415X | 93.8 | 145.7 | 30.5 | 27.6 |
| 800 | 419W | 106.4 | 29.9 | | | | | |
| | 4110W | 105.4 | 29.7 | | | | | |
| | 416X | 105.4 | 29.7 | | | | | |
| 1,000 | 4111W | 104.8 | 27.9 | 413W | 97.6 | ----- | 31.0 | 26.4 |
| | 417X | 104.4 | 27.8 | 416W | 97.8 | 111.7 | 32.0 | 24.7 |
| | 418X | 105.2 | 27.7 | 416X | 98.1 | 109.0 | 32.0 | 27.3 |
| 1,200 | 4112W | 102.8 | 26.2 | | | | | |
| | 419X | 101.4 | 26.2 | | | | | |
| | 4110X | 102.4 | 26.4 | | | | | |

[a]W indicates with rolling direction; X indicates transverse to rolling direction.




(a) Tensile specimen.

(b) Compressive specimen.

Figure 1.- Dimensions of tensile and compressive sheet specimens in inches.

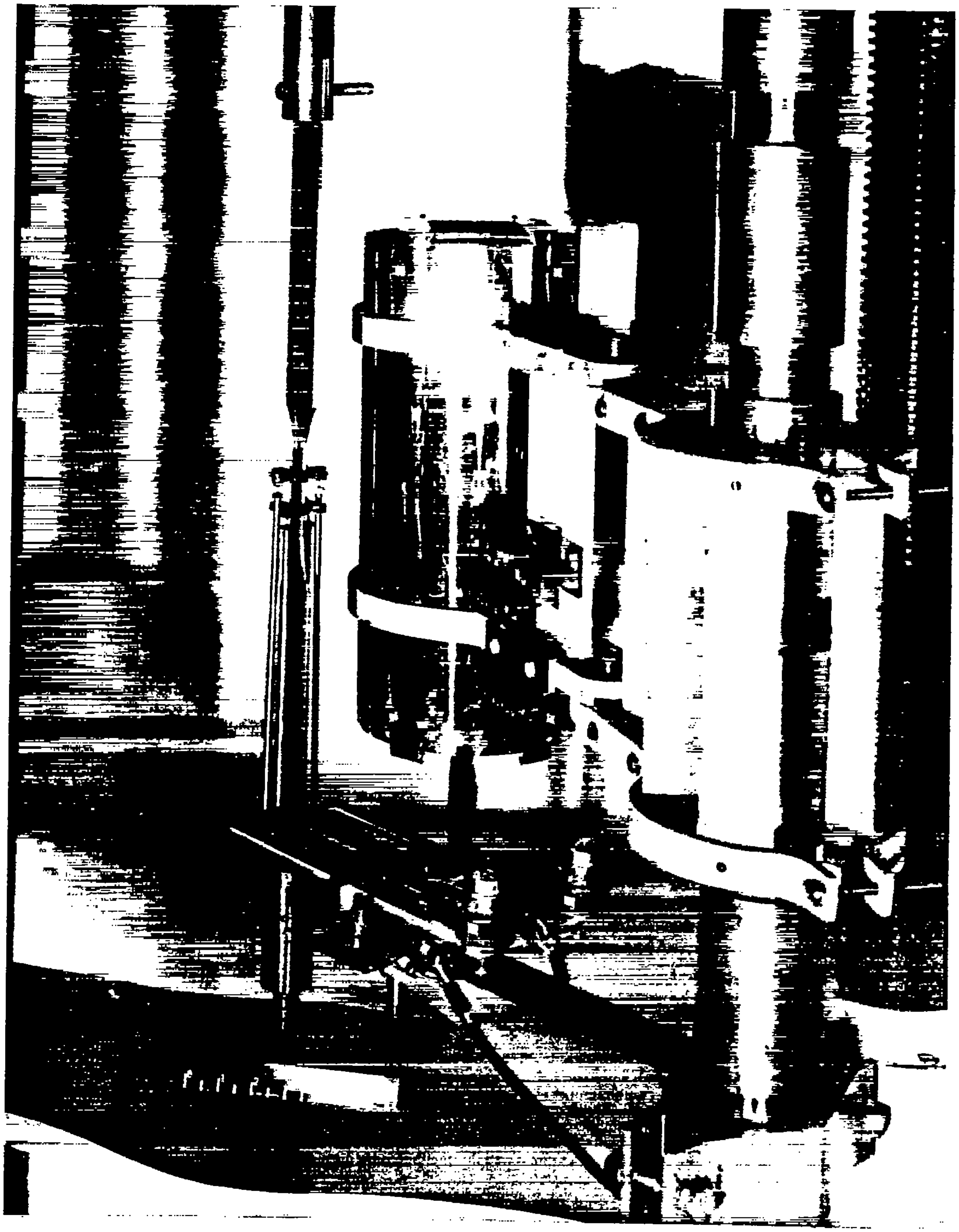


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Figure 2.- Equipment for tensile stress-strain tests at elevated temperatures.

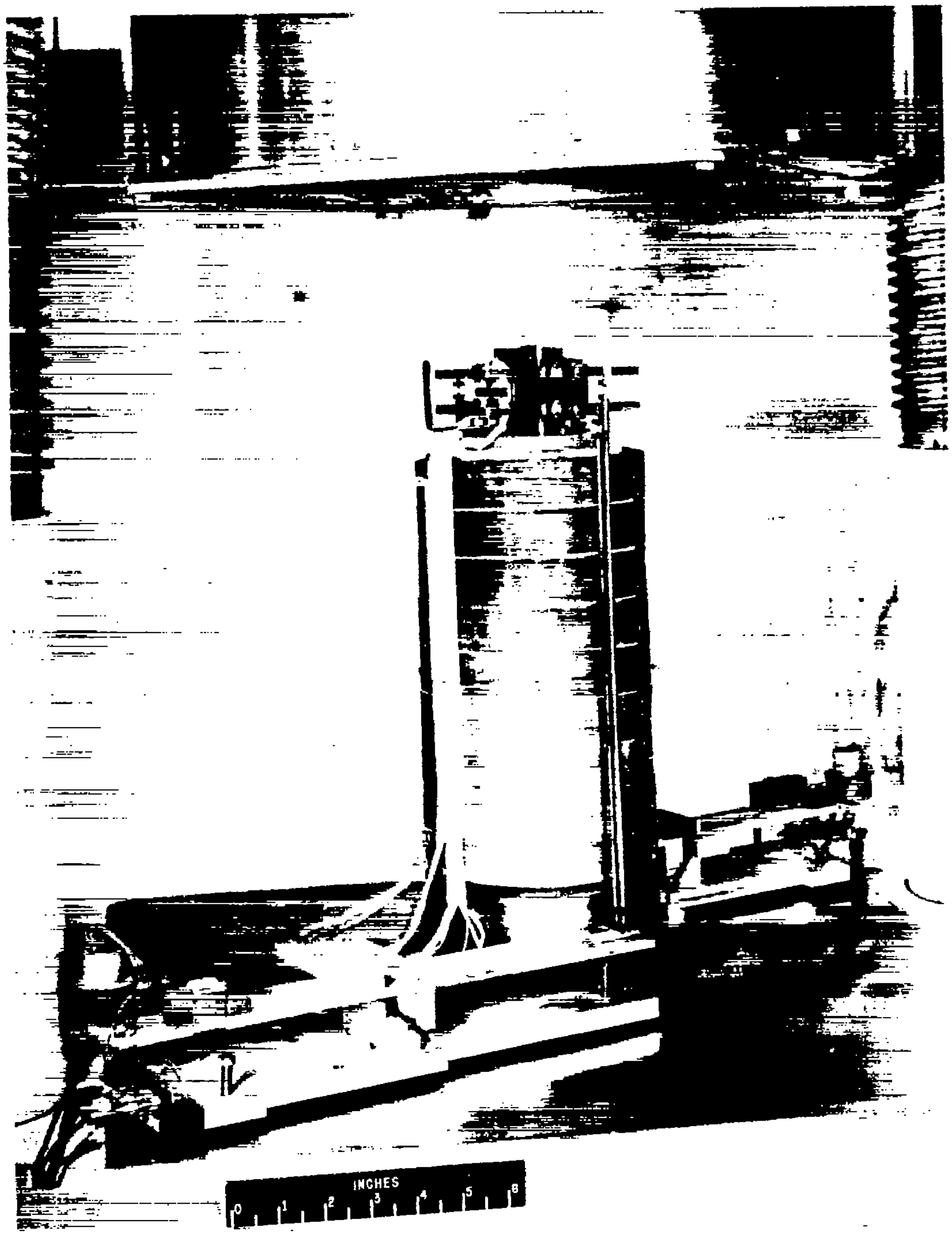


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Figure 3.- Equipment for compressive stress-strain tests at elevated temperatures.

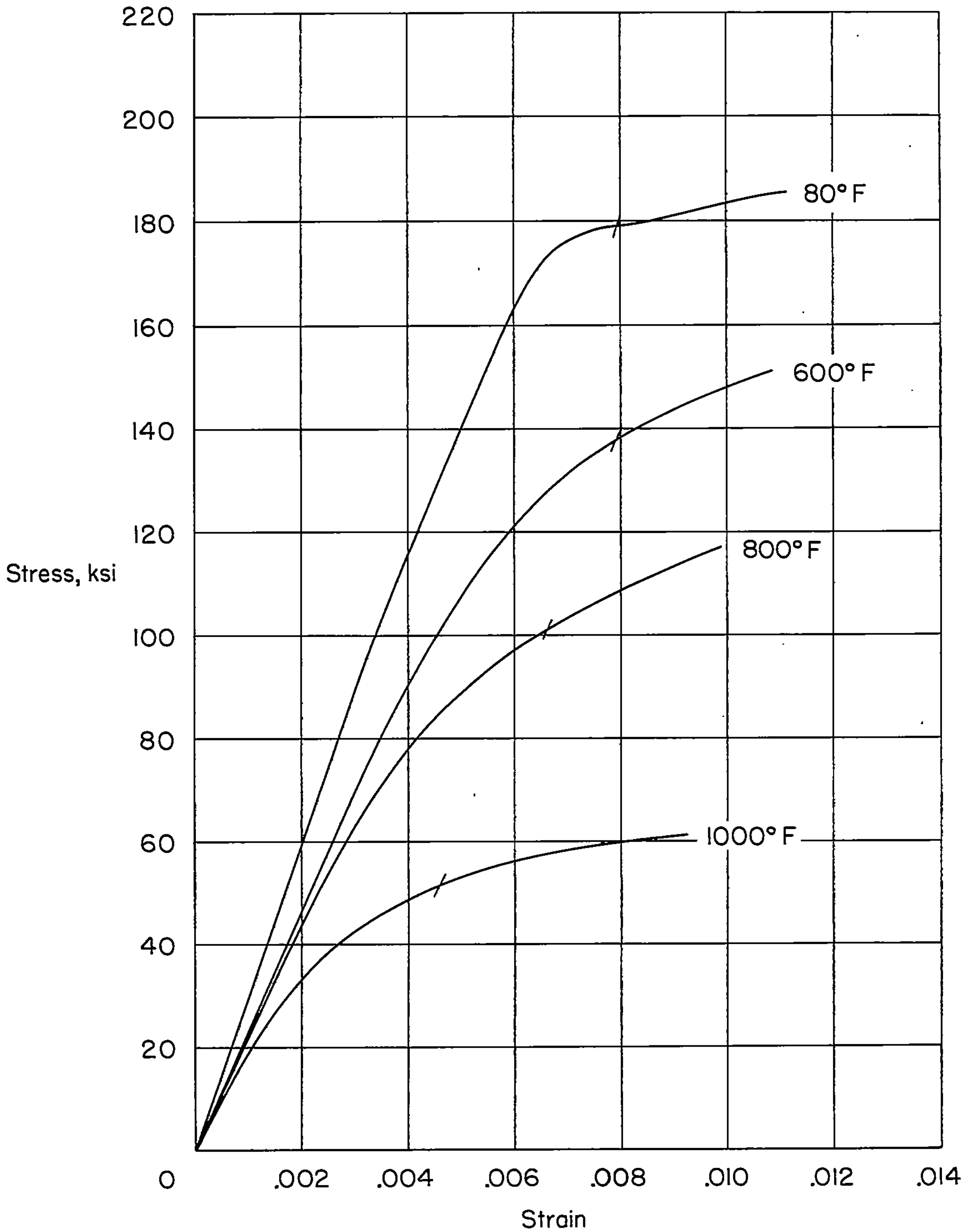


Figure 4.- Tensile stress-strain curves for SAE 4340.

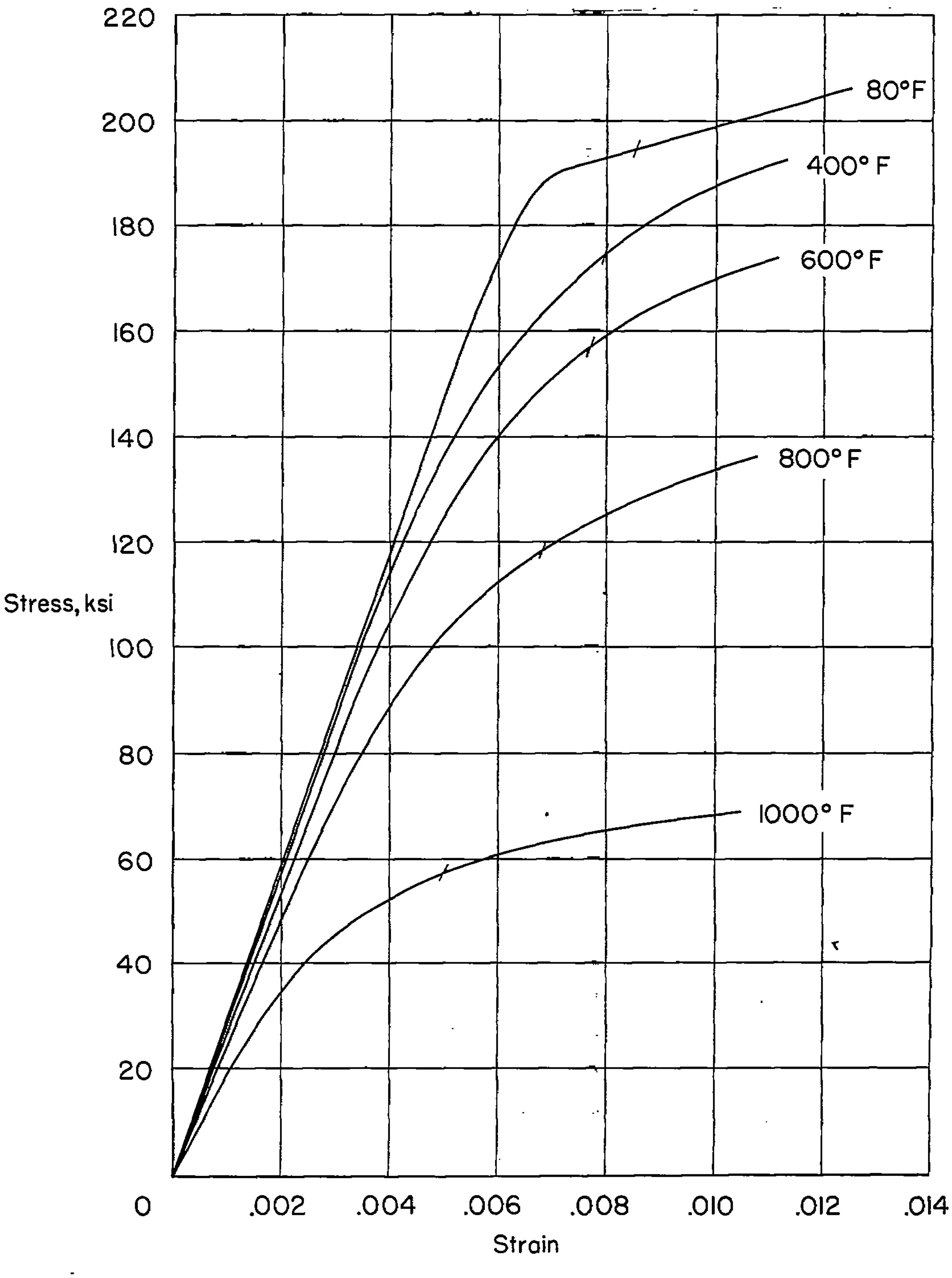


Figure 5.- Compressive stress-strain curves for SAE 4340.

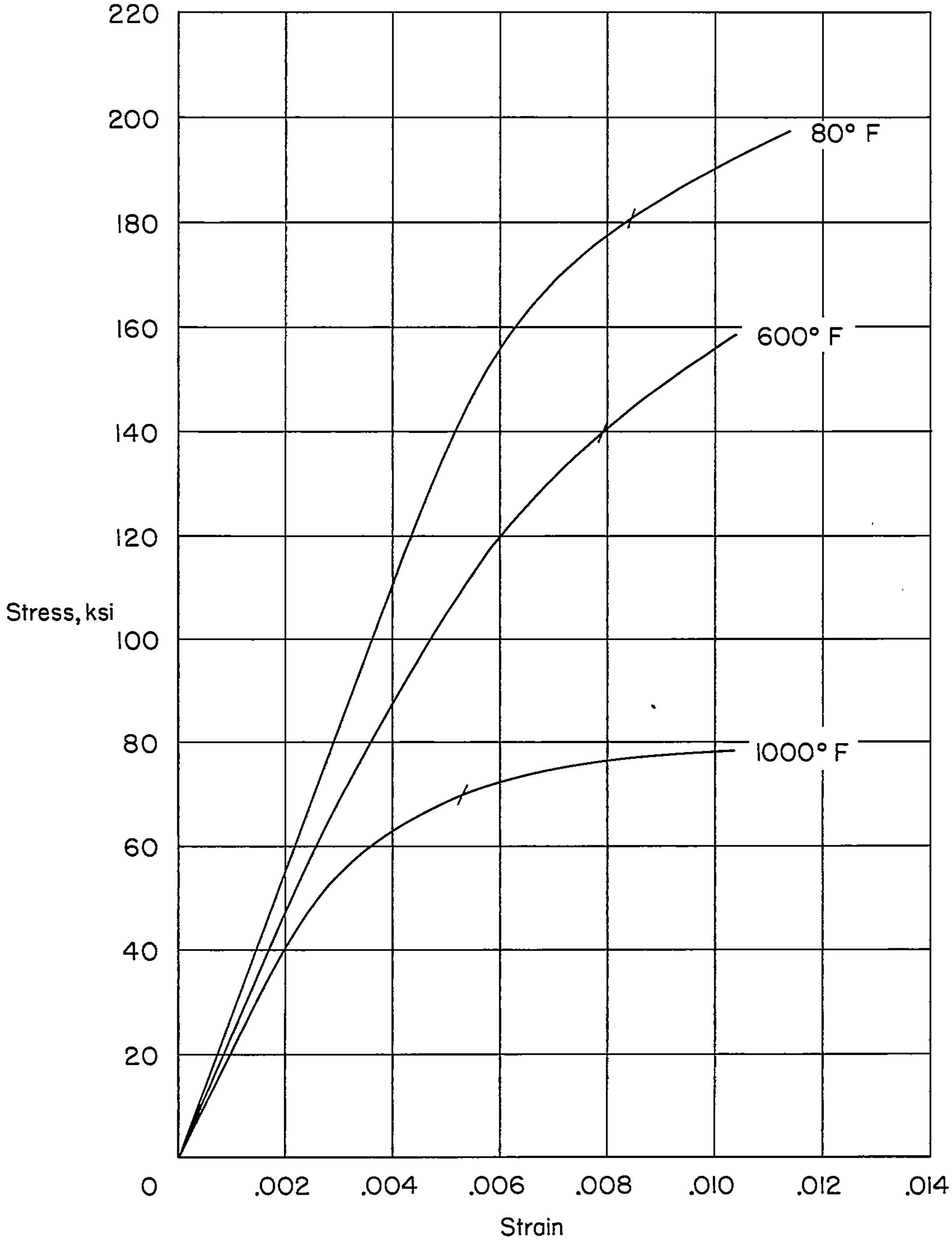


Figure 6.- Tensile stress-strain curves for Hy-Tuf.

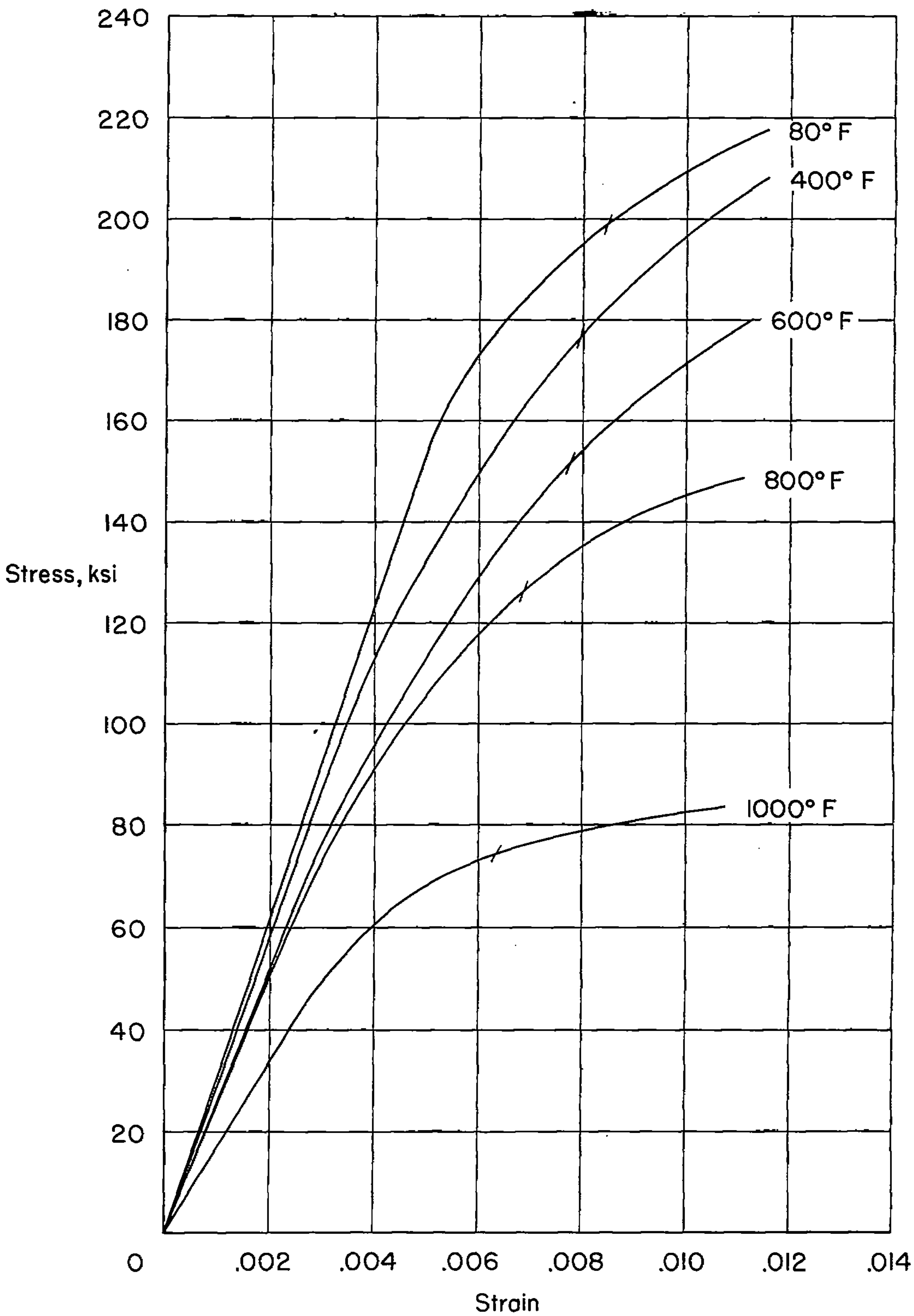


Figure 7.- Compressive stress-strain curves for Hy-Tuf.

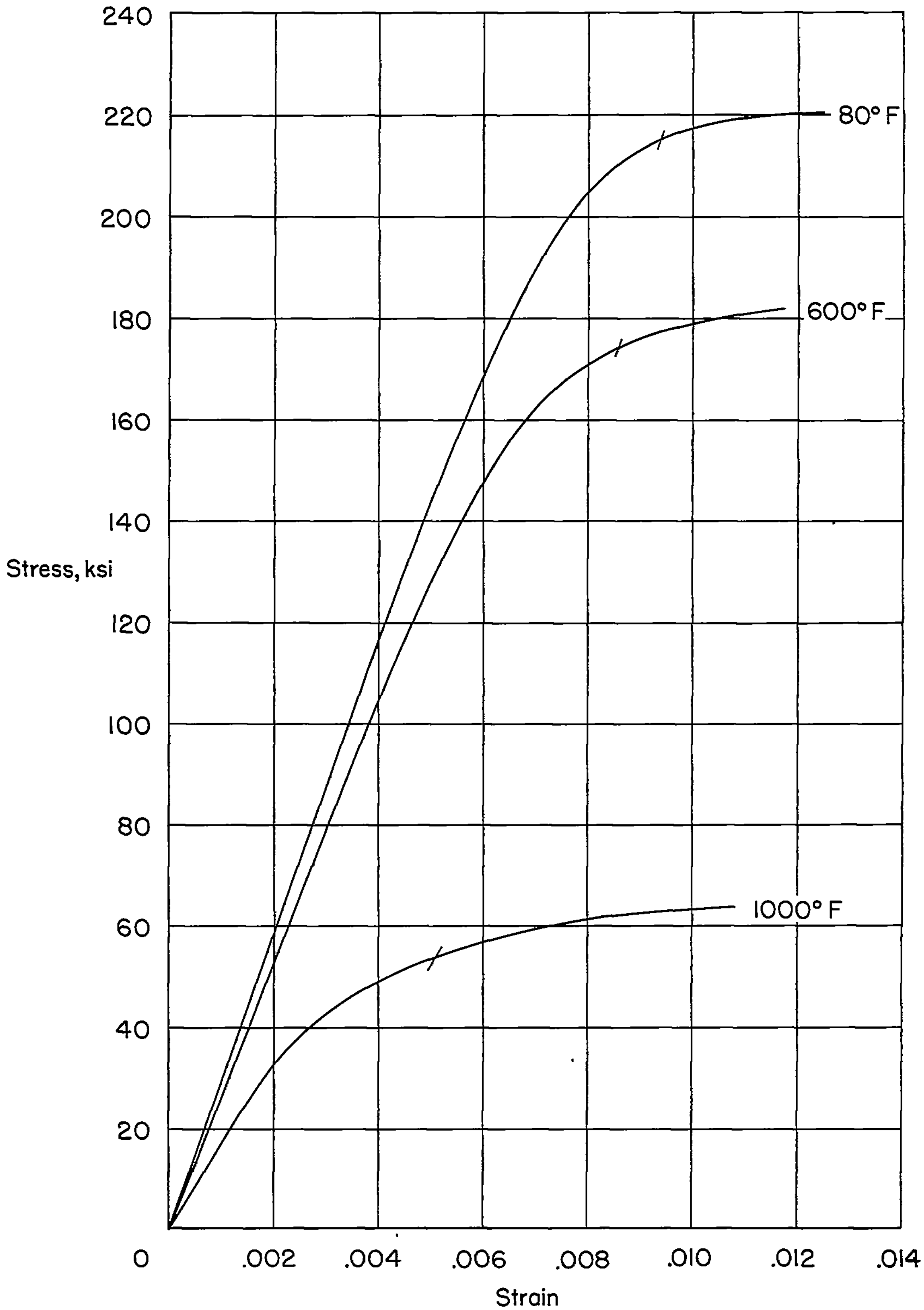


Figure 8.- Tensile stress-strain curves for Stainless W.

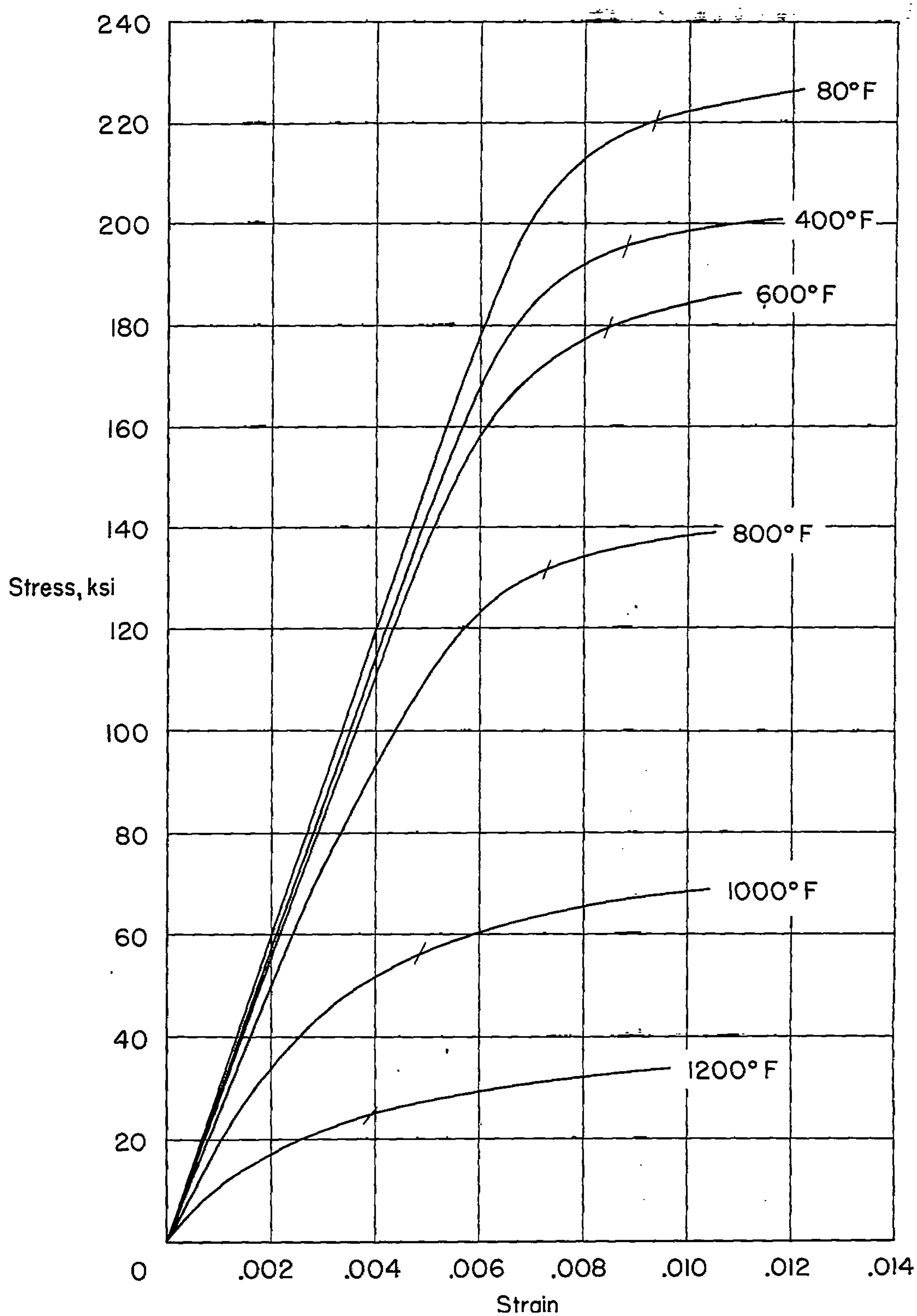


Figure 9.- Compressive stress-strain curves for Stainless W.

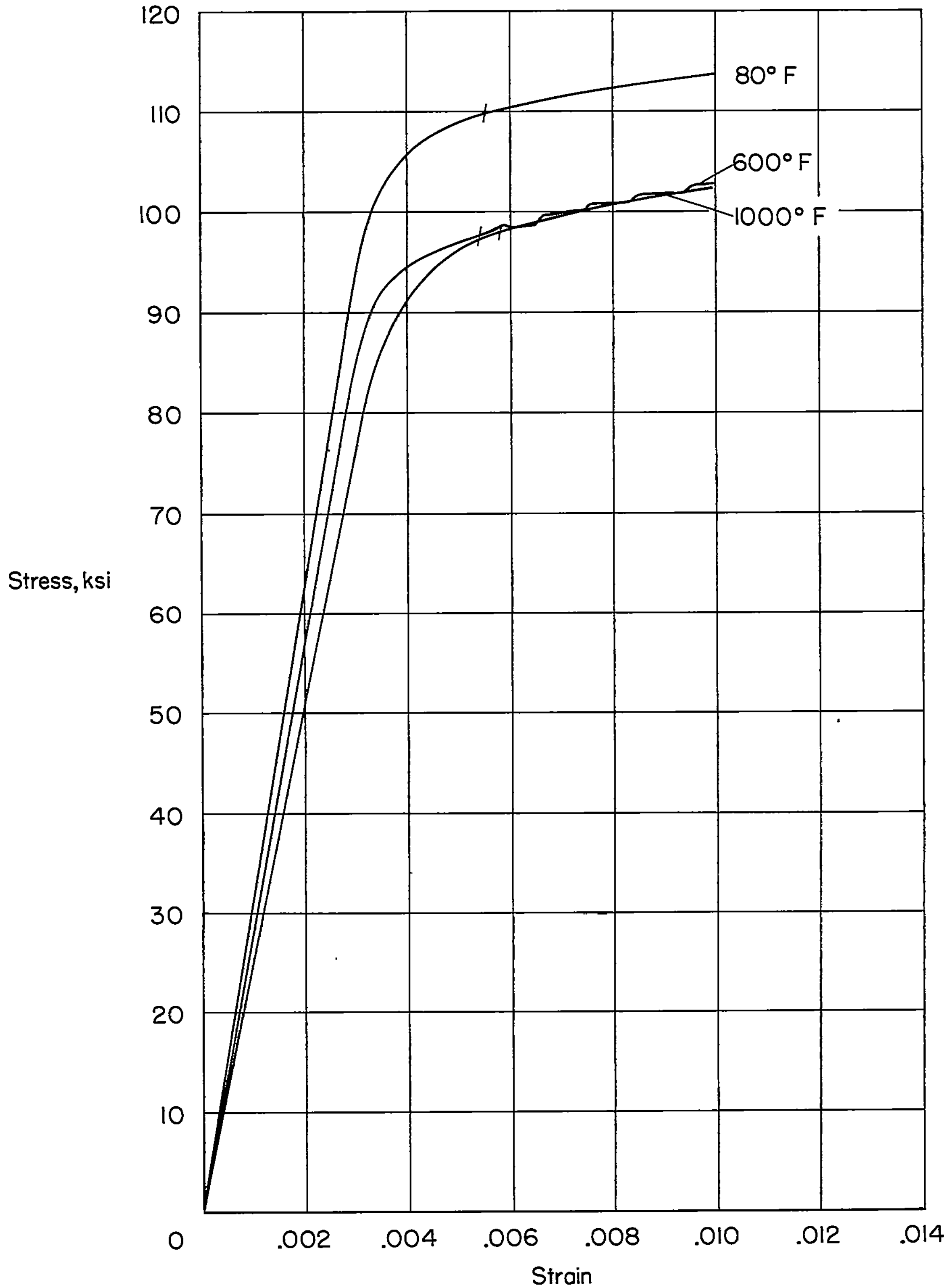


Figure 10.- Tensile stress-strain curves for Inconel X.

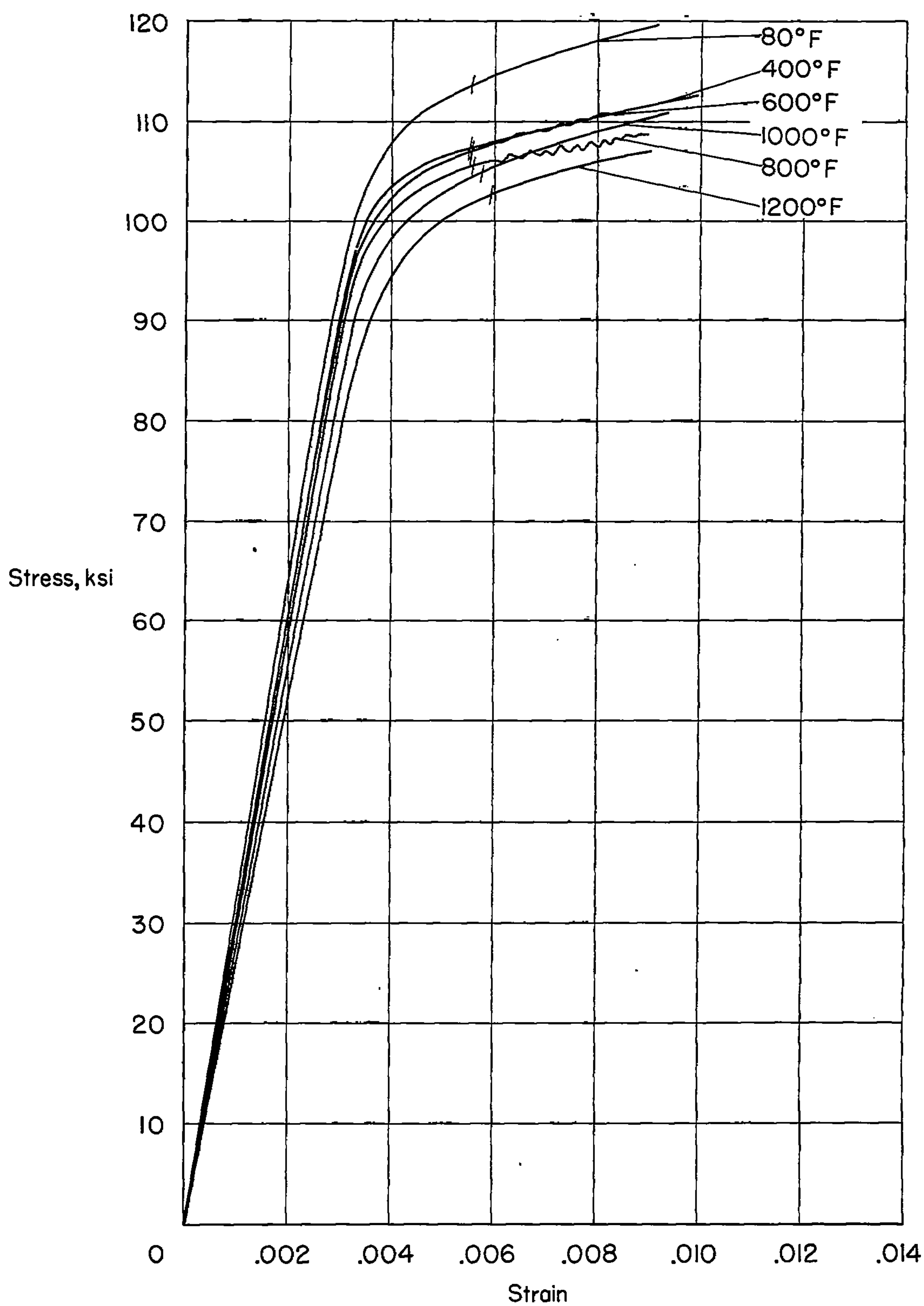


Figure 11.- Compressive stress-strain curves for Inconel X.

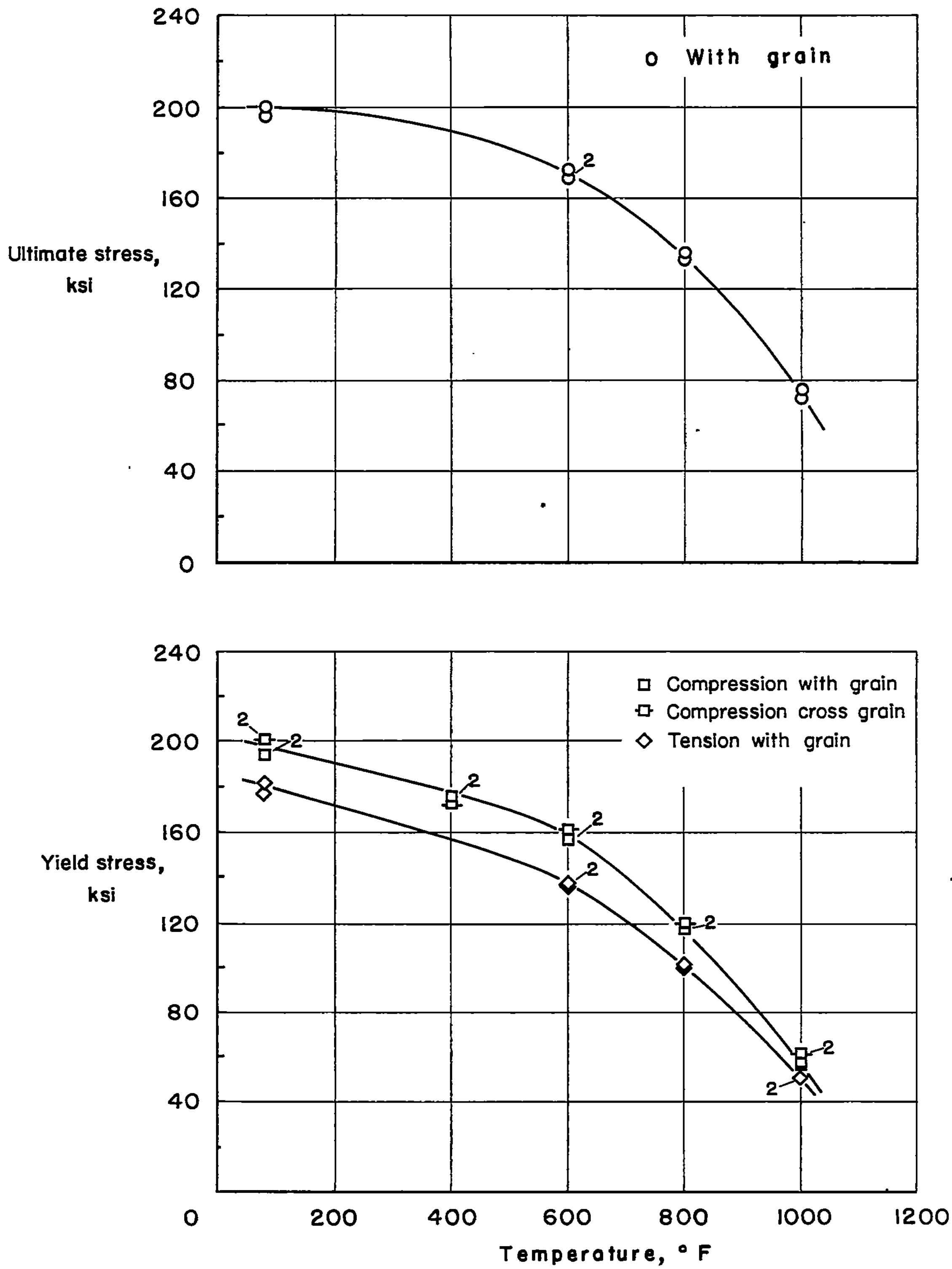


Figure 12.- Variation of tensile ultimate and tensile and compressive yield stresses with temperature for SAE 4340.

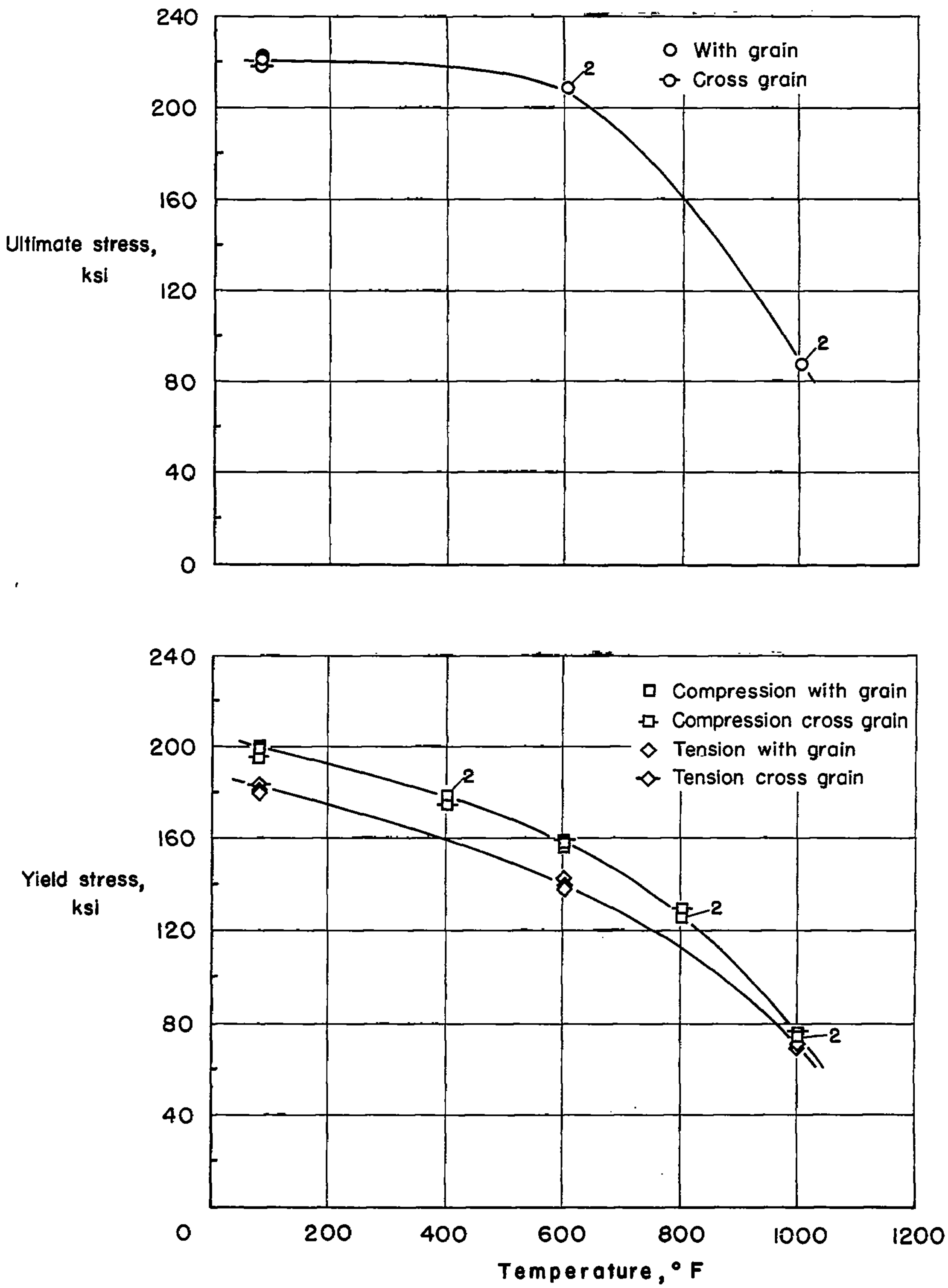


Figure 13.- Variation of tensile ultimate and tensile and compressive yield stresses with temperature for Hy-Tuf.

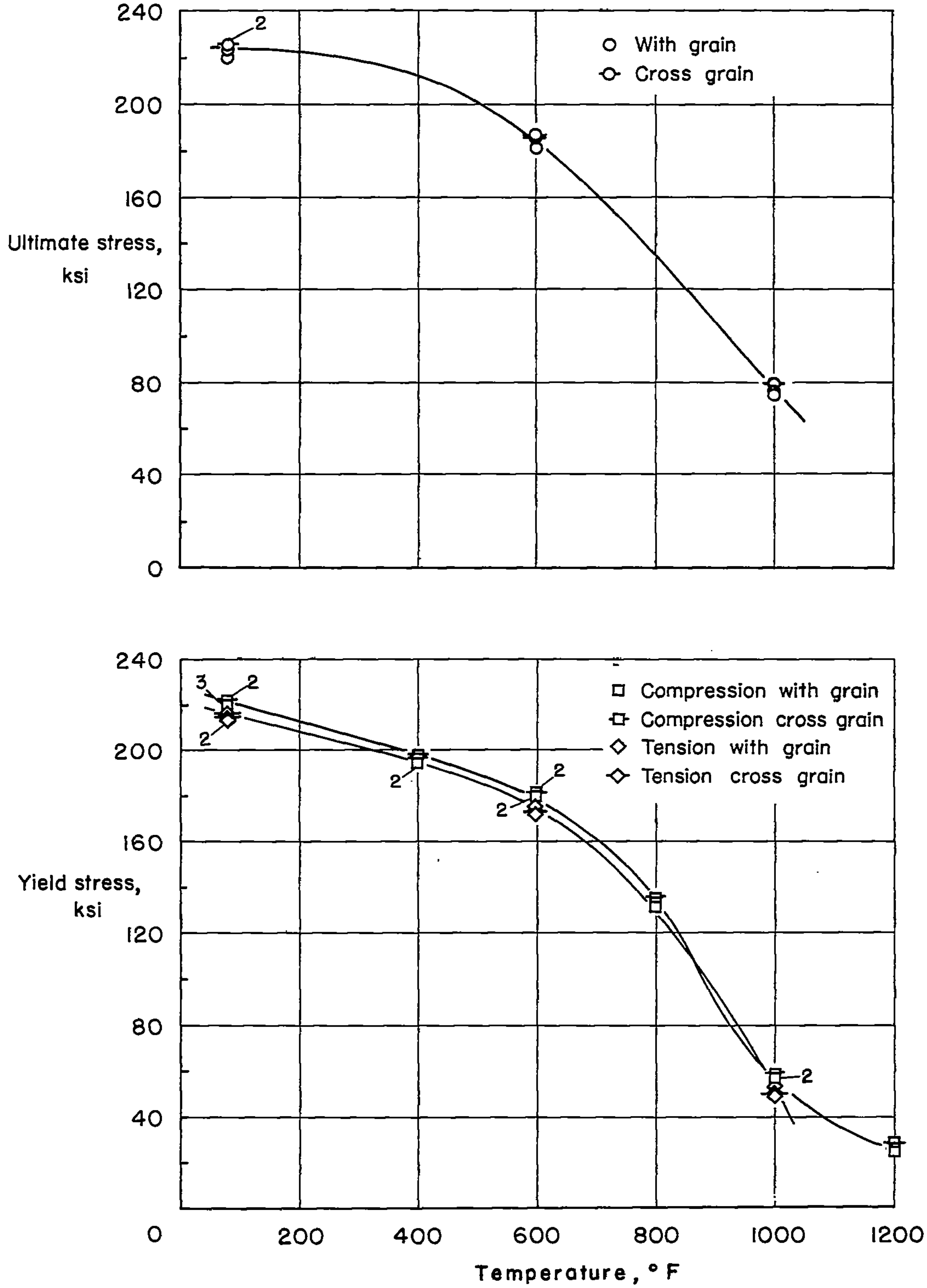


Figure 14.- Variation of tensile ultimate and tensile and compressive yield stresses with temperature for Stainless W.

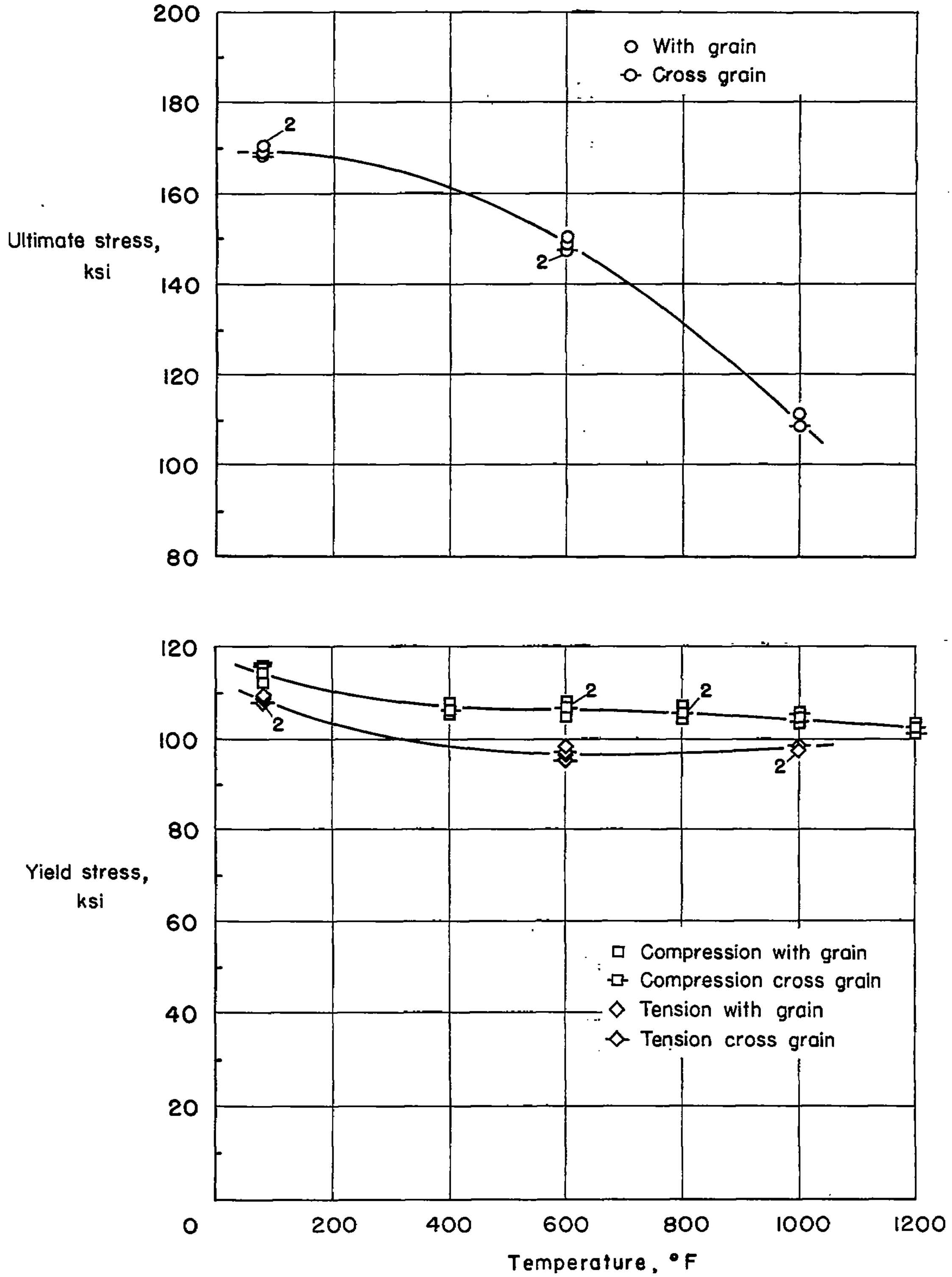


Figure 15.- Variation of tensile ultimate and tensile and compressive yield stresses with temperature for Inconel X.

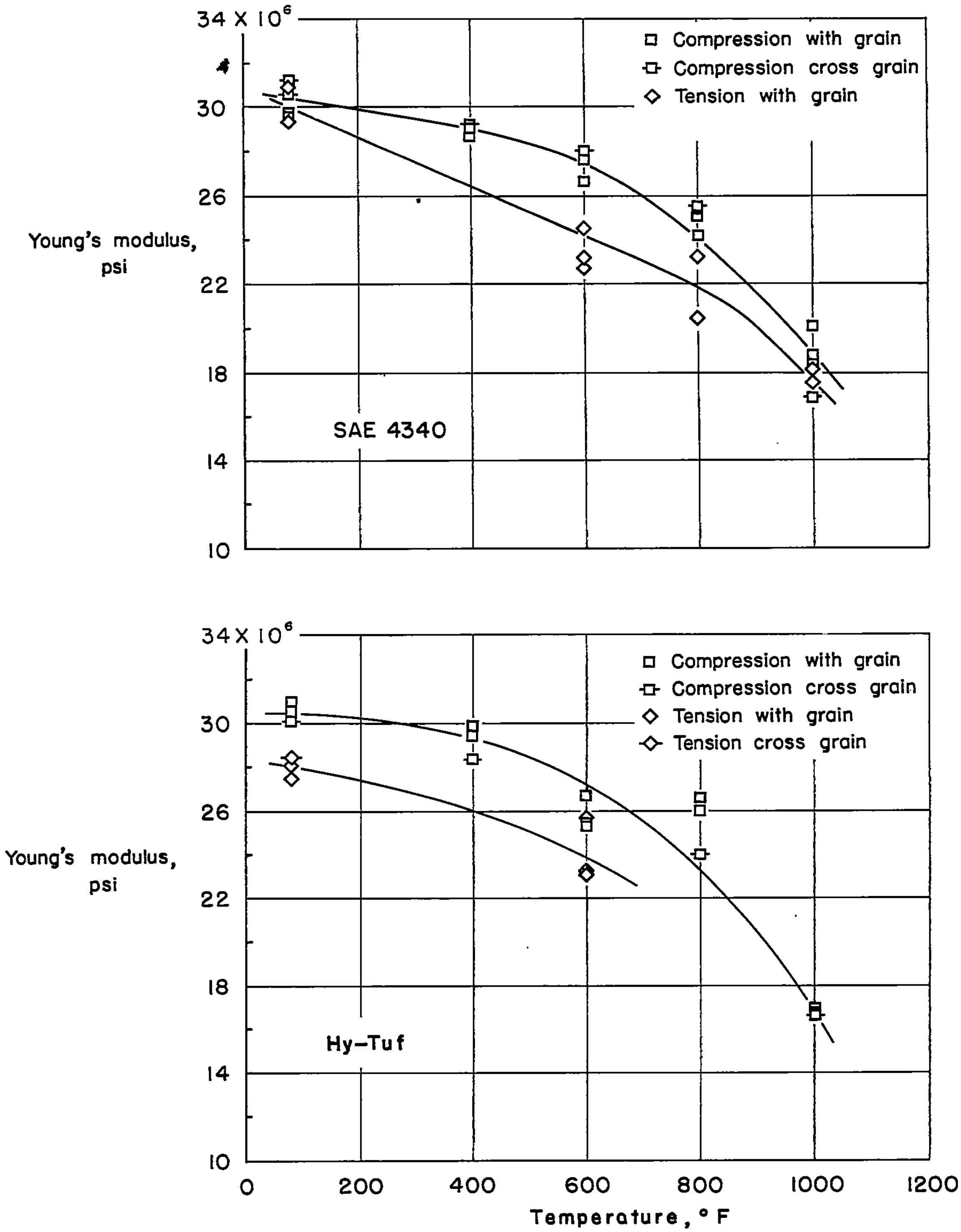


Figure 16.- Variation of Young's modulus with temperature in tension and compression for SAE 4340 and Hy-Tuf.

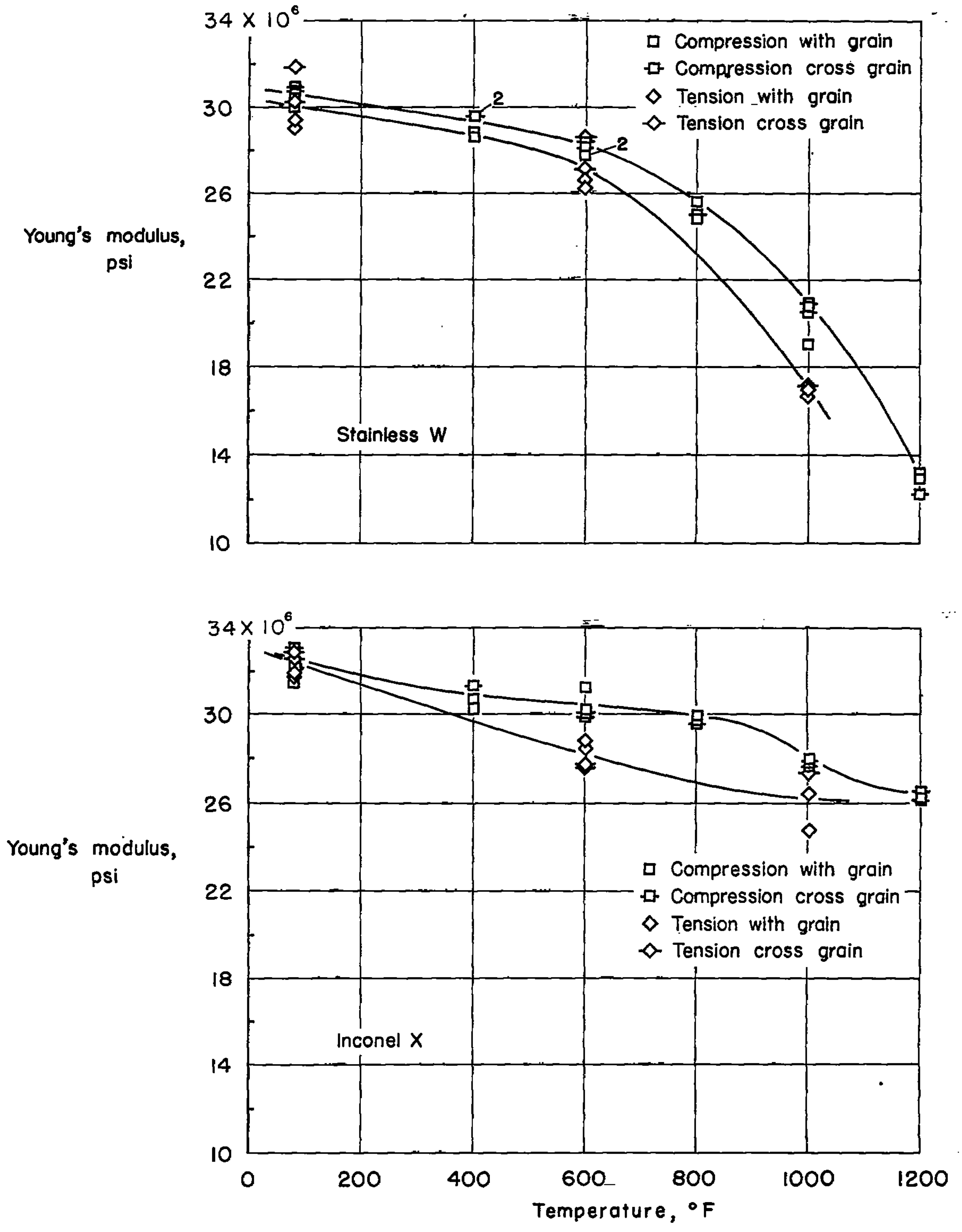


Figure 17.- Variation of Young's modulus with temperature in tension and compression for Stainless W and Inconel X.

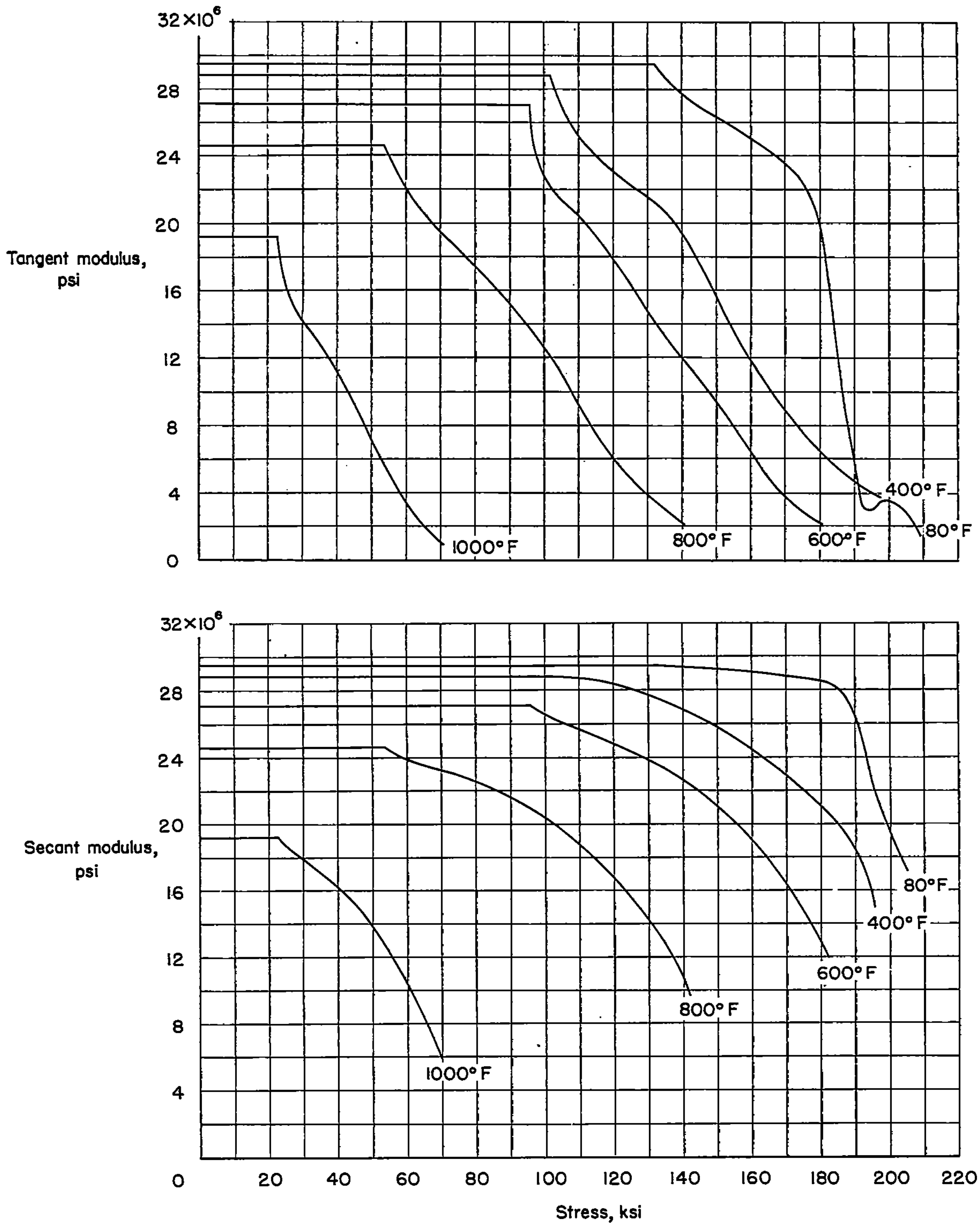


Figure 18.- Variation of secant and tangent moduli with stress for SAE 4340 at elevated temperatures in compression.

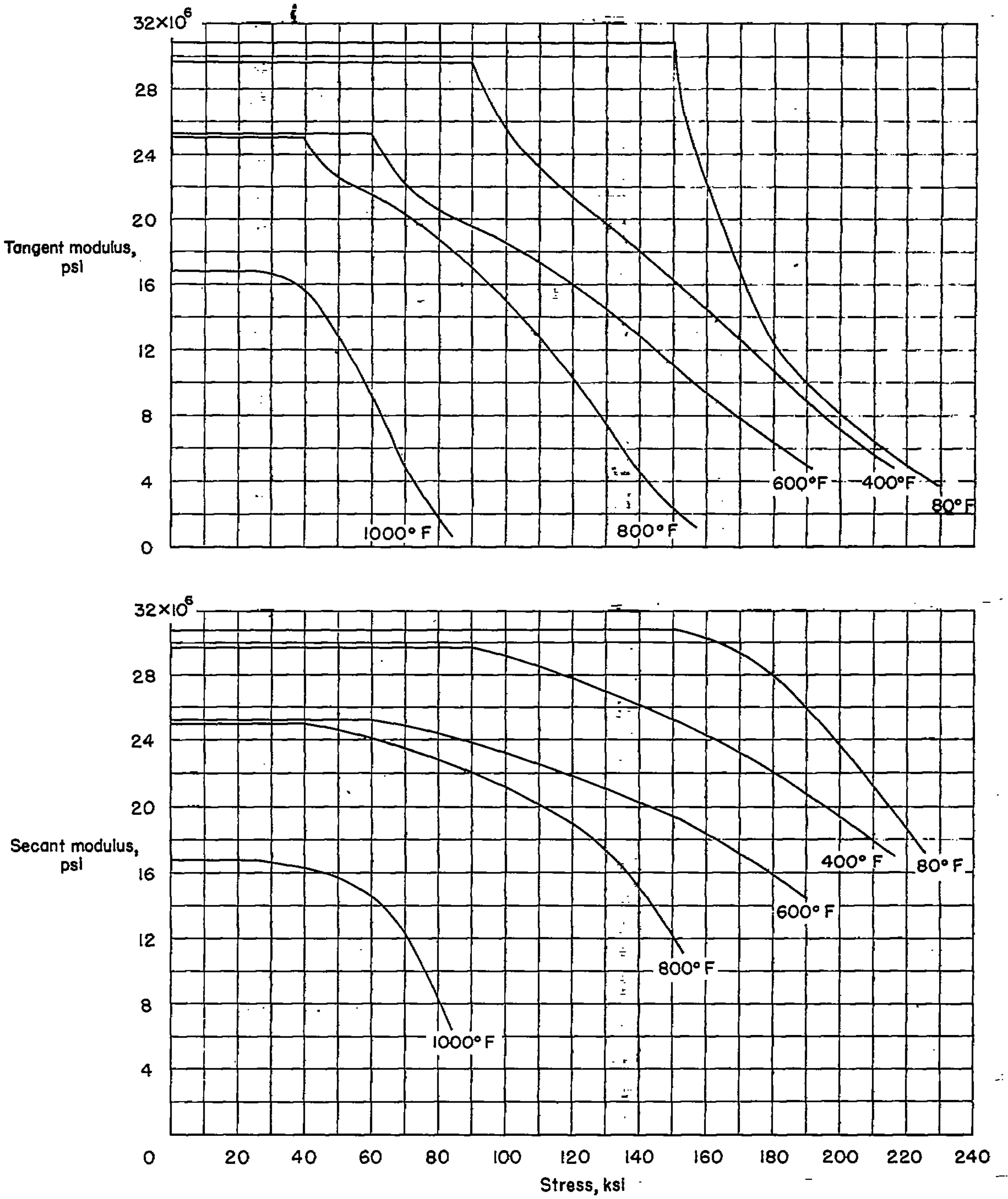


Figure 19.- Variation of secant and tangent moduli with stress for Hy-Tuf at elevated temperatures in compression.

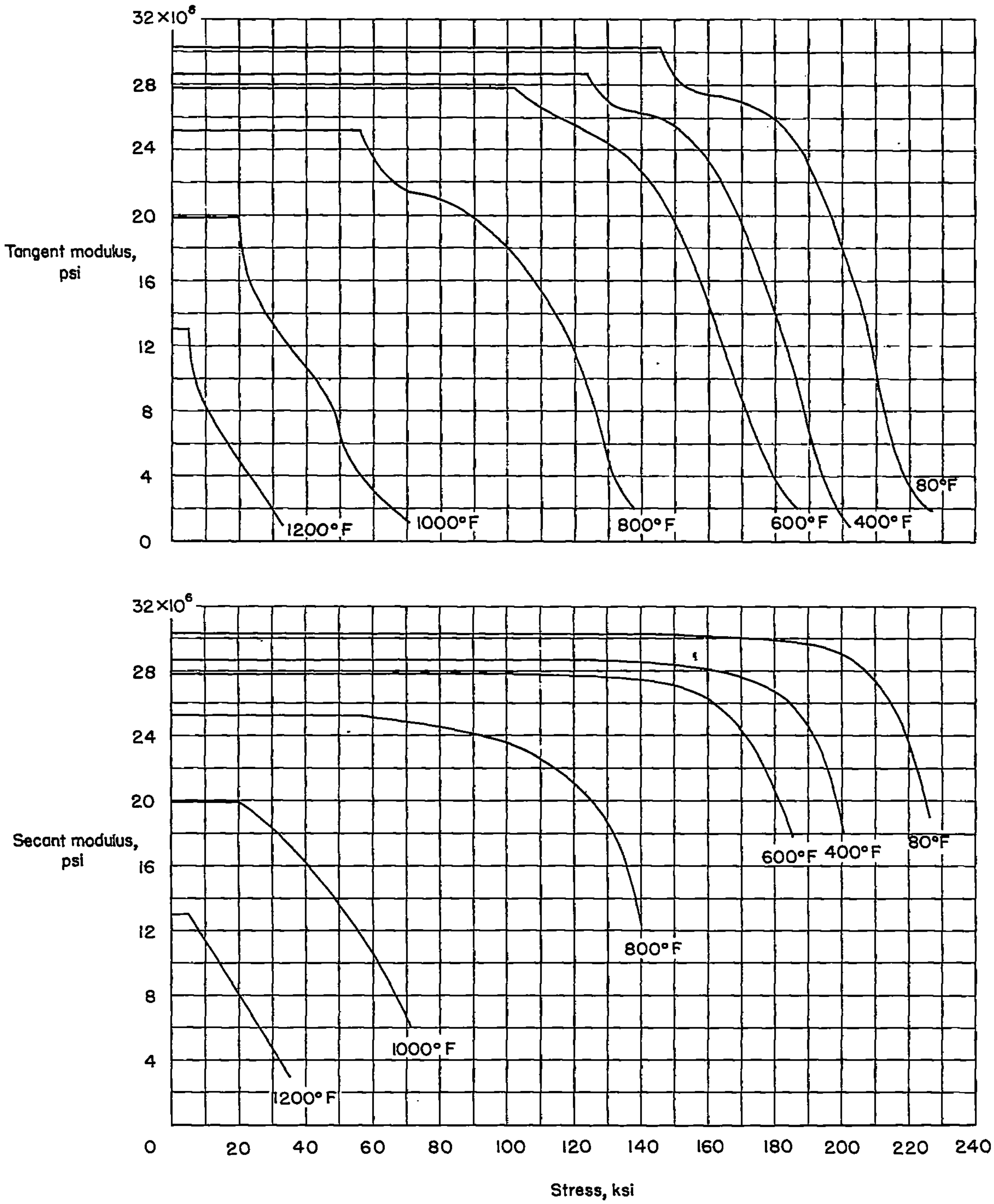


Figure 20.- Variation of secant and tangent moduli with stress for Stainless W at elevated temperatures in compression.

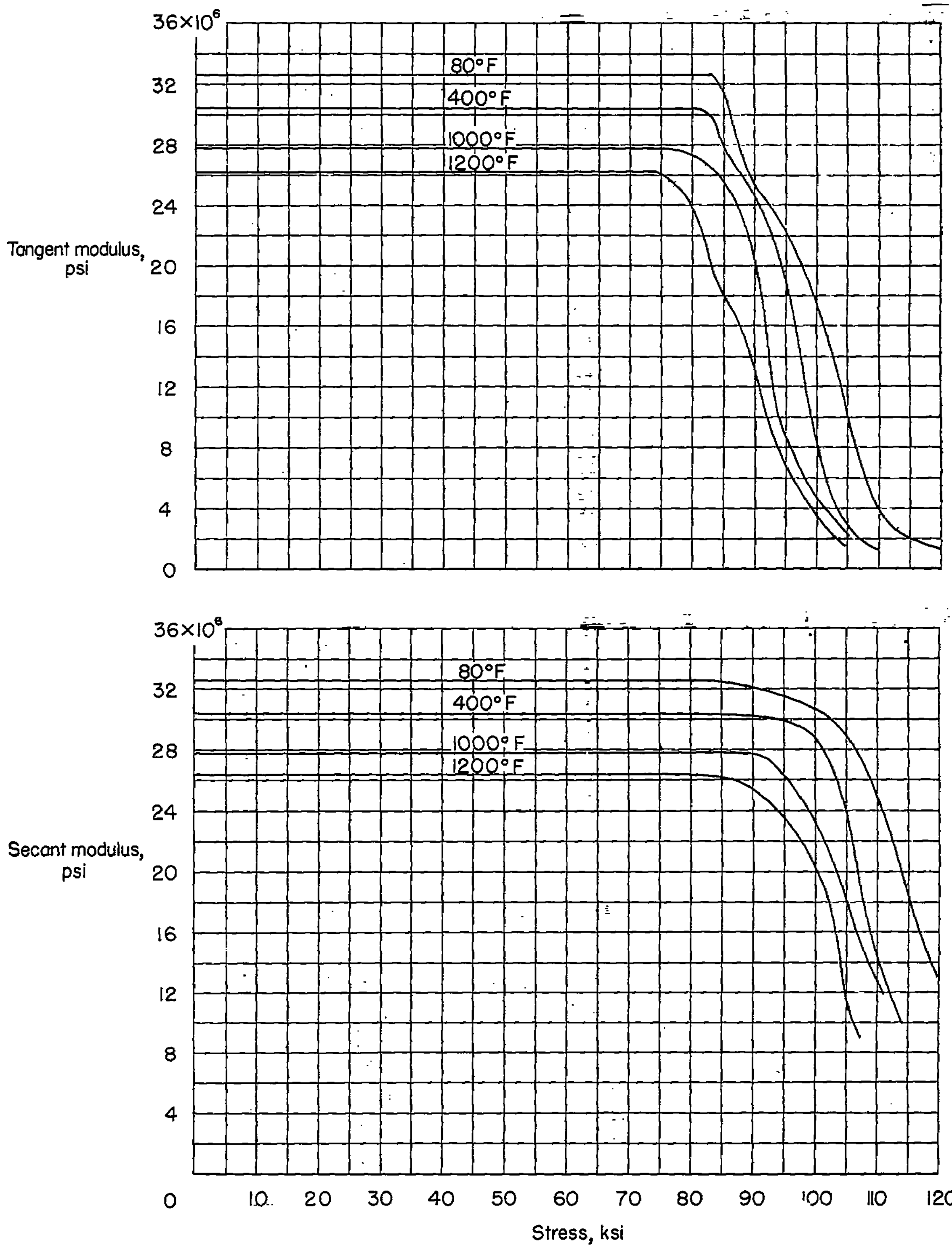


Figure 21.- Variation of secant and tangent moduli with stress for Inconel X at elevated temperatures in compression.

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