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AN EVALUATION OF SOME CURRENT PRACTICES FOR SHORT-TIME ELEVATED-TEMPERATURE TENSILE TESTS OF METALS

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SUMMARY

The effect of different testing practices on the short-time elevated-temperature tensile properties was determined for 2024-T3 aluminum-alloy, HM21A-T8 and HK31A-H24 magnesium-alloy, and 12 MoV stainless-steel sheet. Tests were made under single strain-rate and single head-speed conditions. A dual strain-rate test was also included. An evaluation of the effects of these practices is given for the tensile and yield strengths, the elongation in 2 inches, and the uniform elongation. The need for a uniform testing practice is demonstrated. Recommended practices suggested by different organizations are included.

INTRODUCTION

In recent years, extensive short-time elevated-temperature tensile and compressive data have been obtained on materials for high-speed-aircraft and missile applications. The test results at elevated temperatures depend largely on the testing practice, although such was not the case in the past inasmuch as variations in testing technique at normal temperatures were not generally of great importance.

The need for uniform testing practice has been generally recognized and has recently led to various recommended practices for short-time elevated-temperature tensile tests, the subject of this paper. These testing techniques have been suggested by the American Society for Testing Materials (ref. 1), the Aerospace Industries Association of America, Inc. (ref. 2), and the Materials Advisory Board (ref. 3). A canvass with regard to practices of the steel industry was also made by the American Society for Testing Materials (ref. 4). These practices are summarized in appendix A. In addition to the short-time test in which the material is heated and loaded slowly, recommended practices have been suggested for another type of tension test in which the material is heated rapidly and loaded either at conventional or at rapid rates (refs. 5 and 6).

Factual information on the effects of various testing practices for the short-time tensile test is needed as the recommended practices are tentative and indefinite in some respects (ref. 1). In order to provide such information, short-time elevated-temperature tensile tests were run on 2024-T3 aluminum-alloy, HK31A-H24 and HM21A-T8 magnesium-alloy, and 12 MoV stainless-steel sheet. On the basis of the results obtained in these tests an evaluation is made in this paper of the effect of various loading practices on the short-time elevated-temperature tensile properties.

TEST PROCEDURES

Specimens

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The tensile stress-strain specimens were cut from 2024-T3 aluminum-alloy, HK31A-H24 and HM21A-T8 magnesium-alloy, and 12 MoV stainless-steel sheet with the longitudinal axis of the specimen parallel to the rolling direction. With the exception of a few specimens of HM21A-T8 magnesium alloy which were cut from an additional sheet, all the specimens for each material were cut from a single sheet. The dimensions of the elevated-temperature tensile specimen are shown in figure 1. Information on sheet thickness, heat treatment, density, and suppliers is given in table 1.

Method of Testing

As is customary in the short-time elevated-temperature tensile stress-strain test, the specimen was placed in a preheated furnace and kept at test temperature for 1/2 hour before loading. Loading was accomplished in a hydraulic testing machine by manually controlling the loading in such a way as to maintain either a constant strain rate or a constant head speed. Strains were measured over a 1-inch gage section. A detailed description of the equipment (fig. 2) and the procedures used is given in appendix B. Information on the strain rates and head speeds is summarized in table 2.

Strain rates of either 0.002 or 0.005 per minute were maintained throughout some of the constant strain-rate tests; these tests are hereinafter referred to as the single strain-rate tests. The former rate was selected because it is about the slowest rate which has been used for such tests; the latter rate was used because it has been recommended for this type of test (refs. 1 and 2). In other constant strain-rate tests, a strain rate of 0.005 per minute was maintained to yield and then a rate of 0.04 per minute was used to failure; these tests are referred to as dual strain-rate tests. This latter rate was used because it is in the range of the recommended rates (refs. 1, 2, and 3).

Single head speeds of either 0.11 or 1.46 in./min were used in the constant head-speed tests. The head speed of 0.11 in./min was selected because it corresponded to a constant strain rate of 0.005 per minute in the elastic region for the specimens used in these tests, whereas the head speed of 1.46 in./min was the maximum head speed of the testing machine.

RESULTS AND DISCUSSION

Results of the elevated-temperature tensile tests of 2024-T3 aluminum-alloy, HK31A-H24 and HM21A-T8 magnesium-alloy, and 12 MoV stainless-steel sheet are presented in figures 3 to 14 and tables 3 to 5. The average strain rates for the dual strain-rate tests and the single head-speed tests, which are used in presenting the results, are given in table 2. These average strain rates are the numerical average of the initial strain rate and the strain rate from yield to fracture. The strain rates in the elastic and plastic regions and the ratio of plastic to elastic strain rates are also given in table 2 for the single head-speed tests. The effect of testing practice with regard to loading on the yield strength and tensile strength, elongation in 2 inches and uniform elongation, stress and elongation ratios, and reduction in area is shown in the following sections.

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Tensile Stress-Strain Curves to Failure

The effect of testing practice on the tensile stress-strain curves to failure is shown in figures 3 to 6 for the various materials. Each curve is representative of the results obtained at a particular strain rate and temperature. Tests were made at all strain rates and head speeds for each material with the exception of 0.002 per minute for HM21A-T8 magnesium alloy and 12 MoV stainless steel. One test was made at room temperature at a head speed of 0.11 in./min for the 12 MoV stainless steel.

An examination of figures 3 to 6 shows that the effect of the testing practice on the stress-strain curve beyond the elastic range depends largely upon the material and the test temperature. Materials such as HK31A-H24 and HM21A-T8 magnesium alloys are noticably sensitive to the testing practice at room temperature (figs. 4(a) and 5(a)). The 2024-T3 aluminum alloy is considerably affected by the test technique at 600° F (fig. 3(b)), but shows relatively little effect at lower temperatures. The greatest effect of the testing practice was obtained with HK31A-H24 magnesium alloy at 600° F (fig. 4(b)). The stress-strain curves for 12 MoV stainless steel were sensitive to the testing practice at $1,000^\circ$ F and $1,200^\circ$ F (fig. 6(b)) but showed little effect below this temperature. In general, the highest strength in the plastic region resulted from the highest constant head speed of 1.46 in./min with the exception of 2024-T3 aluminum alloy at 75° F and 200° F (fig. 3(a)) and 12 MoV at temperatures below $1,000^\circ$ F (fig. 6(a)). The slowest strain rates of 0.002 and 0.005 per minute resulted in the lowest strength in almost every case.

An increase in the strain rate from 0.002 to 0.005 per minute has a noticeable effect on the stress-strain curves at elevated temperatures for 2024-T3 aluminum alloy and HK31A-H24 magnesium alloy at 600° F (figs. 3(b) and 4(b)). This change in strain rate had little effect at room temperature for these materials (figs. 3(a) and 4(a)). Although similar data on HM21A-T8 magnesium alloy and 12 MoV stainless steel are lacking, a change in strain rate from 0.002 to 0.005 per minute may also be expected to affect the stress-strain curves for HM21A-T8 but have little effect on the curves for 12 MoV stainless steel except at the highest temperature.

In general, the dual strain-rate test (0.005 per minute to yield and 0.04 per minute to failure) and the single head-speed test (0.11 in./min) gave approximately the same results (figs. 3 to 6). This latter test is equivalent to a constant strain rate of 0.005 per minute in the elastic range and about 0.03 per minute in the plastic range.

Nonuniform plastic flow was obtained in the tests of 2024-T3 aluminum alloy at room temperature (fig. 3(a)) and of 12 MoV stainless steel at 400° F (fig. 6(a)). These results are characterized by irregular wavy curves in the plastic region, which are associated with nonuniform plastic flow such as that which occurs when Luders' lines develop. Various aspects of this type of flow have been noted in other materials and are discussed in reference 7.

Yield and Tensile Strength

Effect of strain rate.- The change in yield and tensile strength of the four test materials with strain rate at various temperatures is shown in figures 7 to 10. Test points are average values of the individual results given in table 3; the average strain rates are given in table 2.

The largest effect of strain rate on strength is noted for HK31A-H24 magnesium alloy at 600° F (fig. 8). A moderate increase in strength with an increase in strain rate is shown by HM21A-T8 magnesium alloy (fig. 9), but this was not the case for 2024-T3 aluminum alloy or 12 MoV stainless steel, which either increase or decrease in strength with increasing strain rate (figs. 7 and 10).

The effect of an increase in testing speed from 0.002 or 0.005 per minute to 1.46 in./min over the entire temperature range is shown in figures 11 and 12 for each material. These results indicate that the magnesium alloys are more rate sensitive than either the stainless steel or the aluminum alloy and, thus, a larger increase in strength is obtained for the same increase in strain rate. Such differences in strength point out the desirability of standardizing the testing practice in order to obtain comparable results.

Stress ratios.- The effect of testing practice on the ratio of tensile strength to yield strength is presented in table 3 for each test condition and each material. Values of the ratio remained relatively constant for the range of strain rates and head speeds covered at any given temperature for each material with the exception of HK31A-H24 magnesium alloy at 600° F. This ratio, although relatively constant at each temperature for the range of testing speed covered herein, can be expected to increase with higher testing speeds than those covered in this program, especially at elevated temperatures.

The effect of the testing practice on the ratio of the yield or tensile strength for each test condition to the corresponding yield or tensile strength obtained in tests in which a constant strain rate of 0.005 per minute was used throughout the test is presented in table 4. The stress ratios of table 4 indicate that the effect of the strain rate is more pronounced as the temperature increases. The largest increase in the stress ratio, for each material occurs at the fastest testing speed and the highest temperature.

Elongation in 2 Inches and Uniform Elongation

The effect of testing practice on elongation in 2 inches and uniform elongation is shown in figures 13 and 14. Points shown in the figures are the average of individual values in table 3. The elongation in 2 inches was measured in the usual manner after the test was completed. The uniform elongation was taken as the strain on the stress-strain curve (figs. 3 to 6) at which the maximum stress occurred. Under elevated-temperature slow strain-rate conditions this criterion may be conservative inasmuch as necking may not begin until some time after the maximum stress is reached. Under fast strain-rate conditions or at low temperatures, however, this criterion may be reasonably satisfactory.

The effect of strain rate on the elongation in 2 inches and the uniform elongation of the four test materials at room and elevated temperatures is shown in figures 13(a) to 13(d). There is no general trend as to the effect of strain rate on the elongation in 2 inches that fits the materials included herein. The elongation in 2 inches for the magnesium alloys is relatively unaffected by strain rate except for HK31A-H24 at 600° F (fig. 13(b)), where the elongation in 2 inches decreases with increasing strain rate, and for HM21A-T8 at 400° F and above (fig. 13(c)), where the elongation may either increase or decrease with increasing rate. The elongation in 2 inches for the 12 MoV stainless steel (fig. 13(d)) and 2024-T3 aluminum alloy (fig. 13(a)) is only slightly affected by a change in strain rate except at 600° F and 800° F for the steel and at 400° F and 600° F for the aluminum. A general trend may be noted for the uniform elongation in that it remains relatively constant for all strain rates and temperatures for the materials included herein with the exception of 2024-T3 aluminum alloy (fig. 13(a)).

In figures 14(a) to 14(d), the effect of temperature on the elongation in 2 inches and the uniform elongation is shown for all strain rates and head speeds. The magnesium alloys show large increases in elongation in 2 inches with increasing temperature except for HM21A-T8 at 600° F (fig. 14(c)), whereas the elongation for 2024-T3 aluminum alloy (fig. 14(a)) and for 12 MoV stainless steel (fig. 14(d)) may either increase or decrease with increasing temperature. These trends are also
shown by the dashed curves in figures 14(b) and 14(d) for the magnesium L
alloy and the stainless steel obtained from references 8 and 9, respec- 5
tively. Uniform elongation for the magnesium alloys and the stainless 4
steel is relatively unaffected at each strain rate and head speed over 9
the entire temperature range except at 1,000° F and 1,200° F for 12 MoV. The aluminum alloy shows a decrease in uniform elongation with increasing temperature for all rates and head speeds.

Reduction in Area

Representative values of the reduction in area for the four sheet materials are given in table 3. These values are shown because the reduction in area may be a more significant measure of ductility than elongation in 2 inches. The procedure for measuring the reduction in area is described in appendix B.

The reduction in area for 2024-T3 aluminum alloy was relatively unaffected by a change in strain rates over the entire temperature range (table 3). The reduction in area for HK31A-H24 magnesium alloy decreased generally as the strain rate increased at each temperature with the exception of the dual strain-rate test at 200° F and the test at 0.005 per minute at 600° F. For the HM21A-T8 magnesium alloy and 12 MoV stainless steel, the reduction in area first remained relatively constant and then tended to decrease with increasing strain rate at each temperature. The maximum decrease in reduction in area for all the materials except the aluminum alloy came at the highest temperature. On the basis of these tests, it should be noted that testing procedure may have a marked effect on the results obtained for reduction in area.

Characteristics of Constant Strain-Rate and Constant Head-Speed Tests

The basic difference between constant strain-rate tests and constant head-speed tests is that in the constant strain-rate test the strain rate is controlled and constant in both the elastic and plastic regions, whereas in the constant head-speed test the strain rate increases in an uncontrolled manner in going from the elastic region to the plastic region. The strain rate in the plastic range may be of the order of five or more times that in the elastic range and will depend upon such factors as testing speed, size and shape of specimen, stiffness of testing machine, testing temperature, and kind of material. Although strain rates in the elastic and plastic region may differ considerably in the constant head-speed test, the strain rate in each region is nearly constant. With this in mind the constant head-speed test may be regarded as a dual strain-rate test in which the strain rates are uncontrolled. The constant head-speed test, although the simplest kind of test, is the least desirable from the standpoint of providing uniform test conditions.

Actual changes in strain rate in going from the elastic to plastic region in the constant head-speed tests may be noted in table 2. A review of the strain rate ratios in table 2 for a head speed of 0.11 in./min shows that the ratio of the plastic to elastic strain rate for the two magnesium alloys and the aluminum alloy remains relatively constant over the entire temperature range. For a head speed of 1.46 in./min, the strain rate ratio decreased with increasing temperature to a minimum of 2.8 at 600° F for the aluminum alloy, remained relatively constant over the entire temperature range for the magnesium alloys with the exception of HM21A-T8 at 400° F, and remained quite constant to 1,000° F after which it increased considerably for the 12 MoV stainless steel.

Although the ratios of plastic to elastic strain rates are relatively constant for each head speed and each material for the data shown over the entire temperature range, the ratio drops considerably with an increase in head speed from 0.11 to 1.46 in./min.

CONCLUDING REMARKS

The effects of different testing practices were determined from short-time elevated-temperature tensile tests of 2024-T3 aluminum-alloy, HK31A-H24 and HM21A-T8 magnesium-alloy, and 12 MoV stainless-steel sheet, which were made under various strain-rate and head-speed conditions. The results showed that both the strength and ductility were affected by the testing practice at elevated temperatures for all of the materials. Noticeable effects were also obtained in the tests of the magnesium alloys at room temperature.

The results of this investigation bear out the need for a uniform testing practice for the short-time elevated-temperature tensile test. Differences in practices recommended by various organizations should be resolved as soon as possible. There is general agreement that a strain rate of 0.005 per minute should be used up to yield load and a rate of 0.05 per minute for the region from yield to fracture. This procedure is recommended herein for the short-time elevated-temperature tensile test for metals. It may be noted that different testing procedures may be required to provide data for various specific applications. Such tests cannot be readily standardized.

Short-time elevated-temperature tensile tests, made under constant L
head-speed conditions, have little to recommend them except the simplicity 5
of the test. Such tests are not desirable from the standpoint of insuring 4
uniform test results because the strain rates are uncontrolled. 9

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 6, 1960.

APPENDIX A

RECOMMENDED PRACTICES FOR SPEED OF TESTING FOR SHORT-TIME ELEVATED-TEMPERATURE TENSILE TESTS

American Society for Testing Materials

In reference 1 the American Society for Testing Materials has recommended that a constant strain rate of either 0.005 or 0.05 per minute should be used up to the yield load and either a strain rate of 0.05 or 0.10 per minute should be used from yield load until fracture. The strain rate is the rate of strain in the specimen gage length and not the speed of the head of the testing machine.

Aerospace Industries Association

In reference 2 the Aerospace Industries Association of America, Inc., has recommended that for airframe applications a strain rate during loading of 0.005 per minute be used up to the 0.2 percent yield point and a rate of 0.05 per minute be used beyond the 0.2 percent yield point, or the strain rate beyond yield may be increased to produce failure in 1 additional minute.

Materials Advisory Board

A task force on uniform precedures for structural-design-data collection of the panel on titanium sheet rolling program of the Materials Advisory Board has pointed out the acute need for uniform procedures in procuring the data for evaluating various titanium alloys. In reference 3 the recommendation is made that a strain rate of 0.003 to 0.007 per minute be used to slightly beyond the yield strength and a rate of straining of approximately 0.05 per minute be used beyond yield.

Steel Industry

The American Society for Testing Materials has canvassed a representative cross section of the steel industry with regard to the speed of testing. The steel industry prefers the speed of testing to be specified in terms of the rate of separation of the testing machine crossheads under load, as this method lends itself to easier measurement. (See ref. 4.) Current practice is to use a crosshead separation speed of 0.01 to 0.10 in./min under load to the yield strength. No limit of the speed of separation of the crossheads above yield strength to fracture is specified. Ordinarily, the speed is increased after the yield strength is reached.

APPENDIX B

EQUIPMENT AND TECHNIQUE

The tension tests were made in a 100,000-pound-capacity hydraulic testing machine. The specimens were loaded through a linkage and bolt system above and below the furnace. Templin load bars and spherical seats were employed at the top and bottom of the loading system. Loads were measured with a 2,000-pound or 5,000-pound-capacity Baldwin SR-4 L
load cell located below the specimen. Strains were measured over a 5
1-inch gage length at the center of the specimen by means of an exten- 4
someter system consisting of two linear differential transformer strain 9
gages mounted on a strain transfer device which is actuated by extensometer rods extending down alongside the specimen (fig. 2). Flexure plates are used at the fulcrums of these strain transfer devices. The gage points, which are replaceable, are clamped to a supporting plate welded to the end of the extensometer rod. One gage point on each unit has a sharp point which seats in a fine punch mark in the specimen; the other gage point is rounded and stabilizes the extensometer rod system against rotation. Inconel X springs are used to clip the extensometer onto the specimen. Both the load and strain were recorded against time on a 2-channel strip-type potentiometer. Temperatures were maintained within $\pm 5^{\circ}$ F during the test.

A constant strain rate was maintained in the constant strain-rate tests by adjusting the loading rate of the hydraulic testing machine manually in such a manner that the pen recording the strain followed a predetermined slope on the potentiometer chart. The extensometer was reset during the test in order to measure large strains. When the range of the extensometer was exceeded (about 5 percent), a head motion indicator and pacing disk device were used to maintain a constant rate. The disk speed was adjusted after yielding occurred so that it corresponded to the head-motion-indicator speed. Inasmuch as the relation between the head speed and the strain rate was approximately constant in the plastic range for the material, strains greater than those measured with the extensometer were estimated from the head speed and the time. The strain corresponding to the stress when the specimen failed was determined from the time indicated on the potentiometer chart.

The reduction in area was determined from measurements of the thickness and the width of the specimen cross section at the fracture by means of a dial-gage setup. A sharp conical point was attached to the stem of the dial gage and the specimen thickness or width was measured by passing the specimen between the movable point and a similar fixed point directly below. The plane of the specimen was kept horizontal or vertical, depending on whether the thickness or width was being measured. The reduction in area was calculated as the difference between this fractured area and the original area and was expressed as a percentage of the original area.

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TABLE 1.- DESCRIPTION OF SHEET MATERIAL

Material	Thickness, in.	Received condition	Additional heat treatment	Manufacturer	Density, lb/cu in.
USS-12 MoV stainless steel	0.100	Annealed	Austenitize 15 min. to 1,850° F. Air cool to room temp. Temper 4 hrs. at 800° F and air cool to room temp.	U.S. Steel Corp.	0.279
HM21A-T8 magnesium alloy	.064	T8	None	The Dow Chemical Co.	.064
HK31A-H24 magnesium alloy	.091	H24	None	The Dow Chemical Co.	.065
2024-T3 aluminum alloy	.072	T3	None	Aluminum Co. of America	.10

TABLE 2.- SCHEDULE OF TESTING SPEEDS

(a) Constant Strain-Rate Tests

Type of test	Strain rate, per min		
	Elastic[a]	Plastic[b]	Average[c]
Single strain rate	0.002	0.002	-----
Single strain rate	.005	.005	-----
Dual strain rate	.005	.04	0.022

(b) Constant Head-Speed Tests

Material	Temp., °F	Head speed, in./min	Strain rate, per min			Plastic strain rate / Elastic strain rate
			Elastic[a]	Plastic[b]	Average[c]	
2024-T3 aluminum alloy	75	0.11	0.005	0.030	0.017	6.0
	75	1.46	.084	.455	.270	5.4
	200	.11	.005	.033	.019	6.0
	200	1.46	.082	.400	.244	4.9
	400	.11	.0056	.036	.021	6.4
	400	1.46	.099	.388	.244	3.9
	500	1.46	.086	.392	.239	4.5
	600	.11	.0054	.032	.019	5.7
	600	1.46	.190	.525	.355	2.8
HK31A-H24 magnesium alloy	75	0.11	0.0048	0.031	0.018	6.4
	75	1.46	.071	.327	.200	4.6
	200	.11	.0048	.034	.020	7.1
	200	1.46	.077	.345	.211	4.5
	400	.11	.0052	.038	.022	7.3
	400	1.46	.098	.490	.295	5.0
	600	.11	.0050	.030	.017	6.0
	600	1.46	.103	.488	.295	4.8
HM21A-T8 magnesium alloy	75	0.11	0.0054	0.031	0.018	5.7
	75	1.46	.115	.340	.228	2.9
	200	.11	.0052	.030	.017	5.8
	200	1.46	.12	.393	.256	3.3
	400	.11	.0053	.0380	.022	7.2
	400	1.46	.10	.480	.290	4.8
	600	.11	.006	.044	.025	7.3
	600	1.46	.125	.465	.295	3.7
	700	1.46	.137	.455	.295	3.3
12 MoV stainless steel	75	1.46	0.052	0.215	0.133	4.1
	200	1.46	.053	.220	.137	4.1
	400	1.46	.058	.225	.142	3.9
	600	----	------	------	-----	---
	800	1.46	.055	.255	.155	4.6
	1,000	1.46	.064	.242	.153	3.8
	1,200	1.46	.065	.405	.235	6.2

[a]Initial rate.

[b]Rate beyond yield.

[c]Average of elastic and plastic strain rates.

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TABLE 3.- TENSILE PROPERTIES OF TEST MATERIALS

(a) 2024-T3 aluminum-alloy sheet

Temp., °F	Strain rate, per min	Head speed, in./min	Yield stress, ksi	Tensile stress, ksi	Tensile stress / Yield stress	Modulus of elasticity, psi	Elongation in 2 in., percent	Uniform elongation, percent	Reduction in area, percent
75	0.002		54.3	71.4	1.31	10.4×10^6	15.0	14.7	
75	.002		54.8	71.8	1.31	10.5	15.0	14.9	
75	.005		54.7	72.0	1.31	10.2	15.0	15.2	
75	.005		54.0	71.0	1.31	9.9	17.0	17.2	15.5
75	.005 and .04		53.8	71.1	1.32	10.2	12.0	10.7	
75	.005 and .04		54.2	71.0	1.31	10.0	12.0	10.7	13.0
75		0.11	52.7	70.4	1.33	10.0	15.0	12.7	13.7
75		.11	53.3	71.2	1.34	10.1	14.0		
75		1.46	54.2	71.0	1.31	10.4	13.0	13.9	20.0
75		1.46	52.8	70.0	1.33	10.5	12.0	13.7	
200	.002		52.0	65.0	1.25	10.0	13.5	14.2	11.8
200	.002		52.0	66.0	1.27	10.0	15.0	10.0	13.0
200	.005		52.0	66.7	1.28	10.0	15.0	15.0	
200	.005		51.6	66.4	1.29	10.0	17.0	16.0	
200	.005 and .04		52.0	67.0	1.29	10.0	14.5	12.6	
200	.005 and .04		52.0	67.0	1.29	10.0	13.0		
200		.11	51.1	68.0	1.33	9.9	14.5	11.8	12.8
200		.11	50.8	67.6	1.33	10.0	14.0	12.0	11.9
200		1.46	49.3	66.0	1.34	10.0	13.0	11.2	11.8
200		1.46	49.1	65.2	1.33	10.0	14.0	14.0	
400	.002		47.0	49.0	1.04	8.9	5.0	2.5	11.0
400	.002		48.5	51.0	1.05	9.0	5.0	2.1	12.0
400	.005		48.2	54.0	1.12	9.4	7.0	6.1	
400	.005		46.3	54.1	1.17	9.3	7.0	5.9	11.2
400	.005 and .04		48.5	54.0	1.11	9.0	8.5	5.6	
400	.005 and .04		47.3	54.3	1.15	9.1	10.5	6.4	12.9
400		.11	47.8	54.0	1.13	8.9	11.5	6.7	12.2
400		.11	48.2	54.0	1.12	9.2	12.0	5.8	
400		1.46	48.4	55.6	1.15	9.1	13.5	6.0	
400		1.46	45.6	54.4	1.19	9.0	15.5	6.4	
500	.002		32.5	33.0	1.02	8.6	7.0	1.0	
500	.002		31.4	33.6	1.07	8.6	8.5	1.0	11.4
500		1.46	33.8	37.0	1.10	8.7	8.0	3.2	
500		1.46	34.4	37.0	1.08	8.7	8.0	2.5	
600	.002		16.3	16.4	1.00	8.0	8.0	.8	
600	.002		16.4	16.6	1.01	8.0	9.0	.8	12.8
600	.005		17.7	18.2	1.03	7.6	8.0	.8	
600	.005		17.1	17.4	1.02	7.7	7.0	.8	
600	.005 and .04		17.5	18.5	1.06	8.0	13.0		
600	.005 and .04		18.2	18.8	1.04	8.0	10.0	1.4	
600		.11	18.6	19.8	1.07	7.8	14.0	2.5	
600		.11	18.0	19.4	1.08	8.0	11.0	2.0	
600		1.46	19.0	21.0	1.10	7.7	12.5	2.7	
600		1.46	18.6	20.0	1.08	7.7	11.5	2.8	

TABLE 3.- TENSILE PROPERTIES OF TEST MATERIALS - Continued

(b) HK31A-H24 magnesium-alloy sheet

Temp., °F	Strain rate, per min	Head speed, in./min	Yield stress, ksi	Tensile stress, ksi	Tensile stress / Yield stress	Modulus of elasticity, psi	Elongation in 2 in., percent	Uniform elongation, percent	Reduction in area, percent
75	0.002		27.4	32.8	1.20	5.9×10^6	15.0	3.0	
75	.002		27.2	31.6	1.16		13.5	3.0	
75	.005		27.7	32.9	1.19		12.0	2.7	13.0
75	.005		27.3	33.3	1.22	6.2	16.0	3.3	
75	.005 and .04		27.5	34.4	1.25	6.4	15.0	5.4	10.0
75	.005 and .04		27.4	34.1	1.24	6.2	8.0	5.0	10.0
75		0.11	28.2			6.0	11.0	5.1	
75		.11	28.5	34.0	1.19	6.1	9.0	5.3	
75		1.46	30.5	34.9	1.15	6.0	10.0	4.2	
75		1.46	29.6	35.0	1.18	6.0		4.2	
200	.002		24.4	24.5	1.00	5.4	20.0	.8	
200	.002		24.6	24.7	1.00	5.4	23.0	.8	
200	.005		24.6	24.8	1.01	5.9	19.0	1.0	
200	.005		24.7	24.9	1.01	5.9	19.0	1.0	37.0
200	.005 and .04		25.2	26.8	1.06	5.6	11.0	4.7	
200	.005 and .04		24.6	27.4	1.11	5.5	6.0	4.9	7.0
200		.11	24.4	26.6	1.09	5.5	10.0	2.5	
200		.11	24.4	26.6	1.09	5.5	12.0	2.7	
200		1.46	25.5			5.7	19.0	4.6	26.0
200		1.46	24.9	28.8	1.16	5.8		4.6	
400	.002		17.7	18.6	1.05	5.0	15.0	.9	
400	.002		17.3	18.3	1.06	5.0	15.0	.7	
400	.005		18.2	18.4	1.01	4.9	20.0	.8	
400	.005		18.4	18.6	1.01	4.9	23.0	.9	51.0
400	.005 and .04		18.6	19.7	1.06	5.0	24.0	2.1	37.0
400	.005 and .04		18.4	19.6	1.06	5.0	25.5	2.0	47.0
400		.11	18.6	18.9	1.02	4.8	22.0	1.1	42.0
400		1.46	20.2	21.6	1.07	4.8	16.0	2.8	
400		1.46	20.1	21.5	1.05	4.8	25.0	2.8	41.0
600	.002		3.9	4.5	1.15	3.9	110.0	1.0	87.0
600	.005		5.3	6.0	1.13	3.8		2.4	85.0
600	.005		5.7	5.8	1.01	3.9	135.0	2.4	93.0
600	.005 and .04		6.4	10.7	1.67	3.7		3.5	
600	.005 and .04		6.2	10.3	1.66	3.7	45.0	3.7	71.0
600		.11	6.7	9.7	1.43	3.4	70.0	2.6	
600		.11	7.3	8.8	1.20	3.7	74.0	3.0	
600		1.46	12.0	14.0	1.17	3.8		1.7	
600		1.46	12.0	13.4	1.12	3.7	32.0	1.9	69.0

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TABLE 3.- TENSILE PROPERTIES OF TEST MATERIALS - Continued

(c) HM21A-T8 magnesium-alloy sheet

Temp., °F	Strain rate, per min	Head speed, in./min	Yield stress, ksi	Tensile stress, ksi	Tensile stress / Yield stress	Modulus of elasticity, psi	Elongation in 2 in., percent	Uniform elongation, percent	Reduction in area, percent
75	0.005		28.0	31.4	1.12	6.0×10^6	9.0	2.5	13.0
75	.005		27.4	31.7	1.15	6.1	10.0	2.7	13.5
75	.005 and .04		27.7	33.2	1.20	6.1	8.0	2.7	
75	.005 and .04		27.7	33.2	1.20	6.1	9.0	2.7	13.0
75		0.11	28.4	32.0	1.12	5.8	6.5	2.6	13.0
75		1.46	29.8	34.6	1.16	6.0	10.0	2.8	
75		1.46	29.3	34.4	1.17	5.9	10.5	3.2	
200	.005		24.4	26.7	1.09	6.0	9.0	3.8	30.4
200	.005		25.0	26.0	1.04	6.0	10.0		
200	.005 and .04		24.2	26.0	1.07	5.9	15.0	2.0	21.5
200	.005 and .04		24.6	28.0	1.14	5.8	8.0	2.0	13.0
200		.11	24.6	26.4	1.07	5.5	9.0	2.3	
200		1.46	24.8	28.7	1.16	4.9	9.0	2.2	
200		1.46	25.0	28.9	1.16	5.7	7.5	2.2	14.0
400	.005		17.7	18.1	1.02	4.9	12.5	.8	37.5
400	.005		17.9	18.3	1.02	4.9	15.0	.8	41.7
400	.005 and .04		17.6	19.0	1.08	5.3	33.0	2.2	57.4
400	.005 and .04		17.6	19.0	1.08	5.3	24.0	2.2	40.8
400		.11	18.8	20.2	1.07	5.4	19.0	2.4	
400		1.46	19.6	21.4	1.09	5.4	19.5	2.2	32.7
400		1.46	19.6	21.7	1.11	5.0	20.0	2.3	
600	.005		12.1	12.6	1.04	4.7	20.0	2.0	
600	.005		12.3	12.6	1.02	4.7	23.0	2.0	
600	.005 and .04		14.0	14.6	1.04	4.6	12.5	1.6	34.4
600	.005 and .04		12.5	13.5	1.08	4.5	16.5	1.5	36.6
600		.11	14.4	14.6	1.01	4.1	11.0	1.2	
600		1.46	13.8	15.2	1.10	4.3	16.0	2.0	40.0
600		1.46	13.8	14.8	1.07	4.3	21.0	2.0	
700	.005						38.5		56.0
700	.005		8.3	8.8	1.06	3.4	31.0	1.5	54.4
700	.005 and .04		10.0	11.5	1.15	3.2	46.0	2.0	61.0
700		1.46	9.7	12.0	1.24	3.3	35.0	2.0	

TABLE 3.- TENSILE PROPERTIES OF TEST MATERIALS - Concluded

(d) 12 MoV stainless-steel sheet

Temp., °F	Strain rate, per min	Head speed, in./min	Yield stress, ksi	Tensile stress, ksi	Tensile stress / Yield stress	Modulus of elasticity, psi	Elongation in 2 in., percent	Uniform elongation, percent	Reduction in area, percent
75	0.005		190	234	1.23	29.4×10^6	11.0	4.0	31.6
75	.005		190	234	1.23	28.9	11.0	4.0	32.0
75	.005 and .04		190	236	1.24	28.9	11.0	3.5	
75	.005 and .04		194	236	1.21	29.1		3.5	
75		0.11	190	235	1.24	28.8	10.5		
75		1.46	195	236	1.21	28.8	10.5		
75		1.46	191	235	1.23	29.0	10.0	3.5	
200	.005		184	234	1.27	28.5	10.5	4.6	
200		1.46	180	228	1.27	29.0	10.5	4.0	25.0
400	.005		176	232	1.32	28.0	8.0	4.8	
400		1.46	165	220	1.33	27.8	8.0	3.8	27.6
600	.005		167	236	1.42	27.1	9.0	6.8	
600	.005		165	236	1.43	27.2	10.0	5.2	
600	.005 and .04		160	227	1.51	27.7	10.0		
600	.005 and .04		161	235	1.46	27.7	10.0	4.3	
600		1.46	151	226	1.50	27.5	6.5	3.2	18.4
600		1.46	151	224	1.49	27.5	6.0	3.4	14.1
800	.005		151	219	1.45	25.0	10.5	5.0	
800	.005		151	221	1.47	25.5	12.0	5.2	
800	.005 and .04		150	220	1.47	25.0	12.0	5.2	
800	.005 and .04		152	216	1.42	25.0	12.0	4.2	27.8
800		1.46	151	216	1.43	26.1	10.0	4.6	
800		1.46	154	216	1.40	24.5	9.0	4.6	23.4
1,000	.005		140	177	1.26	22.9		2.4	
1,000	.005		140	170	1.21	22.5	9.5	2.2	28.6
1,000	.005 and .04		134	182	1.37	22.7	7.5	2.7	
1,000	.005 and .04		138	182	1.33	22.7	8.5	2.7	26.9
1,000		1.46	134	184	1.37	23.8		3.0	
1,000		1.46	137	182	1.33	22.5		2.8	
1,200	.005		42	48	1.14	19.0		1.2	
1,200		1.46	49	60	1.22	19.1	19.0	1.6	76.5

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TABLE 4.- RATIOS OF YIELD AND TENSILE STRENGTH FOR TESTS AT VARIOUS SPEEDS TO CORRESPONDING STRENGTHS FOR A STRAIN RATE OF 0.005 PER MINUTE THROUGHOUT THE TEST

Temp., °F	Stress ratio for constant-strain-rate test at -			Stress ratios for constant-head-speed test at -			
	0.002 per min		0.005 per min to yield 0.04 per min to failure	0.11 in./min		1.46 in./min	
	Yield strength	Tensile strength	Tensile strength	Yield strength	Tensile strength	Yield strength	Tensile strength
2024-T3 aluminum-alloy sheet							
75	1.00	1.00	0.99	0.98	0.98	0.98	0.98
200	1.00	.98	1.01	.95	1.02	.95	1.02
400	.99	.92	1.00	1.00	1.00	1.00	1.00
600	.93	.92	1.04	1.08	1.09	1.08	1.09
HK31A-H24 magnesium-alloy sheet							
75	0.99	0.98	1.06	1.04	1.05	1.09	1.08
200	.99	.98	1.09	.99	1.06	1.02	1.15
400	.95	.98	1.07	1.02	1.02	1.09	1.17
600	.67	.74	1.77	1.21	1.60	2.05	2.32
HM21A-T8 magnesium-alloy sheet							
75			1.05	1.035	1.01	1.06	1.09
200			1.03	1.00	1.01	1.01	1.09
400			1.05	1.07	1.11	1.11	1.18
600			1.07	1.17	1.16	1.14	1.19
700			1.31		1.30	1.15	1.37
12 MoV stainless-steel sheet							
75			1.01	1.00		0.98	1.01
200						.97	.97
400						.93	.94
600			.98			.93	.95
800			.99			1.00	.98
1,000			1.05			1.00	1.06
1,200						1.17	1.25

TABLE 5.- RATIOS OF ELONGATION IN 2 INCHES AT VARIOUS SPEEDS TO CORRESPONDING ELONGATIONS FOR A STRAIN RATE OF 0.005 PER MINUTE THROUGHOUT THE TEST

Temp., °F	Elongation ratio for constant-strain-rate test at -		Elongation ratio for constant-head-speed test at -	
	0.002 per min	0.005 per min to yield 0.04 per min to failure	0.11 in./min	1.46 in./min
2024-T3 aluminum-alloy sheet				
75	0.94	0.75	0.90	0.85
200	.90	.84	.90	.89
400	.71	1.35	1.70	1.95
600	.97	1.45	1.55	1.60
HK31A-H24 magnesium-alloy sheet				
75	1.02	1.15	0.71	0.71
200	1.13	.45	.58	1.00
400	.71	1.15	1.02	.95
600		.33	.53	.23
HM21A-T8 magnesium-alloy sheet				
75		0.89	0.70	1.08
200		1.25	.94	.88
400		2.05	1.40	1.50
600		.69	.57	.86
700		1.50		1.15
12 MoV stainless-steel sheet				
75		1.00	0.96	0.94
200				1.00
400				1.00
600		1.04		.68
800		1.05		.84
1,000		.84		

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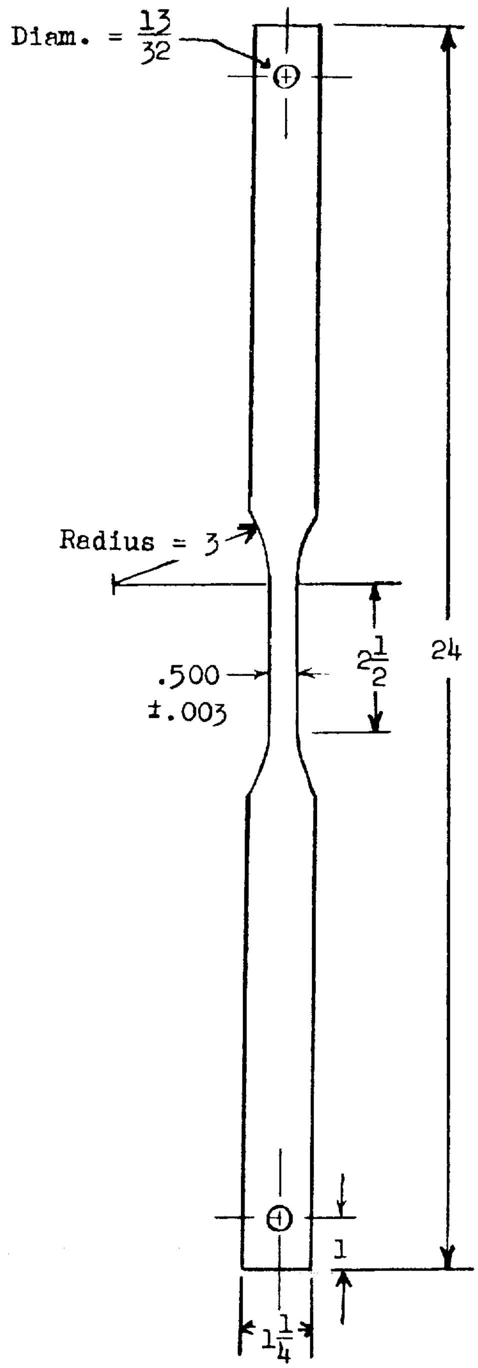

Figure 1.- Elevated-temperature tensile specimen. Dimensions are in inches.

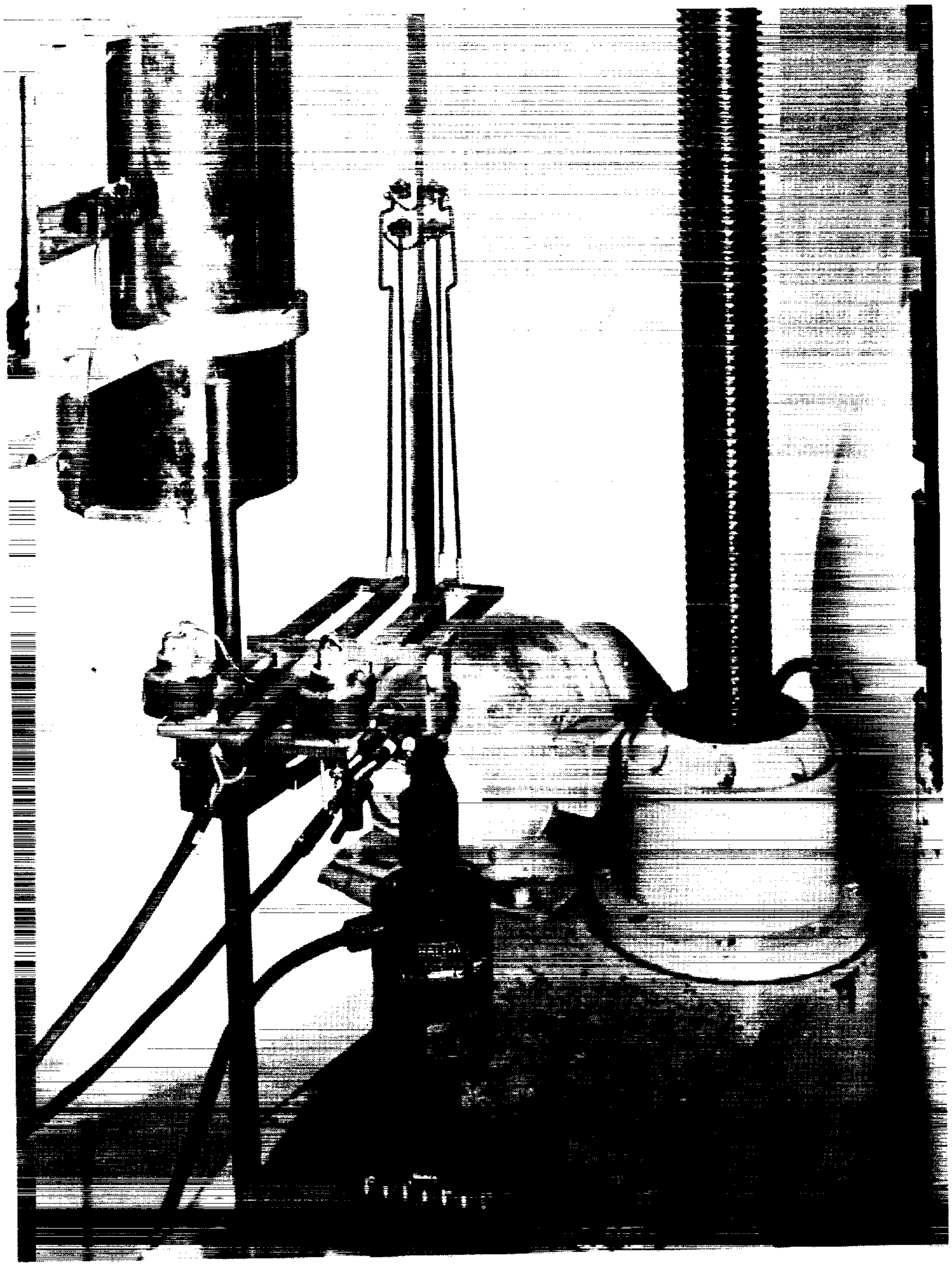

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Figure 2.- Equipment for tensile stress-strain tests at elevated temperature.

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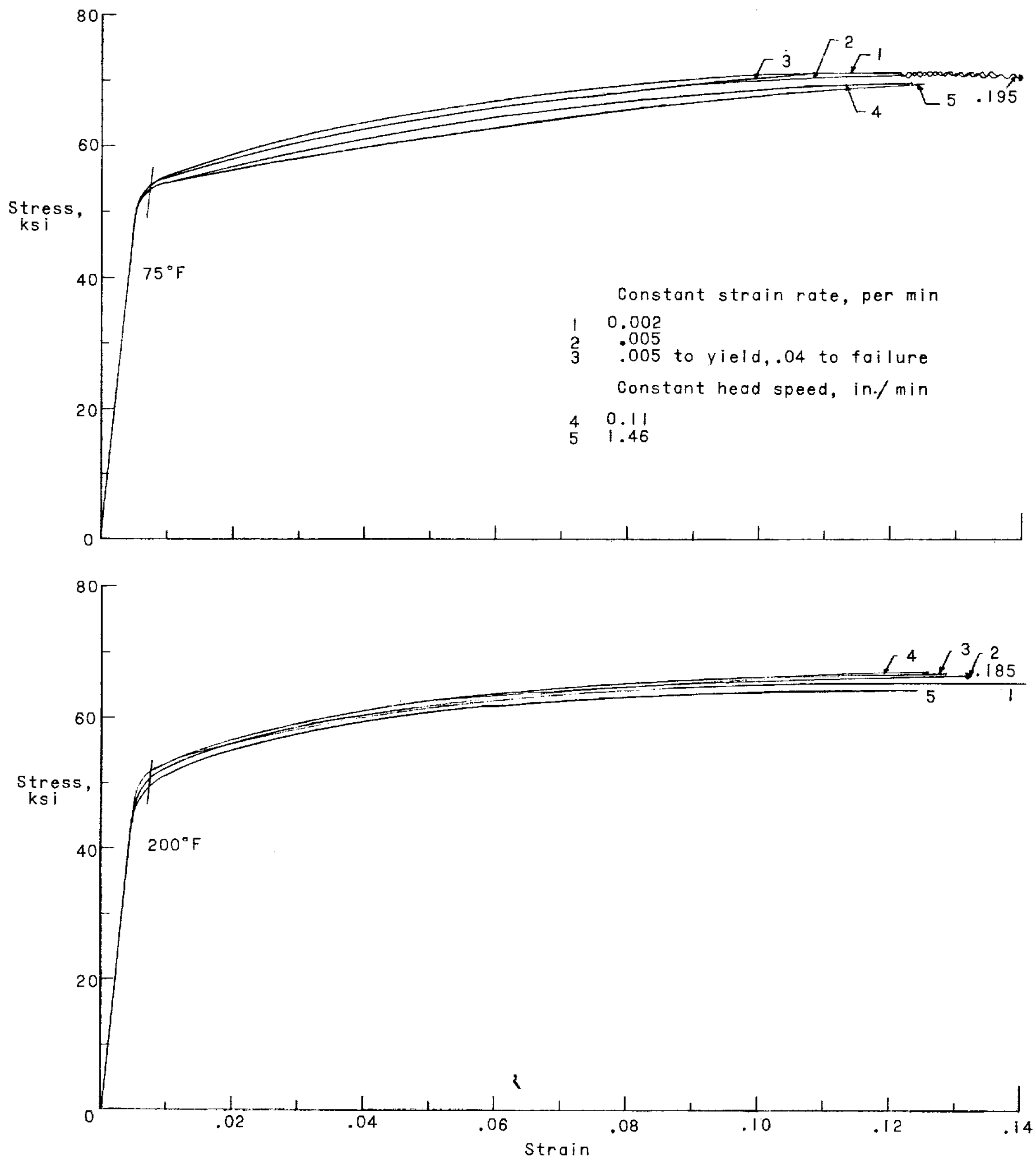
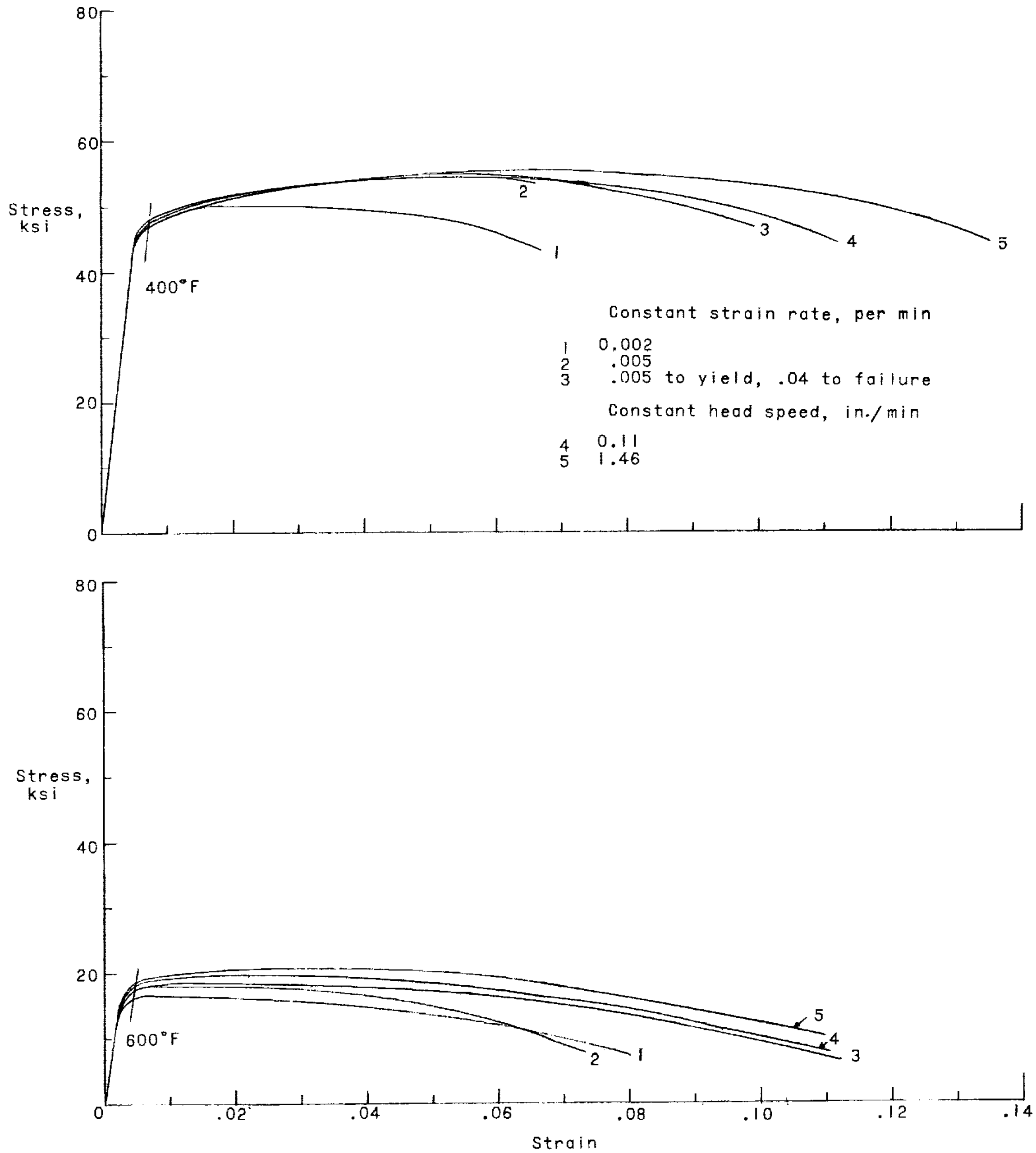


(a) 75° F and 200° F.

Figure 3.- Tensile stress-strain curves for 2024-T3 aluminum alloy at various strain rates and temperatures after 1/2-hour exposure at test temperature.



(b) 400° F and 600° F.

Figure 3.- Concluded.

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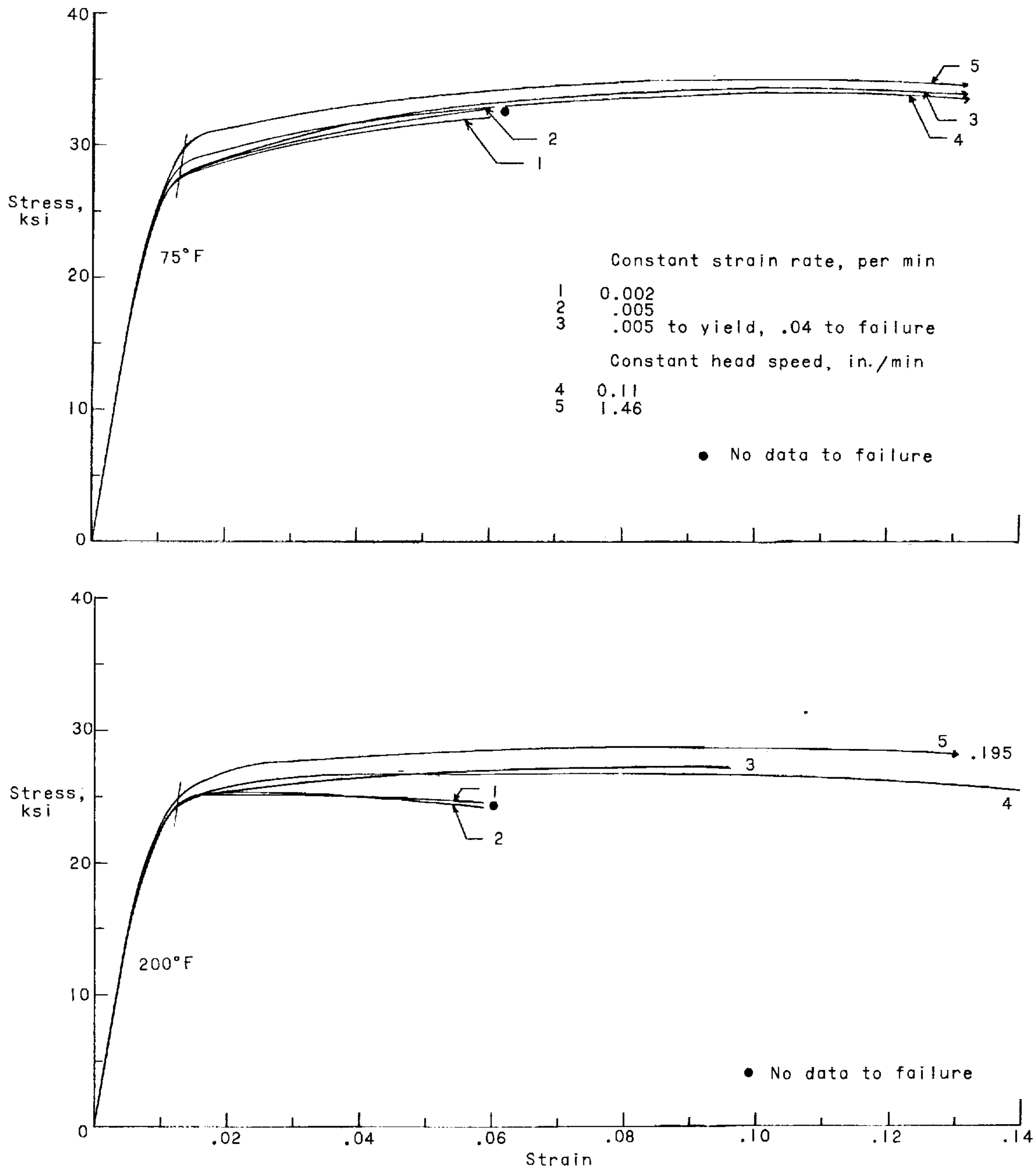
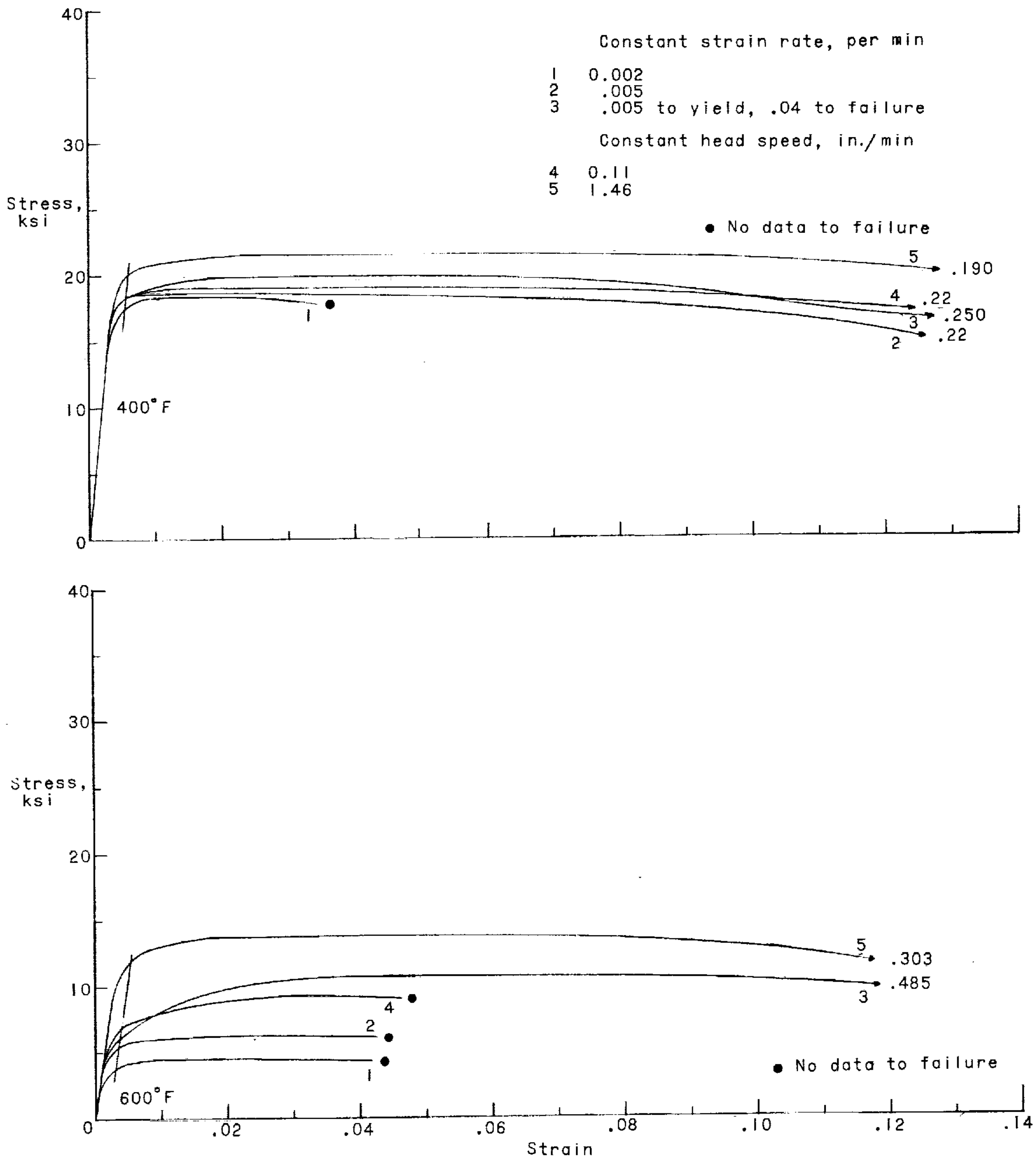


(a) 75° F and 200° F.

Figure 4.- Tensile stress-strain curves for HK31A-H24 magnesium alloy at various strain rates and temperatures after 1/2-hour exposure at test temperature.



(b) 400° F and 600° F.

Figure 4.- Concluded.

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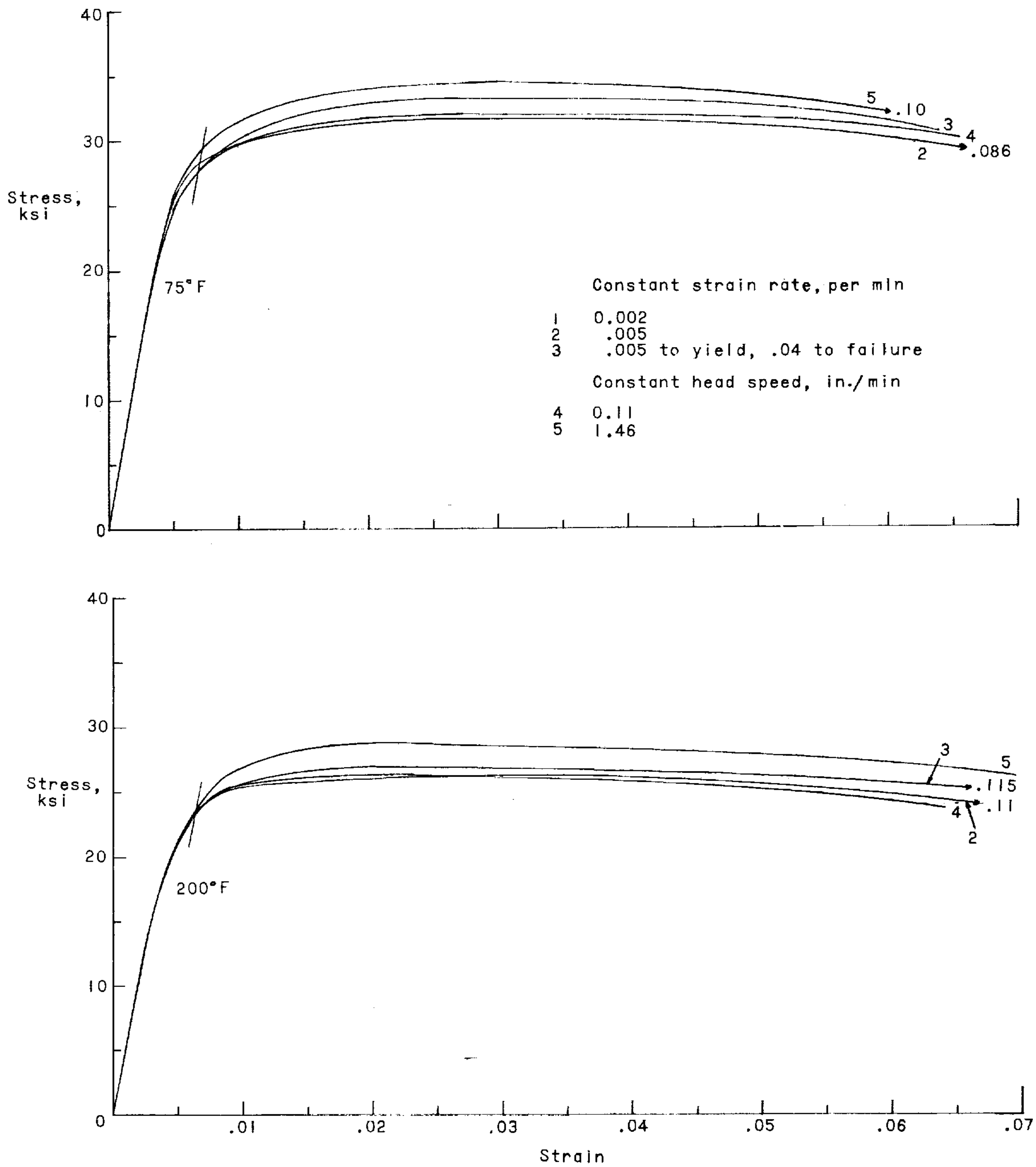
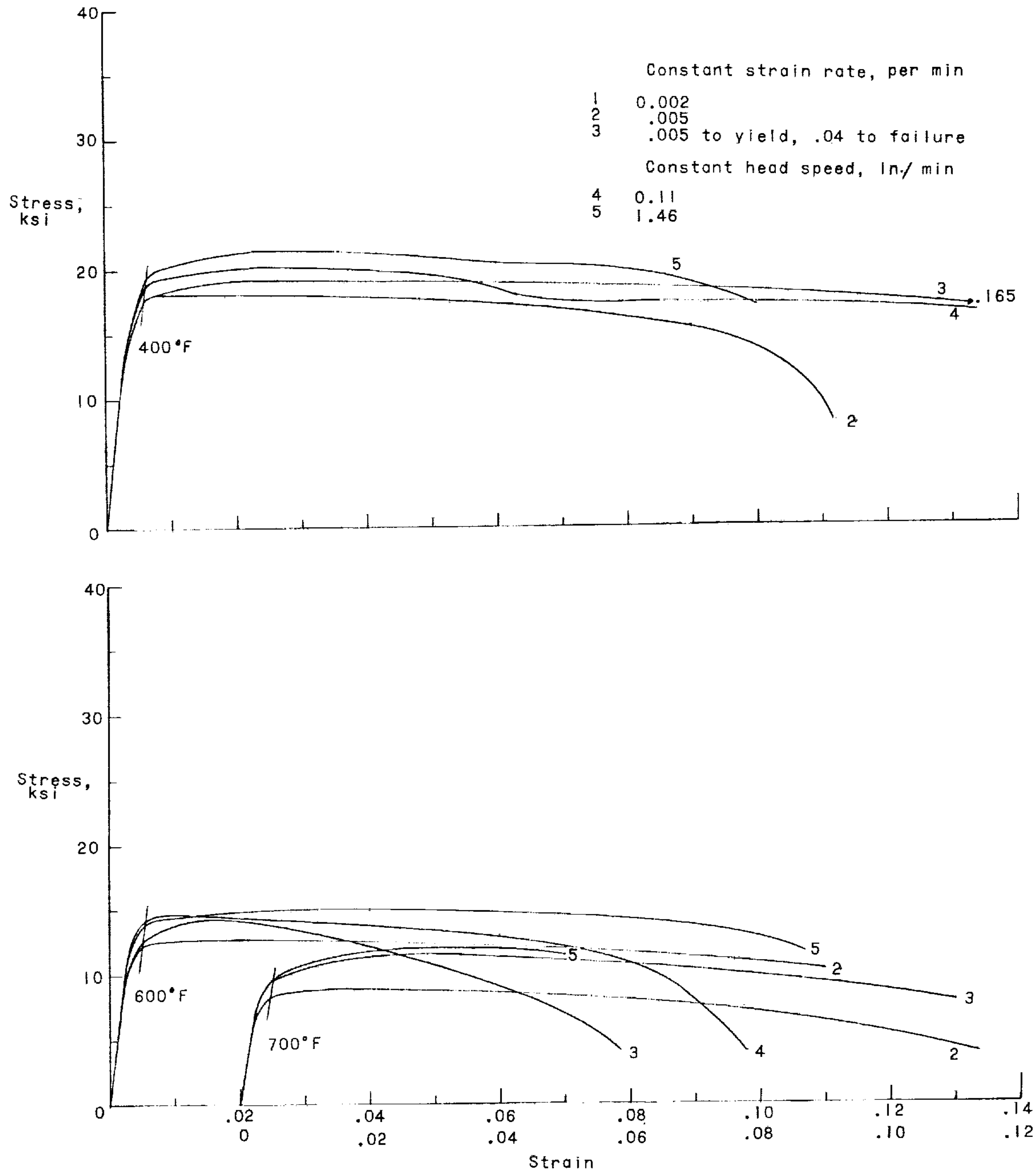


(a) 75° F and 200° F.

Figure 5.- Tensile stress-strain curves for HM21A-T8 magnesium alloy at various strain rates and temperatures after 1/2-hour exposure at test temperature.



(b) 400° F, 600° F, and 700° F.

Figure 5.- Concluded.

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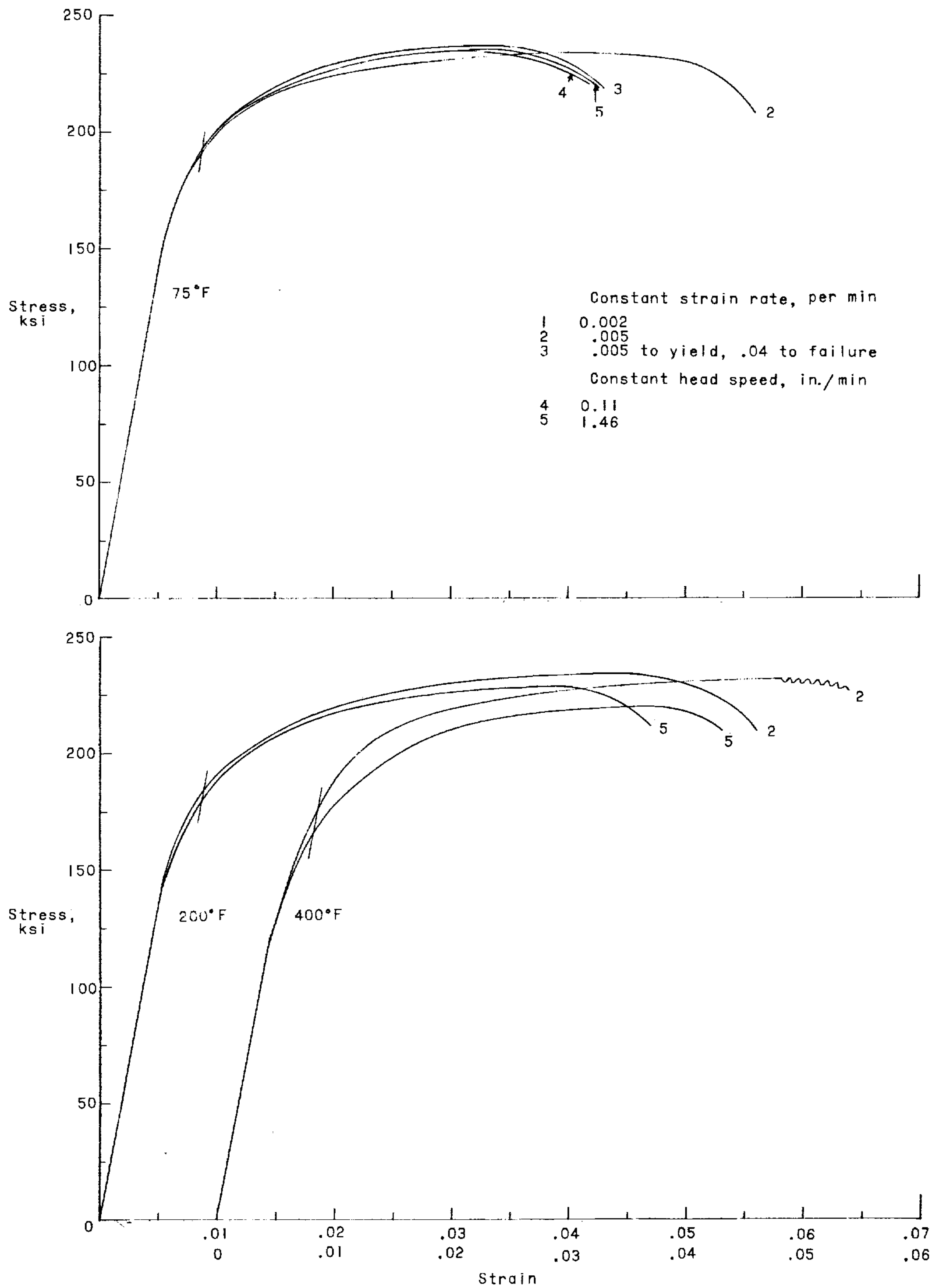
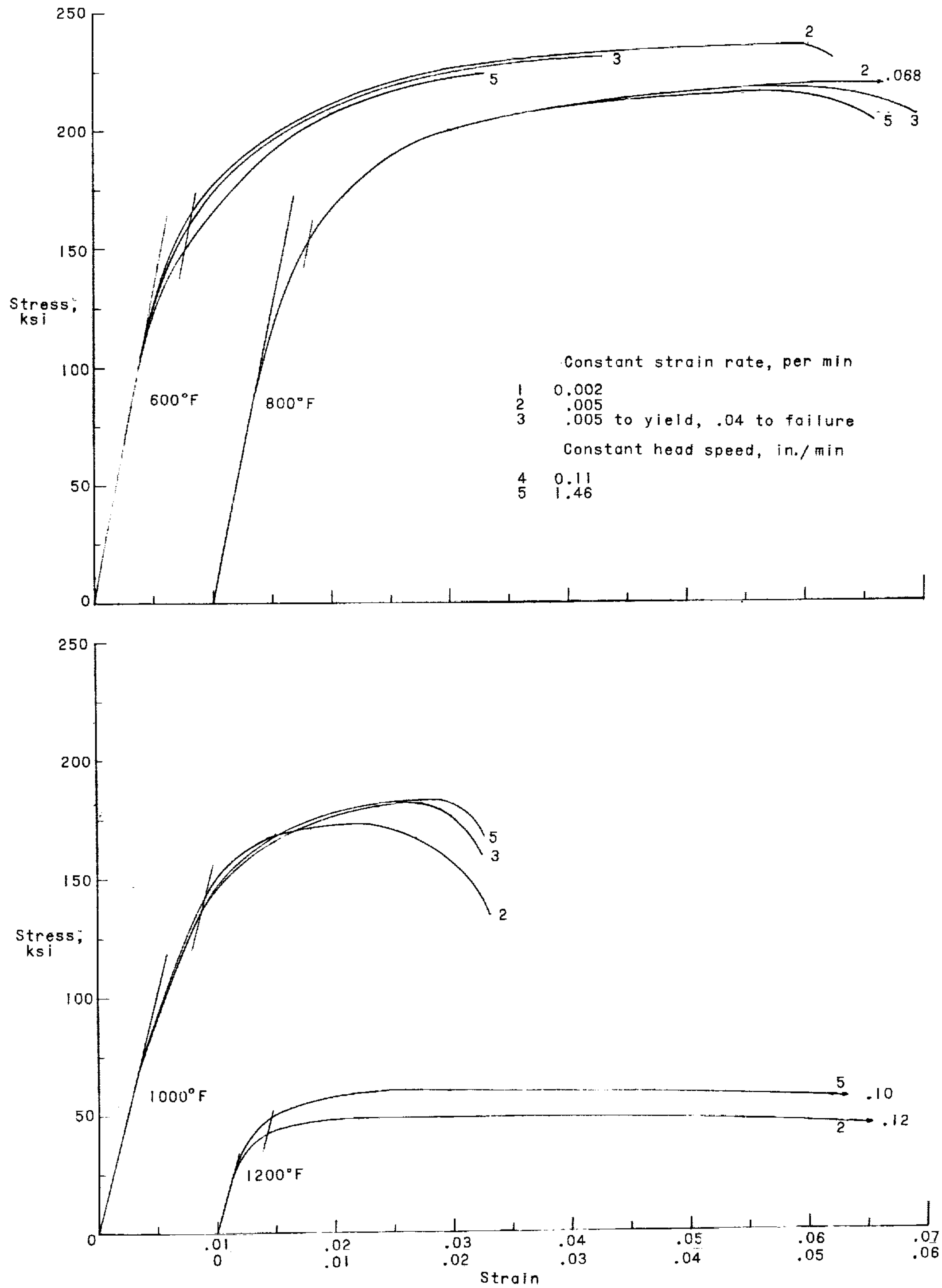


(a) 75° F, 200° F, and 400° F.

Figure 6.- Tensile stress-strain curves for 12 MoV stainless steel at various strain rates and temperatures after 1/2-hour exposure at test temperature.



(b) 600° F, 800° F, 1,000° F, and 1,200° F.

Figure 6.- Concluded.

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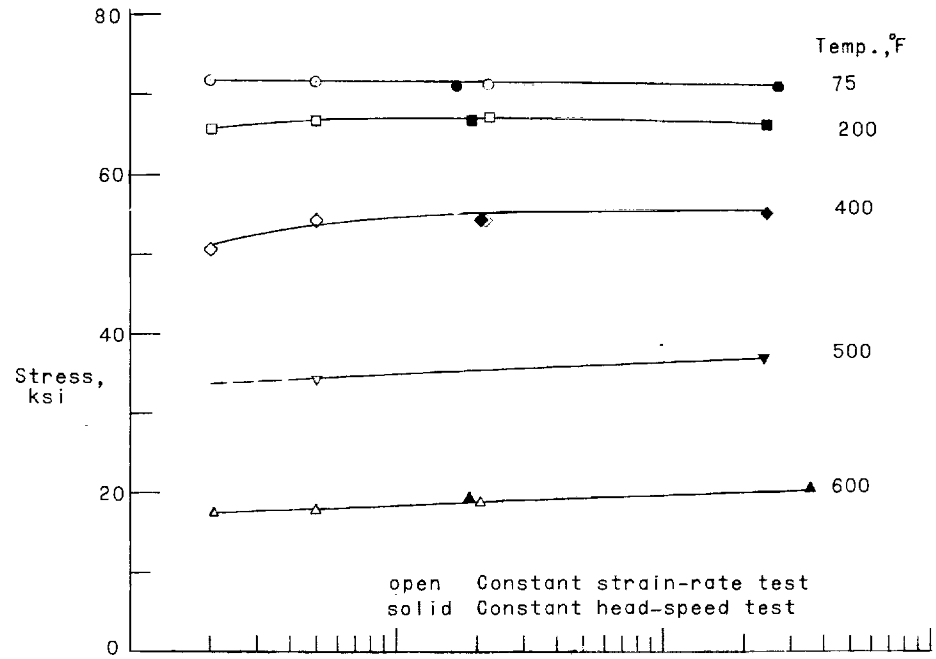
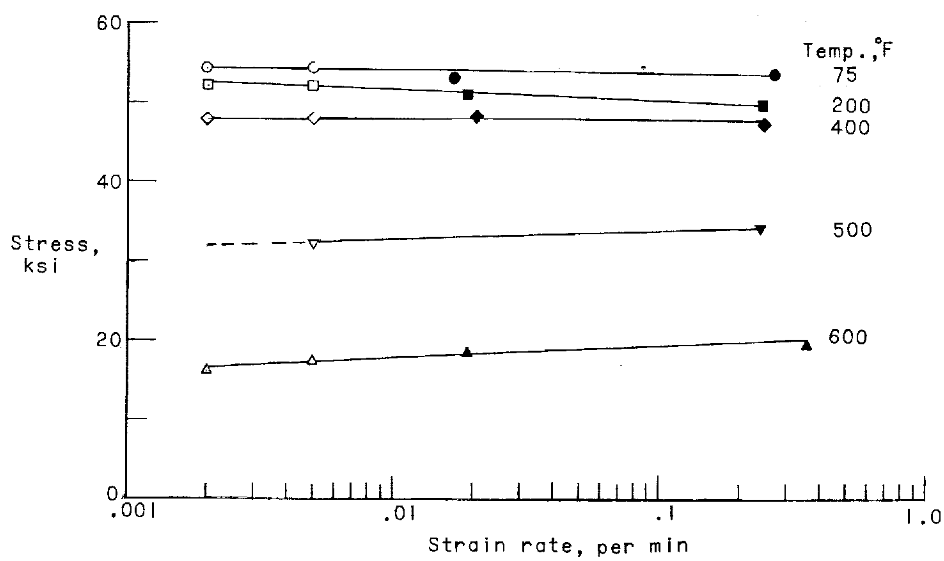
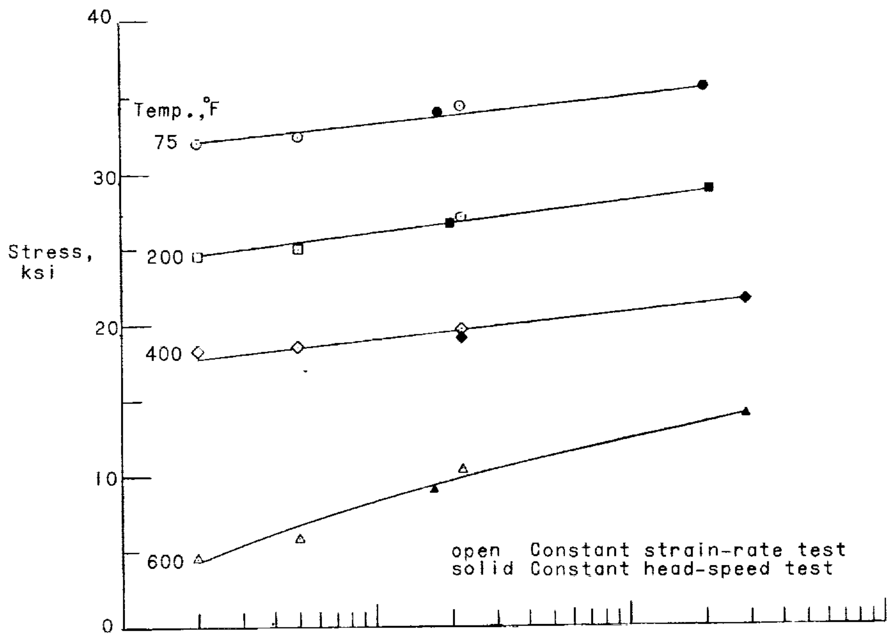


(a) Tensile strength.

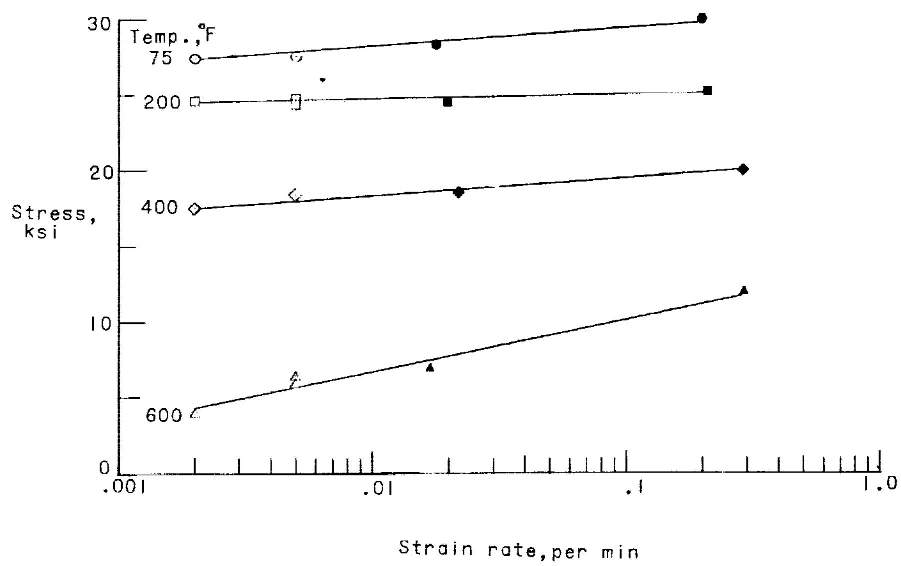


(b) Yield strength.

Figure 7.- Effect of strain rate on the yield and tensile strength of 2024-T3 aluminum alloy at elevated temperatures after 1/2-hour exposure at test temperature.



(a) Tensile strength.



(b) Yield strength.

Figure 8.- Effect of strain rate on the yield and tensile strength of HK31A-H24 magnesium alloy at elevated temperatures after 1/2-hour exposure at test temperature.

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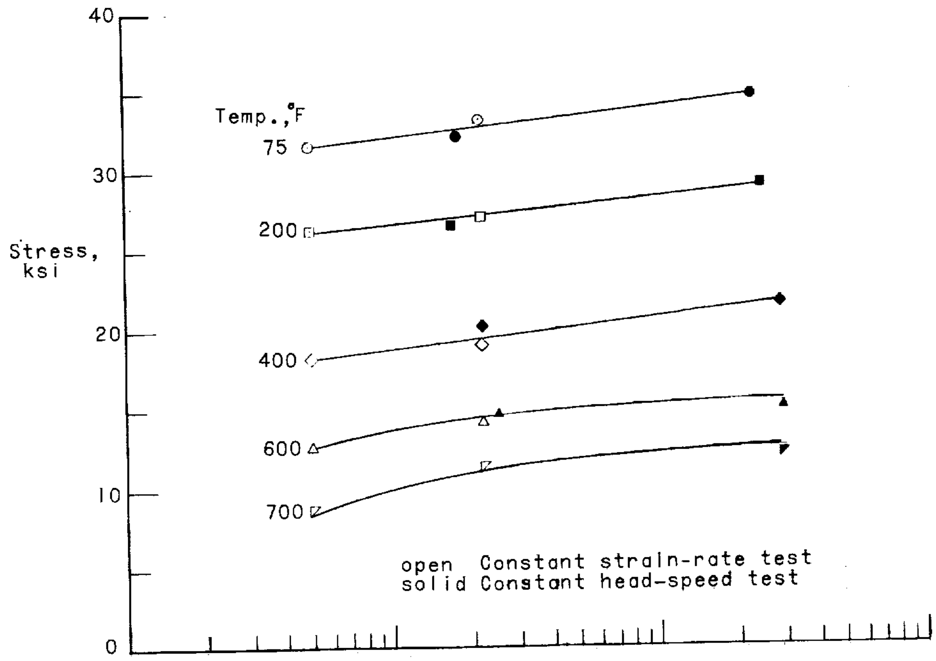
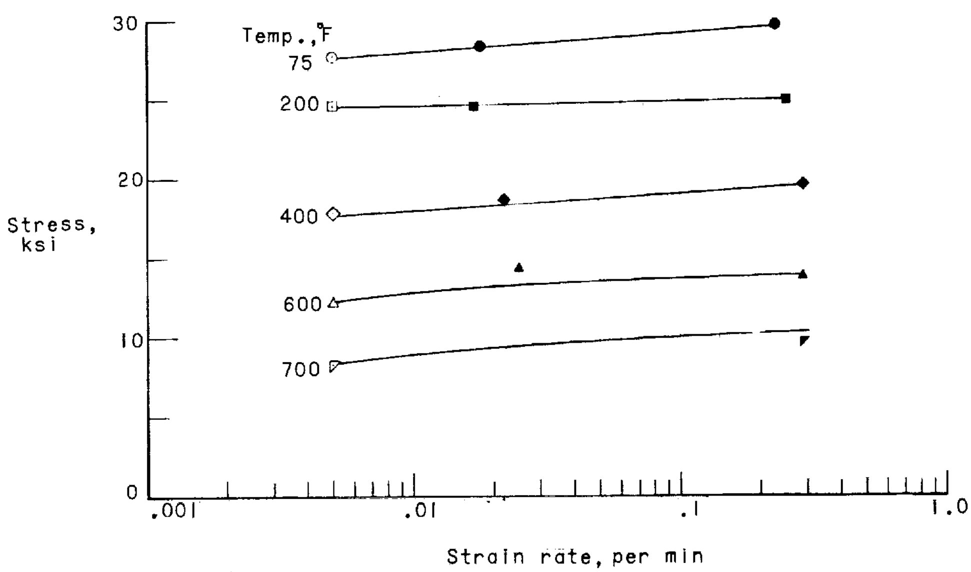
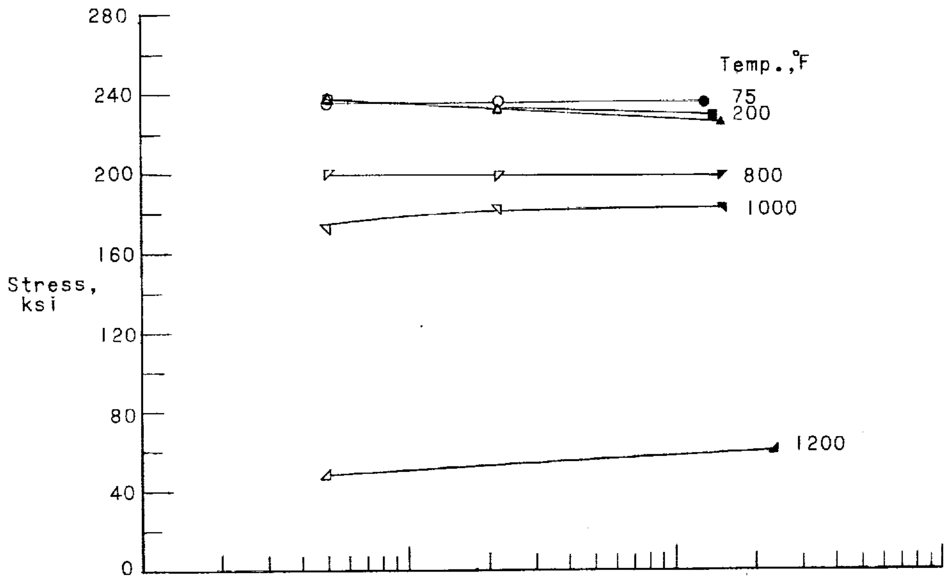


(a) Tensile strength.

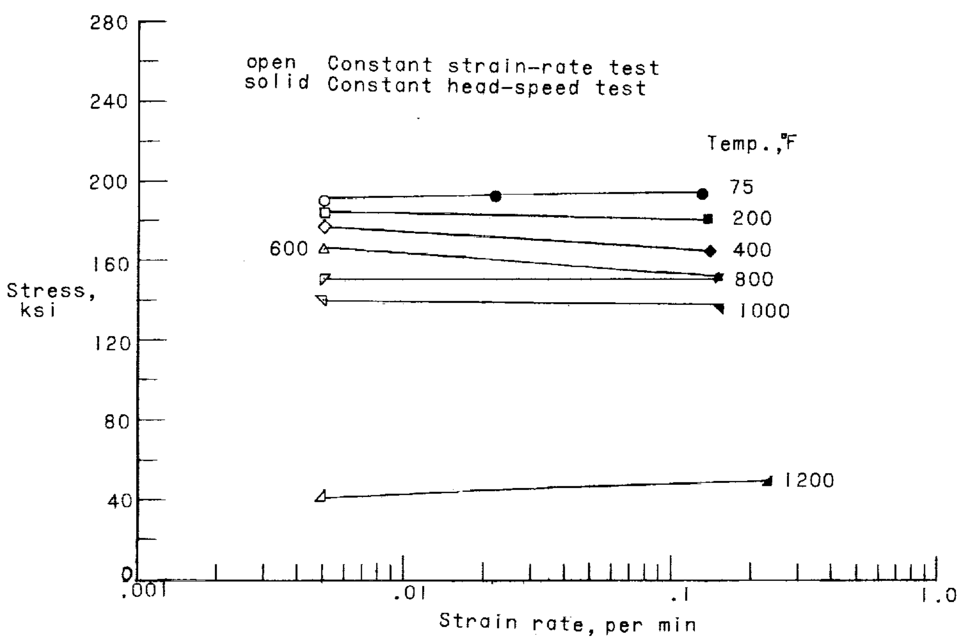


(b) Yield strength.

Figure 9.- Effect of strain rate on the yield and tensile strength of HM21A-T8 magnesium alloy at elevated temperatures after 1/2-hour exposure at test temperature.



(a) Tensile strength.



(b) Yield strength.

Figure 10.- Effect of strain rate on the yield and tensile strength of 12 MoV stainless steel at elevated temperatures after 1/2-hour exposure at test temperature.

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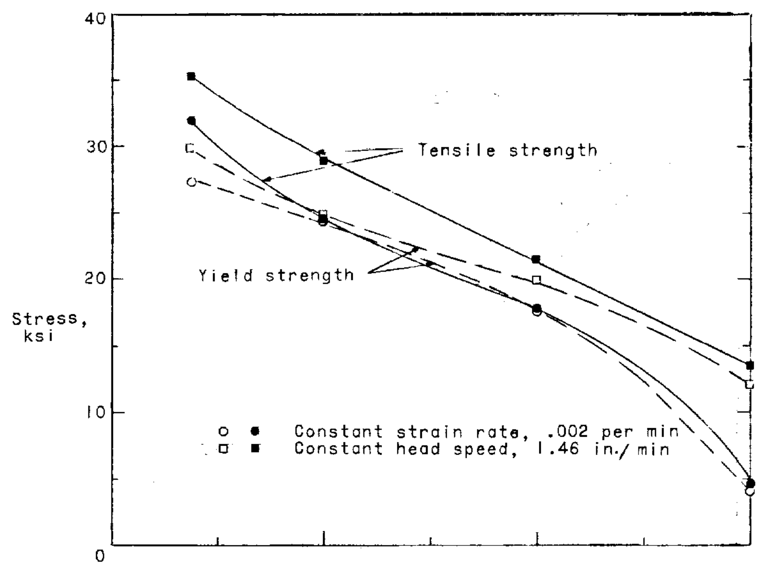
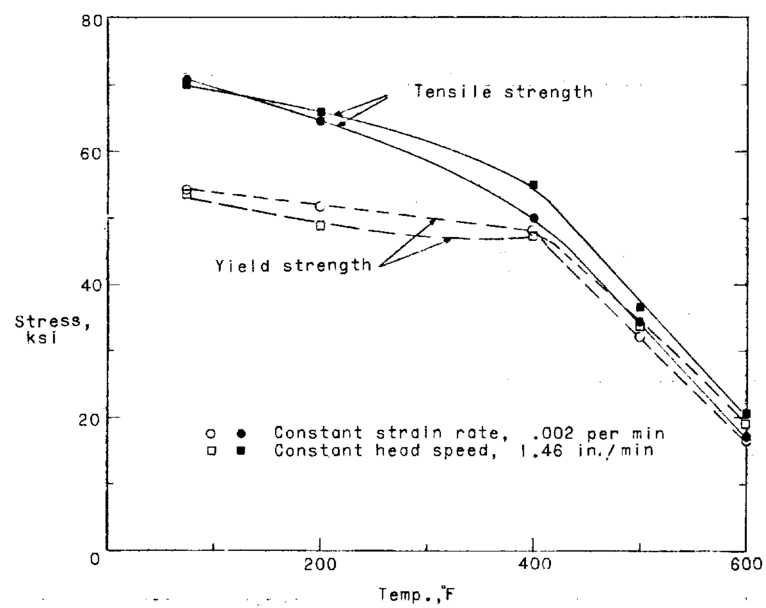
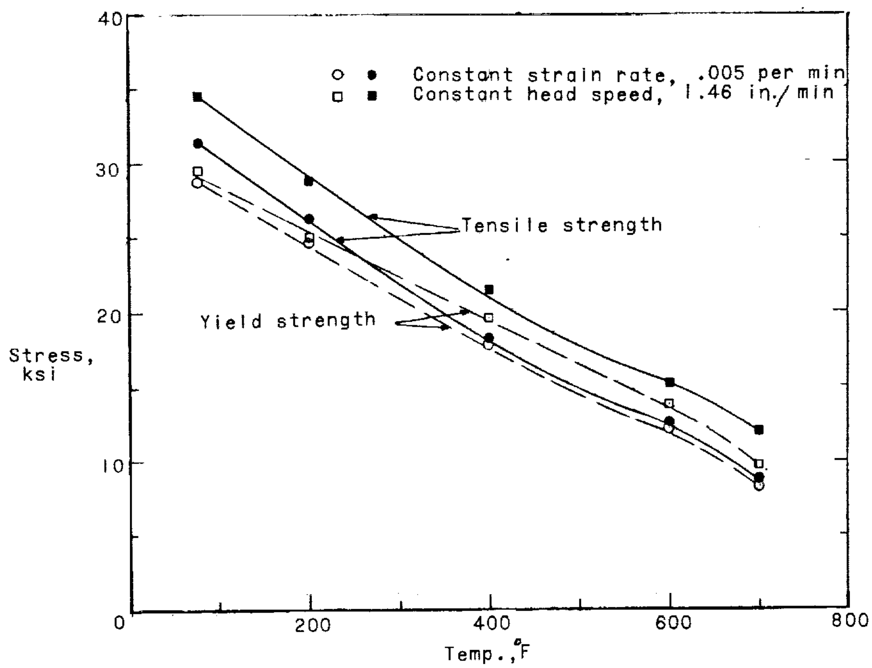


(a) HK31A-H24 magnesium alloy.

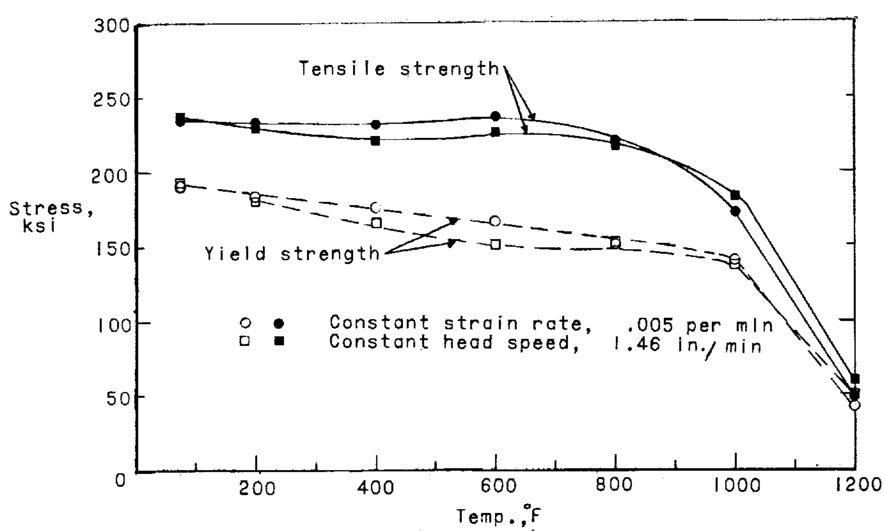


(b) 2024-T3 aluminum alloy.

Figure 11.- Effect of temperature on yield and tensile strength for HK31A-H24 magnesium alloy and 2024-T3 aluminum alloy at a strain rate of 0.002 per minute and a head speed of 1.46 in./min after 1/2-hour exposure at test temperature.



(a) HM21A-T8 magnesium alloy.



(b) 12 MoV stainless steel.

Figure 12.- Effect of temperature on yield and tensile strength for HM21A-T8 magnesium alloy and 12 MoV stainless steel at a strain rate of 0.005 per minute and a head speed of 1.46 in./min after 1/2-hour exposure at test temperature.

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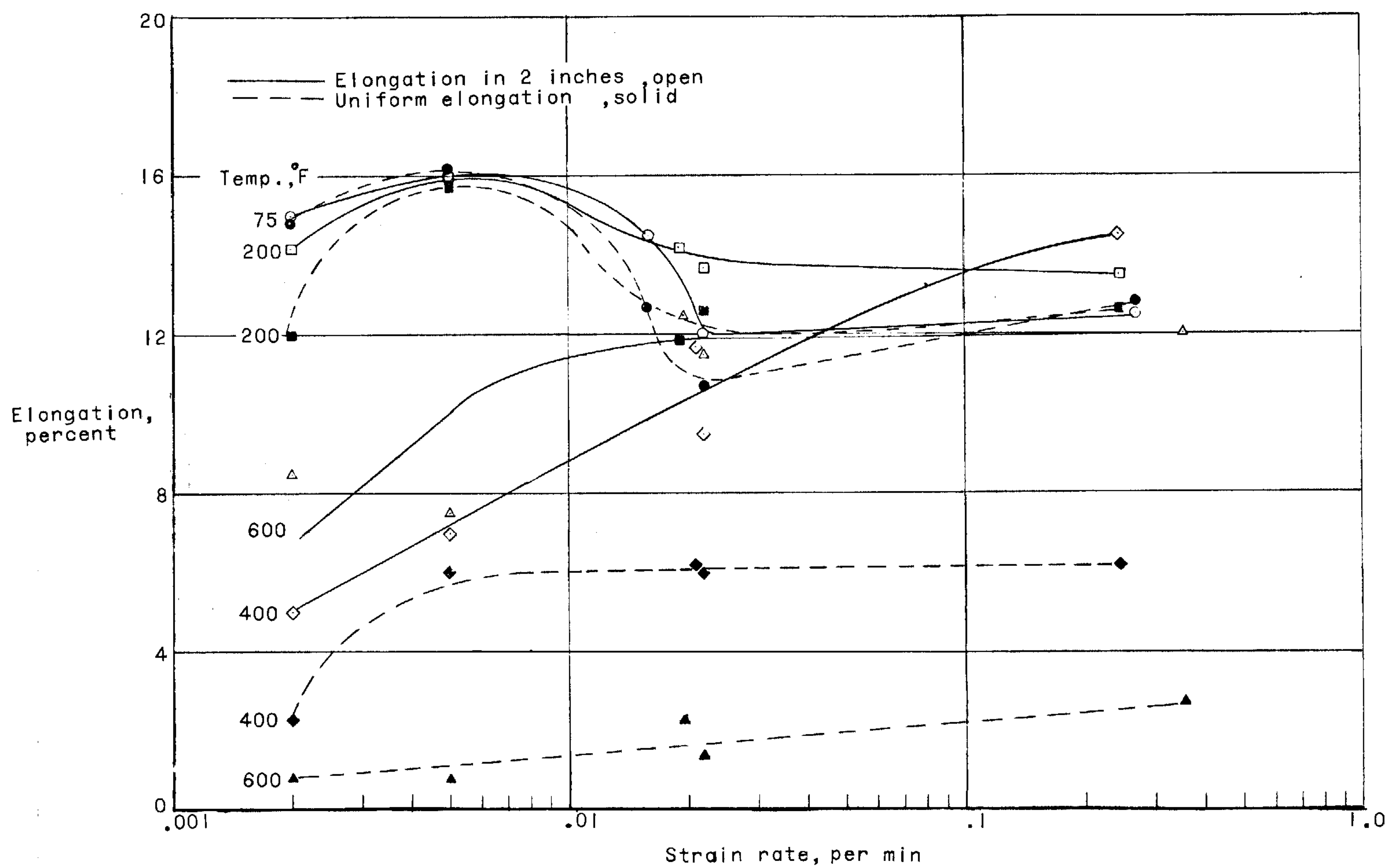
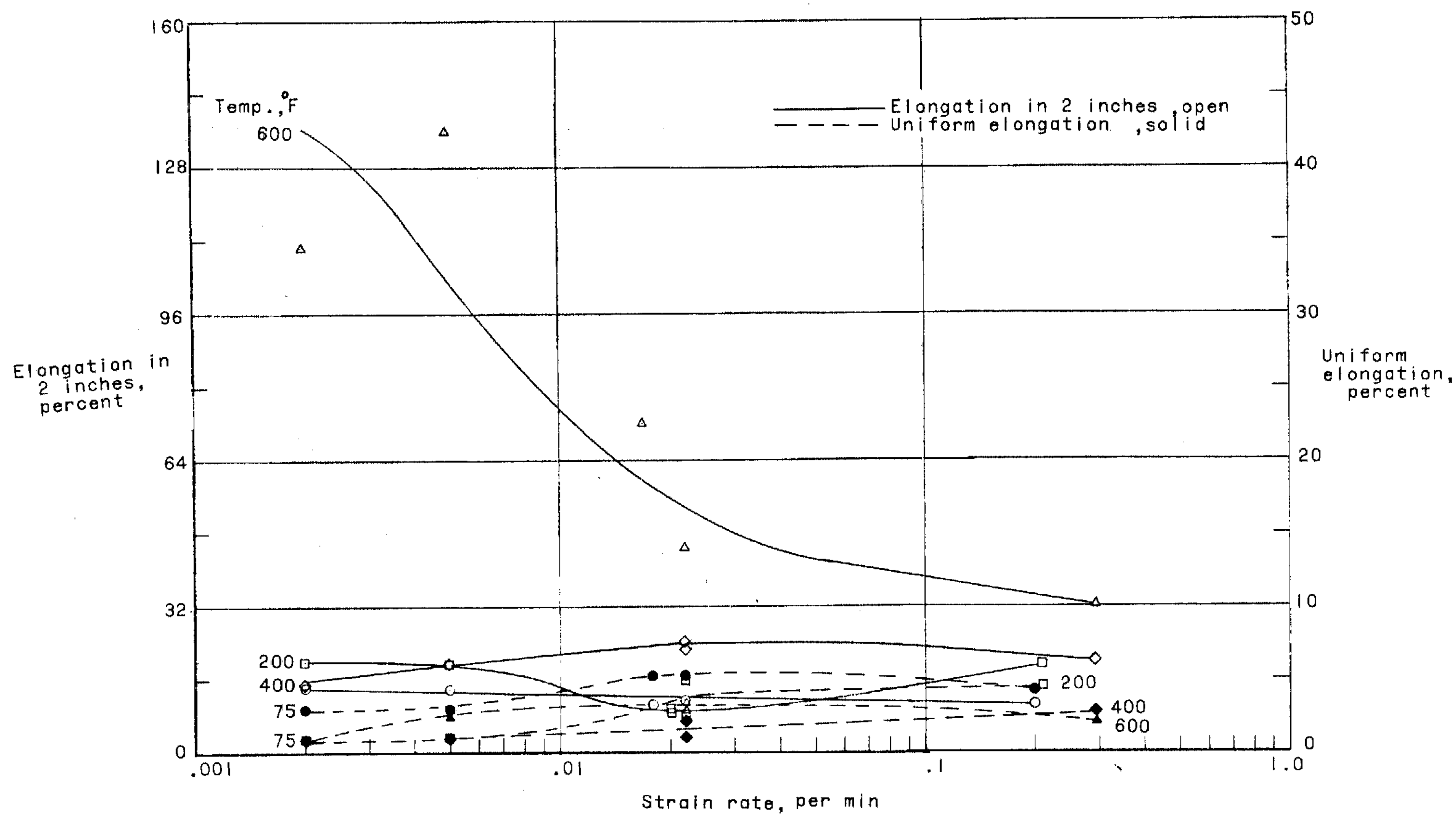


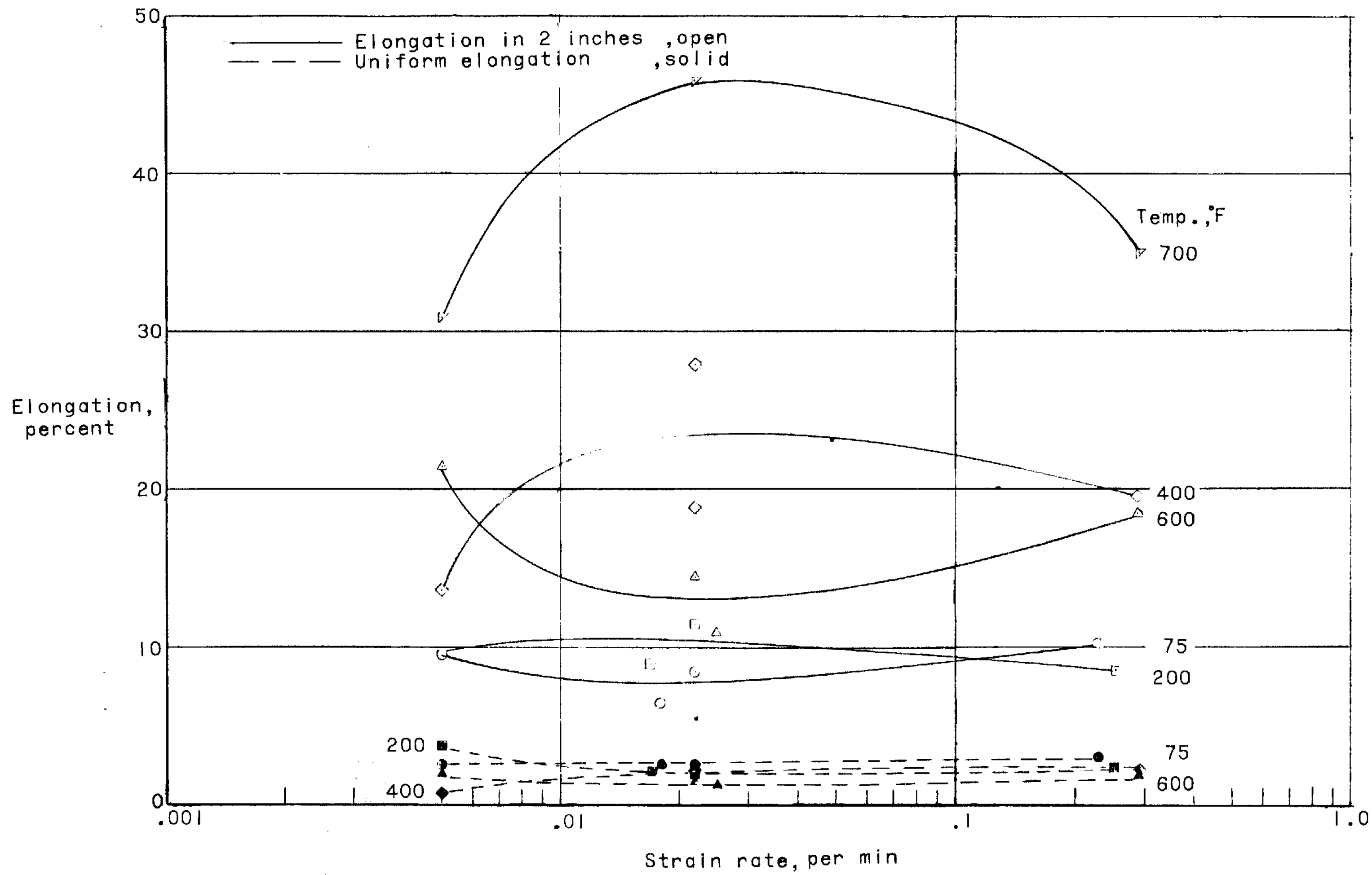
(a) 2024-T3 aluminum alloy.

Figure 13.- Effect of strain rate on the elongation in 2 inches and the uniform elongation for the test materials at room and elevated temperatures.



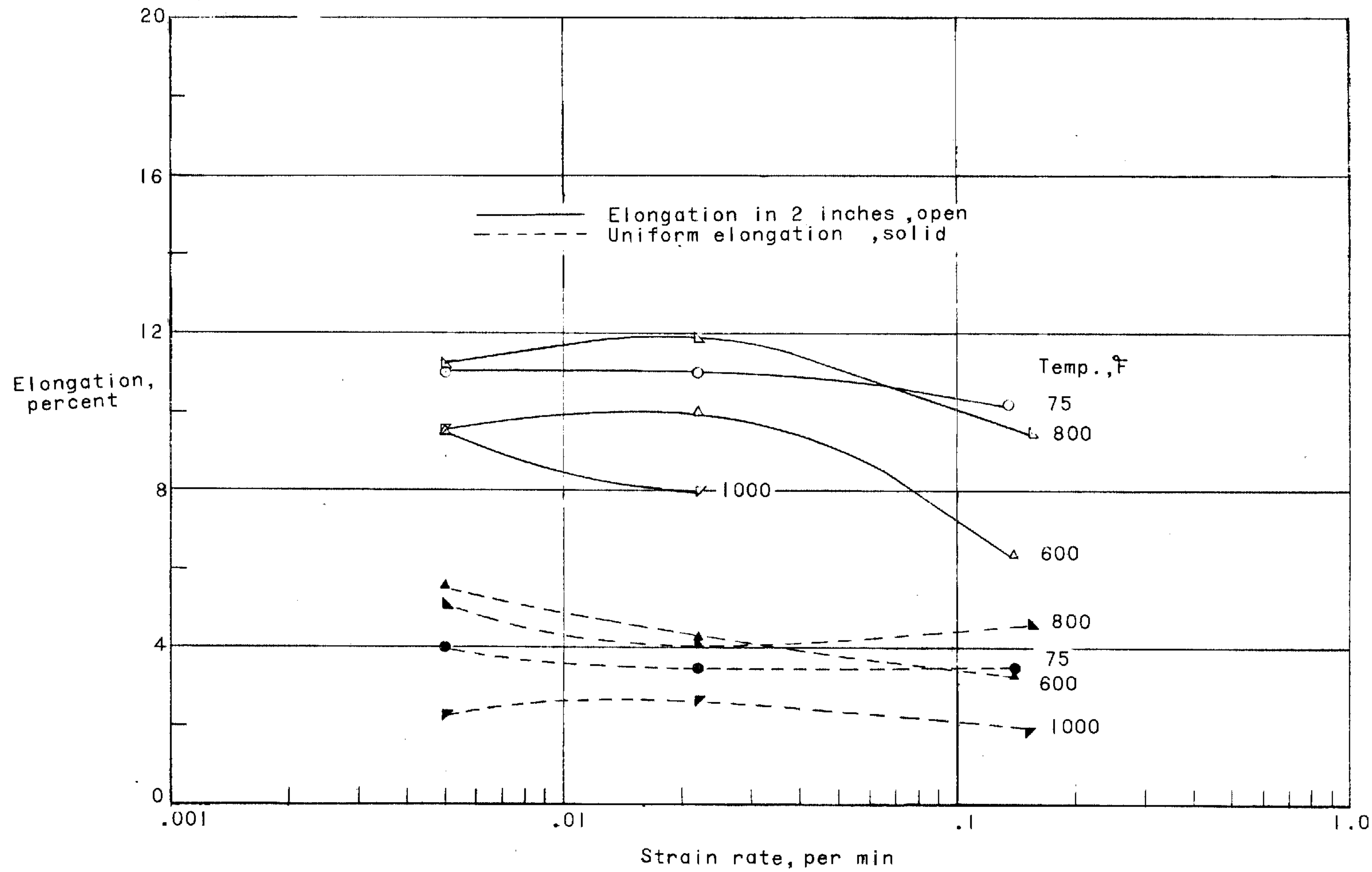
(b) HK31A-H24 magnesium alloy.

Figure 13.- Continued.



(c) HM21A-T8 magnesium alloy.

Figure 13.- Continued.



(d) 12 MoV stainless steel.

Figure 13.- Concluded.

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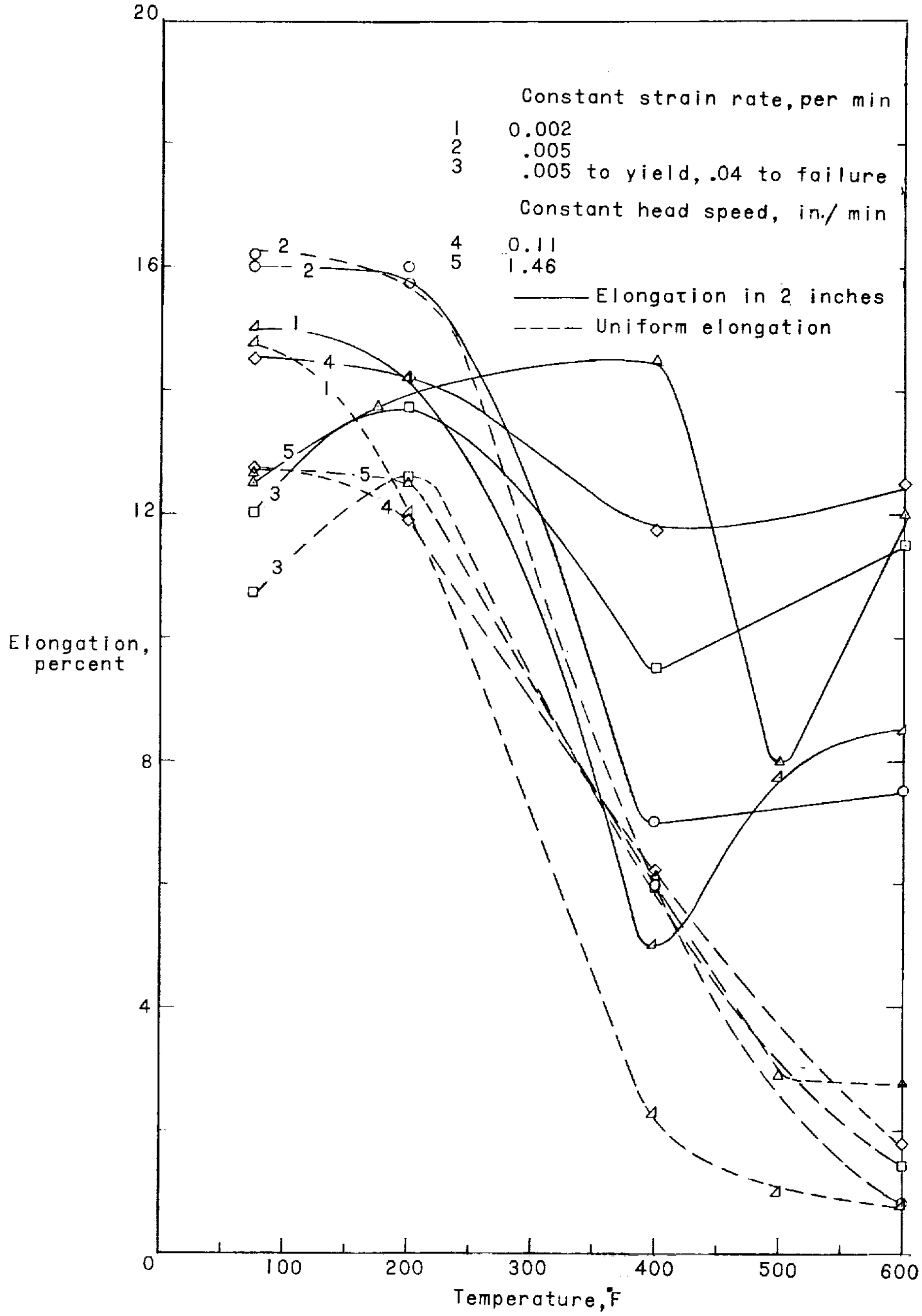
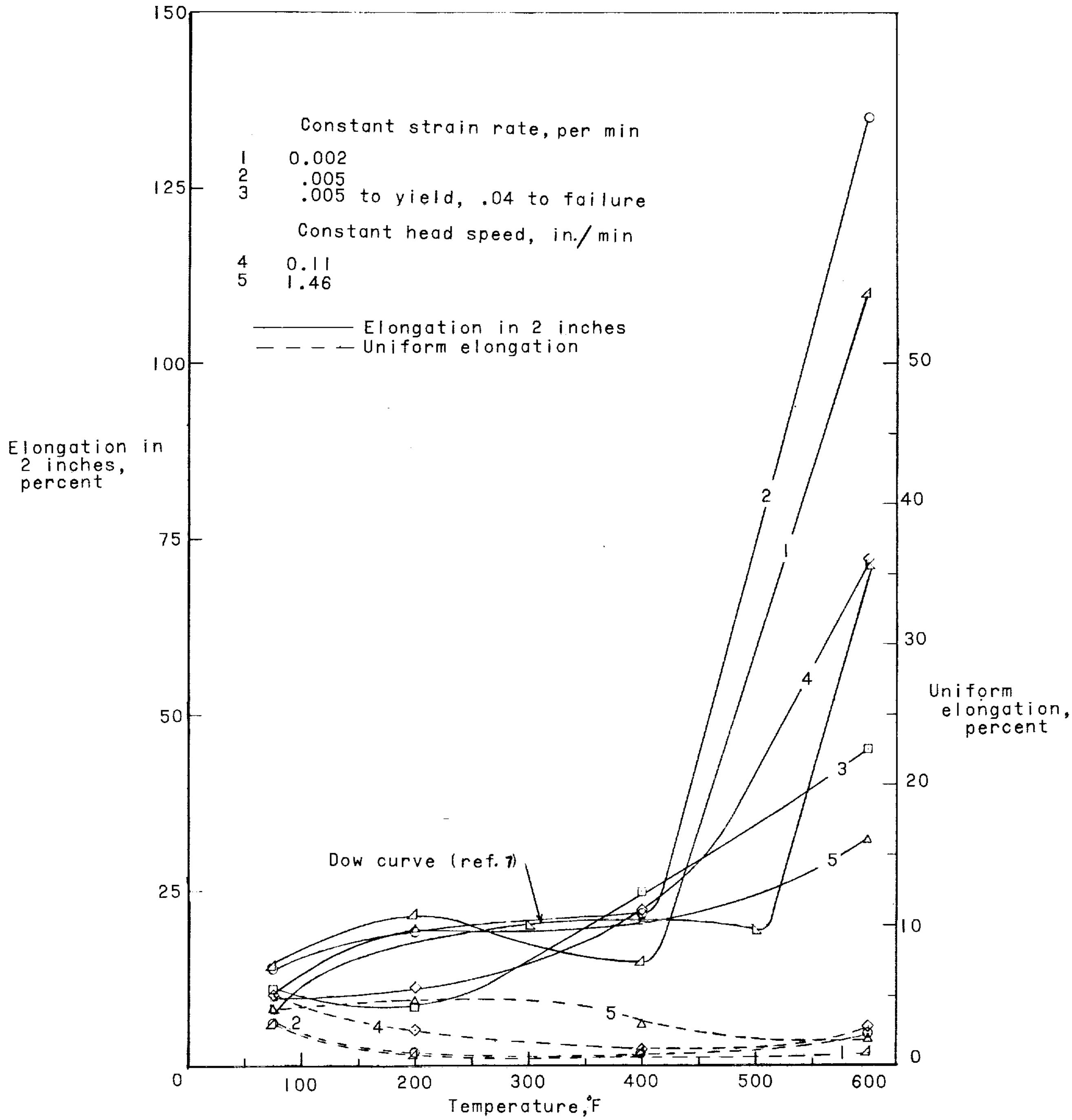


(a) 2024-T3 aluminum alloy.

Figure 14.- Effect of temperature on the elongation in 2 inches and the uniform elongation for the test materials at various testing speeds.



(b) HK31A-H24 magnesium alloy.

Figure 14.- Continued.

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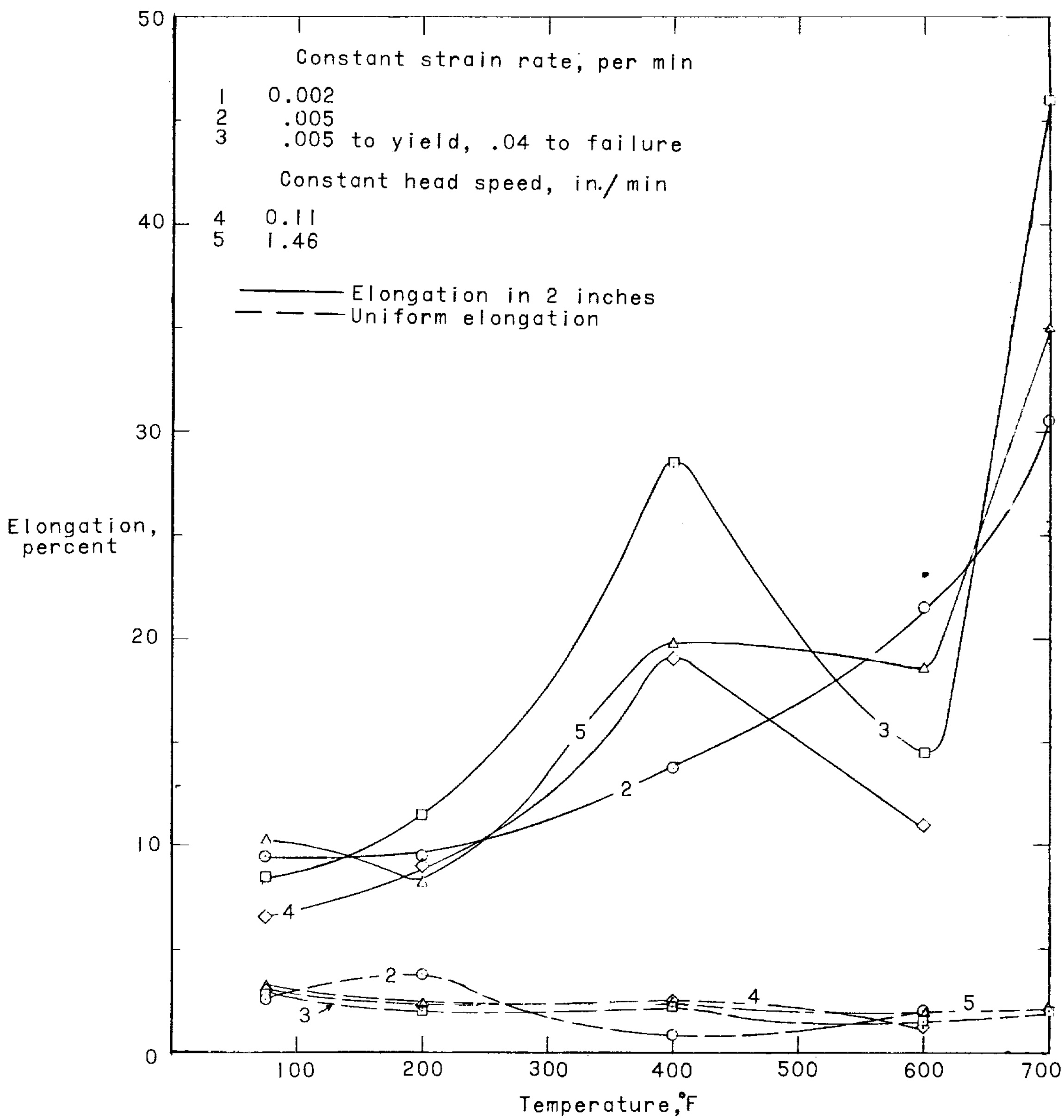
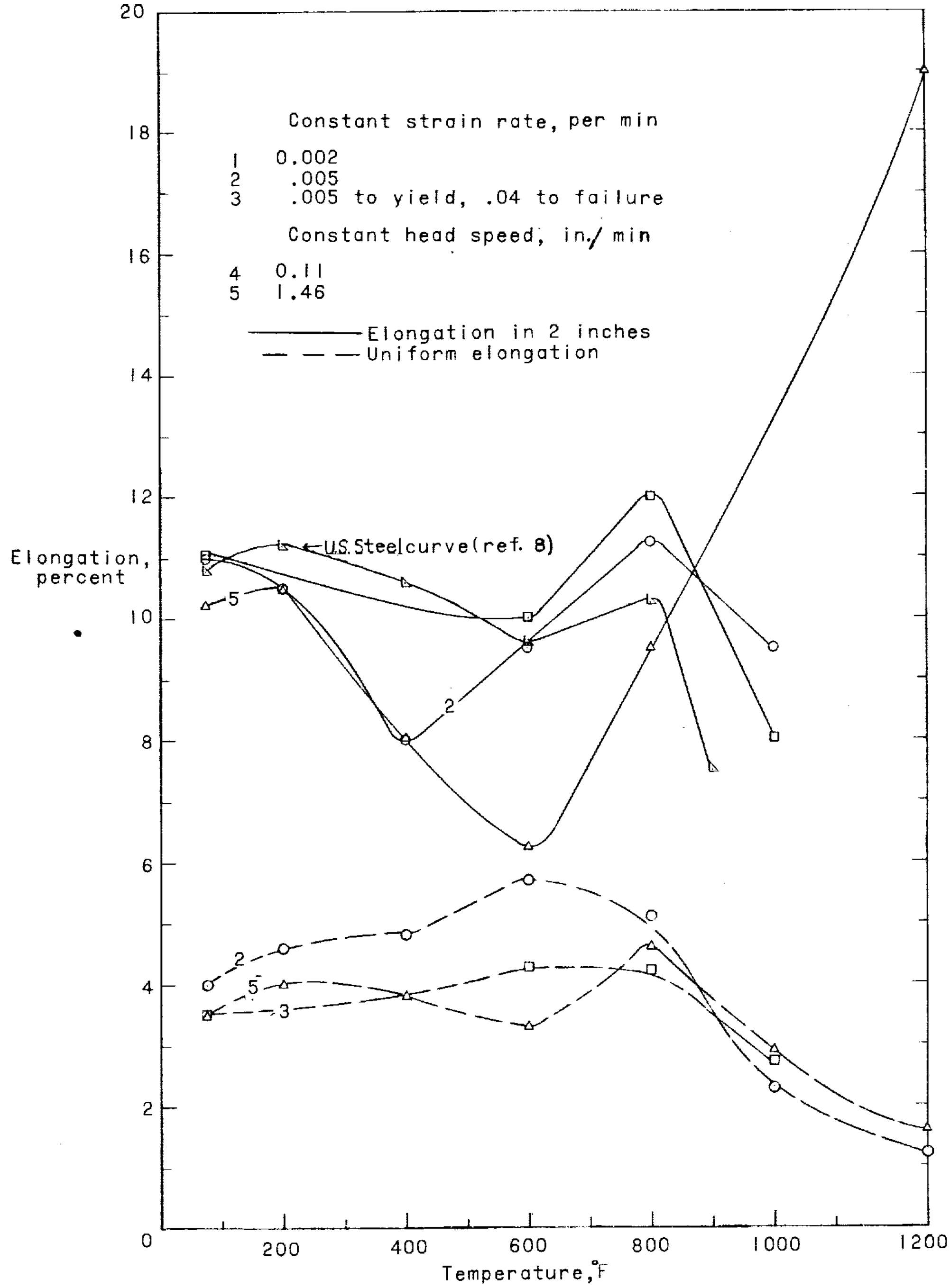


(c) HM21A-T8 magnesium alloy.

Figure 14.- Continued.



(d) 12 MoV stainless steel.

Figure 14.- Concluded.

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