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GENERAL ELECTRIC RESEARCH LABORATORY

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WRIGHT AIR DEVELOPMENT CENTER
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FOREWORD

This report was prepared by the General Electric Company Research Laboratory under United States Air Force Contract No. AF-33(616)-2120. This contract was initiated under Task No. 70627, "Deformation Mechanisms of Metals," a part of Project 7351, "Metallic Materials", and was administered under the direction of the Aeronautical Research Laboratory, Directorate of Research, Wright Air Development Center, with Major A.A. Marston as Task Scientist.

ABSTRACT

True-stress, true-strain data are presented for two lots of high-purity aluminum annealed to produce several different grain sizes from each lot. The testing temperature range 20° to 873°K (0.021 to 0.94 T/Tm) was explored and the effect of strain rate was measured at 77° and 300°K.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER

Aldro Lingard
ALDRO I. LINGARD
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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TENSILE DEFORMATION OF ALUMINUM AS A FUNCTION OF TEMPERATURE, STRAIN RATE, AND GRAIN SIZE

R. P. Carreker, Jr. and W. R. Hibbard, Jr.

INTRODUCTION

This report is one of a series concerned with the experimental documentation of the deformation behavior of pure metals over a wide range of temperature. Previous reports in the series describe the creep behavior of platinum[1] and aluminum[2] and the tensile behavior of copper,[3] silver,[4] and molybdenum.[5] Subsequent reports will describe the creep behavior of copper and silver and the tensile behavior of platinum, thus providing extensive creep and tensile data on four face-centered-cubic metals tested under comparable conditions.

MATERIAL

Two lots of high-purity aluminum were used in this investigation. One lot, designated AC, was obtained direct from the Aluminum Company of America as high-purity aluminum in "notch-bar" form. A typical analysis of this type of aluminum is 0.006 silicon, 0.015 copper, 0.006 iron and 99.975 aluminum. Lot BS was obtained from Dr. J. I. Hoffman of the Bureau of Standards as a portion of the "Aluminum A," described in his report of the redetermination of the atomic weight of aluminum.[6] Lot BS originated with the Aluminum Company of America, also, and was received in the standard notch-bar form. A detailed chemical and spectroscopic analysis of Lot BS has been published.[6] Principal impurities were: 0.006 silicon, 0.003 iron, 0.002 copper; aluminum >99.987.

Samples were processed identically by room-temperature swaging and drawing to 0.030-inch-diameter wires from approximately 1/2-inch-diameter rods that were machined from the notch-bar pigs. Samples were cut from the cold-drawn wire, placed in a grooved graphite

block in groups of thirteen and annealed in air for one hour at each of several temperatures, with the following results:

Annealing Temperature	Average Grain Diameter, mm BS	AC
300°C	0.027	0.021
350	.039	--
400	.046	.118
450	.065	--
500	.105	.143

Representative photomicrographs of annealed specimens are shown in Fig. 1. The two lots of aluminum responded quite differently to annealing, the behavior of Aluminum AC suggesting that its grain growth was controlled by impurities. The recrystallization texture of aluminum of similar purity comparably treated has been reported as predominantly <111> fiber with some <100> fiber present.(7)

TESTING PROCEDURE

The testing procedure and method of analyzing the data have been described previously.(2, 3) Five-inch gage length, annealed specimens were tested in an Instron tensile testing machine at a constant strain rate of 0.04 min^{-1} at a number of temperatures. Instantaneous ten-fold rate changes were employed in some tests to determine the strain-rate sensitivity. The symbol σ is used to indicate true stress and ϵ to indicate true strain, defined by:

$$\sigma = \frac{P}{A} = \frac{P}{A_o}\left(1 + \frac{\Delta l}{l_o}\right)$$

and

$$\epsilon = \int \frac{dl}{l} = \ln\left(1 + \frac{\Delta l}{l_o}\right),$$

where P = load, A = area and l = length. The subscript zero refers to initial values; all other symbols refer to instantaneous values.

THE TESTING PROGRAM

The testing program is schematically presented in Fig. 2, in which each circle represents one or more tests at the indicated temperatures and each horizontal row represents specimens having the particular annealing temperature indicated by the vertical cross-bar. The crosses, displaced slightly downward for clarity, represent tests in which the strain-rate was changed during the test in order to determine rate sensitivity. Because of the large amount of data collected, the primary experimental data are presented in tabular form, together with typical families of curves, summary plots and cross plots showing the effect of experimental variables.

EFFECT OF TEMPERATURE

Figures 3-5 show the effect of temperature on the tensile strength, the yield strength and the per cent elongation for the two lots of aluminum annealed at several different temperatures. Note that grain size (or annealing temperature) has a pronounced effect on the yield and tensile strengths of Aluminum AC, but has a comparatively slight effect on the yield strength of Aluminum BS and a negligible effect on its tensile strength. The virtual independence of the tensile strength on grain size (or annealing temperature) is consistent with the behavior of 99.999 per cent copper.[2]

Figure 6 shows a typical family of true stress-true strain curves for Aluminum BS tested at several temperatures. Figure 7 is a logarithmic plot of the same data. A straight line on such coordinates implies a stress-strain relationship of the form $\sigma = K\epsilon^{m}$. The data of Fig. 7 do not conform to that relationship over the entire range of strain, but in the range $\epsilon = 0.01$ to $\epsilon = 0.10$, they approximate the relationship sufficiently well for m at $\epsilon = 0.10$ to be a quantitative measure of strain hardening. Values of the strain-hardening exponent, m, are plotted as a function of temperature in Fig. 8. As would be expected, strain hardening decreases with increasing temperature. However, the shape of the curve is quite different from the approximately linear dependence observed for copper[3] and silver.[4]

Figure 9 is a composite plot of tensile strength as a function of temperature, including all comparable data from the literature and data on both BS and AC Aluminum from the present report. A 10 per cent scatter band includes all data, except a portion of Inokuty's[8] in the region where impurities have their maximum effect. The consistency of the tensile strength of nominally pure metals in the annealed condition,

regardless of the details of testing procedures, minor impurities, grain size, and metallurgical history, has been noted in previous reports on copper[3] and silver.[4]

The scatter bands for these face-centered-cubic metals are compared in Fig. 10 on a reduced temperature scale. The behavior of copper and silver are strikingly similar. The reduced temperature scale normalizes the shape of all three--copper, silver, and aluminum--curves above T/Tm = 0.2, but the tensile strength values do not coincide. A second shift, along the stress axis, would be necessary to make them superpose; the degree and direction of the stress axis shift apparently is proportional to the melting point of the metal. The large increase in tensile strength of aluminum below T/Tm = 0.2 is not shown by copper or silver. It is similar to the temperature dependence of the tensile strength of body-centered-cubic metals, in which impurities exert a strong influence.[5, 12]

Figure 11 is a plot of the true flow stress at several arbitrary strains as a function of temperature for both the BS and AC lots after 400°C anneals. The shapes of these curves in the region below 400°K are indicative of strain aging.

THE EFFECT OF STRAIN RATE

The use of the rate-change test to determine rate sensitivity has been described.[2] Briefly, a specimen is strained to a prescribed nominal strain (in this case $\epsilon = 0.09$) at a standard strain rate; at that strain the strain rate is changed suddenly to a new value and the test continued to a prescribed strain (in this case $\epsilon = 0.11$), whereupon the strain rate is changed suddenly to the standard rate. In these tests the strain rates employed were 0.04/.004/.04 min^{-1}. At constant strain and temperature, strain rate is known to effect the flow stress through the relation $\sigma = K'\dot{\epsilon}^n$. Under the conditions of these tests, the strain-rate exponent, n, is given by the difference in the logarithm of the flow stress at the two rates. Typical rate-change tests are shown in Fig. 12. The strain-rate exponent, n, of the expression $\sigma = K'\dot{\epsilon}^n$, was determined at 77°K and 300°C on samples representing each annealing treatment of both AC and BS Aluminum. The strain-rate sensitivity was the same for all annealing treatments in both lots, within the accuracy of our measurements. The n values obtained were:

T°K	n
77	0.010 ± 0.001
300	0.005 ± 0.001

It is somewhat surprising to find the larger rate sensitivity at the lower temperature. The rate sensitivities of both copper and silver were observed to increase linearly with increasing temperature.[3, 4] However, Lubahn[13] has noted that rate sensitivities of materials known to undergo strain aging pass through minima when plotted as a function of temperature. For example, 61S aluminum alloy has a minimum in rate sensitivity at approximately 273°K. Strain aging effects are usually considered to be associated with soluble impurities. It appears that there is some manifestation of strain aging, even in this relatively pure aluminum.

DISCONTINUOUS YIELDING

A qualitative difference between the two lots of aluminum was apparent in their initial yielding behavior. Aluminum AC had definite yield points at 195°K and below when annealed at 300°C, whereas Aluminum BS did not have such yield points. The effect was noted in AC Aluminum annealed at 300°C, not in AC Aluminum annealed at 400°C and 500°C. Figures 13 and 14 show tracings of the autographic load-elongation records. It should be mentioned that the testing machine used was relatively stiff and utilized a weigh-bar mounting a resistance-wire strain gage whose output was recorded by a short-response time recorder. Such a system is sensitive to the rapid fluctuations in load that accompany discontinuous yielding.

Yield points are not commonly observed in nominally pure face-centered-cubic materials; the effect is usually associated with body-centered-cubic metals containing interstitial impurities.[12] Smallman, Williamson, and Ardley[19] have recently described yield points observed in careful tests of aluminum alloy single crystals.

The same general mechanism that is widely accepted as the explanation of yield points in body-centered-cubic metals, namely the pinning of dislocations by impurities through their mutual interaction, can apply to face-centered-cubic metals. The question is one of degree. The difference in the yielding behavior of the two lots of aluminum is presumably due to a difference in impurity content. It is somewhat surprising that a 300°C anneal should produce a yield point when higher-temperature anneals did not, since the yield-point phenomenon is considered to be due to soluble impurities. However, it is commonly observed that the magnitude of the yield-point phenomenon in iron-carbon allows decreases with increasing grain size.

EFFECT OF GRAIN SIZE

The annealing treatments resulted in a range of grain size from 0.027 mm to 0.105 mm average diameter for BS Aluminum and from 0.021 mm to 0.143 mm for AC Aluminum. Figure 15 shows the effect of grain size on the flow stress at selected strains for BS Aluminum at 20° and 300°K. At 300°K, the grain size dependence of the flow stress is similar to that previously reported for copper[3] and for silver,[4] being most pronounced at small strains and insensitive to grain size at strains of the order of 0.05. At 20°K the flow stress is not a rational function of grain size. Examination of the data in Tables I and II shows that the systematic grain size dependence observed at 300°K is the exception, rather than the rule, in these experiments. The derived values of the strain-hardening exponent, m, and the strain-rate exponent, n, are independent of grain size. Both these quantities were observed to depend on grain size in the cases of copper[3] and silver.[4] Presumably, the effects of grain size are obscured by experimental scatter and aging effects in the present experiments.

DISCUSSION

Aluminum has been the subject of much research in recent years, due in no small part to its suitability for interesting experimental techniques. A large body of experimental observations is now available in the literature, including descriptions of the slip process details, substructure formation and growth, annealing characteristics and thermodynamic properties. So much information about aluminum is available that it has often been used as the epitome of the important face-centered-cubic class of metals. Yet, the most striking general conclusion to be drawn from the present research is that aluminum is atypical when its mechanical properties are compared with copper and silver.

Many of the features of the influence of temperature on the mechanical properties of aluminum described above suggest that the small concentration of impurities present produced important effects. Recall the following observations:

1. Distinct yield points, of the type usually associated with body-centered-cubic metals containing interstitial impurities, were observed in this relatively high purity, face-centered-cubic metal. The yield points were evident in fine-grained specimens tested at low temperatures.

2. The shape of the strain hardening versus temperature curve, which rises markedly below room temperature and is virtually flat

TABLE I

Tensile Test Data of Aluminum BS

No.	T°K	T.S. psi	% El.	Y.S. $\epsilon = 0.005$	σ at $\epsilon =$ 0.01	0.02	0.05	0.10	0.20	0.30	m $\epsilon = 0.1$
Aluminum BS. Annealed 1 Hour at 300°C. Average Grain Diameter 0.021 mm.											
1082	20	37,600	36.4	7,390	8,570	11,200	18,100	27,800	41,500	50,400	0.58
1058	77	18,900	29.6	6,250	7,330	9,160	13,200	18,000	22,800		.40
1065	140	11,600	21.4	5,210	5,890	7,210	9,620	12,000			.27
1064	195	9,120	21.2	4,550	5,130	6,160	7,960	9,540			.25
1062	300	6,930	18.0	4,550	5,000	5,630	6,610	7,500			.18
1087	400	5,120	26.8	3,910	4,170	4,540	5,060	5,580	6,240		.15
Aluminum BS. Annealed 1 Hour at 350°C. Average Grain Diameter 0.039 mm.											
1083	20	37,600	26.4	7,100	8,570	11,800	19,600	30,200	44,050		.56
1070	77	19,500	23.6	5,300	6,570	8,660	13,400	18,600	24,000		.41
1069	140	12,000	16.4	4,600	5,430	6,950	9,980	12,700			.26
1073	195	9,800	17.6	4,700	5,460	6,560	8,460	10,300			.25
1072	300	7,300	17.6	4,300	4,710	5,320	6,460	7,700			.23
1088	400	5,500	23.2	3,200	3,570	4,080	4,860	5,700	6,650*		.22
Aluminum BS. Annealed 1 Hour at 400°C. Average Grain Diameter 0.046 mm.											
1084	20	38,000	28.8	8,500	10,700	14,300	22,600	33,000	46,200		.52
1057	77	20,300	26.2	5,100	6,290	8,340	13,200	18,900	24,600		.44
1066	140	12,000	19.4	5,300	6,000	7,290	9,950	12,500			.29
1063	195	9,500	15.4	5,700	6,190	6,920	8,510	10,100			.23
1061	300	7,200	17.4	3,800	4,400	5,160	6,420	7,600			.24
1089	400	5,400	22.8	3,100	3,500	3,970	4,780	5,600	6,300*		.22
1103	523	2,500	32.6	1,600	1,740	1,980	2,350	2,700	3,020		.20
1097	623	1,200	44.8	920	1,000	1,090	1,210	1,300	1,330	1,280	.09
1099	773	420	9.6	370	400	420	440				
1101	873	260	6.8	260	266	266	264				
Aluminum BS. Annealed 1 Hour at 450°C. Average Grain Diameter 0.065 mm.											
1085	20	39,200	30.4	6,800	8,360	11,300	19,200	30,200	45,300		.60
1075	77	20,800	21.4	6,200	7,570	9,810	14,800	20,200			.40
1078	140	12,600	16.0	4,700	5,570	7,110	10,200	13,200			.30
1077	195	9,800	15.2	4,300	5,000	6,280	8,450	10,400			.27
1074	300	7,200	16.0	3,400	4,000	4,900	6,300	7,700			.25
1090	400	5,200	16.8	3,000	3,400	3,870	4,680	5,500			.23
Aluminum BS. Annealed 1 Hour at 500°C. Average Grain Diameter 0.105 mm.											
1086	20	37,100	20.4	7,000	8,790	11,900	20,400	32,200			.59
1054	77	20,000	16.8	5,800	7,140	9,350	14,500	20,500			.31
1067	140	11,250	12.0	5,000	5,840	7,310	10,000				
1056	195	8,100	3.6	4,100	5,040	6,380					
1053	300	6,400	6.0	3,200	3,970	4,980	6,550				
1091	400	4,600	7.2	3,100	3,530	3,970	4,720				

*Extrapolated.

TABLE II

Tensile Test Data of Aluminum AC

No.	T°K	T.S.	% El.	σ at ε = const. 0.005	0.01	0.02	0.05	0.10	0.20	0.30	m ε = 0.1
		Aluminum AC. Annealed 1 Hour at 300°C. Average Grain Diameter 0.027 mm.									
1044	20	35,000	32.2	6,500	7,430	10,100	16,700	26,000	38,900		0.58
773	77	17,300	25.2	5,400	5,930	7,620	11,700	16,200	21,000		.42
1068	140	12,200	23.6	5,400	6,110	7,400	9,980	12,500	14,800		.29
775	195	9,300	20.6	4,800	5,210	6,200	8,080	9,800			.25
770	300	6,300	18.8	4,700	5,000	5,450	6,240	6,900			.15
1093	400	5,300	29.6	4,300	4,440	4,780	5,260	5,800	6,160		.14
		Aluminum AC. Annealed 1 Hour at 400°C. Average Grain Diameter 0.118 mm.									
1045	20	42,100	20.0	6,800	8,710	12,300	21,800	36,000			.66
1002	77	26,300	21.2	5,600	7,240	10,100	17,100	25,100			.45
1006	195	12,700	13.2	4,100	5,210	6,920	10,400	13,400			.35
960	300	8,600	13.6	4,200	4,930	5,890	7,660	9,400			.29
1094	400	6,300	15.2	3,400	3,890	4,530	5,590	6,700			.23
1102	523	2,800	26.2	1,600	1,830	2,080	2,550	3,000	3,400		.24
1096	623	1,200	41.6	880	964	1,080	1,250	1,360	1,400	1,380	.10
1098	773	44C	14.8	390	414	433	457	460			
1100	873	230	7.4	220	226	229	256				
		Aluminum AC. Annealed 1 Hour at 500°C. Average Grain Diameter 0.143 mm.									
1046	20	33,000	12.0	6,000	7,710	11,200	21,100	35,600			.75
1004	77	19,000	8.0	4,400	6,000	8,950	1,630				
1007	195	8,000	4.4	3,400	4,460	6,560					
1135	300	5,900	3.6	3,400	4,430	5,860					
1095	400	4,700	4.4	3,200	3,640	4,270					

in the range 200° to 500°K, is decidedly different from the approximately linear temperature dependence observed for copper and silver. It seems evident that some recovery process occurs in aluminum at temperatures well below room temperature to an extent that does not occur in copper or silver at the same or even much higher homologous temperature. This observation brings to mind the evidence of low-temperature polygonization in aluminum.[14] It also suggests that measurements of changes in electrical resistivity[15] or stored energy[16] during annealing should be performed on aluminum deformed at very low temperatures. Comparison should be made with copper.

3. The shapes of the flow stress versus temperature and the tensile strength versus temperature curves are similar to such data on body-centered-cubic metals, in which impurities interact with dislocations to inhibit slip, with resultant yield-point and strain-aging phenomena.

4. The apparent anomaly in the effect of temperature on strain-rate sensitivity, the rate effect at 77°K being several times greater than that at room temperature, is typical of metals in which strain-aging effects are found.[13]

Much of our current understanding of yield points and strain-aging effects is due to Cottrell and collaborators,[12, 20] who have considered in detail the "pinning" of dislocations by impurities. Solute atoms having appreciable misfit in the lattice condense into dislocations because of an elastic interaction with them. Interstitial solute atoms such as carbon and nitrogen produce non-spherically symmetrical distortions in body-centered-cubic and hexagonal-close-packed metals, distortions that interact with both edge and screw dislocations. Substitutional solute atoms in face-centered-cubic metals produce only spherically-symmetrical distortions which can interact only with edge dislocations. However, Cottrell[20] has pointed out that the dissociation of dislocations in face-centered-cubic metals into partial dislocations, as discussed by Heidenreich and Shockley,[21] always leads to some edge-type component which can be anchored by substitutional impurities. Since the two partial dislocations are elastically bound to one another, the whole dislocation may be pinned by impurities. Thus, face-centered-cubic metals can be expected to have yield points, but to a much less pronounced degree than body-centered-cubic metals.

Suzuki[17] pointed out that the "fault" or ribbon-like region between two partial dislocations is a region that is crystallographically

equivalent to a layer of hexagonal-close-packed structure of two atomic planes in thickness. As such, it is characterized by an interfacial free energy, twice that of a coherent twin boundary, and possesses a solubility for a particular impurity that is different from the surrounding crystal. There is thus a driving force for the segregation of impurities to the fault between partial dislocations. Segregation of impurities to the fault inhibits separation of the dislocation ribbon from the impurity concentration. Thus, the Suzuki concept also leads to the prediction of yield points in face-centered-cubic metals. Note that both concepts lead to the impurity pinning of a ribbon-like dislocation configuration in face-centered-cubic metals as contrasted to the pinning of a single-line dislocation in body-centered-cubic crystals. The question remains as to why aluminum should show the effects of impurities interacting with dislocations to a much greater extent than, say, copper.

Fullman(18) has measured the ratios of the interfacial free energies of coherent twin boundaries to that of grain boundaries in both aluminum and copper, the values being, aluminum: 0.21 ± 0.05, copper: 0.036 ± 0.006. Suzuki(17) gives the approximate width, l_A, of an extended dislocation fault in metal A to be:

$$l_A \approx l_{Cu} \frac{\sigma^t{}_{Cu} \mu_A}{\sigma^t{}_A \mu_{Cu}} ,$$

where σ^t is the coherent twin boundary energy, and μ is the shear modulus. Suzuki gives l_{Cu} as approximately 50 A. μ_{Al}/μ_{Cu} is approximately 1/2. In the absence of an absolute measurement of the grain boundary energy of aluminum, we may take $\sigma^b{}_{Cu}/\sigma^b{}_{Al} \approx \Delta H^{fusion}_{Cu} / \Delta H^{fusion}_{Al} = 50/94 \approx 1/2$. Appropriate values may then be substituted in Suzuki's equation to give the width of the extended dislocation fault in aluminum as follows:

$$l_{Al} \approx l_{Cu} \left[\frac{\sigma^t{}_{Cu}/\sigma^b{}_{Cu}}{\sigma^t{}_{Al}/\sigma^b{}_{Al}} \right] \left(\frac{\Delta H^f{}_{Cu}}{\Delta H^f{}_{Al}} \right) \left(\frac{\mu_{Al}}{\mu_{Cu}} \right)$$

$$l_{Al} \approx 50 \left(\frac{0.036}{0.21} \right) \left(\frac{1}{2} \right) \left(\frac{1}{2} \right) \text{A}$$

$$l_{Al} \approx 2 \text{ A.}$$

Admitting the crude approximation, it seems evident that the faults between dissociated dislocations in aluminum are quite narrow and might better be likened to a line than to a ribbon. Impurity pinning in aluminum would then be expected to be characterized by a relatively strong, narrow interaction in contrast to the weaker and broader interaction in copper. The impurity interaction in aluminum would then be of similar form as, but of much less strength than, the interaction caused by interstitial impurities in body-centered-cubic metals. Thus, aluminum should exhibit a propensity for yield points and strain-aging phenomena intermediate to iron and copper.

A comparison of the temperature dependence of the yield strength or tensile strength of copper and aluminum is consistent with such an argument. As discussed by Suzuki,(17) thermal fluctuations do not markedly affect the critical shear stress of an extended dislocation pinned by a heterogeneous distribution of solute atoms. On the other hand, thermal fluctuations will markedly affect the critical shear stress of a dislocation pinned by a strong, narrow impurity interaction. Thus, we note the yield strength and tensile strength of aluminum rise markedly with temperature as the temperature is decreased below $T/Tm \approx 0.2$, as compared to the moderate increase in strength observed for copper.

SUMMARY

Constant-strain-rate tensile tests have been performed on polycrystalline wires of two lots of high-purity aluminum designated AC and BS. Tests were made of five groups of BS specimens annealed at 300°, 350°, 400°, 450°, and 500°C, and three groups of AC specimens annealed at 300°, 400°, and 500°C. The annealing treatments produced a range of grain sizes extending from 0.02 mm to 0.14 mm average grain diameter. The specimens were tested at a strain rate of 0.04 min^{-1} over the range 20° to 873°K (0.021 to 0.94 T/Tm). The experimental data are presented as tabulated tensile strength and per cent elongation values and true stress values for selected strains. The data were analyzed to determine the effect of temperature on the flow stress at selected strains, tensile strength, yield strength and strain hardening. Rate-change tests were used to measure the strain-rate sensitivity at 77° and 300°K.

It is concluded that:

1. The flow curves of aluminum are generally regular over the range 0.021 to 0.94 of the absolute melting temperature. Some discontinuous yielding was observed in one lot of aluminum at 195°K and below.

2. The yield strength, tensile strength and true flow stress at arbitrary strains extrapolate to finite values at the absolute zero of temperature.

3. Strain hardening, as measured by the strain-hardening exponent m, increases markedly with decreasing temperature in the region below 200°K and is virtually constant in the region 200° to 550°K. This temperature dependence is qualitatively different from that previously observed for copper and silver, both of which showed approximately linear temperature dependence until annealing temperatures were approached.

4. Complexities in the shapes of flow stress versus temperature curves suggest strain-aging effects were operative in these relatively high-purity aluminum samples.

5. The effects of grain size, within the 0.02 mm to 0.14 mm average diameter obtained in this investigation, were masked by specimen scatter and side effects, so that no systematic trends were established.

6. The strain-rate sensitivity at 300°K was found to be less than at 78°K, an anomaly that is usually associated with strain aging.

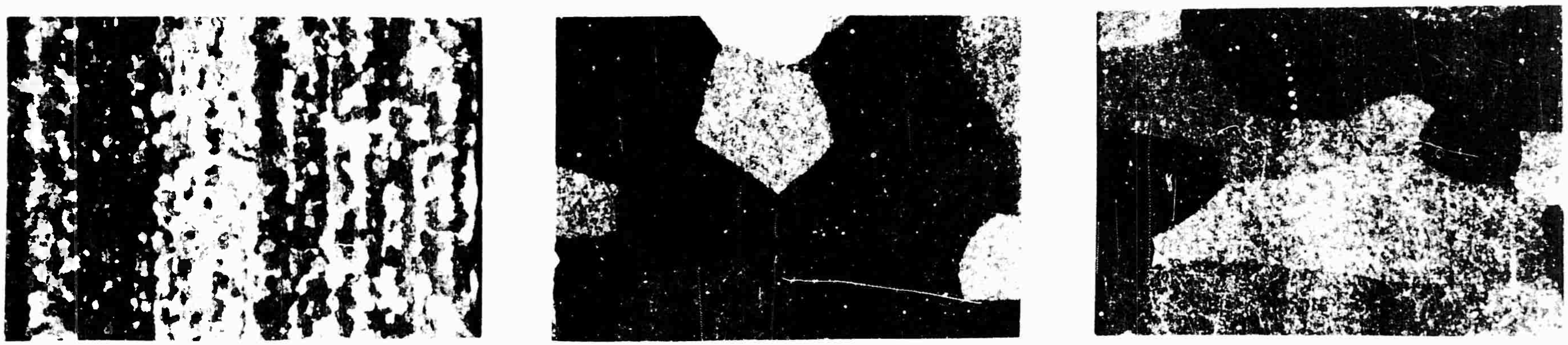
7. As in the case of copper and silver, the tensile strength versus temperature relation for aluminum is influenced but slightly by variations in specimen history. However, the temperature dependence of the tensile strength of aluminum is qualitatively different from copper and silver below an homologous temperature of 0.2 in that the tensile strength of aluminum increases much more rapidly with decreasing temperature.

8. The differences in the behavior of aluminum and copper are ascribed to a deduced difference in the width of the extended dislocation fault in these two face-centered-cubic metals.

Aluminum BS

300°C, .027 mm — 350°C, .039 mm — 400°C, .046 mm — 450°C, .065 mm — 500°C, .105 mm

Aluminum AC



300°C, .021 mm — 400°C, .118 mm — 500°C, .143 mm

Fig. 1 Typical microstructures of two lots of aluminum developed by one hour anneals. Magnification 100X.

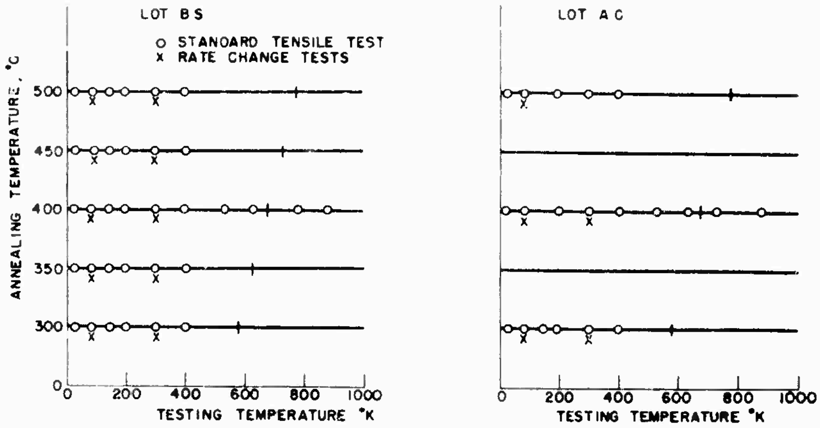


Fig. 2 Diagram showing the testing program in relation to annealing history. Standard tensile test; x rate-change test.

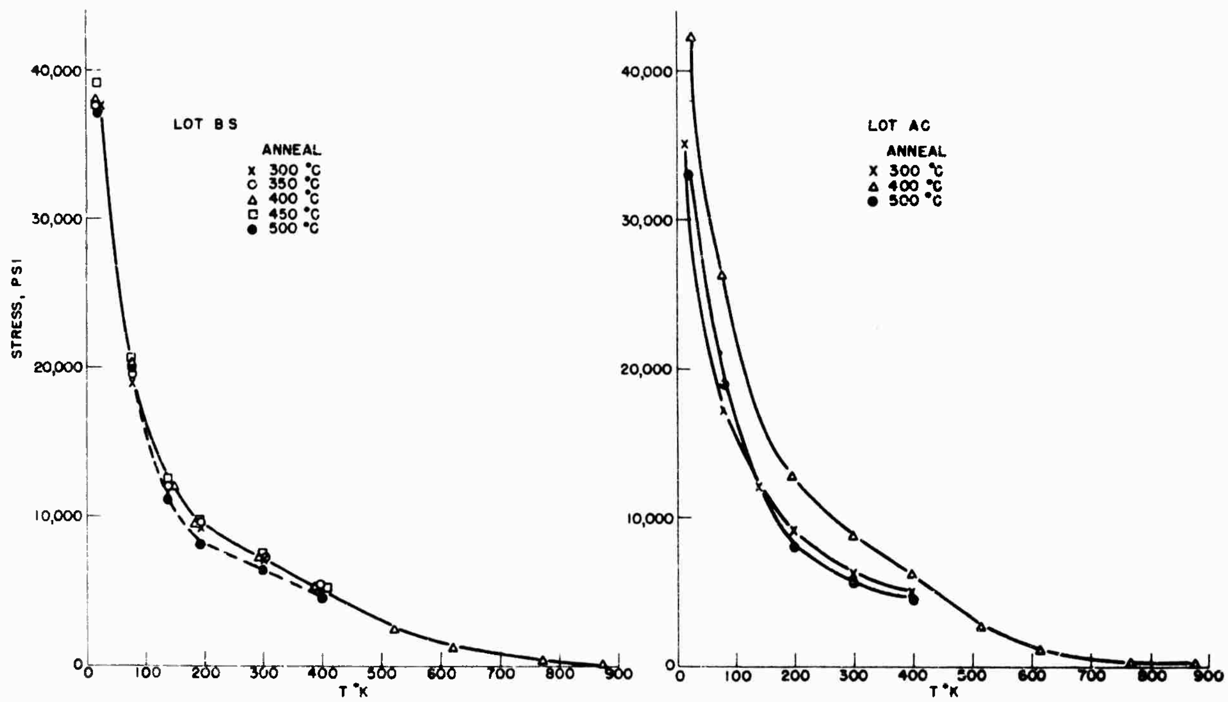


Fig. 3 Tensile strength of two lots of aluminum as a function of temperature and grain size.

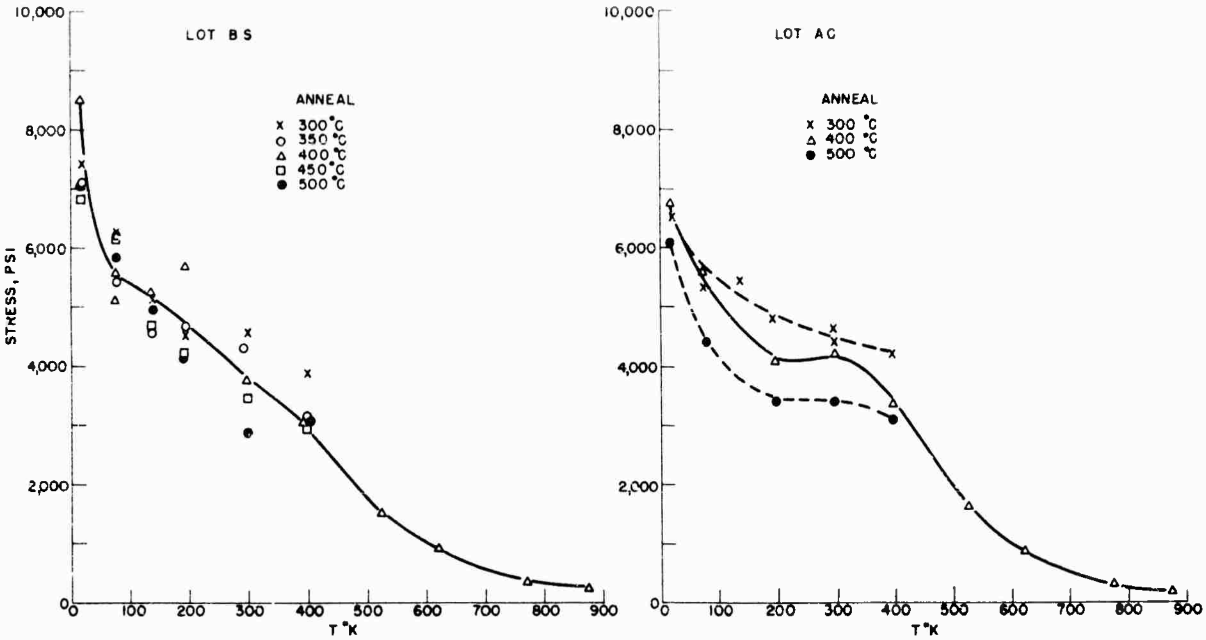


Fig. 4 Yield strength (σ at $\epsilon = 0.005$) of two lots of aluminum as a function of temperature and grain size.

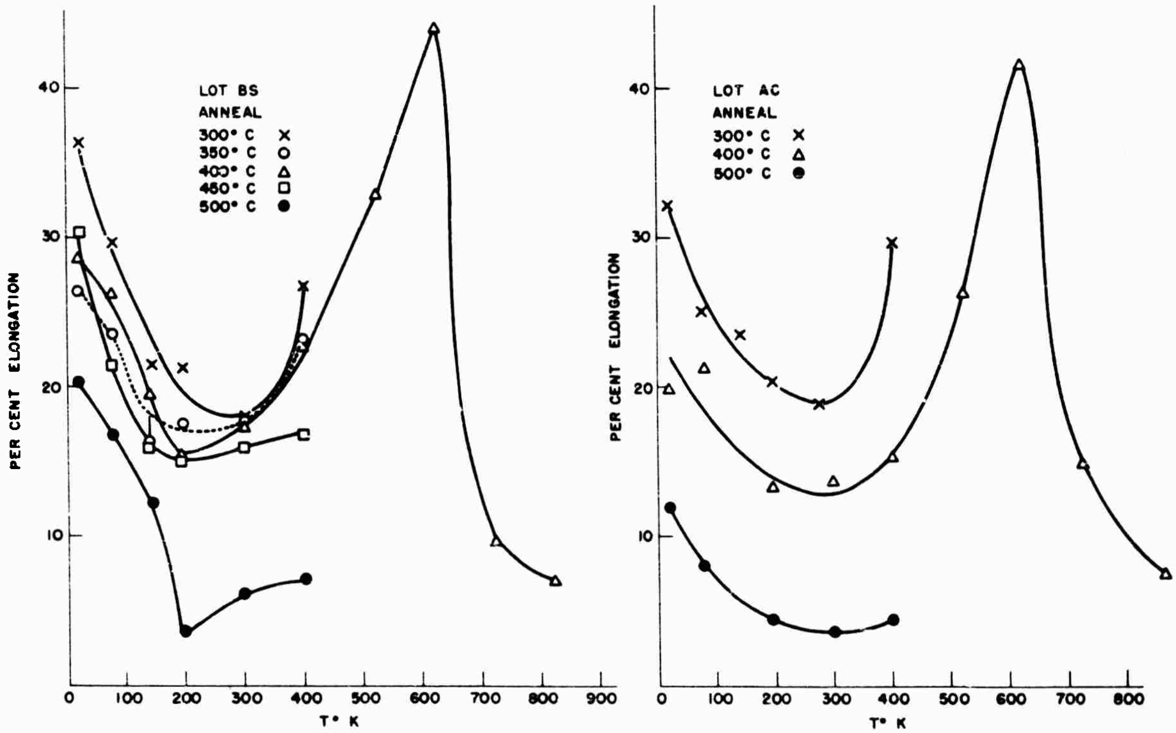


Fig. 5 Per cent elongation of two lots of aluminum as a function of temperature and grain size.

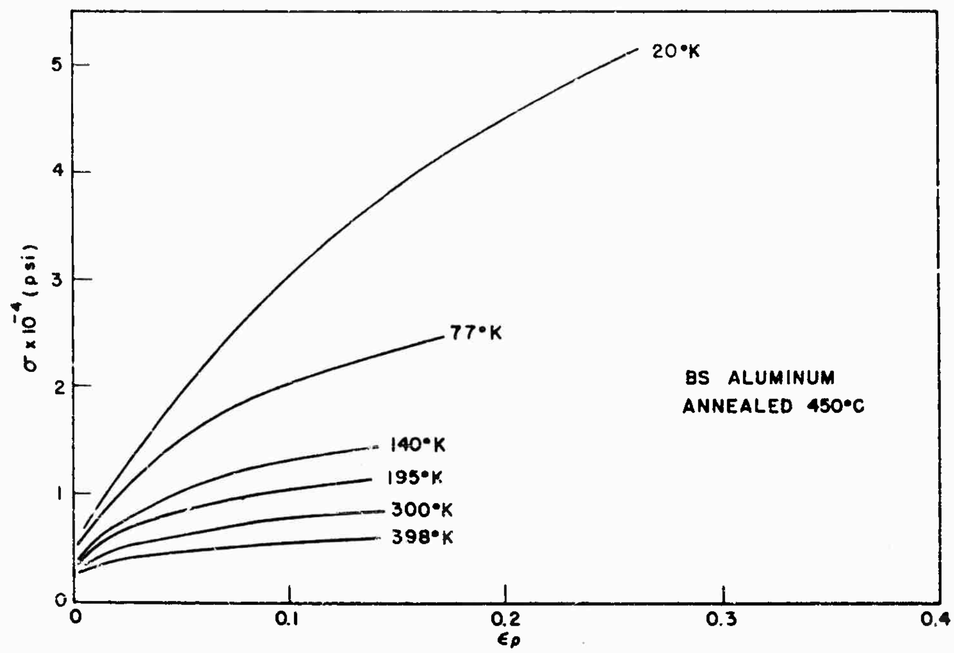


Fig. 6 A typical family of true stress-true strain curves for annealed aluminum at several temperatures. Aluminum BS, annealed 1 hour at 450°C, average grain diameter 0.065 mm.

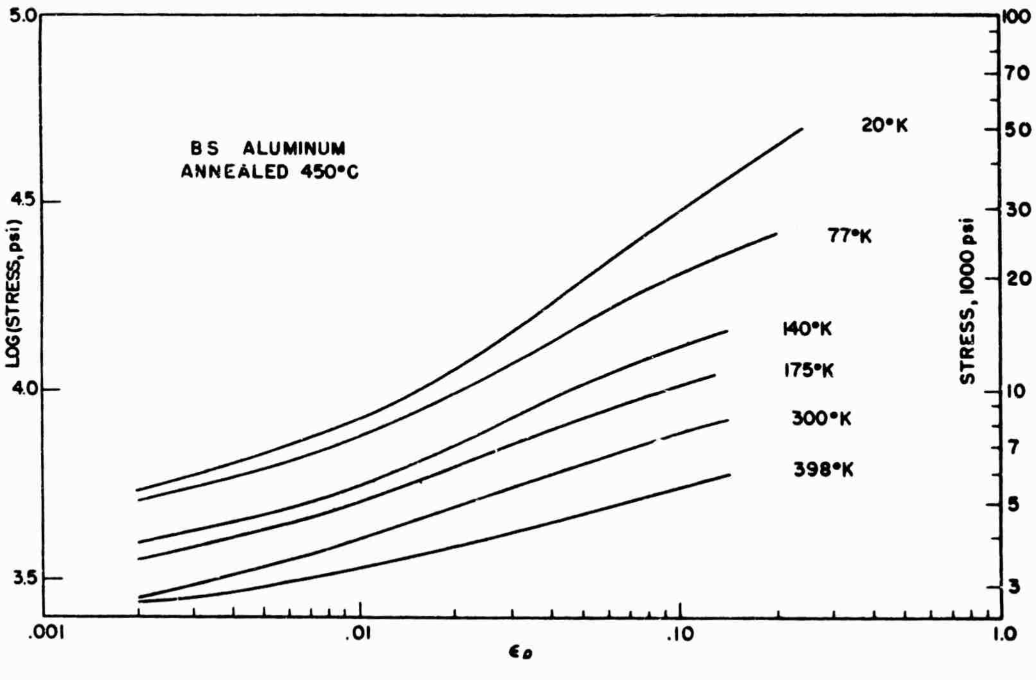


Fig. 7 Logarithmic plot of the data of Fig. 6.

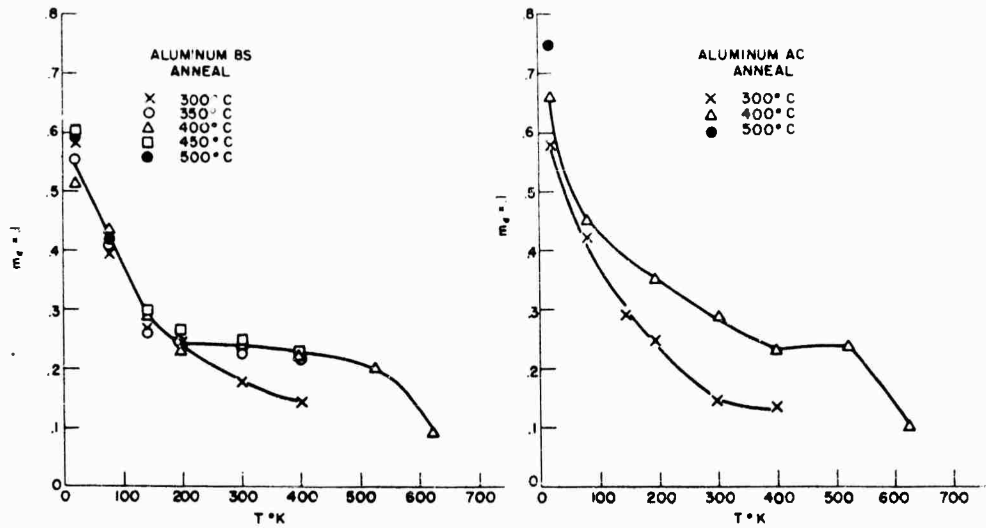


Fig. 8 The strain-hardening exponent, m, at a strain of 0.1, as a function of temperature for several grain sizes.

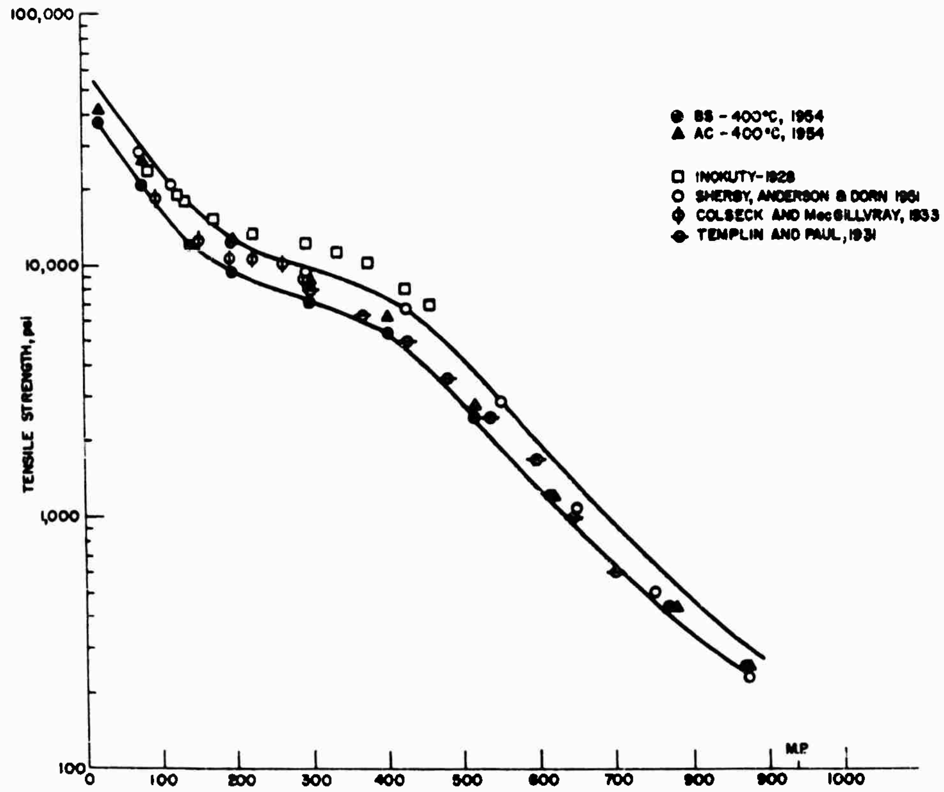


Fig. 9 Composite plot of literature data on tensile strength of aluminum as a function of temperature.

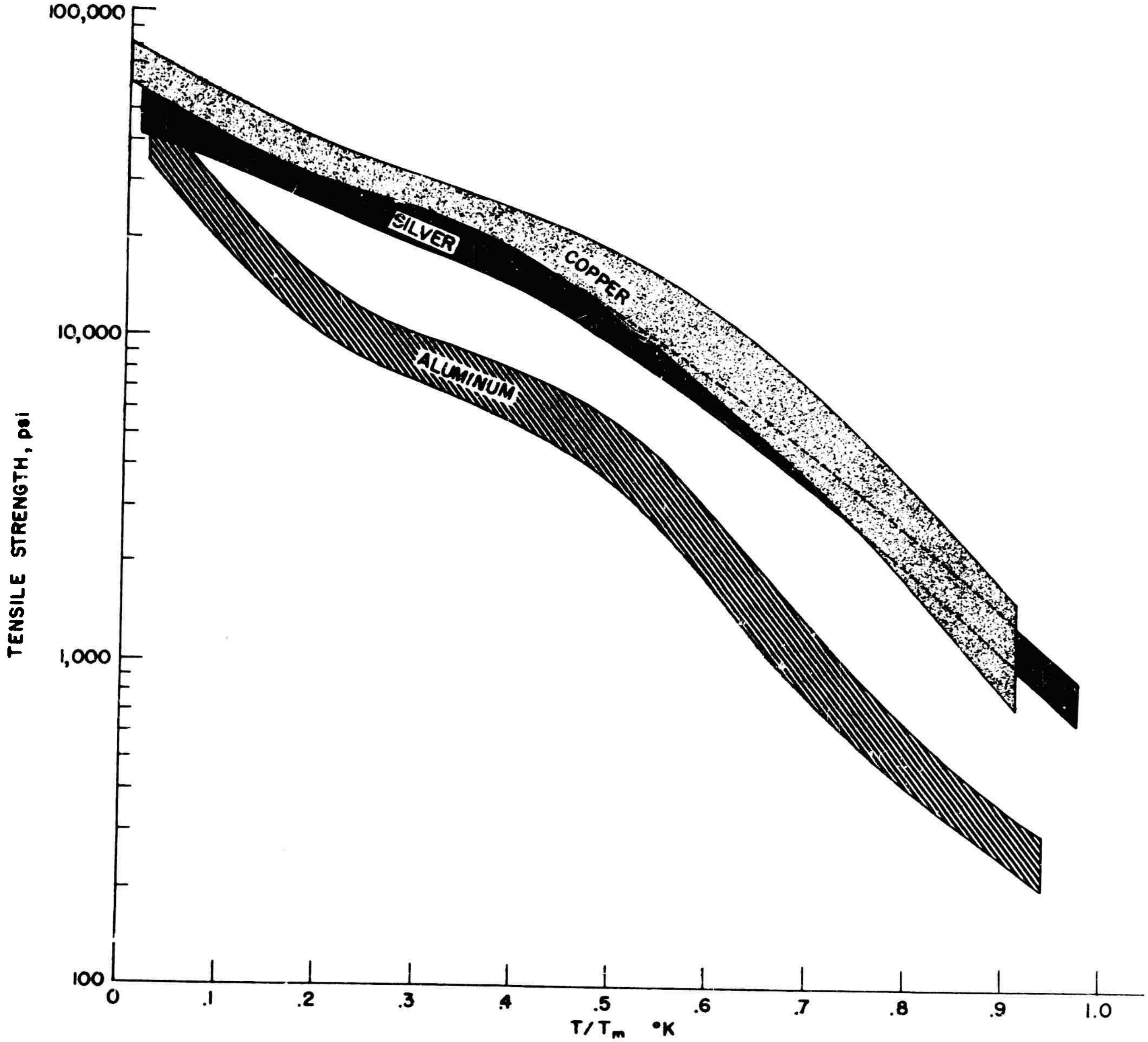


Fig. 10 Comparison of tensile strength of copper, silver and aluminum on a reduced temperature scale.

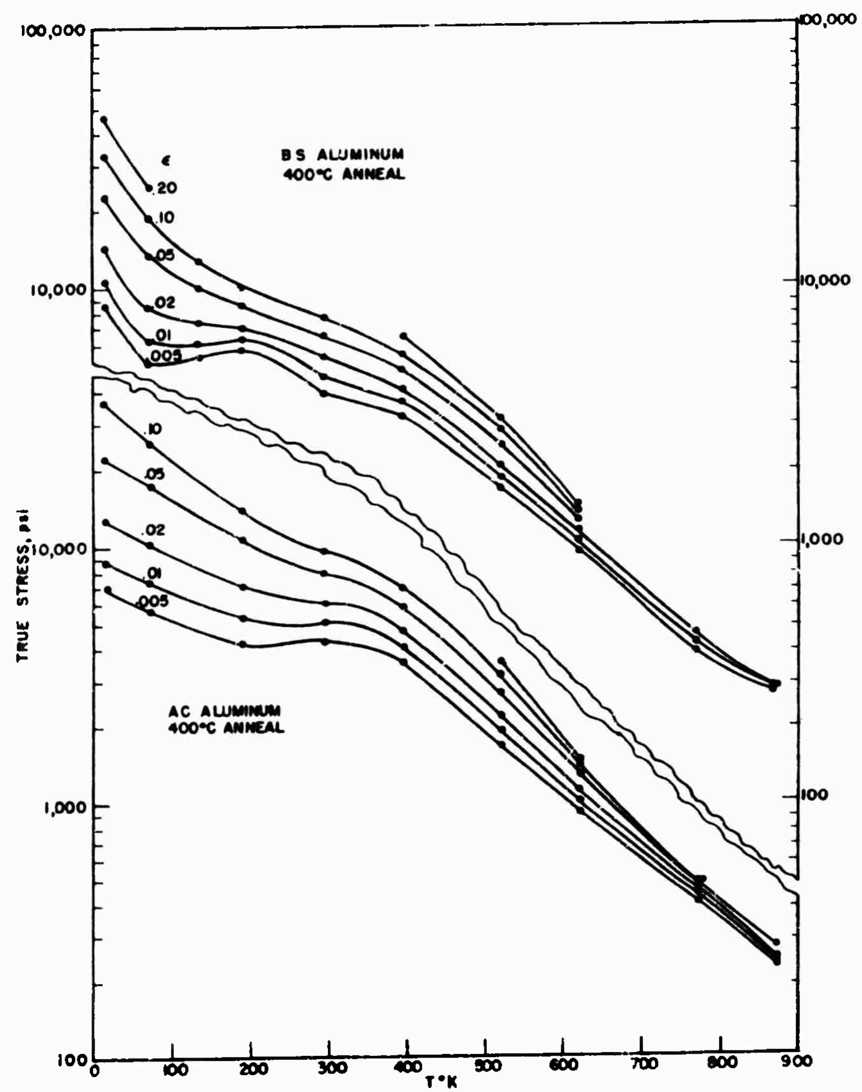


Fig. 11 True flow stress at several strains for two lots of aluminum as a function of temperature.

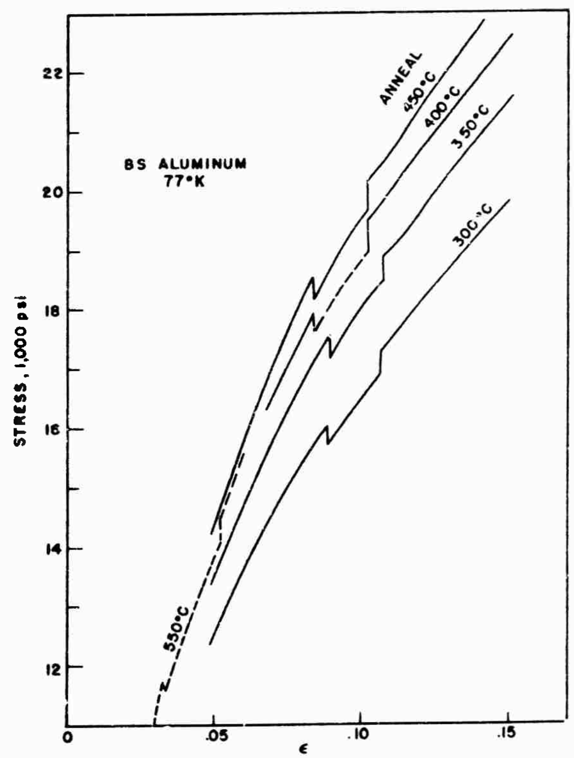


Fig. 12 Typical rate-change tests.

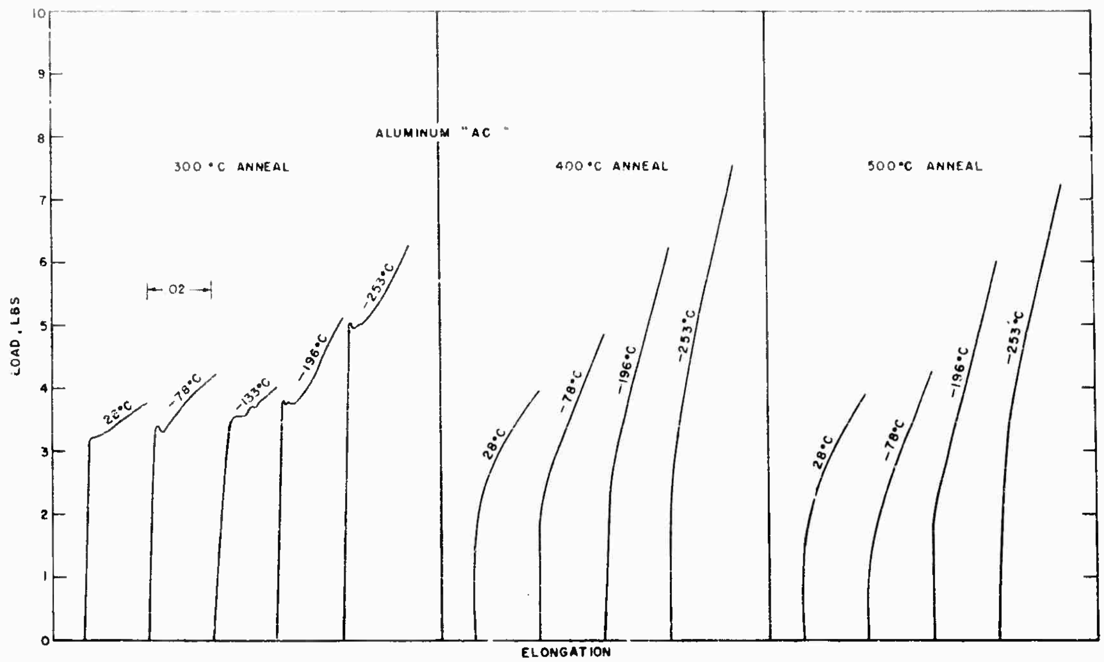


Fig. 13 Load-elongation records showing the initial yielding of Aluminum AC.

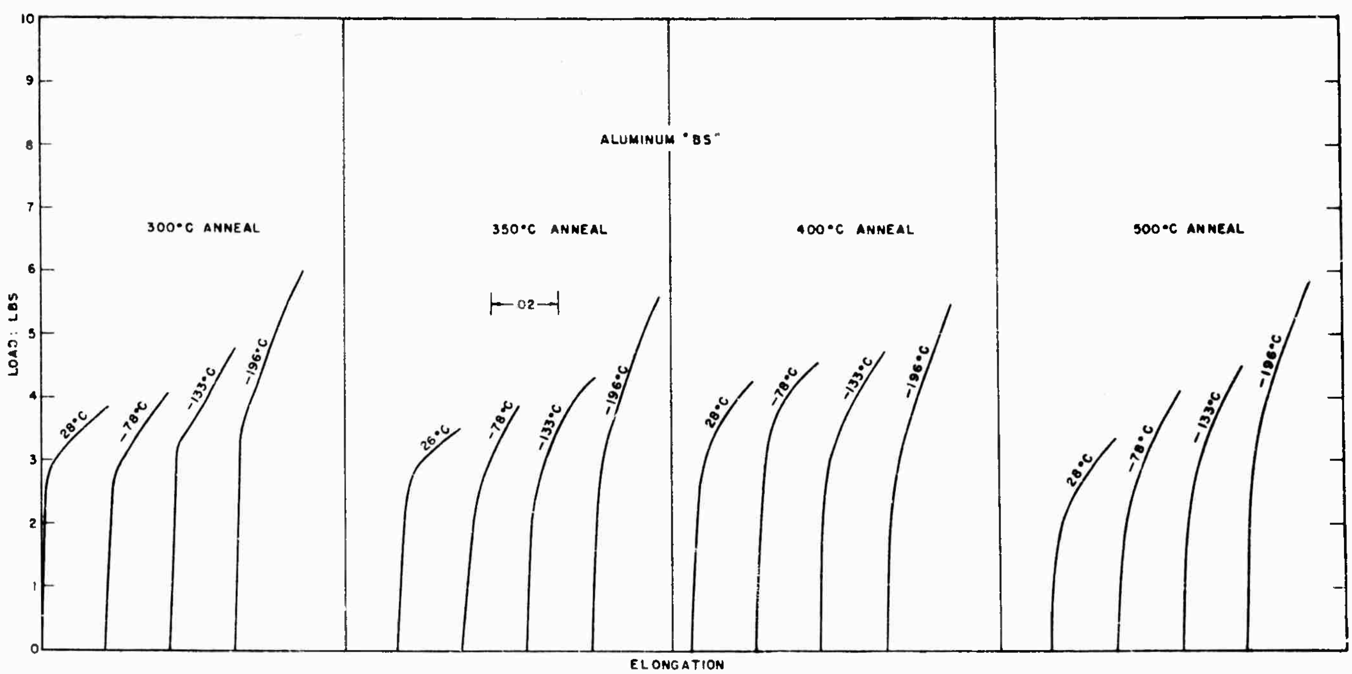


Fig. 14 Load-elongation records showing the initial yielding of Aluminum BS.

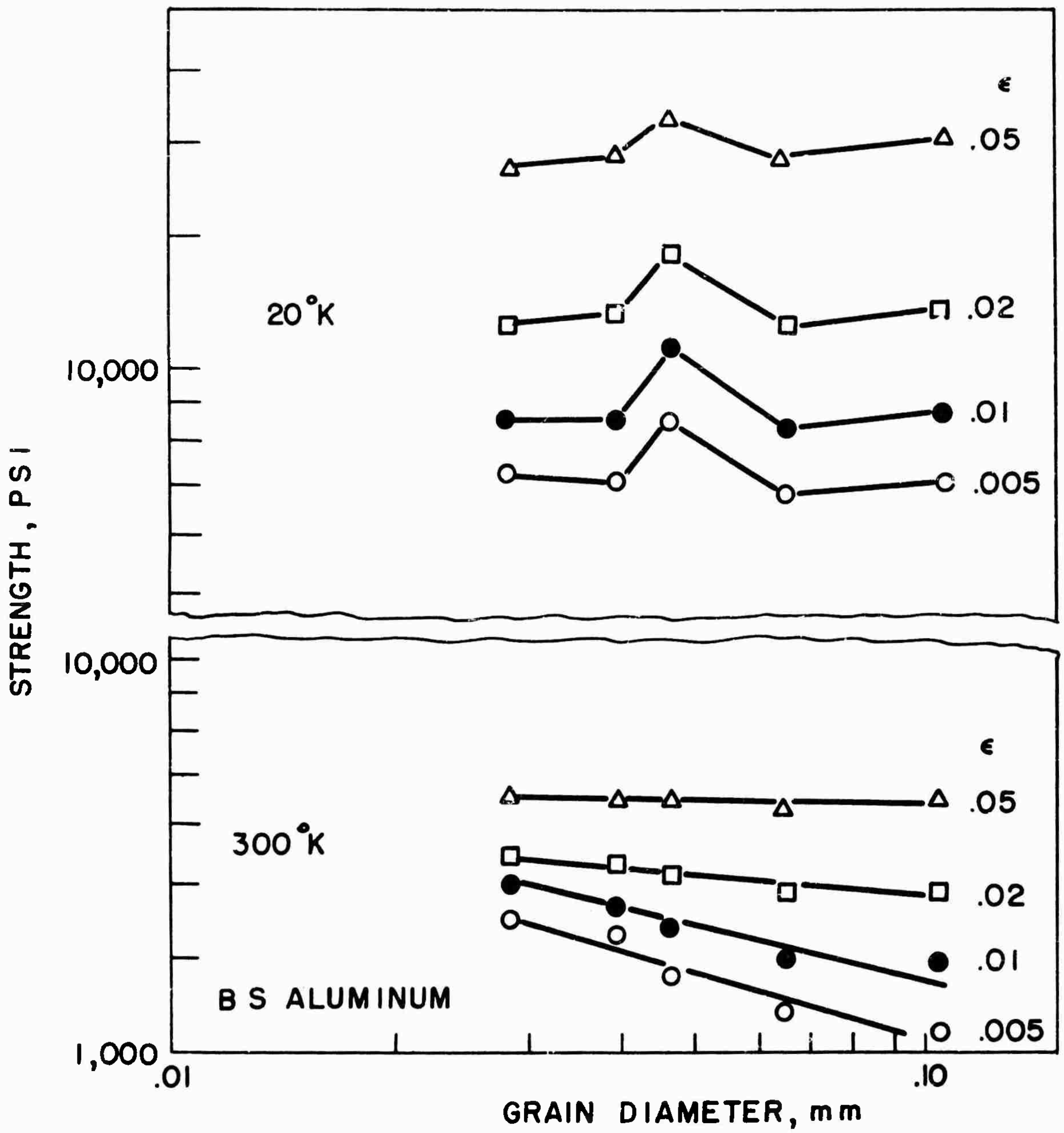


Fig. 15 Effect of grain size on the flow stress of aluminum at arbitrary strains.

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