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SURVEY AND CRITICAL REVIEW OF DYNAMIC MECHANICAL PROPERTIES OF METALS

WATERVLIET ARSENAL

JULY 1974

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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The general technical literature from all known sources that contains mechanical property data on metals at strain rates in the range of 10^{-2} to 10^{-4} sec^{-1} is reviewed. The general trends of the data are discussed for each metal and alloy class. Results on the same material from different sources are compared and consensus results given where possible. The effects of elevated and low temperatures are discussed.

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Block No. 20 Abstract continued

Information is also presented in the form of charts which show the range of strain rate and temperature for which data are available for each metal and alloy class.

WVT-TR-74034

AD

SURVEY AND CRITICAL REVIEW OF DYNAMIC MECHANICAL PROPERTIES OF METALS

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JULY 1974

TECHNICAL REPORT

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INTRODUCTION

The purpose of this report is to provide the designer or the materials engineer with a general review of what is currently known about the effects of high rates of loading on the strength of metals and alloys. The information is presented in the form of charts which show the strain rate and temperature regions in which data are available for each of the 18 metals or alloy classes considered. References to the source of the data are shown on the charts.

Along with each chart is a narrative discussion of the general trends of the data for the material considered. The intent of this discussion is not to provide actual design data or to completely summarize the results available. It is only to present general trends and areas of agreement or disagreement among the various references. Since data on the dynamic behavior of materials can be obtained in a number of different ways and under greatly varying conditions it is the opinion of the author that presentation of design data in a summary report of this type can be misleading and dangerous. To include all of the conditions which may affect the usefulness of the data referenced for design purposes would be prohibitively time consuming and would serve no real purpose. The best source of any data which will be used for actual design purposes is the original work in which the data was published.

An important consideration in using any of the data referenced in this report is the fact that the strain rate sensitivity of any material can be greatly affected by heat treatment, microstructure and cold working. As an example of this, the strain rate sensitivity of a 4340 alloy steel in the quenched and tempered condition can be significantly affected by whether the microstructure is 100 percent martensite or a mixture of martensite and bainite. Therefore, in using any of these data in a critical design application the designer must be sure that the material used in his structure is the same as that used to obtain the test data.

The list of references used for this survey is believed to be as complete as possible in view of the limited time and funds available. However, there are undoubtedly a number of publications that should have been included and were overlooked. If any reader is aware of such publications the author would appreciate hearing of them since the intention is to update this report at some later date.

Papers or reports of a primarily theoretical nature that contain little or no original experimental data have been intentionally omitted from this review. It is not the intent of this work to review all of the many theoretical approaches to the understanding of materials at high rates of strain. This is not intended to diminish the importance of such work but it is not considered as being within the scope of this review.

In order to facilitate the addition of references as they become available, the list of references for this survey are arranged according to the first letter of the last name of the first named author. They are identified by this letter followed by a number which originally represented the alphabetical order of the authors. However, as references were added, no attempt was made to maintain an alphabetical order within a group of references of the same code letter.

In addition to the references used in the discussion of the individual materials, there are several good surveys on high strain rate behavior of metals that have been previously published. Most of the information contained in these surveys has been considered in arriving at the general conclusions given in this report.

The most complete and current surveys are references E1, G7 and L2. Reference G7 contains a very complete review on steels and considers low, intermediate and high strength steels. Reference L2 covers all materials but most of the results given are for pure metals, aluminum alloys and mild steels. Reference E1 considers the combined effect of strain rate and temperature on an extremely wide variety of materials and presents rather complete summaries of the data from all of the references used.

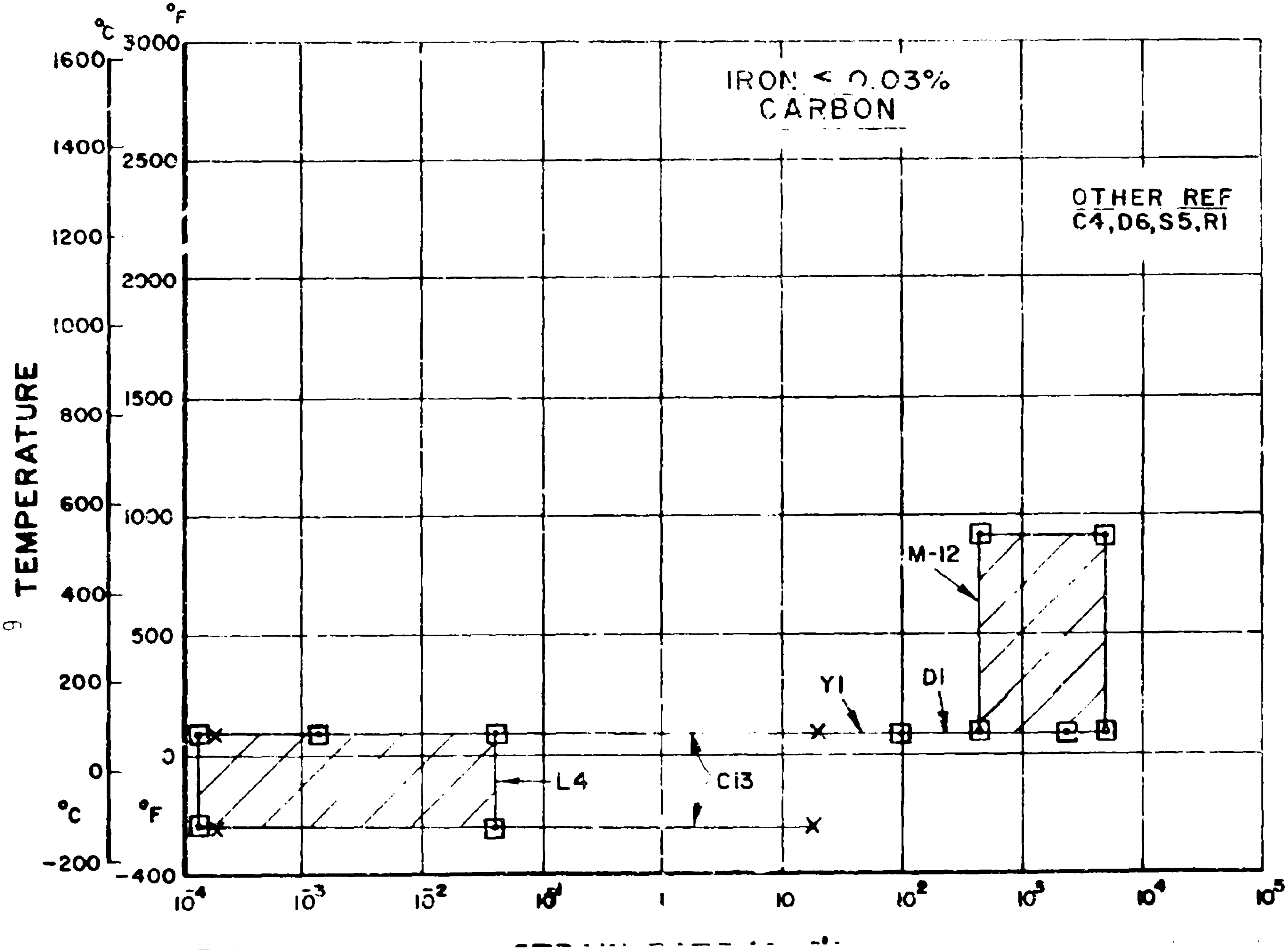
IRON BASED MATERIALS

High Purity and Low Carbon Iron (<0.03%C)

Room temperature results are available for high purity iron, "Armco" and Ferrovac E" irons and a special 0.15% Ti alloy for strain rates ranging from 10^{-4} to $2x10^3$ sec^{-1}. The results are all quite similar showing a linear increase in strength with logarithmic strain rate up to about 10 sec^{-1}. The yield strength increases from about 10 ksi to 30 ksi over this range. At higher rates a more rapid increase is found. The flow stress at various strain values follows the same trend as the yield strength except for the annealed high purity iron at large strains (10-15%). For the latter case this material is rate independent up to a strain rate of 1 sec^{-1} and strongly rate sensitive at higher rates.

Results are also available at low temperatures to -195 C. With decreasing temperature the strength increases considerably while the rate sensitivity decreases. At -195 C the "static" yield strength is about 100 ksi and increases to 120 ksi at a strain rate of 10 sec^{-1}. At elevated temperatures the only available results are for Ferrovac E in the very high strain rate region (0.2 x 10^3 to 6 x 10^3 sec^{-1}). Above 1.5 x 10^3 sec $^{-1}$ a linear relationship between flow stress and strain rate is found. Elevated temperatures up to 500 C (930F) result in a decrease in the slope of this relationship so that the relative strength increase for a strain rate increase from 1.5 x 10^3 sec^{-1} remains essentially constant.

Special conditions studied are effects of neutron irradiation (C4) and of hydrostatic pressure (R1) and strain rate change effects (S5).



IRON < 0.03%
CARBON
OTHER REF
C4, D6, S5, R1
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
M-12
Y1
D1
L4
C13
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5

Plain Carbon Steels (>0.03%C)

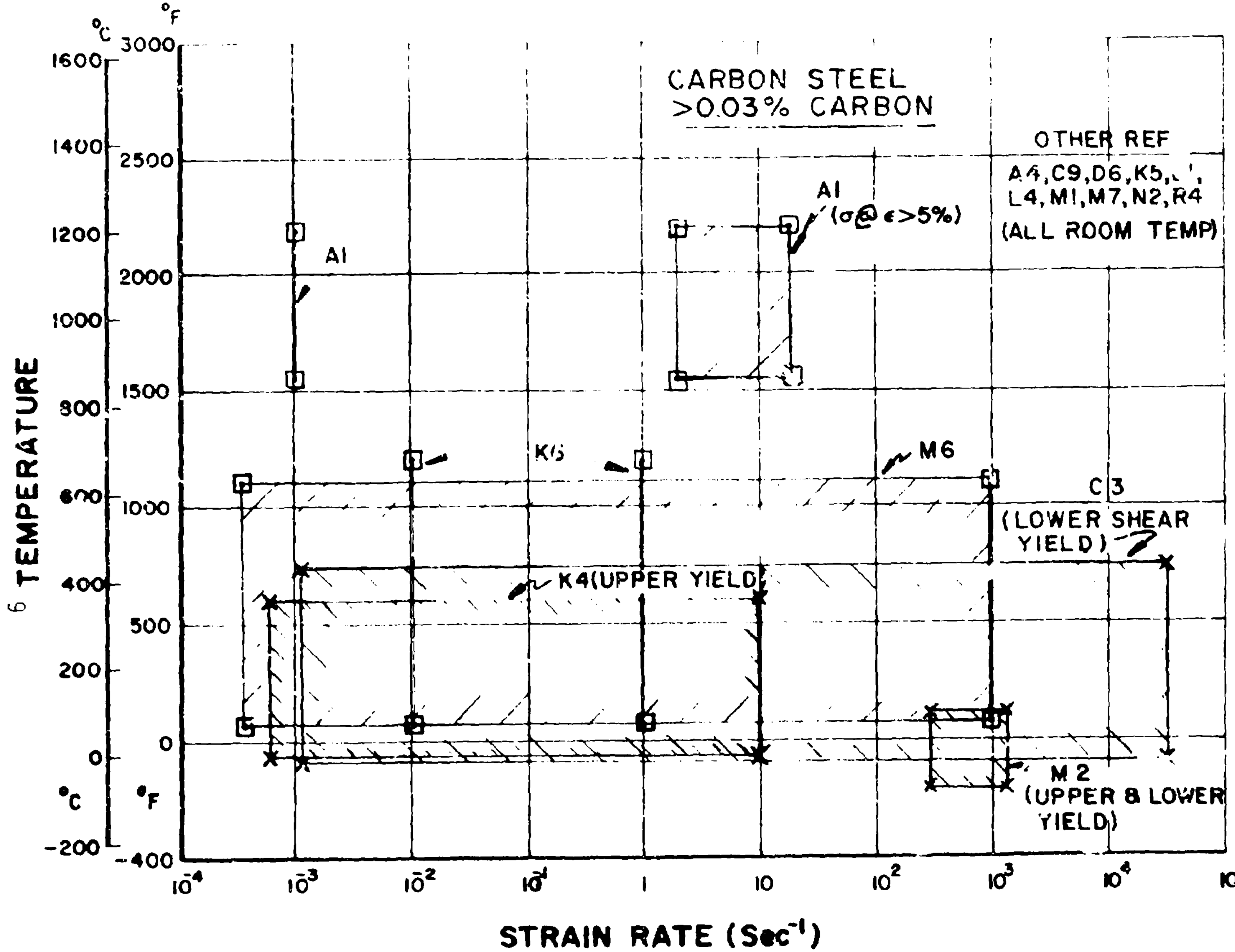
There are over 14 references containing data on this material at room temperature. All of these show this material to be highly rate sensitive at room temperature in the annealed condition. Since this class of materials shows a distinct yield point instability phenomenon, it exhibits both an upper and lower yield strength. It also exhibits a delayed yield phenomenon which causes the upper yield strength to be more rate sensitive than the lower yield strength. The lower yield strength is a linear function of logarithmic strain rate from about 10^{-2} to 10^{3} sec^{-1}. A 100% increase in strength is generally found over this range. At strain rates below 10^{-2} this material is essentially rate insensitive. Above about 5×10^{3} a significant increase in rate sensitivity to a linear relationship is reported. The upper yield strength is a power law function of strain rate for values exceeding 10^{-3}. A 100% increase is found at a strain rate of about 10 sec^{-1}. The upper limit of this power law relationship is not known due to the experimental difficulties in measuring the upper yield strength at very high rates. Results for flow stress at various strain values follow the same trends as the lower yield strength but with decreasing rate sensitivity at higher strain values.

The effects of elevated and low temperatures on the rate sensitivity of this material have been studied quite extensively by several investigators. The effect of increasing temperature is to slightly increase the slope of the yield stress-strain rate curve (on a log-log basis). However, the strain rate dividing the rate sensitive and insensitive regions is significantly increased. Increasing the temperature to 600F (590K) increases this transition strain rate by 3 orders of magnitude. For certain combinations of material, temperature and strain the flow stress may show a negative rate sensitivity (decreasing flow stress with increasing strain rate) in the intermediate strain rate range.

The effects of decreasing temperature are opposite to those given above for increasing temperature.

Most of the available results are for annealed material. Work hardening decreases the rate sensitivity in the intermediate strain rate region, and increases the strain rate dividing the rate sensitive and insensitive regions. Elevated temperature may result in a slight negative rate sensitivity for cold worked steels.

Other conditions considered are grain size effects (K5), biaxial loading (L1) and delay time effects (R4).



CARBON STEEL
>0.03% CARBON
OTHER REF
A4,C9,D6,K5,
L4,M1,M7,N2,R4
(ALL ROOM TEMP)
A1
A1
(σ@ ε>5%)
M6
C3
(LOWER SHEAR
YIELD)
K4(UPPER YIELD
M2
(UPPER & LOWER
YIELD)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)

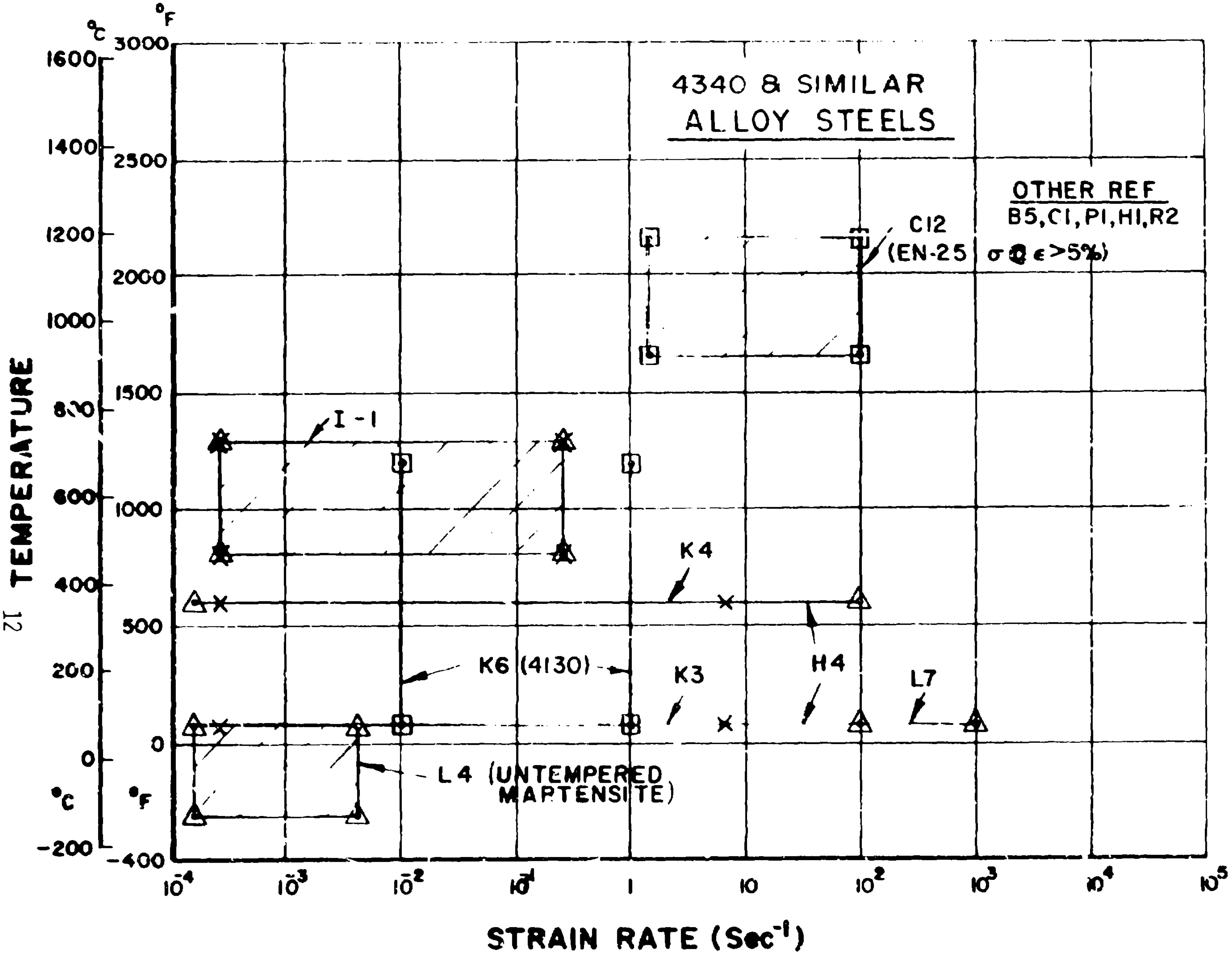
6

Low Alloy Steels (4340 And Similar)

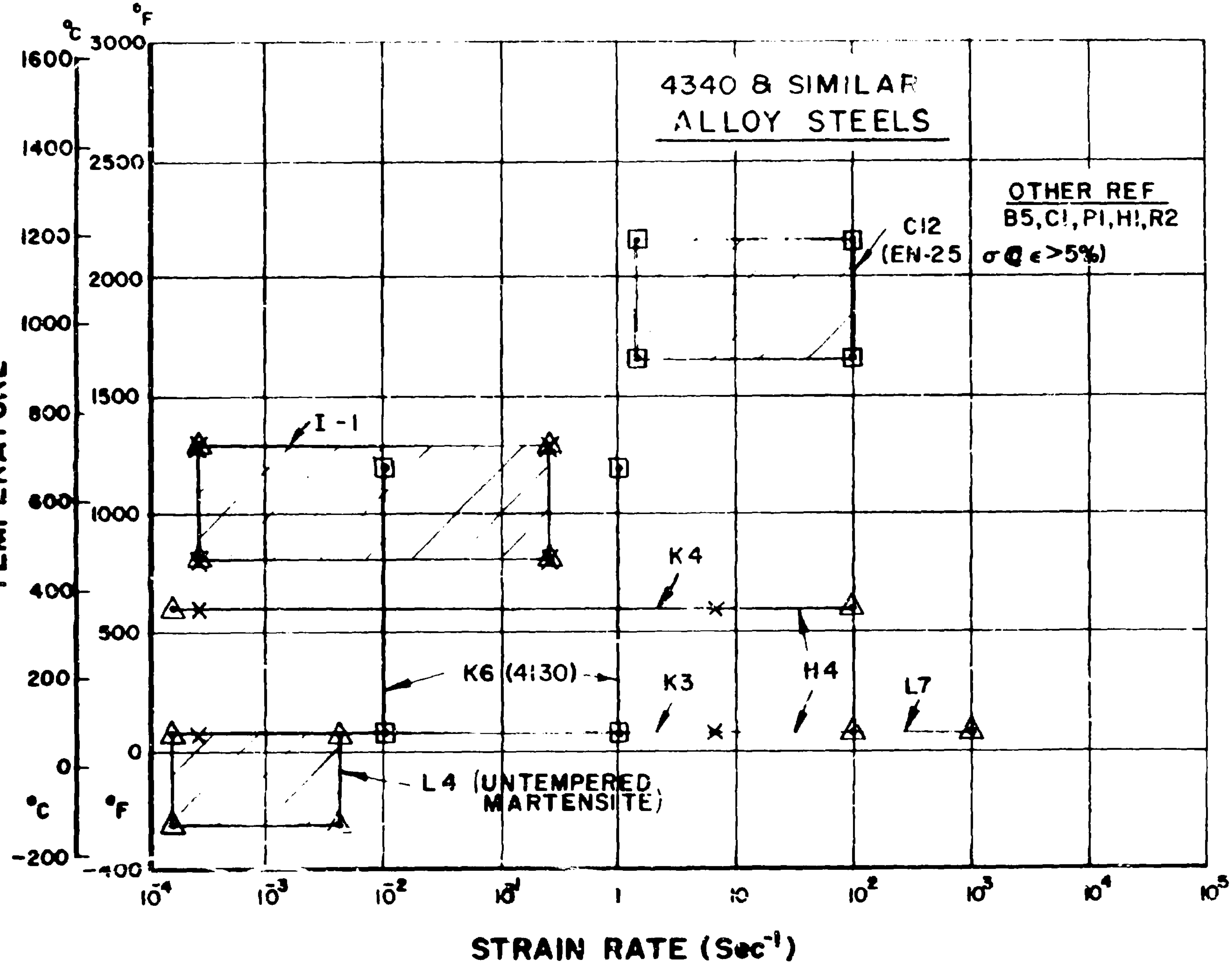
This class of materials generally shows very little strain rate sensitivity both at room temperature and at elevated temperatures in their range of usable operating temperature. However, they do exhibit a region of rate sensitivity at strain rates exceeding some transition rate which ranges from 1.0 to 100 sec^{-1} depending on alloy content, heat treatment and grain size. Fine grained martensitic material shows the highest value of this transition strain rate. Course grained martensite and bainite have progressively lower transition rates. The effect of elevated temperature is to shift this transition rate to higher values, as with mild steels.

At temperatures in the hot working range (900 to 1200C) the flow stress at strain values ranging from 5 to 70% increases significantly with strain rate. These increases range from 50 to 100% for a strain rate of 100 sec^{-1} over that for 1.5 sec^{-1}.

At static strain rates, most alloy steels exhibit a sharp "knee" in the yield strength-temperature curve with the strength decreasing very rapidly with temperatures above this point. The temperature associated with this "knee" ranges from about 800 to 1200 F depending on alloy content. At a temperature just below this "knee" an inverse strain rate sensitivity has been found for several alloys. This can result in a decrease in strength of as much as 20% at a strain rate of about 10 sec^{-1}. This can be attributed to strain aging effects or to a general class of metallurgical phenomena referred to as structural deformational instability. This will be further discussed under aluminum alloys.

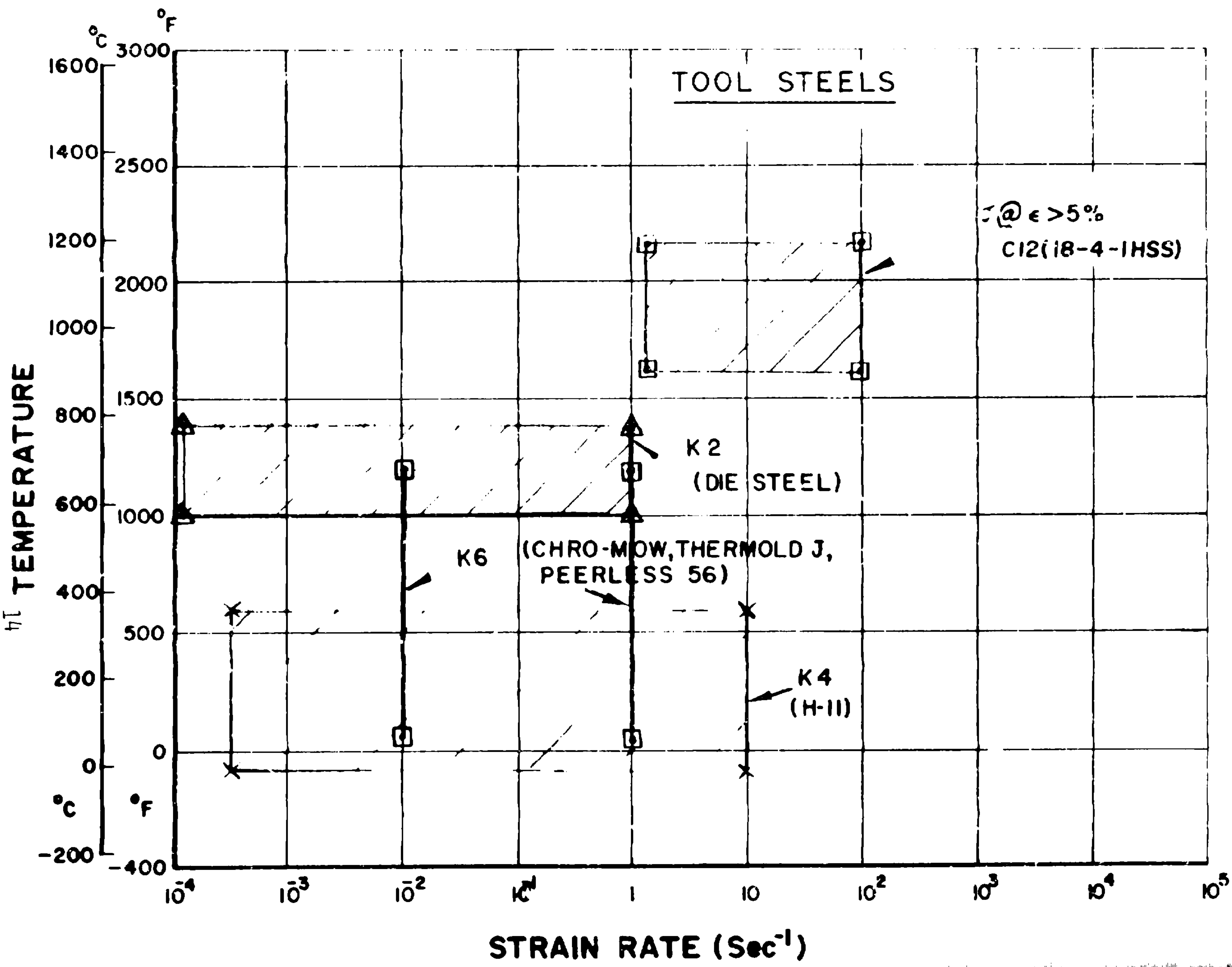


4340 & SIMILAR ALLOY STEELS
OTHER REF
B5, C1, P1, H1, R2
C12
(EN-25
σ @ ε >5%)
I-1
K4
K6 (4130)
K3
H4
L7
L4 (UNTEMPERED MARTENSITE)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}


4340 & SIMILAR ALLOY STEELS
OTHER REF
B5, C1, P1, H1, R2
C12
(EN-25 σ @ ε > 5%)
I-1
K4
K6 (4130)
K3
H4
L7
L4 (UNTEMPERED MARTENSITE)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵

Tool Steels

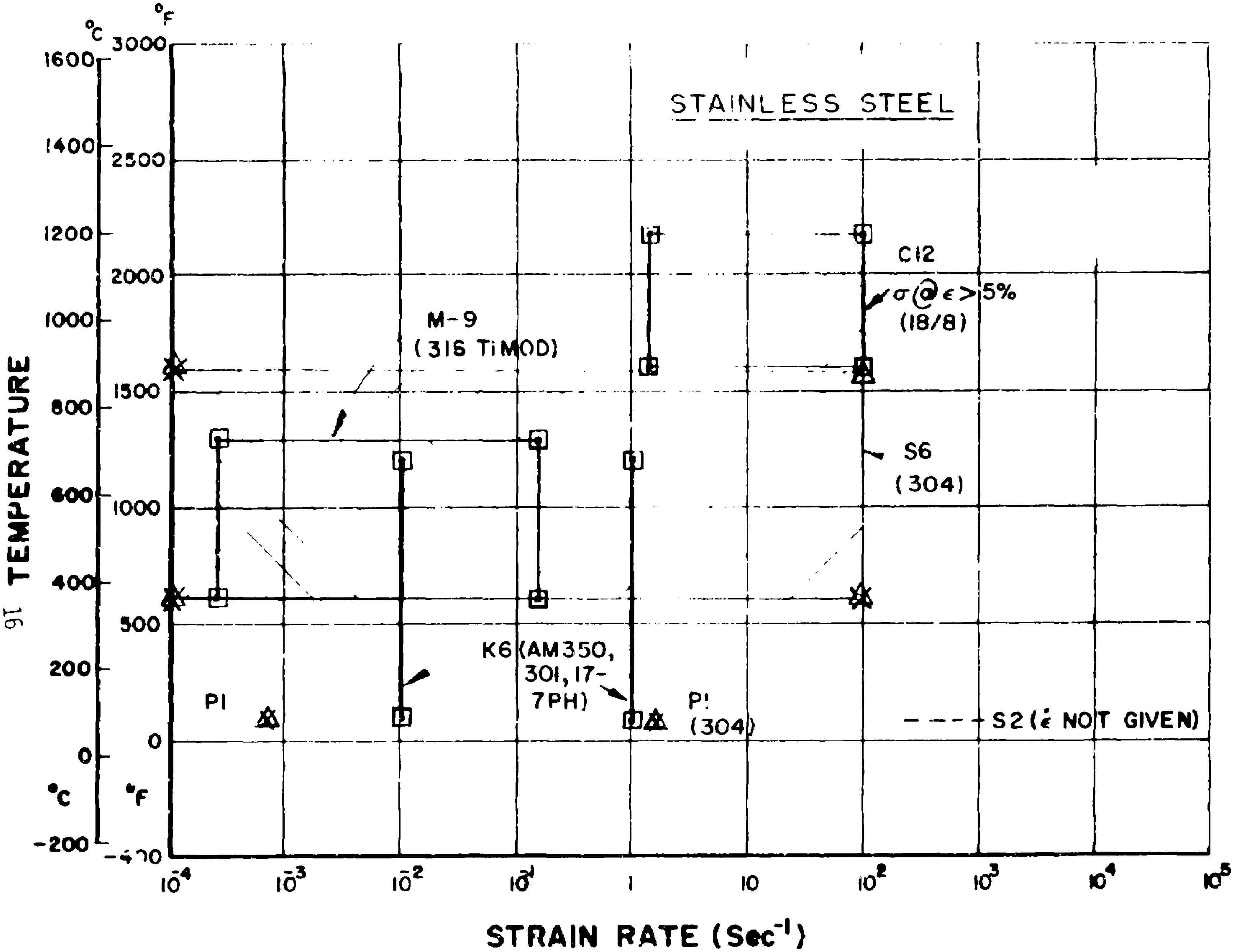
The strain rate sensitivity of the tool steels for which information is available is similar to that of the low alloy steels. At room temperature they are rate insensitive up to some transition strain rate above which they may show some rate sensitivity. Increasing temperature increases the transition rate for temperatures up to about 1000F. Above this an increasing rate sensitivity is found over the entire range of strain rates of interest. In the hot working temperature range the results are essentially the same as for alloy steels except that the stress levels are higher.



TOOL STEELS
@ ε > 5%
C12 (18-4-1HSS)
K2
(DIE STEEL)
K6
(CHRO-MOW, THERMOLD J,
PEERLESS 56)
K4
(H-11)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)

Stainless Steels

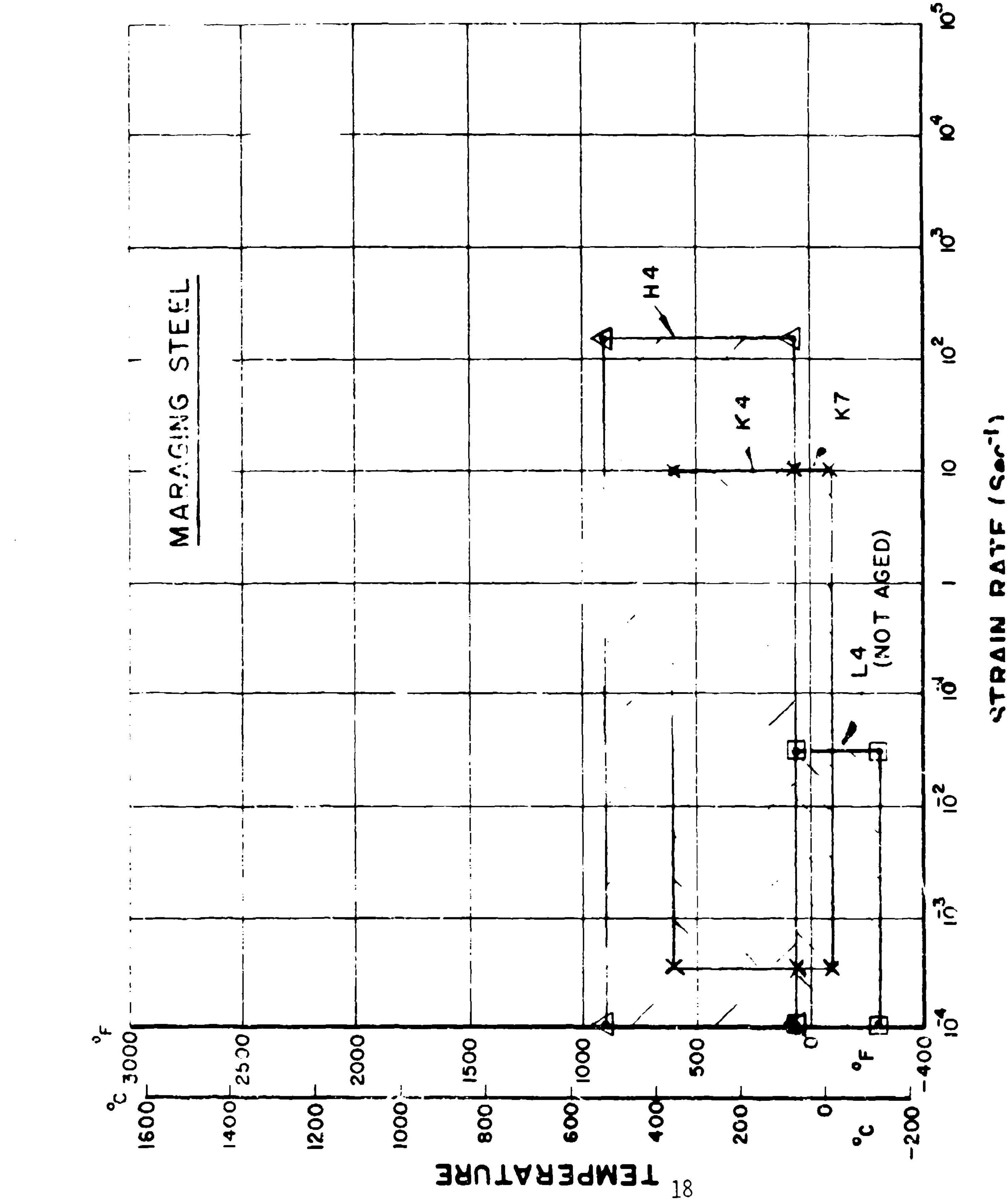
The stainless steels that have been studied are generally rate insensitive at room temperature for all strain rates reported. At temperatures up to about 1000F they remain rate insensitive or possibly show a slight negative rate sensitivity in the 400 to 600 F range. At temperatures above 1000 F the static strength decreases rapidly and the material becomes increasingly rate sensitive.


STAINLESS STEEL
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-4?0
STRAIN RATE (Sec^-1)
10^-4
10^-3
10^-2
10^-1
1
10
10^2
10^3
10^4
10^5
M-9
(316 Ti MOD)
C12
σ @ ε > 5%
(18/8)
S6
(304)
K6 (AM350,
301, 17-
7PH)
P1
P1
(304)
S2 (ε̇ NOT GIVEN)

Maraging Steels

There is a limited amount of data available on maraging steels. Room temperature results show a linear increase in yield strength with logarithmic strain rate in the range of strain rates from 10^{-4} to 10 sec^{-1}. The 18% Ni-300 grade material shows a 10% increase in strength over this range and the 250 grade shows a 5% increase. The difference between yield and tensile strength is essentially constant or may decrease slightly at higher rates. At low temperatures the strain rate sensitivity is about the same as at room temperature.

At elevated temperatures there is a disagreement between the two available references. Ref. H4 shows the same rate sensitivity at temperatures up to 900 F as at room temperature. Ref. K4 shows a decreasing rate sensitivity with increasing temperature and an inverse sensitivity at 600 F. This results in a decrease in yield strength of about 5% for an increase in strain rate from 10^{-4} to 5.0 sec^{-1}. This difference may be due to slight differences in the aging treatment or in heating rate and time at temperature.


MARAGING STEEL
H4
K4
K7
L4 (NOT AGED)
STRAIN RATE (Sec-1)
TEMPERATURE
°F
°C
3000
2500
2000
1500
1000
500
0
-400
1600
1400
1200
1000
800
600
400
200
0
-200
10-4
10-3
10-2
10-1
1
10
102
103
104
105

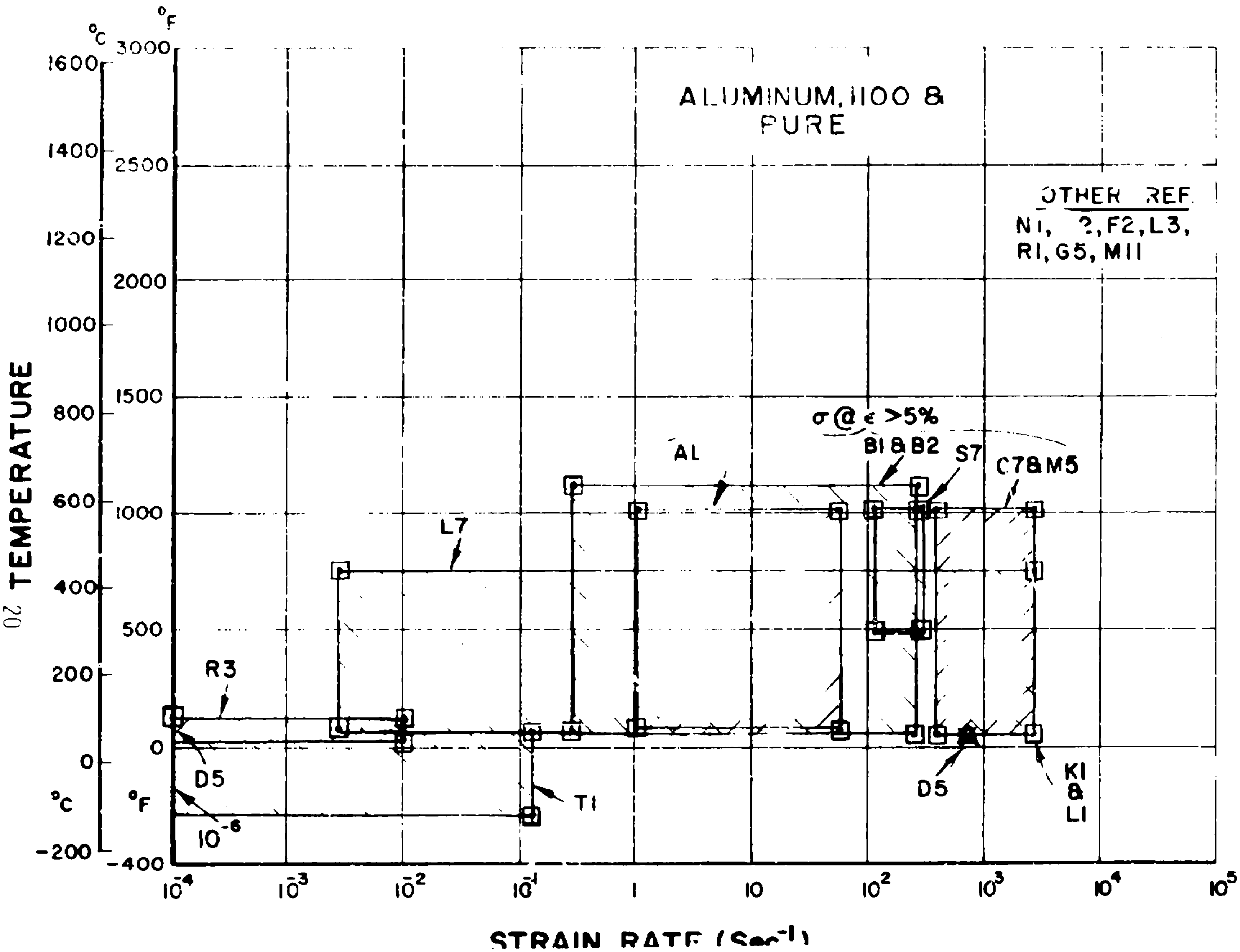
ALUMINUM BASED MATERIALS

Pure Aluminum Including 1100 Grade

Data on pure aluminum from 12 references were examined and general agreement of all of the references was found. At room temperature an approximately linear increase in flow stress with logarithmic strain rate was reported although some investigators reported an increase in the slope of the stress-strain rate curve at strain rates exceeding 100 sec^{-1}. The increase in flow stress with an increase in strain rate from 10^{-3} to 10^{3} sec^{-1} is generally about 15 to 20%. The strain rate sensitivity appears to be only slightly affected by plastic strain and by impurity content.

The effect of increasing temperature is a slight increase in the slope of the flow stress-log strain rate curve. Since the static strength decreases rapidly with temperature this results in a significant increase in relative rate sensitivity. At 750 F the flow stress increases by a factor of 3 with a strain rate increase from 10^{-3} to 10^{3} sec^{-1}.

The effect of strain rate changes are considered in references F2 and N2.

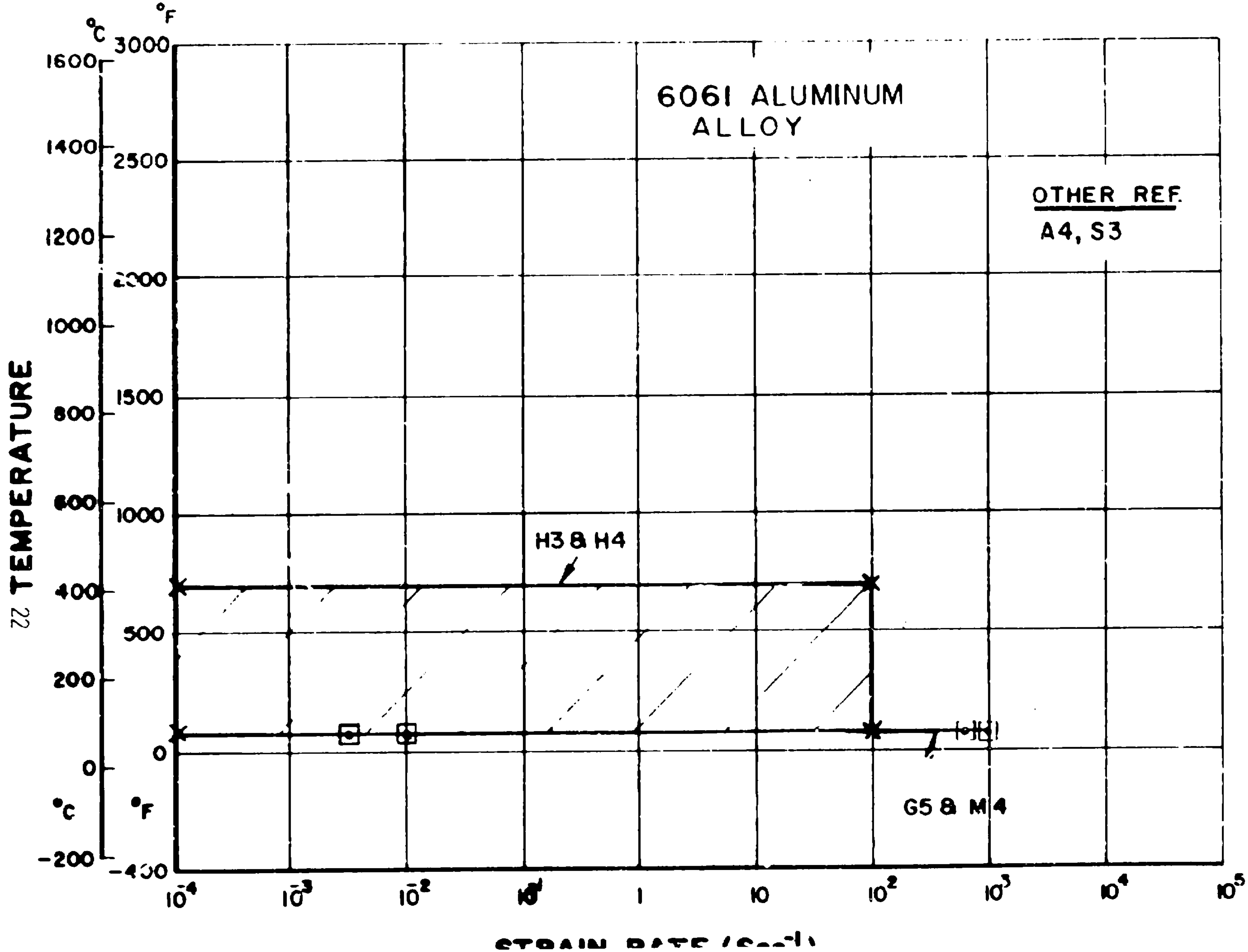


ALUMINUM, 1100 &
PURE
OTHER REF.
N1, ?, F2, L3,
R1, G5, M11
σ @ ε >5%
AL
B1 & B2
S7
C7 & M5
L7
R3
D5
T1
10⁻⁶
K1
&
L1
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
TEMPERATURE
STRAIN RATE (Sec⁻¹)

6061 Aluminum Alloy

All available data on this material is for the T6 or fully aged condition. For strain rates less than 10 sec^{-1} at room temperature this material is almost completely rate insensitive. At higher strain rates some investigators (A3 and H4) have reported a rate sensitive region with a 20% increase in strength between 10 and 10^3 sec^{-1}. Other investigators (M4 and G5) have found no rate sensitivity up to a strain rate of 10^3 sec^{-1}.

The only data on this material at elevated temperatures is in reference H3 (same data as H4). This gives a significant positive rate sensitivity at 500 and 700 F and at strain rates from 1 to 10^2 sec^{-1}. At 700 F the tensile strength increases from 10 to 35 ksi over this strain rate range.

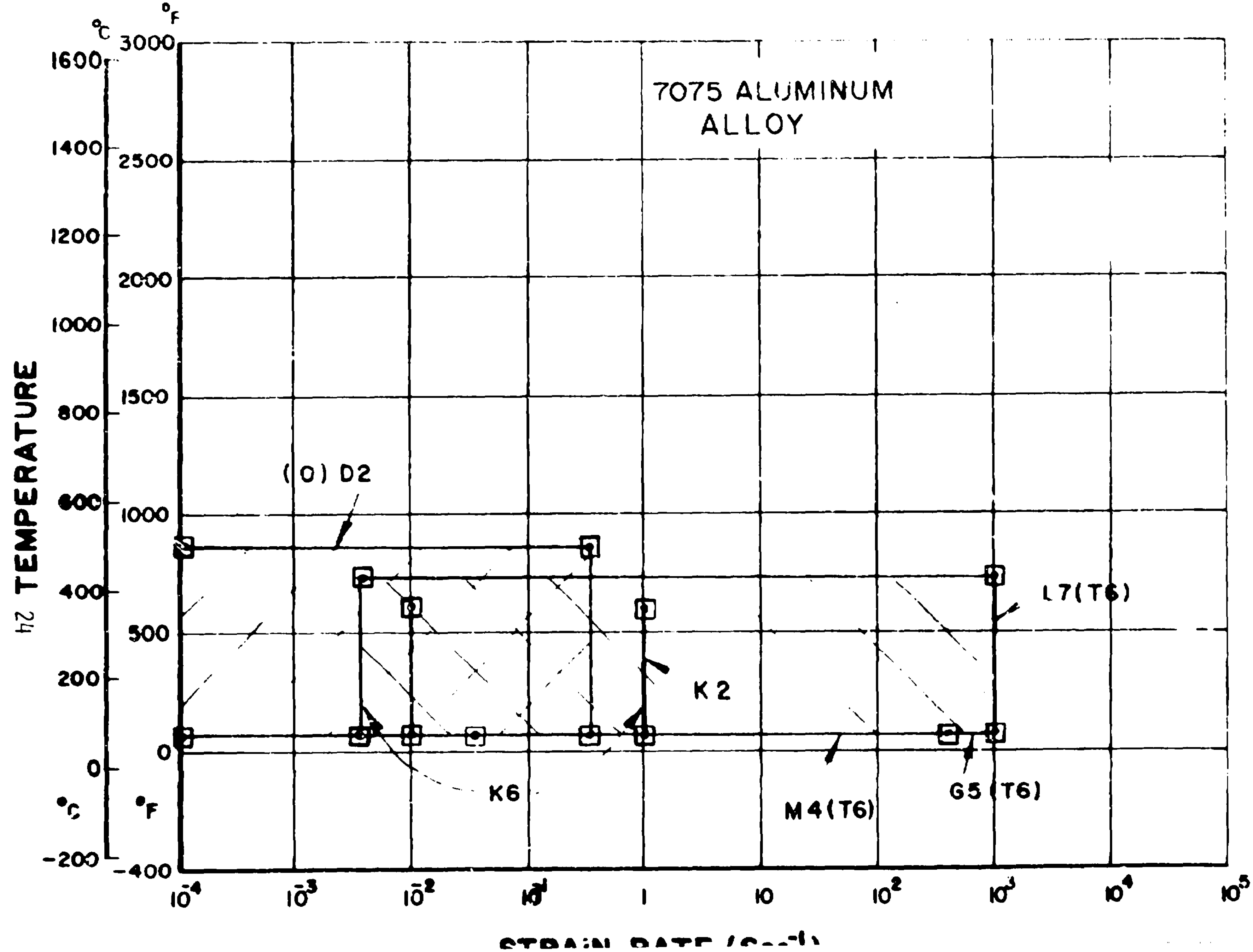


6061 ALUMINUM
ALLOY
OTHER REF.
A4, S3
H3 & H4
G5 & M4
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}

7075 Aluminum Alloy

The results available for the T6 condition are essentially the same as for 6061-T6 as discussed above, except that the stress values are somewhat higher.

In the annealed or "0" condition (not solution annealed) this alloy shows rate insensitive behavior below 10^{-2} sec^{-1} at room temperature and increasing positive sensitivity at higher temperatures. At all temperatures an increase in rate sensitivity is found at strain rates above 10^{-2} sec^{-1}.

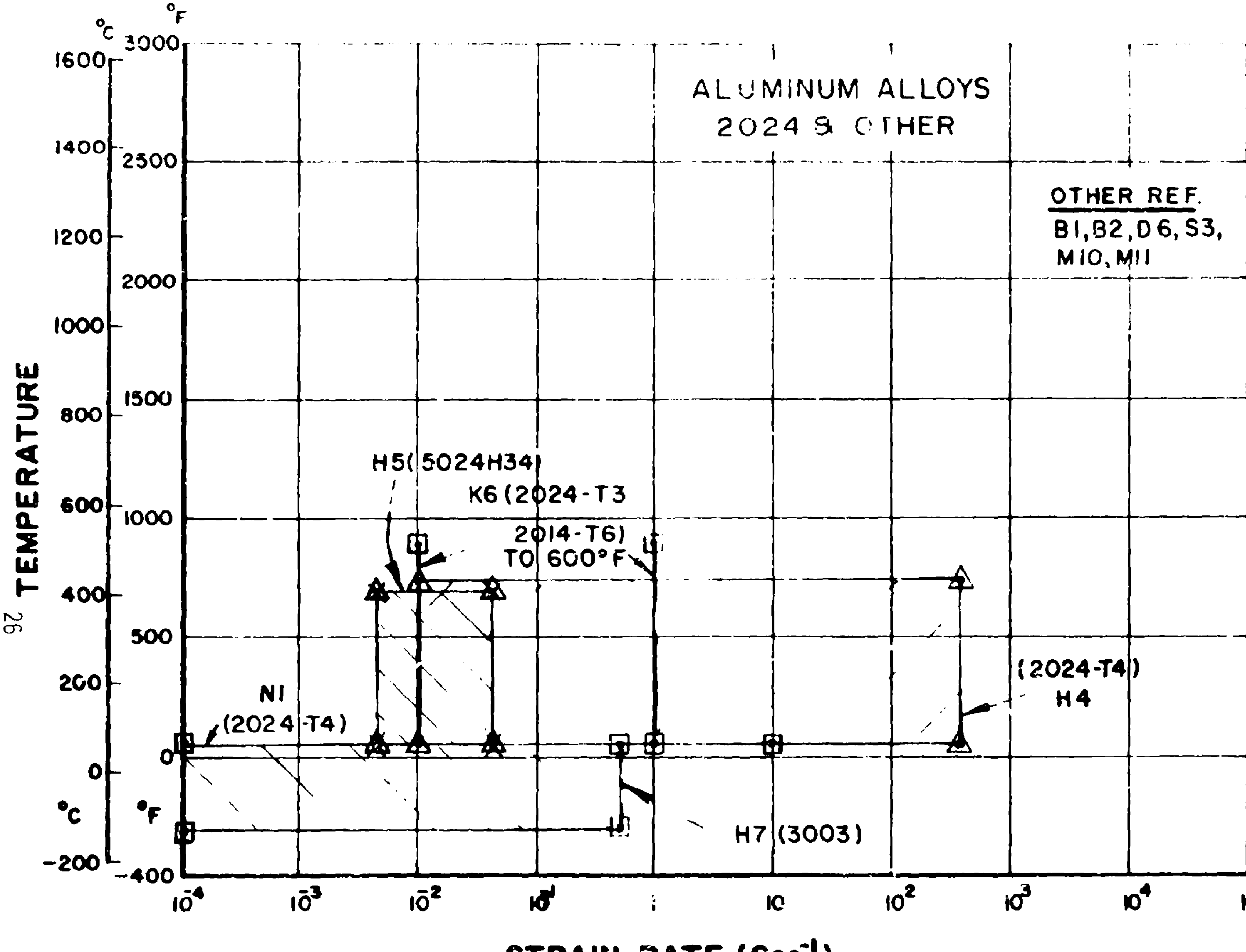

7075 ALUMINUM ALLOY
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
(O) D2
L7(T6)
K2
K6
M4(T6)
G5 (T6)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}

24

Other Aluminum Alloys

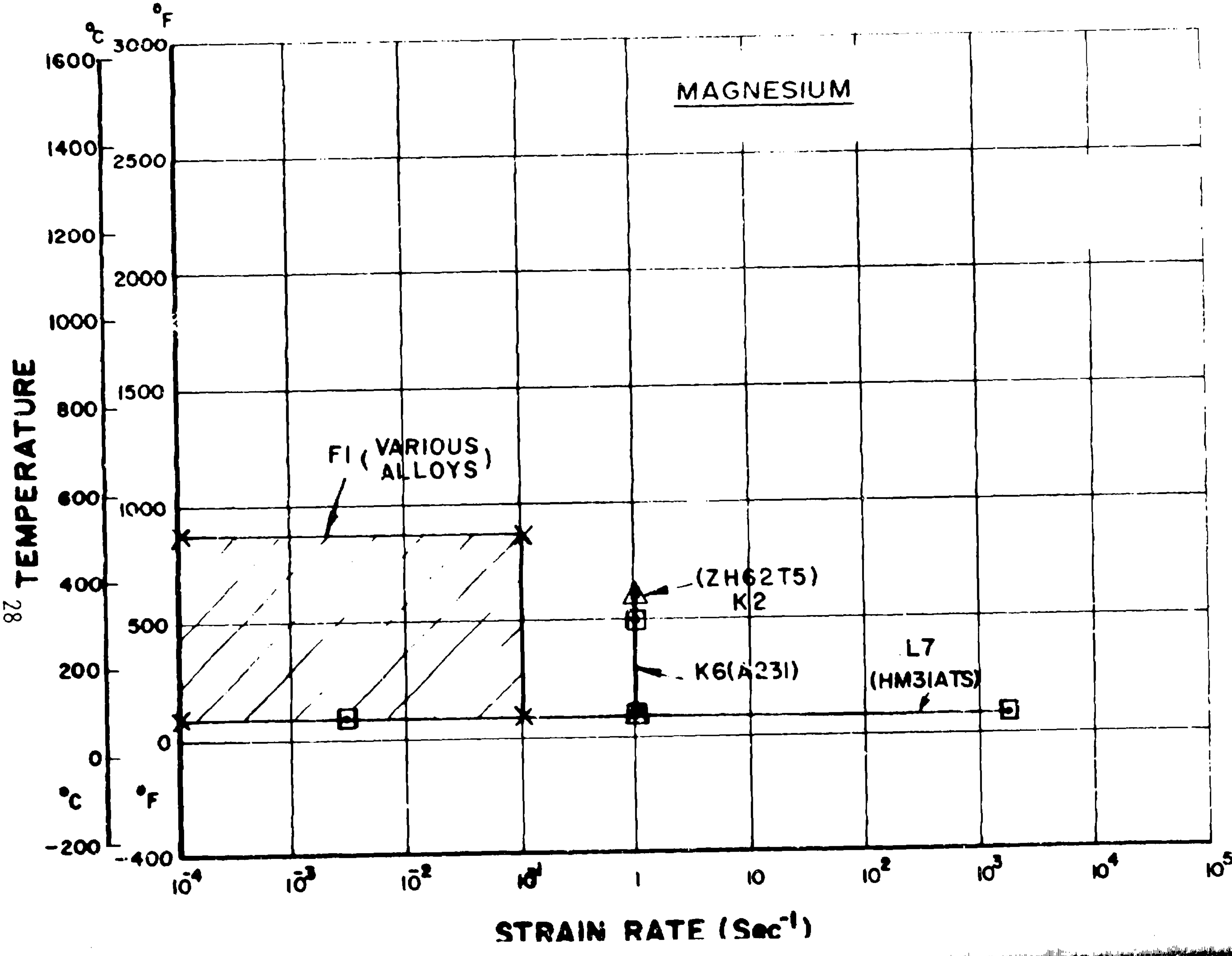
Available data on 2024-T4, 2024-T3, 2014-T6 and 5024-H34 all show similar results to those for 6061-T6. These alloys are all essentially rate insensitive at temperatures below 300 F and strain rates below 10^2 sec^{-1}. At higher temperatures some positive rate sensitivity is found. Since these temperatures are generally above the aging temperatures for these alloys, overaging reactions are taking place at these test temperatures. Therefore, the properties will depend on time at temperature as well as strain rate and temperature.

A 3003 alloy in the solution annealed condition has been shown to exhibit three regions of rate sensitivity at room temperature (H-7). It is rate insensitive up to a strain rate of $2x10^{-2}$ sec^{-1} and then has a positive rate sensitivity up to about 10^{-1} sec^{-1}. Above this rate a negative rate sensitivity was found. A negative rate sensitivity was also found in a 2024 alloy in the solution annealed condition at room temperature and strain rates ranging from 10^{-2} to 0.3 sec^{-1}. This is attributed to a type of dynamic strain aging or structural deformational instability. During low strain rate deformation, the strain in the material triggers changes in the solute configurations which result in increased resistance to dislocation motion. At high strain rates there is not sufficient time for these solute configurational changes to occur resulting in less resistance to dislocation motion and thus lower strength.


ALUMINUM ALLOYS
2024 & OTHER
OTHER REF.
B1, B2, D6, S3,
M10, M11
TEMPERATURE
°C
°F
H5 (5024H34)
K6 (2024-T3
2014-T6)
TO 600°F
N1
(2024-T4)
(2024-T4)
H4
H7 (3003)

MAGNESIUM ALLOYS

Reference F1 gives results for 18 different magnesium base alloys at strain rates up to 0.08 sec^{-1} and temperatures to 900 F. Most of the alloys showed very little rate sensitivity at room temperature except for AZ80Z-T5, ZK60A-T5 and M1AF which showed a 20 percent increase in strength over the range of strain rates used. At elevated temperatures a general increase in rate sensitivity was reported for all alloys with generally linear increases in strength with logarithmic strain rate. The other available references on magnesium alloys give similar results with only a slight increase, if any, in the rate sensitivity at higher strain rates up to 10^3 sec^{-1}. Reference L7 reports an interesting difference between the results for tension and compression loading.


MAGNESIUM
TEMPERATURE
°C
1600
1400
1200
1000
800
600
400
200
0
-200
°F
3000
2500
2000
1500
1000
500
0
-400
F1 (VARIOUS ALLOYS)
(ZH62T5) K2
K6(A231)
L7 (HM31ATS)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
STRAIN RATE (Sec^{-1})

TITANIUM ALLOYS

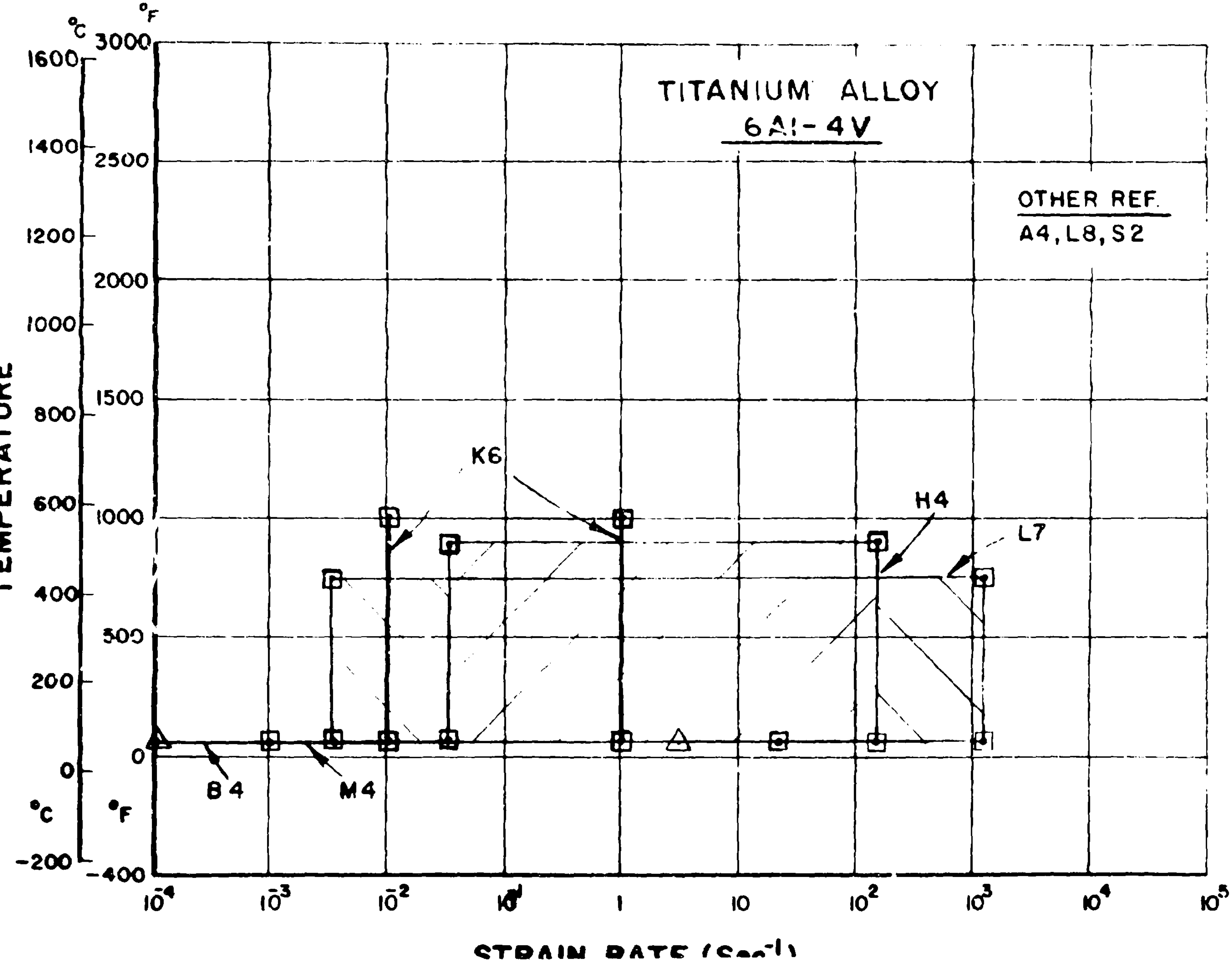
Titanium-6Al, 4V Alloy

There are four major references for this material. They all show this material to be moderately rate sensitive but there is some disagreement as to the shape of the flow stress-strain rate curve. Two references show almost no rate sensitivity at strain rates below 10 sec^{-1} while the other two show about a 10 percent increase between 10^{-3} and 10 sec^{-1}. All references show an increase in rate sensitivity above 10 sec^{-1} with a 10 percent increase in strength between 10 and 10^3 sec^{-1}.

The results at elevated temperatures up to 1000 F are approximately parallel to those at room temperature.

This material is usable in either the solution annealed condition or in an artificially aged condition. The strain rate sensitivity is essentially the same in both conditions.

Other factors considered are notched strength (B4) and biaxial stress (L8).

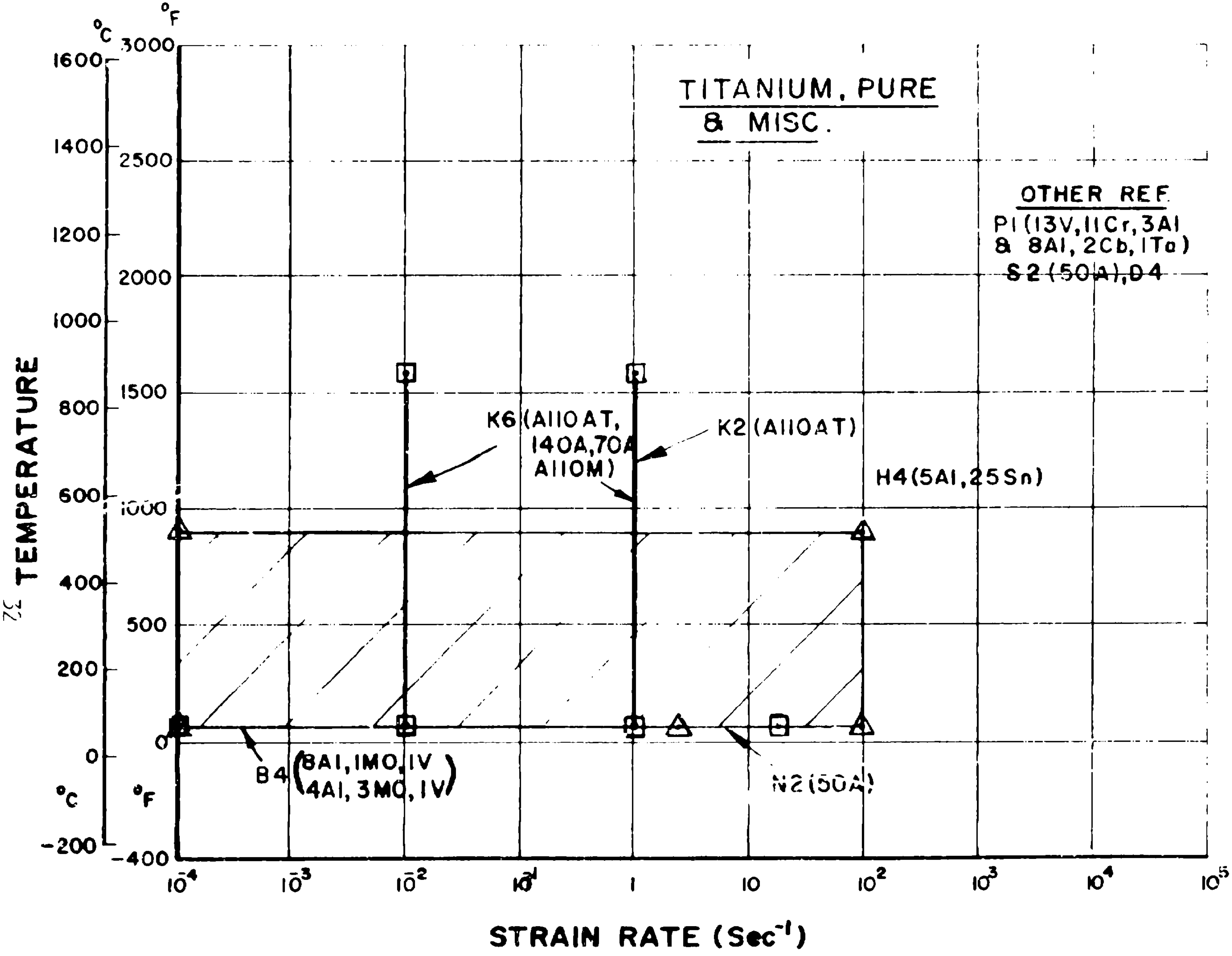

TITANIUM ALLOY
6Al-4V
OTHER REF.
A4, L8, S2
K6
H4
L7
B4
M4
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)

Other Titanium Alloys

Results for several commercially pure titanium alloys such as 50 A, 55A and 70A are available and all show about the same or slightly higher rate sensitivity than that for the 6Al-4V alloy. At elevated temperatures the rate sensitivity is somewhat greater than at room temperature particularly in the 400 to 600 F range.

Other high strength alloys studied are 5 Al-2.5 Sn, 8Al-1Mo-1V, 4Al-3Mo-1V, 5.7Al-2.7Sn(A-110-AT), 1.8Fe-1.8Cr-1.5Mo(140A), 13V-11Cr-3Al, and 8Al,2Cb,Ta. All of these show rate sensitivities very similar to the 6Al-4V alloy.

It appears that titanium alloys are unique in that the strain rate sensitivity does not decrease significantly as the strength is increased by either alloying or heat treatment. This is contrary to the behavior of virtually all other common structural metals.



TITANIUM, PURE
& MISC.
OTHER REF.
P1 (13V, 11Cr, 3Al
& 8Al, 2Cb, 1Ta)
S2 (50A), D4
K6 (A110AT,
140A, 70A
A110M)
K2 (A110AT)
H4 (5Al, 25Sn)
B4 (8Al, 1Mo, 1V
4Al, 3Mo, 1V)
N2 (50A)
TEMPERATURE
°C
°F
STRAIN RATE (Sec⁻¹)

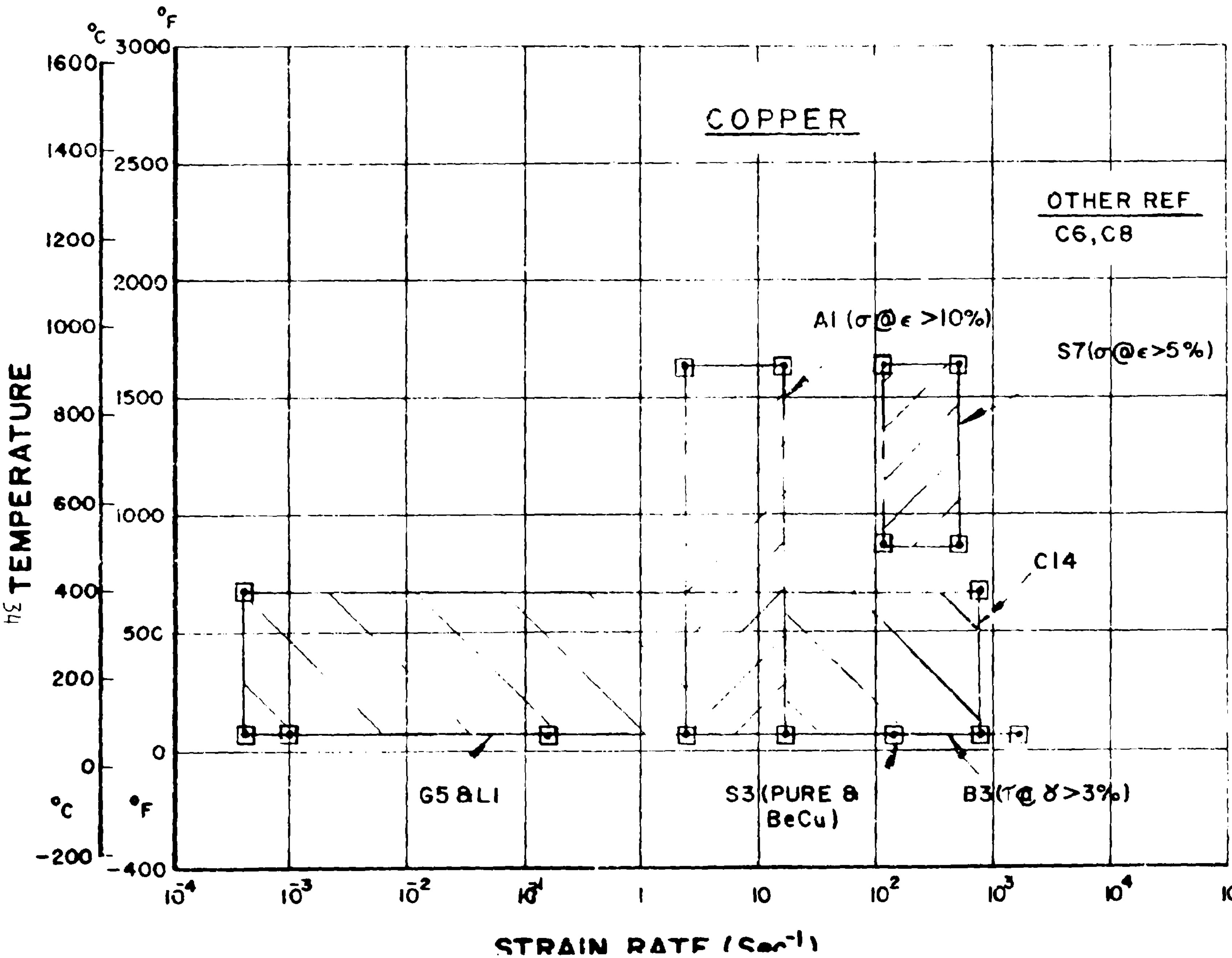
Copper

With the exception of one data point, all of the available data on copper alloys is for high purity or commercially pure copper. No data on brasses or bronzes have been located.

In the fully annealed condition, the yield stress and flow stress of copper at low strain values are only slightly rate sensitive. The strength increases 10 to 20 percent over the range of strain rates from 10^{-3} to 10^{3} sec^{-1}. The rate sensitivity increases with increasing strain values. The rate sensitivity also increases with prior cold working. For copper that has been cold worked to a yield strength of about 40,000 psi, strength increases ranging from 30 to 60 percent have been reported over the range of strain rates from 10^{-3} to 10^{3} sec^{-1}. The flow stress is generally a linear function of logarithmic strain rate over this range.

At elevated temperatures the flow stress-strain rate curves are parallel to the room temperature curves but at lower stress levels.

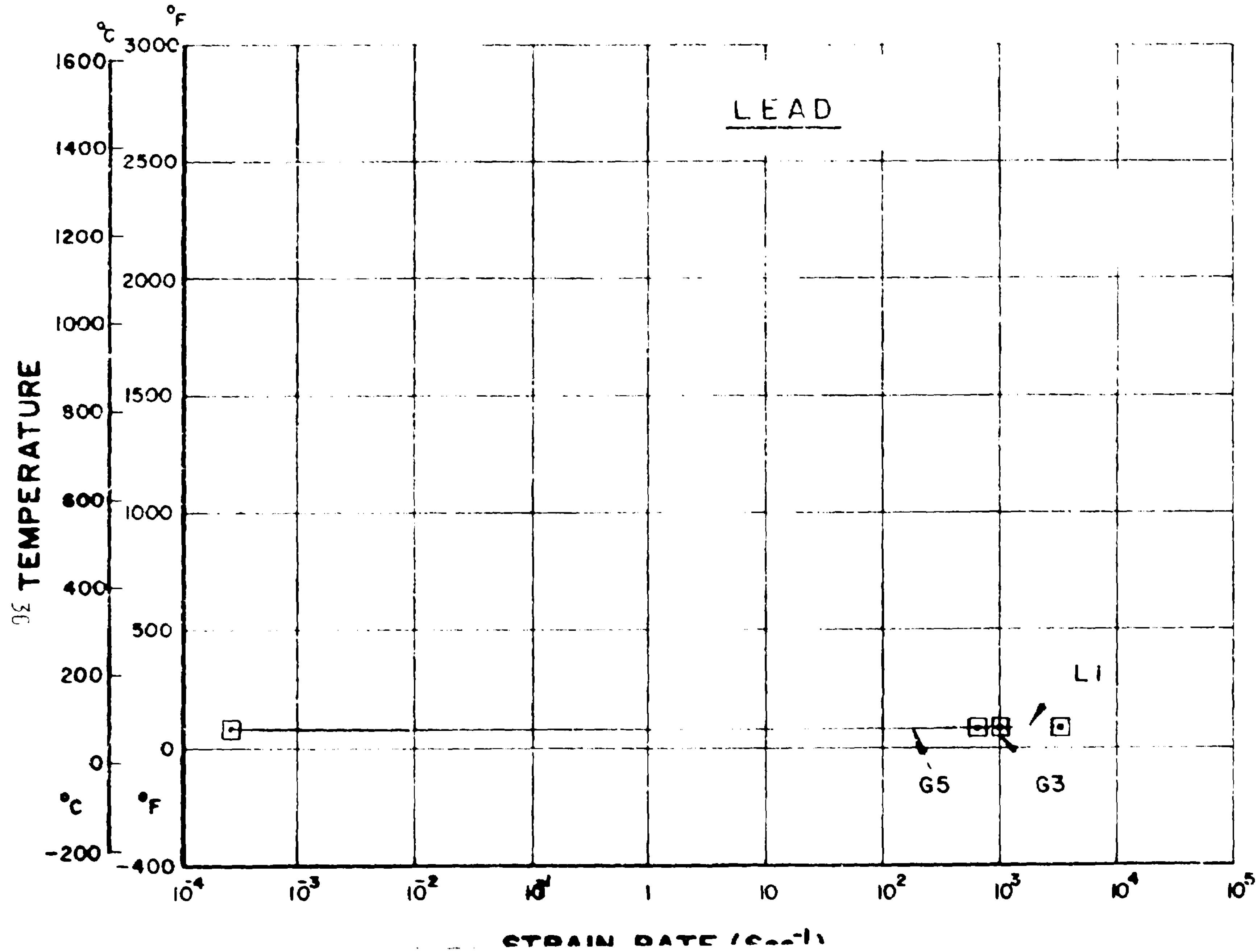
The only other copper alloy studied is beryllium copper (S3) which showed no significant rate sensitivity at 10^{2} sec^{-1} and at room temperatures.


COPPER
OTHER REF
C6, C8
A1 (σ @ ε >10%)
S7 (σ @ ε >5%)
C14
G5 & L1
S3 (PURE & BeCu)
B3 (τ @ γ >3%)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵

Lead

The flow stress of lead is fairly rate sensitive at room temperature. At small strain values (2 to 3 percent) the flow stress increases by 40 to 60 percent over the range of strain rates from 10^{-3} to 10^{3} sec^{-1}. At higher strain values the rate sensitivity increases with an increase in flow stress of up to 75 percent reported for the same strain rate range, at 30 percent strain. The flow stress is a linear function of logarithmic strain rate over this range.

No results for temperatures other than room temperature were found.

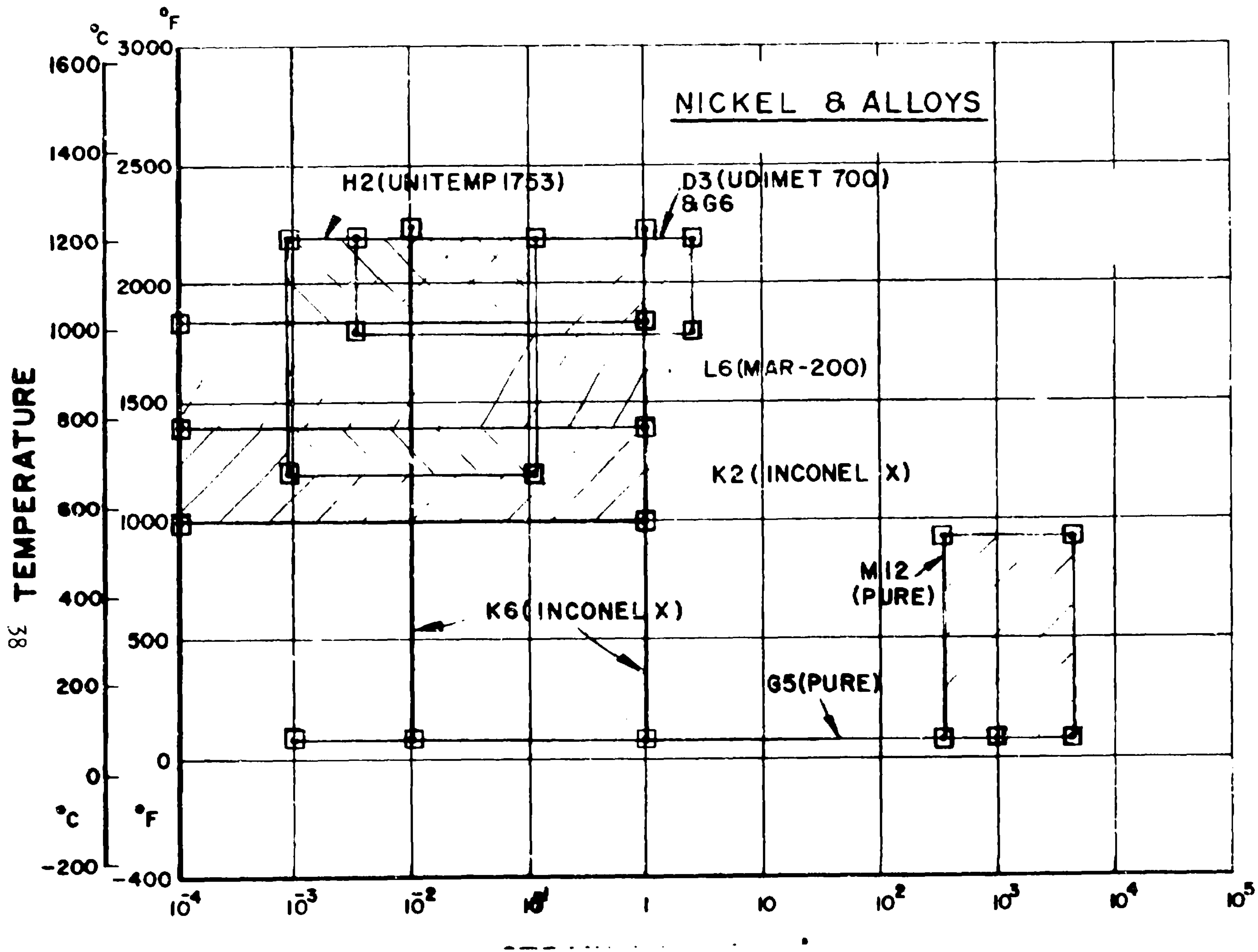


LEAD
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
L1
G5
G3

NICKEL AND NICKEL BASE ALLOYS

Only two references report results for pure nickel. In the annealed condition it is moderately rate sensitive with about a 20 percent increase in strength over the strain rate range from 10^{-3} to 10^{3} sec^{-1} for all strain values. In the cold worked condition it is slightly more rate sensitive. At temperatures up to 500 C the flow stress-strain rate curves are essentially parallel to the room temperature.

Results are available for four nickel base "superalloys". These are Udimet 700, Unitemp 1753, Mar-M200 (single crystals) and Inconel -X. The curve of strength versus temperature at strain rates in the order of 10^{-3} sec^{-1} for all of these materials has a characteristic shape. The strength is essentially constant from room temperature to some temperature in the range of 1200 to 1400F. In this region they are essentially rate insensitive or have a slight negative rate sensitivity near the upper end of this range. Above this temperature the strength drops rapidly until it reaches about 10 ksi at a temperature of about 2000 to 2200 F. In the middle of this decreasing strength range the strength is highly rate sensitive with increases of 30 to 40 ksi reported over the range of strain rates from 10^{-3} to 1.0 sec^{-1}. At the higher temperatures, the absolute rate sensitivity decreases but due to the very low static strength the relative rate sensitivity is about the same.


NICKEL & ALLOYS
H2(UNITEMP 1753)
D3(UDIMET 700)
& G6
L6(MAR-200)
K2(INCONEL X)
K6(INCONEL X)
M12
(PURE)
G5(PURE)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
10^{-4}
10^{-3}
10^{-2}
1
10
10^{2}
10^{3}
10^{4}
10^{5}

REFRACTORY METALS

Molybdenum

Three references give stress versus strain rate results for pure molybdenum. These are all in good agreement and show generally linear increases in strength with logarithmic strain rate over the range of 10^{-4} to 10^{2} sec^{-1}. The yield strength increases by about 100% over this range and the flow stress at various strains shows the same absolute increase. At temperatures above and below room temperature (200-600K) the yield stress-strain rate curves are essentially parallel to the room temperature curves. At very high temperatures (2000 to 4000F) only creep-rupture data are available. These show the same general trends as indicated above.

The molybdenum alloys studied include TZC, ZC-1 and ZC-2. These alloys show a peak in the strength-temperature curves at 2000F for the TZC and at 2700 F for the ZC alloys. This is attributed to dynamic strain aging and results in a negative rate sensitivity which, for the TZC alloy, extends from 900 F to 2100 F. At higher and lower temperatures the rate sensitivity is positive.

An important feature of molybdenum alloys is that they exhibit a very sharp ductile to brittle transition as the temperature decreases. At static strain rates, this transition temperature is usually just below room temperature. However, at higher strain rates this temperature may be shifted to a higher value which may be at, or slightly above, room temperature. This offers a very severe design limitation for these materials.

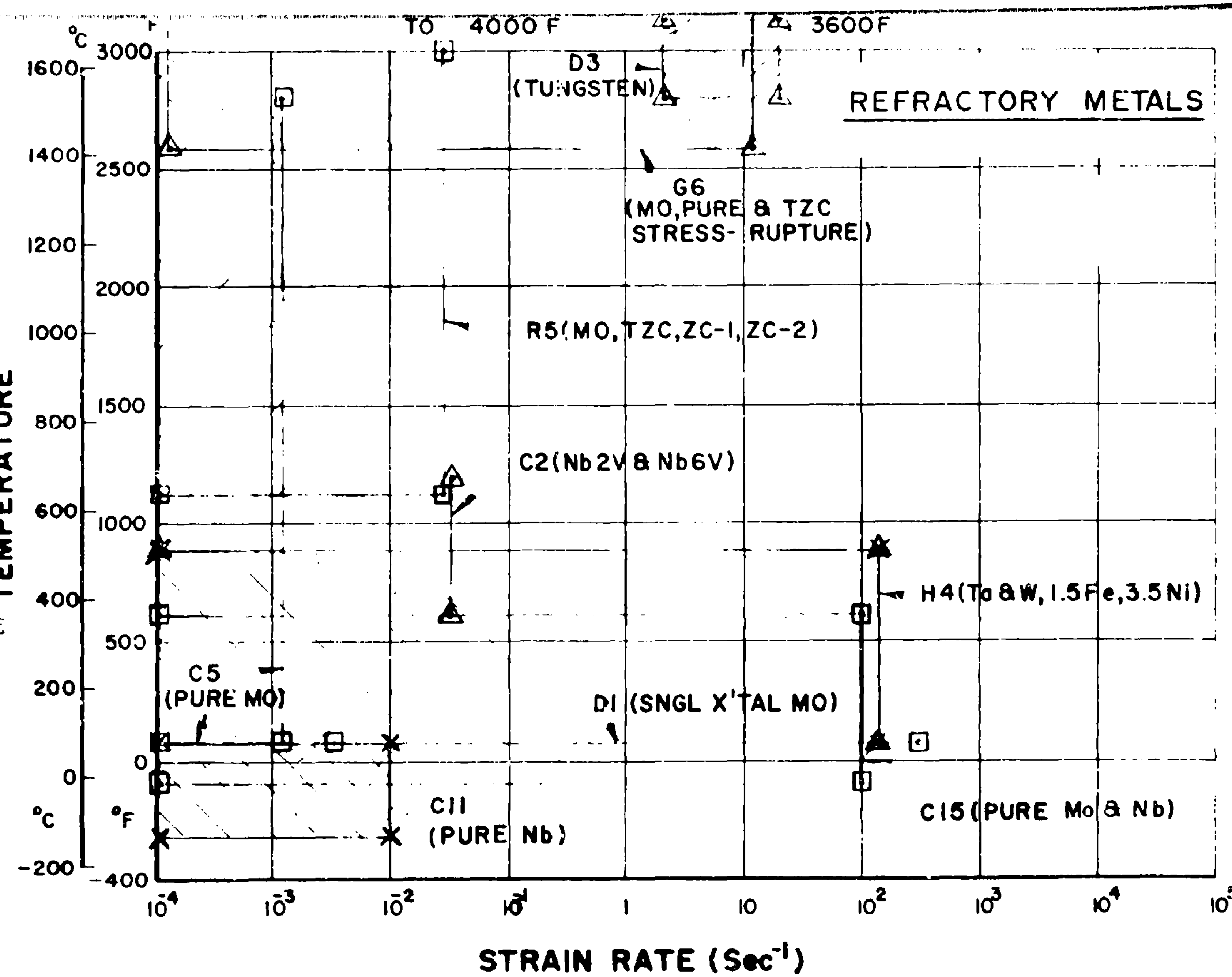
Tungsten and Tantalum

The behavior of these two materials is somewhat similar. Both exhibit a yield point instability phenomenon. The upper yield stress is highly rate sensitive while the peak flow stress is much less rate sensitive. At high strain rates the upper yield stress may be significantly higher than the peak flow stress.

At elevated temperatures to 900 F the behavior is similar to that at room temperature for the two tungsten alloys studied. In pure tantalum a temperature of 500F essentially eliminates the upper yield point and decreases the rate sensitivity.

Niobium (Columbium)

The flow stress and the yield stress of this material at room temperature show a slight rate sensitivity at strain rates below 10^{-2} sec^{-1} and a strong rate sensitivity at higher rates with a 60% increase in strength at 100 sec^{-1}. At lower temperatures the relative rate sensitivity remains about the same as at room temperature. At higher temperatures up to about 500F the rate sensitivity decrease significantly. No data are available for higher temperatures or for niobium based alloys.


REFRACTORY METALS
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
STRAIN RATE (Sec⁻¹)
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵
TO 4000 F
3600F
D3
(TUNGSTEN)
G6
(MO,PURE & TZC
STRESS- RUPTURE)
R5(MO,TZC,ZC-1,ZC-2)
C2(Nb2V & Nb6V)
H4(Ta & W, 1.5Fe,3.5Ni)
C5
(PURE MO)
D1 (SNGL X'TAL MO)
C11
(PURE Nb)
C15(PURE Mo & Nb)

OTHER METALS AND ALLOYS

Uranium

Data are avilable for uranium alloys containing 10% Mo and 8% Mo, 0.5% Ti. Both show similar results at room temperature with an approximately linear increase in strength with logarithmic strain rates. The strength increases by 40 to 50 ksi with an increase in strain rate from 10^{-3} to 10^{3} sec^{-1}. The strength-strain rate curves at temperatures from -65F to 600F are essentially parallel to the room temperature curves.

Thorium

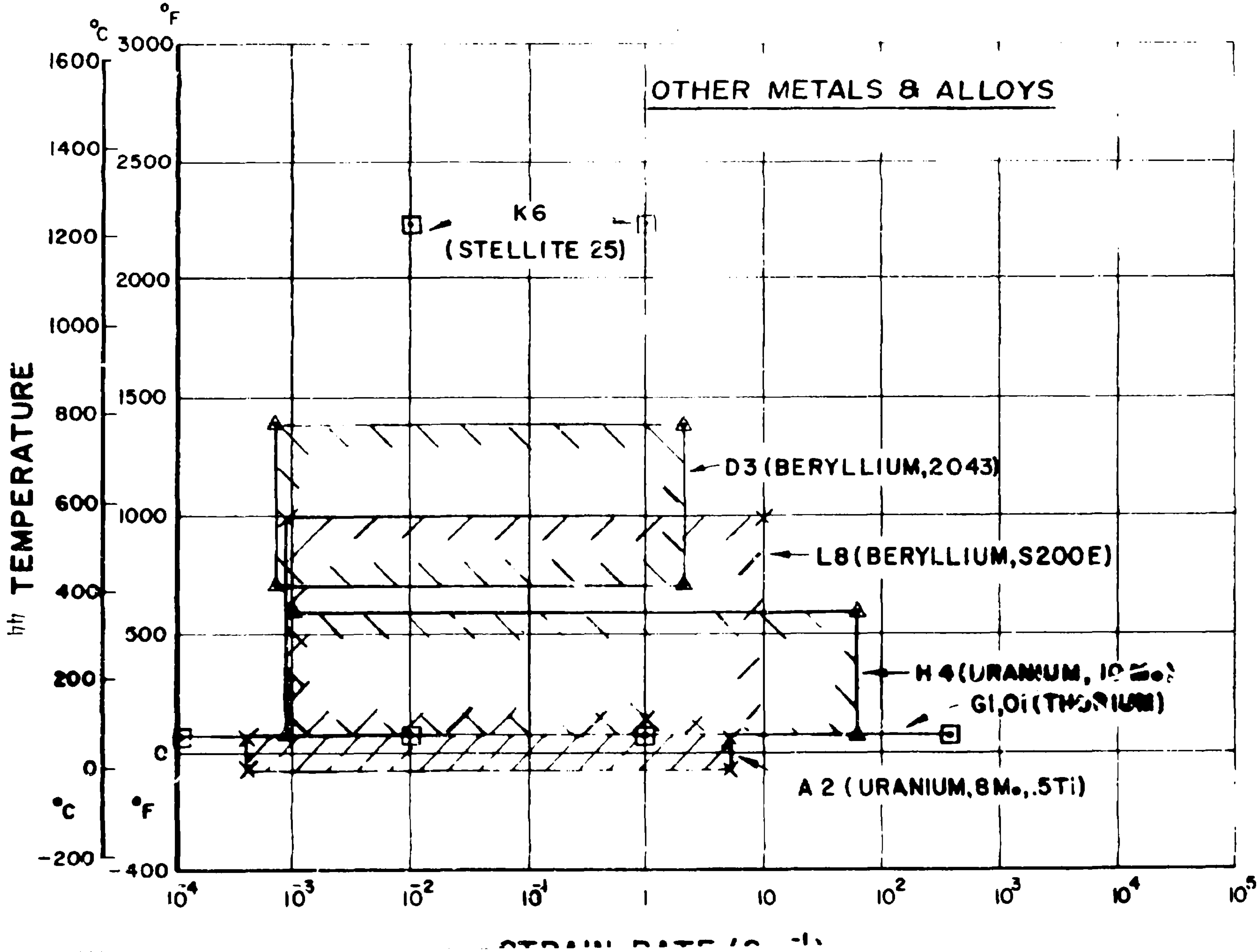
Thorium also shows a linear increase in strength with logarithmic strain rate up to a rate of about 10 sec^{-1}. Above this the rate sensitivity appears to decrease slightly. The flow stress at various values of plastic strain show similar rate sensitivity.

Cobalt Base Alloy (Stellite)

Results are available for annealed Stellite 25 sheet at strain rates of $5x10^{-5}$, 10^{-2} and 1.0 sec^{-1} and at temperatures from room temperature to 2250F. Over this strain rate range the yield strength increases by about 20 ksi at temperatures from room temperature to 400F. At 1200 to 1600F an inverse rate sensitivity is seen and at higher temperatures a significant positive rate sensitivity is found.

Beryllium

Two references give results for hot pressed beryllium. These are designated as 2043 and S-200E materials. Good agreement is found where the data overlaps. Only slight rate sensitivity was found at temperatures up to 1000F. Above this temperature the rate sensitivity increases with a strength increase from 6 ksi to 20 ksi at 1400F for an increase in strain rate from 10^{-3} to 1 sec^{-1}. Extruded S-200E material also showed little rate sensitivity at room temperature but increased sensitivity in the range of temperatures from 600 to 1000F. A strength increase of 30 ksi was obtained for a strain rate increase from 10^{-3} to 10 sec^{-1}.


OTHER METALS & ALLOYS
K6
(STELLITE 25)
D3 (BERYLLIUM,2043)
L8 (BERYLLIUM,S200E)
H 4 (URANIUM,
G1,01 (TH
A 2 (URANIUM,8Mo,.5Ti)
TEMPERATURE
°C
°F
1600
1400
1200
1000
800
600
400
200
0
-200
3000
2500
2000
1500
1000
500
0
-400
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}

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