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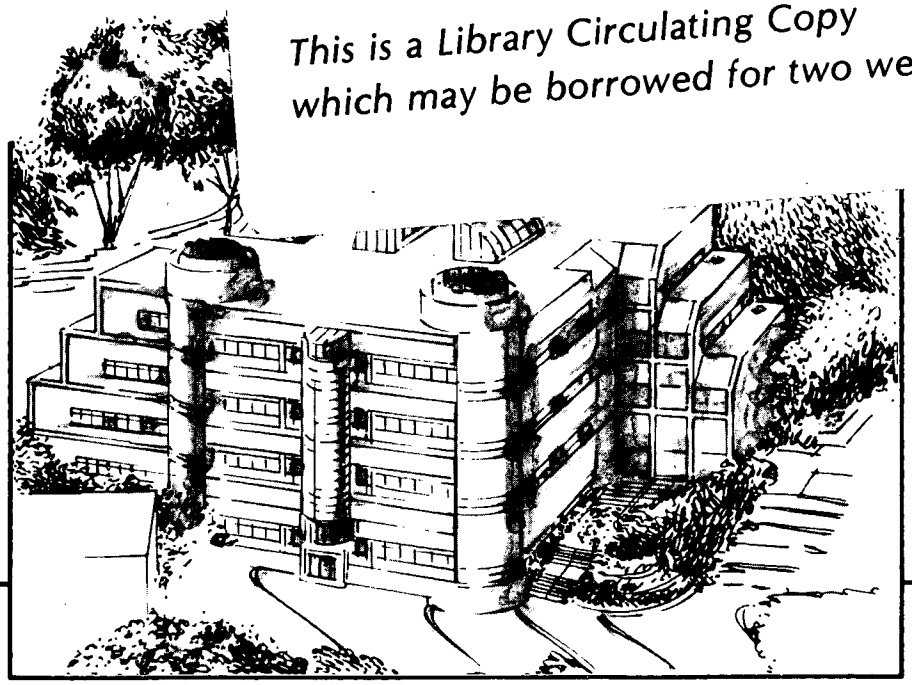

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TENSILE PROPERTIES OF COMMERCIAL ALUMINUM-LITHIUM ALLOYS AT CRYOGENIC TEMPERATURES

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Tensile Properties of Commercial Aluminum-Lithium Alloys at Cryogenic Temperatures

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The mechanical properties of commercially available aluminum alloys at cryogenic temperatures have attracted increasing interest in the past few years because of the large number of potential aerospace applications, primarily in tankage for cryogenic fuels. Aluminum-lithium alloys are of particular interest because of their low density and the extremely good low temperature properties that have been measured to date. This paper compares the behavior of AA 2090-T81 plate and AA 2091-T8 plate, which has not previously been surveyed. The 2090 data include new results at 200 K that indicate that property trends are not monotonic with temperature. The 2091 results show a peak in properties between 77 K and 200 K. These data point to the hazards of doing property screening at 77 K rather than 4 K. They also suggest some avenues for further exploration of the mechanisms that control elongation and fracture toughness.

Introduction

The mechanical properties of commercially available aluminum-lithium alloys at cryogenic temperatures have attracted increasing intersting in the last several years. Because they are light in weight, at least somewhat weldable and have shown cryogenic mechanical properties that are considerably improved over room temperature, they are an appealing choice for cryogenic tankage in a long list of potential space vehicles. Of these, the space shuttle external tank, the advanced launch system and the NASP program are probably the most visible. All of these applications require a structural material with good mechanical properties in the range 100 to 20 K.

The cryogenic properties of 2090 plate in various tempers have been reported by Glazer et al (1986), Dorward (1986), Rao et al (1987) and Glazer et al (1987a). All of these authors find that the mechanical properties are dramatically improved at low temperatures. Glazer et al (1987b) have found that the tensile properties of 2090 sheet processed for superplastic forming behave in the same fashion both before and after superplastic forming.

The properties of 2090-T81 are summarized first. The discussion focusses on properties at T/4. The LT and 200 K properties have not been previously reported. The tensile properties of 2091-T8 are then described. The discussion attempts to compare and

contrast the behavior of the two alloys and to analyze it in the light of existing theories of cryogenic mechanical properties.

Experimental Procedure

The 2090 alloy was studied in several different metallurgical conditions: one-half inch thick plate -T8 (as-received) at T/2 and T/4 and in -T4 condition at T/4 (solution heat treated at 550°C and cold water quenched). Experimental details are given in Glazer, et al. (1987a).

One-and-a-half inch thick (3.8 cm) 2091 plate was received from the Aluminum Company of America in the as-fabricated condition. The composition of the plate as determined by chemical analysis during ingot casting is given in Table 1 below. The composition of the 2090 plate is reproduced for comparison.

Table 1. Elemental composition of the alloys discussed in this paper in weight percent.

Alloy	Al	Li	Cu	Mg	Zr	Si	Fe	Zn	Ti	B	Na	Ca
2091	bal	1.99	2.02	1.34	0.12	0.03	0.04	0.02	0.02	0.0012	0.0008	0.0004
2090 (-T8,-T4)	bal	2.05	2.86	<0.01	0.12	<0.01	0.02	0.01	0.02	ND	ND	ND

The presence of Mn, Cr, Ni and Be was also checked, but none were detectable. The nominal compositions of 2090 and 2091 are Al-2.7Cu-2.2Li-0.12Zr and Al-2.2Cu-2.0Li-1.5Mg-0.12Zr, respectively. The grains are highly elongated. The grain size is slightly larger than for the 2090-T81 half-inch plate. A few small insoluble particles remain in the microstructure after solution heat treatment.

The 2091 material was processed to a T8 temper before mechanical testing. Because it was not possible to stretch the plate after solution heat treatment, the material was instead rolled to introduce a homogeneous distribution of dislocation to encourage uniform precipitation of strengthening phases in the grain interiors. Before heat treating sections of plate were split down the centerline and machined into slabs 0.625 in (1.6 cm) thick to facilitate rolling. To inhibit an observed tendency toward quench cracking the material was solution heat treated at 530 C (990°F) for one hour and quenched into 65°C (150°F) water. The slabs were then rolled 6% in one pass within 15 minutes of quenching. The material was then aged to peak strength at 190°C (375°F) for 24 hours. All specimens for mechanical testing were centered around mid-thickness of the slabs, which corresponds to T/4 in the original plate.

Tensile testing was performed using a servohydraulic testing machine at a nominal strain rate of 8×10^{-4} sec^{-1}. The 2091 specimens had a gauge length of 1.0 in (2.5 cm) and a gauge width of 0.2 in (0.5 cm). Both longitudinal (L) and long-transverse (LT) orientations

were tested. Two specimens were tested at each temperature. Testing was performed at four different temperatures: room temperature, 198 K (the melting point of dry ice in ethyl alcohol), 77 K (liquid nitrogen) and 4 K (liquid helium).

Results

Summary of 2090 properties.

It has been previously reported that the tensile yield strength, ultimate tensile strength and uniform elongation of 2090-T8 (T/2 and T/4), -T6 and -T4 all increase as the testing temperature is lowered from room temperature to 4 K. The behavior of 2090-T8 and -T4 at T/4 at 200 K was investigated. Tensile data in both the L and LT orientations at T/4 are given in Table 2. As expected, the strength values are slightly above their room temperature values; however, the uniform elongations are suppressed significantly below the values obtained at room temperature. We have previously noted that the rise in tensile elongation with decreasing temperature is associated with an increase in the strain hardening rate. The 200 K data appears to be consistent with that interpretation. Figure 1, a plot of the strain hardening rate as a function of true strain for 2090-T4, shows that the strain hardening rate at 200 K is also suppressed. For 2090-T81 the 200 K and 300 K strain hardening rates are roughly the same. All the longitudinal specimens failed when the Considere criterion was satisfied (e.g. true stress equal to strain hardening rate). However, in the LT orientation, specimens tested at temperatures below room temperature failed before this tensile instability point; the tensile elongations are correspondingly decreased at low temperature. The strength of the T/4 specimens is about 15% lower than at T/2 at all temperatures. The elongations are comparable in the L orientation and lower in the LT orientation.

Table 2. Tensile data for 2090-T81. Specimens taken from 0.5" plate at T/4.

Specimen		Test Temp. (K)	σ_y ksi	σ_{uts} ksi	uniform elong. %	total elong %
2090-T81	L	298	66	71	6	6
		200	69	76	5	6
		77	76	91	14	14
		4	78	95	17	18
2090-T81	LT	298	77	82	5	6
		200	80	85	2	2
		77	81	87	3	3

Specimen		Test Temp. (K)	σ_y ksi	σ_{uts} ksi	uniform elong. %	total elong %
2091-T8	L	298	64	69	5	6
		200	67	72	9	12
		77	72	82	10	10
		4	80	91	7	7
2091-T8	LT	298	62	67	2	2
		200	65	72	4	5
		77	70	78	3	3
		4	72	85	3	3

Table 3. Tensile data for 2091-T8 processed as described in the text. Specimens taken at T/4 with respect to the 1.5" plate.

Cryogenic mechanical properties of 2091-T8.

A summary of the tensile properties of 2091-T8 is given in Table 3. In general these properties are not as good as those obtained for 2090-T81. Figure 2 shows that both the yield strength and the ultimate tensile strength are increasing with decreasing temperature at a slightly faster than linear rate in the longitudinal direction. Similar behavior is observed in the LT orientation. However, the tensile elongations (uniform and total) do not show a monotonically increasing trend in either orientation. The peak in ductility is difficult to locate with only four temperatures, but seems to occur in the 77 K to 200 K range. The L orientation shows a decline in elongation from 77 K to 4 K. The magnitude of the improvement in elongation at 200 K in the LT orientation over all other test temperatures is notable and warrants further study.

Tensile specimens broken at 300 K and 200 K necked before failing whereas those broken at 77 K and 4 K did not. A comparison of the true stress and strain hardening rate as a function of strain indicated that the 77 K specimens failed at the instability point when the true stress and strain hardening rate were approximately equal, but that the 4 K specimen broke before this equality was reached (see figure 3). Again this early failure provides a partial explanation for the low elongation. Interestingly, SEM examination of tensile fractures did not indicate a change of fracture mode at 4 K. Comparison of the strain hardening rates at each temperature for longitudinally oriented 2090-T81 and 2091-T8 shows that the strain hardening rates for 2091-T8 are lower in each case, which coupled with the lower strength of 2091 at low temperatures suggests that 2091 may have a lower fracture toughness than 2090 at cryogenic temperatures. Fracture toughness testing is currently in progress.

Discussion

An important result of the 2091 tensile data described above is that the variation in properties with decreasing temperature is not monotonic. Caution must be used in extrapolating or interpolating from a limited data set. Although testing at 77 K remains useful as a screening tool, promising materials should be tested at 4 K to confirm that there is no decrease in properties. A second result is that the L-LT anisotropy in tensile properties varies with temper and test temperature as well as with alloy and product form.

Although further analysis and testing of these materials is required before firm conclusions may be drawn, it seems worthwhile to compare the existing data with extant theories of cryogenic materials.

Webster has recently published a detailed exposition of his theory of the influence of liquid phases on low temperature mechanical properties. It predicts a sharp increase in toughness below room temperature at a intermediate temperature at which the liquid phases solidify, followed by a gradual decline in toughness at still lower temperatures. Webster does not explain how toughness can continue to improve between below 77 K (when all liquid phases should certainly have frozen) in the context of his theory. Furthermore, the 2091 tensile data suggests that the properties may peak in the region between 77 and 200 K.

There are two other available theories of the dependence of fracture toughness on temperature. One view is that the increase in toughness comes from increased intergranular delamination which effectively places the material in plane stress. The other suggestion is based on theories of critical strain-controlled elastic-plastic fracture that predict that toughness increases if the yield strength and strain hardening rate increase and the failure mode remains unchanged. Further fracture toughness measurements coupled with fractographic study of tensile and fracture failures are required to investigate these hypotheses. If the peak in elongation observed for 2091 corresponds to a similar peak in fracture toughness, 2091 should be particularly useful in verifying or modifying the existing theories.

Acknowledgement

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Figure Captions

Figure 1. Variation with test temperature of the instantaneous strain hardening rate $d\sigma/d\varepsilon$ plotted as a function of the true strain ε for longitudinally-oriented 2090-T4 tensile specimens.

Figure 2. Tensile behavior of 2091-T8 as a function of test temperature. a) specimens in L orientation. b) specimens in LT orientation.

Figure 3. Considere plots for longitudinally-oriented 2091-T8 tensile specimens broken at 300 K and 4 K. The specimen broken at 300 K failed after the $d\sigma/d\varepsilon = \sigma$ criterion was satisfied, while the specimen broken at 4 K failed before the Considere criterion was satisfied.

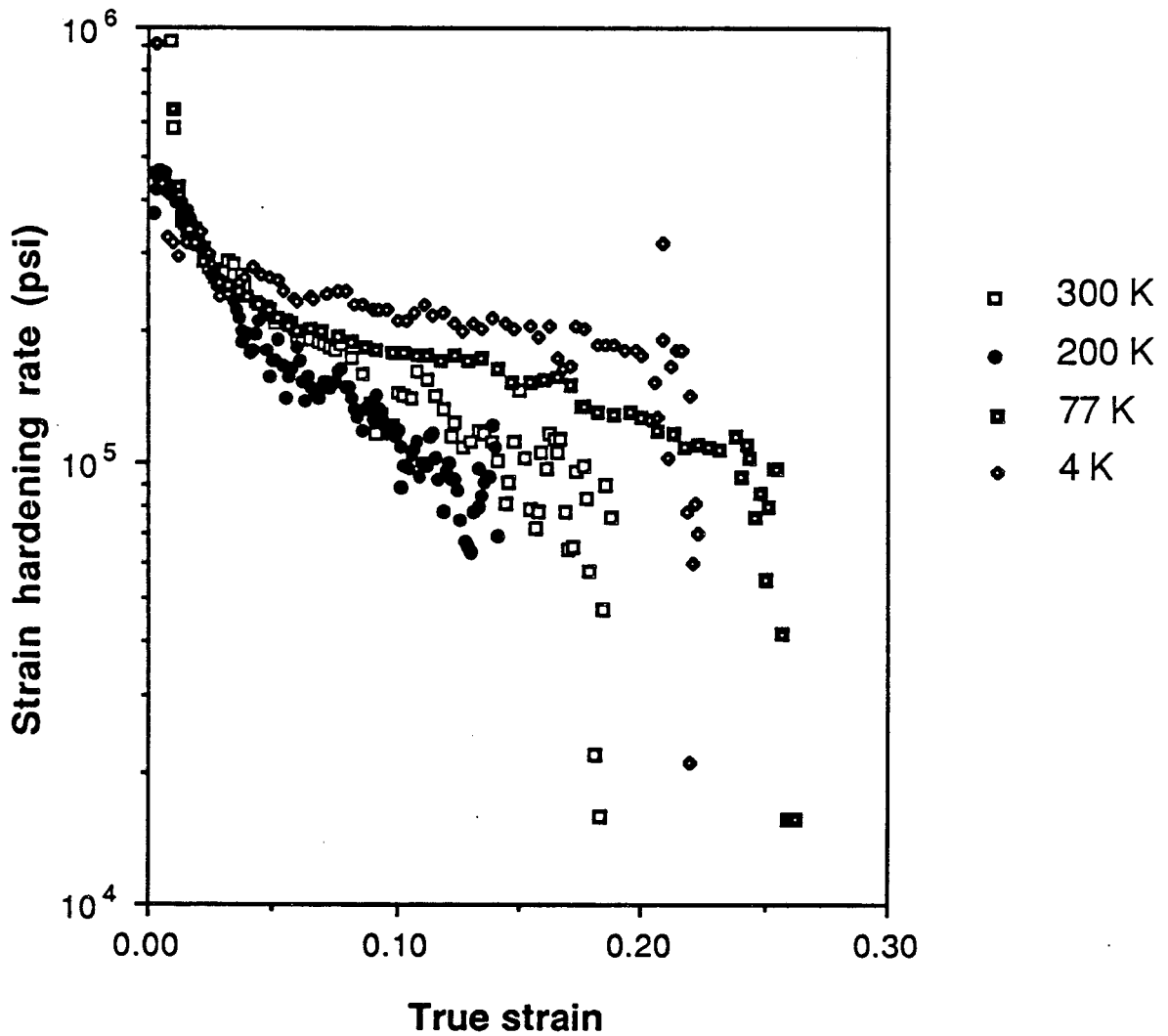
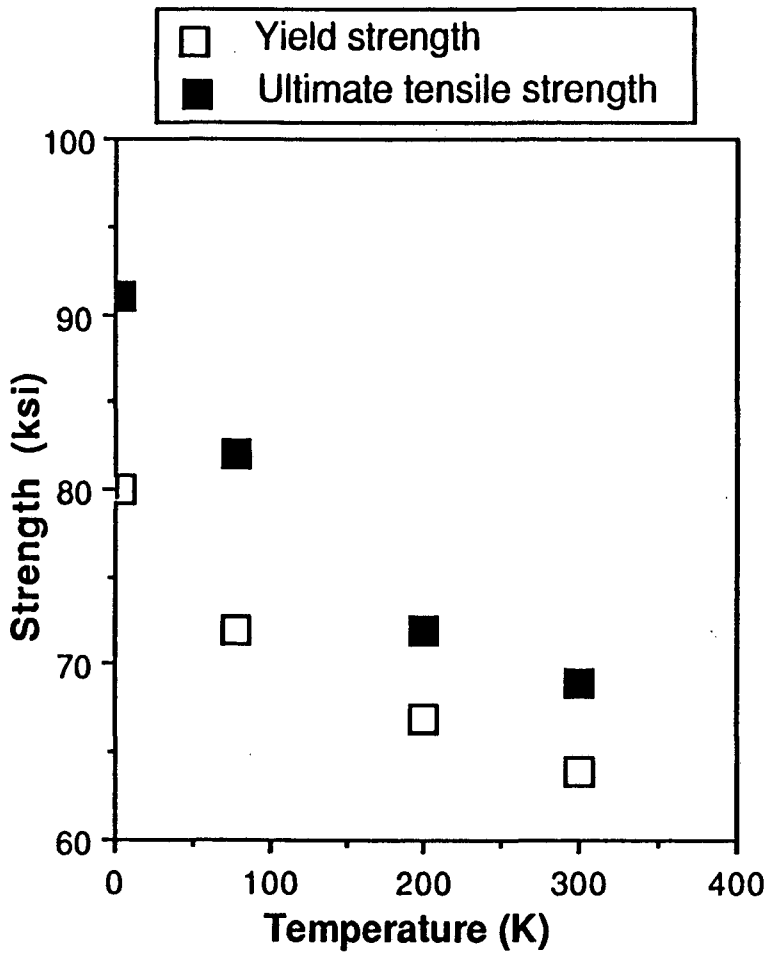

10^6
10^5
10^4
Strain hardening rate (psi)
0.00
0.10
0.20
0.30
True strain
300 K
200 K
77 K
4 K

Figure 1


Yield strength
Ultimate tensile strength
Strength (ksi)
100
90
80
70
60
0
100
200
300
400
Temperature (K)

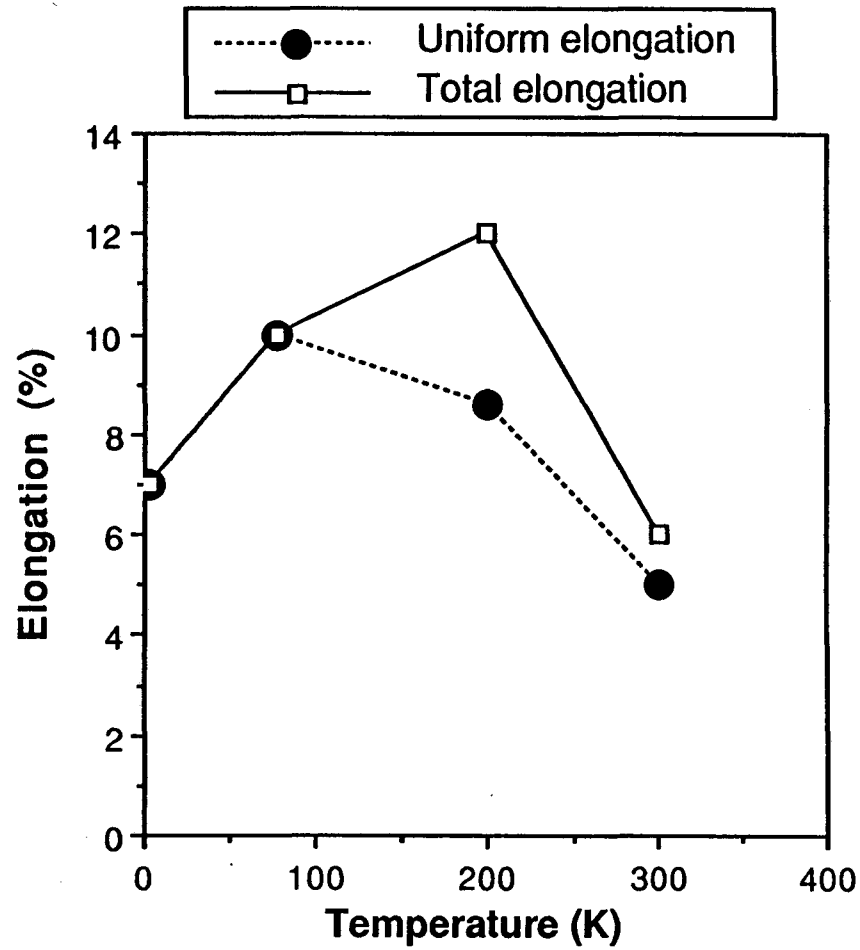

Uniform elongation
Total elongation
Elongation (%)
14
12
10
8
6
4
2
0
0
100
200
300
400
Temperature (K)

Figure 2a

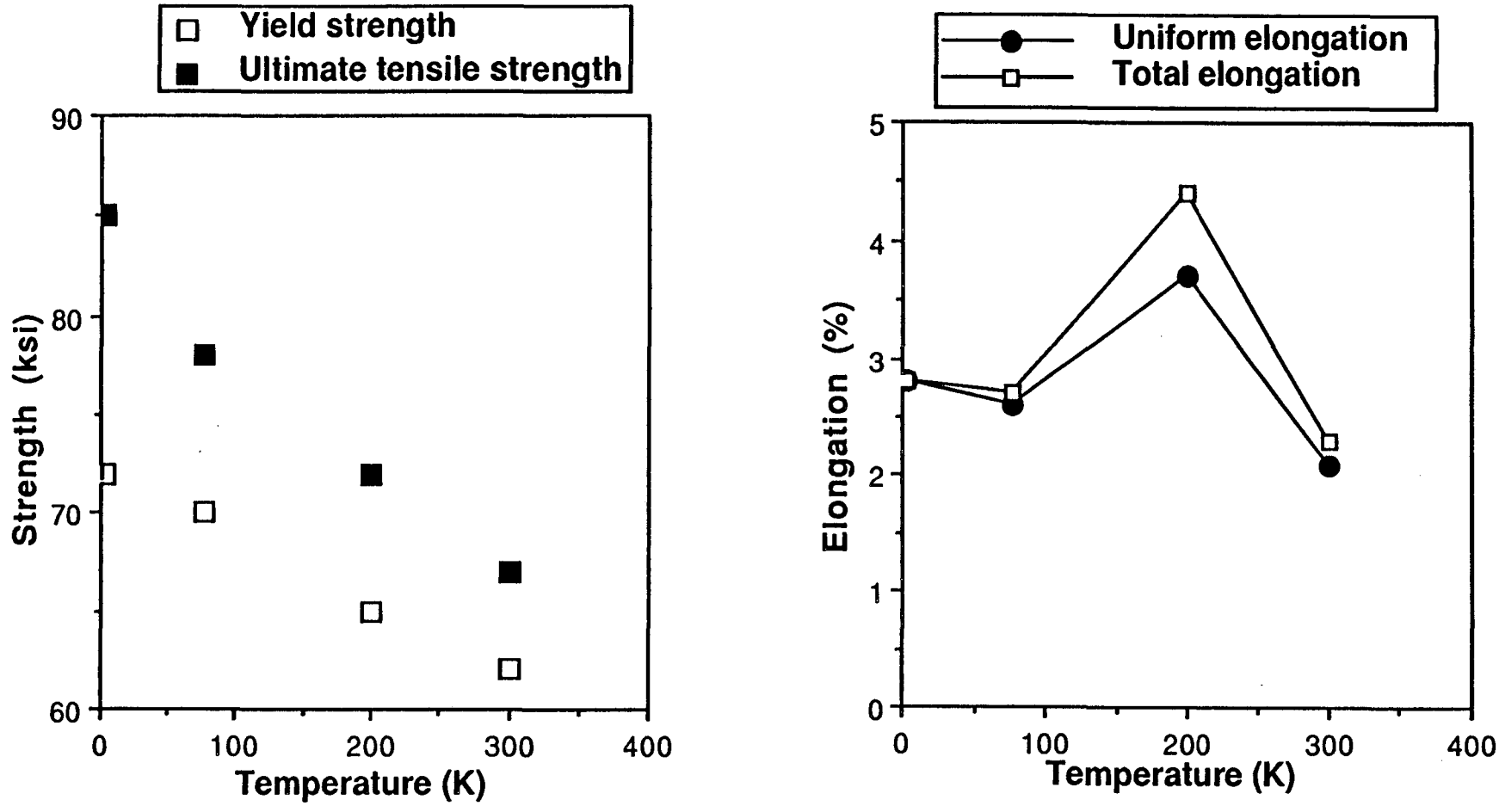

Yield strength
Ultimate tensile strength
Strength (ksi)
90
80
70
60
0
100
200
300
400
Temperature (K)
Uniform elongation
Total elongation
Elongation (%)
5
4
3
2
1
0
0
100
200
300
400
Temperature (K)

Figure 2b

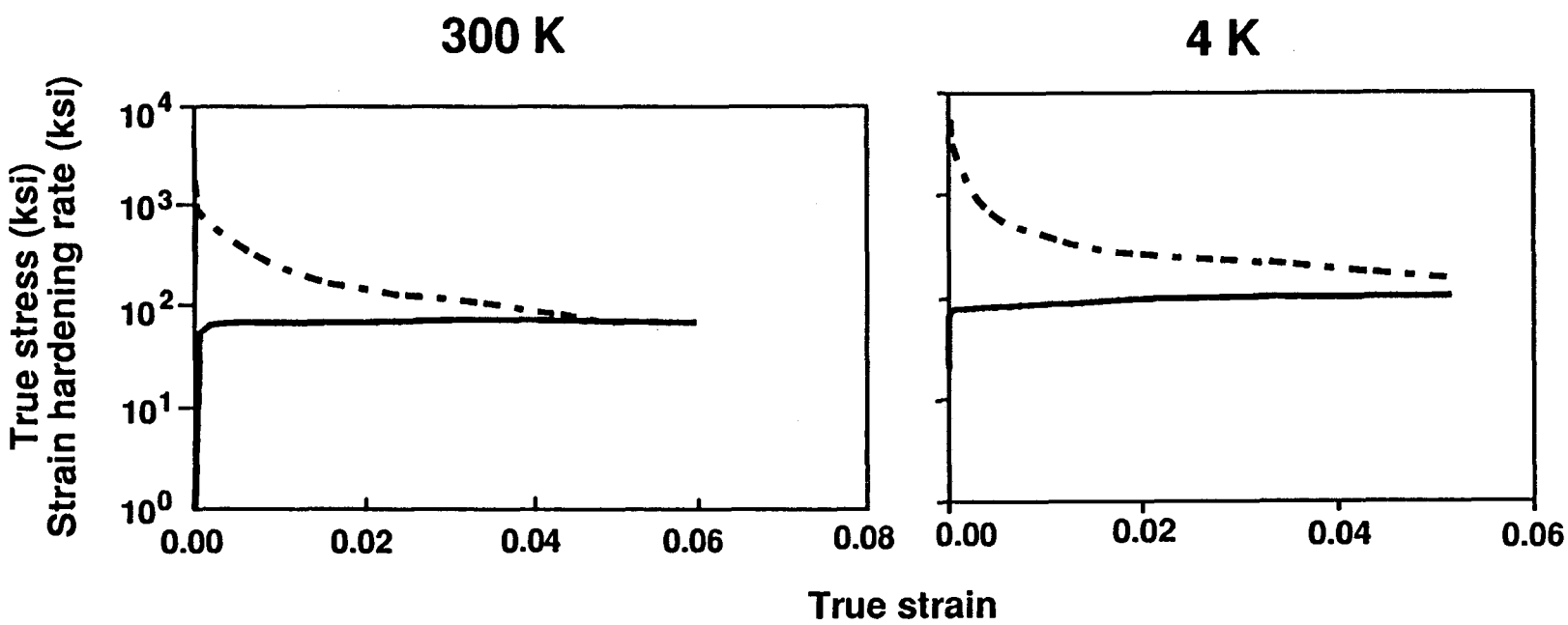

300 K
4 K
True stress (ksi)
Strain hardening rate (ksi)
10^4
10^3
10^2
10^1
10^0
0.00
0.02
0.04
0.06
0.08
0.00
0.02
0.04
0.06
True strain

Figure 3

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