NEW WELDABLE HIGH STRENGTH ALUMINUM ALLOYS FOR CRYOGENIC SERVICE

by

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Introduction

It is apparent that one of the most important of the basic criteria for structural materials for use in space vehicles is a maximum strength/weight ratio consistent with the additional requirements of toughness, fabricability and compatibility with manufacturing, storage and service environments. Liquid-propellant vehicles of the current generation, culminating with the mighty S-IC booster stage of the Saturn V, are constructed principally of aluminum alloys. Weldability and low temperature notch insensitivity requirements greatly influence alloy selection for fuel and oxidizer tankage. Various vehicles have employed Al-Mg alloys, 5456 and 5083 (Saturn I), the Al-Cu-Mg alloy 2014 (Titan II and S-II second stage and S-IVB third stage of Saturn V) and the Al-Cu alloy 2219 (S-IC booster stage of Saturn V). The highest strength weldable alloys commercially available are 2014 and 2219, and in the tempers used these provide yield strengths in the 50 to 60 ksi range and ultimate tensile strengths of 60 to 70 ksi with weld joint efficiencies of 60-80% as-welded.

The higher strength Al-Zn-Mg-Cu alloys 7075 and 7079 are considerably less weldable and have rather poor cryogenic temperature notch-toughness so that they are regarded as unsuitable for oxidizer and fuel tankage. They find extensive use, however, in thrust and interstage structures that are assembled with fasteners as in conventional aircraft construction. Recently developed alloys of the Al-Zn-Mg (Cu-free) type, 7039, X7106 and X7004 are readily weldable and develop potentially useful combinations of tensile properties, cryogenic toughness and weld strength but do not meet the high strength requirements considered essential for improved future vehicles.

Recognizing that further advances in efficiency and increased range or pay-load capability of liquid-propellant boosters are dependent to a large degree upon the availability of even higher strength materials, the Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA) initiated a contract (NAS 8-5452) for the development of a higher strength weldable aluminum alloy with good cryogenic toughness. The goal of the program was an alloy that could be produced as plate with a room temperature ultimate tensile strength approaching 75 ksi, yield strength of 65 ksi and elongation of 15% (later lowered to 10%). A ratio of notched to unnotched tensile strengths (notched/unnotched tensile ratio) of 1.0 at room temperature and 0.9 at -423 F was desired. Good weldability with a room temperature weld efficiency of 80% and an as-welded notched/unnotched tensile ratio at -423 F of 0.85 were additional objectives. Another requirement was good resistance to corrosion and stress-corrosion cracking in industrial and seacoast environments.

Research Program

The preliminary survey to ascertain the most promising avenues for development suggested an interesting approach based on the discovery by Nock(1) in the early 1930's that very small additions of Sn, Cd or In to Al-Cu alloys accelerated elevated temperature precipitation and increased strength. Alloy 27S, based on this effect, was produced on a limited scale starting in 1932. Although this alloy was successfully used in several applications, it was discontinued because of disinterest at that time among structural engineers and aircraft designers in materials with elongations less than 18 to 20%. The principle appeared applicable to alloy 2219 as a means of obtaining a higher strength weldable composition.

It was also concluded that low-Cu alloys of the Al-Zn-Mg type with the addition of Zr, which had been found to improve both weldability and cryogenic toughness[2], offered promise of meeting the program objectives. Al-Mg alloys were considered to have insufficient potential for increased strength to merit more than very cursory experimental work, and the possibility of increasing the strength of Al-Mg_2Si alloys to the desired range was considered so remote that no development effort on them was recommended.

In the initial experimental program 30 alloy compositions were cast and fabricated as sheet. Supplementary survey programs were conducted with additional compositions suggested by the initial results. The alloys were first tested in several tempers produced by established heat treating procedures, and a closely integrated program to optimize heat treating conditions for the more promising compositions was conducted concurrently. Screening evaluations were based on tensile and notched-tensile properties at room temperature and -320 F.

More extensive evaluation of the most promising compositions involved laboratory fabrication of 0.525 and 1.0" plate and performance of tensile and notched-tensile tests at R.T., -112, -320 and -423 F. Tests were made to evaluate weldability and MIG and TIG weld properties in both as-welded and post-weld aged conditions. Corrosion and stress-corrosion tests of parent plate and weldments were conducted in an accelerated exposure by alternate immersion in 3.5% NaCl solution, and longer time tests were initiated in industrial and seacoast exposures. The two alloys selected as having the greatest promise were subsequently mill-fabricated in a range of gages to a maximum thickness of 2-3/8" and subjected to the complete testing program. Because of some deviations in the heat treating response of these full-scale products compared with that of the smaller laboratory-scale sections, additional heat treating development was required.

Results

Al-Zn-Mg Alloys. As background for the selection of the candidate Al-Zn-Mg type alloy and to exemplify the kind of information obtained in the experimental survey program, data relating strength and notch toughness for the series of Al-Zn-Mg alloys are summarized in Fig. 1. The dashed curves are iso-yield strength lines indicating the different combinations of Zn and Mg contents that produce yield strengths of 55, 60, 65, 70 and 75 ksi. The effects of composition on the -320 F notched/unnotched tensile ratios are shown by the solid curves. The heavy solid curve extending from the lower-left toward center-right in the diagram is the approximate loci of compositions having the most favorable combinations of strength and toughness. The tentative Zn and Mg limits for the selected candidate alloy are indicated in Fig. 1 by the small rectangle.

In considering the -320 F notched/unnotched tensile ratios shown in Fig. 1 in relation to those listed later in the paper for the alloy evolved from this work, it may be noted that the Fig. 1 values are considerably lower. There are two reasons for this. First, the survey program alloys for which the data are plotted did not contain Zr. Second, notched/unnotched tensile ratio values for edge-notched sheet specimens are considerably lower than those determined with circumferentially-notched round specimens. The graph further illustrates the well-known fact that, in general, toughness declines with increasing strength. The formulation of alloys with increasing solute content, Zn and Mg, permits attainment of strengths beyond the established goals but only at a considerable sacrifice in toughness as well as reduced fabricability and deterioriation of weldability and resistance to stress-corrosion cracking.

It has been known for some time that Al-Zn-Mg alloys characteristically show a more rapid increase in notch sensitivity with decreasing temperature than is observed for Al-Cu or Al-Mg type alloys. This temperature effect appears to be considerably modified by the addition of a small percentage of Zr (0.12%, nominal) and is reflected in the data illustrated by Fig. 2. These data again were obtained with smooth and edge-notched sheet tensile specimens so that notched/unnotched tensile ratio values are lower than those reported for round specimens. A range of compositions, heat treatments and variations in fabrication is represented and accounts for the relatively broad bands for the two alloy groups.

Among heat treating variables investigated, elevated temperature aging had the most significant effect on the mechanical properties, although rapid quenching was shown to favor higher toughness for a given yield strength. Rapid quenching, however, has been shown to be less desirable than controlled slower quenching with regard to the resistance to stress-corrosion cracking. The nature of the influence of various elevated temperature aging practices on combinations of room temperature strength and -320 F notch toughness is indicated in Fig. 3. In general, strength and toughness for a given alloy bear an inverse relationship to one another with variations in aging up to and including the maximum strength portions of the aging time-temperature curves. The Fig. 3 data show appreciably higher notched/unnotched tensile ratios than those of Fig. 2 because cyclindrical specimens were employed in testing the 1.0" thick plate that provided the information for Fig. 3. It may be noted that the data shown for the two Zr-containing alloys may be considered as representing low and high Mg content versions of the candidate Al-Zn-Mg type alloy selected from the program.

Al-Cu Alloys. Initial results with sheet showed that additions of 0.3% Mg or 0.3% Mg plus 0.3% Si to alloy 2219 increased strength, the improvement in a T6 temper approximating 7 ksi in yield strength and about 2.5 ksi in tensile strength. Higher strengths were obtained with an alloy containing 0.2% Cd, the yield and tensile strength increments with respect to 2219 being about 12 and 8 ksi, respectively. The largest strength improvement was associated with an alloy containing additions of 0.18% Cd and 0.05% Sn which provided tensile and yield strength increases of about 14 and 9 ksi. The latter became the focus of attention for the advanced laboratory evaluation in which 0.525" plate developed room temperature strengths equalling the objectives of 75 ksi tensile strength and 65 ksi yield strength with an elongation of 9% and -320 and -423 F notched/unnotched tensile ratios exceeding 1.0.

Candidate Alloys

These investigations disclosed that selected compositions of both types had sufficient promise of attaining the desired combination of properties to merit continued development effort. After selection of the nominal chemical compositions, additional work was initiated to define appropriate composition limits. The alloys selected were designated X2021 (Al-Cu type) and X7007 (Al-Zn-Mg type), and their nominal compositions and tentative limits are listed in Table 1.

X2021 is a complex composition requiring close control over eleven elements. The basic hardening is provided by precipitation of a transition Al-Cu phase, the nucleation of which is assisted by the presence of Cd and Sn. Manganese provides supplementary strengthening and aids in the control of grain size during fabrication. Titanium is an ingot grain refiner and together with Zr and V minimizes weld cracking. An upper limit is placed on Mg content to avoid formation of the insoluble Mg_2Sn phase which interferes with precipitate nucleation.

X7007 is somewhat less complex, but also necessitates control of nine elements. In addition to the basic hardening combination of Zn and Mg, which confers precipitation hardening of both zone and transition phase types, supplementary elements include Mn, Cr, Ti and Zr for grain control, stress-corrosion benefit and improved weldability. There is evidence that the most favorable cryogenic toughness is obtained with a combination of Zr and Cu, so that the latter element is currently indicated in the nominal composition.

Heat Treatment. The recommended solution heat treating temperature for X2021 is 980 F, and rapid quenching in cold water is the preferred practice. The aging practice required for products of this alloy that must be stretched or roller-leveled after quenching to straighten or flatten is unique among those normally used for aluminum alloys. The strain that accompanies straightening after quenching alters precipitate nucleation and interferes with strength development unless a moderate pre-aging treatment at elevated temperature is used to establish the precipitate pattern prior to straightening. This special sequence of operations for X2021 is identified by an experimental temper designation, T8E31. The pre-aging is normally limited to about one hour at 300 F to keep the strength below a level that would make straightening difficult, and the permanent set during straightening is also limited. Subsequent aging requires 10 hours at 325 F.

The treatment for X7007 will be of the T6 type with some details remaining to be established before selection of the preferred practice. A solution temperature of 860 F is appropriate for this alloy. Some advantage with respect to the resistance to stress-corrosion cracking is expected from controlled moderate-rate quenching. Elevated temperature aging conditions can be adjusted to provide strengths higher than can be attained with X2021-T8E31, but the most attractive compromise between strength and cryogenic toughness appears to be at strength levels comparable with those of the Al-Cu type alloy.

Mechanical Properties of Plate. The amount of testing that has been performed on mill-fabricated plate of the new alloys is insufficient to quote typical properties on the basis that is customary with aluminum producers, that is, statistically derived values representing many lots and many tests. The data listed in Table 2 have been rounded-off and some judgment applied in resolving minor inconsistencies in certain replicate values. They are considered to be representative of the properties to be expected from the new alloys, and comparisons may be made with the older alloys listed. The strengths of the new alloys at room temperature are about 10 to 15% higher than those of the high strength weldable alloys developed prior to the contract. Higher yield strengths are evident for the new alloys at low temperatures also, but the advantage in ultimate tensile strength declines with decreasing temperature. At these increased strength levels the elongation values either remain essentially constant with temperature (X2021-T8E31) or decline with decreasing temperature (X7007-T6 type), which contrasts in either case with the behavior of 2219-T87 and X7106-T6351. A consistent difference in characteristic temperature effects between Al-Cu type alloys (X2021 and 2219) and those of the Al-Zn-Mg type (X7007 and X7106) may be noted in the notched/unnotched tensile ratio values. The Al-Cu alloys show relatively little change in notch toughness with temperature while those of the Al-Zn-Mg type evidence increased notch sensitivity with decreasing temperature. These effects are apparent in the graphical presentation of data for the new alloys, Fig. 4.

The extent to which composition variations within the tentative limits for the two alloys may be expected to affect their mechanical properties may be estimated from the data of Table 3. For each alloy seven compositions were cast and fabricated in the laboratory to 0.525" plate. Maximum and minimum concentrations of the primary strengthening elements as well as other combinations within the limits were included among the variations. Although the strengths observed with the laboratory-fabricated X2021-T8E31 plate were somewhat lower than those measured on the mill-fabricated product, the variations in properties with composition were modest. Somewhat greater variation is to be expected within the limits of X7007, but commercial control with more restrictive composition limits would offer considerable difficulty.

Weldability. The relative weld-cracking tendencies of X2021 and X7007 were evaluated employing tests described by Dowd[3]. These tests involve production of tee-joint double-fillet weld specimens with both continuous and discontinuous welding procedures. Ratings are based upon extent of cracking observed.

Comparative weldability ratings for the new alloys are indicated in bar-graph form in Fig. 5 with those of other high strength alloys that have been used for cryogenic weldments. An exception is 7075, which is seldom welded, but was included to indicate the substantial improvement in weldability represented by X7007.

X2021 is considered as readily-welded by MIG and TIG processes employing 2319 filler as are 5456 welded with 5556 or 2219 welded with 2319. Its rating is definitely superior to that of 2014 welded with 2319, and little difficulty should be experienced with this new alloy.

X7007 is less weldable but is rated as commercially weldable when good control is exercised. This rating is based on the use of an experimental filler which is similar in composition to X7007 but with higher Mg content. A higher weldability rating, comparable with that shown for X7106/X5180, can be assigned to the combination of X7007 welded with X5180 filler. The welds, however, have lower strength, and the gain in weldability would have to be equated against the increased weight of additional weld-land reinforcement needed to compensate for the lower strength. A greater frequency of weld cracking was encountered in welding thicker gages of X7007 by the MIG process than by TIG. As-welded properties obtained by the latter process were appreciably higher, however.

Weld Properties. Welded panels for determining weld properties were radiographed, and those selected for testing exhibited soundness equal to or better than Class II of the Army Ballistic Missile Agency document ABMA-PD-R-27A. Tensile tests were performed with reduced-section and full-section specimens of the designs shown in Fig. 6. The reduced-section specimens are designed to fracture the weld. The full-section specimens, tested without removing the bead, permit failure to occur either through or adjacent to the weld, whichever location is weaker. For notched tensile tests the notches (K_t=10) were located in the weld.

Results obtained with MIG and TIG welded X2021-T8E31 sheet and plate employing 2319 filler are listed in Table 4. The weld properties of the new alloy welded with 2319 are not markedly affected by the welding process used and are slightly higher than are obtained with 2219 welded with this filler. Post-weld aging increases the tensile strength of the welds with some lowering of elongation values but little effect on notched/unnotched tensile ratios. The ratios, 1.00 to 1.10 at room temperature and 0.87 to 1.02 at -320 F, were similar to those determined for 2219 welded with 2319. Additional experiments have been conducted with experimental filler compositions designed to increase the strength of welds made with X2021 plate. Although these tests have not progressed to the point at which an improved filler composition can be recommended, significantly higher weld strengths have been achieved.

The as-welded and post-weld aged strengths of X7007 welded with the experimental filler are the highest that have been observed with welded aluminum alloys that have not been post-weld solution heat treated. The notched/unnotched tensile ratios are very good at room temperature (~ 1.10), but because of the more pronounced temperature effect with this type alloy are lowered to around 0.80 at -320 F. To demonstrate the degree of variability in weld properties resulting from parent plate composition variations within the tentative X7007 limits, average, minimum and maximum data for six laboratory-fabricated lots are tabulated in Table 4. The variations are considered to be modest, and indicate that with good control a high degree of uniformity in weld strength can be maintained.

A comparison of weld ultimate tensile strengths for the new alloys with those of other weldable aluminum alloys used at cryogenic temperatures is shown in Fig. 7.

Corrosion Characteristics. A comprehensive program of corrosion and stress-corrosion tests of plate and weldments is in progress with both accelerated and natural exposures. It is too early, however, to completely define the characteristics of these alloys and establish quantitative ratings. Neither alloy is expected to exhibit the very high resistance to general corrosion associated with Al-Mg alloys such as 5083 and 5456, although X7007 should approach this degree of resistance. Alloy X2021 is expected to be comparable with 2219 and 2014.

Preliminary evidence from accelerated tests indicates that X2021-T6E31 has a high order of resistance to stress-corrosion cracking at high stress levels. Although it may be somewhat inferior to 2219 in artificially aged tempers, it is superior to 2014-T6 which has no record of stress-corrosion cracking in cryogenic service. Alloy X7007 in the T6 type tempers has good resistance to stress-corrosion cracking in the longitudinal and long transverse directions. When high tensile stresses are applied in the short transverse direction, stress-corrosion cracking may occur. In this respect, the alloy is not expected to show a marked departure from the behavior of related alloys such as X7106 and 7039 in the T6 temper.

SUMMARY

Two new aluminum alloys have been developed as high strength candidates for cryogenic structure and tankage applications with particular reference to the requirements of liquid propellant space boosters. Designated X2021 (Al-Cu type) and X7007 (Al-Zn-Mg type), these alloys are suitable for fabrication of plate and other wrought products and will provide strengths 10-15% higher than present commercial weldable aluminum alloys with good toughness at cryogenic temperatures. The alloys have good weldability, and high weld properties can be attained. In resistance to corrosion and stress-corrosion cracking they compare favorably with other high strength aluminum alloys now used for cryogenic service.

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Table 1

Nominal Compositions and Tentative Limits for Aluminum Alloys X2021 and X7007

Alloy No.	X2021			X7007		
	Nominal	Min.	Max.	Nominal	Min.	Max.
Si	-	-	0.20	-	{Si + Fe}	0.40
Fe	-	-	0.30	-		
Cu	6.3	5.8	6.8	0.10	-	0.25
Mn	0.3	0.20	0.40	0.2	-	0.40
Mg	-	-	0.02	1.8	1.4	2.2
Cr	-	-	-	0.12	0.05	0.25
Zn	-	-	0.10	6.5	6.0	7.0
Ti	0.06	0.02	0.10	0.04	0.01	0.06
Zr	0.18	0.10	0.25	0.12	0.05	0.25
V	0.10	0.05	0.15	-	-	-
Cd	0.15	0.05	0.20	-	-	-
Sn	0.05	0.03	0.08	-	-	-
Others, each	-	-	0.05	-	-	0.05
Others, total	-	-	0.15	-	-	0.15

Table 2

Comparison of Mechanical Properties of Experimental and Commercial Alloys(1)

Property	Testing Temp.	X2021-T8E31	X7007-T6 type	2219-T87	X7106-T6351	5456-H343	Goals
Ultimate Tensile Strength, ksi	R.T.	75	77	68	66	56	75
	-112 F	80	82	73	75	-	-
	-320 F	90	93	85	87	72	-
	-423 F	102	104	99	103	75	-
Yield Strength, ksi	R.T.	66	69	56	58	44	65
	-112 F	71	73	59	65	-	-
	-320 F	80	83	68	71	52	-
	-423 F	84	90	72	75	55	-
Elongation, % in 2"	R.T.	9	12	10	13	10	10
	-112 F	9	8	10	13	-	-
	-320 F	9	5	11	14	14	-
	-423 F	9	4	13	15	7	-
Notched/Unnotched Tensile Ratio(2)	R.T.	0.97	1.31	1.13	1.36	0.95	1.0
	-112 F	1.05	1.18	1.10	1.26	-	-
	-320 F	1.03	0.98	1.03	1.06	0.85	-
	-423 F	1.00	0.85	0.94	0.94	0.88	0.9

(1) Properties listed are for mill-fabricated plate 1.0 to 1.25" thick

(2) $K_t = 10$

Table 3

Effect of Composition Variations Within Limits on
Mechanical Properties of Laboratory-Fabricated 0.525" Plate

Testing Temperature	Alloy	X2021-T8E31			X7007-T6 type		
		Avg.	Min.	Max.	Avg.	Min.	Max.
R.T.	Ultimate Tensile Strength, ksi	72.0	71.2	73.0	76.4	69.8	82.7
	Yield Strength, ksi	62.7	61.2	64.6	69.0	62.0	75.9
	Elongation, % in 2"	9.0	8.6	9.3	13.0	11.4	14.3
	Notched/Unnotched Tensile Ratio(1)	1.03	0.95	1.10	1.29	1.18	1.39
-320 F	Ultimate Tensile Strength, ksi	89.3	88.1	90.9	96.1	89.7	102.0
	Yield Strength, ksi	75.0	73.1	77.7	84.4	76.8	91.7
	Elongation, % in 2"	10.4	8.5	11.5	10.8	9.0	15.3
	Notched/Unnotched Tensile Ratio(1)	1.02	0.95	1.06	0.82	0.65	1.06

(1) $K_t = 10$

Table 4

Tensile and Notched Tensile Data from Tests of X2021-T8E31 Sheet and Plate Welded with 2319 Filler

Welded Parallel to Rolling Direction - Transverse Tests

			Full Section Tests(1)			Reduced Section Tests(2)				
Thickness, in.(5)	Welding Process and Condition	Testing Temperature	UTS, ksi	YS, ksi	Elong., % in 10 in.	UTS, ksi	YS, ksi	Elong., % in 2 in.	NTS,(3) ksi	NTS/UTS(3)
0.125	MIG, As-Welded	R.T.	43.8	26.0*	3.2*					
0.525	MIG, As-Welded	R.T.	42.4	37.6	1.1	39.4	19.1	6.0	39.2	1.00
0.525	TIG, As-Welded	R.T.	42.8	33.2	1.4					
0.5	MIG, As-Welded	R.T.	41.4	37.8	0.8					
1.0	MIG, As-Welded	R.T.	42.8	36.2	1.2	38.3	24.2	3.4	41.7	1.09
1.0	TIG, As-Welded	R.T.	43.2	38.5	1.1	42.5	24.1	4.8	44.1	1.05
0.525	MIG, As-Welded	-320 F				53.5	27.0	8.0	46.4	0.87
1.0	MIG, As-Welded	-320 F				52.8	-	3.8	53.2	1.01
1.0	TIG, As-Welded	-320 F				57.4	28.6	4.8	53.3	0.94
0.125	MIG, P-W Aged(4)	R.T.	51.0	43.3*	1.5*					
0.525	MIG, P-W Aged	R.T.	47.4	44.9	0.8	46.8	29.4	2.9	48.2	1.03
0.525	TIG, P-W Aged	R.T.	48.3	45.5	0.6					
0.5	MIG, P-W Aged	R.T.	43.0	-	0.5					
1.0	MIG, P-W Aged	R.T.	46.9	46.4	0.8	42.1	28.6	3.0	46.3	1.10
1.0	TIG, P-W Aged	R.T.	43.5	-	0.7	46.9	31.9	4.0	45.6	1.00
0.525	MIG, P-W Aged	-320 F				57.2	38.3	3.6	53.1	0.93
1.0	MIG, P-W Aged	-320 F				55.5	-	2.8	56.8	1.02
1.0	TIG, P-W Aged	-320 F				62.4	39.0	3.5	55.8	0.94

(1) Specimens as shown in Fig. 6 except for tests of 0.125 in. sheet*
* Gage Length for tests of 0.125" sheet = 2 in.
Yield strength determined at 0.2% offset in 10 in. for tests of plate, at 0.2% offset in 2 in. for tests of 0.125 in. sheet*
(2) Specimens as shown in Fig. 6 except notched specimens not shown.
Gage length = 4D; Yield strength determined at 0.2% offset in 4D.
(3) Notched round specimens, K_t = 10
(4) Post-Weld aging treatment - 16 hours at 325 F
(5) 0.125 and 0.525 in. material laboratory-fabricated; 0.5 and 1.0 in. material mill-fabricated

Table 5

Tensile and Notched-Tensile Data From Tests of MIG Welded X7007 Alloy Plate (0.525" Thick). Includes Six Lots of Laboratory-Fabricated Plate Varying in Composition Within Tentatively Recommended Composition Limits

		Full Section Tests(1)						Reduced Section Tests(2)					
	Weld Filler	Experimental(6)			Parent Metal			Parent Metal			Parent Metal		
	Testing Temperature	R.T.			R.T.			R.T.			-320 F		
Condition	Property	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
As Welded(3)	Ultimate Tensile Strength, ksi	59.7	58.1	61.8	57.9	55.5	61.2	58.9	57.2	61.6	64.0	61.6	66.1
	Yield Strength, ksi	56.3	55.2	58.0	56.1	54.8	57.3	43.3	41.6	44.8	55.0	52.8	57.3
	Elongation(4)	1.0	0.9	1.3	0.9	0.5	1.1	5.3	2.5	7.5	2.3	1.6	2.8
	Notched/Unnotched Tensile Ratio	-	-	-	-	-	-	-	-	-	0.80	0.73	0.91
Post-Weld Aged(5)	Ultimate Tensile Strength, ksi	64.1	62.6	66.4	62.4	61.3	63.1	63.5	61.8	64.9	77.4	75.6	78.9
	Yield Strength, ksi	58.6	57.6	59.6	58.5	58.0	59.0	56.1	55.0	58.3	68.3	65.7	70.7
	Elongation(4)	3.0	0.9	5.4	1.9	1.3	2.7	6.9	2.6	10.0	2.7	1.6	3.6
	Notched/Unnotched Tensile Ratio	-	-	-	-	-	-	-	-	-	0.81	0.72	0.95

(1) Specimen shown in Fig. 6. Fractures generally occurred through or at edge of weld bead
(2) Specimen shown in Fig. 6
(3) Full section specimens aged about 5 months at R.T., Reduced section specimens 11 weeks
(4) Full section specimens - % in 10", Reduced section specimens - % in 1.4"
(5) Post-Weld aging treatment - 8 hours at 225 F plus 16 hours at 300 F
(6) Filler Composition: 6 Zn, 2.25 Mg, 0.30 Mn, 0.18 Zr, 0.12 Ti

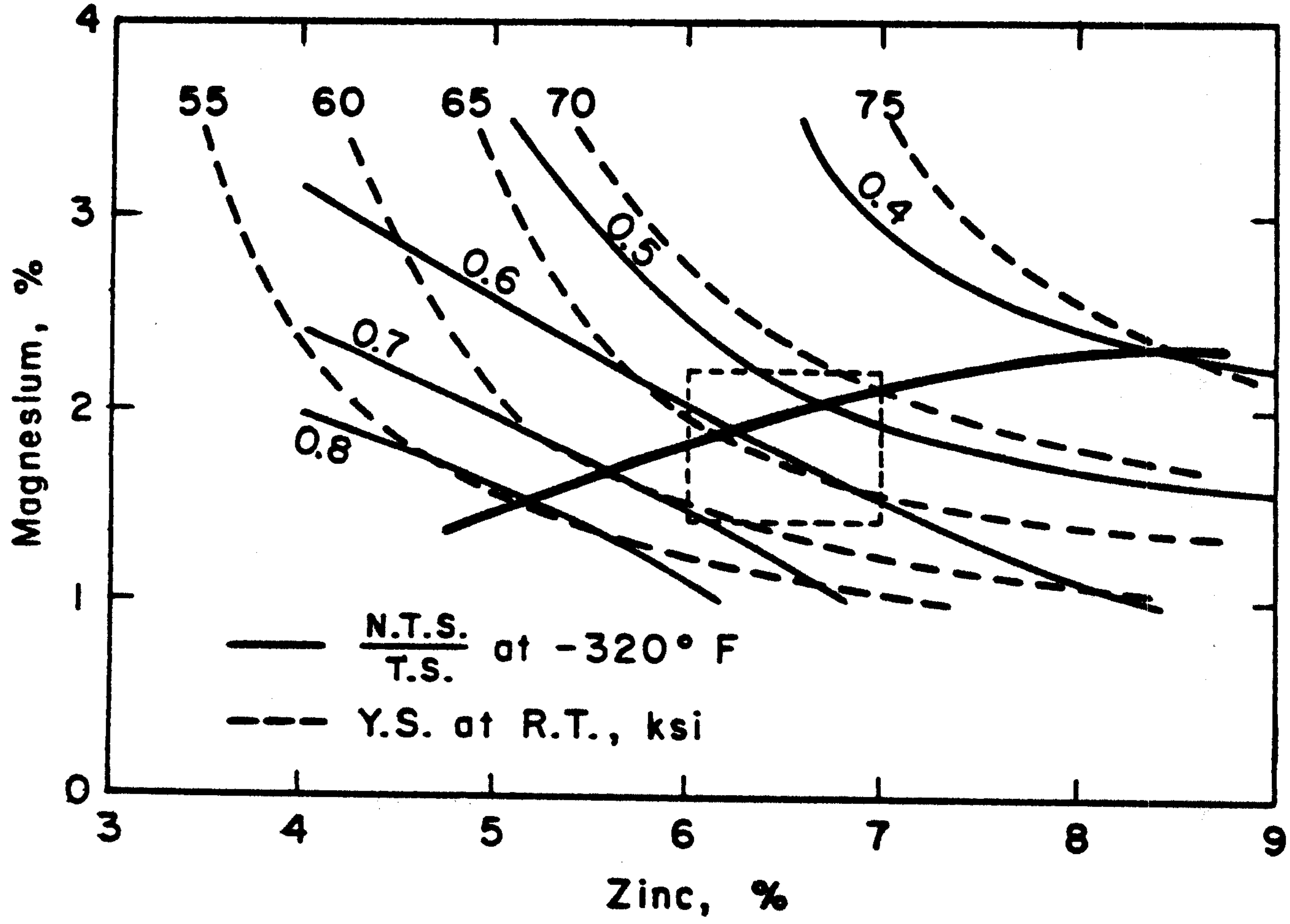

Fig. 1 - Effect of Zn and Mg Contents on the Room Temperature Yield Strength and -320 F Notched/Unnotched Tensile Ratio of Al-Zn-Mg Alloy Sheet.

Transverse Smooth and Notched (K_t = 10) Tensile Specimens Aged 48 Hours at 250 F. Loci of Compositions Having Most Favorable Combinations of Strength and Toughness Indicated by Heavy Curve. Tentative Limits for X7007 Shown as Small Rectangle.

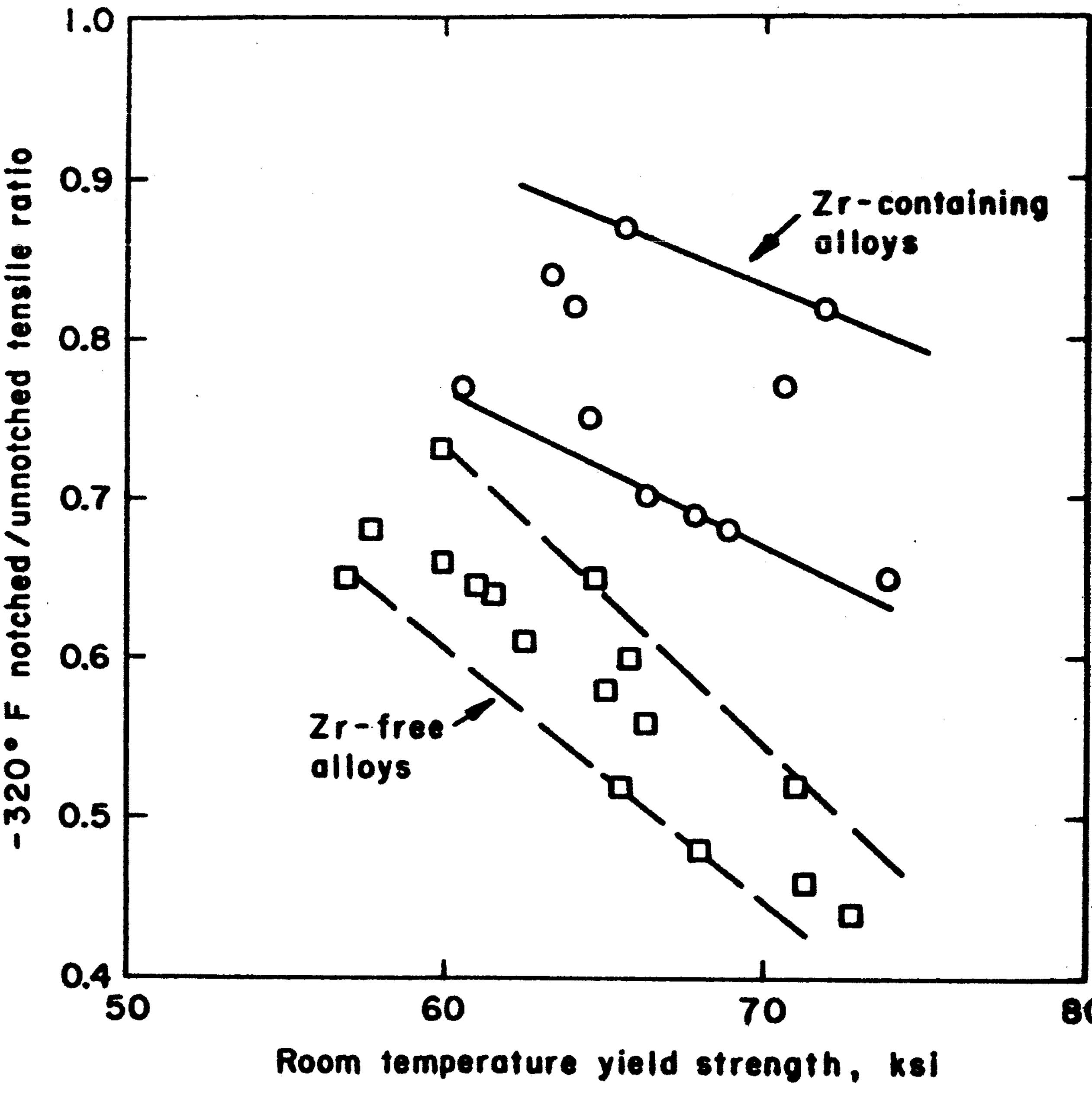

Fig. 2 - Comparison of Room Temperature Yield Strength and -320 F Notched/Unnotched Tensile Ratios of Al-Zn-Mg Alloy Sheet With and Without Zr Addition.

Alloys Contained 5.5 to 7.0% Zn and 1.25 to 2.25% Mg. Data are Included for Several Variations of Heat Treatment and are from Transverse Smooth and Notched (K_t = 10) Sheet Specimens.

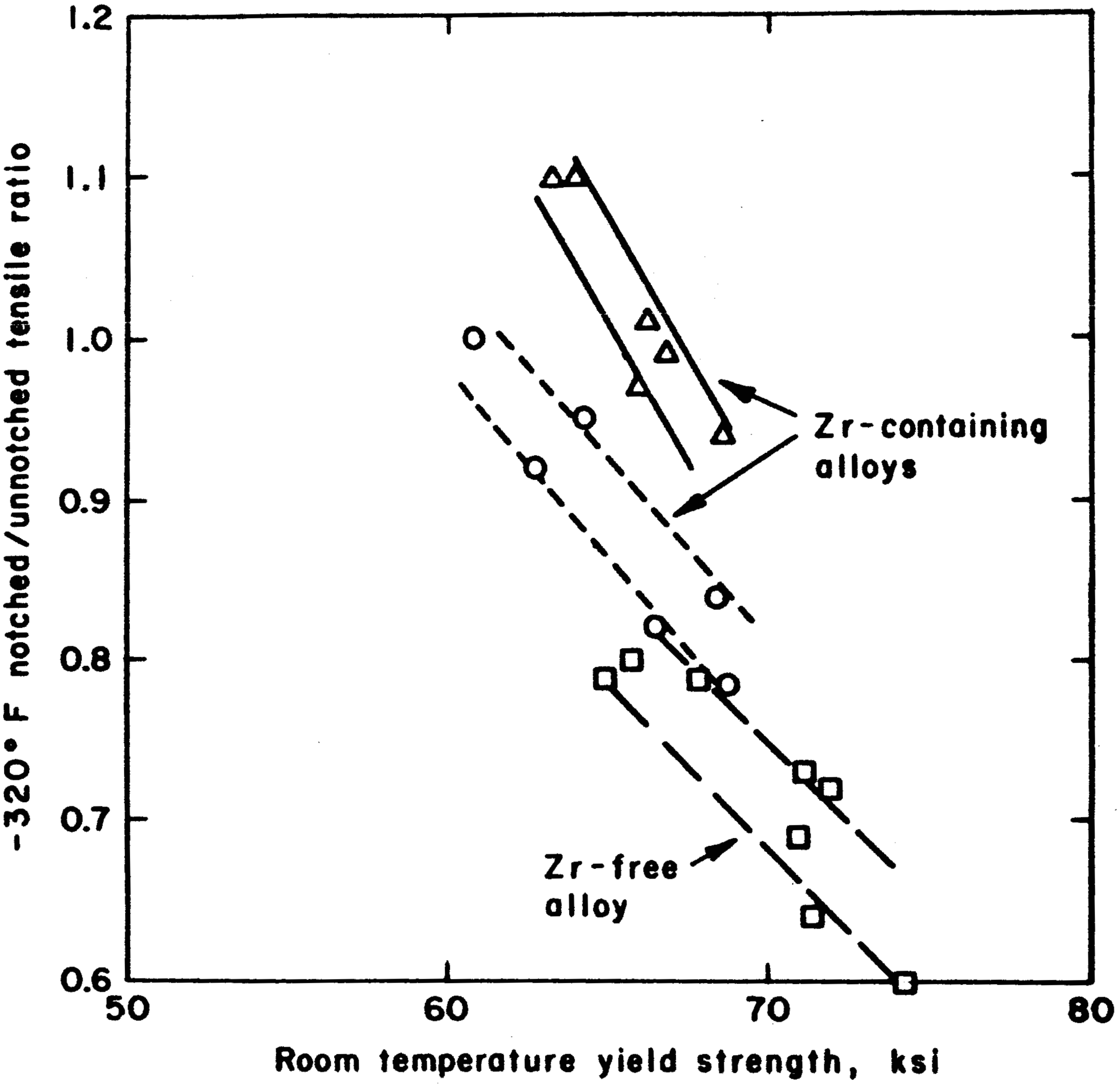

Fig. 3 - Effect of Variations in Elevated Temperature Aging Conditions on Combinations of Room Temperature Yield Strength and -320 F Toughness Determined for 1.0" Plate of Three Al-Zn-Mg Type Alloys.

Aging Time and Temperature Ranges: 4 to 168 Hours, 225 to 300 F. Cylindrical Smooth and Notched (K_t = 10) Specimens.

	Cu	Fe	Si	Mn	Mg	Zn	Cr	Zr	Ti
△	.12	.18	.09	.21	1.64	6.51	.13	.10	.01
○	.12	.16	.09	.21	2.22	6.20	.13	.10	.01
□	.11	.16	.15	.20	2.65	6.18	.12	.00	.01

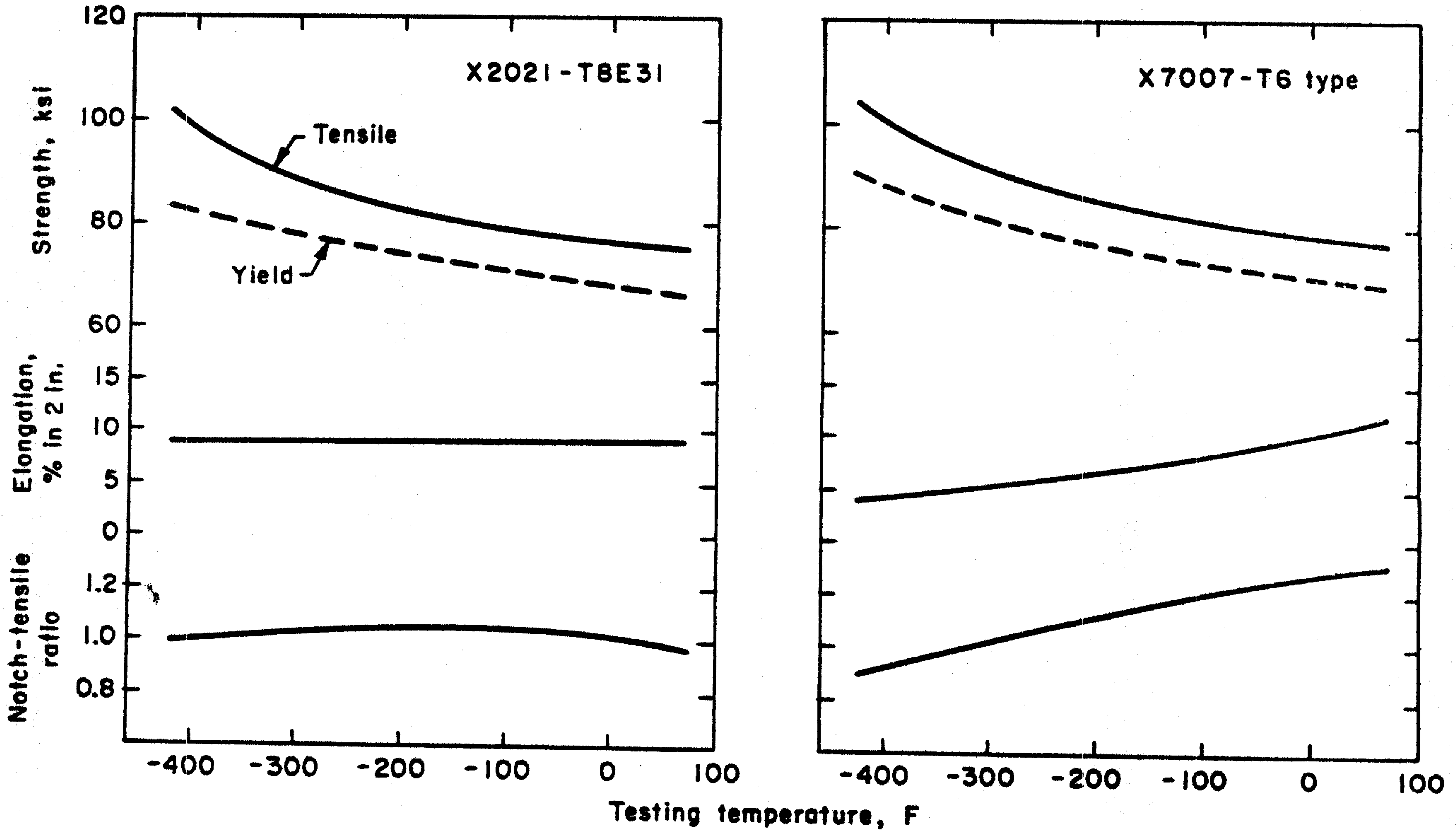

Fig. 4 - Effects of Temperature on Tensile Properties and Notch Toughness of Experimental High Strength Aluminum Alloys. Data are for Mill-Fabricated 0.5 and 1.0 Inch Plate. Cylindrical Notched Specimens had Notch Radius Giving $K_t = 10$.

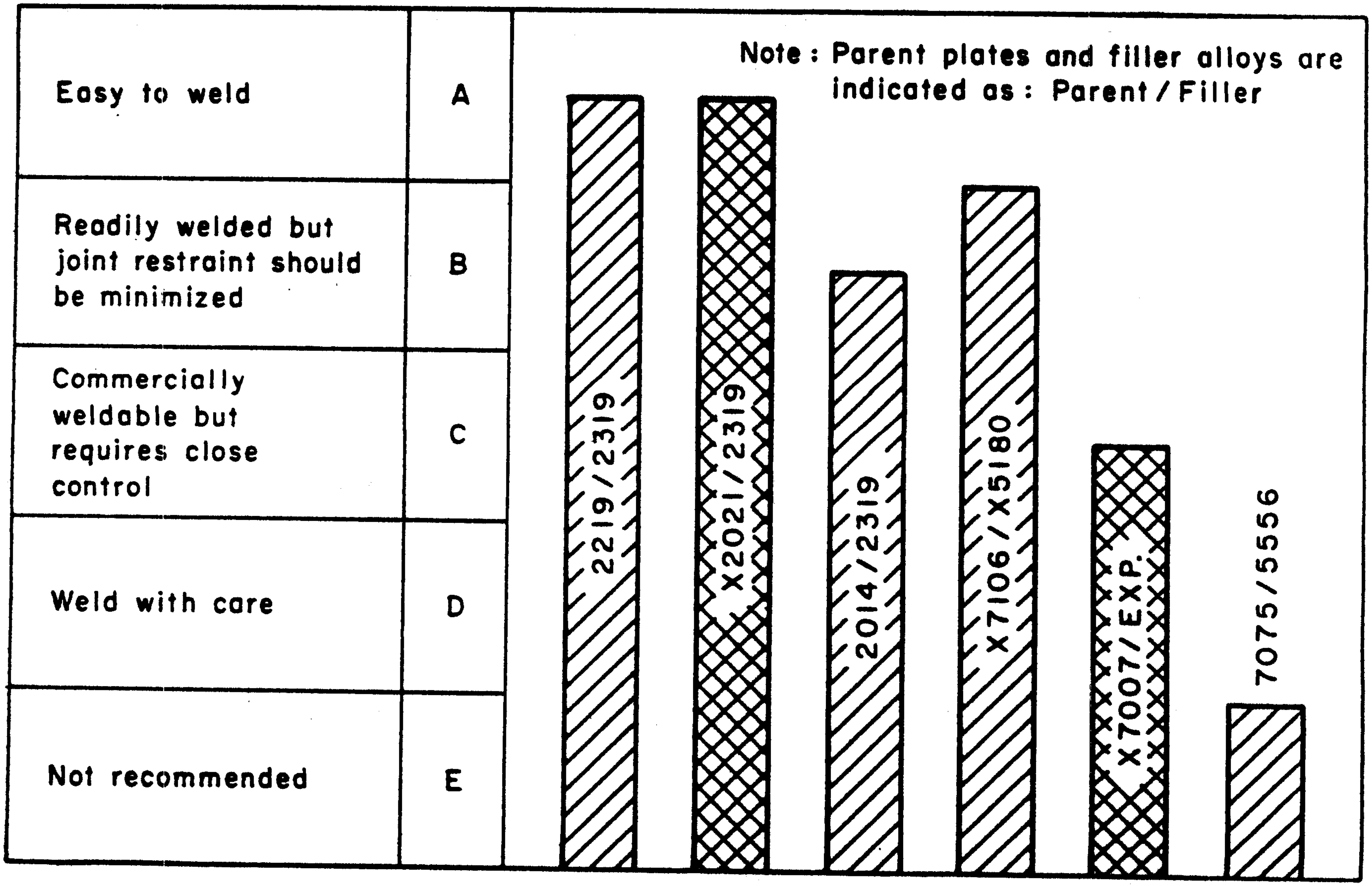

Fig. 5 - Comparative Weldability Ratings of X2021, X7007 and Other Aluminum Alloys Based on Weld Cracking Tendency and Practical Observations.

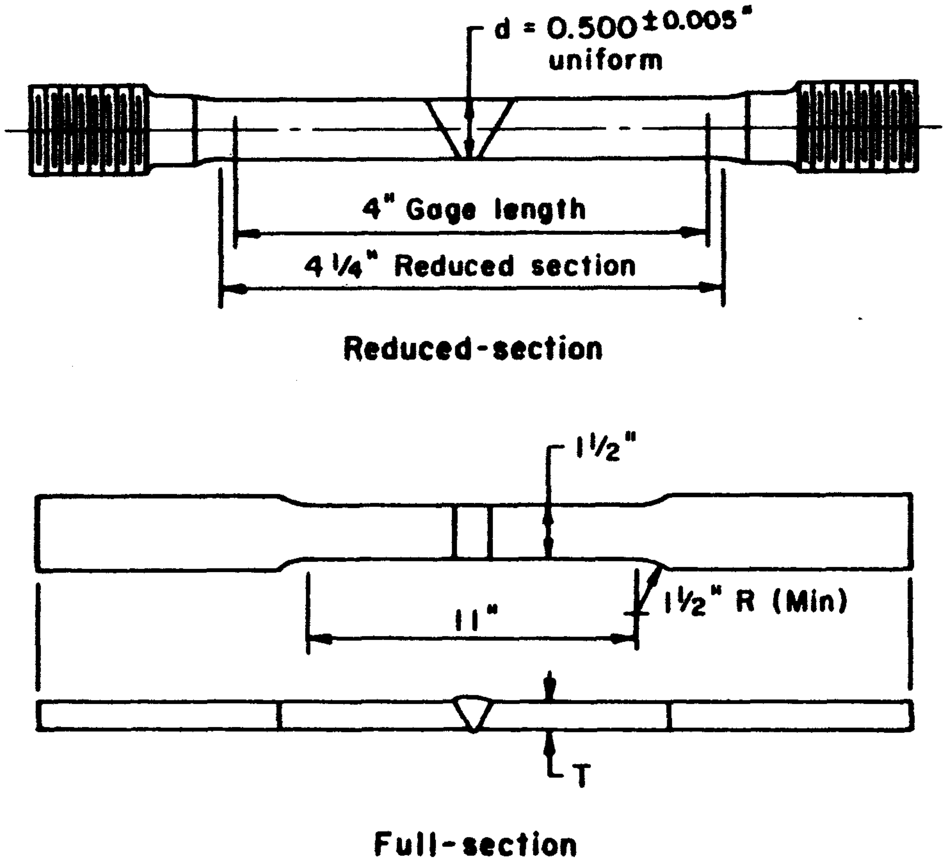

Fig. 6 - Tensile Specimens from Groove-Welded Plate.

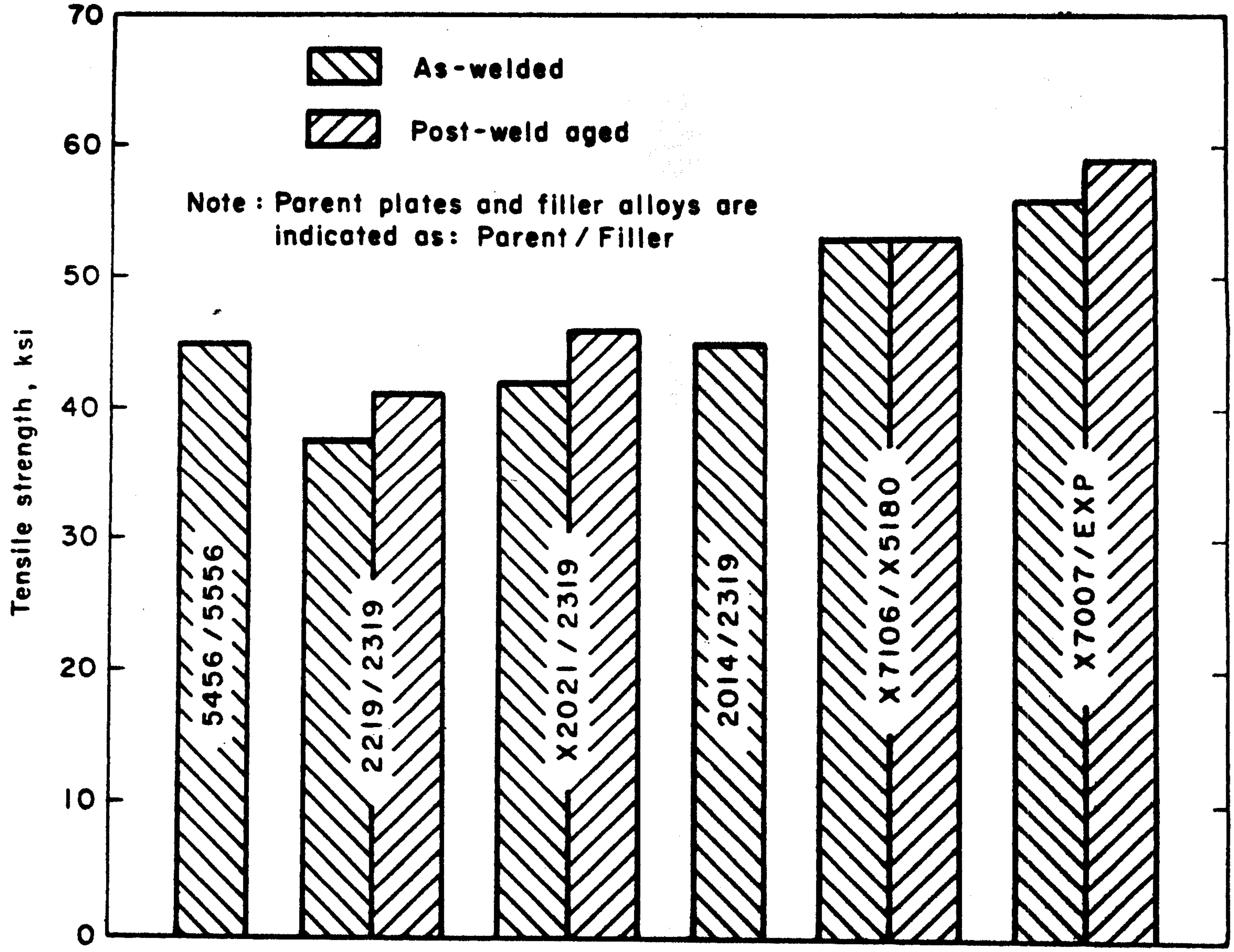

Fig. 7 - Comparison of Weld Strengths. Welds Produced With 1/4 to 1" Thick Mill-Fabricated Plate and Tested as Full-Section Specimens.