The Optimized Mechanical Properties of the New Aluminum Alloy AA 6069

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AA 6069, a new aluminum alloy, has been developed for application in hot and cold extrusion and forging. It contains ~2 Mg + Si, ~1% Cu, 0.2% Cr, and 0.1% V. Nominal T6 properties of the ingot without hot or cold deformation are 415 MPa (60 ksi) ultimate tensile strength (UTS), 380 MPa (55 ksi) yield strength, and 12% elongation. Properties after hot and cold extrusion in the T6 condition range from 380 to 490 MPa (55 to 71 ksi) UTS, 345 to 450 MPa (50 to 65 ksi) yield strength, and 10 to 22% elongation. This alloy also has favorable fatigue and corrosion-fatigue properties due to a combination of composition, high solidification rate, controlled homogenization, thermal and mechanical processing, and T6 practice. Current developmental applications include cold-impact air-bag components, high-pressure cylinders, and automotive suspension and drive-train parts. Unlike alloys 2024-T3 and 7129-T6, of comparable strength, diluted 6069 is scrap compatible with many other *5xxx* and *6xxx* alloys.

Keywords

aluminum alloy, aluminum silicon, extrusion, high strength

1. Introduction

THIS paper reports the results of the development of AA 6069, an aluminum-magnesium-silicon alloy that combines strength, extrudability, and favorable corrosion resistance with low cost and scrap compatibility. Six prospective alloy compositions were studied and discussed in Ref 1; the composition of what is now designated 6069 exhibited the best properties. It will be demonstrated that relatively high-strength and fatigue-resistant ingots and extrusions can be produced from AA 6069. Increased strength was anticipated by increasing silicon, magnesium, and copper concentrations, as these are the principal basis of precipitation strengthening in alloys such as 6061. The magnesium and silicon concentrations exceed the solubility in aluminum. Table 1 shows the specification of alloy AA 6069 and compares it with typical 6061. The mechanical properties of this new 6*xxx* series alloy that were obtained with precise T6 practice will be reported here, and will be compared with other 6*xxx* series alloys.

2. Experimental Procedure

All of the alloys used in this study were supplied by Northwest Aluminum (The Dalles, Oregon), unless otherwise indicated. The compositions of the 6069, 6061, and 6013 alloys used are listed in Table 2, which shows the relatively narrow composition range for the several 6069 ingots that were studied. Aluminum was provided in the form of direct-chill cast ingots using Wagstaff "air slip" tooling. Tensile tests were performed on an Instron type 4505 screw-driven tensile machine with computerized data acquisition. Specimen geometries varied for those extracted from extrusions, but the typical gage dimensions for those used for ingot characterization were 5.1 mm diameter and 25.4 mm length. Specimens were evaluated from random positions within the ingots (although it was determined that the mechanical properties were independent of position). Specimen temperature was controlled to within ±2 °C of the set temperature during solution annealing and aging. A 10 min heat-up period was required to achieve the solution anneal temperature once specimens were inserted in the fur-

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Table 1 Comparison of the alloy compositions of typical 6061 and new 6069

Element	Composition, wt%	
	Typical 6061(a)	6069
Silicon	0.6	0.6-1.2
Iron	0.2	0.4 max
Copper	0.3	0.4-1.0
Manganese	...	0.4 max
Magnesium	1.0	1.2-1.6
Chromium	0.1	0.05-0.30
Titanium	...	0.10 max
Zinc	...	0.10 max
Vanadium	...	0.10-0.30
Strontium	...	0.05 max

(a) Source: Ref 2

Table 2 Alloy compositions

Element	Composition, wt%		
	6069	6061	6013(a)
Silicon	0.87-0.92	0.4-0.8	0.6-1.0
Iron	0.17-0.24	0.7 max	0.5
Copper	0.76-0.78	0.15-0.40	0.6-1.1
Magnesium	1.41-1.46	0.8-1.2	0.8-1.2
Chromium	0.21-0.22	0.15 max	0.1
Titanium	0.016-0.032	0.15 max	0.1
Vanadium	0.09-0.12	...	...
Gallium	0.03 max	...	...
Strontium	...	...	...
Manganese	...	0.15 max	0.20-0.80
Beryllium	0.003-0.006	...	...

(a) Typical (Ref 2)

nace. Specific solution-annealing temperatures and T6 treatments will be delineated for each set of reported tests. Ductility was measured as the engineering strain to failure (percentage elongation) equal to $\Delta L/L_0$, where L_0 is initial length. Yield and ultimate tensile stresses were reported as engineering stresses. The reported yield stress was based on a 0.002 plastic strain off-

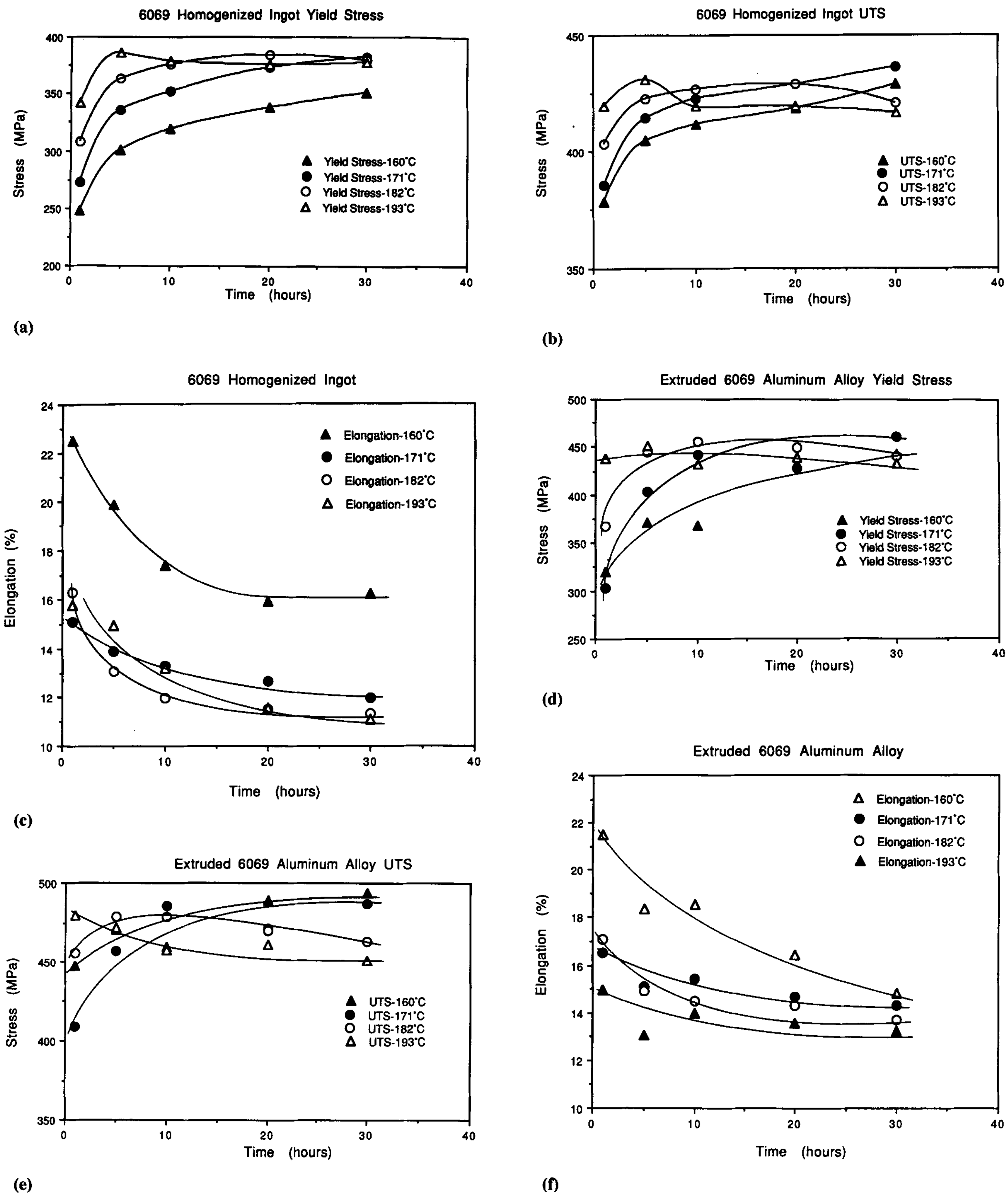

Fig. 1 Ambient-temperature mechanical properties of 6069 ingots and hot extrusions solution treated at 568 °C for 2 h and aged at various temperatures for various times. Each point represents one or two tests.

set. The testing strain rate was always 6.67×10^{-4}/s. Ingots in this study (including those used for extrusions) typically varied from 89 to 110 mm in diameter.

Specimens were kept in the freezing compartment of a refrigerator subsequent to the solution annealing and prior to T6 treatment in order to suppress precipitation. The time from the refrigerator to the T6 temperature was always less than 15 min.

Constant-stress-amplitude fatigue test specimens were removed from random locations within 13 mm diam 6061 extrusions (Alaska Copper and Brass) and 19 mm thick and 55.6 mm wide 6069 bar extrusions, with the long axis of the specimen parallel to the extrusion direction (longitudinal), as well as from 6069 cold-impact extrusions for high-pressure gas cylinders (203 mm ingot diameter). Specimens were machined into circular cross sections of 6.35 mm gage diameter and 19.1 mm gage length prior to T6 heat treatments, and were polished before and after T6. Samples were tested at 1 Hz on a servohydraulic Instron type 8521 machine using a collet-type gripping system. Alignment was checked using four strain gages.

Corrosion-fatigue tests were performed on 6069 and 6061 solid extrusions and ingots, and on 6013 plate. Specimens were machined to 1.0 mm thickness, 178 mm length, and 25.4 mm width. Some specimens were then reduced in width using two 60° notches with a notch radius of 1.27 mm, resulting in a minimum cross section of 1 by 17.78 mm and a stress-concentration factor, K_t, of 3. Other specimens were also reduced in width to 9.53 mm using 76.2 mm radius notches for a K_t of 1. Specimens were then cleaned with a methanol and acetone wipe and loaded into an Instron type 8521 tensile testing machine with a corrosion cell surrounding the specimen. A flow of aerated 3.5 wt% NaCl/water solution was maintained across the specimen at a rate of 0.0105 to 0.0126 L/s, recycled from either a 14 or a 56 L tank for $K_t = 3$ and $K_t = 1$ tests, respectively. All extrusions and rolled plate used a 56 L tank. The 56 L solution was aerated using an air pump with aeration stones; the 14 L solution used only the aeration supplied by the returning saline solution. The saline solution was generally replaced after every two tests. A constant-amplitude fatigue cycle of 103 to 10.3 MPa for $K_t = 3$ specimens and 138 MPa to 13.8 MPa for $K_t = 1$ specimens, both at a frequency of 0.5 Hz, was applied until failure. T6 treatment was performed after machining.

The 6069 specimens for both corrosion-fatigue and constant-stress-amplitude fatigue tests were solution annealed at 568 °C for 2 h and aged at 171 °C for 24 h. The 6061 specimens were solution annealed at 532 °C for 2 h and aged at 177 °C for 8 h. The 6013 specimens were solution annealed at 538 °C for 30 min and aged at 197 °C for 4 h.

3. Results and Discussion

3.1 *T6 Study*

The aging (T6) treatment was first optimized. Ingot and extruded bar specimens were solution annealed at 568 °C for 2 h and then water quenched. They were aged for various times to 30 h at 160, 171, 182, and 193 °C. Results for 6069 ingot and hot-extruded specimens (25 mm thick, 75 mm length) are shown in Fig. 1. A variety of combinations of times between 16 and 24 h and temperatures between 160 and 177 °C produced favorable properties, some combinations resulting in better strength at the expense of ductility. Some aging was performed at 177 °C, although this temperature was not tested in the Fig. 1 portion of the study.

Tensile properties for 6069 ingots were established in Fig. 1. Table 3 lists an average of five 6069 tests for a given T6. Typical strength properties for wrought 6061-T6 (Ref 2) and for rolled 6013-T6 (Ref 3) were exceeded by the 6069 ingots.

3.2 *Extrustions*

The T6 properties of extruded 6069 were also examined. Six configurations were extruded: (1) hollow, relatively thin-wall hot extrusions with a 32 by 32 mm square cross section and a 3.18 mm wall thickness; (2) solid, hot-extruded, 31.8 mm diam circular bars (with relatively small gear "teeth" at the surface); (3) solid, hot-extruded flat (6-to-1 aspect ratio) bars; (4) hot-extruded rectangular (3-to-1 aspect ratio) bars; (5) relatively complex cold-impact-extruded air-bag canisters with concentric thin walls; and (6) cold-impact-extruded high-pressure gas cylinders.

3.2.1 Hot Hollow Extrusions

Ingots with a diameter of 89 mm were heated to 482 to 530 °C to produce hollow extrusions. Tensile specimens were extracted primarily parallel (longitudinal) to the extrusion axis, but also at locations 45° and perpendicular (transverse) to the axis. Data for hollow extrusions are reported in Table 4; each value is an average of two to five tests. The strength of hollow 6069 extrusions was lower in longitudinal directions than for ingots. However, the transverse directions always had higher strength than the longitudinal direction and higher strength than the ingot. Specimens extracted 45° to the extrusion direction exhibited an intermediate strength level, but ductility comparable to that of the longitudinal direction. The decrease in strength of the hollow, square extrusions tensile tested in the longitudinal direction was probably due in part to texture softening. This assumption is supported by the consistent in-

Table 3 Tensile properties of 6069 ingots, extruded 6061-T6, and rolled 6013-T6

Alloy	Yield stress, MPa	Yield stress, ksi	UTS, MPa	UTS, ksi	Elongation, %	T6
6069	373	54.1	408	59.2	11.7	Solution anneal at 566 °C, 1 h; age at 177 °C, 20 h
6061 (extruded)	275	40	310	45	12	Ref 2
6013 (rolled)	324	47	359	52.1	8	Ref 3

creases in strength in specimens tensile tested in the transverse direction and will be discussed further later in this paper.

3.2.2 Hot Round (Solid Circular) Bar Extrusions

Specimens of 6069 were also hot extruded to a solid, circular rod shape with a diameter of approximately 31.8 mm from 89 mm diam ingot. Tensile specimens were cut longitudinal, from both the center and about the half-radius position (both types of longitudinal specimens had essentially identical mechanical properties), and transverse to the extruded rod axis. Extruded specimens from both the longitudinal and the transverse directions had substantially higher T6 strength than the ingots. The fact that the longitudinal and transverse strength values were similar also suggests an absence of a pronounced texture. The strengths also were substantially higher than the thin-wall extrusions cut parallel and 45° to the extrusion axis, and overall strength and ductility were somewhat superior to the transverse thin-wall properties. This suggests that lower longitudinal properties in thin-wall extrusions are not entirely due to texture. Tensile values for solid, circular bar specimens are listed in Table 5.

3.2.3 Hot (Solid Rectangular) Bar and Flat Bar Extrusions

Hot extrusions were also performed by Technical Dynamics Aluminum Corp. on 89 mm diam 6069 ingot. Sets of tensile tests were performed on specimens extracted from flat bar extrusions 12.7 mm thick and 76.2 mm wide, and from bar extrusions 19 mm thick and 55.6 mm wide. These tensile specimens were extracted longitudinal to the extrusion direction and had excellent mechanical properties (Table 5) (Ref 5).

3.2.4 Cold-Impact Extrusions

T6 properties were determined for driver-side automobile air-bag canisters that were cold impact extruded from 92 mm diam 6069 ingot. A canister can be approximately described as three concentric walls of 2.54 to 4.32 mm thickness, parallel to the extrusion direction, attached to a 92.5 mm diam base with a thickness of 5.08 mm. No machining is performed on canisters. The T6 properties were determined for specimens extracted from the base of the cylinder (transverse to the extrusion direction) and from the outermost thin wall (2.6 mm thick), longitudinal to the extrusion direction. Tensile tests revealed favorable properties (Table 6). Some mild strength and ductility anisotropy were noted.

3.3 *AA 6069 Tensile Properties Summary*

Extrusion and ingot data for 6069 are compared with data for other aluminum alloys in Fig. 2 (Ref 2, 3, 6). Overall, 6069-T6 appears to have tensile properties superior to those of 6013-T6 and 6061-T6 and comparable to those of 2024-T3 and 7129-T6. The results of the collective extrusion tests emphasize that the mechanical properties of 6069 extruded alloys

Table 4 Tensile properties of 6069 hot hollow extrusions

Specimen extraction location relative to extrusion axis	Yield stress		UTS		Elongation,	T6
	MPa	ksi	MPa	ksi	%	
Longitudinal	346	50.1	396	57.4	20.9	Solution anneal at 571 °C, 2 h; age at 177 °C, 16 h
Transverse	407	59.0	451	65.4	9.6	Same as above
45°	361	52.4	412	59.7	21.5	Same as above

Table 5 Selected 6069-T6 properties of hot round bar, bar, and flat bar extrusions

Extrusion	Extrusion direction	Yield stress		UTS		Elongation,	T6
		MPa	ksi	MPa	ksi	%	
Round bar	Longitudinal	447	64.8	478	69.3	14.4	Solution anneal at 568 °C, 2 h; age at 177 °C, 16 h
	Transverse	397	57.6	442	64.1	13	Solution anneal at 568 °C, 2 h; age at 177 °C, 16 h
6:1 flat bar	Longitudinal	414	60	448	65	13-17	Solution anneal at 568 °C, 2 h; age at 171 °C, 24 h (Ref 4)
3:1 bar	Longitudinal	441	64	469	68	14.5	Solution anneal at 568 °C, 2 h; age at 171 °C, 18 h (Ref 4)

Table 6 Selected 6069-T6 properties of cold-impact canister extrusions

Extrusion direction	Yield stress		UTS		Elongation,	T6
	MPa	ksi	MPa	ksi	%	
Longitudinal	405	58.7	444	64.4	18	Solution anneal at 568 °C, 2 h; age at 177 °C, 16 h
Transverse	386	56	424	61.5	14	Solution anneal at 568 °C, 2 h; age at 177 °C, 20 h

appear to be extrusion-temperature dependent, and perhaps somewhat configuration dependent. The explanation for this is not always clear, but is the subject of continuing investigation.

3.4 *Fatigue and Corrosion-Fatigue Tests*

Figure 3(a) shows the results of corrosion-fatigue testing of 6069-T6 and 6061-T6 ingots. Very favorable properties are evident in notched ($K_t = 3$) and unnotched ($K_t = 1$) specimens tested in aerated 3.5 wt% NaCl solution. The performance of 6069-T6 is comparable or superior to 6061-T6. The testing procedure was similar to those recently reported in Ref 6. Figure 3(b) compares the 6069-T6 bar extrusions with 6061-T6 solid, circular extrusions and 6013-T6 plate. Again, for $K_t = 3$, the 6069-T6 appears superior to both 6061-T6 and 6013-T6. One complication of these tests is the evident scatter (as much as a factor of ±3 in cycles to failure).

Constant-stress-amplitude fatigue tests were also performed at ambient temperature in air. The 6069-T6 samples were taken from the solid (rectangular) bar extrusions (as for the corrosion-fatigue tests) and also from cold-impact high-pressure gas cylinder extrusions from 203 mm diam ingots. The *S-N* results are shown in Fig. 4. Properties for both types of extrusions are superior to those of 6061-T6 extrusions.

3.5 *Fracture Toughness*

Preliminary fracture toughness tests (Ref 7) on 6069-T6 from other investigators using specimens extracted from cold-impact-extruded ingot into high-pressure gas cylinders indicate a K_{IC} of 35 to 40 MPa$\sqrt{m}$, somewhat higher than for similar extrusions of 6061-T6.

3.6 *Scrap Compatibility*

Although dilution is required to mix 6069 scrap with common alloys, a dilution ratio of only 3:1 or 4:1 is required for mixing with 6061, and a ratio of 7:1 to 8:1 for mixing with

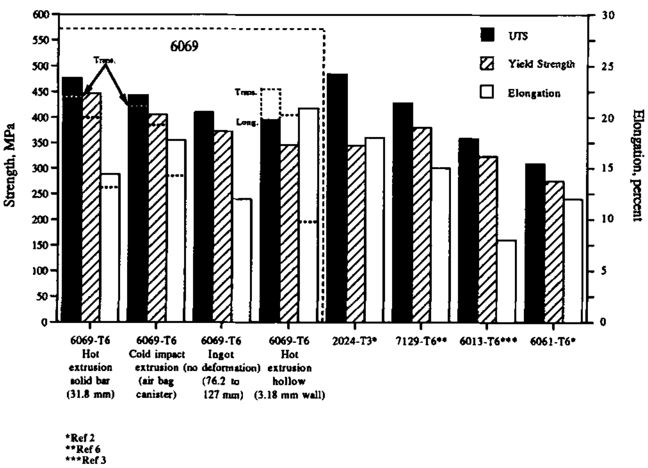

Fig. 2 Comparison of the tensile properties of 6069-T6 ingots and various types of extrusions with other aluminum alloys

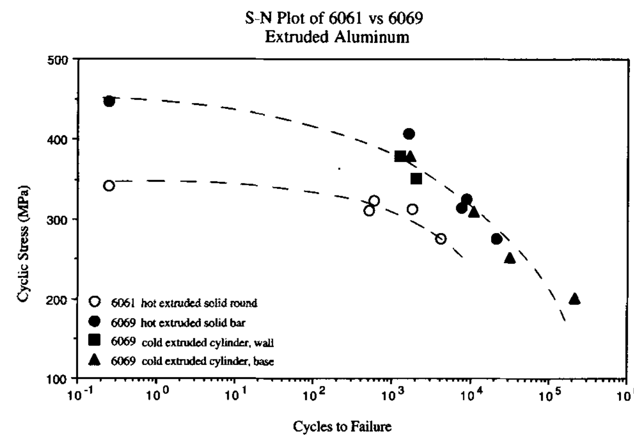

Fig. 4 Extruded 6069-T6 and 6061-T6 constant-strain-amplitude fatigue properties

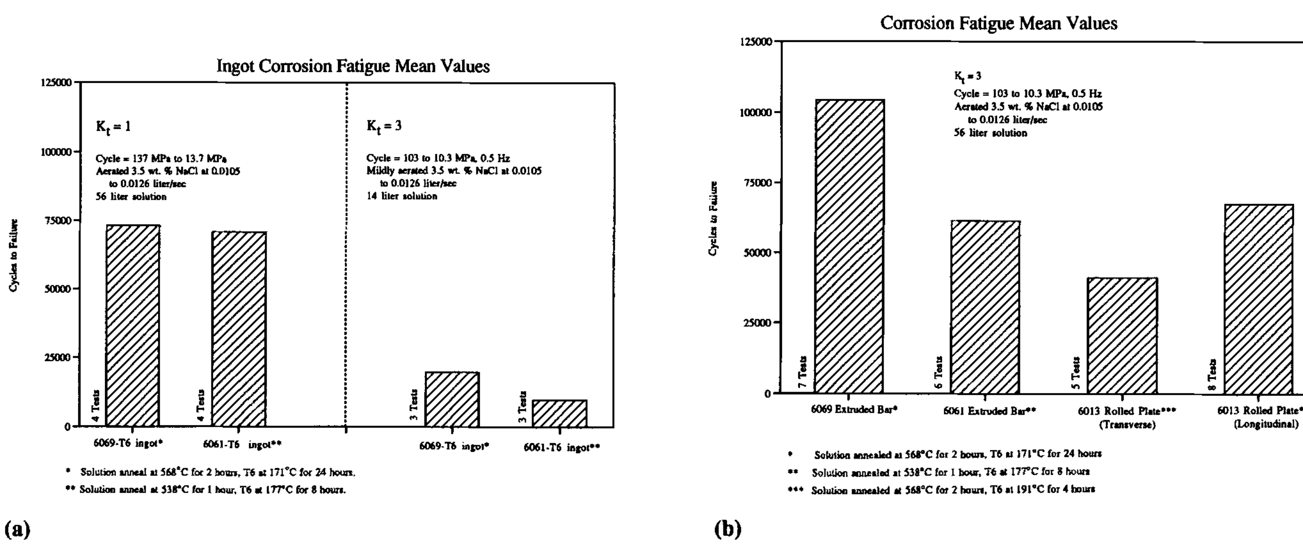

Fig. 3 Comparison of corrosion-fatigue properties of 6069-T6 ingot with 6061-T6 ingot under identical environmental and mechanical conditions with $K_t = 3$ and $K_t = 1$. (b) Comparison of extruded 6069-T6 with 6013-T6 and 6061-T6 ($K_t = 3$)

5052. An average 2*xxx* series alloy would require dilution of 10:1 to 40:1, and 7*xxx* series alloys would require 60:1 to 120:1 dilution.

4. Summary and Conclusions

A new 6069 alloy has been developed for application in hot and cold extrusion and forging. The alloy has favorable formability, with nominal tensile properties after hot or cold extrusion ranging from 380 to 490 MPa (55 to 71 ksi) UTS, 345 to 460 MPa (50 to 67 ksi) yield strength, and 10 to 22% elongation. Good tensile properties appear to be due to a combination of high solidification rate (direct-chill cast ingot), controlled homogenization, composition, and T6 practice. Fatigue and corrosion-fatigue properties are also favorable compared to other aluminum alloys.

Current developmental applications include cold-impact air-bag components, high-pressure gas cylinders, and forged automotive drive-train and suspension parts. Alloy 6069 is scrap compatible with many other 5*xxx* and 6*xxx* alloys.

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References

1. S.C. Bergsma and M.E. Kassner, in *Aluminum Alloys, Their Physical and Mechanical Properties,* Vol 3, T.H. Sanders and E.A. Starke, Ed., Georgia Institute of Technology, 1994, p 187
2. J.E. Hatch, Ed., *Aluminum: Properties and Physical Metallurgy,* American Society for Metals, 1984
3. R.S. Kaneko, L. Barkow, and E.W. Lee, *J. Met.,* Vol 42, 1990, p 16-18
4. Koon-Hall Testing Corp., Portland, OR, April 1994
5. Koon-Hall Testing Corp., Portland, OR, March 1994
6. *Reynolds Aluminum Bulletin No. 279,* Reynolds Aluminum Co., March 1983
7. G. Bhuyan, Powertech, Vancouver, Canada, private communication, Aug 1994