AA 6069: A NEW HIGH STRENGTH ALUMINUM ALLOY

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Abstract

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, 0.1% V. Nominal T6 properties of the ingot without hot or cold deformation are 415 MPa (60 ksi) UTS, 380 MPa (55 ksi) yield strength, and 12% elongation. Properties after hot and cold extrusion in T6 ranged from 380 (55 ksi) to 490 MPa (71 ksi) UTS, 345 (50 ksi) to 450 MPa (65 ksi) yield strength, and 10 to 18% elongation. This alloy also has favorable fatigue and corrosion-fatigue properties. These properties are attributable 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.

Introduction

The general purpose of this study was to develop an aluminum-magnesium-silicon alloy that combined strength, extrudability, favorable corrosion resistance with low cost and scrap compatibility. Six prospective alloy compositions were studied, DF6C2 through 6, and are listed in Table I. AA 6061-T6 properties were used as a comparison. The effects of small composition, T6, and mechanical processing changes on the ambient temperature tensile and fatigue properties of the alloys are reported for ingot and various extruded forms. It will be demonstrated that relatively high strength and fatigue resistant ingot and extrusions can be produced for certain new compositions; now designated AA 6069. Increased strength was anticipated by increasing Si, Mg, and Cu concentration, as these are the principal basis of precipitation strengthening in 6061. Additionally, experiments with other constituents such as V, Be, Ti, Cr, and Sr were performed.

Experimental Procedure

This study utilized aluminum provided in the form of direct chill cast ingots using Wagstaff "Airslip" tooling. Tensile tests were performed on an Instron 4505 screw driven tensile

Table I. Compositions of Typical 6061 and DF6C Alloys (wt%)

	Typical 6061	DF6C2	DF6C3	DF6C4	DF6C5	DF6C5′	DF6C6
Si	.6	.89	.92	.84	.92	.91	.86
Fe	.2	.19	.20	.17	.17	.24	.18
Cu	.3	.89	.83	.77	.78	.76	.75
Mg	1.0	1.45	1.20	1.47	1.41	1.46	1.32
Cr	.1	.20	.24	.20	.22	.21	.20
Ti	—	—	.036	.015	.016	.05	.017
V	—	—	.01	.02	.10	.12	.12
Ga	—	—	.02	.02	.03	—	.02
Sr	—	—	.038	.019	—	—	.038
Be	—	—	.001	—	.003	.006	.007

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 the position). The temperature of the specimens was controlled to within $\pm 2°C$ of the set temperature during solution annealing and aging. A 10 min heat-up was required to achieve the solution anneal temperature once specimens were inserted into the furnace. Specific solution annealing temperatures and T6 treatments will be delineated for each set of reported tests. The ductility was measured as the engineering strain to failure (% El) equal to $\Delta L/L_0$ where L_0 is the initial length. The yield and ultimate tensile stresses are reported as engineering stresses. The reported yield stress is based on a 0.002 plastic strain offset. The testing strain rate was always 6.67×10^{-4} s^{-1}. Ingot and hot extrusion tests were performed on 89 mm to 110 mm diameter ingots.

The plastic "stretch" varied between 1% and 2.5% plastic strain for T6511 treatments. Specimens were kept in the freezing compartment of a refrigerator subsequent to the solution annealing and prior to the stretch and T6 in order to suppress precipitation. The time from the refrigerator to the T6 temperature, subsequent to the stretch, was always less than 1/4 hour.

Constant strain-amplitude fatigue test specimens were removed from random locations within a DF6C5′ 12.7 mm thick flat-extrusion, with the long axis of the specimen parallel with the extrusion direction (longitudinal). Specimens were machined into circular cross-sections of 5.08 mm gage diameter and 10.4 mm gage length. Samples were tested on a servo-hydraulic Instron 8521 using a collet-type gripping system. Strain amplitude was measured across the grips using 25.4 mm and 10 mm extensometers. Cycle frequency was varied to maintain a strain rate of 3.2×10^{-3} s^{-1}. Corrosion fatigue test specimens were removed from random locations within a 110 mm diameter DF6C5 ingot. They were then machined to 1.0 mm thickness, 178 mm length (parallel to the ingot axis), and 25.4 mm width. 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.

Specimens were then cleaned with a methanol and acetone wipe and loaded into an Instron 8521 with a corrosion cell attached to the base of the specimen. A flow of 3.5 wt% NaCl/water solution was maintained across the specimen at a rate of 0.0105 to 0.0126 liters per second. A constant amplitude fatigue cycle of +103.4 to +10.3 MPa, at a frequency of 0.5 Hz, was applied until specimen failure. A new solution was prepared for each test. Specimens for both corrosion-fatigue and constant strain amplitude fatigue tests were solution annealed at 568°C for 1.5 hrs, and aged at 171°C for 24 and 18 hours, respectively.

Results and Discussion

T6 Study

We first attempted to optimize the aging (T6) treatment. The DF6C3 ingot results are shown in Fig. 1. Overall, the best tensile properties occur with a T6 aging of 20 hours at 177°C. Ductility is somewhat low at 188°C and strength is lower at 166°C. Optimal T6 properties will be shown to be slightly dependent on composition for DF6C ingot alloy. Once the composition was optimized based on this T6 treatment, a (slightly) new T6 was determined for the new composition.

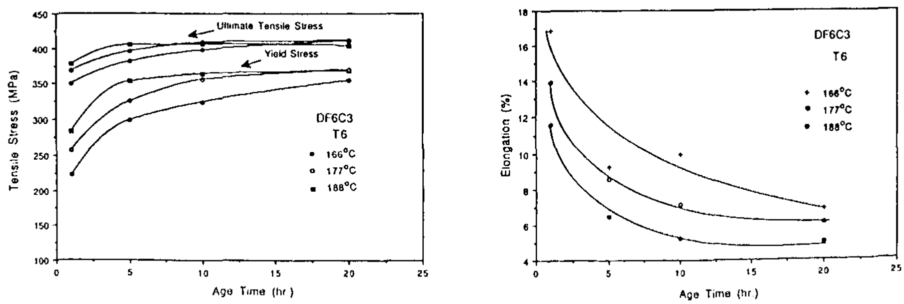

Figure 1. The ambient temperature mechanical properties of DF6C3 ingot with a 571°C solution treatment for 2 hrs and aged at various temperatures for various times. Each point represents 5 tests.

Ingot Study

The tensile properties were established for various composition ingots, DF6C-3 to 6, and the results are listed in Table II. The values listed are an average of 3-5 tests. The table shows that the strength values of DF6C3, 4, 5, and 6 ingots in the T6 condition are fairly similar. One difference is significantly higher ductility with DF6C4, 5, and 6, with overall best *ingot* properties with DF6C4 and 5. Typical 6061-T6 wrought strength properties [1] of 275 MPa (40 ksi) yield strength, 310 MPa (45 ksi) UTS, and 12% El were exceeded by the DF6C ingots as also shown in the table. Some scatter in elongation values was evident in the DF6C6 ingot for unclear reasons.

Table II. Ingot Properties

	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	T6
DF6C3	369 (53.5)	410 (59.5)	6.1	Solution anneal — 571°C, 2 hrs; age — 177°C, 20 hrs
DF6C4	370 (53.6)	414 (60.0)	13.4	Solution anneal — 566°C, 1 hr
DF6C5	373 (54.1)	408 (59.2)	11.7	Same as above
DF6C6	371 (53.8)	412 (59.8)	10.4	Same as above
6061	275 (40)	310 (45)	12	T6 [Ref. 1]

Extrusions

The T6 properties of extruded DF6C alloys were also examined. Four configurations were extruded: a) hollow, relatively thin-wall hot extrusions with a 32 mm × 32 mm cross-section and a 3.18 mm wall thickness, b) solid, hot-extruded, circular, 31.8 mm diameter, bars (with relatively small dimension gear "teeth" at the surface), c) solid, hot-extruded flat bars, and finally, d) relatively complex cold impact-extruded air-bag cannisters with concentric thin walls.

Hot Hollow Extrusions. 89 mm diameter ingots were heated to 482 to 530°C for extrusion. Tensile specimens were extracted primarily parallel (longitudinal) but also perpendicular (transverse) to the extrusion axis. The data for hollow extrusions are reported in Table III. Each value reported is an average of 2-5 tests. The strength of DF6C2, 3, and 4 extrusions was *lower* than for ingots of identical composition. As with ingots, C3 had relatively low ductility. Significant scatter of elongation was observed in the C2 tests of extrusions at ±4%, although slightly better El% is observed in DF6C2 as compared with C3. DF6C4 appears to have similar extruded properties to DF6C2 but less scatter of El% (±2%). Considering these and the DF6C6 ingot data, Sr additions may be associated with ductility losses. The source of elongation scatter in DF6C2 extrusions as with 6C6 ingot is unclear. It was believed that the

Table III. Hot Hollow Extrusion
properties longitudinal to extrusion axis, except as indicated*

		Stretch %	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	T6/T6511**
DF6C2		0	334 (48.4)	374 (54.2)	12.1	Solution anneal — 571°C, 2 hrs
	**	1	354 (51.3)	375 (54.4)	10.6	Age — 177°C, 20 hrs
	**	2.5	351 (50.9)	366 (53.1)	9.8	
	**	2.5	365 (53.0)	383 (55.6)	11.6	
DF6C3		0	341 (49.4)	365 (52.9)	9.3	Same as above
	**	1	352 (51.0)	362 (52.5)	7.6	
	**	2.5	355 (51.5)	362 (52.5)	6.2	
	**	2.5	367 (53.2)	376 (54.6)	7.4	
DF6C4		0	338 (49.0)	370 (53.6)	12	Solution anneal — 568°, 2 hrs
*transverse to extrusion axis		0	343 (49.7)	393 (57.0)	12.8	Same as above (177°C, 16 hrs)

decrease in strength of the hollow, square, extrusions [tensile tested in a direction parallel (or longitudinal) to the extrusion direction] was, possibly, partly due to texture softening. Therefore, a DF6C4 tensile specimen was extracted with the tensile axis perpendicular (transverse) to the hollow extrusion axis. The properties were similar to specimens extracted parallel to the extrusion axis, indicating a lack of pronounced texture effects.

Additionally, one set (of 3) DF6C4 extrusion tensile specimens was ground to 2.54 mm thickness, while a second set (also of 3 specimens) was ground to only 3.00 mm thickness (3.18 mm starting thickness). The yield stress, UTS, and El were identical within testing error, so that the removal of the outermost surface layer does not seem to affect mechanical properties of the extrusion wall.

Hot Solid Circular Bar Extrusions. DF6C5 and DF6C4 specimens were also hot extruded to a solid rod shape approximately 31.8 mm diameter from 89 mm diameter ingot. Tensile specimens were cut longitudinal and transverse to the extruded rod axis, both from the center and about the half-radius position (half-radius and center specimens, both longitudinal, had essentially identical mechanical properties). It was observed that both the parallel and perpendicular directions have substantially higher T6 strength than the thin-wall hollow-square extrusions and ingots (i.e., 25-30% higher than hollow extrusions). The fact that the parallel and perpendicular strength values are similar, as with the specimens extracted from hollow extrusions, also suggests an absence of a pronounced texture effect. The yield strength, UTS, and % El values of solid circular bar specimens are listed in Table IV. Metallography in Fig. 2 indicates that grain structure may also not be an important variable in explaining the disparity in strength between solid and hollow specimens, as both the rod and the hollow extrusions had recrystallized, with similar grain sizes after solution annealing.

Table IV. Summary of Selected T6 Properties
for 31.8 mm Diameter Hot Solid Circular Bar Extrusions

	Extrusion Direction	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	T6
DF6C4 Extrusion (bar)	long. trans.	414 (60.0) 385 (55.9)	461 (66.8) 436 (63.2)	13 14.4	Solution anneal — 568°C, 2 hrs; Age — 177°C, 16 hrs
DF6C5 Extrusion (bar)	long. trans.	447 (64.8) 397 (57.6)	478 (69.3) 442 (64.1)	14.4 13	Same as above

Hot Solid Flat-Bar Extrusions. Hot extrusions were also performed by TDA on 89 mm DF6C5′ ingot. One set of tensile tests was performed on specimens extracted from flat bar extrusions, 12.7 mm thick and 76.2 mm wide, and another used bars 31.8 mm diameter. These tensile specimens were extracted longitudinal to the extrusion direction and had excellent mechanical properties as reported by Koon-Hall [3] in Table V. The 31.8 mm diameter extrusions were identical in configuration to the solid bars in Table IV but are reported here as comparison to the flat bar of identical composition.

Table VI. Summary of Selected T6 Properties for Cold Impact Canister Extrusions

	Extrusion Direction	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	T6
DF6C5 Extrusion (canister)	longitudinal	405 (58.7)	444 (64.4)	18	568°C, 2 hrs; Age — 177°C, 16 hrs
	transverse	386 (56)	424 (61.5)	14	177°C, 20 hrs

The results of the extrusion tests emphasize that the mechanical properties of DF6C extruded alloys appear configuration and extrusion temperature dependent, and not yet fully predictable. The explanation for this is currently unclear, but is the subject of continuing investigation.

Effect of Ambient Temperature Stretch on Extruded T6 Properties

A 1 and 2.5% stretch (T651 treatment) was performed on DF6C2 and DF6C3 hollow extruded specimens and the mechanical properties are reported in Table III. For identical thermal treatment, properties are not improved; rather, a 5% increase in yield stresses, 1-2% decrease in UTS, and a factor of 1.15 to 1.30 decrease in elongation is observed. A modification of the solution anneal from 2 to 25 hours, with a 2.5% stretch, may result in an increase in yield strength by 8%, UTS increase of 3%, and an increase in El of about a factor of about 1.12, still not an impressive change considering the inconvenience of the lengthy time of the solution anneal.

AA 6069

Based upon the above data, the DF6C5 and DF6C5′ alloys appeared superior and are the basis of the new alloy, AA 6069, with the composition specification in Table VII. The T6 of 6069 was re-optimized using a similar procedure as DF6C3 in Fig. 1. Tests from Koon-Hall [2] indicated that, for this revised composition, ingot tensile properties are optimized at 171°C for 24 hours (versus 177°C for 20 hours). This change in optimal T6 probably resulted from composition changes. A summary of 6069 extrusion and ingot data are compared with data from other aluminum alloys in Fig. 3 [1,4,5].

Table VII. AA 6069 Composition

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Sr	Others	
Min.	.6		.4		1.2	.05			.10		each	total
Max.	1.2	.4	1.0	.4	1.6	.30	.1	.1	.30	.05	.05	.15

Fatigue and Corrosion-Fatigue Tests

Figure 4 shows the results of the corrosion-fatigue tests on 6069 (DF6C5) ingot. Very favorable properties are evident in notched (K_t = 3) specimens tested in 3.5 wt% NaCl solution. The results are compared with other alloys reported by [4]. Performance is comparable or superior to the other (unclad) alloys. Constant strain-amplitude fatigue tests

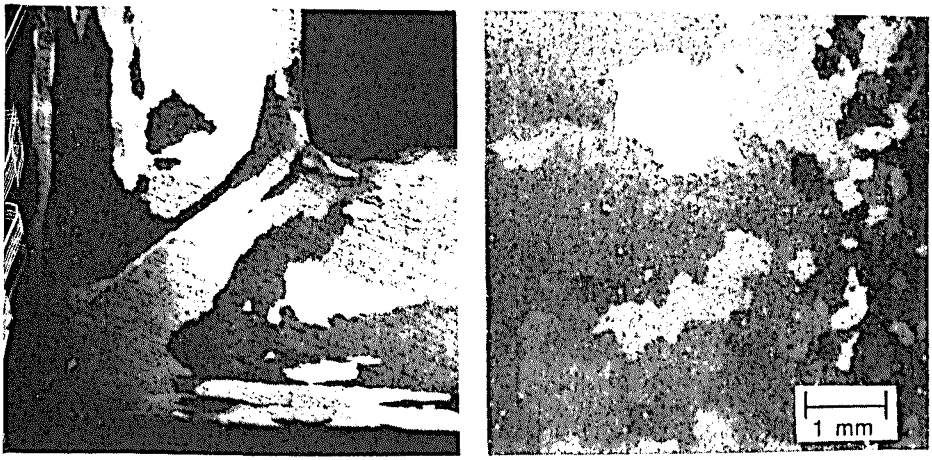

Figure 2. Optical micrographs of extruded hollow bar (left) of DF6C4 and 31.8 mm diameter solid rod, both after T6 treatments. The micrograph planes are normal to the extrusion direction.

Table V. Summary of Selected T6 Properties
of Hot Solid Circular and Flat-Bar Extrusions [3]

	Extrusion Direction	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	T6
DF6C5′ Extrusion (flat)	longitudinal	414 (60)	448 (65)	13-17	568°C, 1.5 hr; Age — 171°C, 18 hrs
(bar)	longitudinal	462 (67)	490 (71)	13	Same as above

Cold Impact Extrusions. T6 properties were determined for driver side automobile air-bag gas canisters that were cold impact extruded from 92 mm DF6C5 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 diameter base, 5.08 mm thick. 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 (same thermal treatments as DF6C5 in Table IV except for a 20 hr age) revealed favorable properties: 405 MPa (58.7 ksi) yield stress, 444 MPa (64.4 ksi) UTS, and 18% El. The base of the canister had somewhat lower properties at 386 MPa (56 ksi) yield stress, 424 MPa (61.5 ksi) UTS, and 14% El. These data are reported in Table VI.

were also performed at ambient temperature in air. The results are shown in Fig. 5. Properties are superior to those reported by others for 6061-T6 [7].

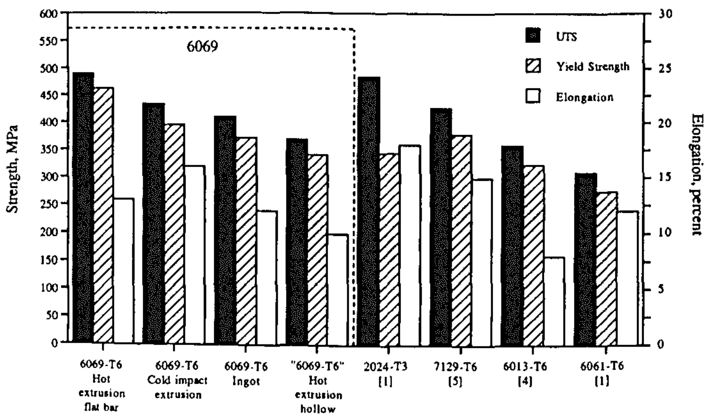

Figure 3. Properties of 6069 T6 ingot and extrusions (DF6C4, 5 and 5′) with other aluminum alloys [1,4,5]. DF6C4 hollow extrusions (quotation marks) are slightly outside 6069 composition range while DF6C5 and 5′ are within the range.

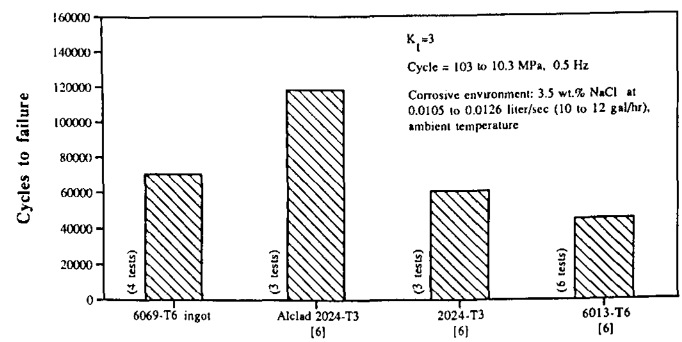

Figure 4. Comparison of corrosion fatigue properties of 6069 (DF6C5) T6 with other aluminum alloys [6] under identical environmental and mechanical conditions.

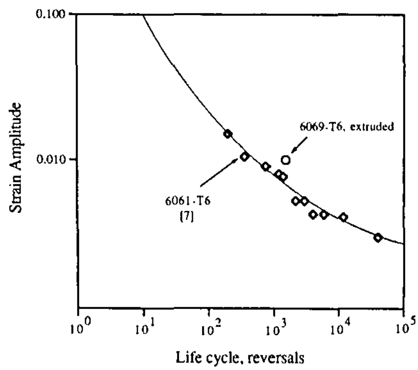

Figure 5. Extruded flat bar 6069-T6 (DF6C5′) constant strain amplitude fatigue properties compared with 6061-T6 [7]. Extensometer on grip section for 6069-T6.

Fracture Toughness

Preliminary tests [8] on specimens extracted (T6) from DF6C5′, cold impact extruded from 109 mm diameter ingot into high pressure gas cylinders, indicate a K_{IC} of 35-40 MPa-$m^{1/2}$, somewhat higher than for similar extrusions of 6061-T6.

Summary and Conclusions

1. A new 6069 alloy was developed for application in hot and cold extrusion and forging.

2. The alloy has favorable formability, with nominal tensile properties after hot or cold extrusion ranging from 380 MPa (55 ksi) to 490 MPa (71 ksi) UTS, 345 (50 ksi) to 460 MPa (67 ksi) yield strength, and 10-18% elongation. Favorable tensile properties appear attributable to a combination of high solidification rate (direct chill cast ingot), controlled homogenization, composition, and T6 practice.

3. Favorable fatigue and corrosion-fatigue properties are also evident as compared to other aluminum alloys.

4. Current developmental applications include cold impact air bag components, high pressure cylinders, and hot extruded automotive door guard beams and forged drive train parts.

5. 6069 is scrap compatible with many other 5XXX and 6XXX alloys.

6. The improved properties are achieved with only incremental increase in cost.

Acknowledgements

We are grateful for the support by the Oregon Economic Development Department, USBM, and Oregon Joint Graduate Schools through the Oregon Metals Initiative. Metallography support and helpful comments by Prof. E. Evangelista of the Univ. of Ancona, Italy, are gratefully acknowledged. The mechanical testing by M.C. Tolle, M. Delos-Reyes, and X. Li was vital.

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