A NEW HIGH STRENGTH 6XXX ALLOY

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Abstract

A new 6XXX alloy has been developed for application in hot and cold extrusion and forging. Currently designated DF6C™ (patent pending), 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 485 MPa (70 ksi) UTS, 345 (50 ksi) to 450 MPa (65 ksi) yield strength, and 10 to 18% elongation. These properties are attributable to a combination of high solidification rate, controlled homogenization, TMP, 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, which are comparable in strength, diluted DF6C is generally scrap compatible with many other 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. Five alloy compositions were studied: DF6C2-6. The compositions of the alloys are listed in Table I. The effects of small composition, heat treatment, and mechanical processing changes on the ambient temperature tensile properties of the alloys are reported, in extruded and ingot form. It will be demonstrated that relatively high strength ingot and extrusions can be produced.

Experimental Procedure

This study utilized aluminum provided in the form of direct chill cast ingots. The compositions of the ingots tested in this study are, again, given in Table I. Tensile tests were performed on an Instron 4505 screw driven tensile machine with computerized data acquisition. Specimen geometries varied, and the typical gage dimensions for ingot

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

	Nominal 6061 (1)	DF6C2	DF6C3	DF6C4	DF6C5	DF6C6
Si	.6	.89	.92	.84	.92	.86
Fe	.25	.19	.20	.17	.17	.18
Cu	.28	.89	.83	.77	.78	.75
Mg	1.0	1.45	1.20	1.47	1.41	1.32
Cr	.20	.20	.24	.20	.22	.20
Ti	—	—	.036	.015	.016	.017
V	—	—	.01	.02	.10	.12
Ga	—	—	.02	.02	.03	.02
Sr	—	—	.038	.019	—	.038
Be	—	—	.001	—	.006	.007

characterization were 5.1 mm diameter and 25.4 mm length. Specimens were evaluated from random positions within the ingots; it was determined that the mechanical properties were independent of the position. Specimens from most extrusions (hollow) had the dimensions shown in Fig. 1. The temperature of the specimens was controlled to within ±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.

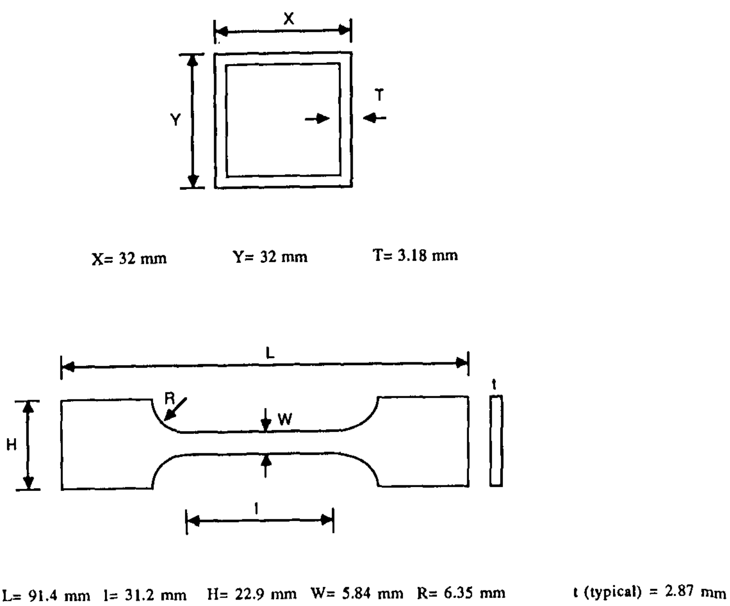

Figure 1. Dimensions of DF6C2, 3, 4 hollow extrusions and extracted tensile specimens.

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}.

The plastic "stretch" varied between 1% and 2.5% plastic strain for T651 treatments. Specimens were kept in the freezing compartment of a refrigerator subsequent to the solution anneals and prior to the stretch and T6 to suppress precipitation. The time from the refrigerator to the T6 temperature and stretch prior to the T6 temperature was always less than 1/4 hour.

Direct chill cast ingots using Wagstaff "Airslip" tooling were extruded by TDA in Oregon. Extrusions of DF6C2 were performed on 114 mm ingot while DF6C3-6 on 89 mm ingot. Extrusions were typically performed between 454°C and 510°C. Tests to determine times and temperatures for optimum T6 properties were performed on ingots that were 111 mm in diameter, except C3, at 105 mm diameter.

Results and Discussion

T6 Study

We first attempted to optimize the aging (T6) treatment. The results are shown in Fig. 2. Basically, these first series of tests confirm that the ultimate tensile strength (UTS) is approximately independent of the T6 temperature for T6 times greater than about 10 hours. The yield strength is independent of T6 temperatures between 177°C and 188°C for times over about 10 hours. 166°C resulted in about 14 MPa lower yield stress after 20 hours. Elongations were highest for 166°C, followed by 177°C, then 188°C. Overall, 166°C and 177°C provide roughly identical properties after a 16-20 hour T6.

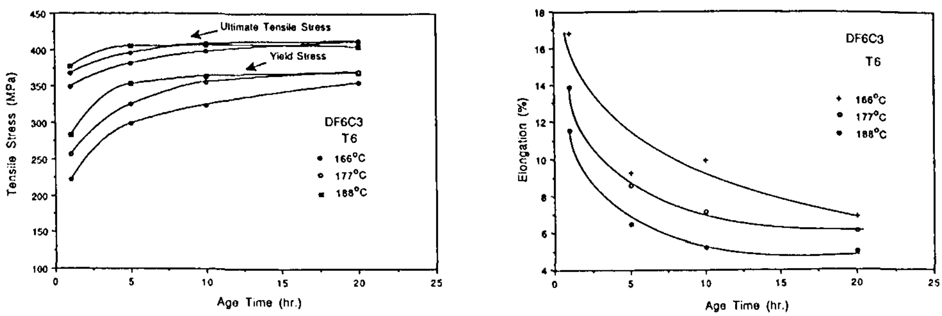

Figure 2. The T6 ambient temperature mechanical properties of DF6C3 ingot (105 mm dia.) with a 571°C solution treatment for 2 hrs. Each point represents 5 tests.

Ingots Study

Once an optimum T6 treatment (177°C for 20 hours) was determined, the properties of other ingots were established and DF6C-3 to 6 results are listed in Table II. The values listed are an average of 3-5 tests.

The table shows that the strength values of DF6C4, 5, and 6 ingots in the T6 condition are fairly similar to C3. One difference is significantly higher ductility with DF6C4, 5, and 6, with overall best ingot properties with DF6C4.

Typical 6061-T6 strength properties [1] of 275 MPa (40 ksi) yield strength, 310 MPa (45 ksi) UTS, and 12-17% El were exceeded by the DF6C3 ingot.

Table II. Ingot Properties (T6 — 177°C, 20 hrs)

	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	Homogenization and Solution Anneal
DF6C3	369 (53.5)	410 (59.5)	6.1	Solution anneal — 571°C, 2 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

Extrusions

The T6 properties of DF6C alloys in the extruded condition were also examined. In particular, three types of configurations were extruded; hollow, relatively thin-wall extrusions with a cross-section illustrated in Fig. 1, circular bars (with relatively small dimension gear "teeth" at the surface), and finally, a relatively complex impact extruded air-bag cannister with concentric thin walls. The hollow extrusions are discussed first.

The extrusion process consisted of heating to 454-510°C 105 mm ingots for C2, and 89 mm ingots for C3, 4, 5, and 6 prior to extrusion. Tensile specimens were extracted parallel to the extrusion axis and the configuration is illustrated in Fig. 1. The data are reported in Table III. Each value reported is an average of 2-5 tests. The DF6C2, 3, and 4 strength values were *lower* for these configuration extrusions than ingots of identical composition, consistent with data listed in [1] for 6061 T6. It should be mentioned that significant scatter of elongation was observed in the C2 tests of extrusions at ±4%. Slightly better El% is observed in DF6C2 as compared with C3. Slightly less scatter in elongation for C3, as compared with C2, may be due to Sr additions. DF6C4 appears to have similar extruded properties to DF6C2 but less scatter of El%.

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

Table III. Extruded Ingot Properties (T6 — 177°C, 20 hrs)
Hollow extrusion, properties parallel to extrusion axis

	Stretch %	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	Homogenization and Solution Anneal
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	
	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	Solution anneal — 571°C, 2 hrs
	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	

(3.18 mm starting thickness). The yield stress, UTS, and El were nearly identical within testing error, so that the removal of the outermost surface layer does not seem to affect mechanical properties of the extrusion wall material.

It was believed that the decrease in strength of the hollow, square, extrusions (tensile tested in a direction parallel to the extrusion direction) was, possibly, partly due to texture softening, which may be less pronounced for a solid bar extrusion. Accordingly, DF6C5 and DF6C4 specimens were extruded in (approx. 25.4 mm diameter) rod shape from 88.9 mm diameter ingot. Tensile specimens were cut parallel to the extruded rod axis, both from the center and about the half-radius position. Specimens were also extracted *perpendicular* to the extrusion direction. It was observed that *both* the parallel and perpendicular directions have substantially higher T6 strength than the thin-wall hollow-square extrusions (half-radius and center specimens had essentially identical mechanical properties). The fact that the parallel and perpendicular strength values are similar suggest an absence of a pronounced texture in the bar. Whether a substantial texture exists in the hollow extrusion requires tests perpendicular to the extrusion direction (or x-ray examination) which were not performed due to the small size. The yield strength, UTS, and % El values are listed in Table IV. Perpendicular specimen dimensions were 2.8 mm diameter, 10.9 mm length. Metallography in Fig. 3 indicates that grain structure may not be an important variable, as both the rod and the hollow extrusions had recrystallized, with similar grain sizes after solution annealing followed by T6 treatments.

T6 properties were determined for an automobile air-bag gas canister cold impact extrusion from DF6C5 ingot. The 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. The T6 properties were determined for specimens extracted from the base of the cylinder (perpendicular to the extrusion direction) and especially from the outermost thin wall (2.6 mm thick) parallel to the extrusion direction. Tensile tests (same

Table IV. Summary of Selected T6 Properties for Extrusions
T6 — 177°C, 16 hrs

	Extrusion Direction	Yield Stress MPa (ksi)	UTS MPa (ksi)	El %	Homogenization and Solution Anneal
DF6C4 Extrusion (bar)	parallel	414 (60.0)	461 (66.8)	13	Solution anneal — 568°C, 2 hrs
	perp.	385 (55.9)	436 (63.2)	14.4	
DF6C5 Extrusion (bar)	parallel	447 (64.8)	478 (69.3)	14.4	Same as above
	perp.	397 (57.6)	442 (64.1)	13	

thermal treatments as DF6C5 in Table IV except for a 20 hr T6) 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.

The results of the extrusion tests emphasize that the mechanical properties of DF6C extruded alloys appear configuration dependent, and not yet fully predictable.

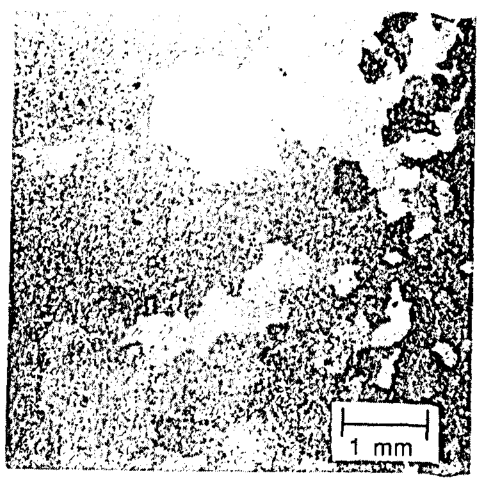

Figure 3. Optical micrographs of extruded hollow bar (left) of DF6C4 (see Fig. 1) and 25 mm diameter solid rod, both after T6 treatments (16x). The micrograph planes are normal to the extrusion direction.

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 were 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 El 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 time of the solution anneal.

Data Reproducibility

It was noted that the ductility of DF6C2 extruded alloy showed some lack of reproducibility. Statistical analysis revealed that Be and Sr additions improved the average standard deviation of ductility (normalized by the average ductility) by a factor of 1.5 to 2.0.

Summary and Conclusions

A new 6XXX alloy has been developed for application in hot and cold extrusion and forging. Currently designated DF6C™ (patent pending), it contains ~2% Mg+Si, ~1% Cu, 0.2% Cr, 0.1% V. Nominal T6 properties of the ingot without hot or cold extrusion 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 485 MPa (70 ksi) UTS, 345 (50 ksi) to 450 MPa (65 ksi) yield strength, and 10 to 18% elongation. These properties are attributable to a combination of high solidfication rate, controlled homogenization, TMP, 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, which are comparable in strength, diluted DF6C is generally scrap compatible with many other 6XXX alloys.

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Reference

1. Aluminum Standards 1988, Aluminum Society of America, Washington, DC, 1988.