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Development and Processing Improvement of Aerospace Aluminum Alloys—Development of AL-Cu-Mg-Ag Alloy (2139)

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Final Report Supplement

Development and Processing Improvement of Aerospace Aluminum Alloys

Development of Al-Cu-Mg-Ag Alloy (2139)

NASA Contract No. NNL04AB64T/GS-23F-0281K

This final report supplement in presentation format describes a comprehensive multi-tasked contract study to continue the development of the silver bearing alloy that was initiated under the original contract study before modification. The initial contract activity included two commercial scale ingots rolled in one inch gauge plate, now registered as aluminum alloy 2139 by the Aluminum Association. It did not include characterization of the rolled product in thicker gauges, or correlation of processing, metallurgical structure, and properties of such thicker gauges. This supplement presents the additional work conducted in this endeavor. The study was funded by the Advanced Space Transportation Programs Office and managed initially by the Metals and Thermal Structures Branch and more recently by the Advanced Materials and Processing Branch, Structures and Materials Competency. Mr. John A. Wagner served as the Technical Representative of the Contracting Officer. The primary contractor was Analytical Services and Materials Inc. and the program manager was Mr. W. Barry Lisagor, a senior scientist with AS&M. The major portion of the experimental work completed under this supplement was conducted by ALCAN Rolled Products LLC., as a principal sub-contractor and the principal investigator was Dr. Alex Cho, a senior scientist with ALCAN Rolled Products.

Under the task supplement on aluminum alloy 2139, considerable progress has been achieved in raising the technology readiness level of this promising new alloy to near application status.

The additional two commercial scale ingots were processed into nominal plate gauges of two, four and six inches, and were extensively characterized in terms of metallurgical and crystallographic structure, and resulting mechanical properties. Emphasis was focused on durability and damage tolerance as well as strength and resistance to environmental degradation.

Alloy 2139 is processed by conventional stress relieve and artificial aging practices but does not require the cold deformation processing to develop attractive combinations of strength, toughness, and fatigue crack growth resistance as do conventional 2XXX alloys. This is due primarily to the fact that the strengthening phase, omega, is homogeneously precipitated upon aging, compared to theta prime in more conventional alloys which is heterogeneously precipitated and requires cold work to develop initiation sites for the aging process.
This report includes comparisons of the property combinations for this alloy and 2XXX and 7XXX alloys more widely used in high performance applications. It shows the dramatic improvement in all combinations of properties, including ballistic impact

performance which cannot be overlooked in this potentially important application. Moreover, the properties of this alloy are retained in all gauge thicknesses, contrary to typical reductions observed in thicker gauges of the other alloys in the comparison. The advancements achieved in this study are expected to result in rapid, widespread use of this alloy in a broad range of ground based, aircraft, and spacecraft applications.

Development of Al-Cu-Mg-Ag Alloy (2139)

Alex Cho

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Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Contents

I. Background

II. Metallurgical attributes of the Al-Cu-Mg-Ag alloy system

III. Development of 2139 (Al-Cu-Mg-Ag alloy) wrought product

- Effect of dispersoid forming elements

IV. Development of 2139 thick gauge plate product

V. Summary & Conclusion

I. Background

Three Alloy Groups for Aerospace Applications

- 2xxx-T8xx (T6xx)
- 7xxx-T7xx (T6xx)
- 2xxx-T3xx

Each of these groups of alloys has unique benefits and shortcomings.

For predominantly damage tolerant applications, 2xxx-T3xx products are commonly used, despite numerous shortcomings as follows:

Damage Tolerance Capability of 2xxx alloys

Limitations of –T3xx type temper

a. Limited Product Thickness

- poor SCC resistance for thick plate (Slow Quench)

b. Limited Product Forms

- Very large amount of cold work by "cold rolling" is available only for thin plate

c. Limited Fabrication Process

- Age Forming cannot be utilized.
- Cannot be processed to "O-temper" product
  Formability of –O temper (annealed) is not available

- Therefore, it would be desirable to develop a 2xxx alloy in an artificially aged temper (T6 or T8 type temper) having DT capabilities of T3xx type temper product.

*II. Metallurgical benefits of Al-Cu-Mg-Ag alloy system**

Goal: 2xxx alloy in an artificially aged temper (T6 or T8 type temper) having Damage Tolerance (DT) and Durability (D) capabilities of T3xx type temper product.

element	Si	Fe	Cu	Mn	Mg	Ag
wt.%	0.1	0.15	4.5 - 5.5	0.20 - 0.6	0.20 - 0.8	0.15 - 0.6

Metallurgical Attributes of Alloy 2139

Major strengthening phase is Ω(Al2Cu) phase

- **Ω phase nucleates homogeneously in the grain matrix without cold work**
- **This leads to less GB precipitation and reduces propensity for intergranular fracture**

Contains no Zr as a dispersoid forming element

- **Reduces GB precipitation**

Contains Mn as a dispersoid forming element

- **Reduces Planar slip to improve Toughness**

*note:This part has been published in the proceedings of The 10th International Conference of Aluminum Alloys at Vancouver, Canada, June 2006

Addition of small amounts of Mg and Ag to Al-Cu alloys promotes the nucleation of plate-like precipitates known as **Ω (Al_2Cu)** phase.

alloy system	example alloys	strengthening phase	nucleation mode	cold work?
Al-Cu	2219,2519	θ' (Al_2Cu)	heterogeneous	yes
Al-Cu-Mg	2024 ,2014	S' (Al_2CuMg)	heterogeneous	yes
Al-Cu-Mg-Ag	**2139**	**Ω (Al_2Cu)**	**homogeneous**	**no**
Al-Zn-Mg	7039,7108	η', η ($MgZn_2$)	homogeneous	no
Al-Zn-Mg-Cu	7050,7075	η', η ($MgZn_2$)	homogeneous	no

Homogeneous nucleation mechanism of Ω phase

- achieve high strength without high level of cold work prior to artificial age.
- more uniform distribution of precipitates without relying on dislocations, sub-grain and grain boundaries as nucleation sites.
- less prone to intergranular and intersubgranular fracture after artificial age

III. Effect of dispersoid forming elements in 2139 –T8**

Optimization of Dispersoid Forming Element – *Why Mn ?*

The experiments were conducted with industrial scale trials using full plant size ingots (13,000 lbs. ingots)

Comparison I

Dispersoid forming Elements ; Mn vs. Zr

	Cu	Mg	Ag	Mn	Zr
Alloy A (Mn)	4.90	0.46	0.38	0.32	0.002
Alloy B (Zr)	4.81	0.45	0.39	0.01	0.14

Comparison II

Dispersoid forming Elements ; Mn vs. Mn + Zr

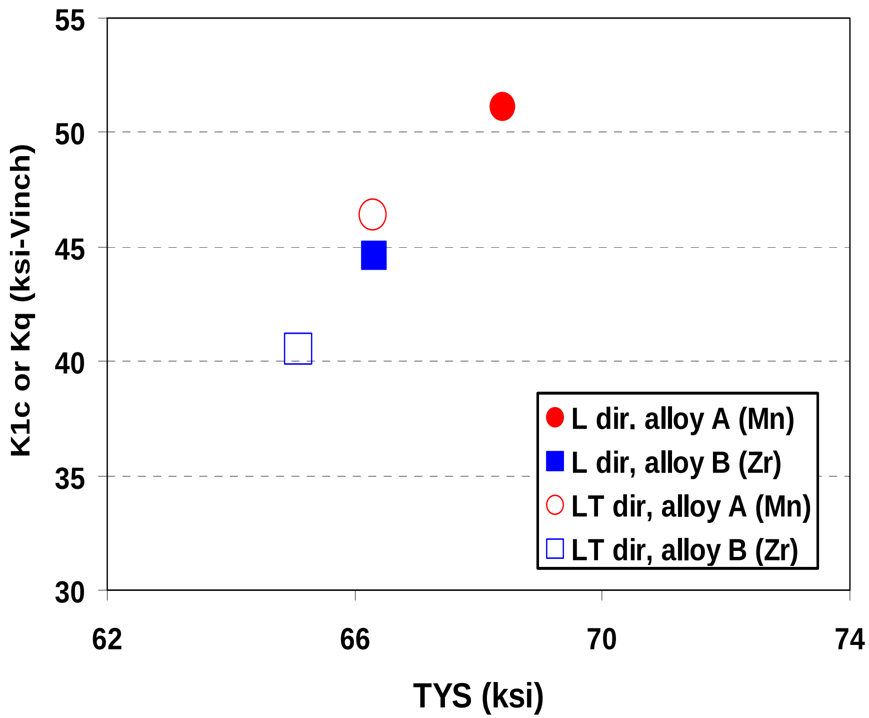
	Cu	Mg	Ag	Mn	Zr
Alloy S (Mn)	4.95	0.45	0.34	0.26	0.001
Alloy P (Mn+Zr)	4.93	0.43	0.34	0.20	0.09

**note: This part has been published in the proceedings of The 10^{th} International Conference of Aluminum Alloys at Vancouver, Canada, June 2006

Alloy A with Mn shows higher combination of Strength and Fracture Toughness

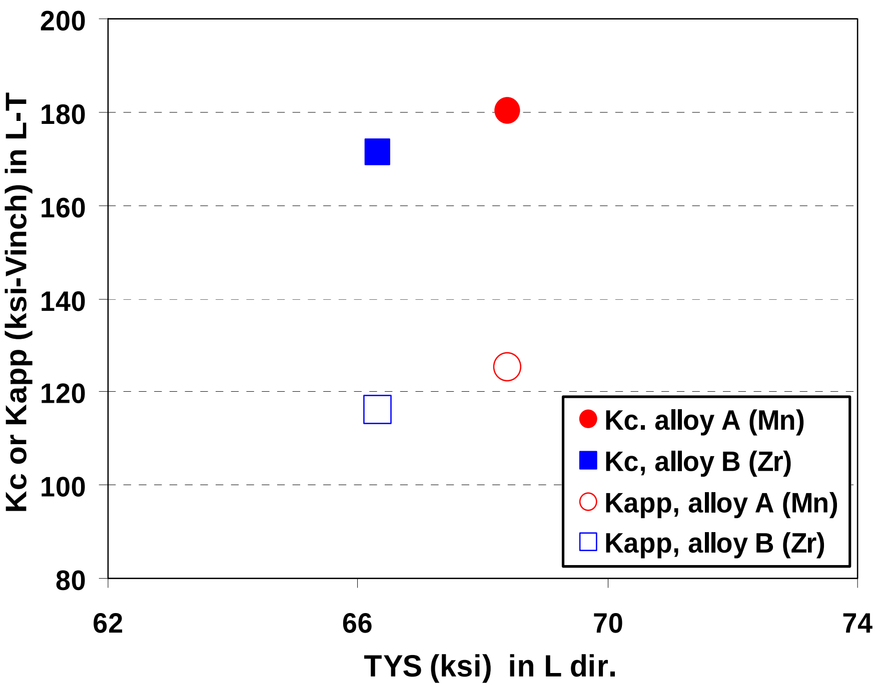
Effect of Dispersoid ; Mn vs. Zr

1 inch ga 2139-T8 plate CT specimen B=1 in. W=3 in.

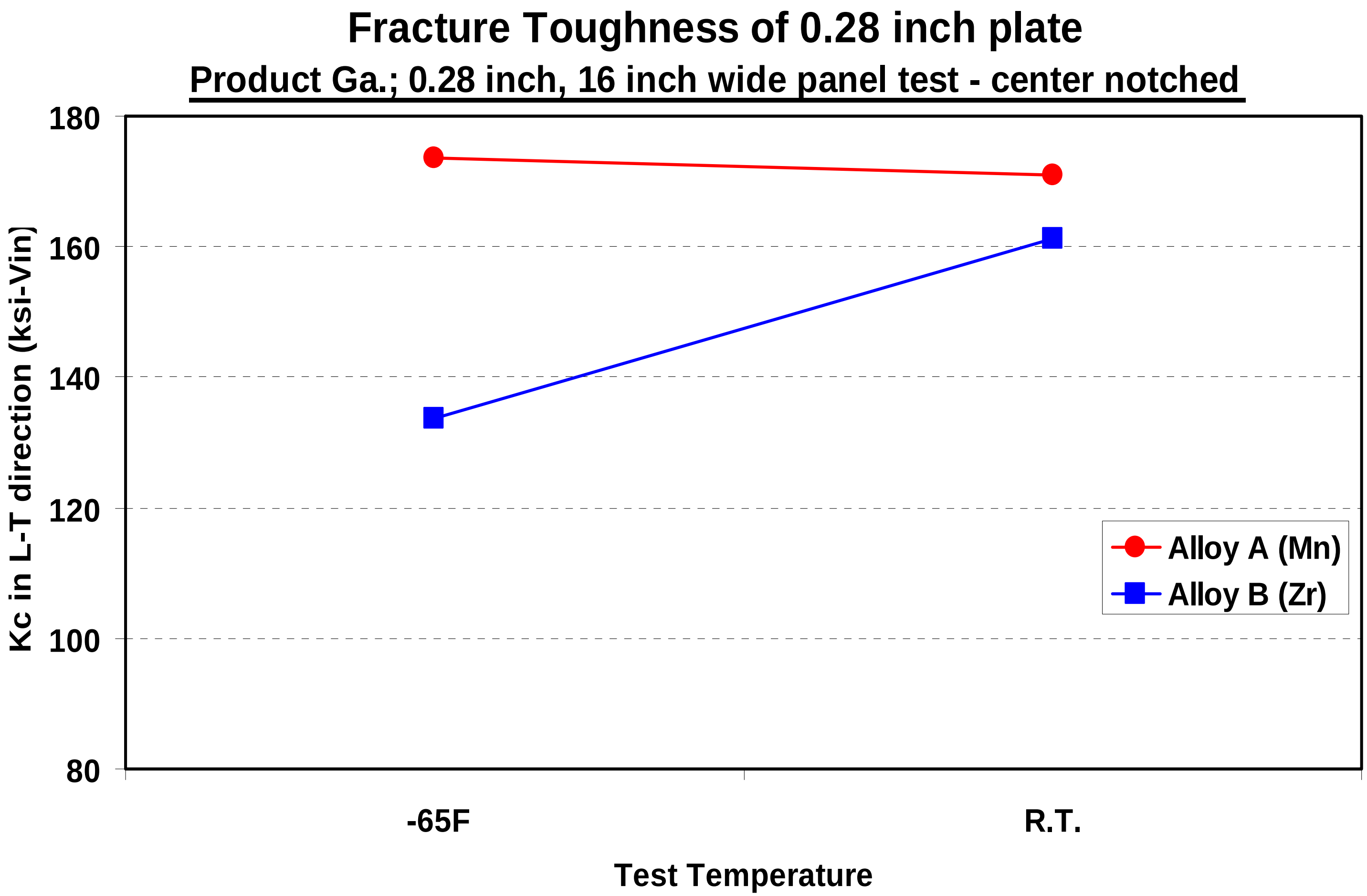


Effect of Dispersoid ; Mn vs. Zr

1 inch ga 2139-T8 plate, M(T) specimen B=0.25 in. W=16 in.



Difference in Fracture Toughness between alloy A(w/Mn) and alloy B(w/Zr) becomes more pronounced at –65 deg F which is the service environment for aircraft flying at high altitude



Alex Cho (304-273-7038), Alcan Rolled Products LLC, December 8, 2006 NASA Contract no. NNL04AB64T with AS&M Inc..

SEM Fractography after fracture tests at –65 deg F

ALLOY A: Al-Cu-Mg-Ag-Mn alloy

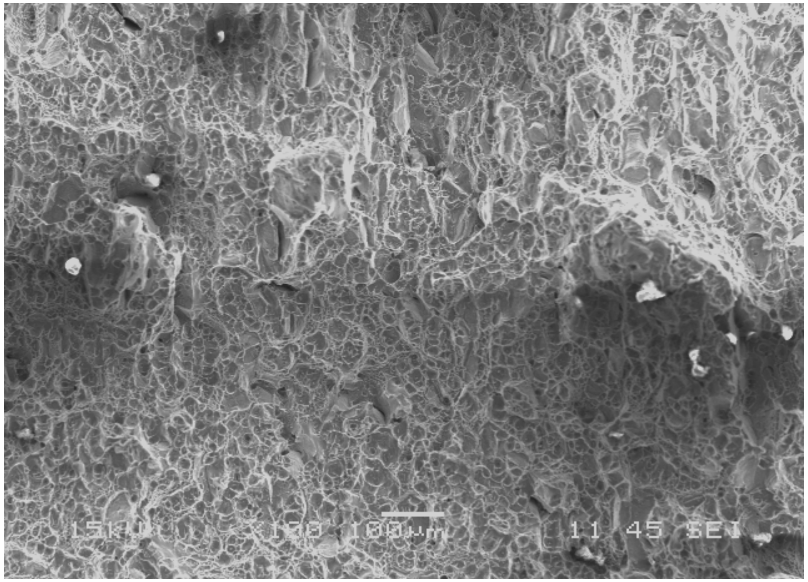


Figure 1. Fractography of A sample tested at -65°F (showing ductile fracture mode)

ALLOY B: Al-Cu-Mg-Ag-Zr alloy

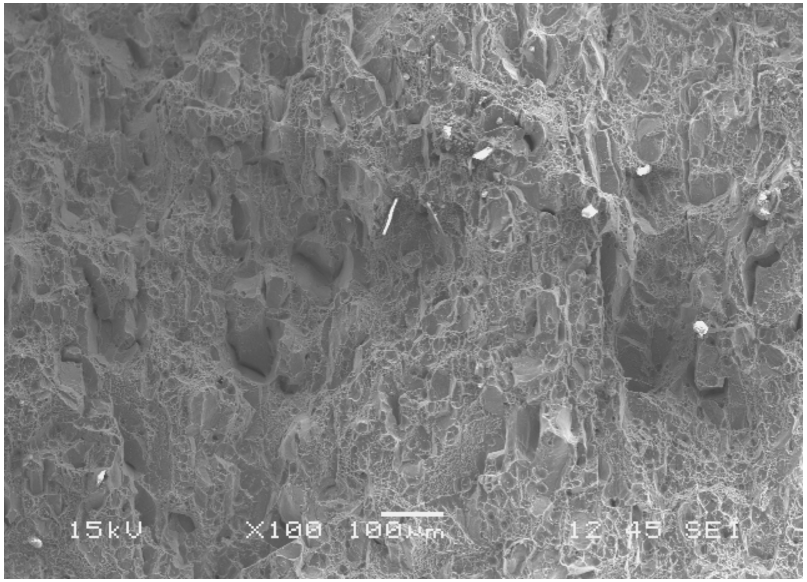
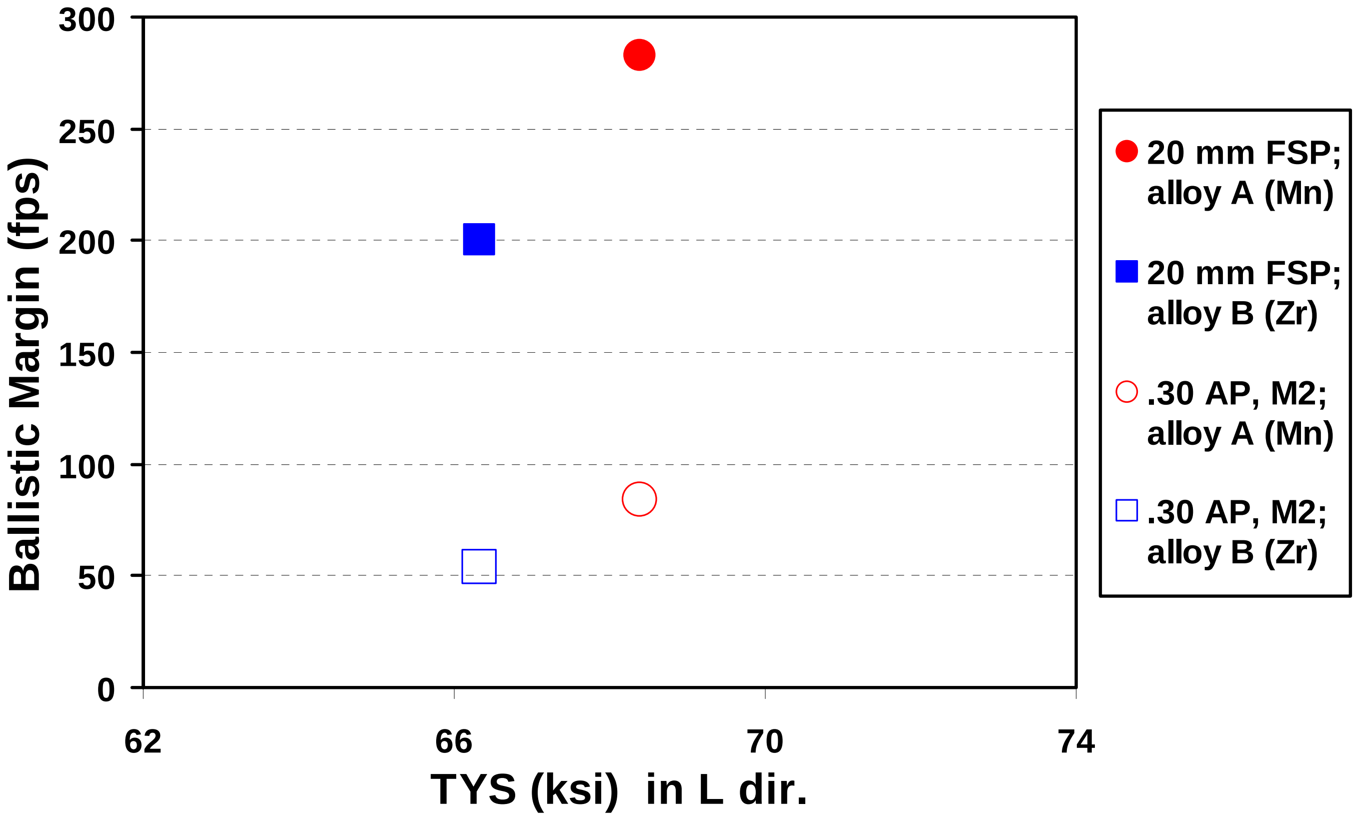


Figure 2. Fractography of B sample tested at -65°F (showing many areas with brittle fracture mode)

Alloy A(w/Mn) shows better ballistic performance,compared to Alloy B(w/Zr)

Effect of Dispersoid on Ballistic Performance

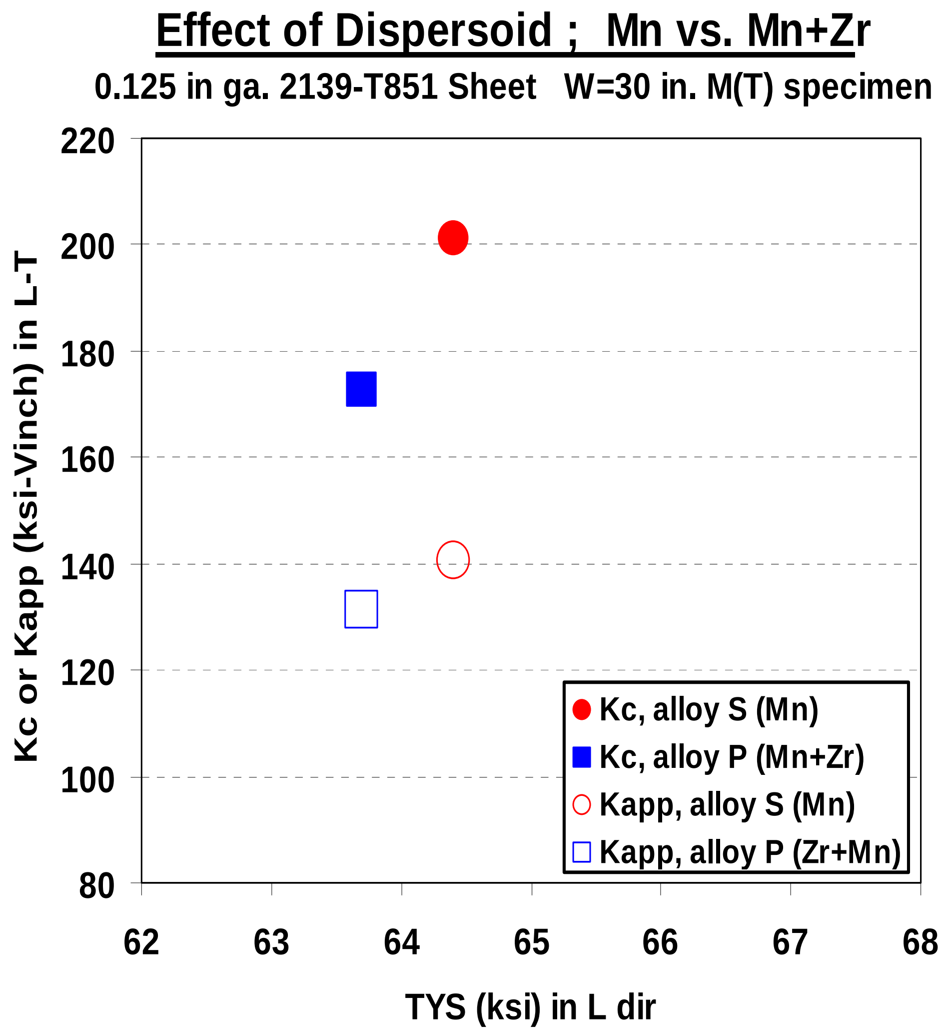
□ **1 inch ga 2139-T8 plate are tested per MIL-DTL-46192C**



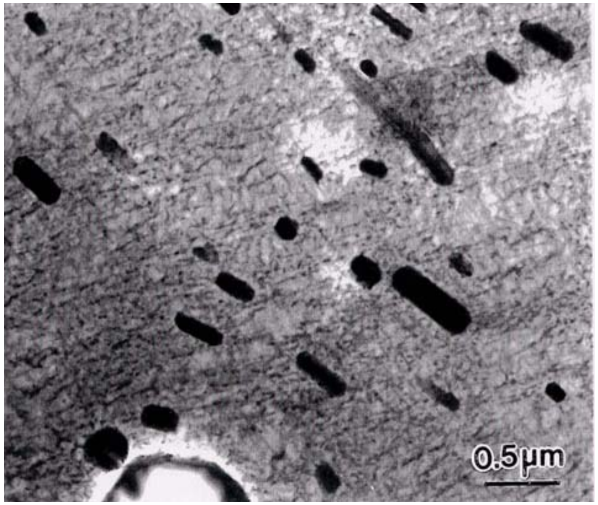
Note: FSP ; Fragmented Shrapnel Penetration tests AP ; Armor Piercing tests

__Adding Zr to Al-Cu-Mg-Ag-Mn alloy lowers Fracture Toughness__

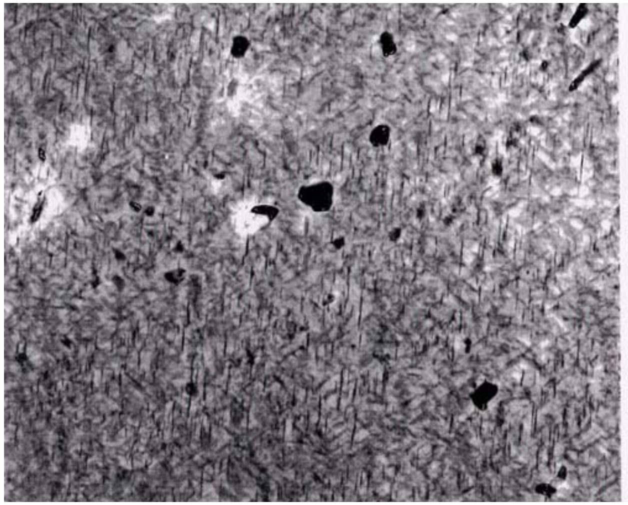
- This indicates that Zr containing dispersoids could be detrimental to Damage Tolerance of Al-Cu-Mg-Ag alloy in T8 temper



Large particles of Mn containing dispersoids in Al-Cu-Mg-Ag-Mn alloy



Al-Cu-Mg-Ag-Mn alloy



Al-Cu-Mg-Ag-Zr alloy

Note: Both figures are under identical magnification.

Zr-containing particles at (sub)grain boundaries provide nucleation sites for Cu-containing particles

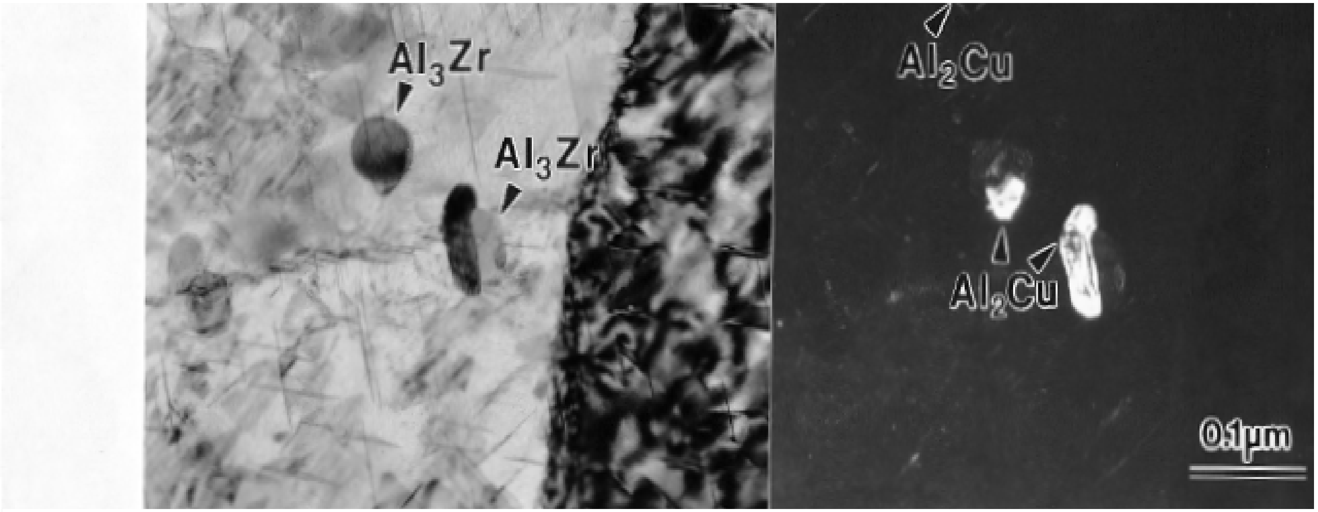


Fig. a) BF image of θ' phase(Al_2Cu) formed at Al_3Zr

Fig. b) DF image shows θ' in the matrix and Al_3Zr by using θ' reflection

Note: Fig. **a** and Fig.**b** are under identical magnification.

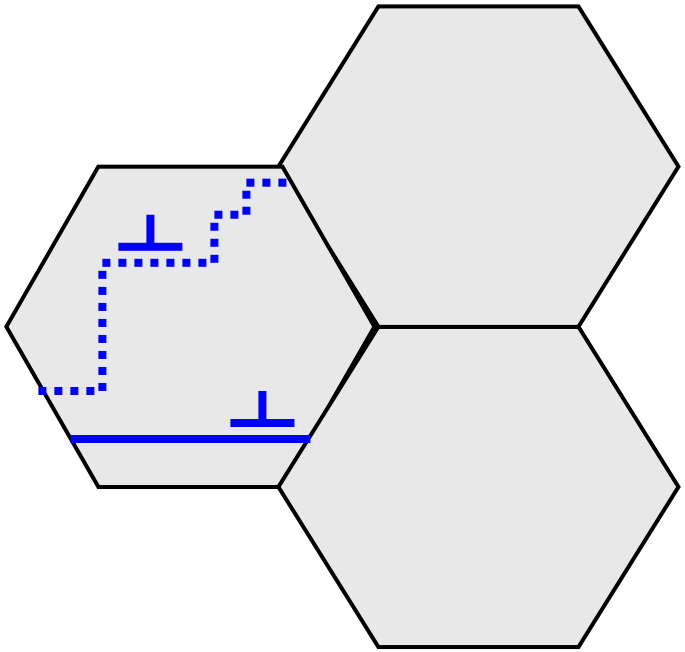
Zr-containing particles at (sub)grain boundaries provide nucleation sites for Cu-containing particles.

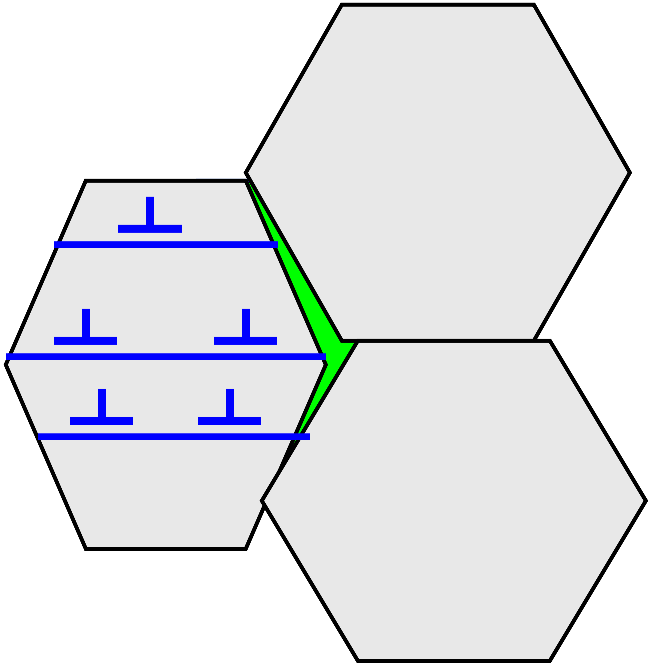
- This would weaken grain boundaries by further promoting boundary precipitation and PFZ’s.

Alloys with weak g.b. strengths are more prone to intergranular fracture at very low service temperatures or at extremely high deformation rates typical of ballistic impact.

Schematic Diagram of Deformation Mode for G.B. Failures

Homogeneous deformation requires both cross slip and planar slip mechanisms





Cross slip mechanism

-**Thermally activated process**

-**Relying on diffusion kinetics**

At Low Temp. or At Very High Deformation rate

- **Cross Slip mechanism is less favored**
- **Planar Slip mode becomes dominant**

Damage Tolerance Capability of 2139 plate can be evaluated by comparing to the commonly used Damage Tolerant Al alloys in Aerospace and Military Applications

2324-T39; Lower wing plate for large commercial Airplanes (1-1.5")
- *best fatigue resistant Al alloy*

2124-T8151; Ribs & Spars for Fighter plane (1"- 6")
- *best fracture toughness in 2xxx-T8xx product*

7475-T7351; Lower Wing for Small Airplanes (1.5" - 4")
- *best fracture toughness in 7xxx-T7xx product*

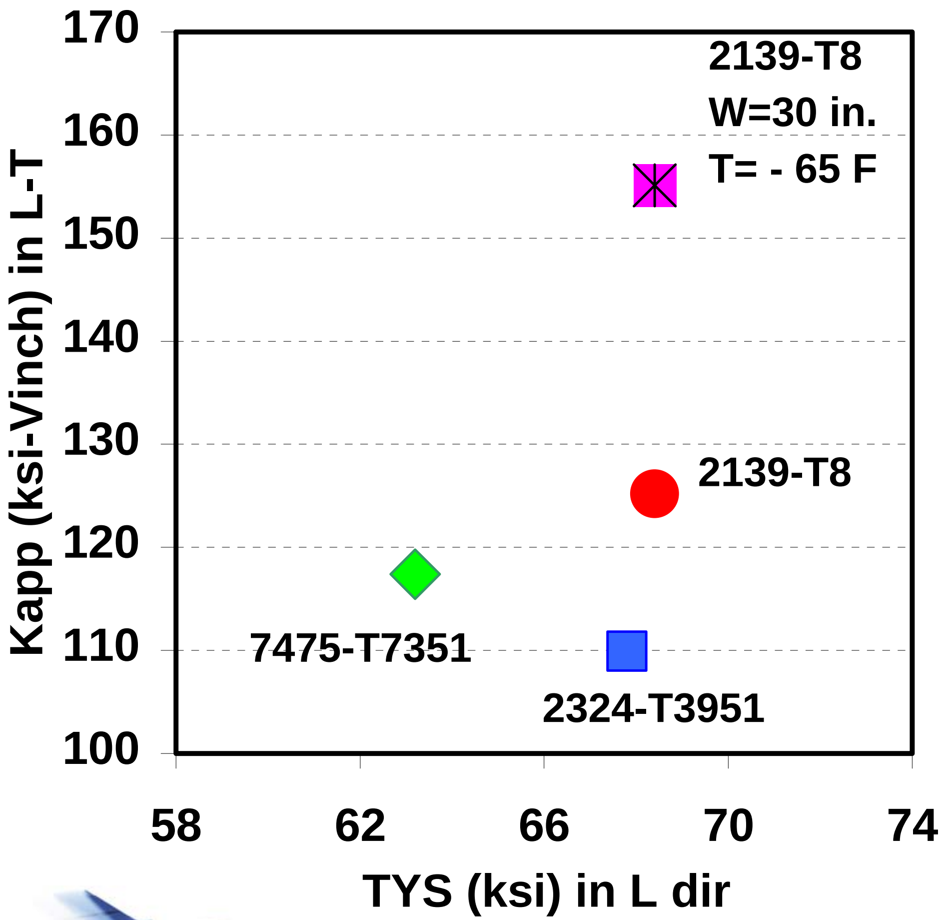
7050-T7451; Ribs & Spars for all aircraft (1.5" - 8"(10"))
- *most commonly used alloy for thick gauge application for good combined properties*

2519-T87; Armor plate application (1" – 6")
- *best ballistic performance*

Property Summary of 1“ ga. 2139-T8 Plate

Plane Stress Fracture Toughness in L-T

M(T) B=0.25 in.(6.3mm) W=16 in.(406mm)



Corrosion Resistance

- 2139-T8; 1.0 inch ga. plate
- → SCC: Passed at 30, 35 & 40 ksi for 20 days when tested in ST per ASTM G47 by ASTM G-38
- → EXCO = EA @ T/2, EB @ T/10, when tested per ASTM G34

Property Summary of 1“ ga. 2139-T8 Plate

Double Open Hole Axial Fatigue Tests on 1.0 in. ga. 2139-T8 Plate

L -dir. at T/2 Max. Stress; 20 ksi, R-Ratio; 0.1 Freq.; 15 Hz

2139-T8		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	1,500,000	Discont.
3	1,500,000	Discont.
4	842,407	A-Hole
5	873,461	A-Hole

Avg. 1,199,521

2324-T39; (Lot 1)		
S.N.	Cycle to Fail	Fail. Loc.
1	599,342	A-Hole
2	260,582	B-Hole
3	249,950	A-Hole
4	229,226	B-Hole
5	243,678	B-Hole

Avg. 293,569

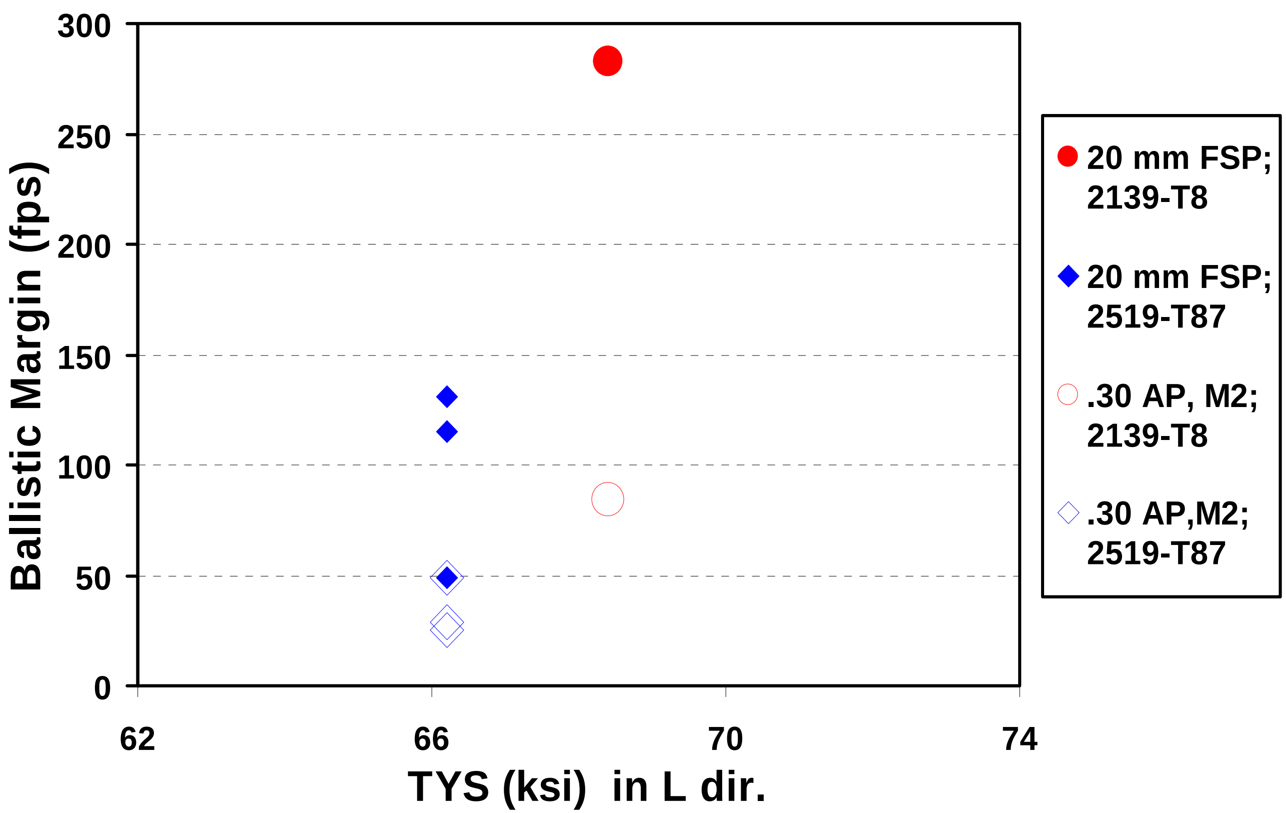
2324-T39; (Lot 2)		
S.N.	Cycle to Fail	Fail. Loc.
1	953,753	B-Hole
2	224,820	A-Hole
3	266,575	A-Hole
4	177,150	A-Hole
5	292,459	B-Hole

Avg. 312,104

Property Summary of 1" ga. 2139-T8 Plate

Ballistic Performance of 1.0 in. ga. 2139-T8 plate

1 inch ga 2139-T8 & 2519-T87 plates are tested per MIL-DTL-46192C



Note: FSP ; Fragmented Shrapnel Penetration tests AP ; Armor Piercing tests

Property Summary of 1“ ga. 2139-T8 Plate

1. Fracture toughness of 2139-T8 plate exceeded that of 2324-T39 and 7475-T7351 plate

2. Fatigue Resistance of 2139-T8 plate exceeded that of 2324-T39 plate

3. Ballistic performance of 2139-T8 plate exceeded that of 2519-T87 plate

4. 2139-T8 plate showed good SCC resistance and EXCO test results

IV. Development of 2139 thick gauge plate product

To evaluate the Damage Tolerance capability of thick gauge plate product, three gauges of 2139-T8 plate were produced from the two plant size ingots (13,000 lbs. ingots)

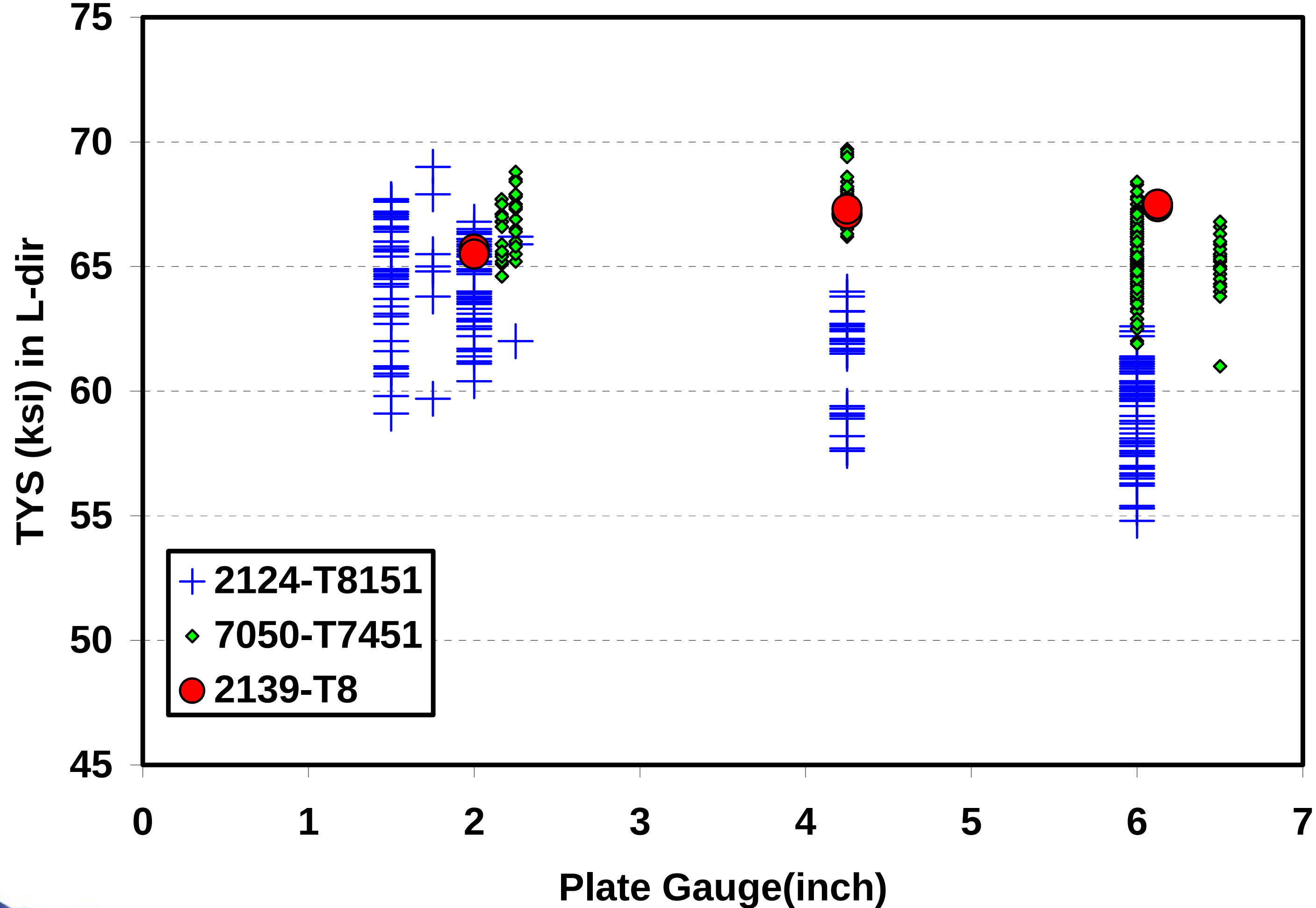
- **2.0 inch (51 mm)**
- **4.25 inch (108 mm)**
- **6.125 inch (156 mm)**

Chemistry of two 2139 alloy ingots

	Cu	Mg	Mn	Ag	Zr
min	**4.5**	**0.2**	**0.2**	**0.15**	**0**
max	**5.5**	**0.8**	**0.6**	**0.6**	**0.03**

Damage Tolerance of 2139-T8 Thick Plate

Effect of Plate Gauge on TYS in L-dir. of 2139-T8



Mechanical Properties of 2 inch gauge 2139-T8 plate

Age	Test dir.	UTS(ksi)	TYS(ksi)	Elong.(%)	K1c(ksiVin.)
Age condition 1	L	68.9	65.7	15.0	57.8
	LT	71.9	65.1	9.0	46.5
	ST	69.3	62.0	9.5	34.4*
Age condition 2	L	68.9	65.5	14.0	58.2*
	LT	71.2	64.3	9.0	44.5
	ST	70.4	63.4	11.0	40.3*

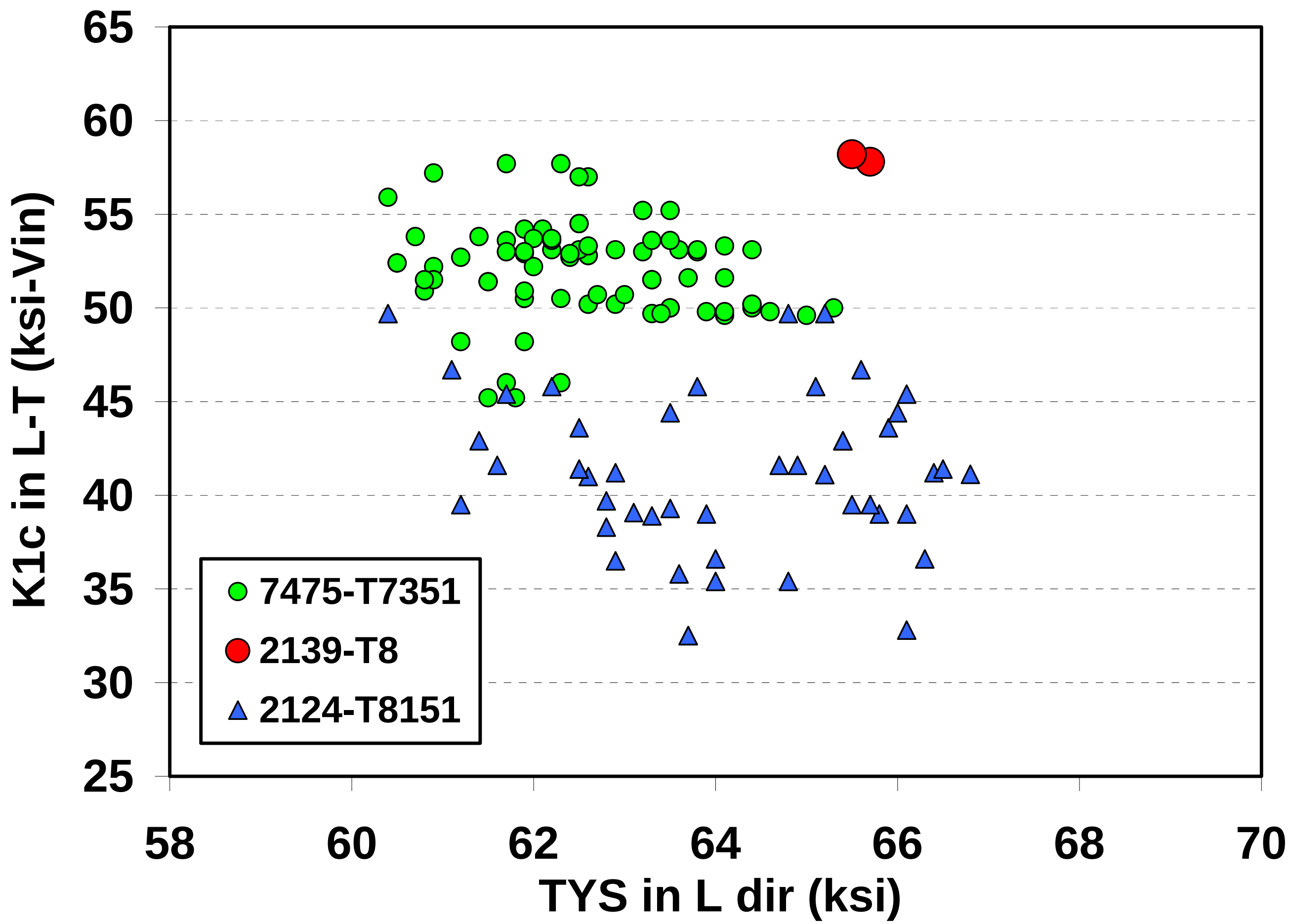
L-T, T-L; tested at t/4 location with B=2", W=4"
S-L; tested at t/2 with B=0.75", W=1.5"
* ; invalid per Invalidity criteria #1 in ASTM E399-05

Damage Tolerance of 2139-T8 Thick Plate

2 inch (51 mm) plate

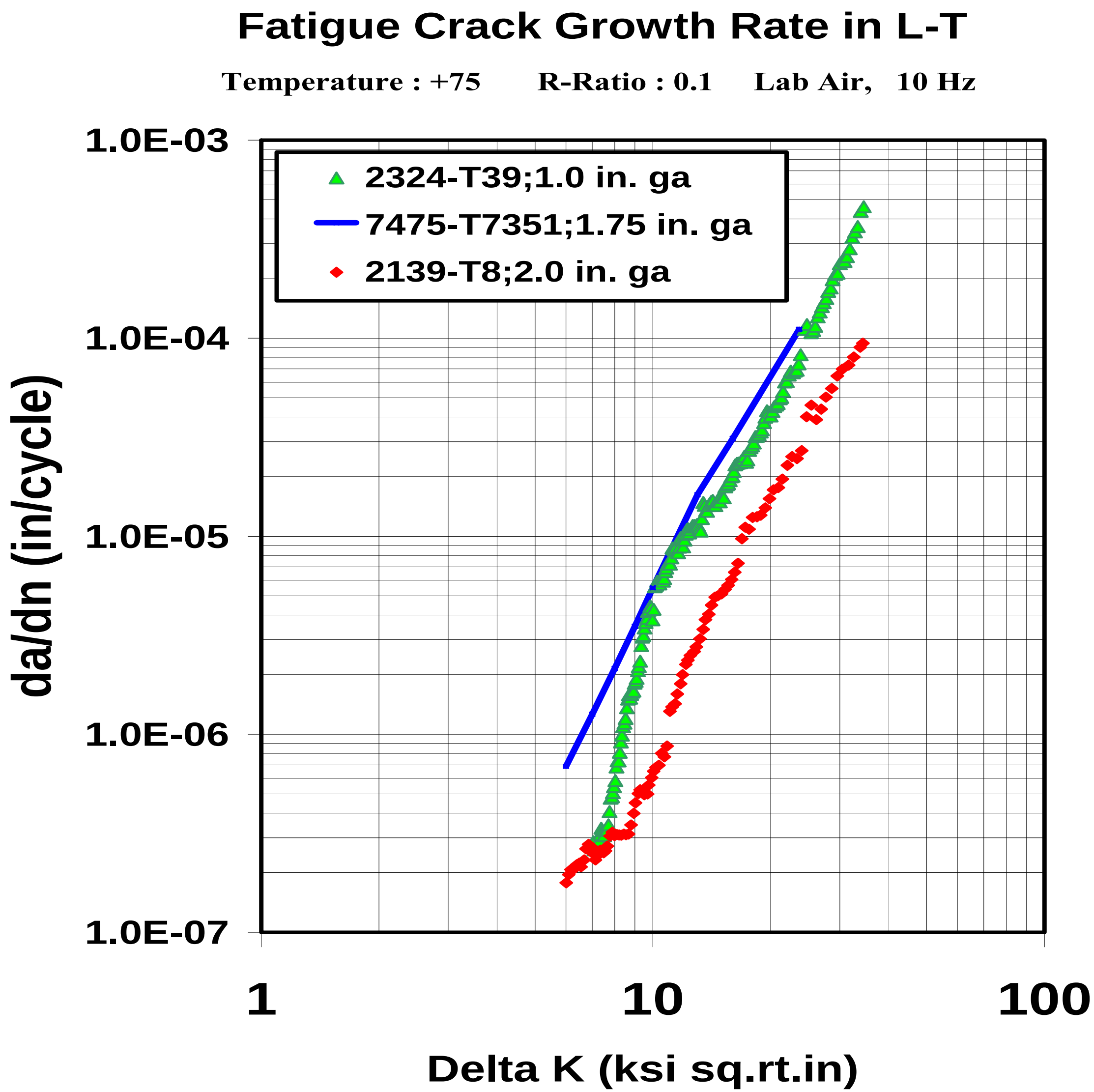
Plane Strain Fracture Toughness of 2 inch ga. Plate

2139-T8, 7475-T7351 & 2124-T8151



Damage Tolerance of 2139-T8 Thick Plate

2 inch (51 mm) plate



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Mechanical Properties of 4.25 inch gauge 2139-T8 plate

Age	Test dir.	UTS(ksi)	TYS(ksi)	Elong.(%)	K1c(ksiVin.)
Age condition 1	L	71.5	66.8	13.0	44.4
	LT	72.8	65.9	9.5	36.8
	ST	67.9	59.7	6.4	34.6
Age condition 2	L	72.2	67.1	13.0	48.1
	LT	73.0	66.4	9.0	35.6
	ST	68.1	61.4	5.0	33.8
Age condition 3	L	72.4	67.3	11.5	45.2
	LT	73.5	66.6	8.0	36.3
	ST	68.7	61.2	5.7	34.2

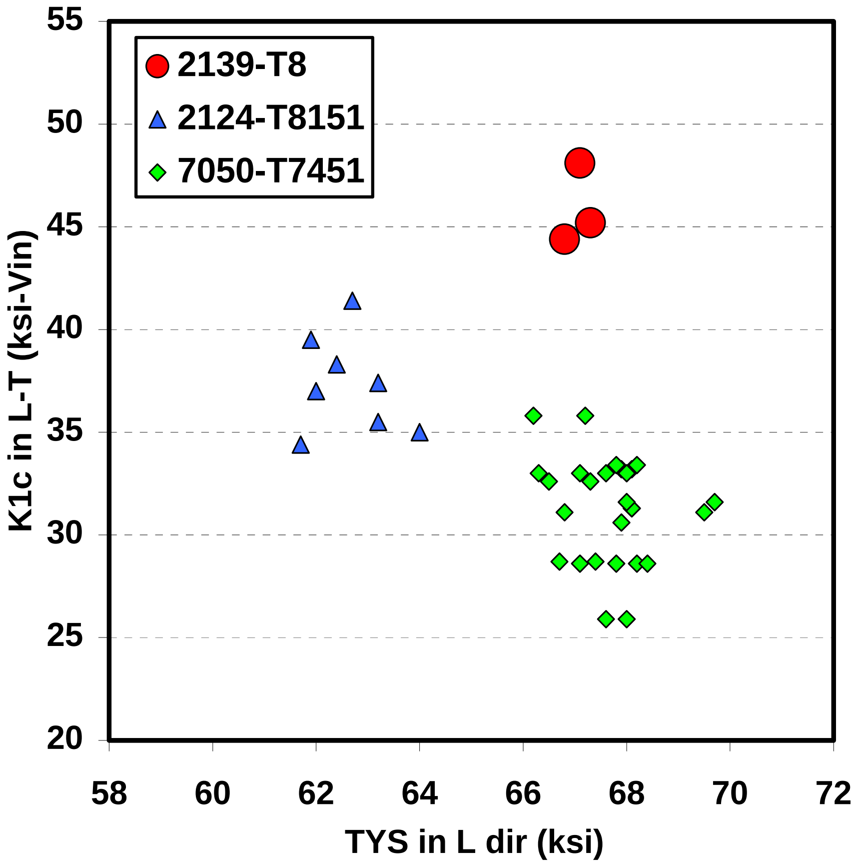
L-T, T-L; tested at t/4 location with B=2", W=4"
S-L; tested at t/2 with B=0.75", W=1.5"

Damage Tolerance of 2139-T8 Thick Plate

4.25 inch (108 mm) plate

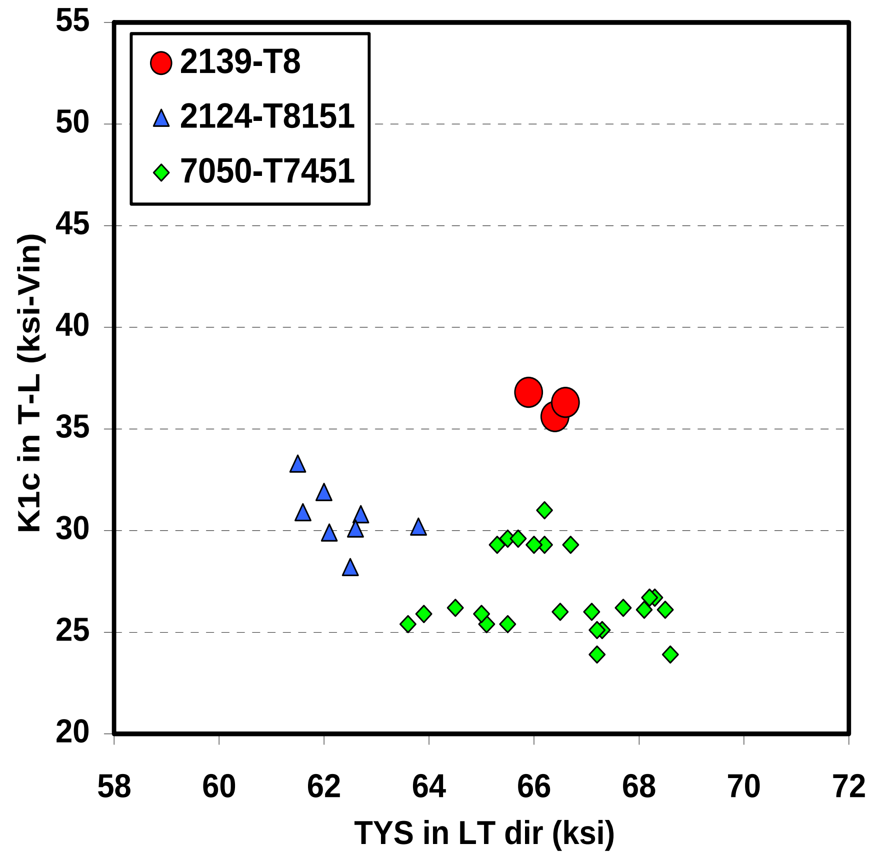
Fracture Toughness of 4.25" in L-T

2139-T8, 2124-T8151 & 7050-T745



Fracture Toughness of 4.25" in T-L

2139-T8, 7050-T7451 & 2124-T8151

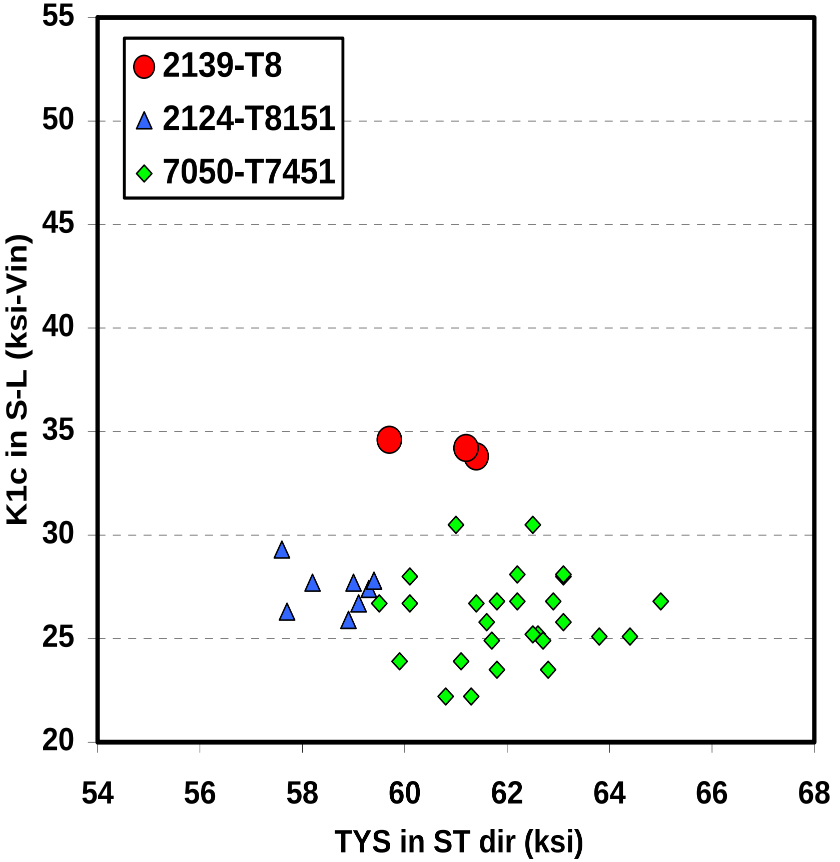


Damage Tolerance of 2139-T8 Thick Plate

4.25 inch (108 mm) plate

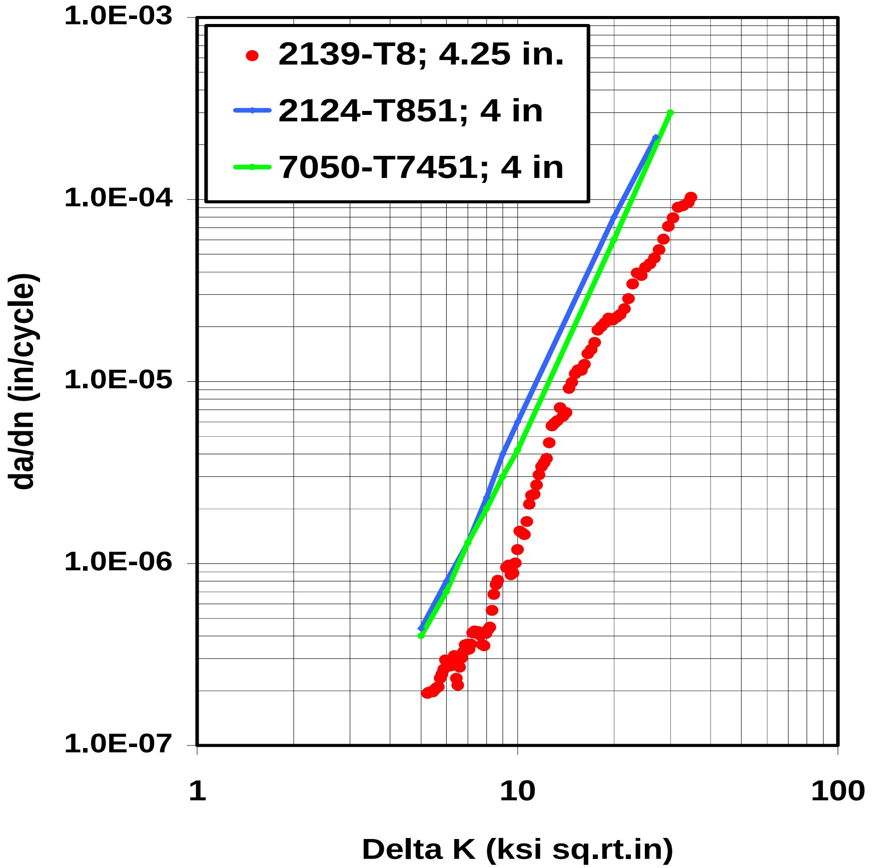
Fracture Toughness of 4.25" in S-L

2139-T8, 7050-T7451 & 2124-T8151



Comparison of FCGR in L-T

Temp:+75 R-Ratio: 0.1 Lab Air Freq: 10



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Mechanical Properties of 6.125 inch gauge 2139-T8 plate

Age	Test dir.	UTS(ksi)	TYS(ksi)	Elong.(%)	K1c(ksiVin.)
Age condition 1	L	73.1	68.1	12.0	33.0
	LT	73.7	66.0	9.5	32.2
	ST	67.2	59.3	4.7	36.5
Age condition 2	L	72.9	67.4	10.0	32.9
	LT	73.4	65.5	9.5	32.2
	ST	67.8	60.2	4.7	33.9
Age condition 3	L	72.7	67.5	9.5	32.3
	LT	73.6	66.2	8.0	31.9
	ST	68.1	59.8	6.1	33.5

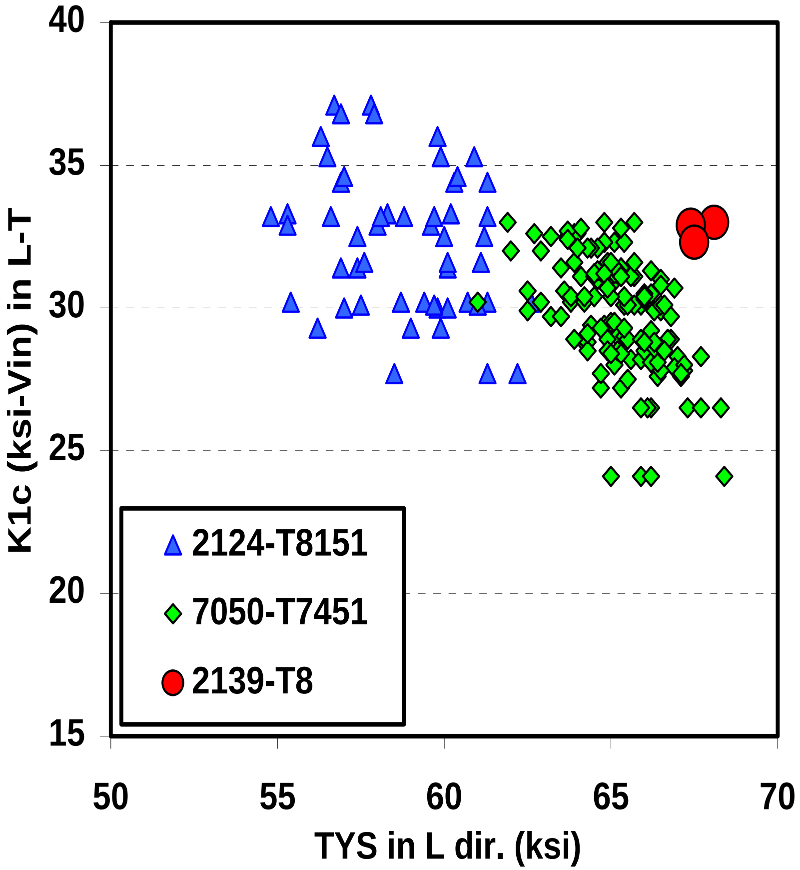
L-T, T-L; tested at t/4 location with B=2", W=4"
S-L; tested at t/2 with B=0.75", W=1.5"

Damage Tolerance of 2139-T8 Thick Plate

6.125 inch (156 mm) plate

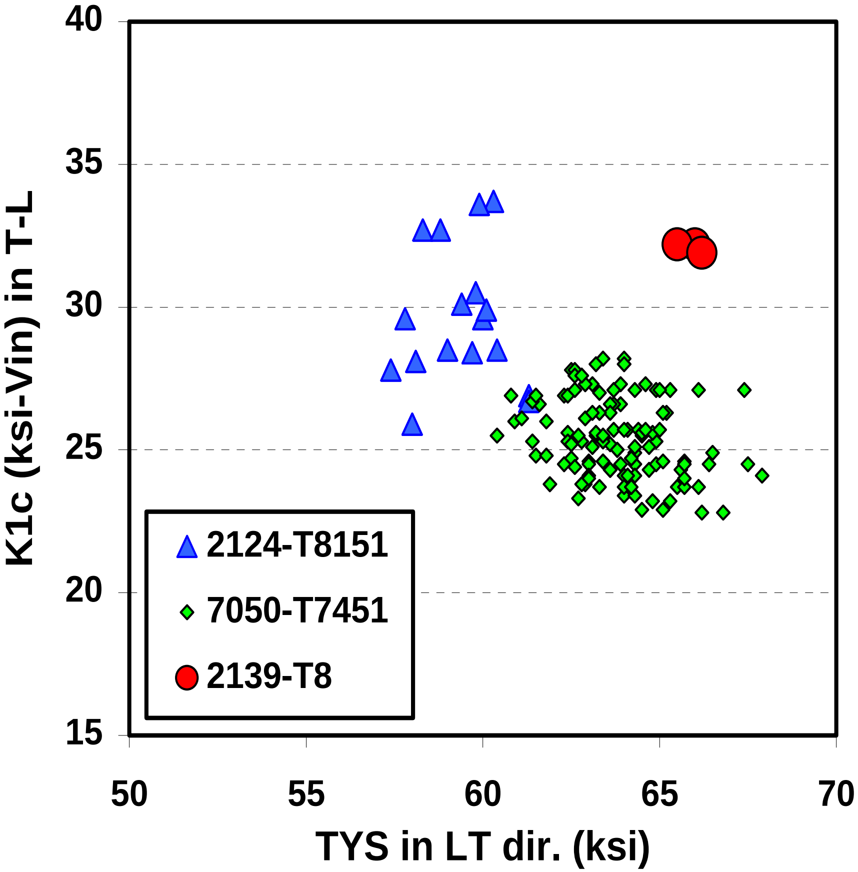
Fracture Toughness of 6.125" in L-T

2139-T8, 7050-T7451(6") & 2124-T8151(6")



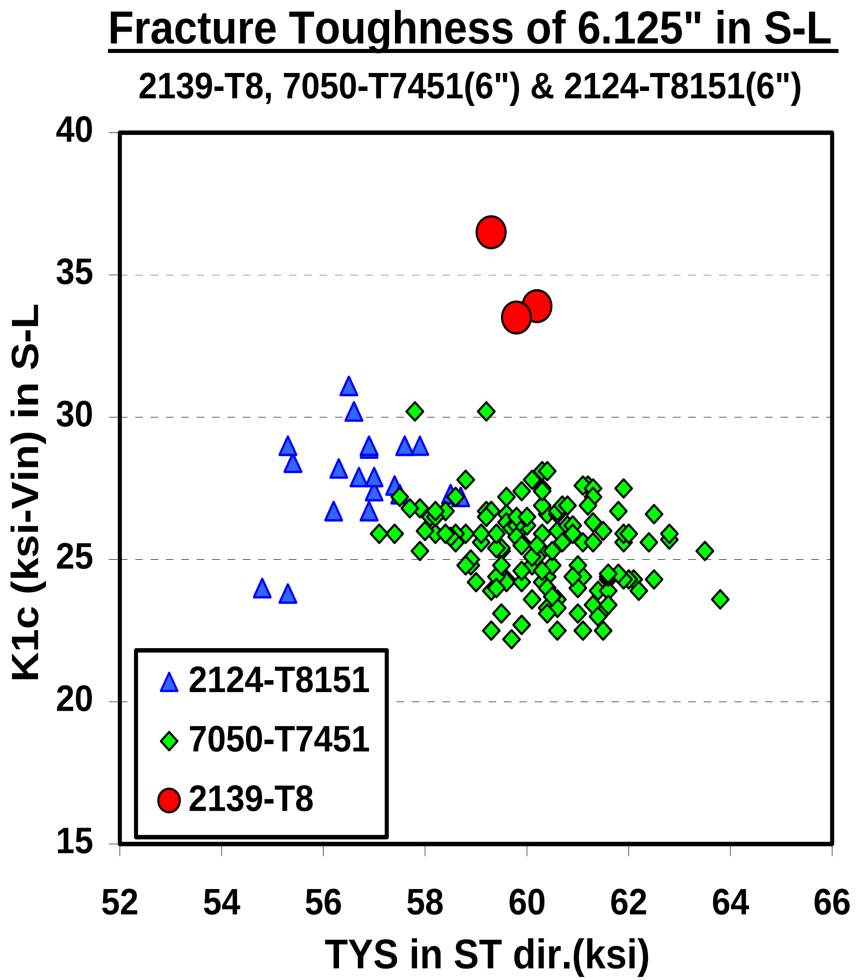
Fracture Toughness of 6.125" in T-L

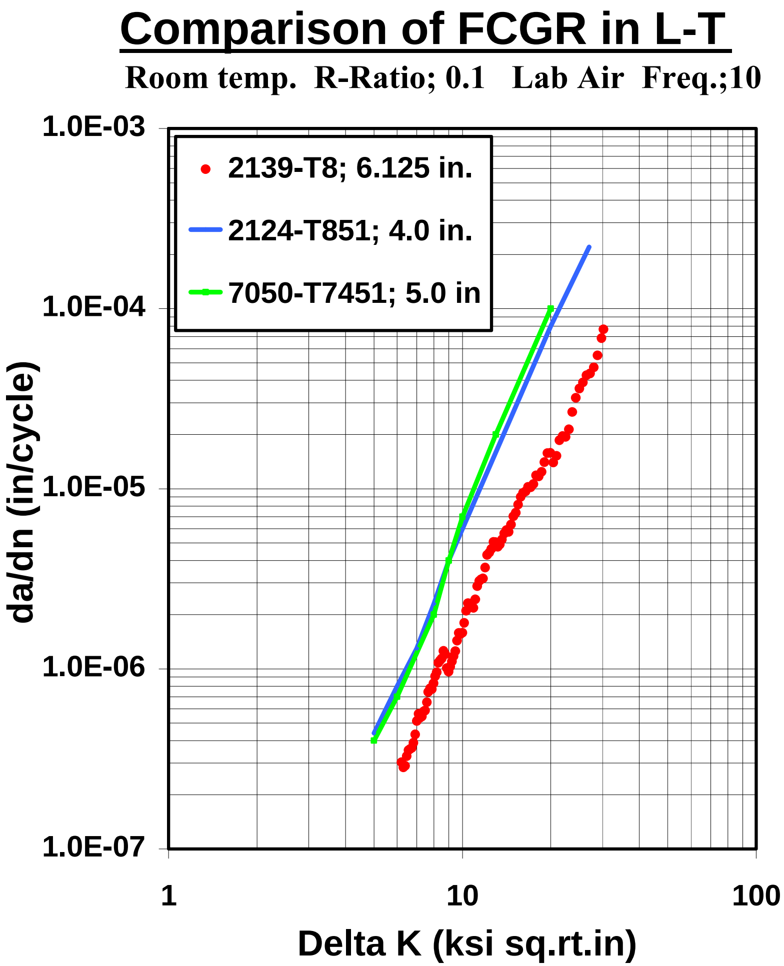
2139-T8, 7050-T7451(6") & 2124-T8151(6")



Damage Tolerance of 2139-T8 Thick Plate

6.125 inch (156 mm) plate





Texture components (volume %) of 2139-T3 plate at two through-thickness locations from four different gauge plates

Volume% of Texture components of 2139 -T3 plate at t/2 location

Alloy	Gauge(inch)	Temper	Location	Cube	Goss	Brass	S	Cu	R-Cube	Cube+Goss	Brass+S
2139	**1**	**T3**	**t/2**	**10.7**	**2.0**	**5.0**	**7.8**	**3.6**	**2.3**	**12.6**	**12.8**
2139	**2**	**T3**	**t/2**	**3.0**	**2.1**	**3.7**	**5.4**	**2.4**	**6.8**	**5.0**	**9.0**
2139	**4.25**	**T3**	**t/2**	**5.0**	**2.1**	**2.6**	**4.1**	**2.4**	**8.1**	**7.1**	**6.7**
2139	**6.125**	**T3**	**t/2**	**4.5**	**2.7**	**4.6**	**6.0**	**3.5**	**3.5**	**7.1**	**10.6**

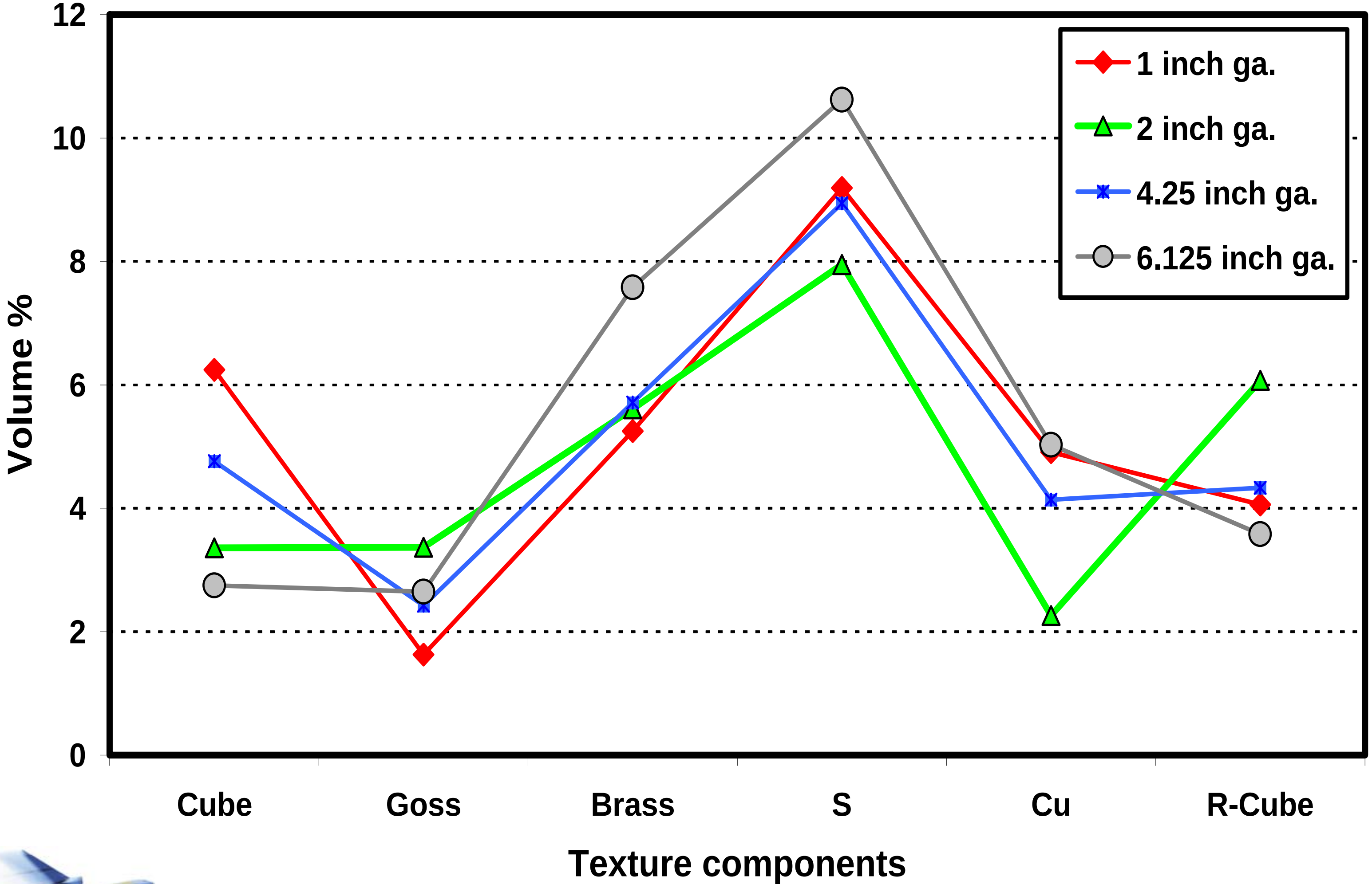
Volume% of Texture components of 2139 -T3 plate at t/4 location

Alloy	Gauge(inch)	Temper	Location	Cube	Goss	Brass	S	Cu	R-Cube	Cube+Goss	Brass+S
2139	**1**	**T3**	**t/4**	**6.2**	**1.6**	**5.3**	**9.2**	**4.9**	**4.1**	**7.9**	**14.4**
2139	**2**	**T3**	**t/4**	**3.4**	**3.4**	**5.6**	**8.0**	**2.3**	**6.1**	**6.7**	**13.6**
2139	**4.25**	**T3**	**t/4**	**4.4**	**1.9**	**8.4**	**11.7**	**4.1**	**2.9**	**6.3**	**20.1**
2139	**6.125**	**T3**	**t/4**	**2.8**	**2.7**	**7.6**	**10.6**	**5.0**	**3.6**	**5.4**	**18.2**

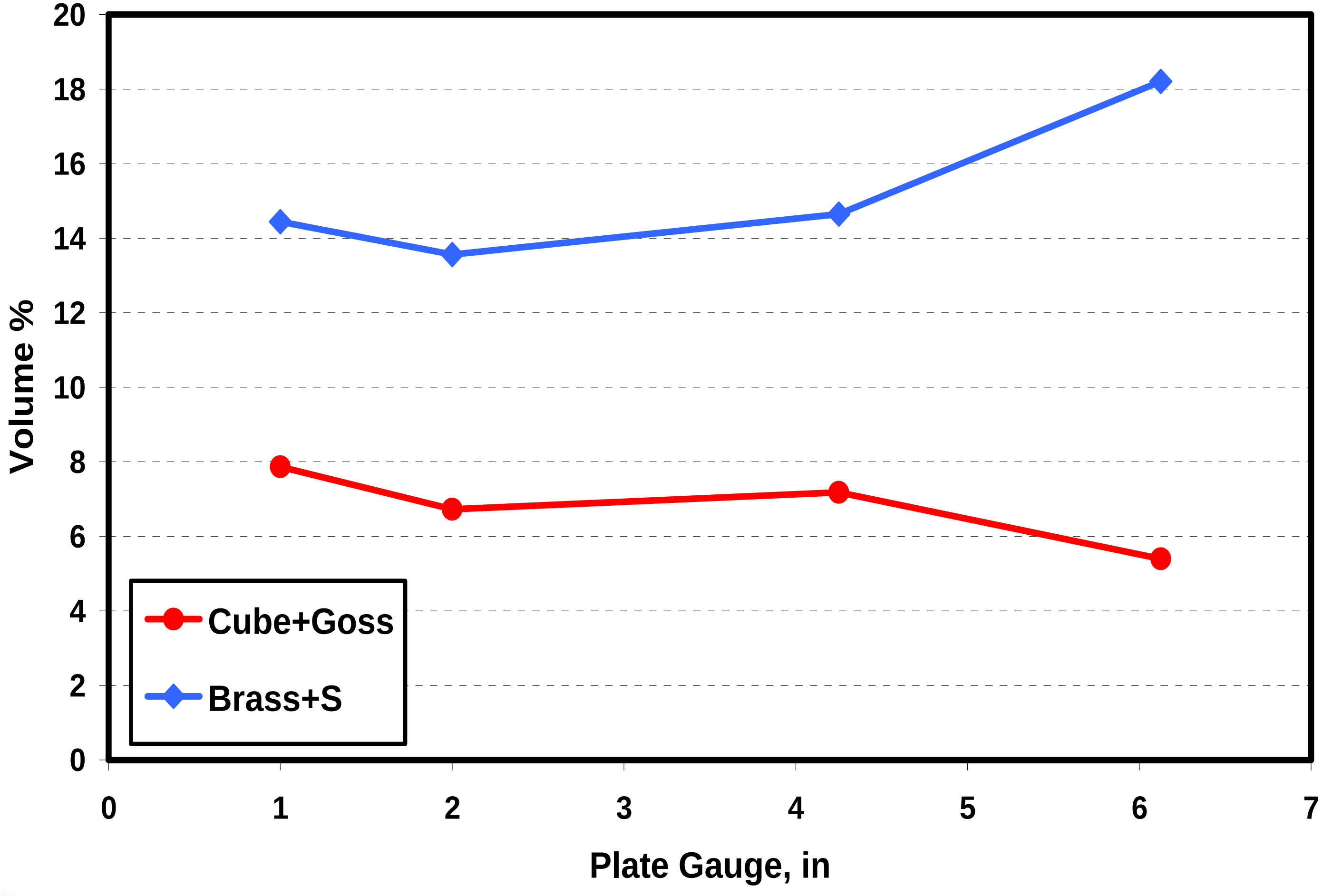
Note:

Cube : {100}<100>   Goss ; {011}<100>   S ; {123}<634>   Brass ; {011}<211>   Cu ; {112}<111>   Rotated Cube ; {100}<011>

Texture components (vol%) of 2139-T3 plate at t/4



Recrystallization(Cube&Goss) and Deformation (S & Brass) components of 2139-T3 plate at t/4



SCC tests of 2139-T8 plate in ST direction per ASTM G47 by ASTM G-38

SCC tests in ST direction for 20 days per ASTM G47 by ASTM G-38

Test Speciemen	Plate Ga.(in).	Age (hours)	Test Plane	Test Orient.	Applied Stress(ksi)	Pass /Fail
1	2	24	t/2	ST	30	Pass
2	2	24	t/2	ST	30	Pass
3	2	24	t/2	ST	30	Pass
1	4.25	24	t/2	ST	30	Pass
2	4.25	24	t/2	ST	30	Pass
3	4.25	24	t/2	ST	30	Pass
1	6.125	20	t/2	ST	30	Pass
2	6.125	20	t/2	ST	30	Pass
3	6.125	20	t/2	ST	30	Pass

V. Summary & Conclusion

1. 2139-T8 thick plate was evaluated in three gauges, 2.0“(51mm), 4.25“(108mm) and 6.125“(156mm)

2. 2139-T8 plate did not show loss in strength as gauge increases as seen in other 2xxx-T8xx plate products. Instead, 2139-T8 plate maintained strength levels comparable to 7050-T7451 in all gauges tested

3. Combined properties of strength and fracture toughness in three testing directions exceeded those of other conventional damage tolerant Al alloys in all three gauges

4. 2139-T8 plate showed exceptionally good FCG Resistance in all three gauges

5. Over all, 2139-T8 thick plate demonstrated superior DT capability, compared to 2324-T39, 7475-T7351, 2124-T8151, and 7050-T7451 in comparable gauges tested so far - up to 6 inches thick (156mm)

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14. ABSTRACT
This final report supplement in presentation format describes a comprehensive multi-tasked contract study to continue the development of the silver bearing alloy now registered as aluminum alloy 2139 by the Aluminum Association. Two commercial scale ingots were processed into nominal plate gauges of two, four and six inches, and were extensively characterized in terms of metallurgical and crystallographic structure, and resulting mechanical properties. This report includes comparisons of the property combinations for this alloy and 2XXX and 7XXX alloys more widely used in high performance applications. Alloy 2139 shows dramatic improvement in all combinations of properties, moreover, the properties of this alloy are retained in all gauge thicknesses, contrary to typical reductions observed in thicker gauges of the other alloys in the comparison. The advancements achieved in this study are expected to result in rapid, widespread use of this alloy in a broad range of ground based, aircraft, and spacecraft applications.

15. SUBJECT TERMS
Al-Cu-Mg-AG alloy; Mechanical properties; Fracture toughness; Fatigue crack growth; Texture

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