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Development and Processing Improvement of Aerospace Aluminum Alloys

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December 2007

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DEVELOPMENT AND PROCESSING IMPROVEMENT OF AEROSPACE ALUMINUM ALLOYS

INDEX

Final Report

Development and Processing Improvement of Aerospace Aluminum Alloys

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

This final report, in multiple presentation format, describes a comprehensive multi-tasked contract study to improve the overall property response of selected aerospace alloys, explore further a newly-developed and registered alloy, and correlate the processing, metallurgical structure, and subsequent properties achieved with particular emphasis on the crystallographic orientation texture developed. The study was funded by the Exploration Systems and Space Operations Directorate and managed by the Metals and Thermal Structures Branch, Research and Technology Directorate, NASA Langley Research Center. Mr. John A. Wagner served as the Technical Representative of the Contracting Officer. The primary contractor was Analytical Services and Materials, Inc. (AS&M) and the program manager was Mr. W. Barry Lisagor, a senior scientist with AS&M. The major portion of the experimental work was conducted by Pechiney Rolled Products Inc. (PRP) as a principal sub-contractor and the principal investigator was Dr. Alex Cho, a senior scientist with PRP.

Under the task on aluminum alloy 2195, the selected alloy for the Space Shuttle Super Lightweight tank, modifications to plate processing (particularly with regard to hot rolling practices) resulted in significant improvement in important mechanical properties. The work also resulted in an enhanced understanding of the correlation of processing, crystallographic texture, and mechanical properties achieved.

Under the task on aluminum alloy 2297, similar improvements were accomplished for this alloy, which is used for fabrication of the Space Shuttle external tank thrust panels. Successes achieved in this processing improvement will allow for utilization of the newly-developed procedures in production when improved properties are desired.

For the task on the aluminum-copper-silver based alloy system, efforts have resulted in substantial contributions to processing knowledge and property database for this recently registered alloy, AA 2139, which may have widespread utilization in future aerospace applications. This alloy composition was first explored under the earlier NASA High Speed Research program.

For the task on aluminum alloy 7050, significant new insight has been achieved in the correlation of chemistry, crystallographic texture, and properties which adds to the understanding of this important aerospace alloy.

The advancements achieved under this contract were substantial given the available resources and ambitious schedule, and would not have been possible without the efforts and insight of the AS&M and PRP Senior Research Scientists leading this activity.

Overview

Processing Improvement of Aluminum Alloys

&

Development of An Al-Cu-Mg-Ag Alloy

Alex Cho

Pechiney Rolled Products
Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Processing Improvement of Aluminum Alloys

& Development of An Al-Cu-Mg-Ag Alloy

Contents:

Processing Improvement of Aluminum Alloys

- 2195, 2297 and 7050

& Development of An Al-Cu-Mg-Ag Alloy

- 2139

TASKS:

I. 2195

II. 2297

III. 7050

IV. Al-Cu-Mg-Ag alloy - 2139

1. Background

a brief description of four alloys of interest

- *2195: 4.0 Cu -1.0 Li- 0.4 Mg - 0.4Ag - 0.13 Zr*
  - Space Shuttle External Fuel Tank application
  - 1.575” & 1.85” gage Plate in T8 temper
  - In-Plane Design properties are measured at t/6 location
- *2297: 3.0 Cu -1.25Li - .4 Mn - 0.1 Zr*
  - Originally developed for F-16 bulkhead application
  - Replaced 2219 plate in the External Fuel Tank
  - 2.4” gage Plate in T8 temper
  - In-Plane Design properties are measured at t/6 location
- *7050: 6.5 Zn - 2.2 Mg - 2.1 Cu- 0.1 Zr*
  - Most used wrought product alloy for aerospace structures
  - Broad range of plate thickness (1.5” – 8”) in -T7451 temper (over aged)
  - In-Plane Design properties are measured at t/4 location
- *Al-Cu-Mg-Ag alloy(2139): 5.0 Cu – 0.5 Mg – 0.4 Ag - 0.4 Mn*
  - Excellent DT & D capability in age hardened temper

1. Background

Metallurgical characteristics of four alloys selected

- *2195: 4.0 Cu -1.0 Li- 0.4 Mg - 0.4Ag - 0.13 Zr*
  - High strength alloy with high solute content (at solubility limit)
  - Strengthened by T_1 phase(Al_2CuLi) on (111) – contribute to strength anisotropy
  - Precipitate nucleation & coarsening kinetics are strongly influenced by dislocation density
  - Strong crystallographic texture - contribute strength anisotropy
  - Mechanical properties are highly anisotropic

- *2297: 3.0 Cu -1.25Li - .4 Mn - 0.1 Zr*
  - Medium strength alloy with moderate solute content
  - Strengthened by T_1 phase(Al_2CuLi) on (111) – contribute to strength anisotropy
  - Precipitate nucleation & coarsening kinetics are strongly influenced by dislocation density

- *7050: 6.5 Zn - 2.2 Mg - 2.1 Cu- 0.1 Zr*
  - Very high strength in its peak strength temper condition
  - Excellent property balance in over aged –T7451 temper
  - Strengthened by multiple phases ($MgZn_{2(1.5)}$, $Al_xMg_xZn_x$ types, Al_2CuMg etc.)
  - Precipitate nucleation & coarsening kinetics are marginally influenced by dislocation density

- *Al-Cu-Mg-Ag alloy(2139): 5.0 Cu – 0.5 Mg – 0.4 Ag - 0.4 Mn*
  - *Excellent property balance in its peak strength condition*
  - Strengthened by Ω phase (Al_2Cu) with habit plane of (111)
  - Precipitate nucleation & coarsening kinetics are marginally influenced by dislocation density

2. Issues/Objectives

Mechanical Property issues of the four alloys

- *2195: 4.0 Cu -1.0 Li- 0.4 Mg - 0.4Ag - 0.13 Zr*
  - Low L UTS at t/6 (L UTS << LT UTS)
  - SST Fracture Toughness fails sometimes at t/6
- *2297: 3.0 Cu -1.25Li - .4 Mn - 0.1 Zr*
  - Low L UTS at t/6 (L UTS << LT UTS)
  - K1c in S-L direction at Cryogenic temperature are marginal
- *7050: 6.5 Zn - 2.2 Mg - 2.1 Cu- 0.1 Zr*
  - Low L UTS at t/4 (L UTS < LT UTS) in 2.5" – 4" gage range
  - SCC Resistance/Electrical Conductivity fails sometimes
- *Al-Cu-Mg-Ag alloy(2139): 5.0 Cu – 0.5 Mg – 0.4 Ag - 0.4 Mn*
  - Better balanced properties in all directions
  - Strength/Corrosion characteristics at very thick gage are unknown

.

Processing Improvement of Aluminum Alloys – 2195, 2297 & 7050

& Development of an Al-Cu-Mg-Ag Alloy

3. Approach

- *2195: 4.0 Cu -1.0 Li- 0.4 Mg - 0.4Ag - 0.13 Zr*
  - Evaluated alternate hot rolling practice
  - Explored various cold work practices prior to Artificial Aging
  - Examined effects of crystallographic texture

- *2297: 3.0 Cu -1.25Li - .4 Mn - 0.1 Zr*
  - Evaluated combination of : Hot Rolling / Chemistry / Cold work
  - Examined effects of crystallographic texture

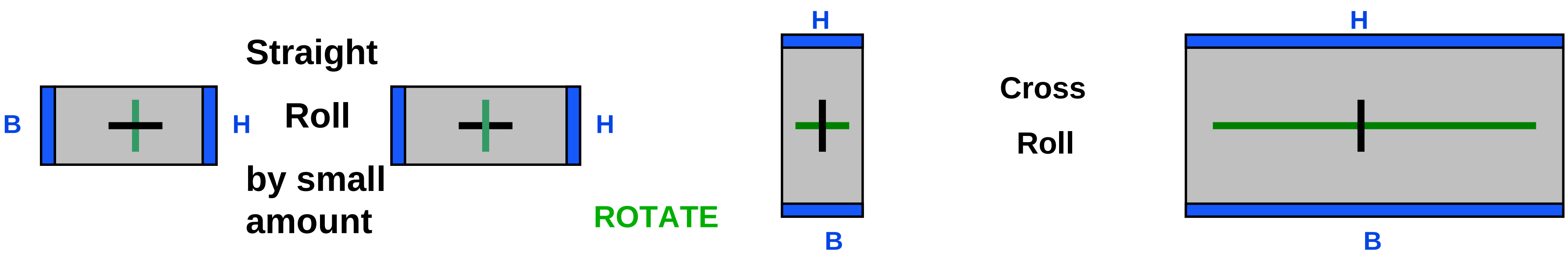
- *7050: 6.5 Zn - 2.2 Mg - 2.1 Cu- 0.1 Zr*
  - Evaluated various plate gages
  - Studied evolution of crystallographic texture through hot rolling gages

- *Al-Cu-Mg-Ag alloy(2139): 5.0 Cu – 0.5 Mg – 0.4 Ag - 0.4 Mn*
  - Examined the effects of two dispersoid forming elements
  - Two ingots have been cast for additional thicker gage product

Brief Description of Results

I. 2195-T8 Plate - alternate hot rolling process

current Ravenswood Hot Rolling Practice for 2195 – (McCook Practice)

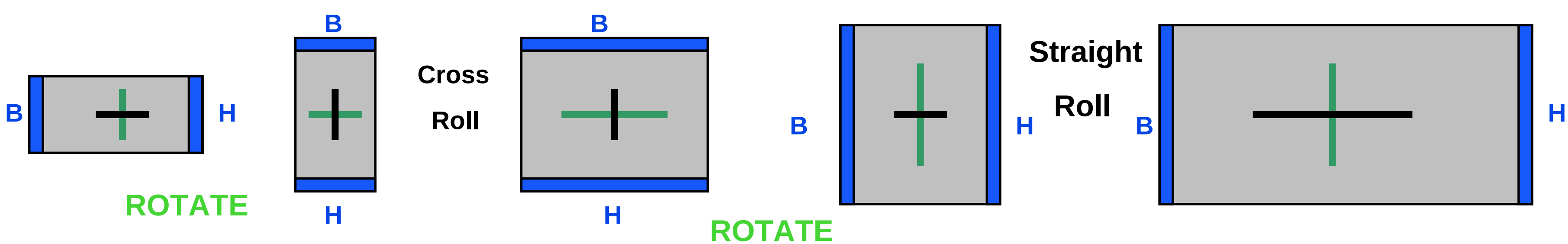


Current practice provides essentially Uni-Directional Deformation

Lengthen. vs. Broaden.

1.2X vs. 7.4X

Proposed Two-Directional Rolling Practice



Broaden. vs. Lengthen.

Proposed practice provides balanced deformation in two directions

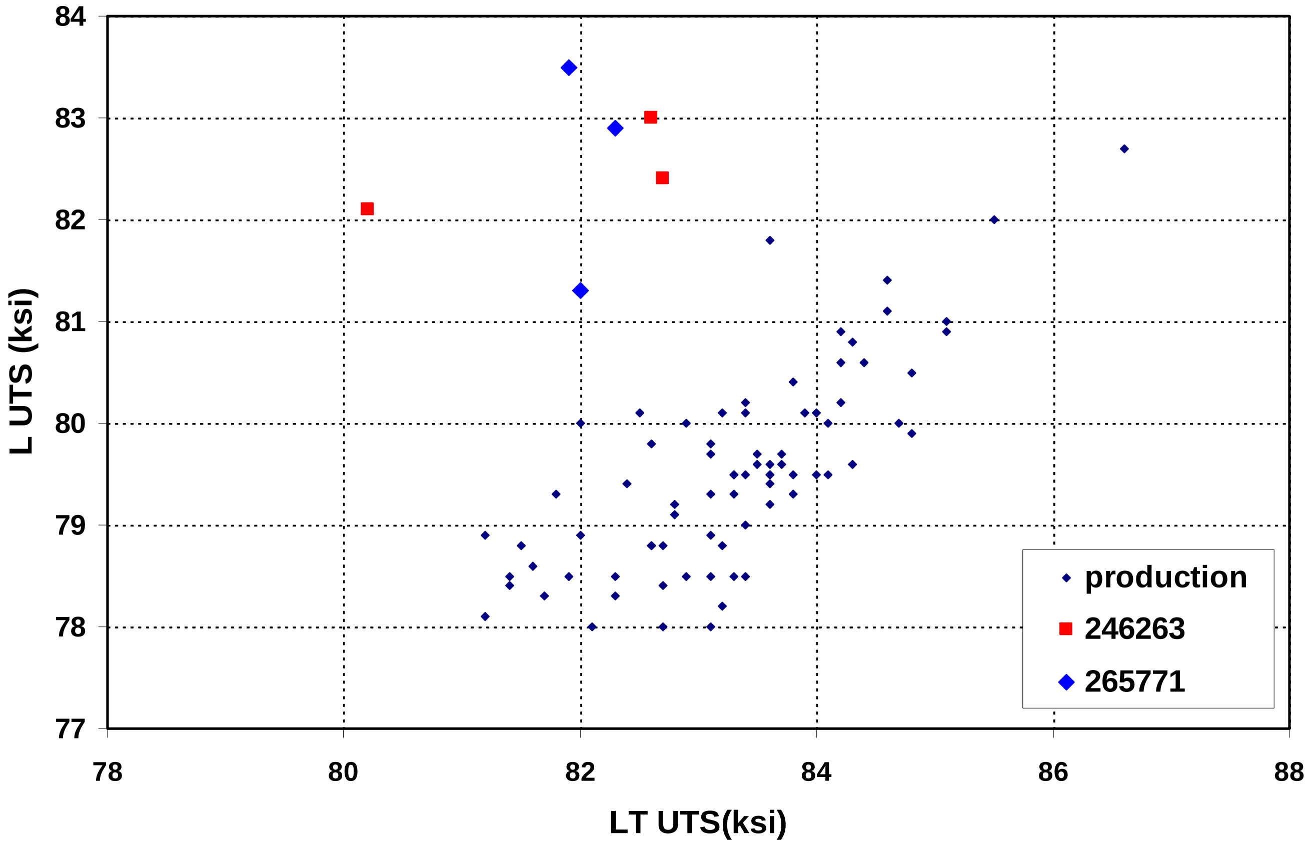
2.4X vs. 3.7X

Brief Description of Results

I. 2195-T8 Plate

L UTS & LT UTS of two-directionally rolled production plate are better than those of standard production plate.

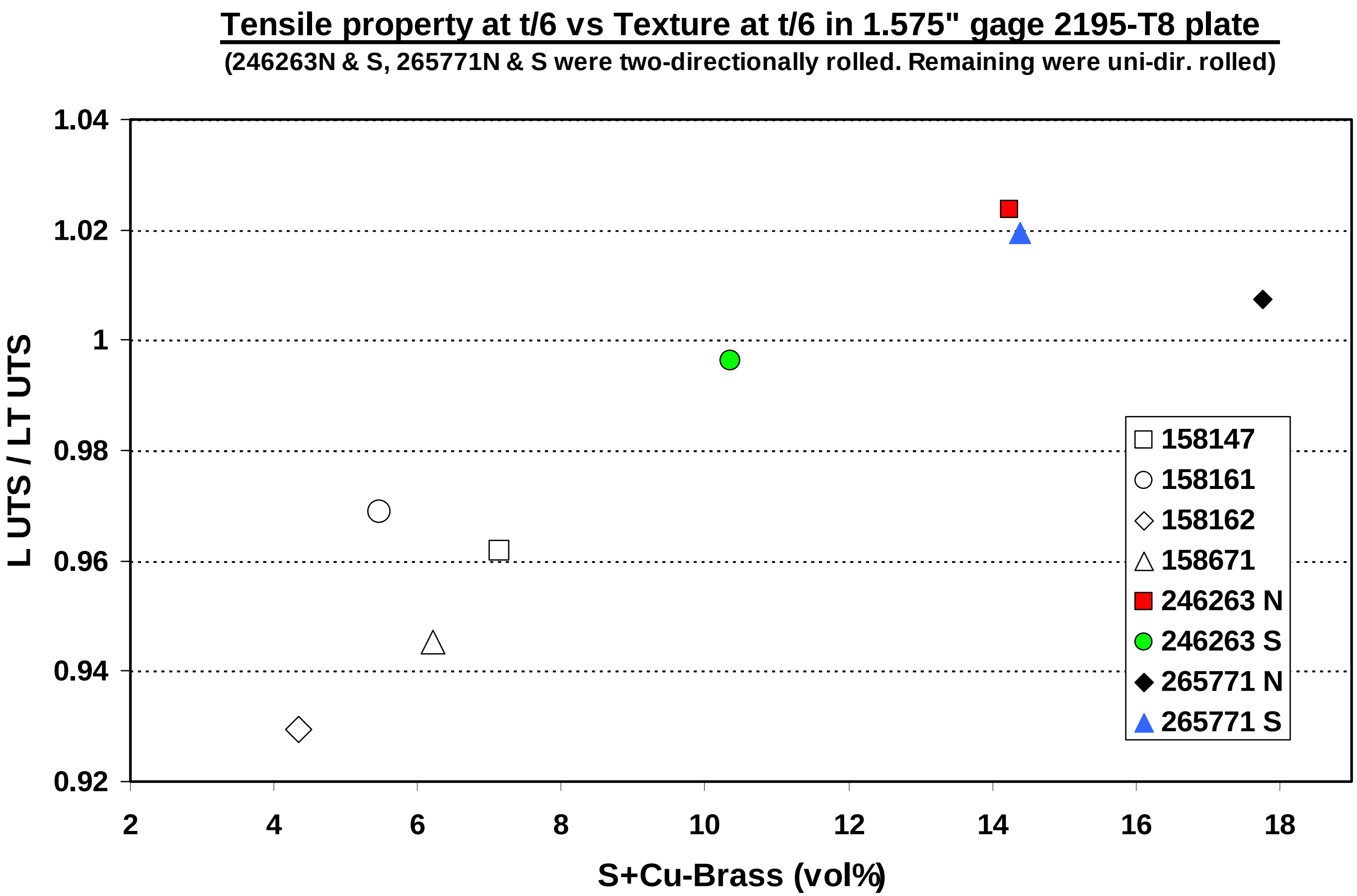
Tensile Prop.(t/6) vs Hot Rolling Temperature of 1.575 inch 2195-T8 plate
(production by uni-dir roll, 246263 & 265771 by two-dir roll)



Brief Description of Results

I. 2195-T8 Plate

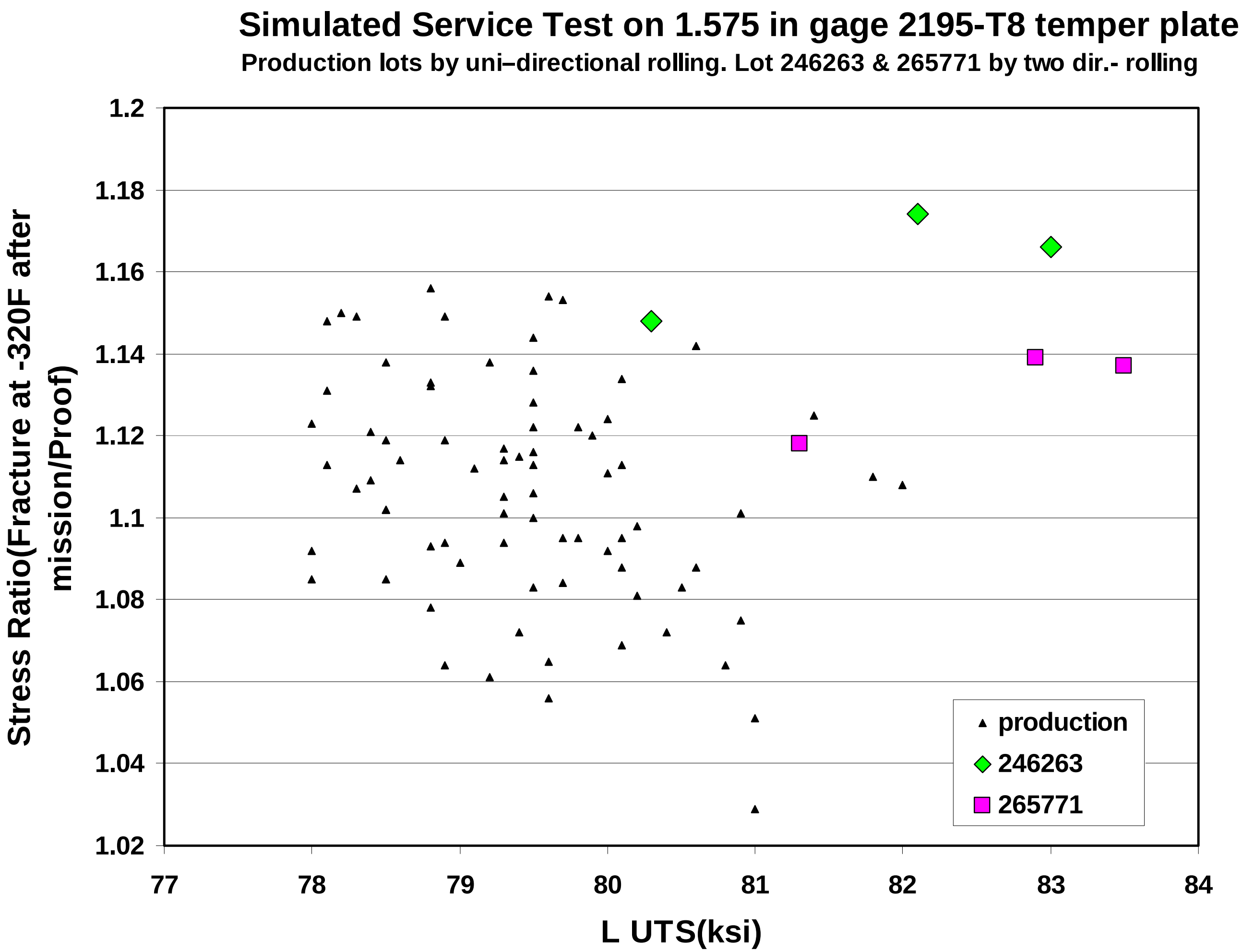
Higher volume % of Cu and S components favor L-direction strength, while higher vol % of Brass component would lower L UTS compared to LT UTS. Therefore, the ratio of L UTS/LT UTS increases as the vol % of (S+Cu-Brass) components increases.



Brief Description of Results

I. 2195-T8 Plate

Improved Combination of Stress Ratio and L UTS was achieved by two-directionally rolled plate



Brief Description of Results

I. 2195-T8 Plate

In addition to examining alternate hot rolling practice, various combinations of % Cold roll and % Stretch have been examined for through-thickness-strength uniformity by controlled experiments in a laboratory scale and plant scale trials.

Alternate Temper Development for 2195 Plate

A: Effect of Stretch on Through-Thickness Strength Uniformity

B: Effect of "Cold Roll & Stretch" prior to Age on Through-Thickness Strength Uniformity and Fracture Toughness

B-1: Lab scale experiment

B-2: Plant scale trial

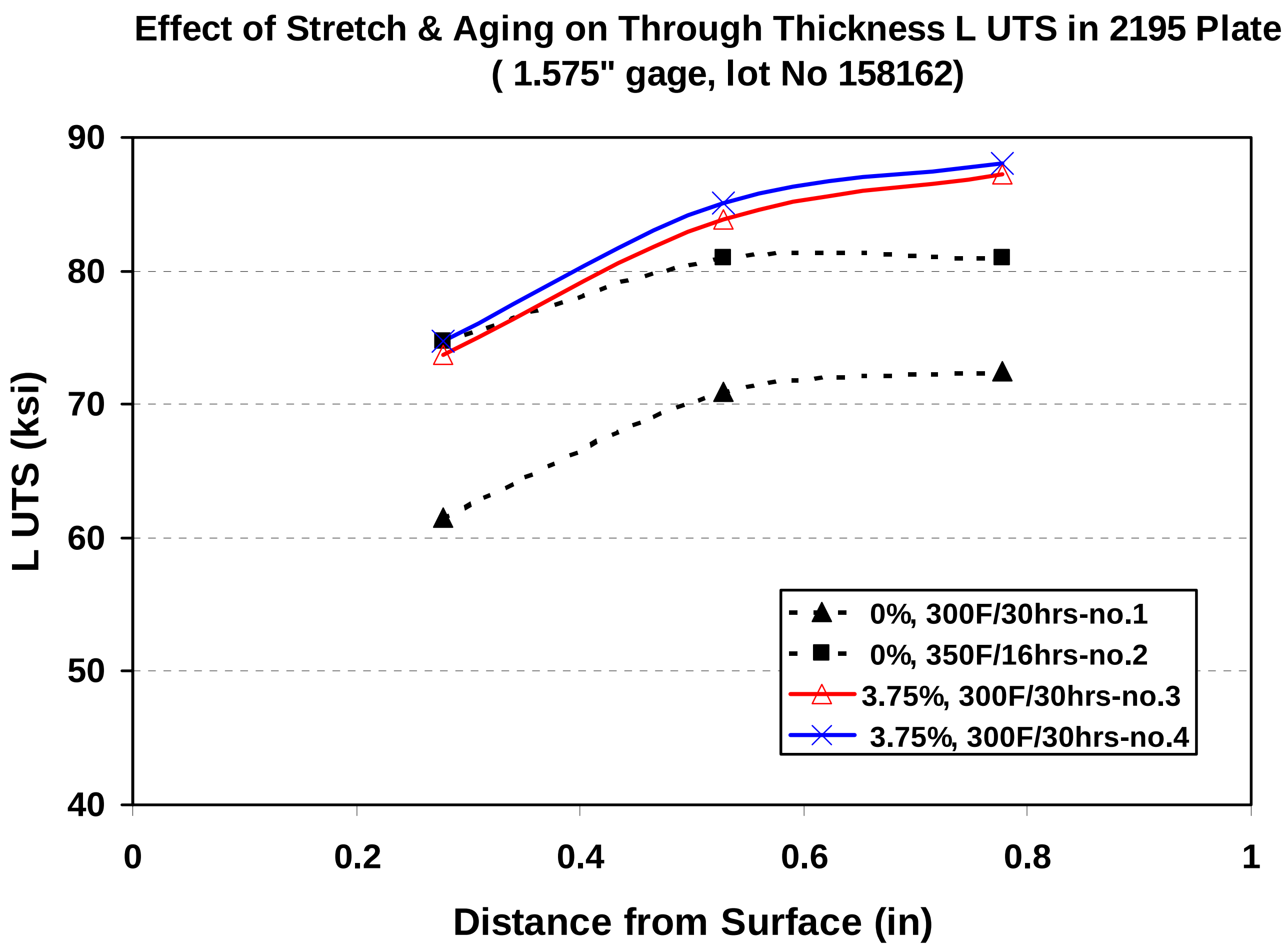
C: Effect of "Multi- Step Stretch Prior to Aging" on Through-Thickness Strength Uniformity

- Lab scale experiment

Brief Description of Results

I. 2195-T8 Plate

- Stretch prior to aging significantly raises L UTS; greater effect at t/2 location
- L UTS is more uniform through thickness in T6 temper condition (i.e., 0 % stretech)



Brief Description of Results

II. 2297-T8 Plate

Examination of chemistry, hot rolling practice and % cold work (cold roll + stretch)

Processing Study of 2.4 inch gage 2297-T8 plate

Lot no.	*Alloy*	*Hot Roll dir.*	*Cold Work*
Prev. 8 lots	high Li(1.3%)	One-dir. roll	stretch
200601	**high Li(1.3%)**	**Two-dir.roll**	**stretch**
682321	**low Li(1.2%)**	**Two-dir.roll**	**stretch**
682311	**low Li(1.2%)**	**Two-dir.roll**	**Cold Roll+stretch**

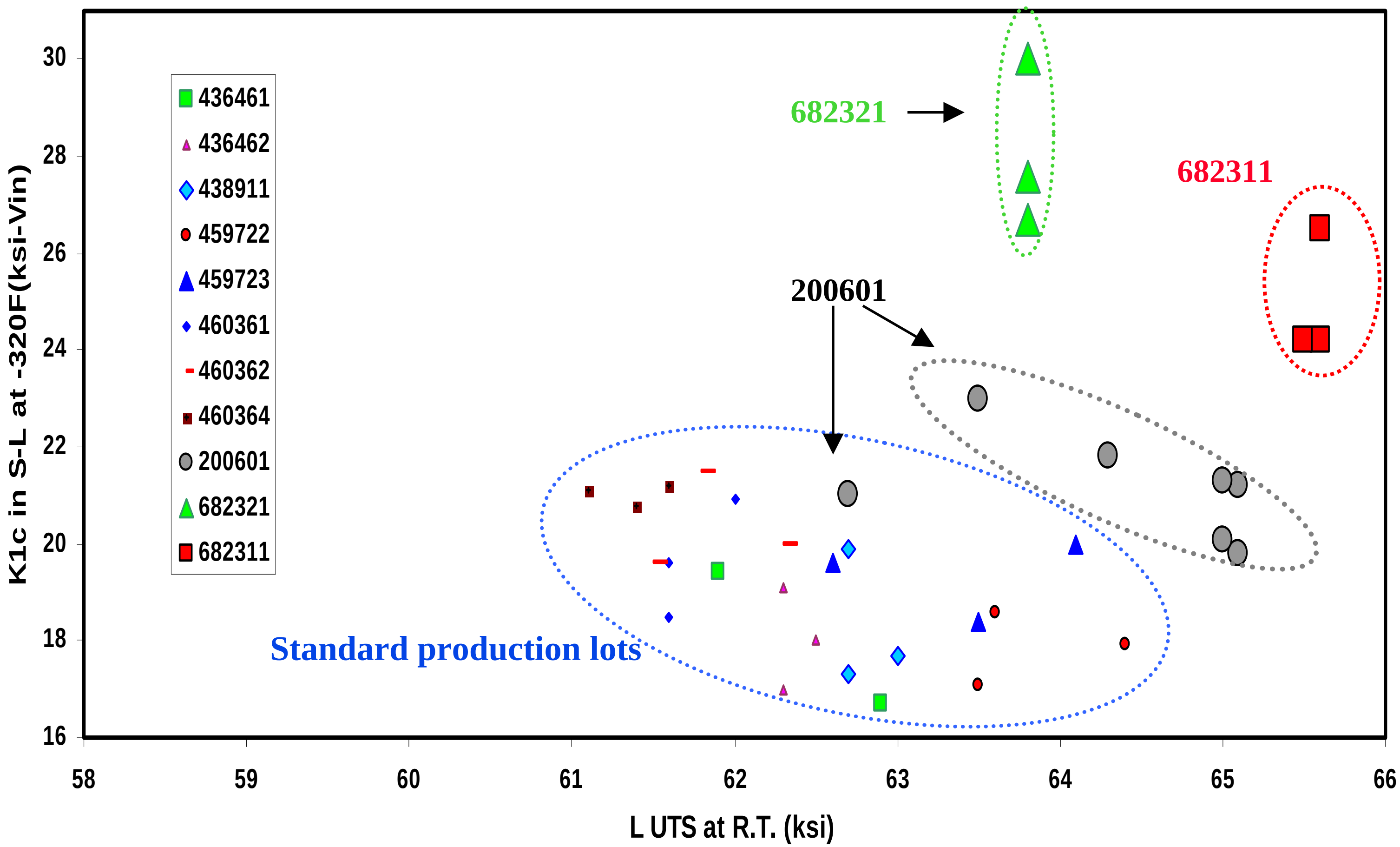
Brief Description of Results

II. 2297-T8 Plate

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Standard production lots had low K1c's in S-L & L UTS at Room temperature. Two-directionally rolled plates (200601, 682321 & 682311) show the significant improvement on both properties.

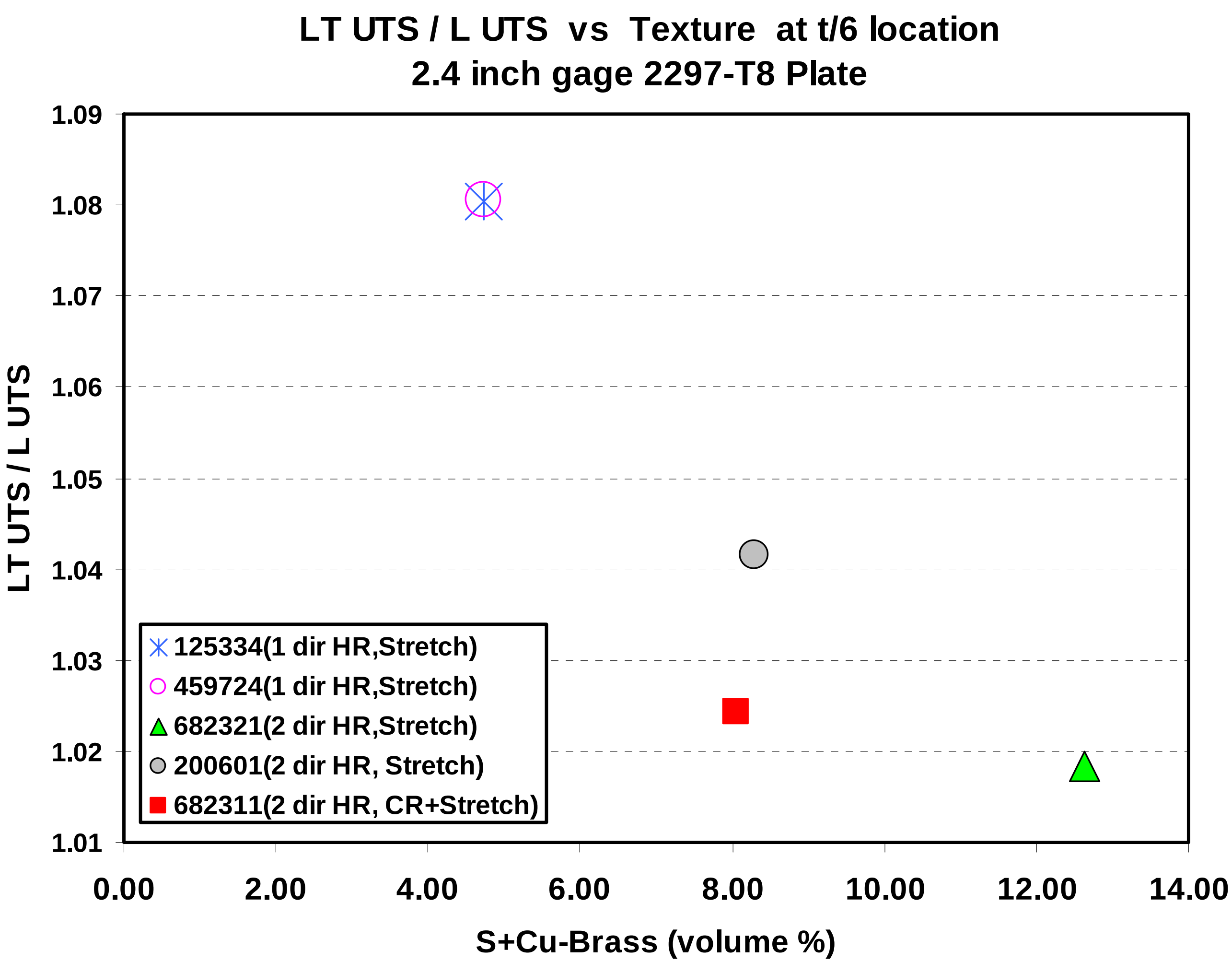
K1c in S-L at -320F vs. L UTS at R.T.



Brief Description of Results

II. 2297-T8 Plate

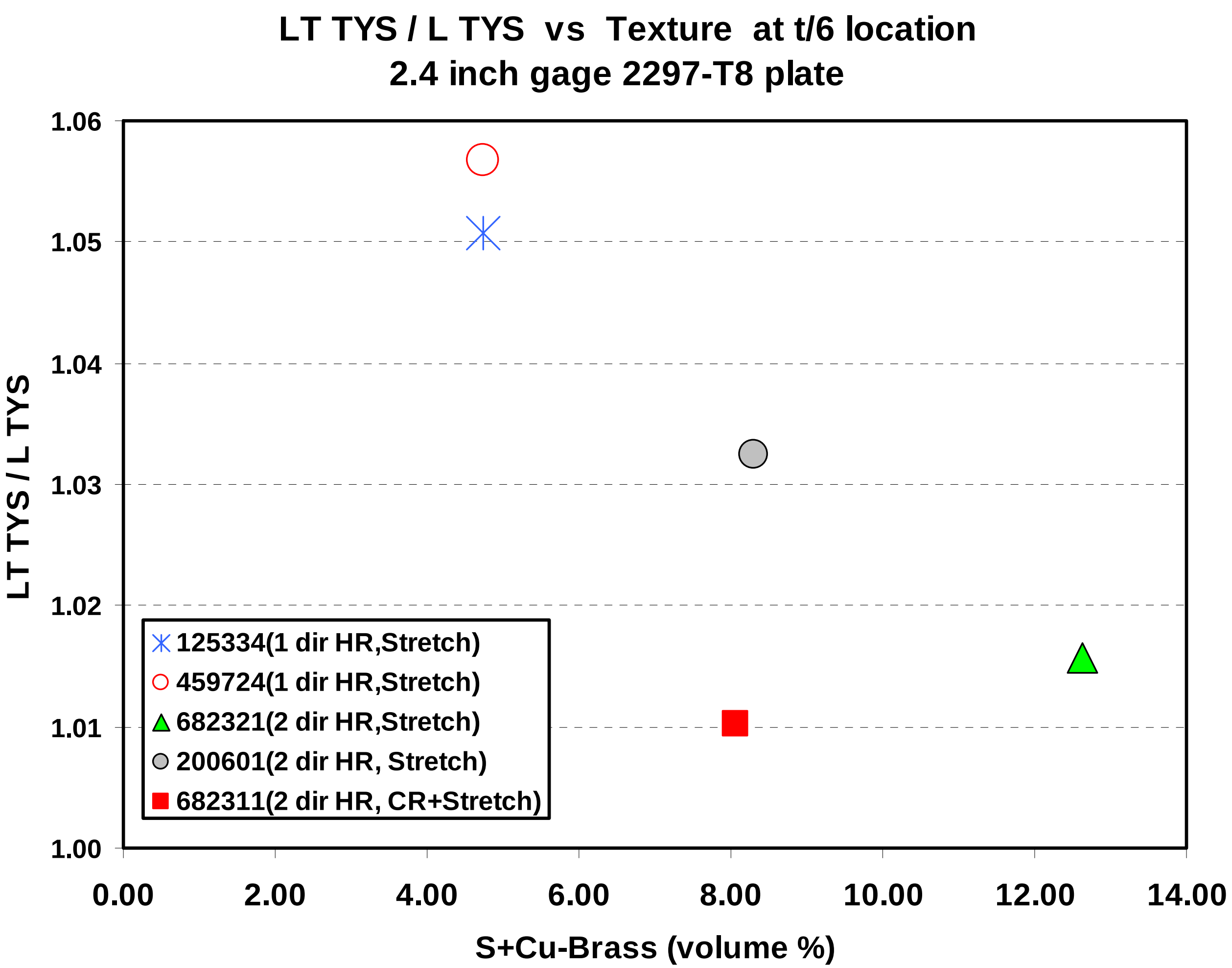
The ratio of LT UTS & L UTS shows good correlation with texture combination of S+Cu-Brass components except Lot 682321. It appears that 5.3% of Cold Rolling reduces degree of strength anisotropy for the the plate with a similar texture.



Brief Description of Results

II. 2297-T8 Plate

The ratio of LT TYS & L TYS shows good correlation with texture combination of S+Cu-Brass components except lot 682311. It appears that 5.3% of Cold Rolling reduces degree of strength anisotropy for the plate with similar texture.



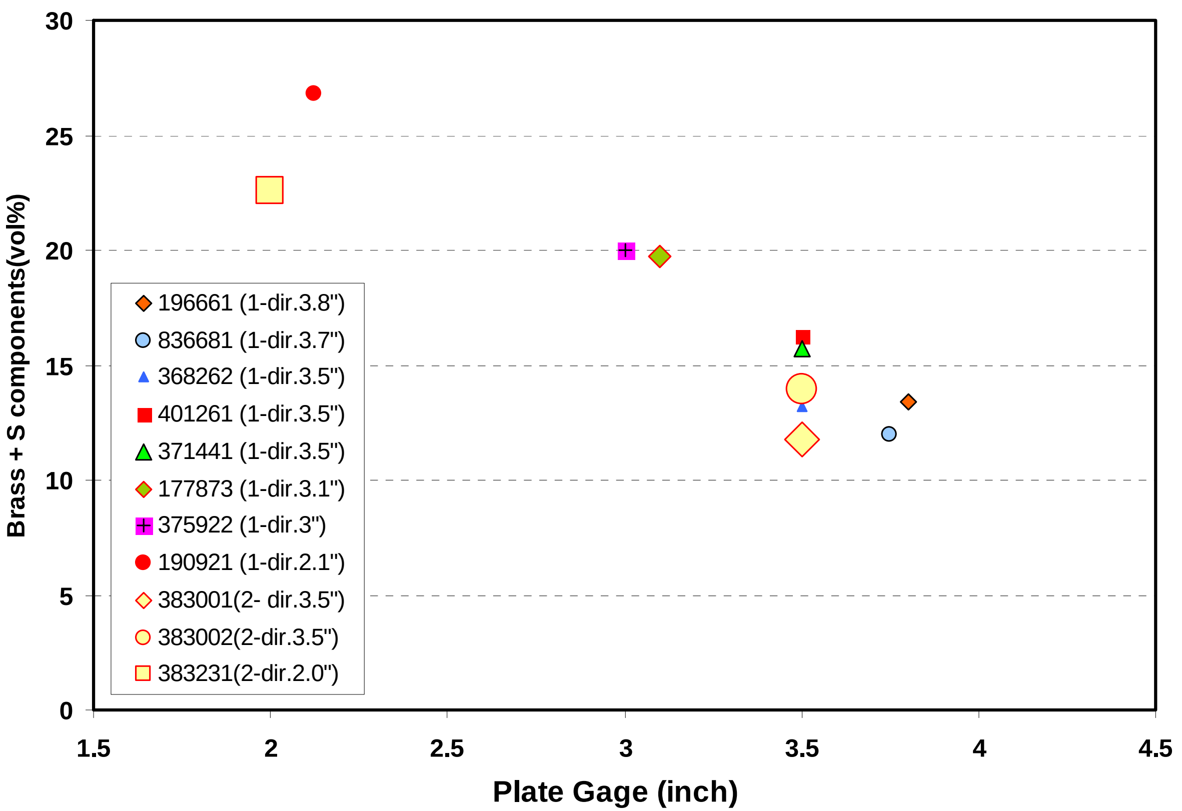
Brief Description of Results

III. 7050-T7451 Plate

Correlation of Plate gage, Crystallographic Texture and Tensile properties of one and two-directionally rolled plate

Crystallographic texture of 7050 plate showed good correlation with plate gages. However, no significant differences are observed in texture between uni-directionally rolled plate and two-directionally rolled plate

Rolling Texture at t/4 location vs. Gage of 7050-T7451 plate
Comparison of Uni -dir. Rolling vs. Two-dir. Rolling

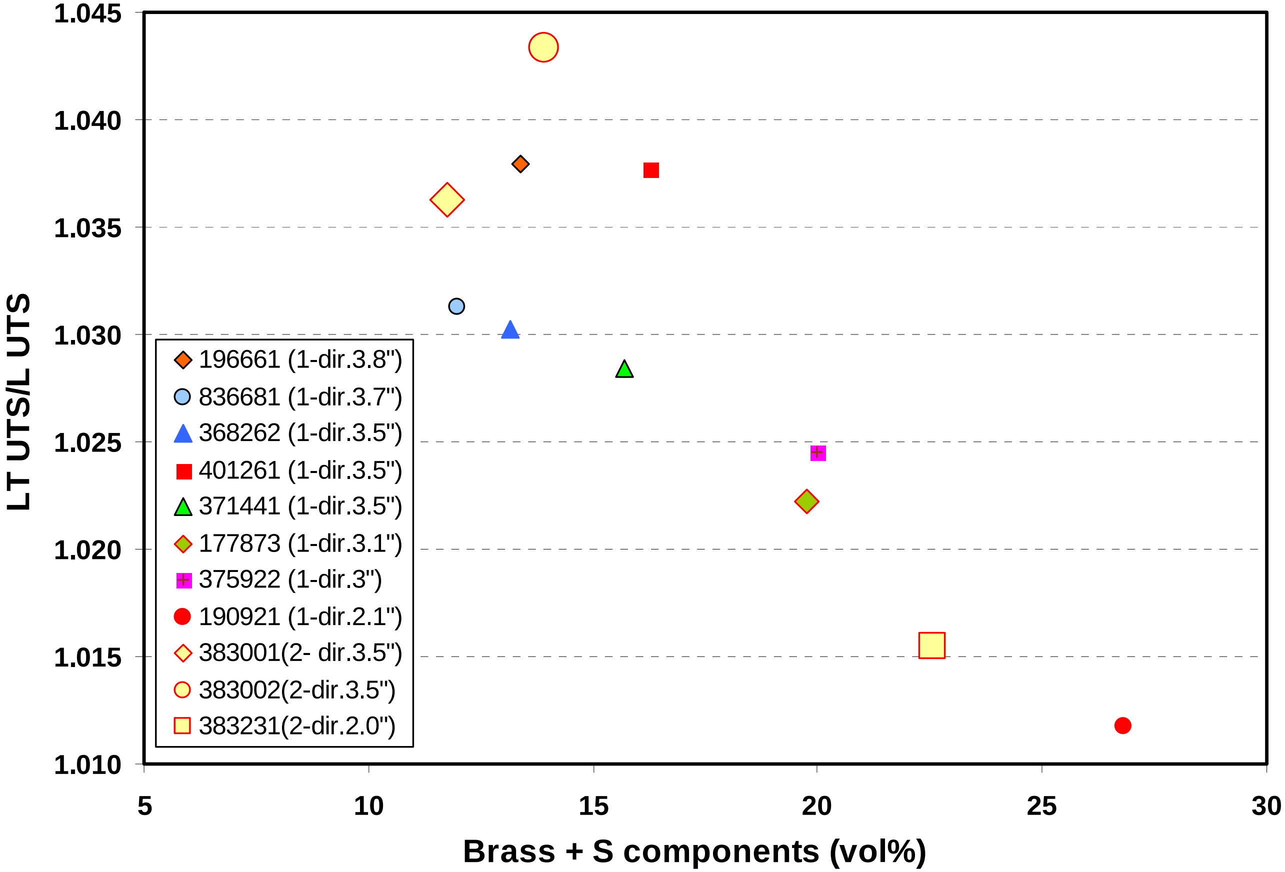


Brief Description of Results

III. 7050-T7451 Plate

The ratio of LT UTS/L UTS correlates with the deformation texture within the range of 2.0 to 3.8 inch. As deformation texture increases, the ratio of LT UTS/L UTS decreases. Two-directionally rolled plate shows no significant difference compared to uni-directionally rolled plate.

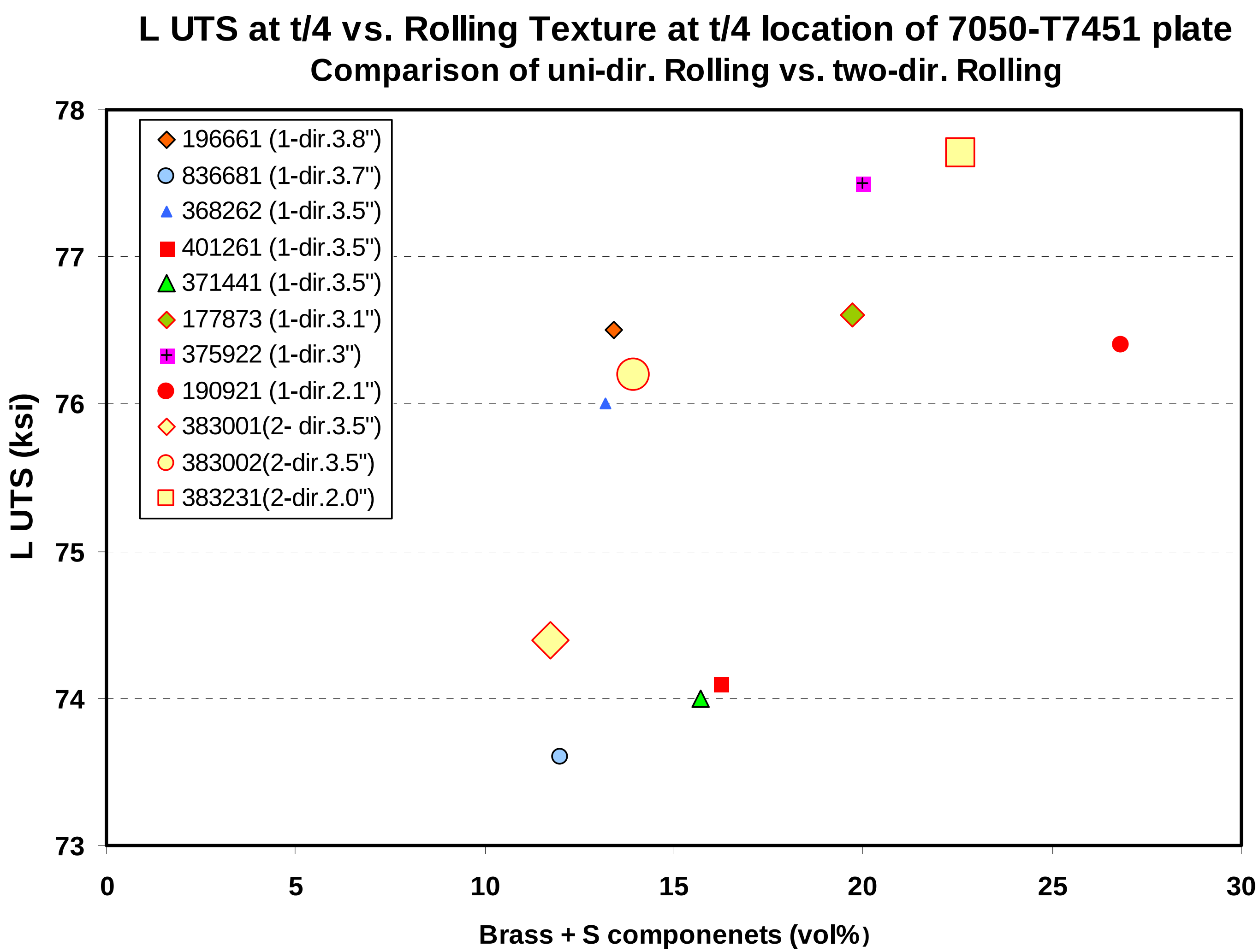
Ratio of LT UTS/L UTS at t/4 vs. Texture at t/4 of 7050-T7451 plate
Comparison of uni-dir. Rolling vs. two-dir. Rolling



Brief Description of Results

III. 7050-T7451 Plate

Only marginal correlation could be observed between L UTS values and deformation texture



Processing Improvement of Aluminum Alloys – 2195, 2297 & 7050

4. Conclusions

- For 2195 and 2297 alloys, alternate hot rolling practices (two-directional rolling) provide a desirable crystallographic texture, and significant improvement of L UTS values.
- For 2297 alloy plate, a slightly low solute alloy with higher amount of cold work provided best combined properties
- For 7050 plate, crystallographic texture of plate are strongly influenced by plate gage, but not by alternate hot rolling practice (i.e., two-directional rolling). Furthermore, two-directional rolling did not reduce strength anisotropy
- For better understanding of strength and strength anisotropy of 7050-T7451 plate, additional study on chemistry and aging practice would be needed

IV. Al-Cu-Mg-Ag Alloy; 2139-T8 plate

-Two ingots were cast to evaluate Al-Cu-Mg-Ag based alloy

-To examine the effect of dispersoid forming elements (Zr vs. Mn)

- Plate products were evaluated at two different gages

Chemistry of two Al-Cu-Mg-Ag based alloy ingots:

	Cu	Mg	Ag	Mn	Zr	Ti
Alloy A (Mn)	4.90	0.46	0.38	0.32	0.002	0.09
Alloy B (Zr)	4.81	0.45	0.39	0.01	0.14	0.02

Each ingot was hot rolled to two different gage plates for evaluation

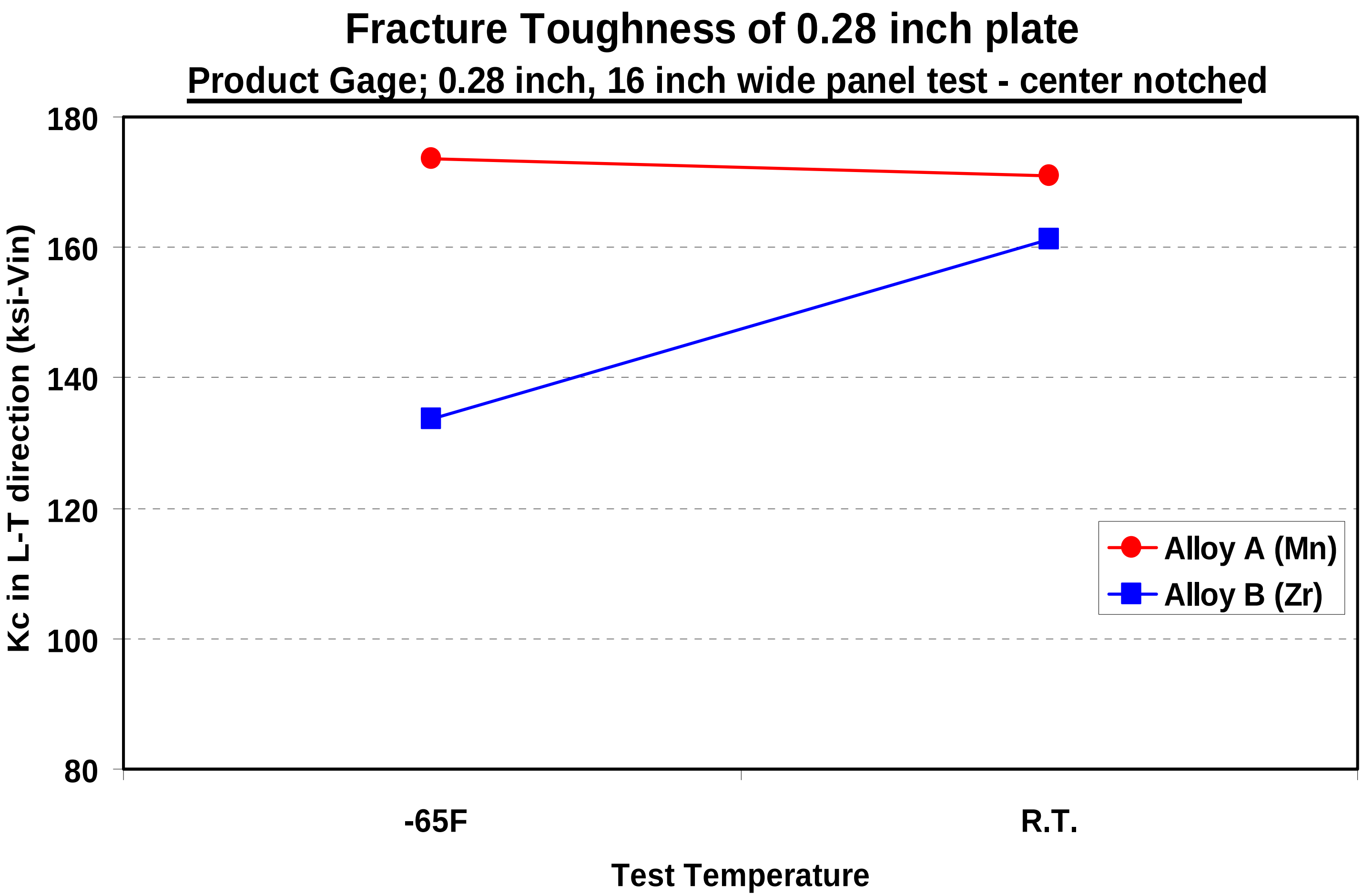
1) 0.28 inch gage

2) 1.0 inch gage

Brief Description of Results

IV. Al-Cu-Mg-Ag Alloy ; 2139-T8 Plate

Difference in Fracture Toughness between alloy A(w/Mn) and alloy B(w/Zr) becomes larger at –65 deg F than that at room temperature



Brief Description of Results

IV. Al-Cu-Mg-Ag Alloy ; 2139-T8 Plate

Test results on Fatigue Resistance showed that Lot No. 831571 (Al-Cu-Mg-Ag-Mn alloy) is better than Al-Cu-Mg-Ag-Zr alloy and far superior compared to alloy 2324-T39

Fatigue Resistance of Al-Cu-Mg-Ag alloys and 2324-T39 Plate

Notch Fatigue Tests on 1 inch gage Plate

Notched Fatigue Tests on 1.0 in. gage Al-Cu-Mg-Ag-Mn (Alloy A & B) Plate in T8

L -dir. at t/2 Max. Stress; 39 ksi, R-Ratio; 0.1 Freq.; 15 Hz

Alloy A(Lot No.831571)		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	1,500,000	Discont.
3	1,500,000	Discont.
4	1,500,000	Discont.
5	158,968	Gage Sec.

Avg. 957,492

Alloy B(Lot No.831581)		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	223,747	Gage Sec.
3	1,500,000	Discont.
4	1,500,000	Discont.
5	455,387	Gage Sec.

Avg. 807,760

2324-T39;(Lot 980Y667A)		
S.N.	Cycle to Fail	Fail. Loc.
1	162,653	Notch
2	157,222	Gage Sec.
3	157,360	Gage Sec.
4	164,409	Gage Sec.
5	183,183	Gage Sec.

Avg. 164,701

Brief Description of Results

IV. Al-Cu-Mg-Ag Alloy ; 2139-T8 Plate

SCC resistance of Al-Cu-Mg-Ag alloys (both alloy A & alloy B) is better than any other 2xxx alloy currently available commercially

Corrosion Resistance of 1.0 inch gage 2139-T8 Plate

- Alloy A(Lot no. 831571); 1.0 inch gage Plate

  SCC: Passed at 30, 35, and 40 ksi for 20 days
  when tested in ST direction
  per ASTM G47 by ASTM G-38-01

- Alloy B(Lot no. 831581); 1.0 inch gage plate

  SCC: Passed at 30, 35, and 40 ksi for 20 days
  when tested in ST direction
  per ASTM G47 by ASTM G-38-01

Brief Description of Results

IV. Al-Cu-Mg-Ag Alloy ; 2139-T8 Plate

Casting of Two Ingots

For additional development, two more ingots of Al-Cu-Mg-Ag-Mn alloy have been cast.

Ingot #1; 17.5 inch x 88 inch x 125 inch (usable length)

Ingot #2; 17.5 inch x 88 inch x 126 inch (usable length)

Chemistry of Two Al-Cu-Mg-Ag-Mn alloy ingots

Drop	Si	Fe	Cu	Mn	Mg	Cr	Ti	Ag	Zr
Target	0.04	0.07	5	0.35	0.5	0	0.04	0.35	0
min	0	0	4.5	0.3	0.45	0	0.03	0.3	0
max	0.08	0.1	5.5	0.4	0.55	0.025	0.05	0.4	0.03
Ingot #1	**0.0287**	**0.054**	**5.2**	**0.359**	**0.481**	**<0.0004**	**0.042**	**0.389**	**0.0016**
Ingot #2	**0.0223**	**0.04**	**5.23**	**0.361**	**0.493**	**<0.0004**	**0.042**	**0.358**	**<0.0005**

note: All chemistries are in weight %

Development of Al-Cu-Mg-Ag Alloy ; 2139-T8 plate

4. Conclusions

- Al-Cu-Mg-Ag alloy with Mn-containing dispersoids showed higher fracture toughness and fatigue resistance compared to Zr –containing dispersoids.
- Al-Cu-Mg-Ag alloys, having excellent Fracture Toughness, SCC Resistance and Fatigue resistance, would be most suitable for DT & D applications.
- Two ingots of Al-Cu-Mg-Ag-Mn alloy have been cast to explore thicker gage product.

Processing Improvement of Aluminum Alloys

- 2195, 2297 and 7050

& Development of An Al-Cu-Mg-Ag Alloy

- 2139

TASKS:

- **2195**
- **2297**
- **7050**
- **Al-Cu-Mg-Ag alloy - 2139**

Effect of Processing Modifications on Texture and Mechanical Properties of 2195-T8 Plate

Alex Cho

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Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Part I :

Effect of Alternate Hot Rolling Processing on Texture and Mechanical Properties of 2195-T8

Part II:

Effect of cold work prior to Artificial Age on the Mechanical Properties of 2195-T8 Plate

Part I :

Effect of Alternate Hot Rolling Processing on Texture and Mechanical Properties of 2195-T8

Effect of Alternate Hot Rolling Process on Texture and Mechanical Properties of 2195-T8

Contents:

Processing Modifications of 2195-T8 Plate

I. Objective

Improve the longitudinal tensile strength of 2195-T8 plate to produce a more isotropic plate product and improve damage tolerance

Processing Modifications of 2195-T8 Plate

II. Approach

Examine the past performance of 2195-T8 plate, identify an alternative hot rolling process and evaluate the effect on texture and mechanical properties by conducting a plant trial

III. Background Information for 2195-T8 Plate :

- Current standard processing of 2195-T8 plate product results in ultimate tensile strengths in the longitudinal direction (**L UTS**) frequently lower than the long transverse direction.
- Property improvement is most desirable in 1.575 inch plate at the t/6 and 5t/6 thickness locations.
- The objective is to improve L UTS values by at least 2 ksi, compared to typical values of the plate produced by current standard processing.

Average values from 130 lots of 1.575" gage 2195-T8	
	Average(130 lots)
L UTS	79.1 ksi
LT UTS	82.9 ksi

IV. Process Description of Standard vs. Proposed Trial Lots

Current Ravenswood Uni-directional Practice on 2195 plate

-Full size ingot: 16” x 60” x 120”

-Straight Roll to 142” from 120”

-Rotate 90 deg., Cross Roll to finish to 440” long from 60”

-SHT /Stretch/Age

Proposed Two-directional Hot Rolling Practice

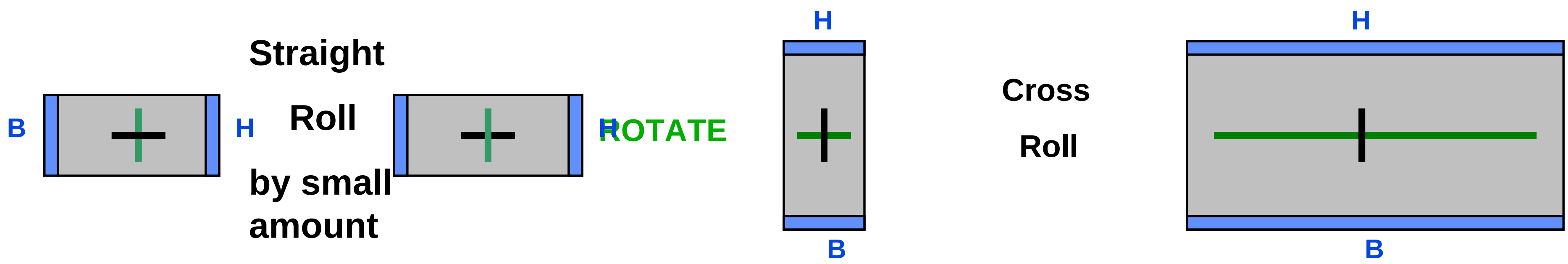
-Full size ingot: 16” x 60” x 120”

-Cross Roll to 142” wide from 60”

-Rotate 90 deg., straight roll to finish to 440” long from 120”

-SHT /Stretch/Age

current Ravenswood Hot Rolling Practice for 2195 – (McCook Practice)

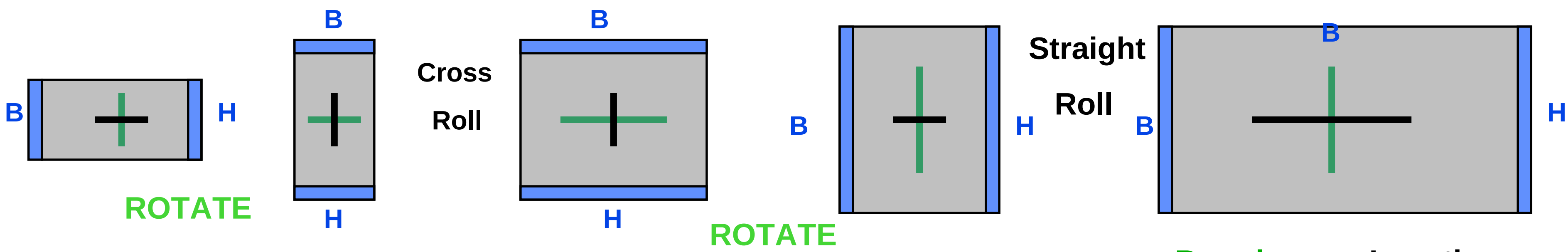


Current practice provides essentially One Directional Deformation

Lengthen. vs. Broaden.

1.2X vs. 7.4X

Proposed Two-Directional Rolling Practice



Broaden. vs. Lengthen.

2.4X vs. 3.7X

Detailed Description of Proposed Hot Rolling Trials for 2195-T8 Plate

- Select 2 ingots of 16” x 60” x 120” (approx. 11,000 lbs) for Hot Rolling Trials

Lot No. 246263: 4.06 Cu - 0.95 Li - 0.35 Mg - 0.32 Ag - 0.14 Zr

Lot No. 265771: 3.97 Cu -0.96 Li - 0.31 Mg - 0.33 Ag - 0.14 Zr

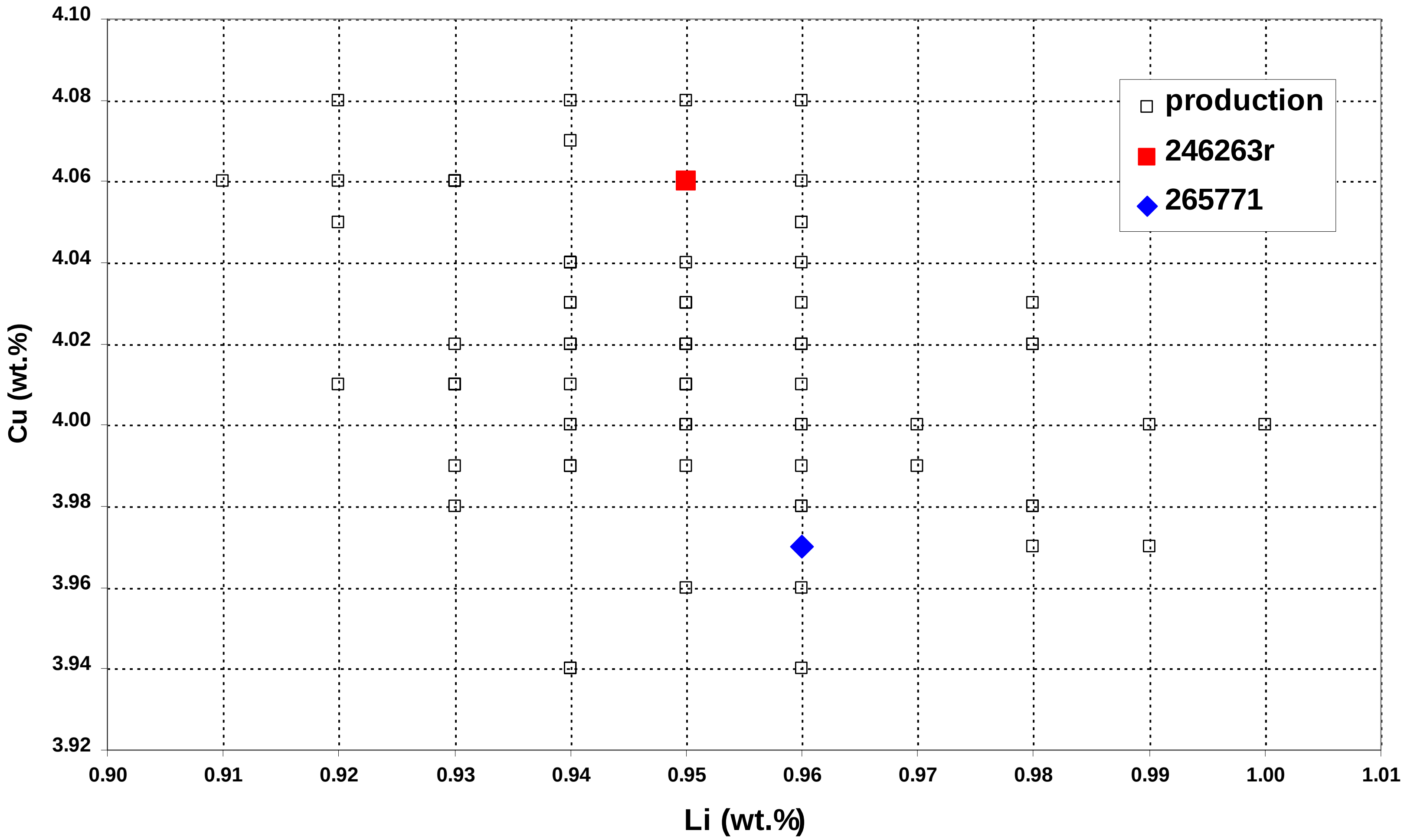
- **Cross Roll (two-directional) to 142” wide from 60”**
  Rotate 90 deg.,
  straight roll to finish to 440” long from 120”
  SHT/Stretch/Age (32 hours at 300 deg F)
  Final Gage : 1.575”

	Hot Rolling Practice		SHT	Amount of Stretch		Conductivity(%IAC)	
Lot No.	Lay-on(degF)	Exit(deg F)	Soak time(hr)	Right Edge	Left Edge	Top surf.	Bottom surf.
246263	880	729	4.8	3.50%	3.85%	22.8 / 23.7	22.9 / 24.1
265771	872	770	4.8	3.88%	3.50%	22.9 / 23.6	22.7 / 23.7

- Artificial Aging condition was selected to enable comparison with the mechanical properties of standard straight rolled plate

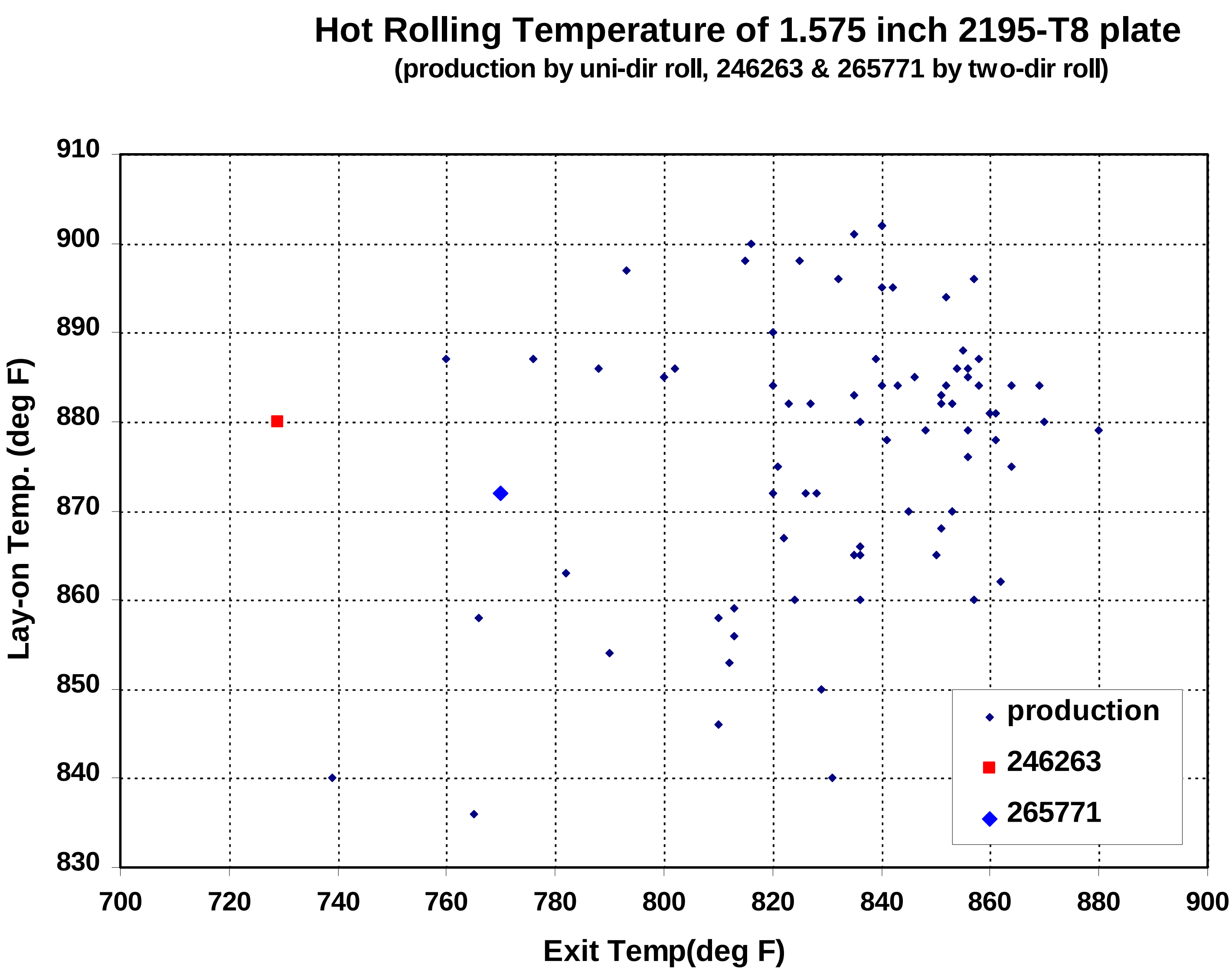
- Chemistry of trial ingots are within standard range
- Li content, the most significant alloying element, is very close to the average value of the past production ingot chemistries.

Chemistry of 1.575 inch 2195-T8 plate
(production by uni-dir roll, 246263 & 265771 by two-dir roll)



Alex Cho (304-273-7038), Pechiney Rolled Products LLC, Aug. 09, 2005 NASA Contract no. NNL04AB64T with AS&M Inc.

Lay-on temperatures during rolling of the trial ingots were similar to the average value of the standard product. However, Exit temperatures from hot rolling for these two ingots werere lower then most of the standard production runs

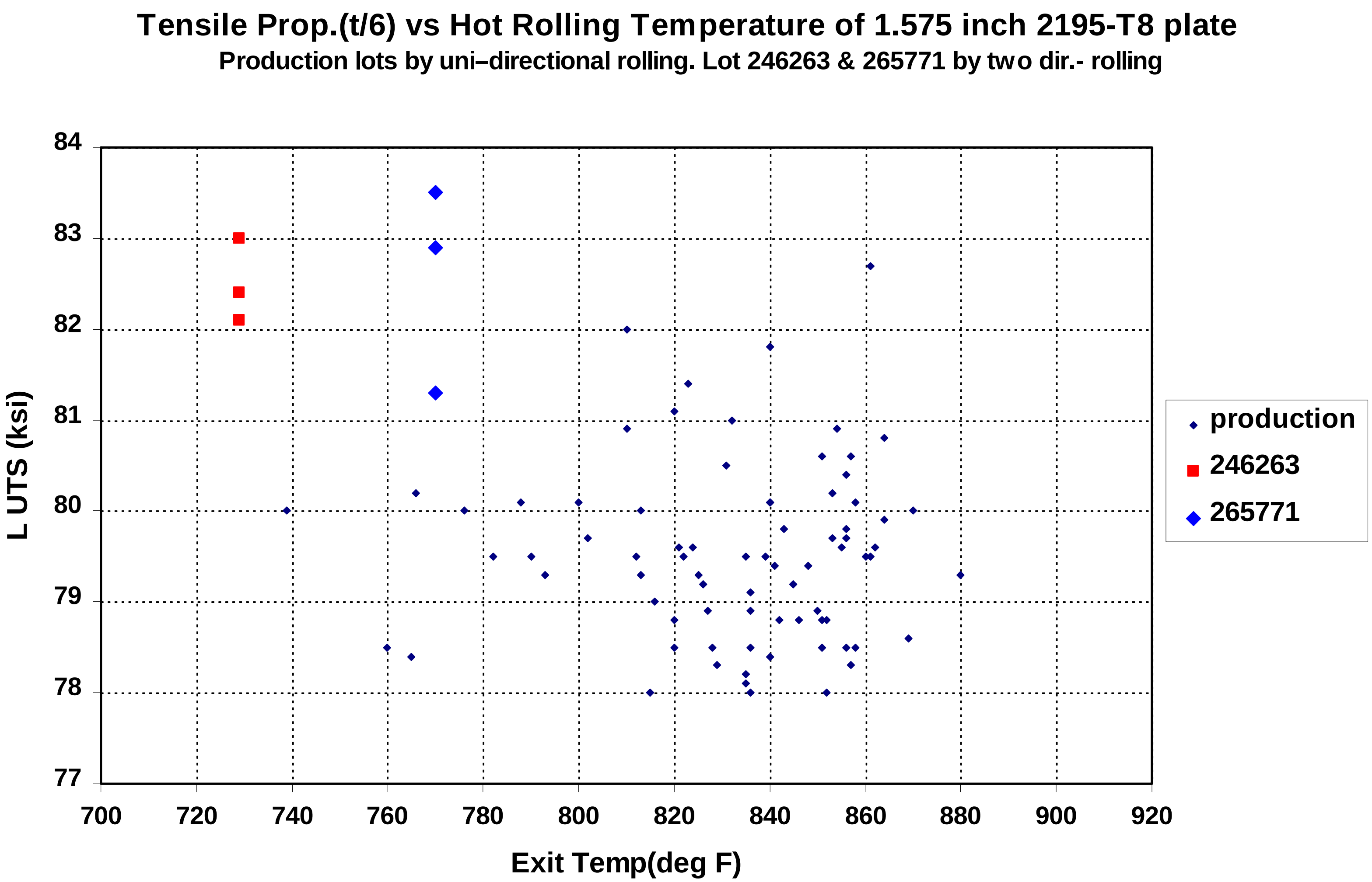


V. Property Test Results for Standard Plate and Trial Ingots

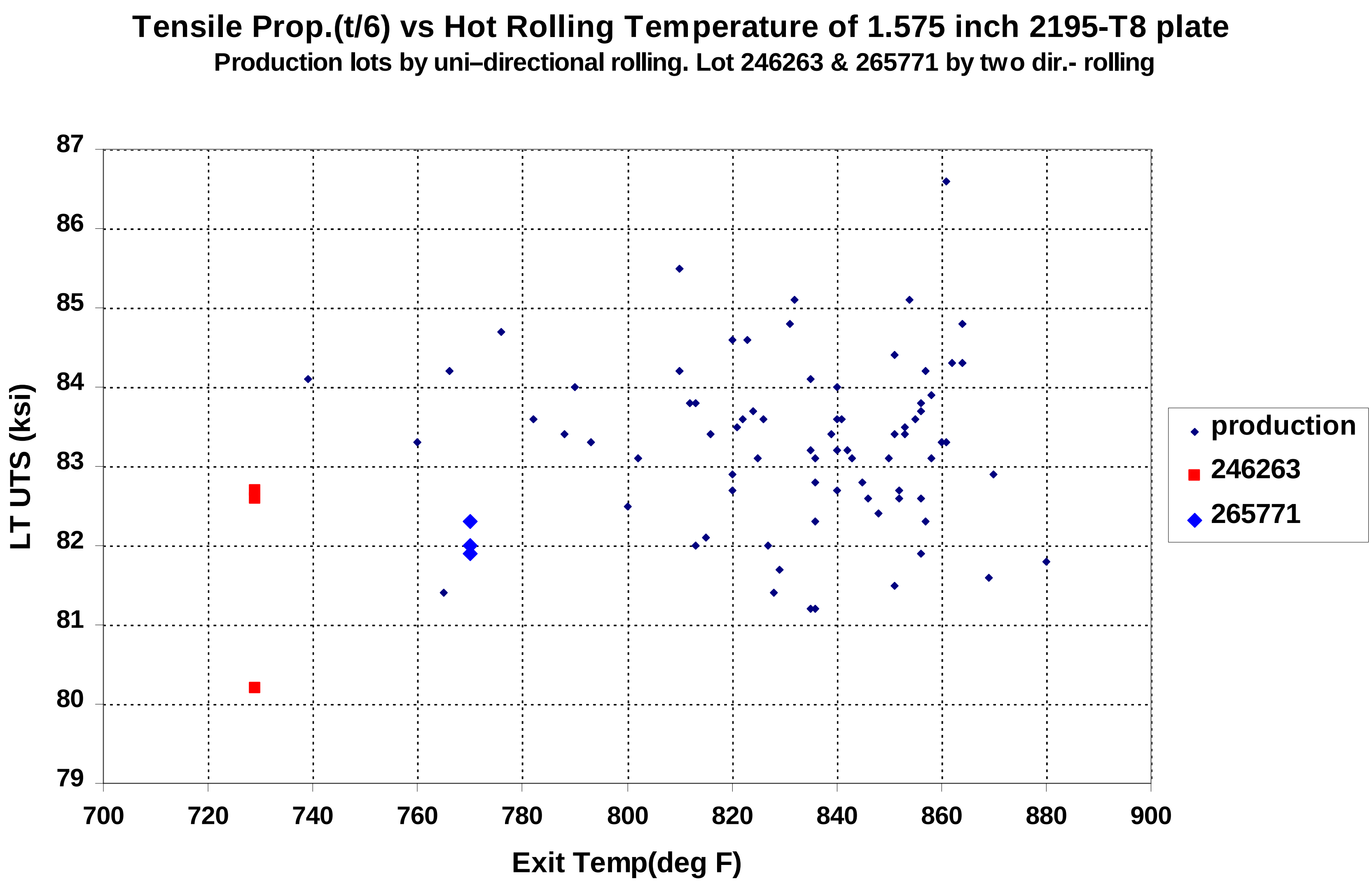
- Trial ingots, 246263 and 265771, are two-directionally rolled. All other 75 production ingots were uni-directionally rolled (i.e., standard practice)

- Tensile properties and Simulated Service Tests (SST) were performed on the two trial processed at three plate locations each and the results are compared to those of standard production lots.

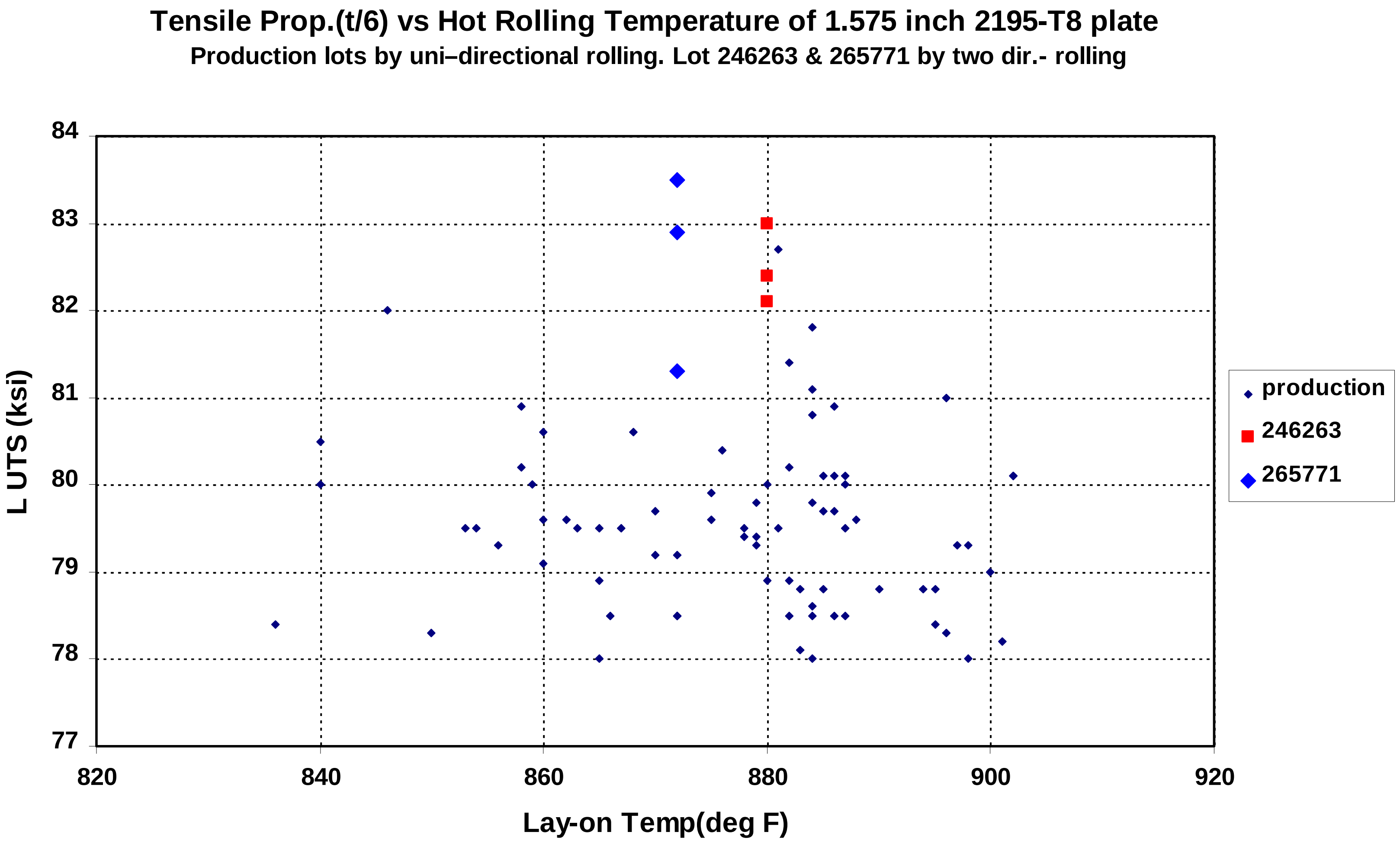
Examination of the standard process plate showed that when the exit temperatures overlap, the L UTS is higher for the two –directionally rolled plate, lot no.246263 & 265771



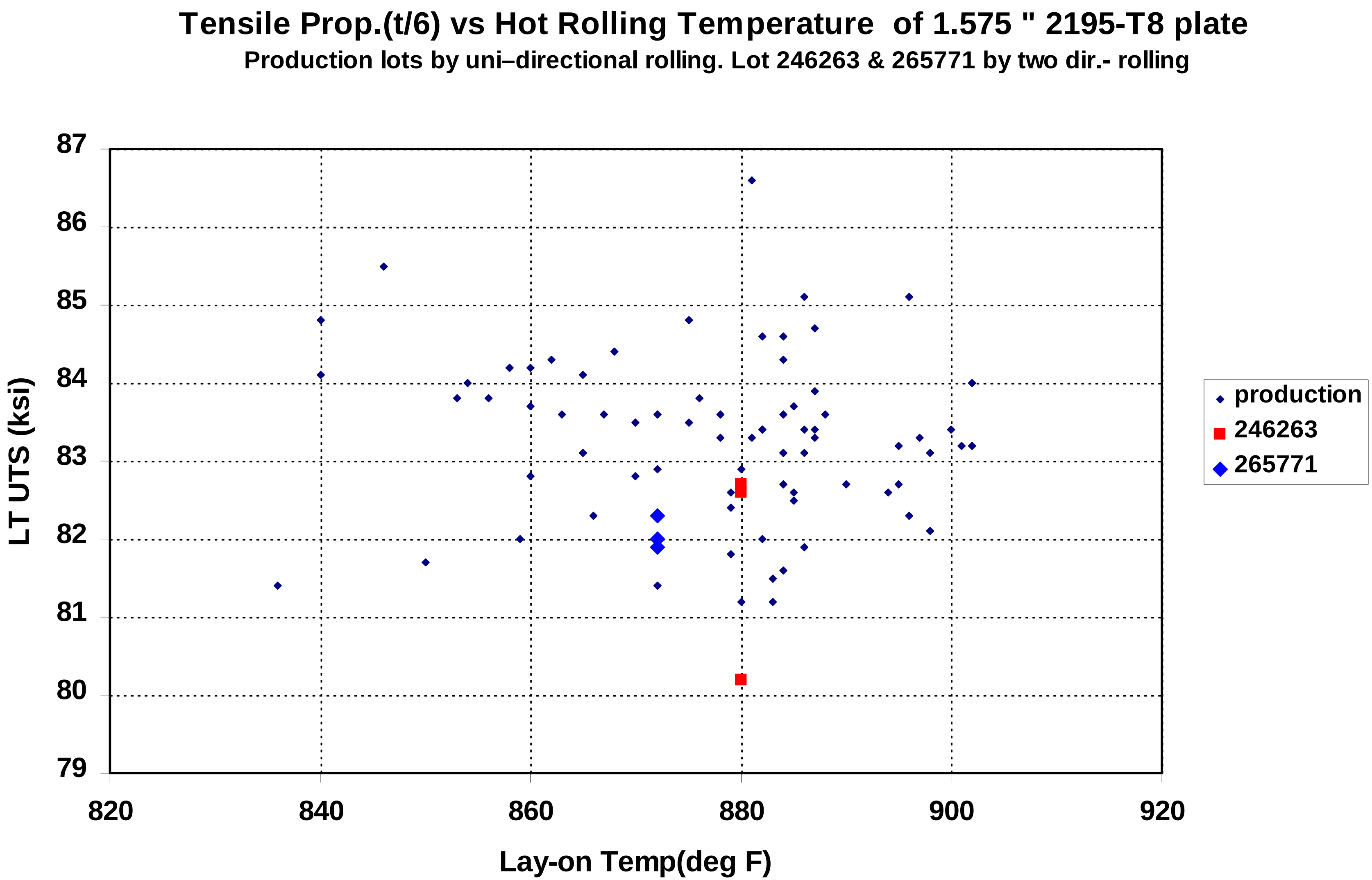
LT UTS for two-directionally rolled plate is comparable to production plate regardless of exit temperature.



L UTS are higher for two-directionally rolled plate at simialr lay-on temperatures

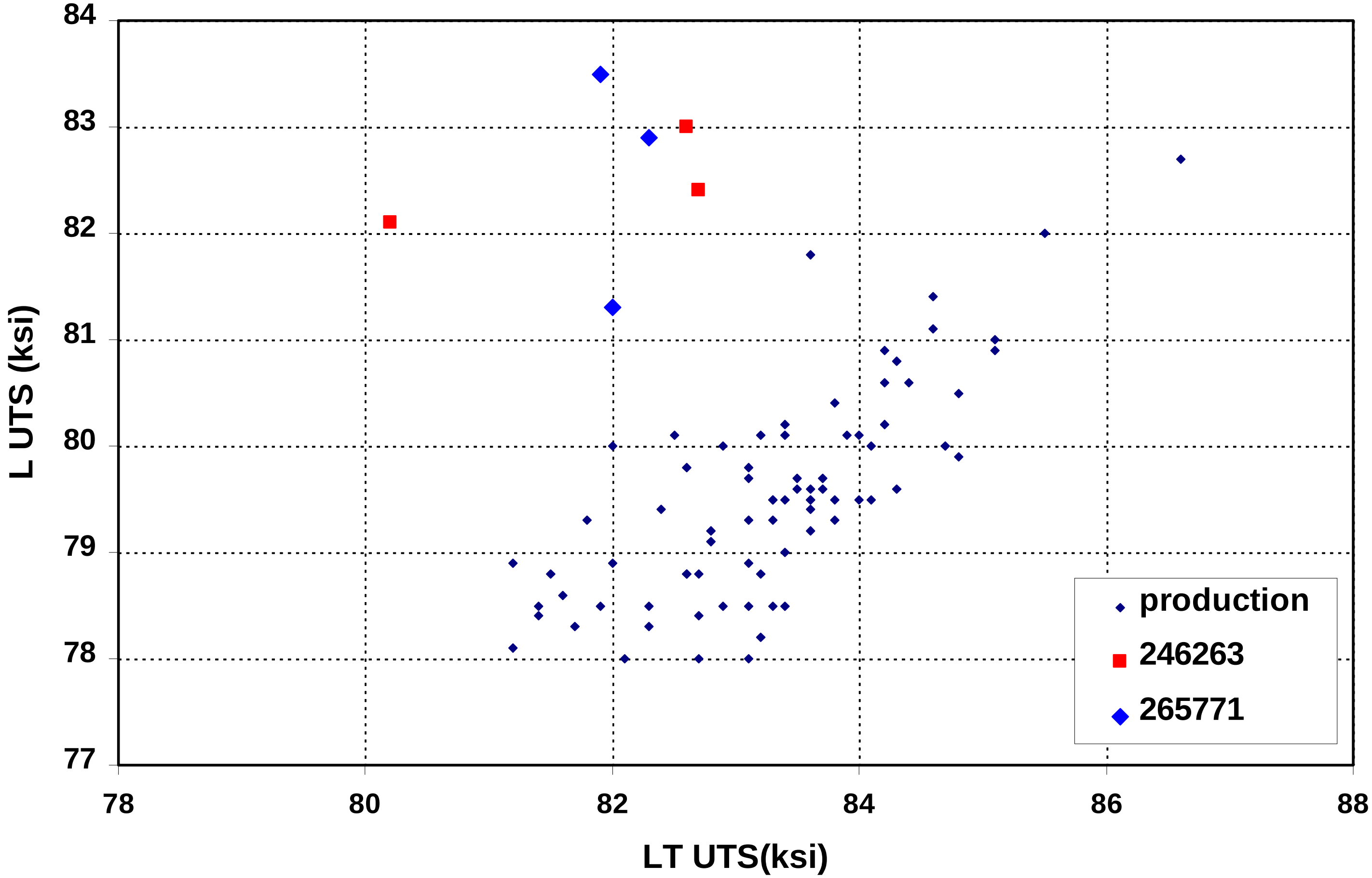


LT UTS of trial processed plate is comparable to production plate



L UTS & LT UTS for two-directionally rolled plate are better than production plate.

Tensile Prop.(t/6) vs Hot Rolling Temperature of 1.575 inch 2195-T8 plate
(production by uni-dir roll, 246263 & 265771 by two-dir roll)



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- Two-directionally rolled plate showed higher average value of L UTS by 3 ksi compared to the uni-directionally rolled plate.

Comparison of Tensile Properties for Plate Processed by Two-directional rolling vs. Uni-directional rolling

Tensile properties in L-dir. from two-directionally roll. plate
10 locations from 2 lots after aged at 300F for 32 hours

Lot No.	Sample Location*	Test direction	Test plane	L UTS ksi	L TYS ksi	L e %
246263	N2	L	t/6	82.1	78.9	6.5
246263	N2	L	5t/6	83.4	77.7	7.5
246263	N4	L	t/6	83	79.5	8
246263	S2	L	t/6	82.4	79.5	7.5
246263	S2	L	5t/6	80.3	77.9	5.5
265771	N2	L	t/6	82.9	79.5	7.5
265771	N2	L	5t/6	82.8	79.5	7.5
265771	N4	L	t/6	81.3	78.2	8
265771	S2	L	t/6	83.5	79.7	7
265771	S2	L	5t/6	83.4	79.8	6.5
note*:see a diagram in page 25				80.3	77.7	5.5
			Max	83.5	79.8	8
			Average	82.51	79.02	7.15
			STD Dev	1.03	0.79	0.78

uni-directionally rolled Plate 75 lots aged at 300F for 32 hrs.	Min	78	73.7	7
	Max	82.1	77.9	10.5
	Average	79.45	75.83	9.11
	STD Dev	0.87	0.94	0.71
Difference between uni-dir. & two-dir. rolled plate after aged at 300F for 32 hrs	min	2.3	4	-1.5
	max	1.4	1.9	-2.5
	Average	**3.06**	**3.19**	**-1.96**
	STD Dev	0.16	-0.14	0.07

• Two-directionally rolled plate showed lower average value of LT UTS by 1 ksi compared to the uni-directionally rolled plate. However, average value of LT UTS of uni-directionally rolled plates are higher by 4 ksi compared to the average value of L UTS. This would make the plate more isotropic in strength.

Comparison of Tensile Properties for Plate Processed by Two-directional rolling vs. Uni-directional rolling

Tensile properties in LT -dir. from two-dir. rolled Plate
10 locations from 2 lots after aged at 300F for 32 hours

Lot No.	Sample Location*	Test direction	Test plane	LT UTS ksi	LT TYS ksi	LT e %
246263	N2	LT	t/6	80.2	77.6	6.5
246263	N2	LT	5t/6	83.3	77.7	7.5
246263	N4	LT	t/6	82.6	76.5	8
246263	S2	LT	t/6	82.7	77.3	6.5
246263	S2	LT	5t/6	82.9	77.8	6.5
265771	N2	LT	t/6	82.3	76.5	8
265771	N2	LT	5t/6	81.7	76.2	7.5
265771	N4	LT	t/6	82	76.3	8
265771	S2	LT	t/6	81.9	75.7	10
265771	S2	LT	5t/6	82	75.8	8.5
note*:see a diagram in page 25			Min	80.2	75.7	6.5
			Max	83.3	77.8	10
			Average	82.16	76.74	7.7
			STD Dev	0.85	0.79	1.09

uni-directionally rolled Plate 75 lots aged at 300F for 32 hrs.	Min	81.2	73.4	7
	Max	85.5	78.7	10
	Average	83.25	76.10	8.47
	STD Dev	0.98	1.12	0.67
Difference between uni-dir. & two-dir. rolled plate after aged at 300F for 32 hrs	Min	-1	2.3	-0.5
	Max	-2.2	-0.9	0
	Average	**-1.09**	**0.64**	**-0.77**
	STD Dev	-0.13	-0.32	0.41

• Two-directionally rolled plate showed higher average value of 45 deg TYS by 2 ksi and average 45 deg UTS by 0.3 ksi compared to the uni-directionally rolled plate.

Comparison of Tensile Properties for Plate Processed by Two-directional rolling vs. Uni-directional rolling

Tensile properties in 45 deg -dir. from two-dir. rolled Plate
10 locations from 2 lots after aged at 300F for 32 hours

Lot No.	Sample Location*	Test direction	Test plane	45 UTS ksi	45 TYS ksi	45 e %
246263	N2	45	t/6	81.9	75.6	6.5
246263	N2	45	5t/6	82.5	75.6	8.5
246263	N4	45	t/6	81	73.9	9
246263	S2	45	t/6	82.1	75.1	10
246263	S2	45	5t/6	81.9	75.5	9.5
265771	N2	45	t/6	81.9	74.8	8.5
265771	N2	45	5t/6	81.3	74	8
265771	N4	45	t/6	80.6	73.6	9
265771	S2	45	t/6	81.6	74.4	8.5
265771	S2	45	5t/6	82.1	74.8	8.5
note*:see a diagram in page 25			Min	80.6	73.6	6.5
			Max	82.5	75.6	10
			Average	81.69	74.73	8.6
			STD Dev	0.57	0.73	0.94

uni-directionally rolled Plate 75 lots aged at 300F for 32 hrs.	Min	78.5	68.2	7
	Max	86.1	77.8	11
	Average	81.35	72.75	10.07
	STD Dev	1.13	1.39	0.71
Difference between uni-dir. & two-dir. rolled plate after aged at 300F for 32 hrs	Min	2.1	5.4	-0.5
	Max	-3.6	-2.2	-1
	Average	**0.34**	**1.98**	**-1.47**
	STD Dev	-0.56	-0.65	0.23

• Two-directionally rolled plate showed higher average values of ST UTS by 2.9 ksi and ST TYS by 2.6 ksi compared to the uni-directionally rolled plate.

Comparison of Tensile Properties for Plate Processed by Two-directional rolling vs. Uni-directional rolling

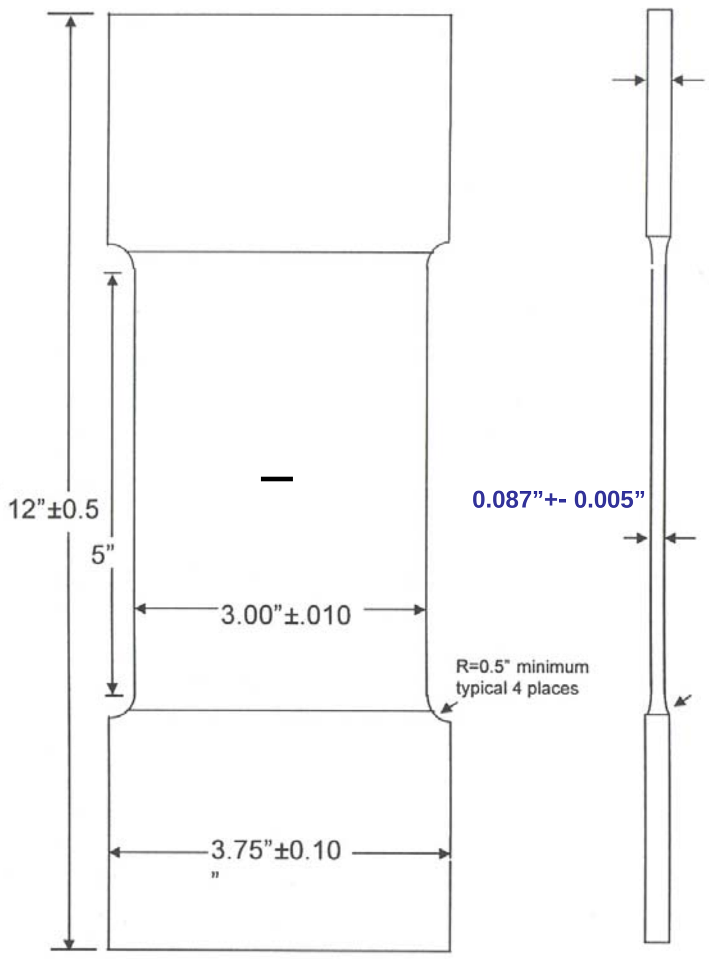
Tensile properties in ST -dir. from two-dir. rolled Plate
6 locations from 2 lots after aged at 300F for 32 hours

Lot No.	Sample Location*	Test direction	Test plane	ST UTS ksi	ST TYS ksi	ST e %
246263	N2	ST	t/2	87.5	76.5	3.6
246263	S2	ST	t/2	85.6	74.2	3
246263	N4	ST	t/2	88.8	76.8	3.1
265771	N2	ST	t/2	86.7	75.2	3.3
265771	S2	ST	t/2	85.6	73.9	3
265771	N4	ST	t/2	86.5	74.1	3.1
note*:see a diagram in page 25			Min	85.6	73.9	3
			Max	88.8	76.8	3.6
			Average	86.78	75.12	3.18
			STD Dev	1.22	1.27	0.23

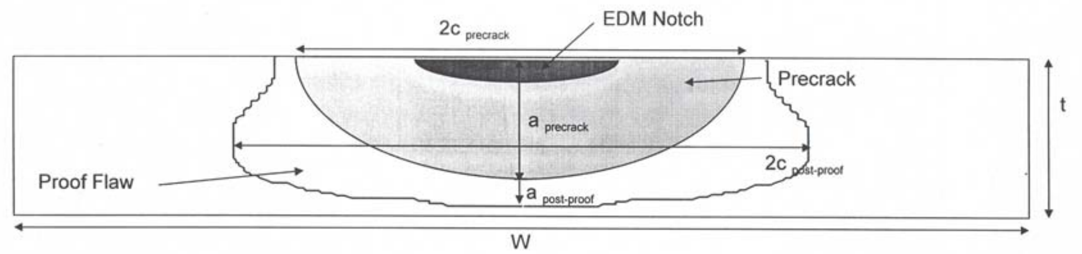
uni-directionally rolled Plate 75 lots aged at 300F for 32 hrs.	Min	78.3	65.6	2
	Max	88.9	77.9	7.8
	Average	83.91	72.53	4.41
	STD Dev	1.93	1.55	1.32
Difference between uni-dir. & two-dir. rolled plate after aged at 300F for 32 hrs	Min	7.3	8.3	1
	Max	-0.1	-1.1	-4.2
	Average	**2.87**	**2.59**	**-1.22**
	STD Dev	-0.70	-0.28	-1.09

Simulated Service Test

Surface Crack Tension Specimen



Surface Crack Tension Specimen Cross Section



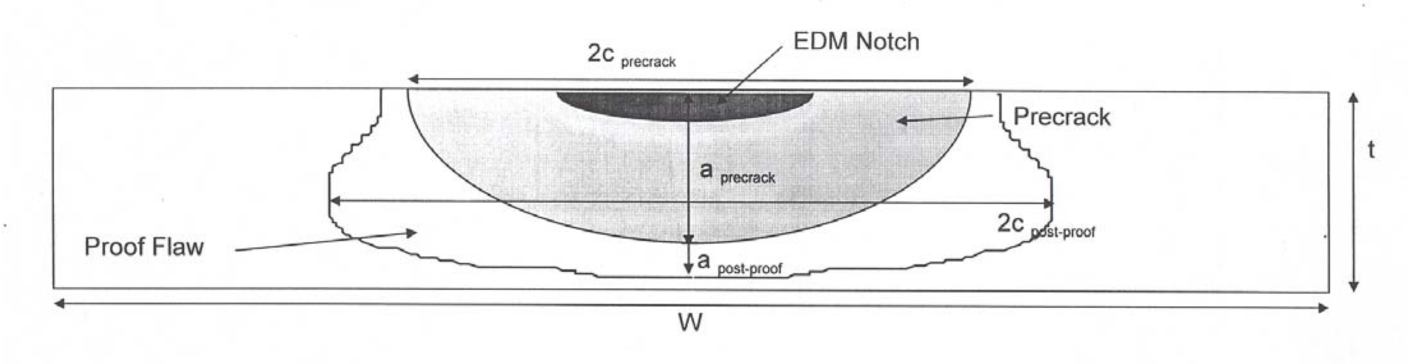
Net Section Stress(precrack)=Fracture load/($tW-\pi a_{precrack}2c_{precrack}/4$)

Net Section Stress(post-proof)=Proof load/($tW-\pi a_{post\text{-}proof}2c_{post\text{-}proof}/4$)

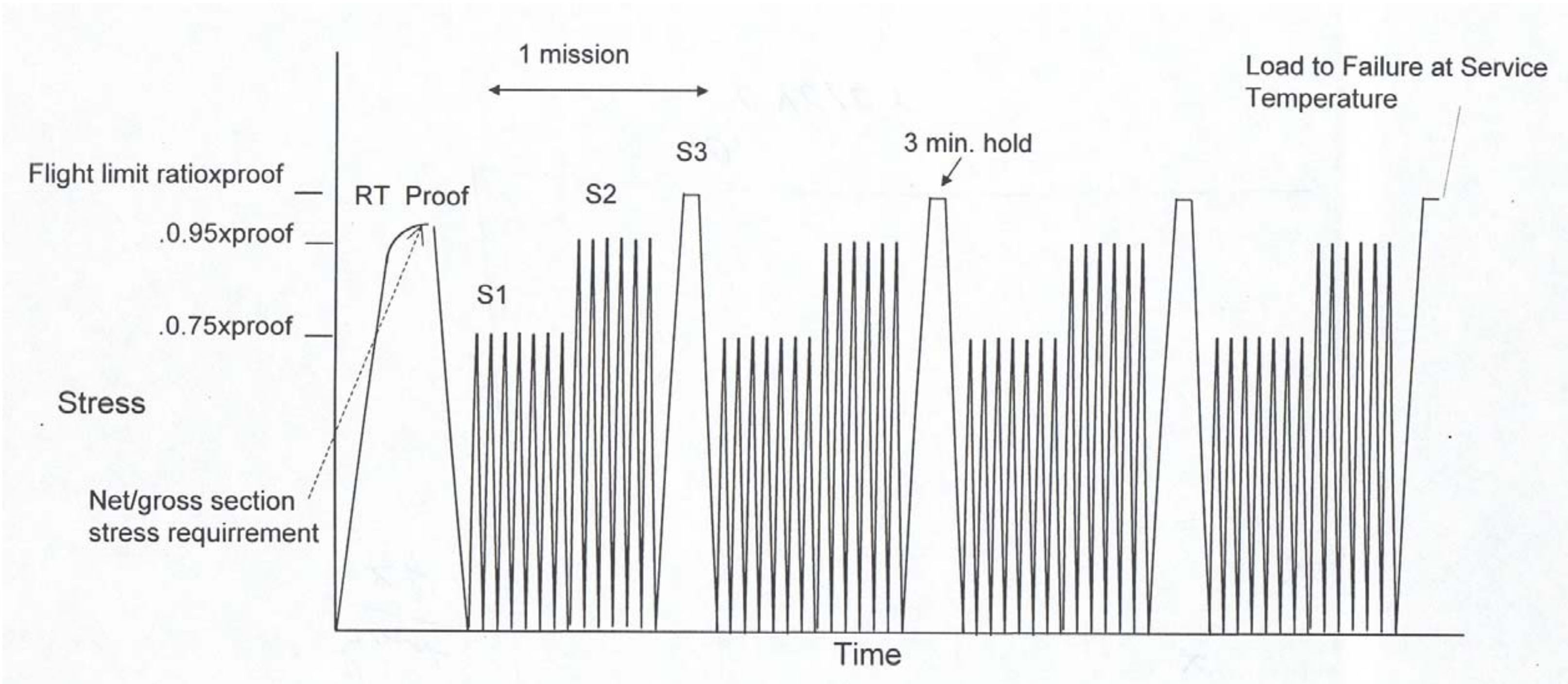
Testing Procedure

1. SST requires two specimens per lot
2. Specimen #1 is to measure "proof offset" and "proof stress" at room temperature
3. Specimen #2 is to measure fracture stress at –320F after four mission cycles at –320 deg F

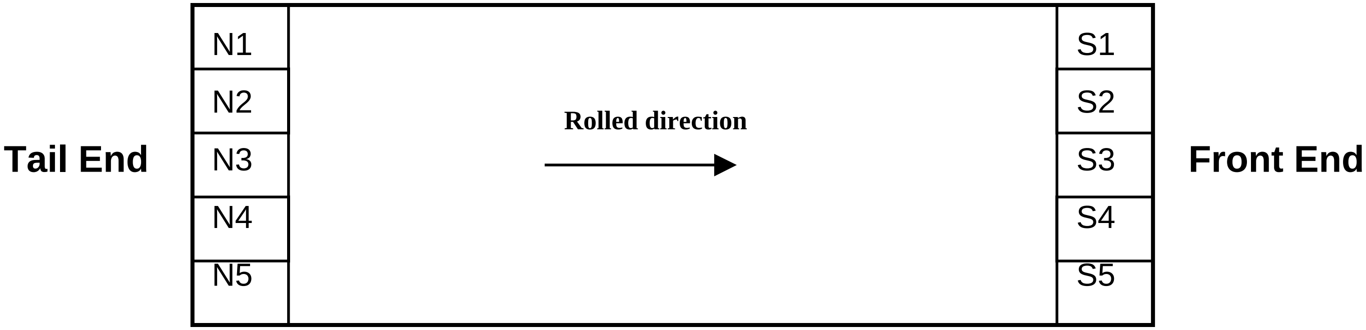
Surface Crack Tension Specimen Cross Section



Stress Ratio = Fracture Stress after mission cycles at –320 deg F / Proof Stress at R.T.



Schematic diagram of test sample locations from 1.575" gage 2195 plate



Simulated Service Test Results for Two-Directionally Rolled Plate

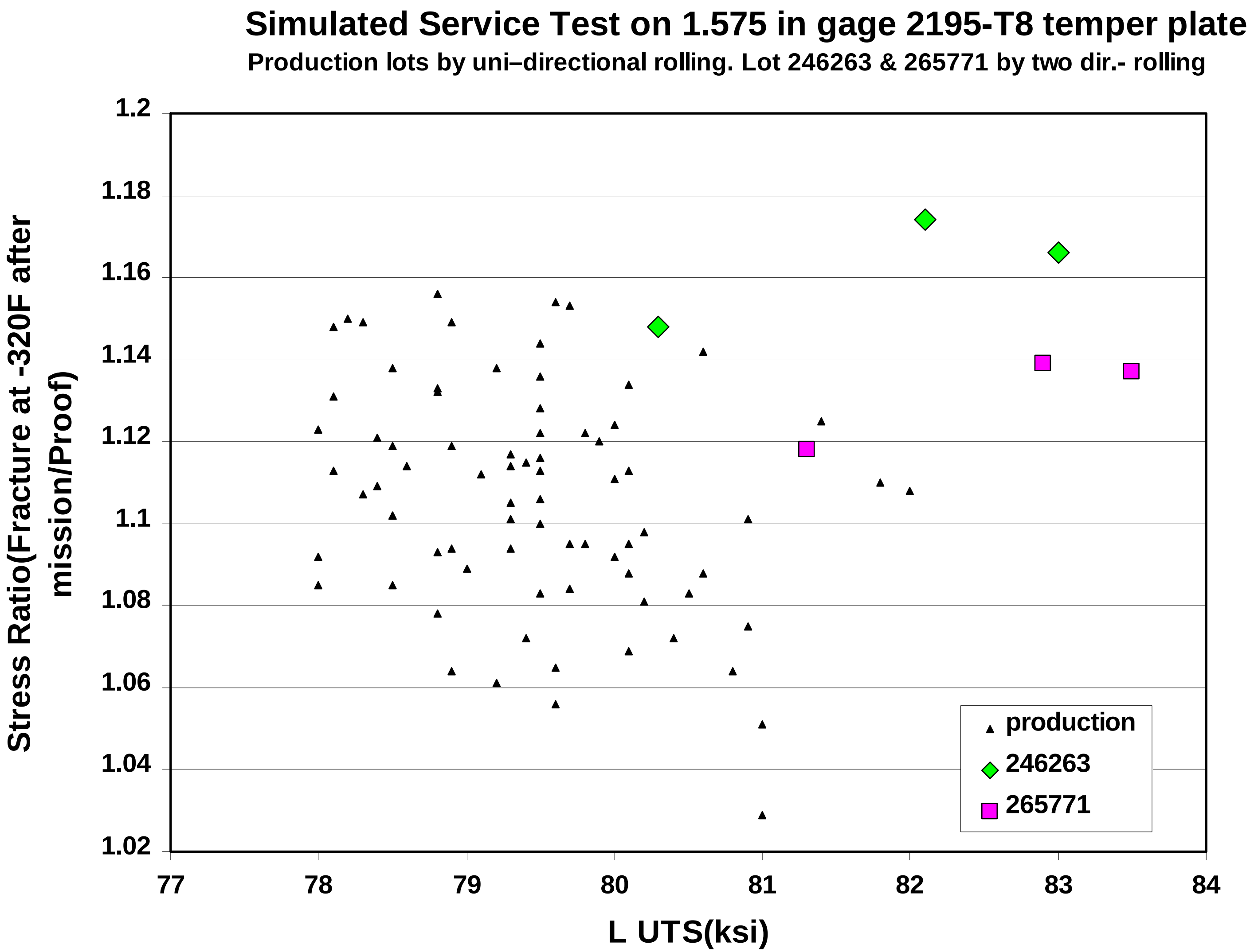
(Sample Orientation in T-S, Aged at 300 deg F for 32 hours)

Lot No.	Sample Location	test plane	Ke (proof)	Ke fracture (post mission)	Net Fracture Stress	Net Proof Stress(post proof flaw)	Failure Stress after Mission cycle/ Proof	L UTS (ksi)
246263	N2	t/6	28	32.9	75.6	76.7	1.174	82.1
246263	N4	5t/6	27.7	32.3	75	77	1.166	83
246263	S2	5t/6	27.7	31.8	75.1	76.3	1.148	80.3
265771	N2	t/6	28.5	32.5	73.6	75	1.139	82.9
265771	N4	5t/6	28.6	32	76.1	78.3	1.118	81.3
265771	S2	t/6	28.3	32.2	75.2	76	1.137	83.5

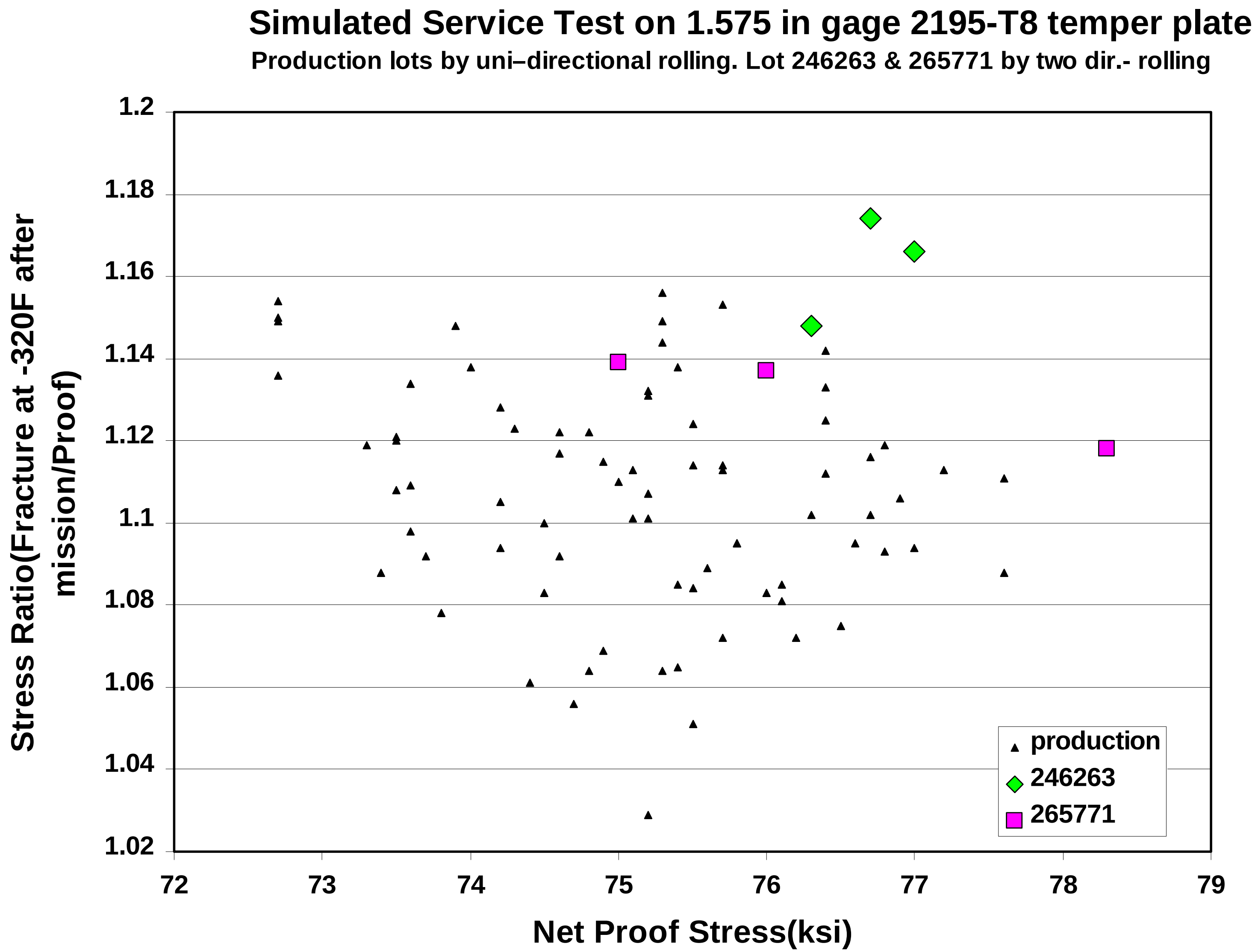
Note: Ke values are in Ksi-√inch

Note: Stress values are in Ksi

Improved Combination of Stress Ratio and L UTS Achieved with Two-directionally Rolled Plate



Small improvement in Stress Ratio achieved for two-dimensionally Rolled Plate for similar Proof Stress values



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Summary of Tensile and Simulated Service Test Results

Compared with production plates, two-directionally rolled plate showed:

- L UTS values are higher by 3 ksi
- More isotropic strengths
- Higher strengths in all directions except LT UTS
- SST results showed more favorable Stress Ratios vs. L UTS and Net Proof Stress

VI. Texture Study Results

- To investigate the effect of hot rolling practice on crystallographic texture of 2195-T8 plate, the CODF(crystallographic orientation distribution function) was measured at t/6 plane locations for 10 lots of standard production plate and two lots of two-directionally rolled plate
- Since there are only two lots of two-directionally rolled plate, two locations, front end (N) & tail end (S) of each plate were sampled and tested. All other production lots were tested at tail end(N)
- The results are presented by volume % of each texture components as follows:

Cube:	{001} <100>,
Goss:	{011} <100>,
Brass:	{011} <211>,
S:	{123} <634>
Cu:	{112} <111>
rotated Cube:	{001} <110>

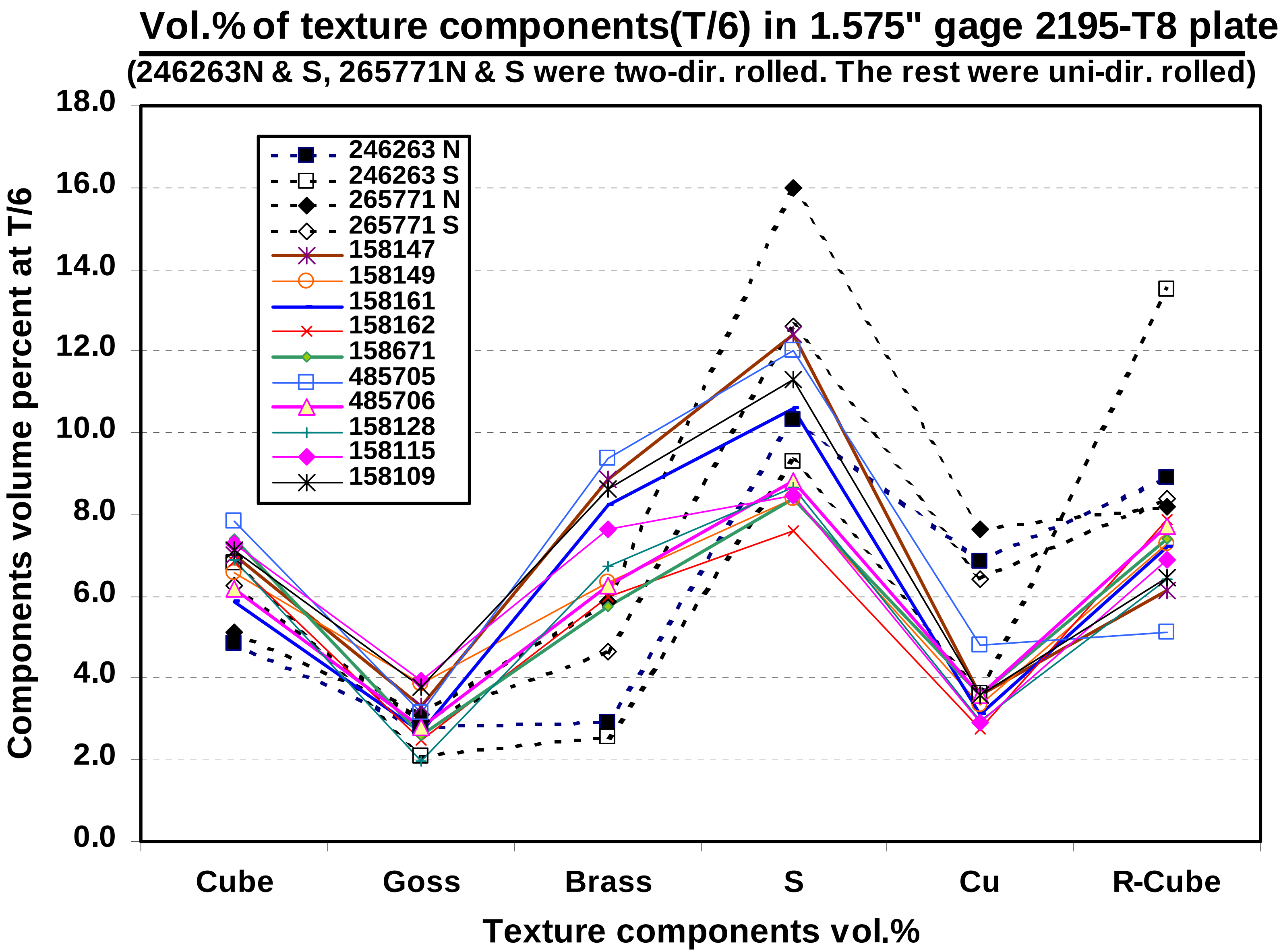
- For S component, there are large overlaps in vol% values between two-directionally rolled and uni-directionally plate. However, two directionally rolled plate tended to have higher values.
- For Cu component, two-directionally rolled plate generally had a higher volume % except for 246263 S(front end).
- For Brass & Cube components, two-directionally rolled plate tended to have lower volume % with slight overlap in values.

Crystallographic Texture of 1.575” gage 2195-T8 Plate at t/6 location

(Texture components in vol.%)

(246263N & S, 265771N & S are two-dir. rolled. Remaining lots are uni-dir. rolled)

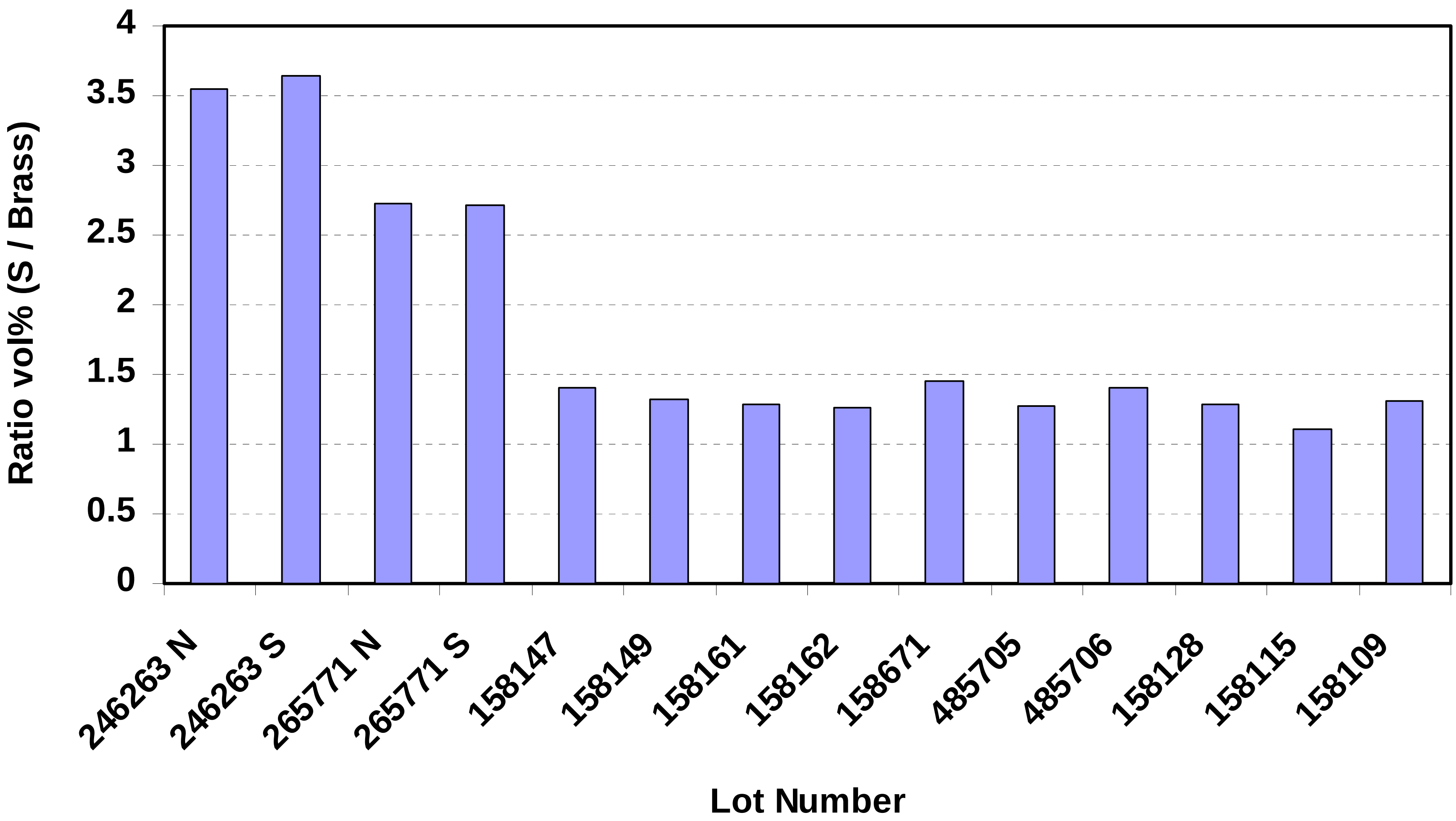
Lot	Cube	Goss	Brass	S	Cu	R-Cube	S/Brass	Cu + R-Cube
246263 N	***4.9***	***2.8***	***2.9***	***10.3***	***6.8***	***8.9***	***3.55***	***15.7***
246263 S	***6.8***	***2.1***	***2.6***	***9.3***	***3.6***	***13.5***	***3.65***	***17.1***
265771 N	***5.1***	***3.1***	***5.9***	***16.0***	***7.6***	***8.2***	***2.72***	***15.8***
265771 S	***6.3***	***3.0***	***4.7***	***12.6***	***6.4***	***8.4***	***2.71***	***14.8***
158147	7.0	3.3	8.9	12.4	3.6	6.1	1.40	9.7
158149	6.6	3.9	6.4	8.4	3.3	7.3	1.32	10.6
158161	5.9	2.7	8.2	10.6	3.1	7.2	1.29	10.3
158162	6.9	2.5	6.0	7.6	2.7	7.9	1.27	10.6
158671	7.4	2.6	5.8	8.4	3.6	7.4	1.46	11.0
485705	7.8	3.1	9.4	12.0	4.8	5.1	1.28	9.9
485706	6.2	2.8	6.3	8.8	3.6	7.7	1.41	11.3
158128	6.9	2.0	6.8	8.7	3.0	6.4	1.28	9.4
158115	7.3	3.9	7.7	8.5	2.9	6.9	1.10	9.8
158109	7.1	3.8	8.6	11.3	3.6	6.4	1.31	10.0


Vol.% of texture components(T/6) in 1.575" gage 2195-T8 plate
(246263N & S, 265771N & S were two-dir. rolled. The rest were uni-dir. rolled)
Components volume percent at T/6
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
246263 N
246263 S
265771 N
265771 S
158147
158149
158161
158162
158671
485705
485706
158128
158115
158109
Cube
Goss
Brass
S
Cu
R-Cube
Texture components vol.%

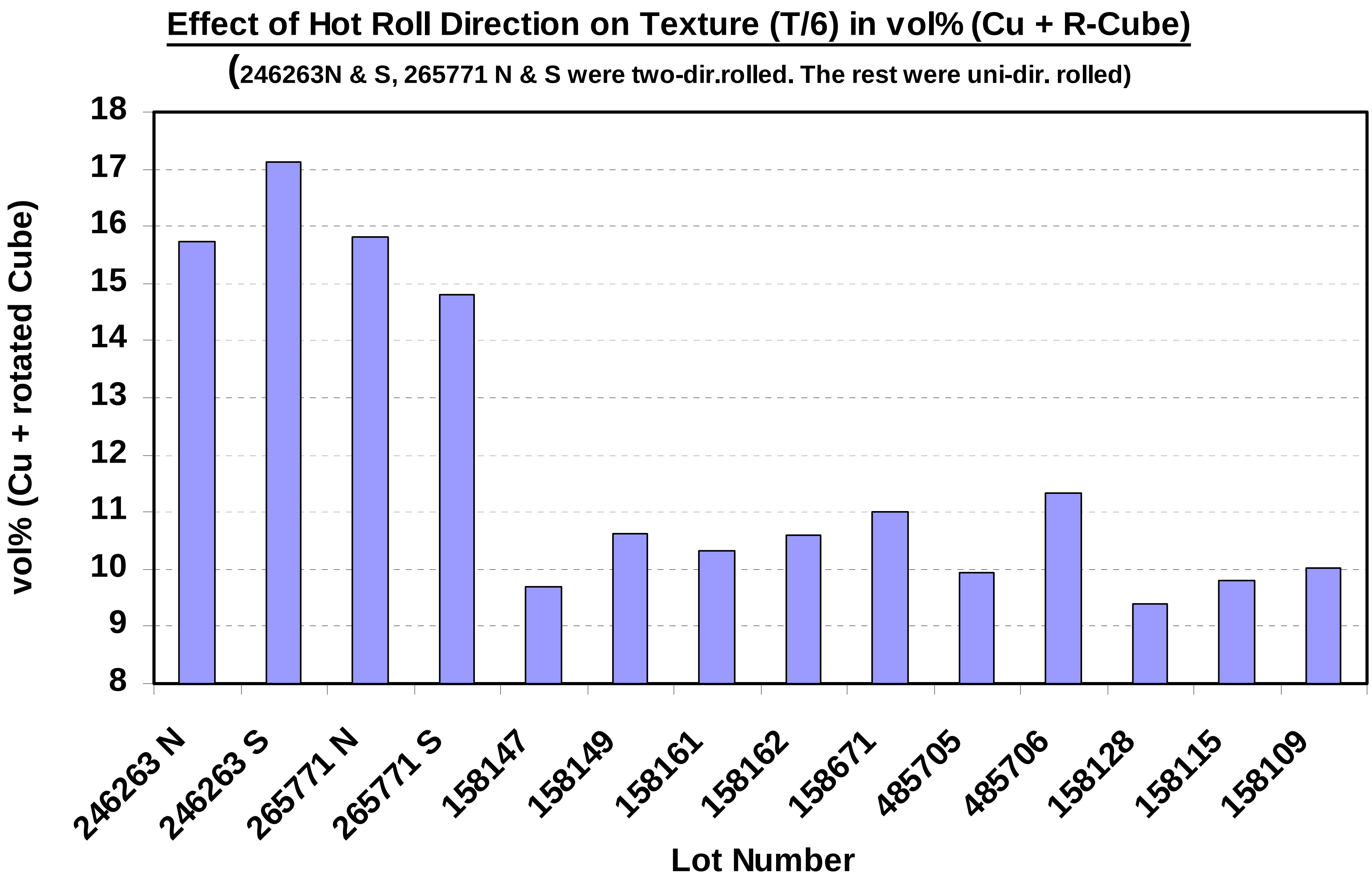
- The volume% ratio of S/Brass components of two-directionally rolled plate are distinctively higher than those of uni-directionally rolled plate

Effect of Hot Roll Direction on Texture vol% (S/Brass) at T/6

(246263N & S, 265771N & S were two-dir. rolled. The rest were uni-dir. rolled)



- Sum of the vol.% of Cu & rotated Cube components of two-directionally rolled plate are distinctively higher than those of uni-directionally rolled plate



VII. Correlation of Texture on L vs LT direction strengths

- Favored slip planes for fcc metals such as aluminum alloys are (111) planes. In 2195-T8 plate, the major strengthening phase is $T_1(Al_2CuLi)$ phase with habit planes on (111) planes. The micro-mechanics of these interactions are not well known.
- However, assuming 2195-T8 plate still deforms with slip system on (111) with <011> type burgers vector, S and Cu components would favor increases in L direction strength and make strength directionality more isotropic, while Brass component would lower L direction strength.

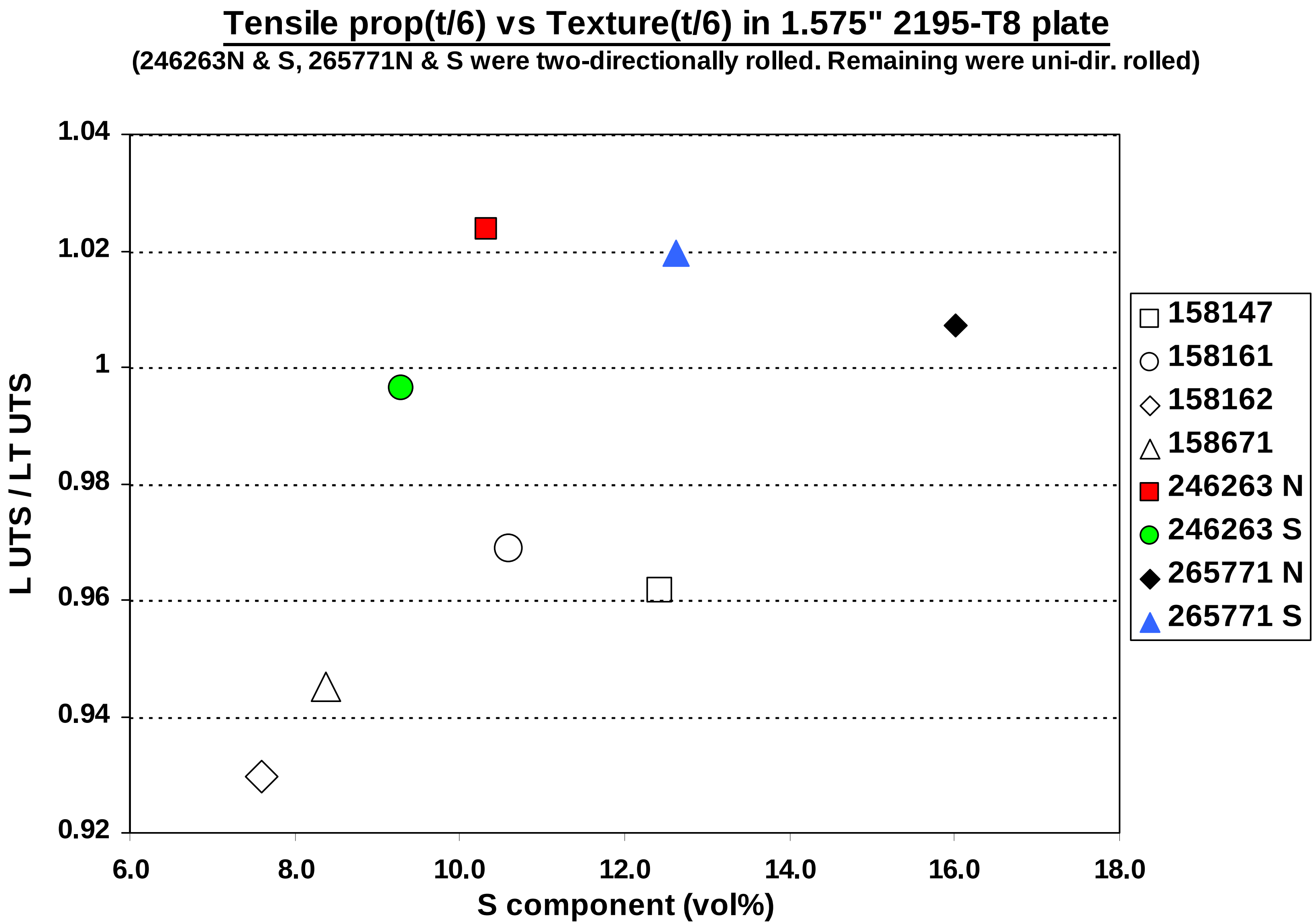
Tensile Properties of 1.575" gage 2195-T8 plate at t/6 location

(246263 N & S, 265771 N & S were two-directionally rolled, The rest were uni-dir. rolled)

Lot No.	L UTS (ksi)	L TYS (ksi)	L el (%)	Lt UTS (ksi)	Lt TYS (ksi)	Lt el (%)	St UTS (ksi)	St TYS (ksi)	St el (%)	45 UTS (ksi)	45 TYS (ksi)	45 el (%)
158147	77.9	73.2	11	81	72.5	9.5	80.4	69.7	4.4	79.1	70	10
158161	77.8	72.1	10	80.3	72.6	7.5	75.3	61.1	7.3	76.5	66.9	10.5
158162	75.2	68.7	10	80.9	72.9	9	82.5	70.5	4.5	78.7	68.1	10
158671	77.6	74	9.5	82.1	74.7	9.5	82.8	70.9	4.7	79.9	71.7	11
246263 N	82.1	78.9	6.5	80.2	77.6	6.5	87.5	76.5	3.6	81.9	75.6	6.5
246263 S	82.4	79.5	7.5	82.7	77.3	6.5	85.6	74.2	3	82.1	75.1	10
265771 N	82.9	79.5	7.5	82.3	76.5	8	86.7	75.2	3.3	81.9	74.8	8.5
265771 S	83.5	79.7	7	81.9	75.7	10	85.6	73.9	3	81.6	74.4	8.5

NOTE: Aged at 300 deg F for 32 hours

Higher volume % of S component favors L-direction strength. Therefore, ratio of L UTS/LT UTS tends to increase as S component increases.



Alex Cho (304-273-7038), Pechiney Rolled Products LLC, Aug. 09, 2005 NASA Contract no. NNL04AB64T with AS&M Inc.

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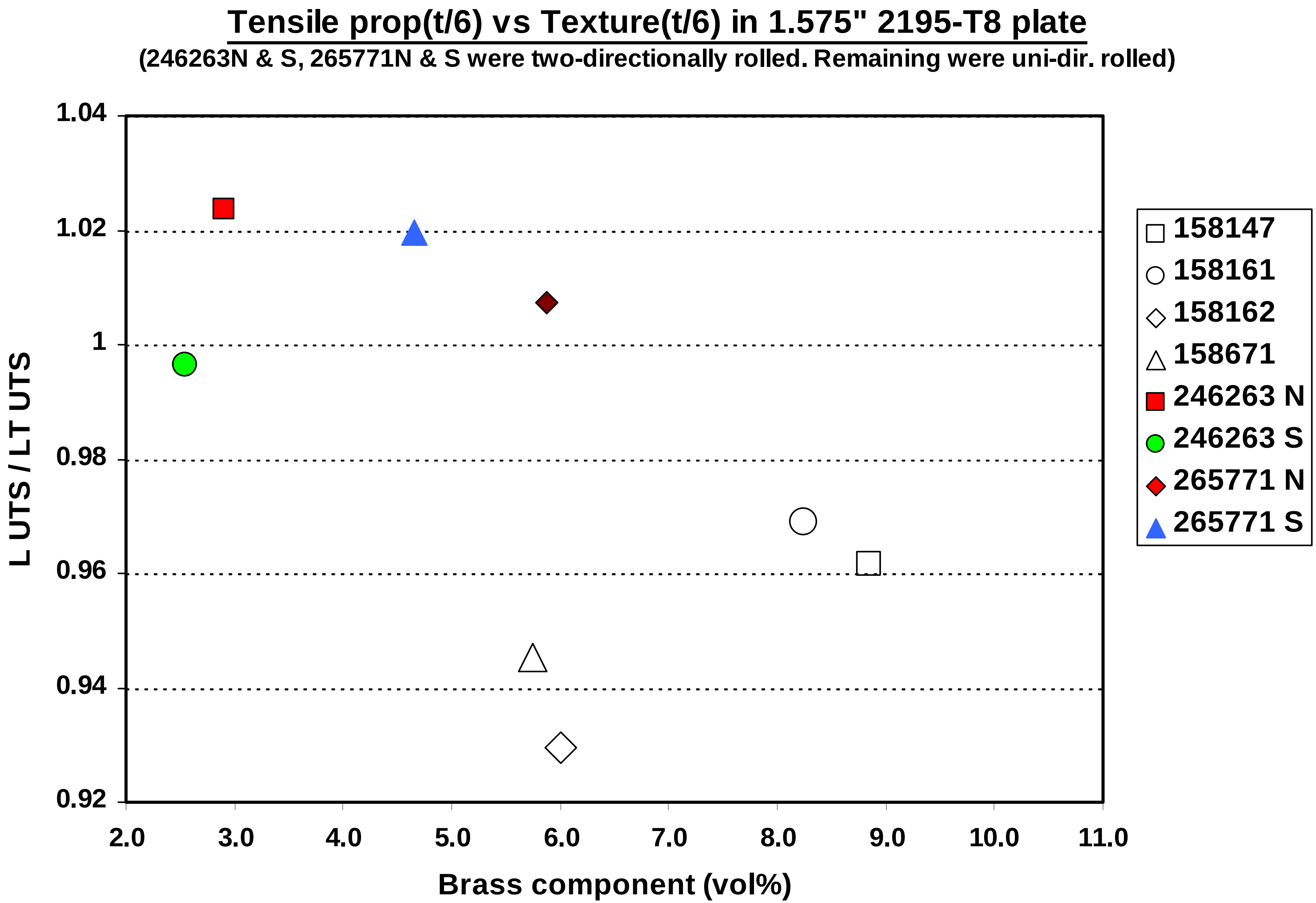
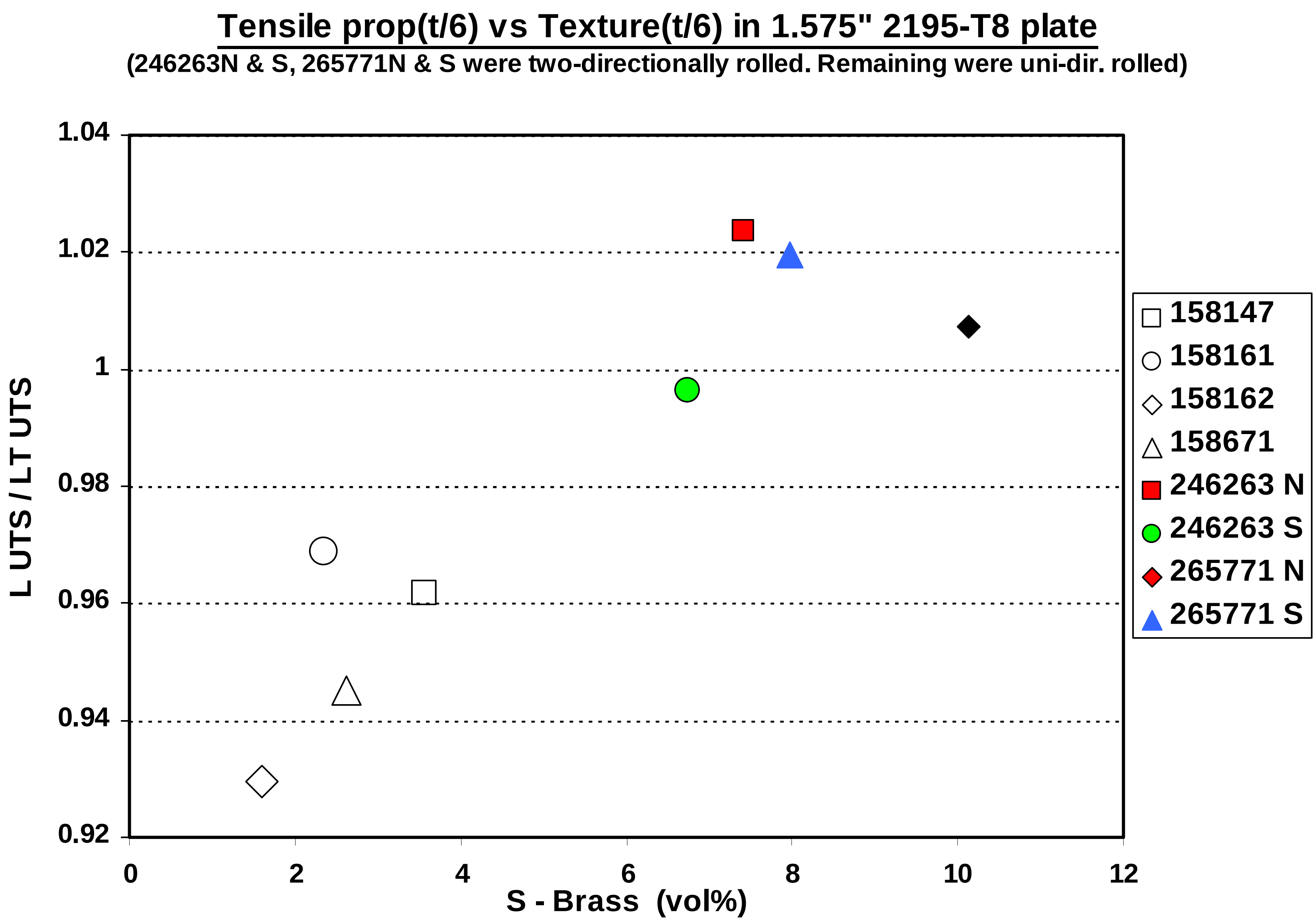
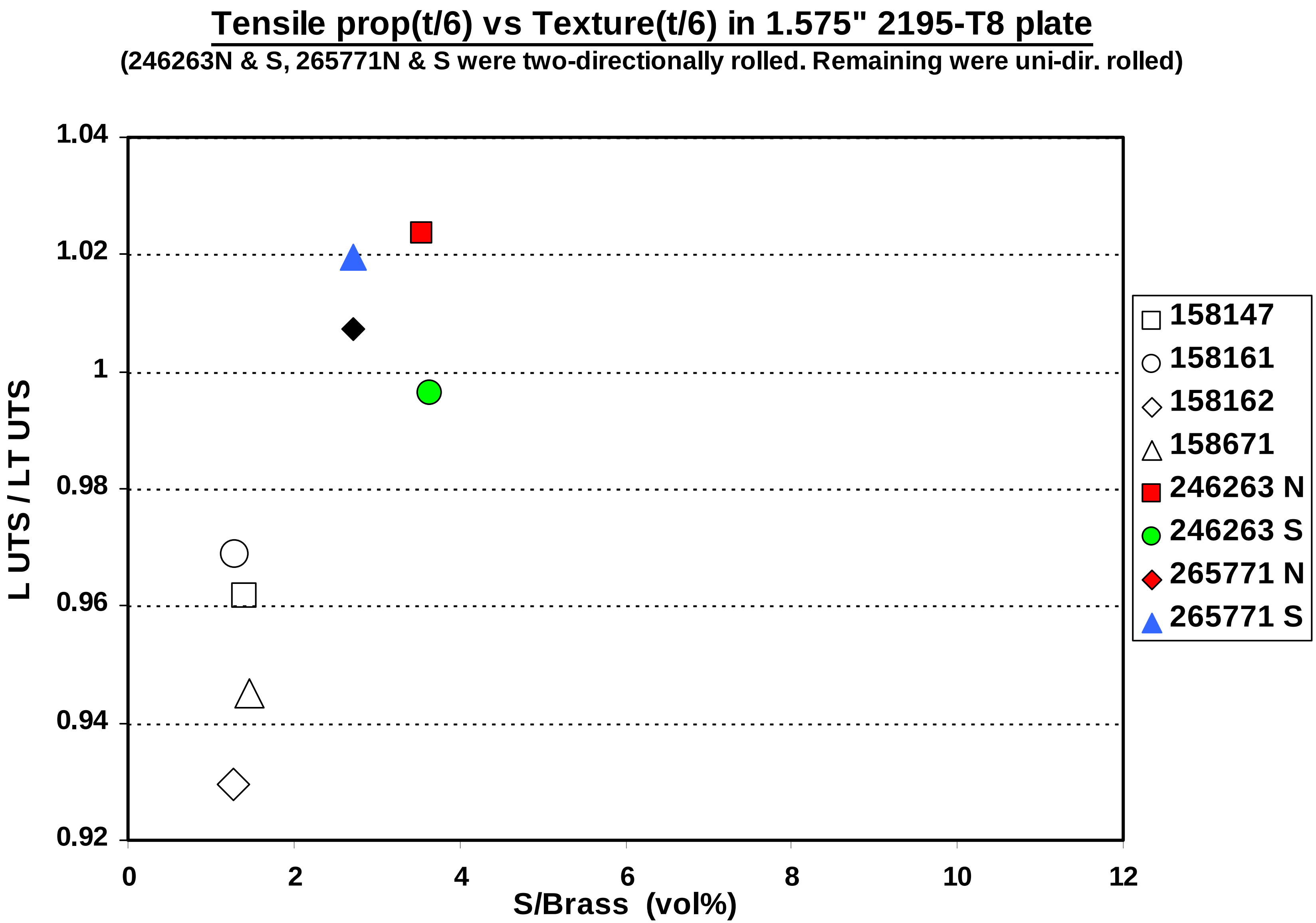
Higher volume % of Brass component favors lower L-direction strength. Therefore, ratio of L UTS/LT UTS tends to decrease as vol % of Brass component increases.



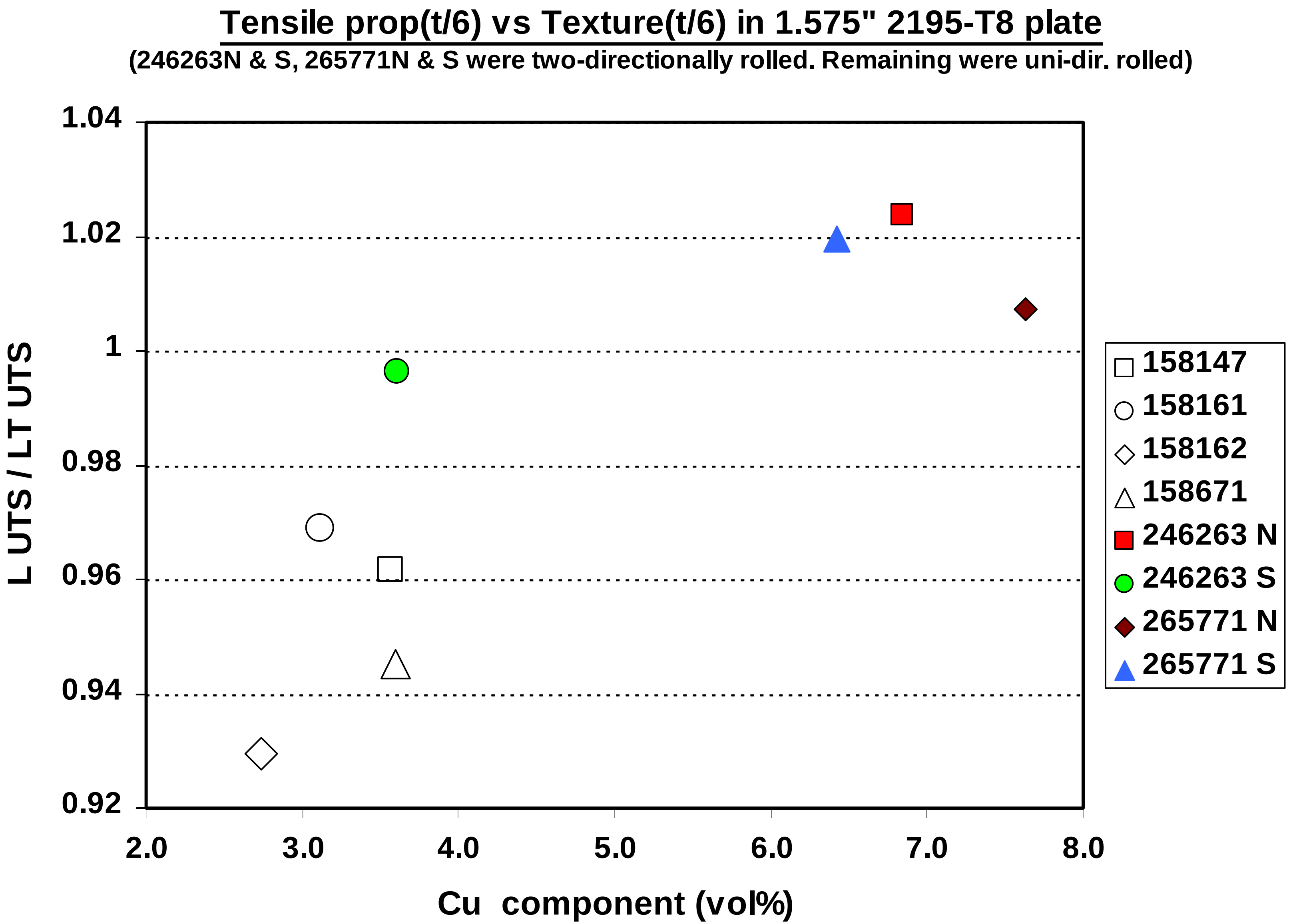
• The greater the difference between the vol% of S and Brass components, the higher the ratio of L UTS/LT UTS



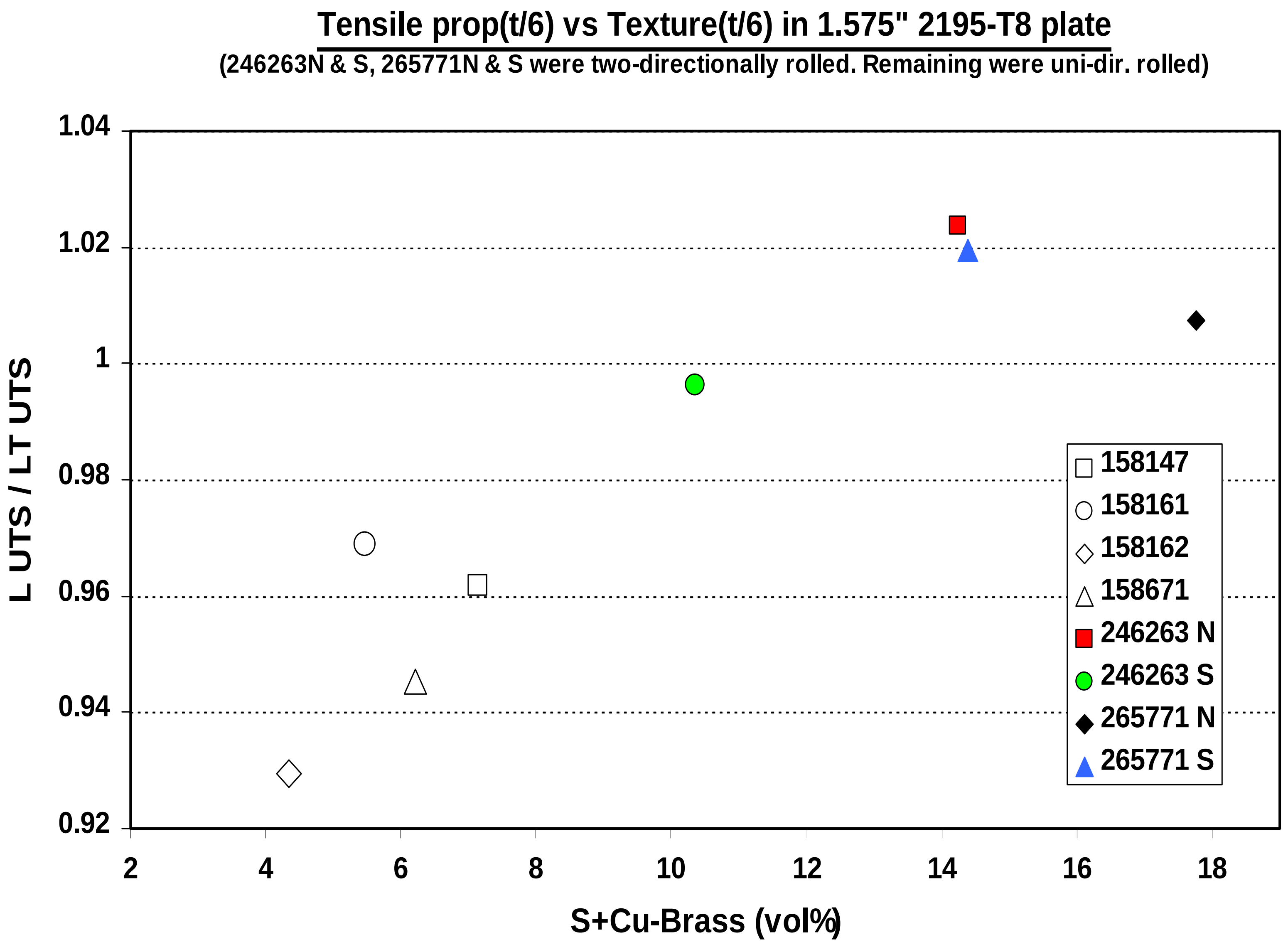
The Ratio of S/Brass for uni-directionally rolled plate fall into a very narrow range, almost a constant value. Similarly for the two-directionally rolled plate. This observation suggests that the ratio of S/Brass is a good indication of over all deformation between L and LT direction in plate rolling.



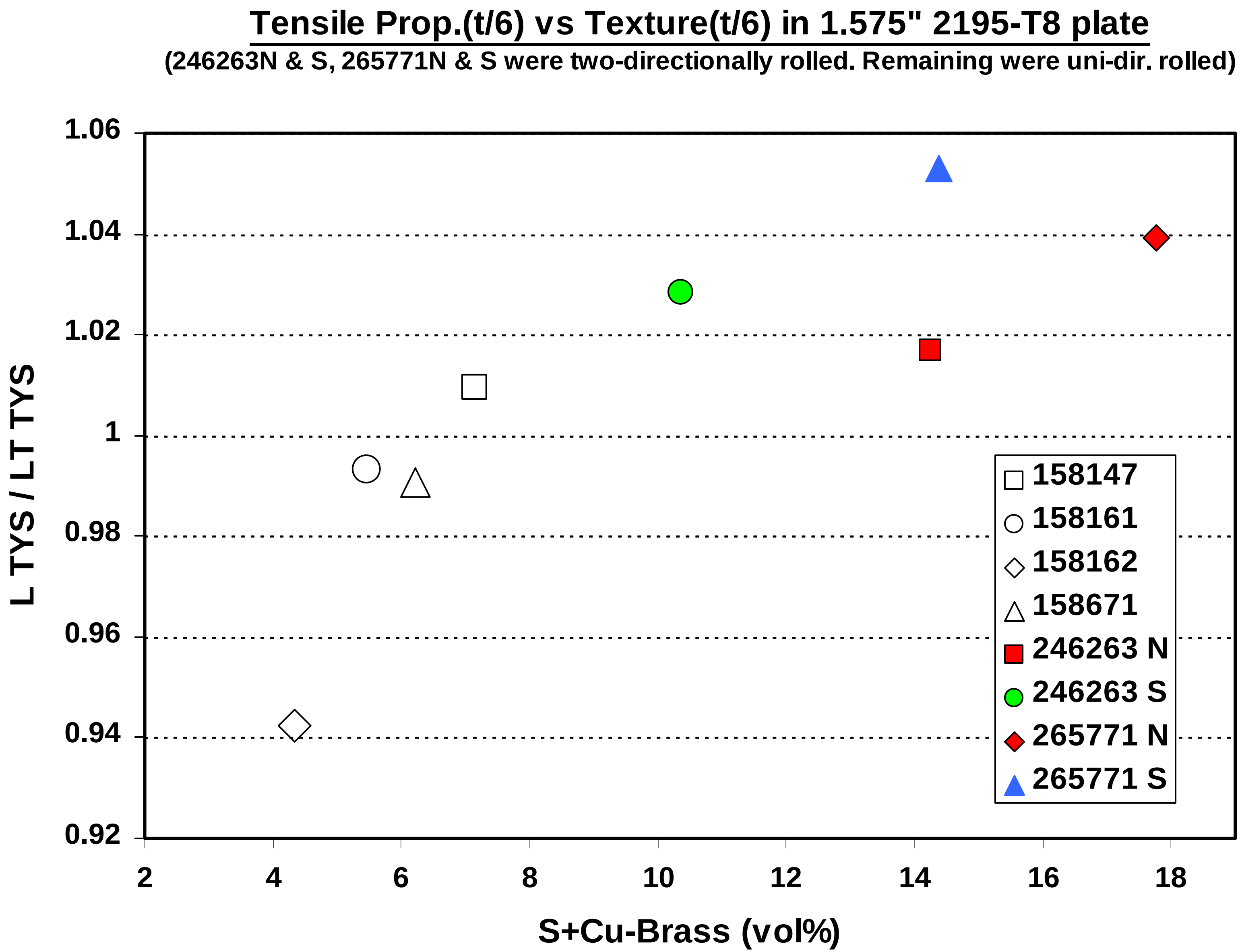
Higher volume % of Cu component favors L-direction strength. Therefore, ratio of L UTS/LT UTS tends to increase as Cu component increases.



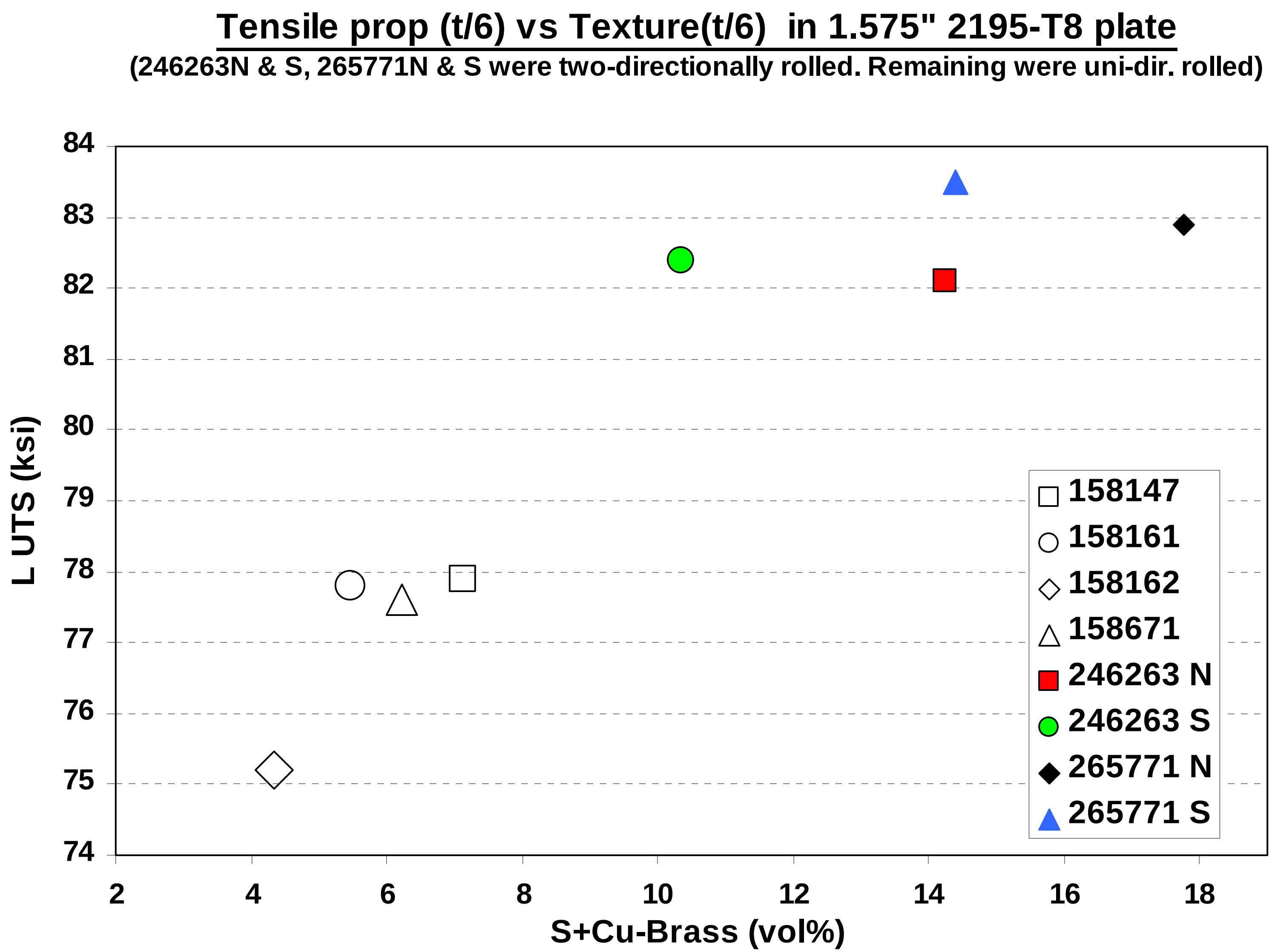
Higher volume % of Cu and S components favor L-direction strength, while higher vol% of Brass component favors higher strength in LT direction. Therefore, the ratio of L UTS/LT UTS increases as the vol % of (S+Cu-Brass) components increases.



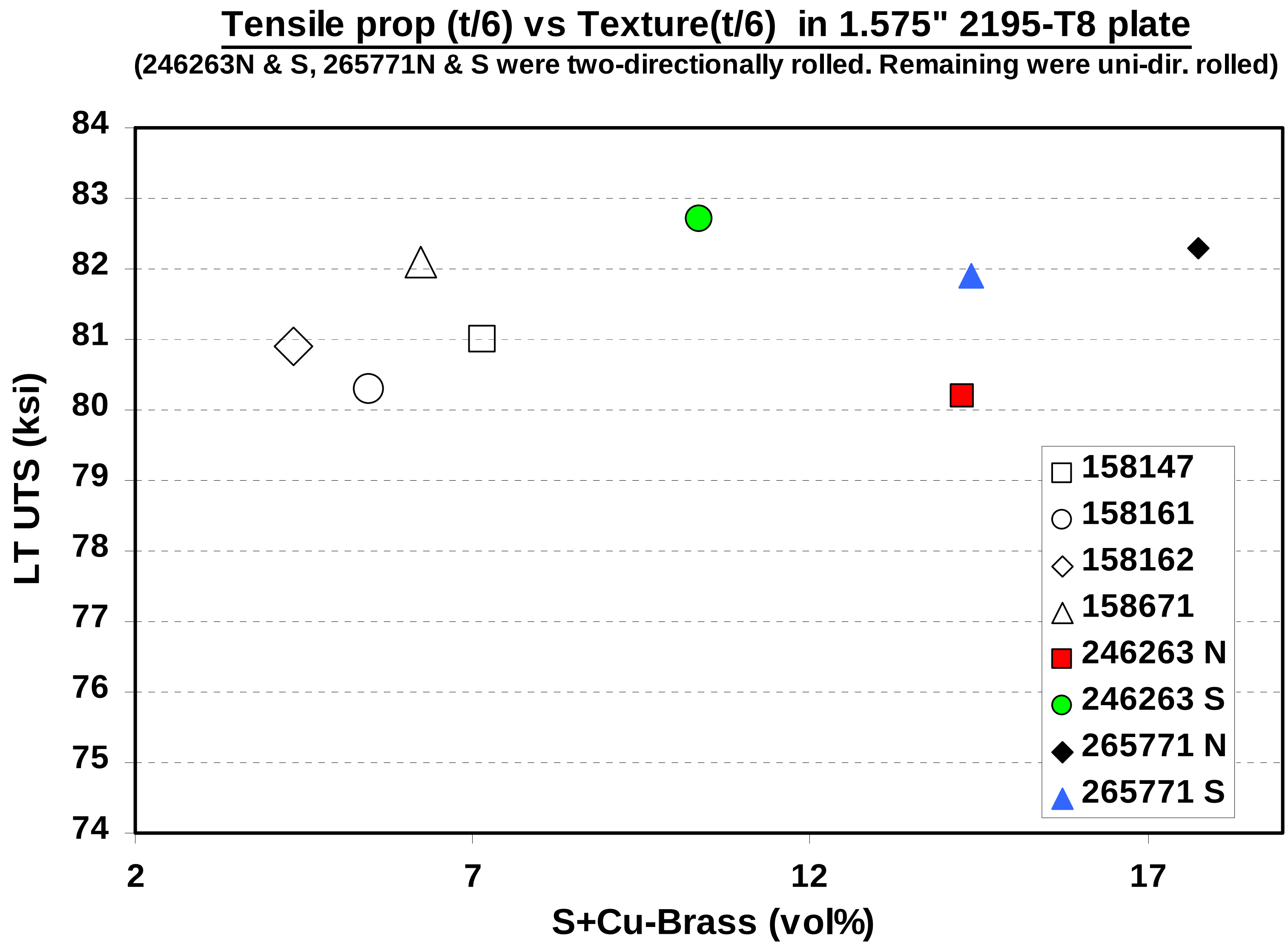
Higher volume % of Cu and S components favor L-direction strength, while higher vol% of Brass component favors lower L direction strength. Therefore, the ratio of L TYS/LT TYS increases as the vol % of (S+Cu-Brass) components increases.



As the ratio of L UTS/LT UTS correlate with vol% of (S+Cu-Brass), L UTS values correlate with the vol% of (S+Cu-Brass)



LT UTS values for these 8 lots do not correlate with S+Cu-Brass components. Therefore, L UTS values are largely responsible for the good correlation between the ratio of L UTS/LT UTS and texture components of (S+Cu-Brass)



Alex Cho (304-273-7038), Pechiney Rolled Products LLC, Aug. 09, 2005 NASA Contract no. NNL04AB64T with AS&M Inc.

VIII. Conclusions:

1. Test results from two-directionally rolled plate showed the average L UTS values increased by 3 ksi compared to uni-directionally rolled plates

2. Two-directionally rolled plate showed higher L UTS strengths and more favorable results from SST (Simulated Service Test) compared to the plates produced by uni-directional rolling

3. Improvement in L UTS values could not be attributed to either chemistry or hot rolling temperatures

4. Compared to uni-directionally rolled plate, two-directionally rolled plate showed higher volume% of S and Cu texture components and lower volume % of Brass component which would favor high L direction strength

5. Two-directionally rolled plate showed more isotropic properties between L and LT directions

Effect of Processing Modifications on Texture and Mechanical Properties of 2195-T8 Plate

Part II

Effect of Cold work Prior to Aging on Mechanical Properties and Through-Thickness Strength Uniformity

Alex Cho

Pechiney Rolled Products
Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Part I :

Effect of Alternate Hot Rolling Process on Texture and Mechanical Properties of 2195-T8 Plate

Part II:

Effect of Cold work Prior to Aging on the Mechanical Properties and Through-Thickness Strength Uniformity

Effect of Cold Work Prior to Aging on the Mechanical Properties of 2195-T8 Plate on Mechanical Properties

contents:

I. Objective

Current application of 2195-T8 plate is driven by the mechanical properties at the near surface location(t/6 location). However, the mechanical properties decrease from the mid plane (i.e t/2 location) to the t/6 location. Since mechanical properties of 2195-T8 temper plate vary with the amount of cold work prior to artificial aging, the objective of this work is to improve mechanical properties at the t/6 location by exploring the effect of variation of cold work on through–thickness properties.

II. Approach

The effects of cold work on mechanical properties were examined in both lab scale experiments as well as plant scale trials. In this study, experimental variables include % stretch, % cold roll and multiple steps of stretch as well as various combinations of both.

Plant trials were conducted to examine the effect of cold rolling on mechanical properties and, to a limited degree, on damage tolerance of the plate by Simulated Service Testing (SST).

III. Alternate Temper Development for 2195 Plate

Content:

A: Effect of Stretch on Through-Thickness Strength Uniformity

B: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity and Fracture Toughness

B-1: Lab scale experiment

B-2: Plant scale trial

C: Effect of Multi- Step Stretch Prior to Aging on Through-Thickness Strength Uniformity

- Lab scale experiment

III. Alternate Temper Development for 2195 Plate

A: **Effect of Stretch on Through-Thickness Strength Uniformity**

Material: Lot No. 158162: 1.575 inch gage 2195-F temper plate

Chemistry: 4.0 Cu – 1.0 Li – 0.32 Mg – 0.31 Ag – 0.14 Zr

Rolling temperature : Lay-on Temp: 872 F, Exit Temp: 828 F

Lab processing: SHT at 950F for 2 hrs.

CWQ

% Stretch: 0% for samples no.1 & no.2

3.75 % for samples no. 3 & no. 4

A. Effect of Stretch on Through-Thickness Strength Uniformity

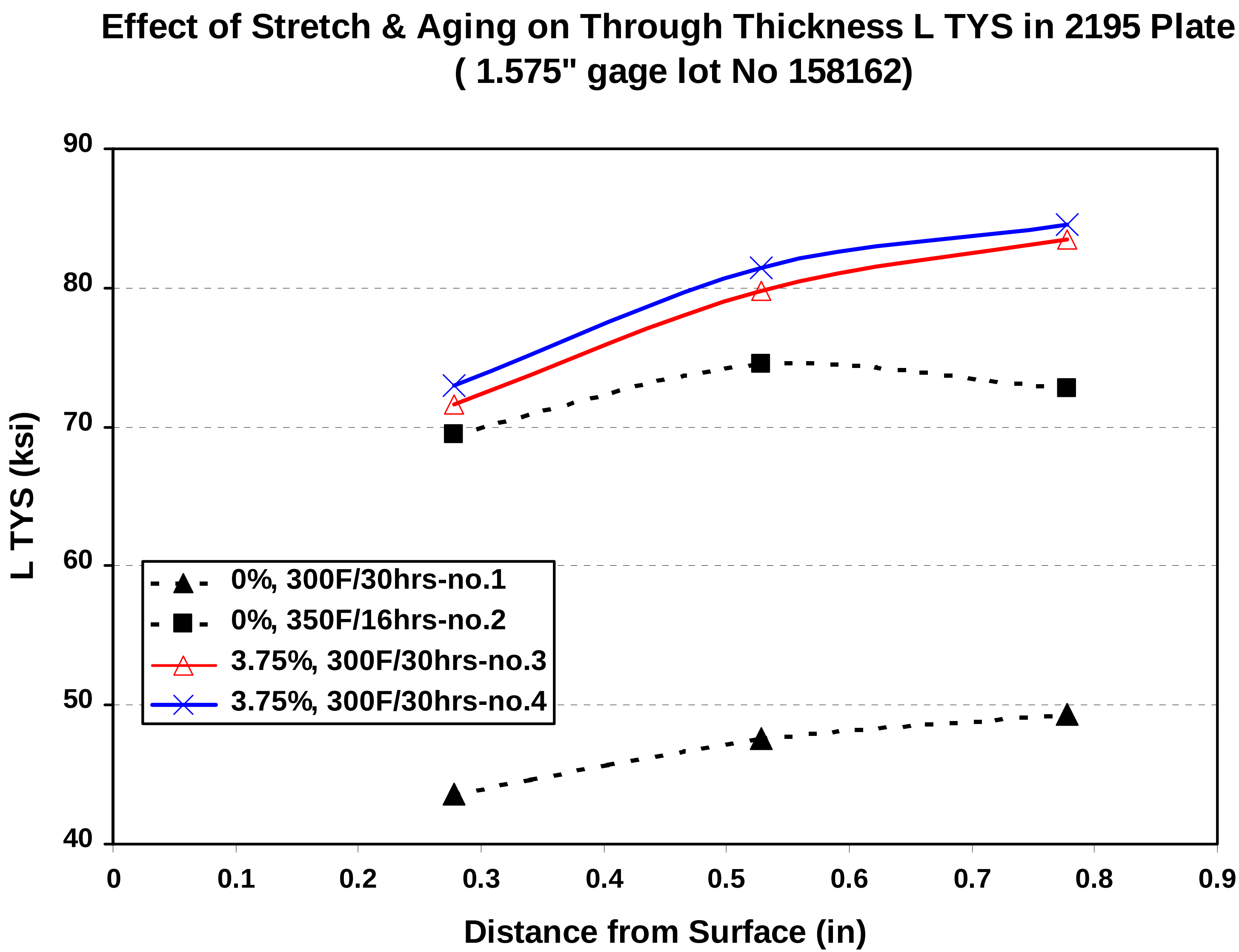
- Tensile Test results

Sample No.	Stretch %	Age Practice time at Temp.	Test location from surface	L TYS ksi	UTS ksi	Elongation %
1	0	30 hrs at 300F	0.278	43.6	61.5	24.8
			0.528	47.6	70.9	16.6
			0.778	49.4	72.5	15.3
2	0	16 hrs at 350F	0.278	69.4	74.7	6.7
			0.528	74.5	81.0	6.4
			0.778	72.8	81.0	5.9
3	3.75	30 hrs at 300F	0.278	71.7	73.7	8.2
			0.528	79.8	83.9	8.6
			0.778	83.6	87.2	6.5
4	3.75	30 hrs at 300F	0.278	72.9	74.7	5.4
			0.528	81.5	85.1	6.3
			0.778	84.5	88.1	6.9

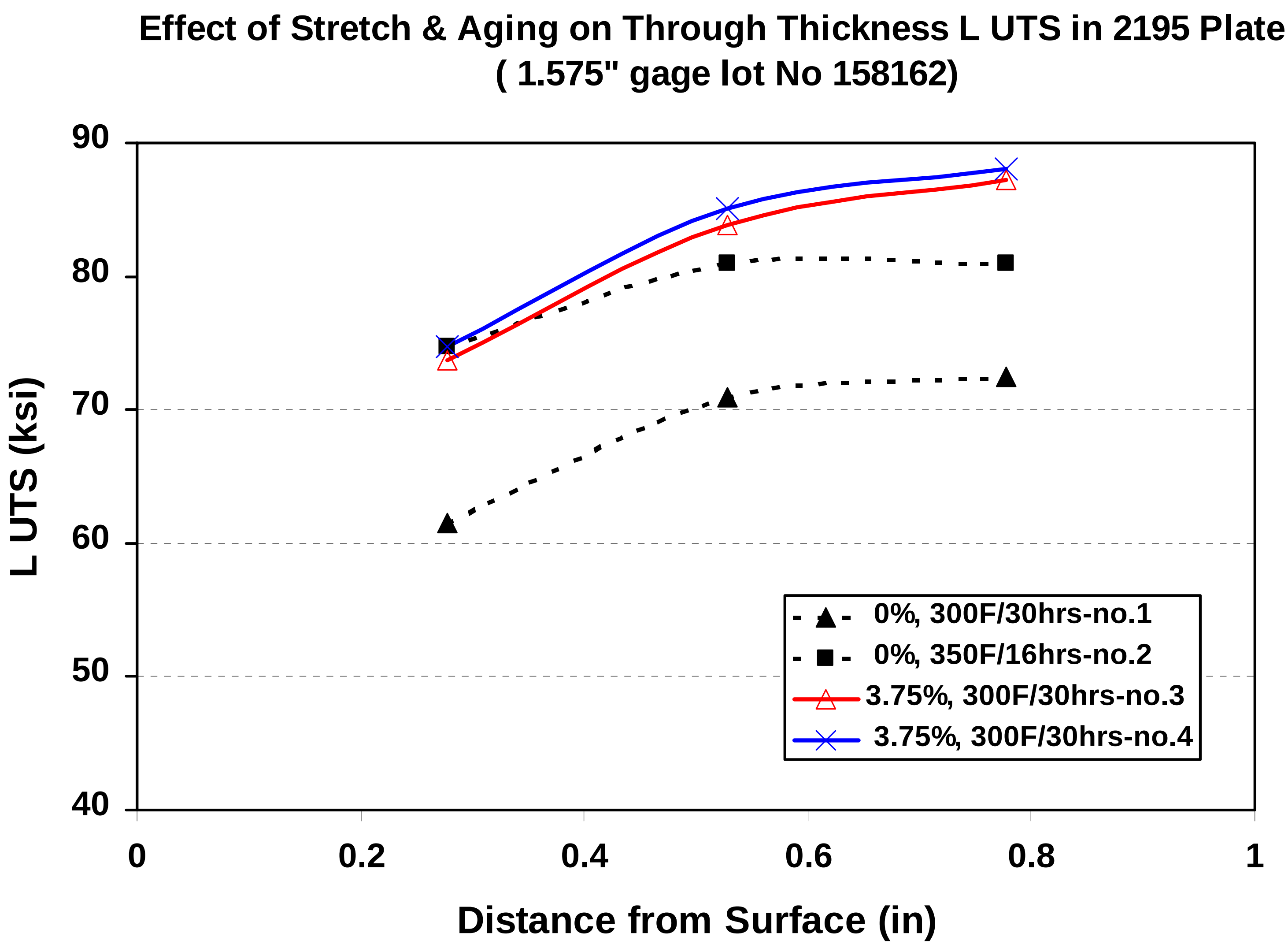
NOTE: Test Location from Surface: 0.278 inch (t/6), 0.528 inch (t/3) and 0.778 inch (t/2)

NOTE: Sample No. 3 & No. 4 are duplicates

- Stretch prior to aging significantly raises L TYS; with greater effect at t/2 location
- L TYS is more uniform for –T6 temper condition (i.e., 0 % stretech)



- Stretch prior to aging significantly raises L UTS; with greater effect at t/2 location
- L UTS is more uniform for –T6 temper condition (i.e., 0 % stretech)



Alternate Temper Development for 2195 Plate

A: Effect of Stretch on " Through-Thickness Strength Uniformity"

SUMMARY

- 1.575" gage 2195 plate in T6 temper (0% stretch prior to age) shows more uniform through-thickness tensile properties after aging at two different age practices.
- 1.575" gage 2195 plate in T8 temper (3.75% stretch prior to age) shows higher strength at t/2 location compared to that at either at t/4 and at t/6 locations.
- Results showed that stretch prior to age significantly increases strength at t/2 location, but is not effective in increasing strength at near surface locations.

Alternate Temper Development for 2195 Plate

B: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity and on Fracture Toughness

- As a baseline, one sample was processed using standard practice of stretch only operation (no cold rolling)
- A laboratory scale experiment was conducted with four samples having different combinations of % stretch and % cold rolling
- A plant scale trial was conducted comparing the standard practice vs. cold roll & stretch practice prior to aging.

Alternate Temper Development for 2195 Plate

B-1: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity

Experimental Parameters for Laboratory Scale Experiment

1; Cold Roll 6% + 2.5% stretch

2; Cold Roll 3% + 3.75% stretch

3; Cold Roll 3% + 3.75% stretch

4; Cold Roll 6% + 2.5% stretch

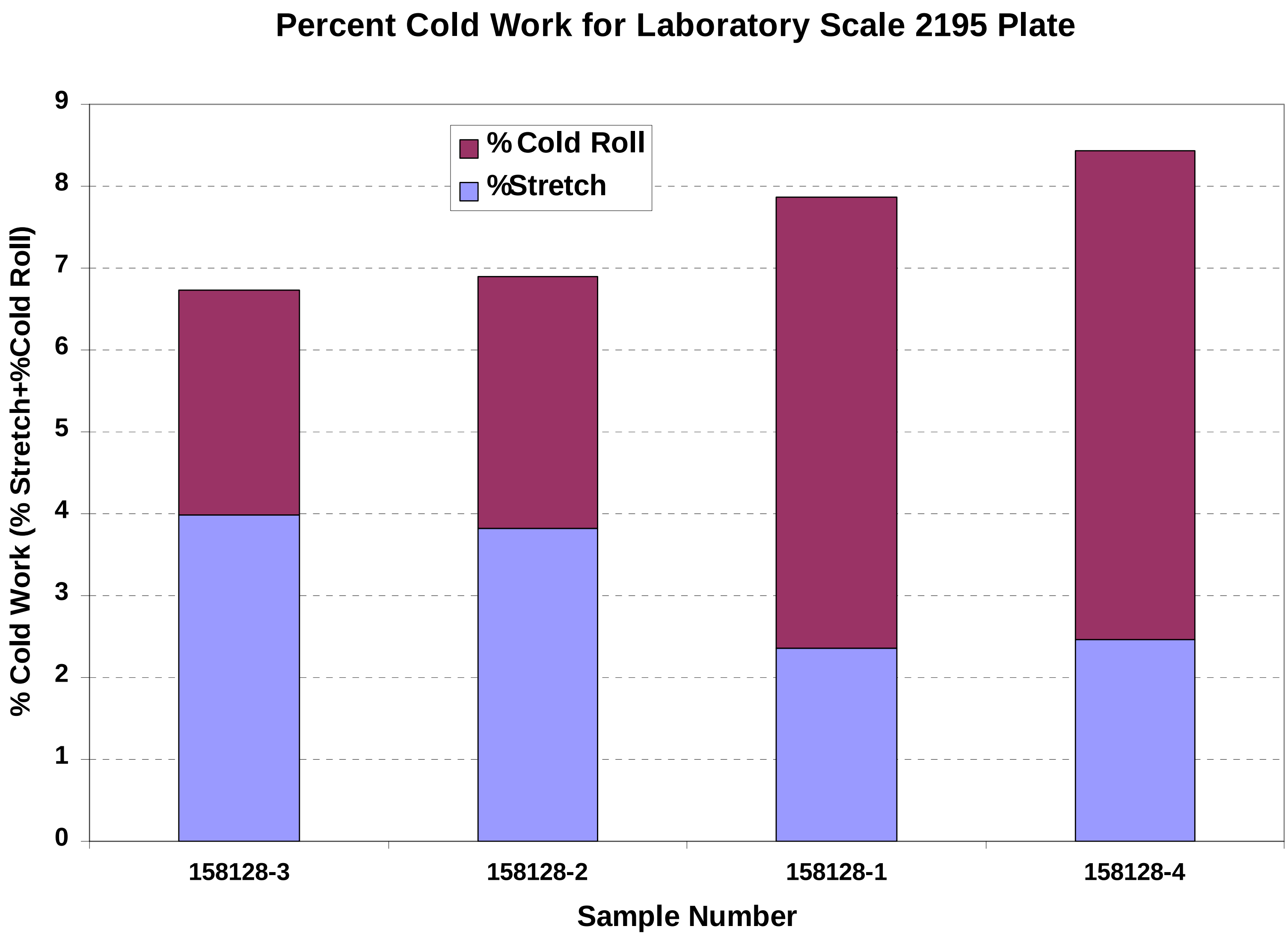
Baseline Standard practice ; 0 % cold roll + 3.75% stretch

B-1: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity

Percent Cold Work and Tensile Properties for Baseline 2195 Standard Practice

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158162	-1	none	3.82%	3.82%	5t/6	34	L	79.0	75.8	9.5
					t/6	34	L	79.4	76.3	9.0
stretch: 3.82% by single step					2t/3	34	L	89.4	85.4	9.0
					t/3	34	L	88.9	85.0	9.0
					t/2	34	L	92.0	88.4	9.0

B-1: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity



B-1: Effect of "Cold Roll & Stretch" prior to Age on Through-Thickness Strength Uniformity

Percent Cold Work and Tensile Properties for Laboratory Scale 2195 Plate

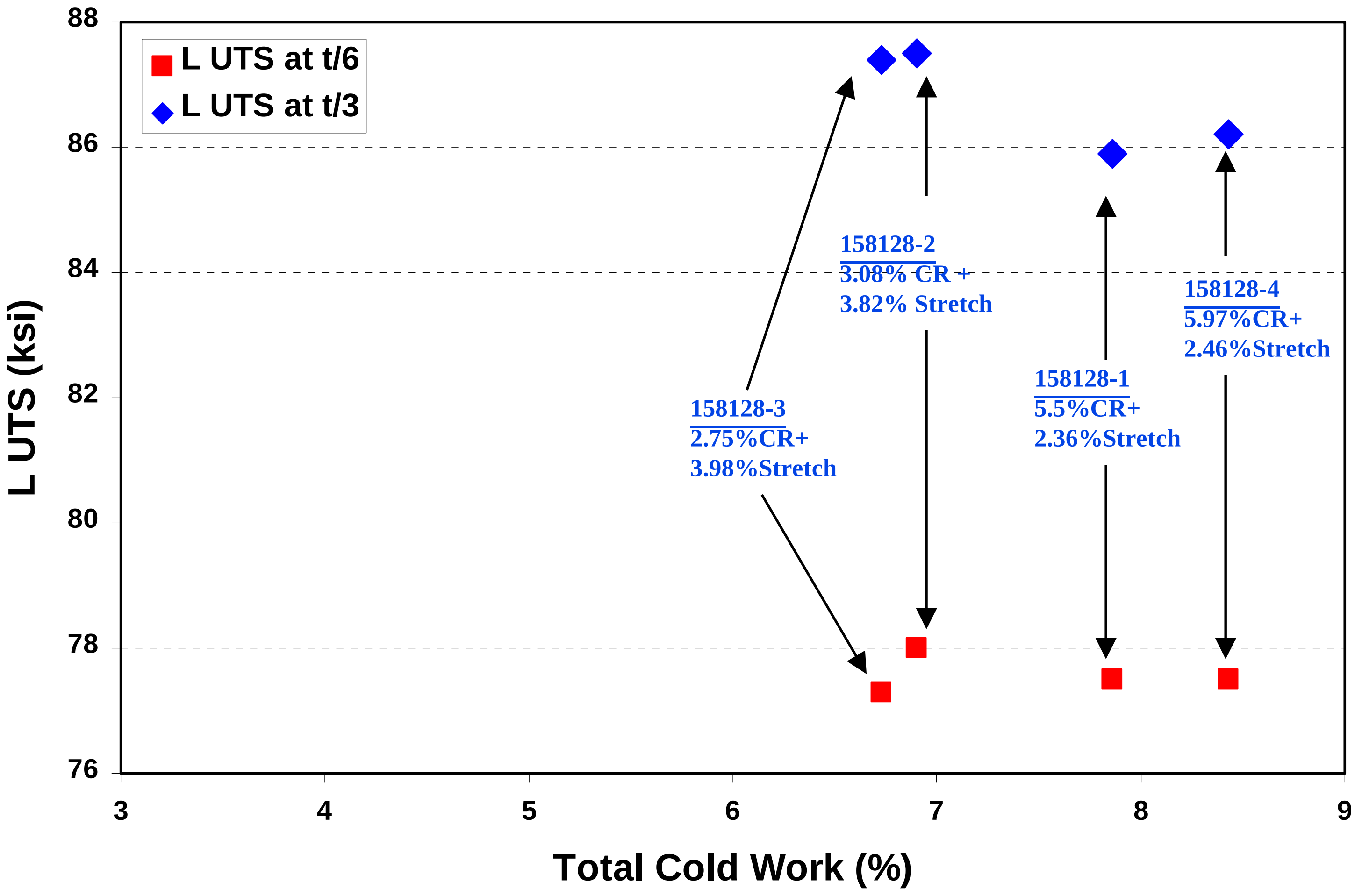
(1.575" gage 2195 Plate)

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158128	-1	5.5	2.36	7.86	5t/6	18	L	77.4	76.5	5.5
					t/6	24	L	77.5	76.4	5.5
					2t/3	18	L	84.3	81.8	8.5
					t/3	24	L	85.9	83.4	8.5
158128	-2	3.08	3.82	6.9	5t/6	18	L	78.2	77.3	5.5
					t/6	24	L	78.0	77.0	11.5
					2t/3	18	L	84.6	82.4	7.5
					t/3	24	L	87.5	85.1	9.0
158128	-3	2.75	3.98	6.73	5t/6	18	L	77.5	76.3	7.0
					t/6	24	L	77.3	76.3	8.5
					2t/3	18	L	85.1	82.3	8.5
					t/3	24	L	87.4	84.6	9.5
158128	-4	5.97	2.46	8.43	5t/6	18	L	77.7	76.7	6.5
					t/6	24	L	77.5	76.5	6.5
					2t/3	18	L	85.7	82.6	8.5
					t/3	24	L	86.2	83.1	8.5

- 158128-2&-3 show higher strength at t/3 because of their higher %stretch, despite of lower total %cold work
- There are little differences in strengths at t/6 location with total %cold work over 6.5% or so, regardless of the mode of cold work

B-1: Effect of "Cold Roll & Stretch" prior to Age on Through-Thickness Strength Uniformity

Effect of Total Cold Work on L UTS(ksi) at two thickness locations after 24 hr Age
1.575" gage 2195-T8 Plate



- 158128-2&-3 show higher strength at t/3 because of their higher %stretch, despite of lower total %cold work
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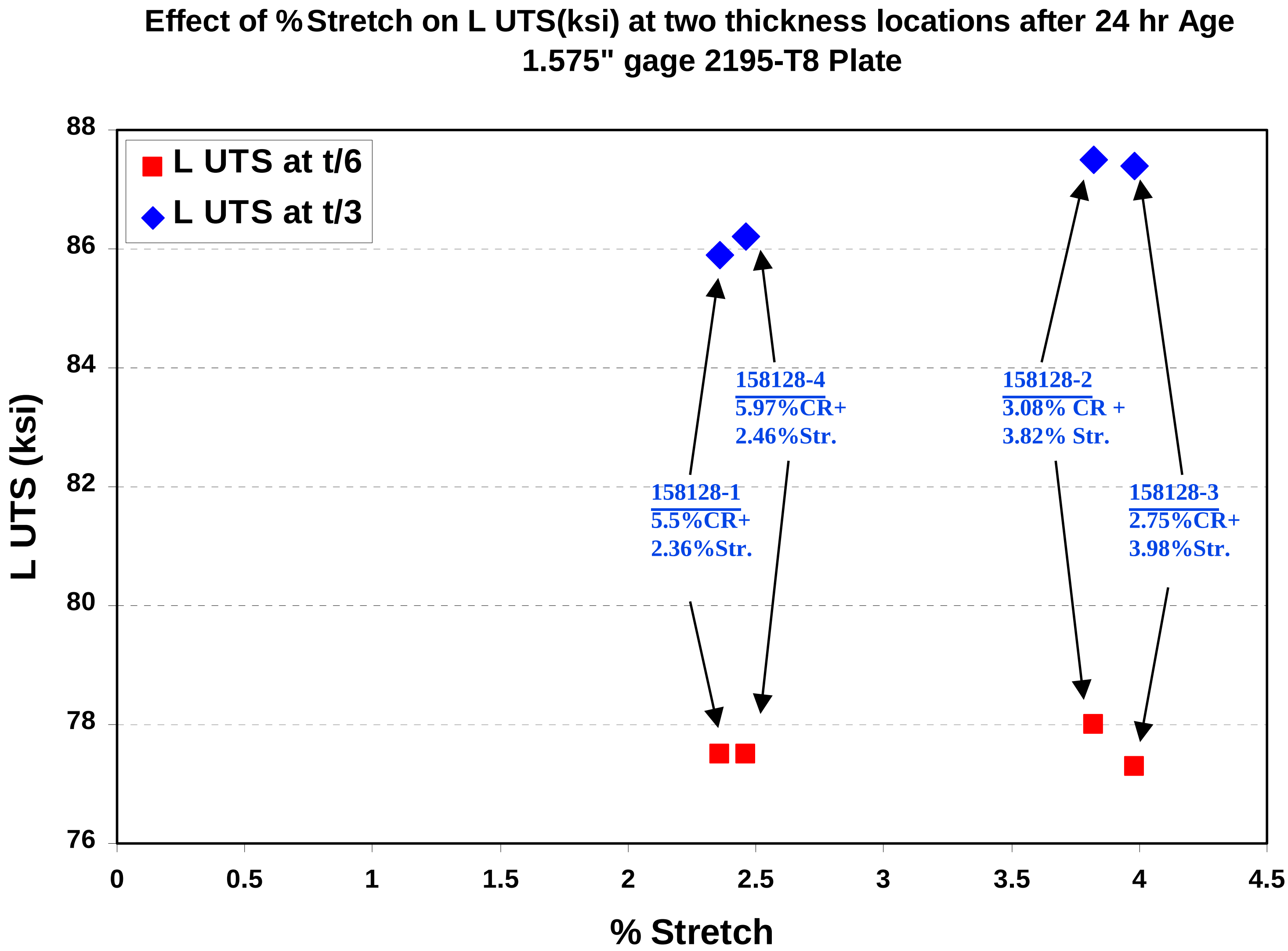
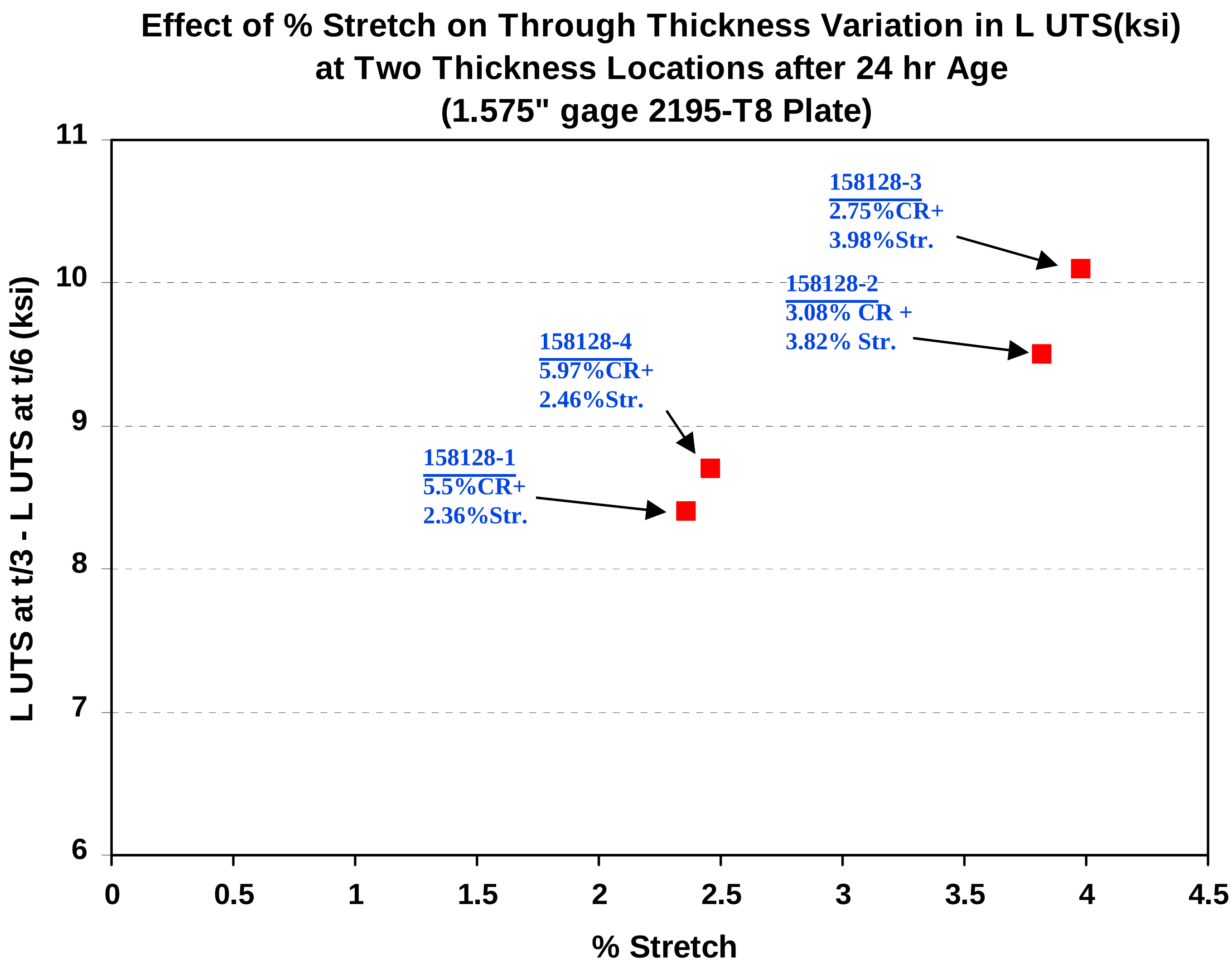
B-1: Effect of "Cold Roll & Stretch" prior to Age on Through-Thickness Strength Uniformity



Higher % stretch induces larger difference between strengths at t/6 vs t/3

Study B-1: Effect of Cold Roll & Stretch prior to Age on Through-Thickness Strength Uniformity



B: Effect of Cold Roll & Stretch Prior to Age on Through-Thickness Strength Uniformity

SUMMARY on **B-1** : Lab scale experiment:

1. L UTS at t/6 was not significantly affected by total % cold work. L UTS remained at approximately 78 ksi after aging at 300 deg F for 24 hours , regardless of % cold roll or % stretch
2. Strengths at t/3 location were more responsive to % stretch, not to % cold rolling.
3. Comparing the L UTS differences at t/6 and t/3 locations, the through-thickness strength variation for these four samples are very comparable to the baseline sample plate based on % stretch,which was 3.8% cold worked only by stretch and having L UTS difference of 9.5 ksi between t/6 & t/3 locations.

Study B-2: Effect of Cold Roll & Stretch Prior to Aging on Through-Thickness Strength Uniformity and Fracture Toughness - Plant Scale Trial

Two lots of 1.575 inch gage plate were available for the plant scale experiment

Chemistry

Lot No.	Ingot No.	Li(%)	Zr (%)	Cu (%)	Mg (%)	Ag (%)
158149	18-516	0.96	0.14	3.99	0.31	0.32
158151	18-518	0.96	0.14	3.97	0.30	0.32

Processing Information

Lot No.	gage(in)	Hot Rolling	Lay-On Temp.	Exit Temp.	Anneal	SHT hr.
158149	1.575	standard	852	705	yes	5.0
158151	1.575	standard	832	738	yes	5.2

B: Effect of Cold Roll & Stretch Prior to Age on Through-Thickness Strength Uniformity and on Fracture Toughness

B-2: Plant Scale Trial

Lot 158151: Aging Curve Development at 300 deg F

Lot No.	%cold roll	%Stretch	%cold work	test location	Age time(hr)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158151	none	3.55%	3.55%	t/6	30	L	78.5	75.5	7.5
				t/6	34	L	78.0	75.5	7.5
stretch: 3.55% by single step				t/3	30	L	88.2	84.2	6.0
				t/3	34	L	89.7	85.3	7.5
				t/2	30	L	85.8	82.4	5.5
				t/2	34	L	86.7	82.7	8.5

Lot 158149: Aging Curve Development at 300 deg F

Lot No.	%cold roll	%Stretch	%cold work	test location	Age time(hr)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158149	4.70%	2.07%	6.77%	t/6	18	L	79.1	78	6.5
				t/6	20	L	78.8	77.7	8.0
stretch: 4.7% cold roll + 2% stretch				t/3	18	L	88.8	85.7	8.5
				t/3	20	L	88.5	85.7	9.0
				t/2	18	L	84.4	81.6	8.5
				t/2	20	L	85.3	81.8	8.5

Percent Cold Work and Tensile Properties for Plant Scale 2195 Plate

Lot 158151: Parent Plate Properties after age at 300 F for 32 hrs.

Lot No.	%cold roll	%Stretch	%cold wor	test plane	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158151	none	3.55%	3.55%	t/6	L	78.8	76.1	8.0
				t/6	LT	83.5	77.4	8.0
stretch: 3.55% by single step				t/6	45 deg	81.4	73.5	10.5
				t/6	ST	85.3	73.3	6.2

Lot 158149: SST (Simulated Service Tests)

Net Proof Stress	Ke @proof	Ke @fracture	Stress Ratio(fracture / proof)
73.8 ksi	27.5 ksi Vinch	30.4 ksiVinch	1.103

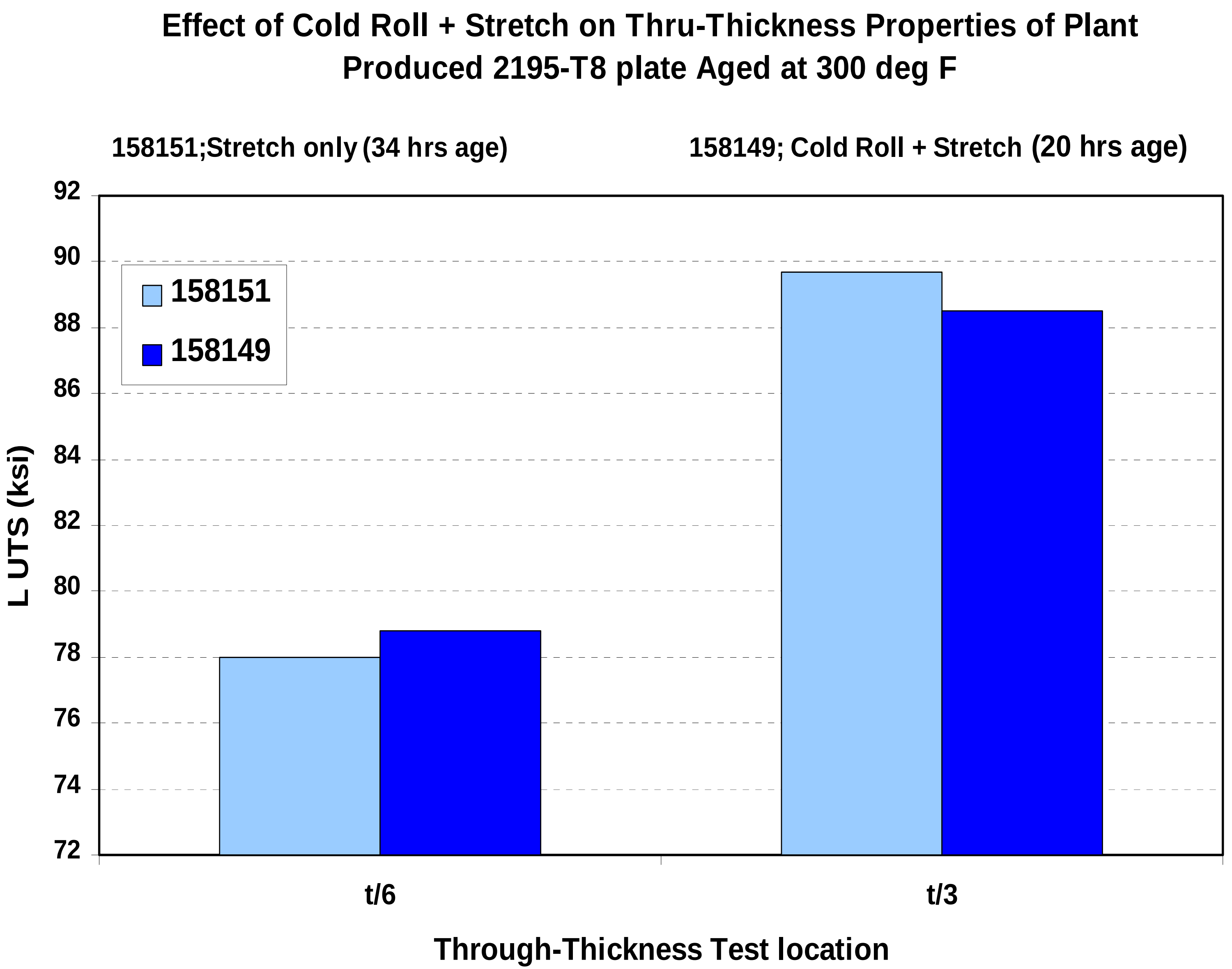
Lot 158149: Parent Plate Properties after age at 300F for 20 hrs

Lot No.	%cold roll	%Stretch	%cold wor	test plane	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158149	4.70%	2.07%	6.77%	t/6	L	79.5	77	7.0
				t/6	LT	84.5	78.1	6.0
stretch:4.7% cold roll+2% stretch				t/6	45 deg	81.9	75.9	9.0
				t/6	ST	84.4	78.1	6.0

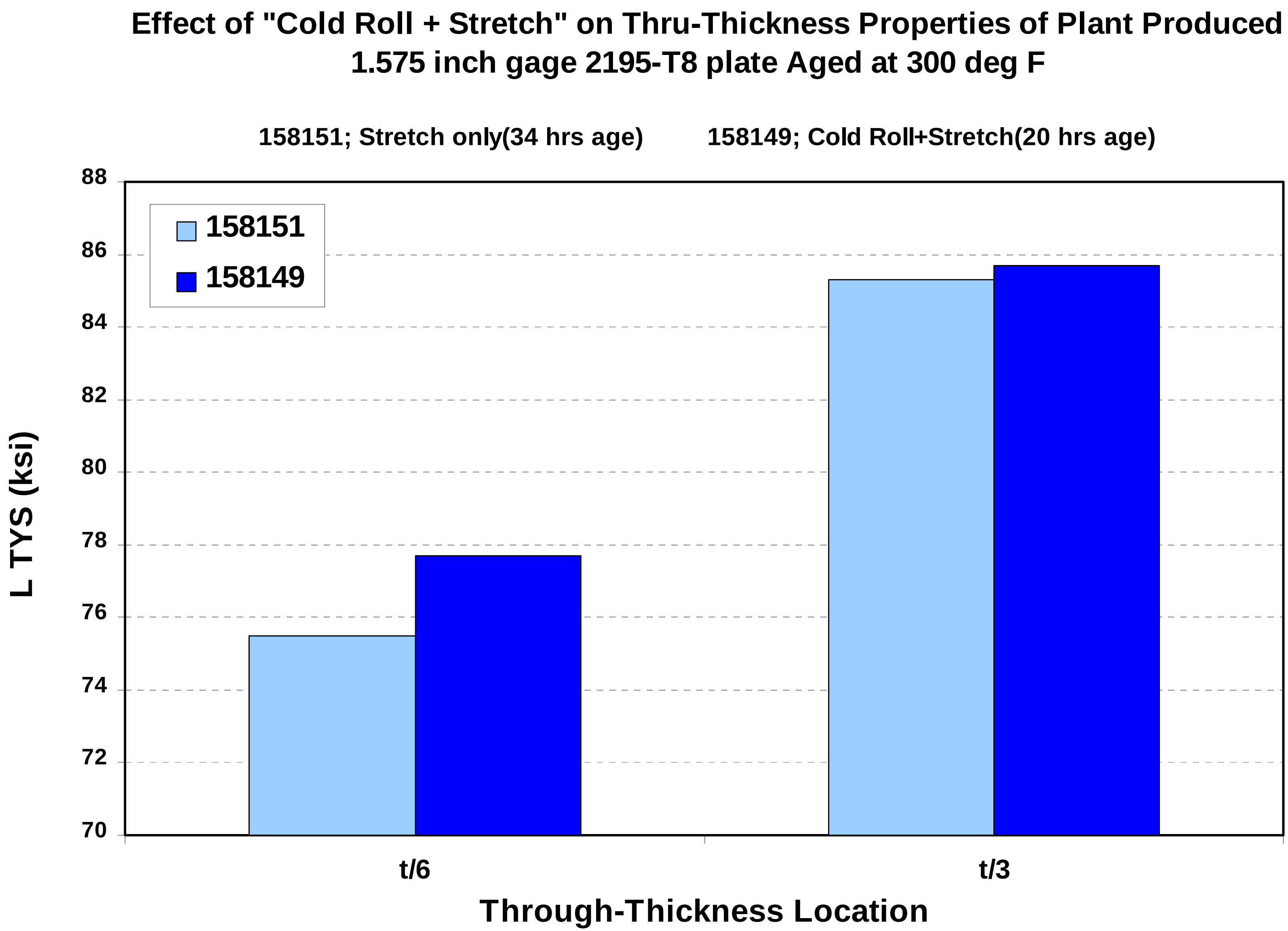
Lot 158149: SST (Simulated Service Tests)

Net Proof Stress	Ke @proof	Ke @fracture	Stress Ratio(fracture / proof)
76 ksi	28.3 ksi Vinch	32 ksiVinch	1.131

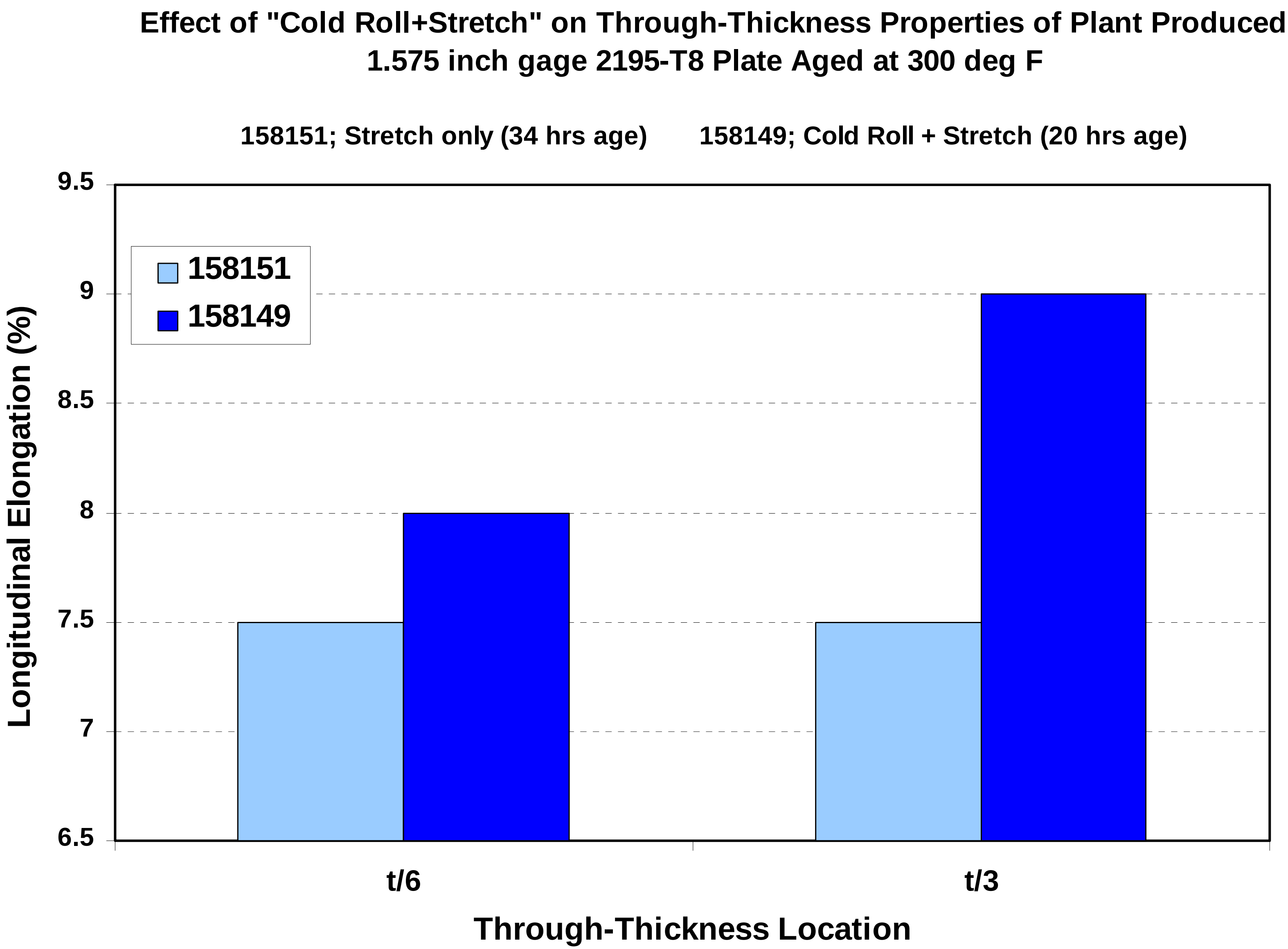
- 158151 shows higher L UTS value at t/3 because of their higher % stretch, despite lower total % cold work
- 158149 shows slightly higher L UTS value at t/6 as a result of cold roll in addition to stretch



- % cold roll appears to be effective in raising L TYS values at both t/6 and t/3 locations.



• Despite the higher % total cold work, 158149 shows better ducility at both t/6 & t/3 locations due to less % stretch, compared to 158151



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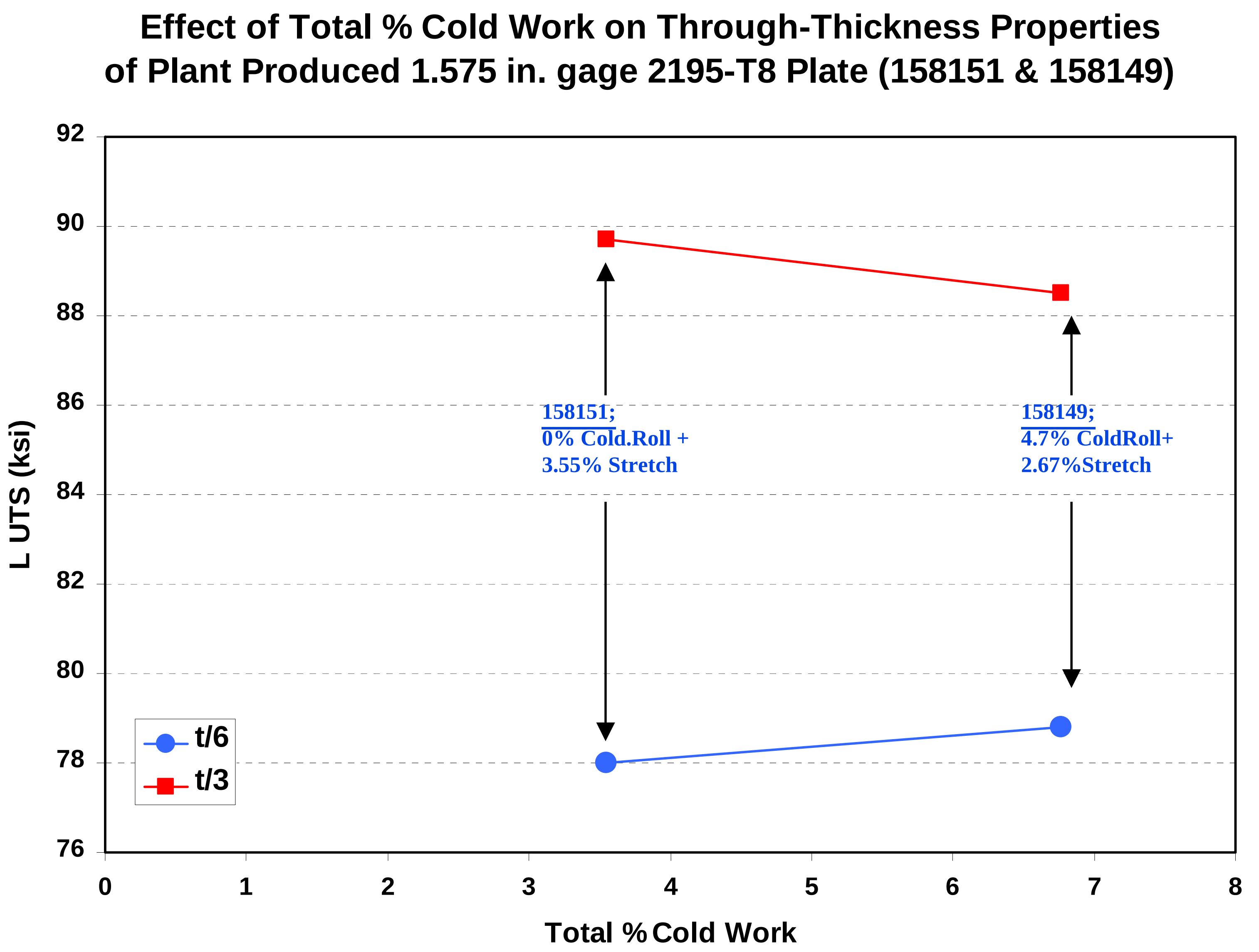
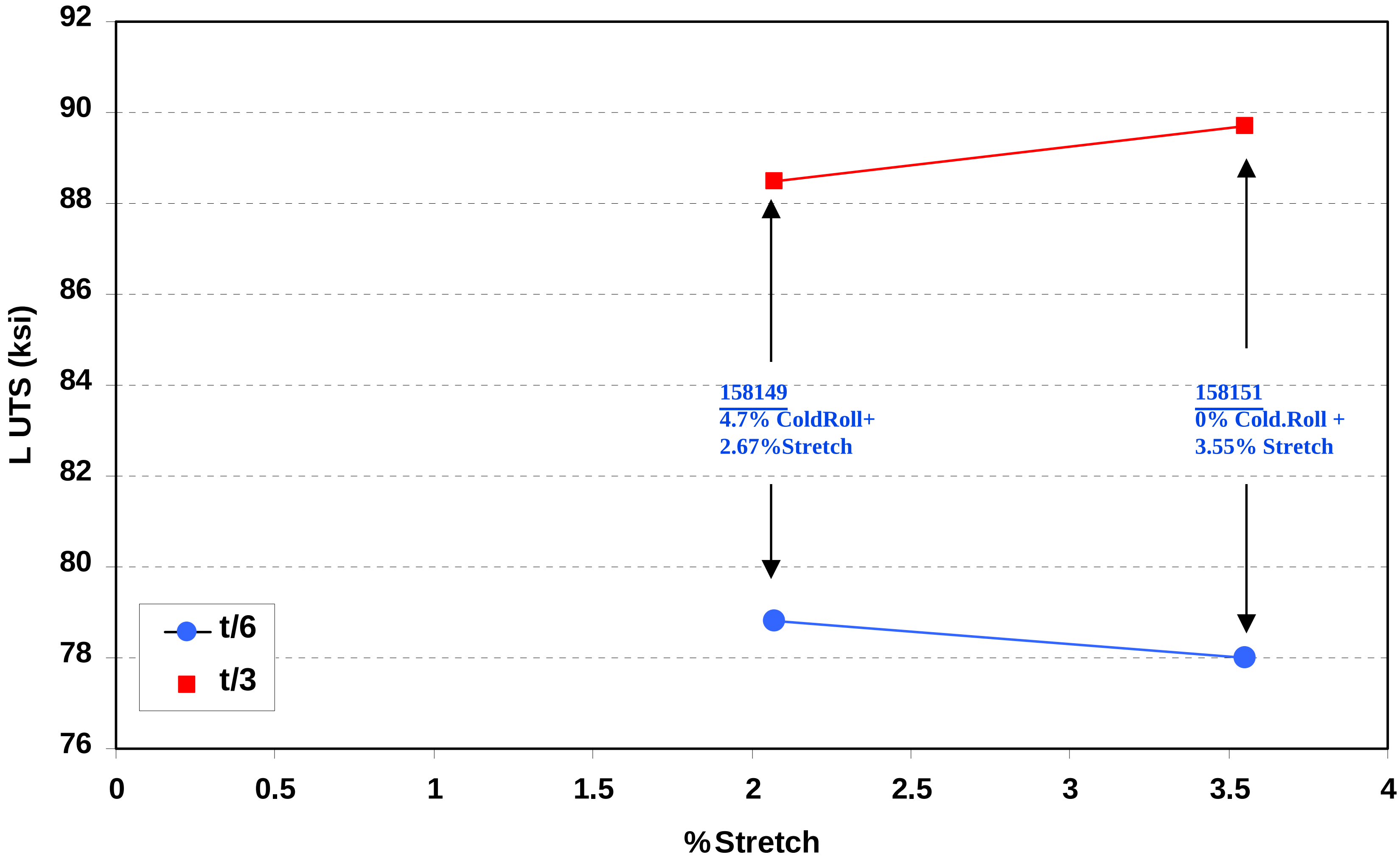
- 158149 shows slightly higher L UTS value at t/6 as a result of cold roll in addition to stretch

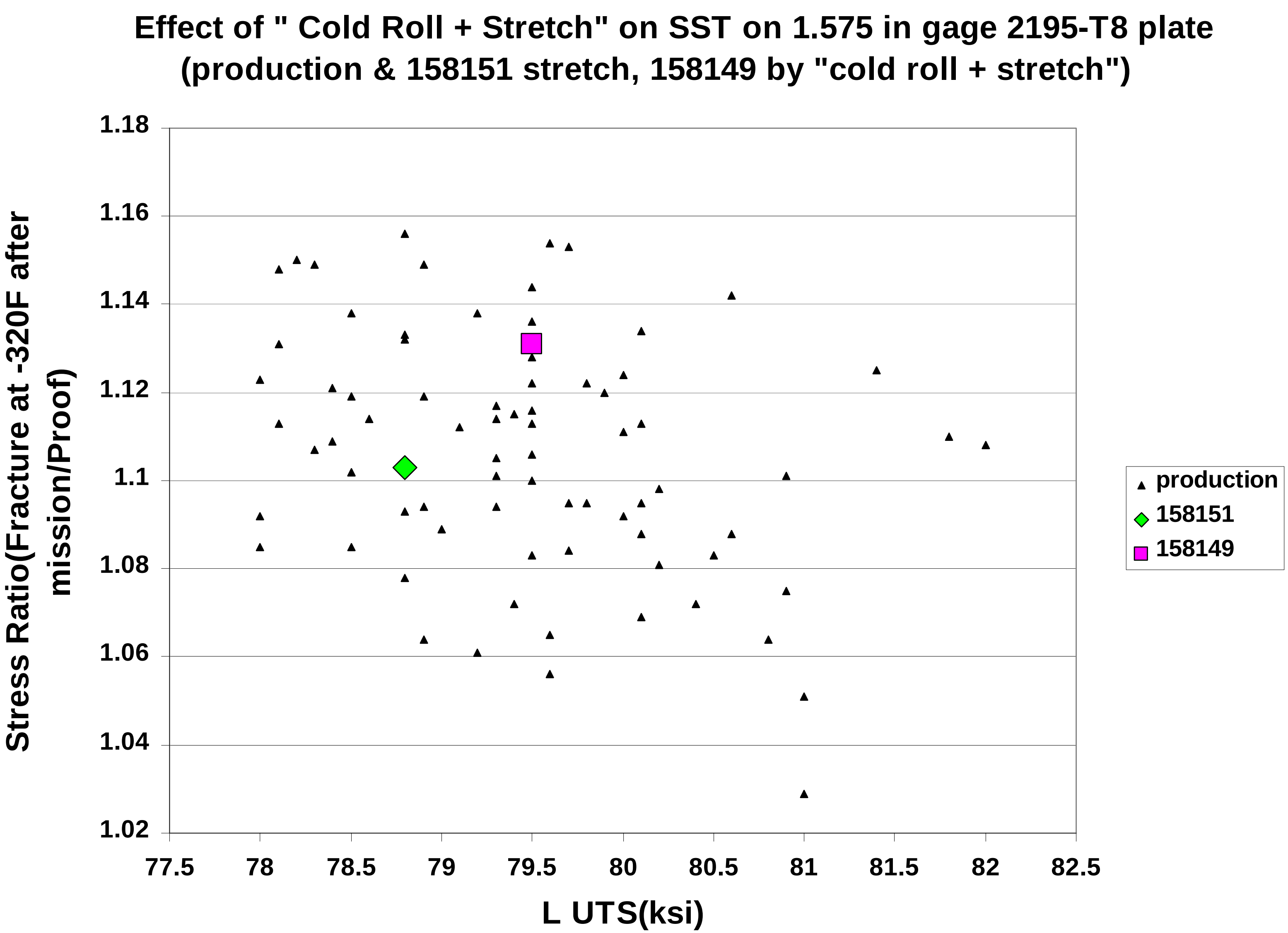


- 158151 shows higher L UTS value at t/3 because of their higher % stretch, despite lower total % cold work
- 158149 shows slightly higher L UTS value at t/6 as a result of cold roll in addition to stretch

Effect of % Stretch on Thru-Thickness Properties of Plant produced 1.575 inch gage 2195-T8 Plate (158151 & 158149)



- Cold roll + Stretch appears to improve SST performance, but the difference in effect falls within scatter for production material



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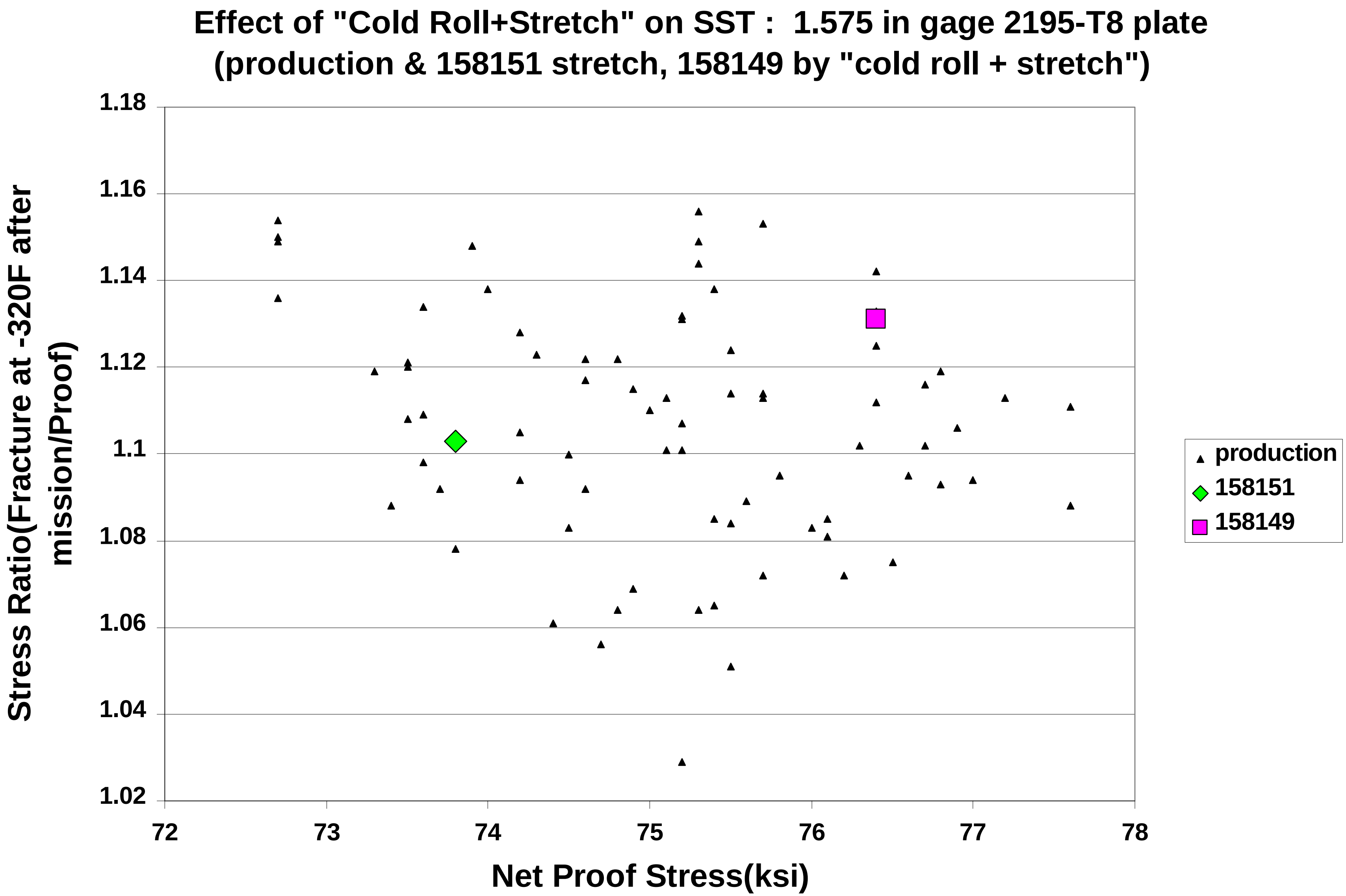


B-2: Effect of Cold Roll & Stretch Prior to Aging on Through-Thickness Strength Uniformity and on Fracture Toughness

Summary - Plant scale experiment:

1. Strengths at t/6 were increased by additional % cold roll prior to stretch.
2. Tensile strengths at t/3 location were more affected by the total % stretch, which was consistent with the results from Lab scale experiment.
3. Cold roll + Stretch appears to improve SST performance, but the difference in effect falls within scatter for production material.

Alternate Temper Development for 2195 Plate

C: Effect of Multiple - Step vs. Single Step Stretch prior to Age on Mechanical properties

Experimental Parameters for Lab. Trial on " Multi-step Stretch"

-1; 2% stretch + Unload for 2 min delay + 1.8% stretch

-2; 2% stretch + Unload for 24 hr delay + 1.8% stretch

-3; 2% stretch + 2min delay in compression + 1.8% stretch

baseline : Standard practice :single step 3.75% target (3.82% actual) stretch

Process Parameters and Tensile Properties for 2195-T8 Plate using Multi-Step Stretching Practice on 1.575" gage 2195 Plate

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158153	-2	none	3.80%	3.80%	5t/6	30	L	77	74.5	10.0
					t/6	34	L	80.2	77	9.0
stretch: 2%+2min+1.8%					2t/3	30	L	86.6	82.7	9.5
					t/3	34	L	87.4	82.7	8.5
					t/2	34	L	90.6	86.7	11.0

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158162	-2	none	3.85%	3.85%	5t/6	30	L	78	75	9.0
					t/6	34	L	78.5	75.2	9.0
stretch: 2%+2min+1.8%					2t/3	30	L	87.1	82.6	9.5
					t/3	34	L	86.2	81.3	7.5
					t/2	34	L	89.1	85.1	8.5

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158153	-3	none	3.82%	3.82%	5t/6	30	L	76.1	73.8	9.0
					t/6	34	L	78.2	75.5	9.0
stretch: 2%+24 hrs+1.8%					2t/3	30	L	84.6	80.7	9.0
					t/3	34	L	86.4	82.4	11.0
					t/2	34	L	88.5	84.8	10.0

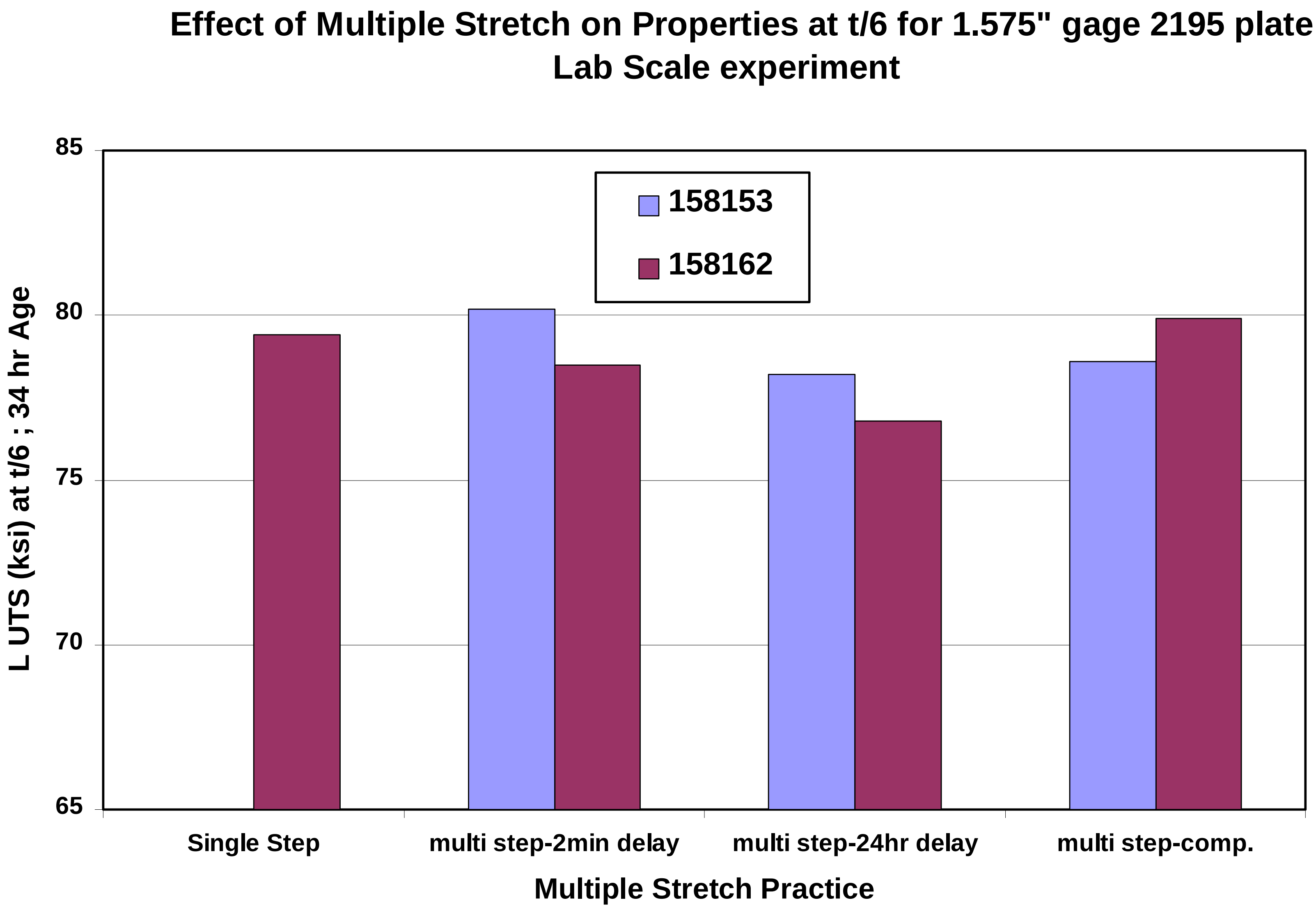
Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158162	-3	none	3.84%	3.84%	5t/6	30	L	76.1	72.8	9.5
					t/6	34	L	76.8	73.9	9.0
stretch: 2%+24 hrs+1.8%					2t/3	30	L	85.7	80.9	9.0
					t/3	34	L	87	82.6	9.0
					t/2	34	L	89.6	84.8	12.0

Process Parameters and Tensile Properties for 2195 Plate using Multi-Step Stretching and Compression Practice on 1.575" gage 2195 Plate

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158153	-4	none	3.85%	3.85%	5t/6	34	L	78.7	75.91	9.0
					t/6	34	L	78.6	75.53	9.5
2% Stretch +6.8ksi Compression +1.8% Stretch					2t/3	34	L	91	87.22	9.5
					t/3	34	L	88	84.33	7.5
					t/2	34	L	90.9	87.25	9.0

Lot No.	S.N.	%cold roll	%Stretch	%cold work	test plane	Age (300F)	test dir.	UTS(ksi)	TYS(ksi)	El(%)
158162	-4	none	3.82%	3.82%	5t/6	34	L	79.5	76.70	9.5
					t/6	34	L	79.9	77.01	9.5
2% Stretch+6.8ksi Compression +1.8% Stretch					2t/3	34	L	89.8	86.02	9.0
					t/3	34	L	88.7	85.00	8.5
					t/2	34	L	90.3	86.59	9.5

• There is no indication that multi-step stretch increases L UTS values



Alternate Temper Development for 2195 Plate

C: Effect of Multi- Step stretch vs. Single Step Stretch prior to Age on Fracture Toughness in Transverse direction

Summary on tensile data

- There is no indication that multi-step stretch increases L UTS values, which is consistent with past experience in high Lithium containing alloys

- SST Fracture Toughness tests were not conducted due to insufficient width of available material

Alternate Temper Development for 2195 Plate

IV. Conclusions:

1. Results showed that stretch prior to age significantly increases strength at t/2 and t/3 locations, but is not effective in increasing strength at near surface locations such as t/6.
2. Compared to the properties at the t/6 location, strengths at the t/3 location are more responsive to the amount of % stretch, not to the amount of % cold rolling. This could partially explain the strong through- thickness strength variation in the standard production 2195 –T8 plate which is cold worked by stretch only.
3. Plant scale experiments showed that "cold roll + stretch" appeared to improve SST performance compared to "stretch only" prior to age.
4. There is no indication that multi-step stretch increases L UTS values

Process Improvement of 2297 Plate

Alex Cho

Pechiney Rolled Products
Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Process Improvement of 2.4 inch gage 2297-T8 Plate for Aerospace Application

Contents:

1. Objective
2. Approach
3. Background of 2.4 inch gage 2297-T8 Plate for Aerospace application
4. Process description of standard and three trial lots
5. Property test results from standard vs. trial Lots
6. Comparison of crystallographic texture of 2297-T8 plate at t/6 location
7. Correlation of texture and tensile properties in longitudinal (L) and long transverse (LT) directions
8. Conclusions

Alex Cho (304-273-7038), Pechiney Rolled Products LLC, Aug.09, 2005 NASA Contract no. NNL04AB64T with AS&M Inc.

Process Improvement of 2.4 inch gage 2297-T8 Plate for Aerospace Application

1. Objective

Improve t/6 longitudinal tensile properties and S-L Fracture Toughness at t/2 location at room temperature and –320 deg F

Process Improvement of 2.4 inch gage 2297-T8 Plate for Aerospace Application

2. Approach

Evaluate an alternative hot rolling process and temper practices of 2.4 inch gage 2297-T8 plate by conducting plant scale trials. Examine the effects of these processing variables on texture and mechanical properties

3. Background of 2.4” gage 2297-T8 plate for aerospace application:

- McCook’s past recovery rate of 2297 plate for Aerospace has not been satisfactory
- PRP’s lot failure of 2297 plate has been largely due to marginal mechanical properties
- Among the properties, **K1c in S-L direction at –320F** and **L UTS** values are the most difficult to constantly maintain at an acceptable level
- Alternative process methods were identified to explore overall level and consistency of mechanical properties.

4. **Process description of standard vs. three trial lots**

Factors influencing plant practice for Al alloy production

a. product dimensional requirement

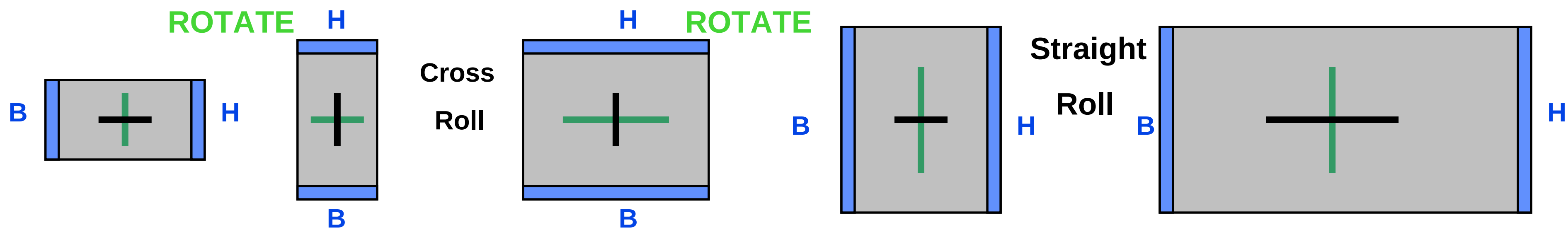
b. metallurgical considerations

c. adaptation to facility limitations

Description of alternative processing

- *current standard practice at Ravenswood is identical to McCook process*
- Metallurgical considerations related to Alternate process
  a. deformation directions
  b. testing location
- Alternate practice will impart more balanced rolling deformation

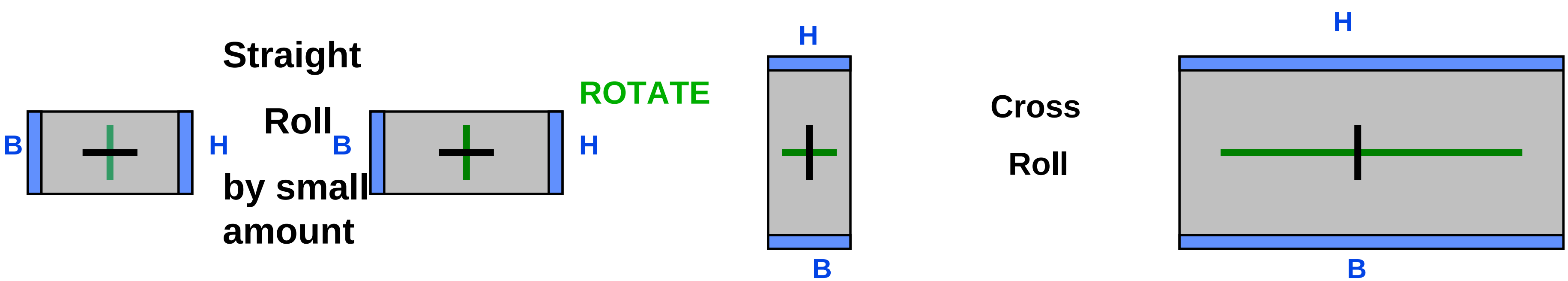
Proposed Practice – Hot Rolling



Broaden. vs. Lengthen.

2.33X vs. 2.5X

current 2297 Practice – (McCook Practice)

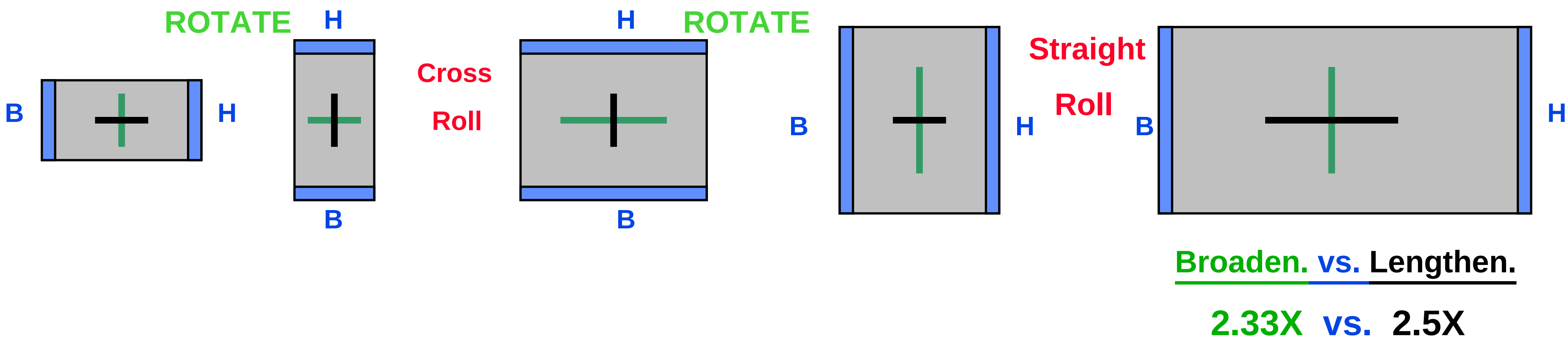


Lengthen. vs. Broaden.

1.07X vs. 5.56X

Current practice provides essentially One Directional Deformation

Proposed Process – Hot Rolling

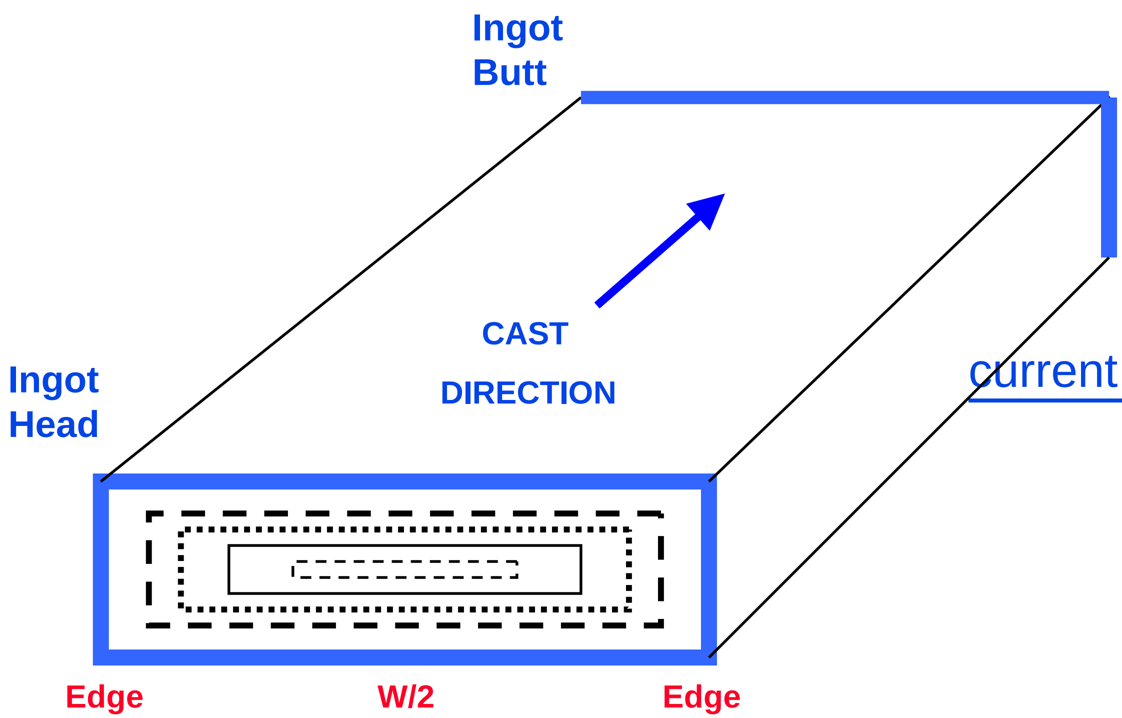


Balanced deformation in Ingot Width vs. Length

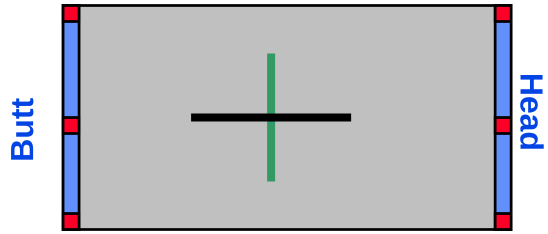
- balanced strengths in L vs. LT
- Improved 45 deg strength
- balanced Fracture Toughness in L-T vs T-L
- Improved K1c in S-L relative to L UTS

Plate Testing Locations

Standard testing practice characterize plate properties across the ingot cross section



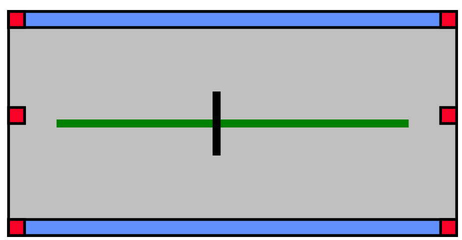
Proposed Practice



Broaden. vs. Lengthen.

2.33X vs. 2.5X

current Ravenswood Practice (McCook)



Lengthen. vs. Broaden.

1.07X vs. 5.56X

PECHINEY ROLLED PRODUCTS

5. Property test results from standard and trial lots

Summary of processing study of 2297 plate

Lot no.	*Alloy*	*Hot Roll dir.*	*Cold Work*
Prev. 8 lots	high Li(1.3%)	Uni-dir. roll	stretch
200601	**high Li(1.3%)**	**Two-dir.roll**	**stretch**
682321	**low Li(1.2%)**	**Two-dir.roll**	**stretch**
682311	**low Li(1.2%)**	**Two-dir.roll**	**cold roll+stretch**

Lot no. 200601

-Full size ingot: 16” x 60” x 132”

-Chemistry: standard 2297 alloy

Cu	Li	Mn	Zr	Si	Fe	Ti
3.04	1.28	.33	.10	.04	.04	.02

-Hot Rolling : lay-on at 942F, exit at 856F

-Broaden to 6.4” gage (58% reduction)

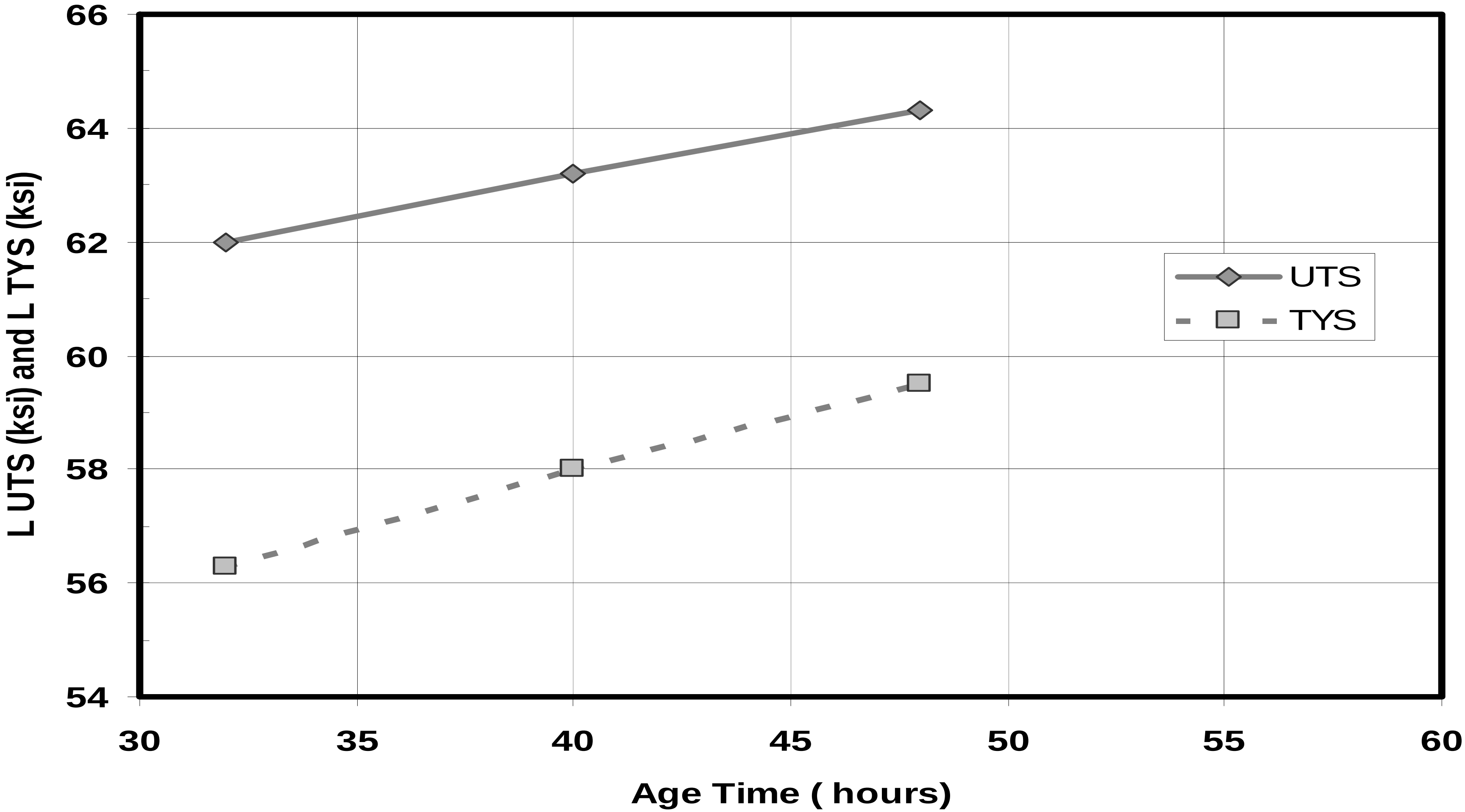
-Rotate 90 deg., straight roll to finish at 2.59”(59% reduction)

-SHT at 975F for 8hrs. 47 min.

-Stretch 3.87%

-Aged at 320F for 40 hrs.

Age Curves of Lot No.200601



Lot no. 682321

-Full size ingot: 16” x 60” x 132”

-Chemistry: standard 2297 alloy (2297)

Cu	Li	Mn	Zr	Si	Fe	Ti
2.99	1.20	.31	.10	.04	.06	.02

-Hot Rolling by broadening to 5.2” thick x 88” wide

-Air cool, saw to 160” long

-Re heat to roll; lay-on at 850F

-Broaden to 111” wide from 88” (total 47% reduction)

-Rotate 90 deg., straight Roll to finish at 2.59” gage (total 57% reduction)

-SHT at 975F

-Stretch 3.5%

-Aged at 320F for 60 hrs.

Lot no. 682311

-Full size ingot: 16” x 60” x 132”

-Chemistry: standard 2297 alloy (2297)

Cu	Li	Mn	Zr	Si	Fe	Ti
2.94	1.18	.32	.10	.04	.04	.02

-Hot Rolling by broadening to 5.3” thick x 82” wide x 192” long

-Air cool, saw to 163” long

-Re heat to roll; lay-on at 819F

-Broaden to 114” wide from 82” (total 48% reduction)

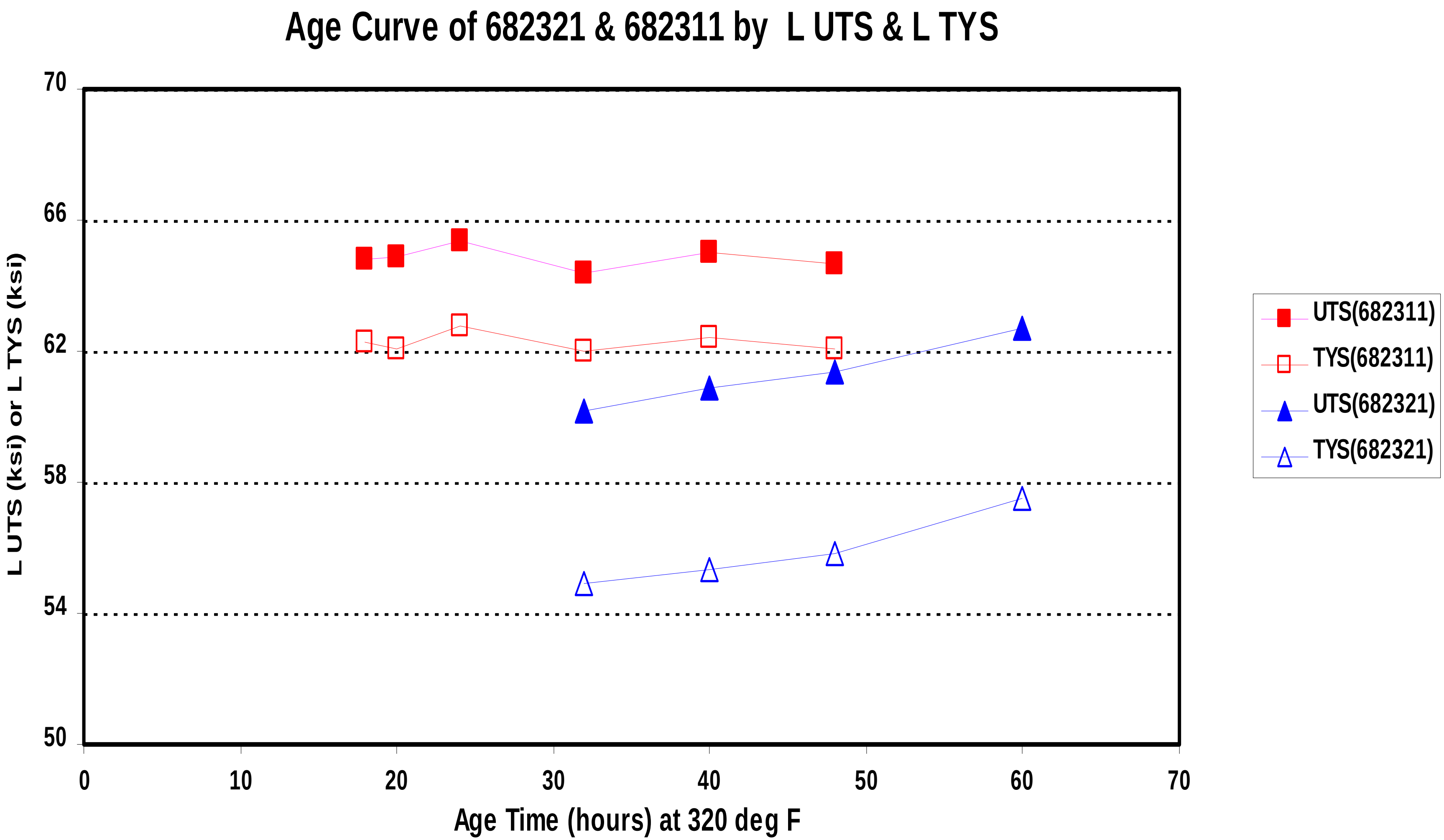
-Rotate 90 deg., straight Roll to finish at 2.67” gage (total 55% reduction)

-SHT at 975F

-Cold Roll 5.3% (target; 3%)then Stretch by 2.5%

-Aged at 320F for 20 hrs.

Since Lot 682311 was heavily cold worked (5.3% by cold rolling and 2.5% by stretch), it appears that the strength in T3 temper condition already reached peak strength. Subsequent artificial aging step seems to be merely balancing of softening by anneal of cold work and strengthening by age hardening. The other two lots were stretched only, and demonstrated as normal age strengthening curve. Strength increases as aging time increases (as shown by 682321 in this chart and 200601 in page 12)



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PECHINEY ROLLED PRODUCTS

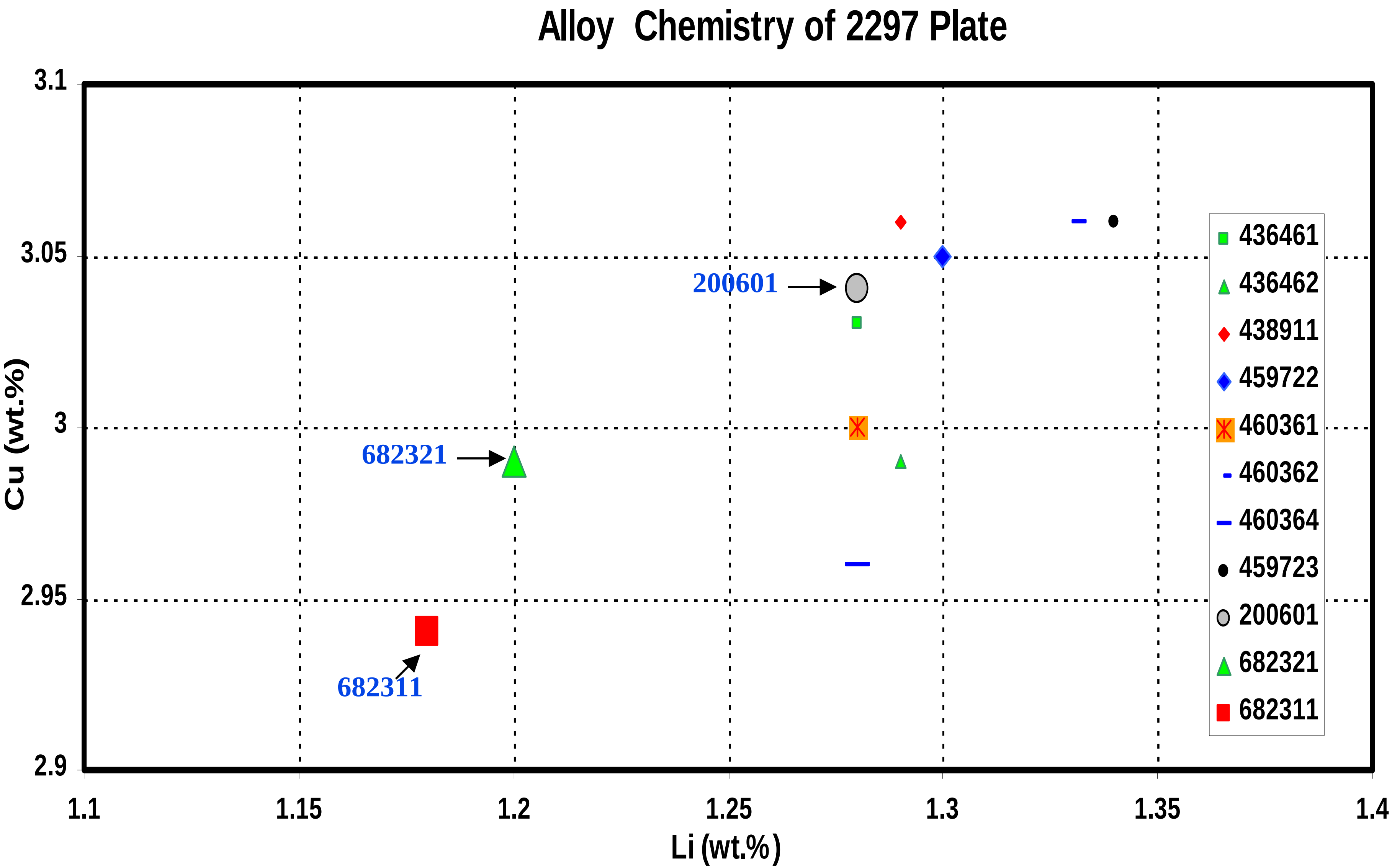
5. Property test results from standard and trial Lots

Chemistry of 2.4 inch gage 2297-T8 plate (in weight %)

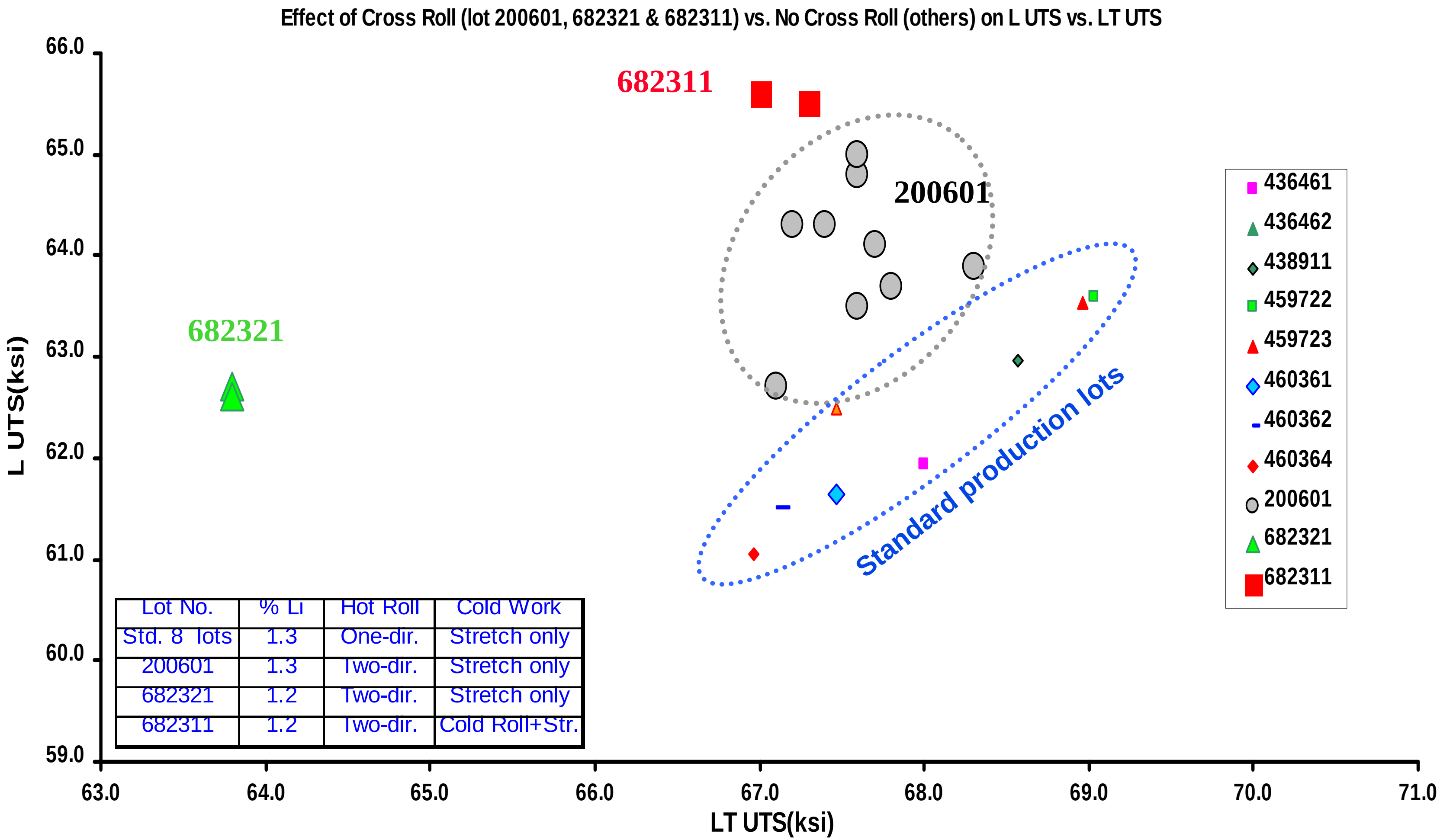
Lot No.	Cu	Li	Mn	Mg	Zr	Ti	Si	Fe
436462	2.90	1.29	0.34	0.01	0.11	0.03	0.04	0.04
459722	3.05	1.30	0.33	0.01	0.10	0.02	0.04	0.04
460361	3.00	1.28	0.32	0.01	0.10	0.02	0.04	0.05
460362	3.06	1.33	0.34	0.01	0.10	0.02	0.04	0.05
460364	2.96	1.28	0.31	0.01	0.09	0.02	0.04	0.04
459723	3.06	1.34	0.32	0.01	0.10	0.02	0.04	0.05
200601	*3.04*	*1.28*	*0.33*	*0.01*	*0.10*	*0.02*	*0.03*	*0.04*
682321	*2.99*	*1.20*	*0.31*	*0.01*	*0.10*	*0.03*	*0.04*	*0.06*
682311	*3.94*	*1.18*	*0.32*	*0.01*	*0.10*	*0.02*	*0.04*	*0.04*

Note: Chemistries of 436461 &438911 were not available because these two lots were scrapped earlier and their chemistries were deleted from database.

Lot 200601 and other production lots contain high Li (approx.1.3%), and Lot 682321 & 682311 contain low Li (approx. 1.2%).



Lot 682321 shows isotropic tensile properties due to two-directional rolling. However, LT UTS was too low due to low Li content. LT UTS could be increased either by higher Li content (two-directionally rolled Lot 200601) or by an increase in the amount of cold work (8%) on a low Li alloy (two-directionally rolled Lot 682311). LT UTS values of both 200601 and 682311 are comparable to the one-directionally rolled high Li containing standard production lots. Lot 682311 shows highest L UTS values at comparable LT UTS values of the standard production lots.

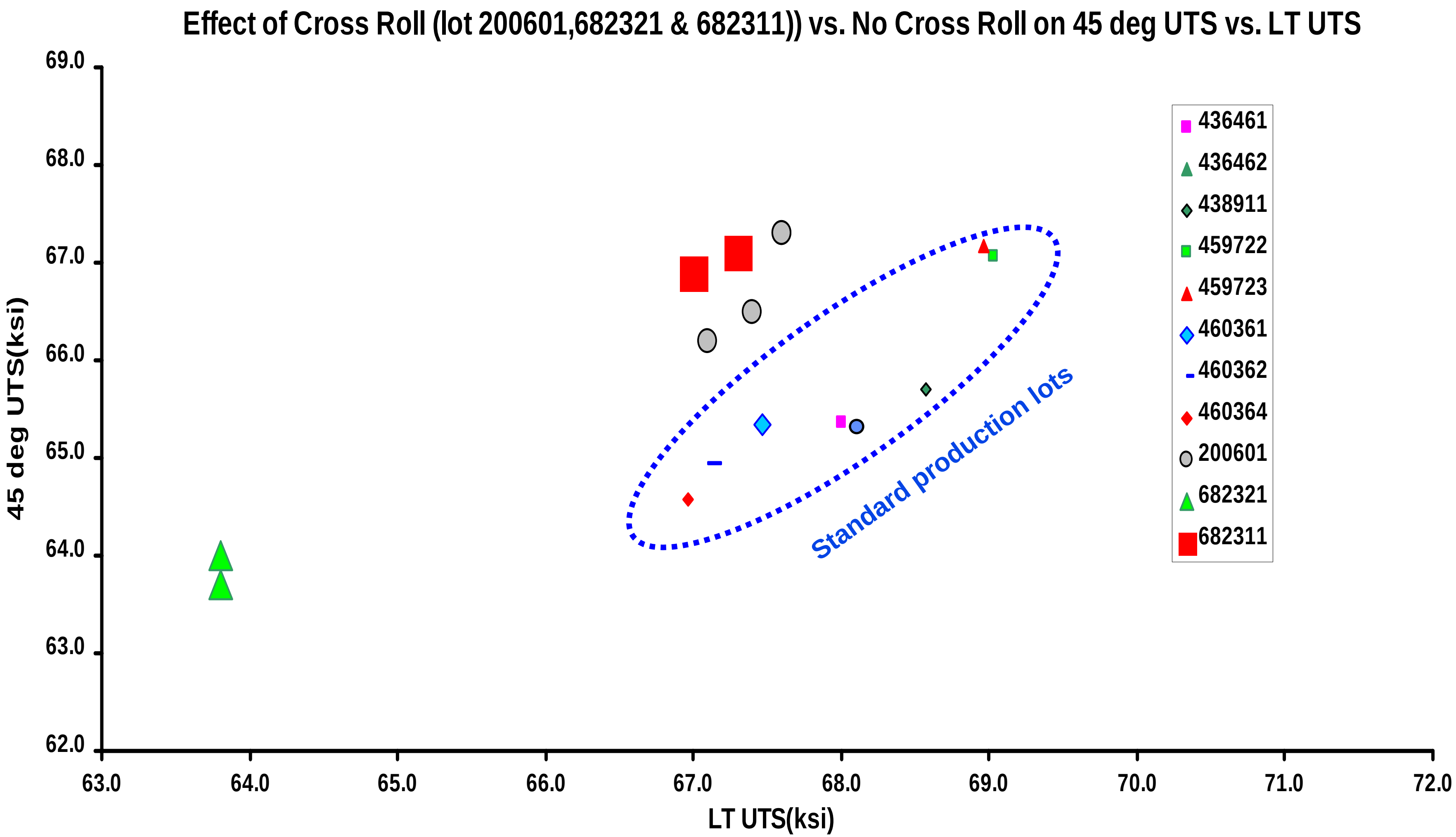


Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

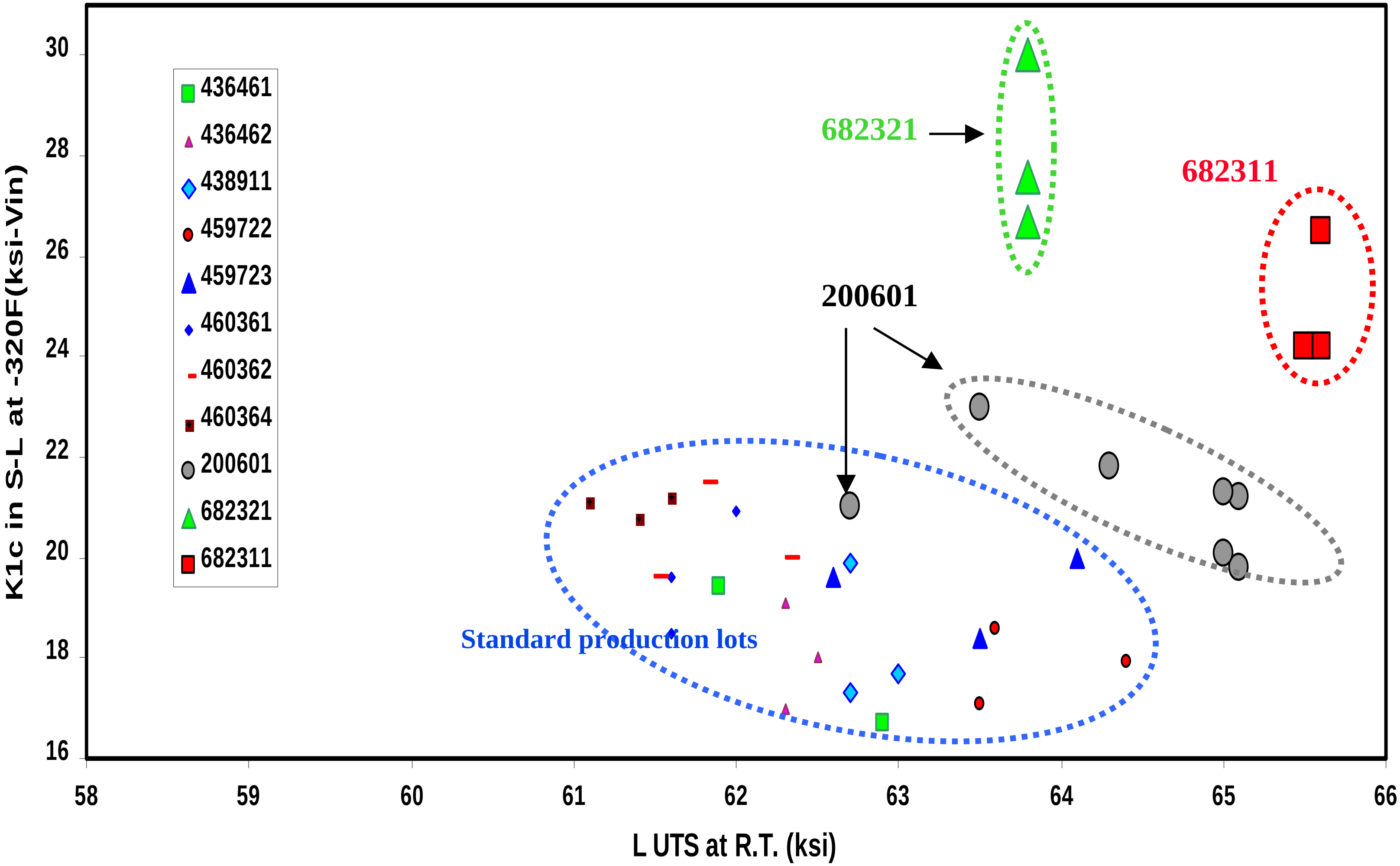
All three lots(682321, 682311 & 200601) of two directionally rolled plate show isotropic behavior. 200601 and 682311 show higher 45 deg UTS values at similar LT UTS values than one directionally rolled plate (i.e. other standard production lots)



Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Standard production lots had low K1c's in S-L & L UTS at Room temperature. Two-directionally rolled plates (200601, 682321 & 682311) show the significant improvement on both properties.

K1c in S-L at -320F vs. L UTS at R.T.



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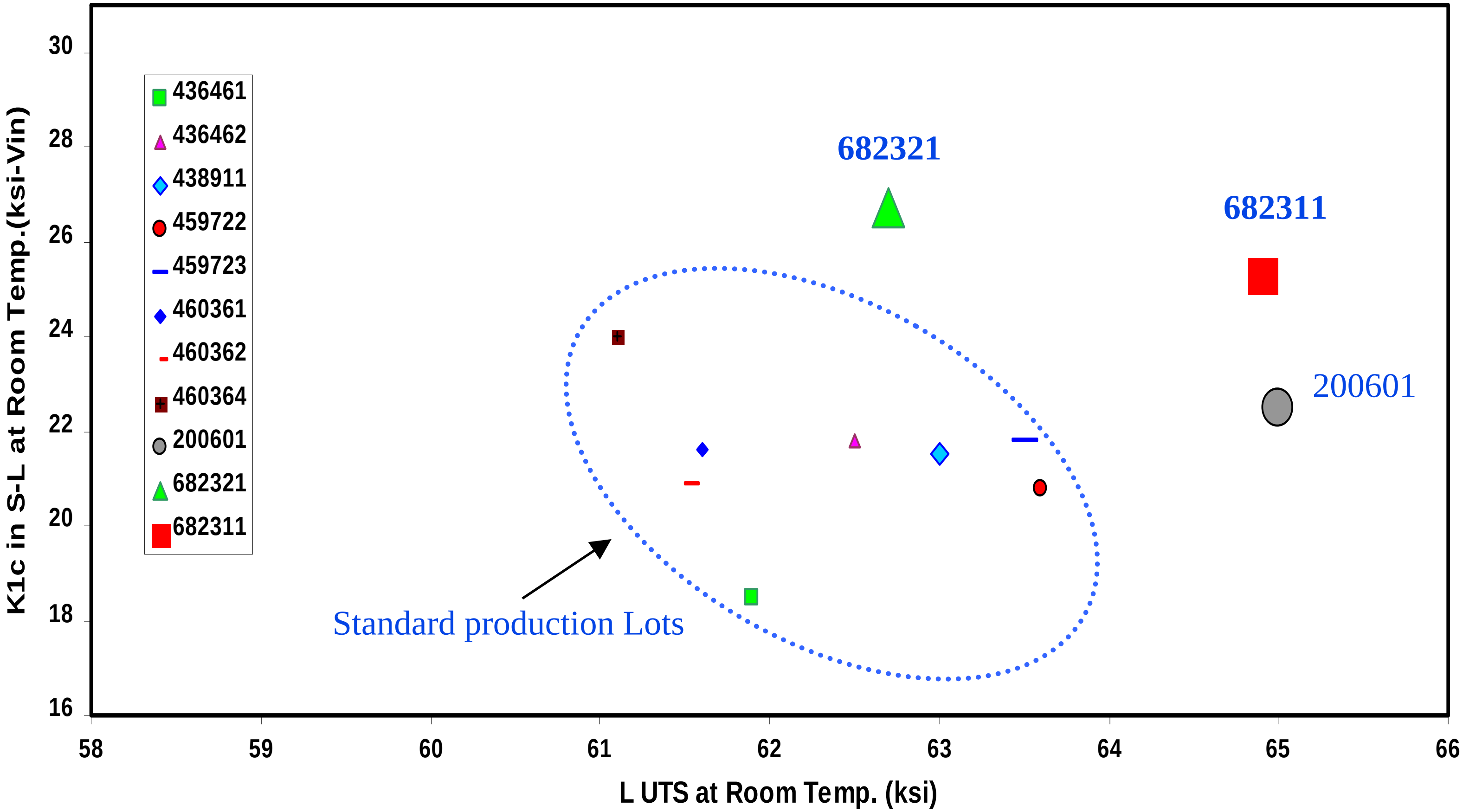
PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

- Standard production lots had low K1c's in S-L at –320 F & L UTS at Room temperature. Two-directionally rolled plates (200601, 682321 & 682311) show the significant improvement on both properties.

K1c in S-L at Room Temp. vs. L UTS at Room Temp.



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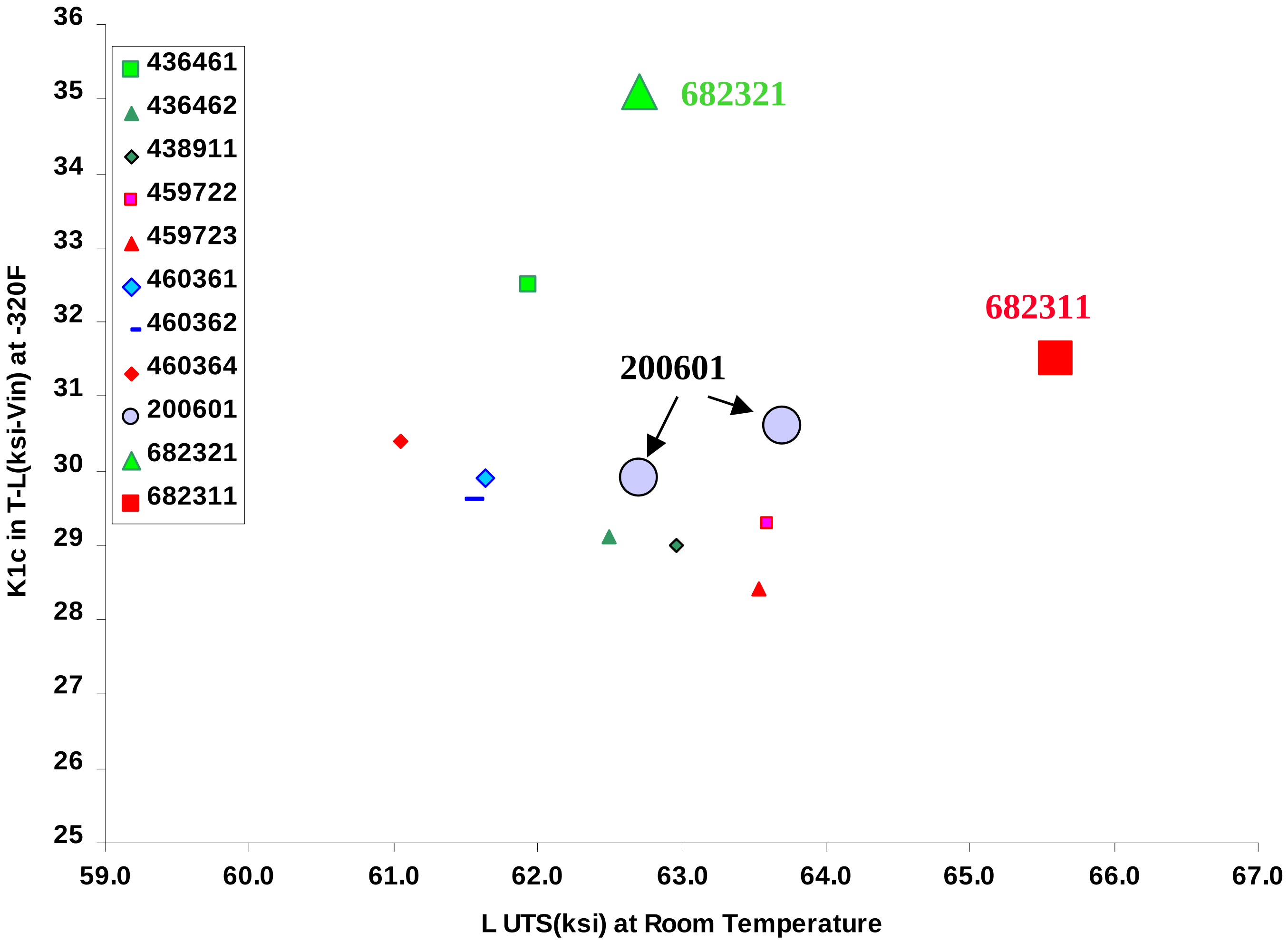
PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Two directionally rolled plate (200601, 682321 & 682311) shows higher K1c in T-L at similar or higher L UTS values

Effect of Cross Roll (lot 200601&682321), Cold Roll(lot 682311) vs. No Cross Roll (others) on K1c in T-L vs. LT UTS



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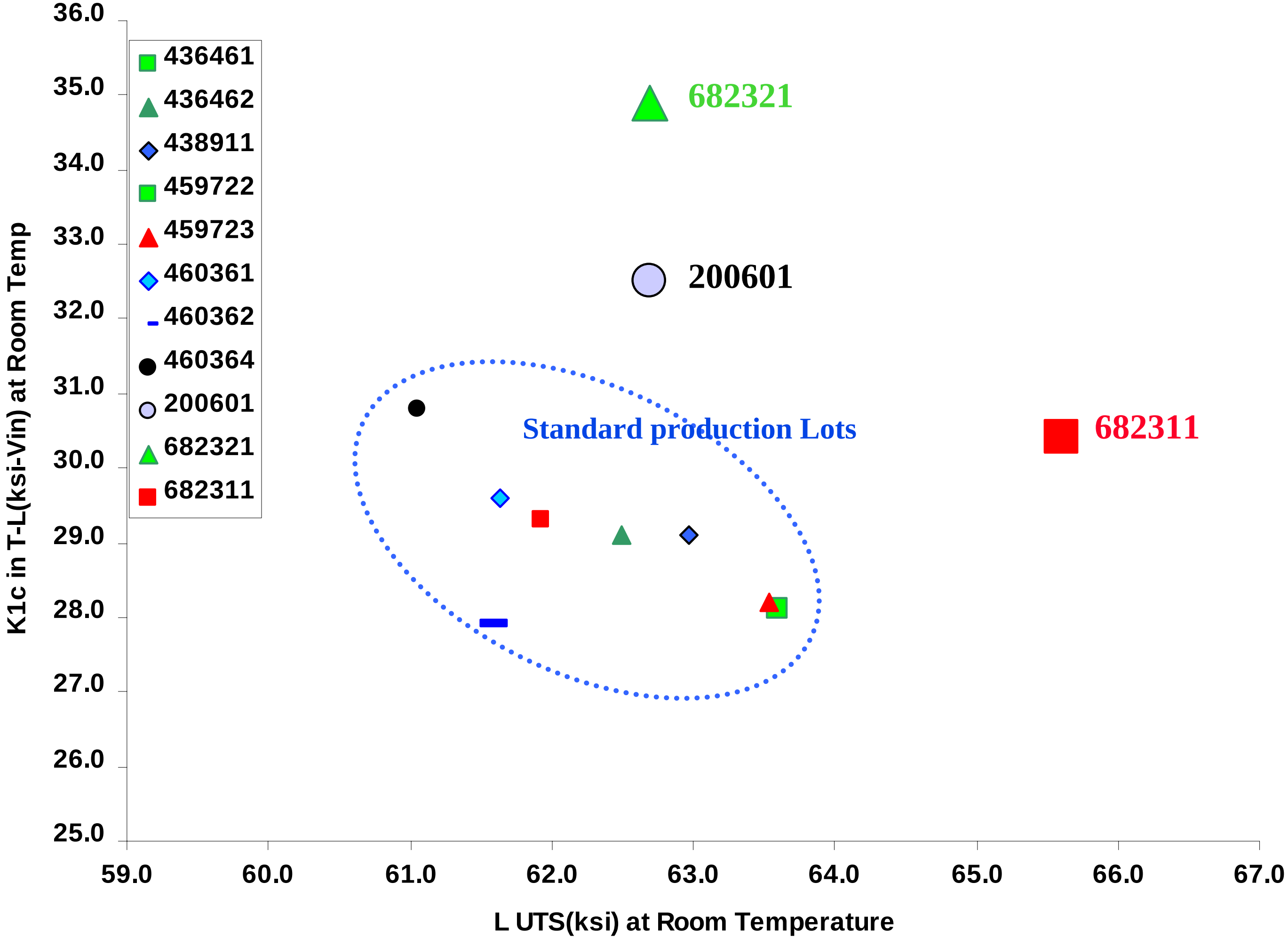
PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Two directionally rolled plate (200601, 682321 & 682311) shows higher K1c in T-L at similar or higher L UTS values

Effect of Cross Roll (lot 200601. Lot 682321), Cold Roll(682311) vs. No Cross Roll (others) on K1c in T-L vs. LT UTS



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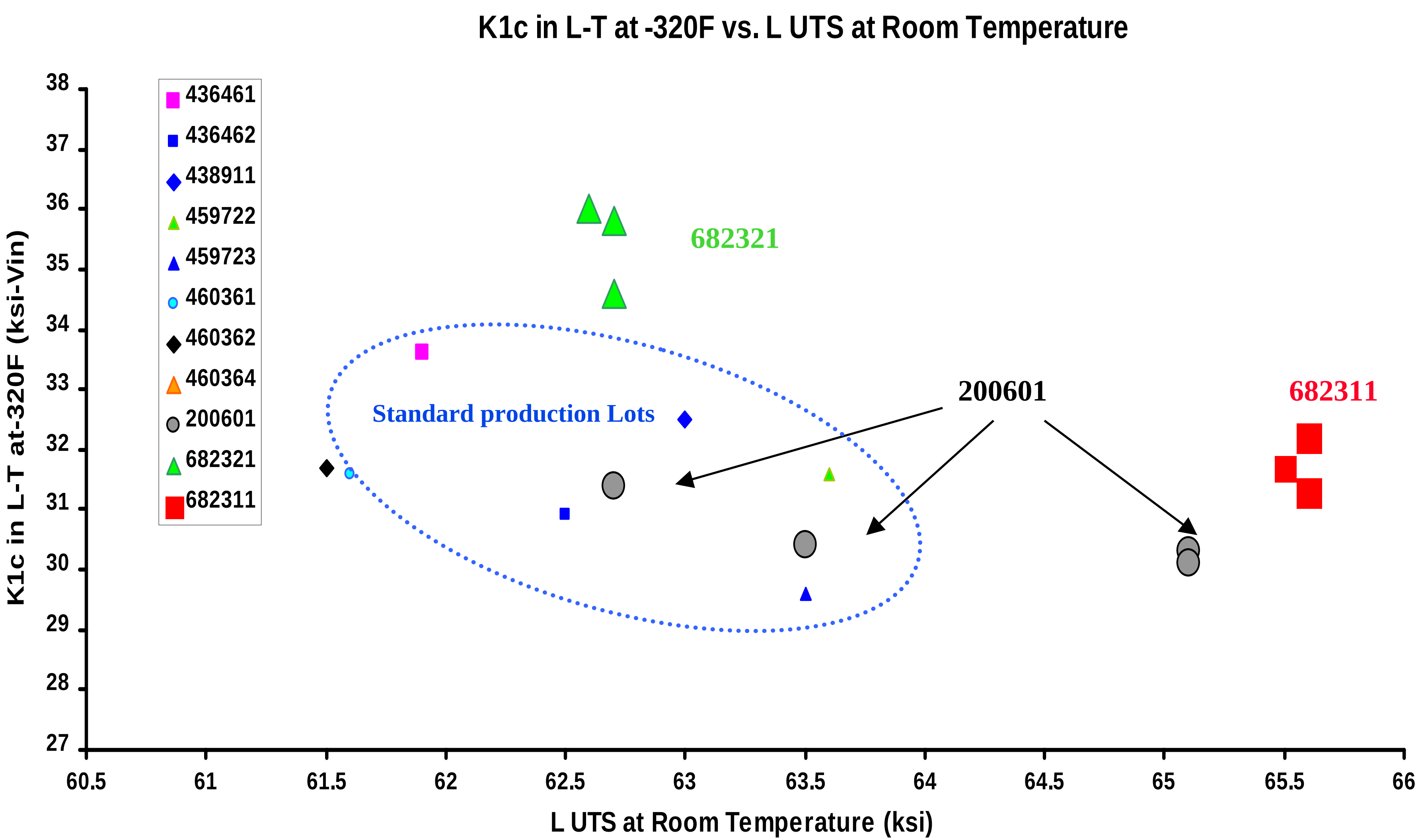
PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Plate containing 1.3% Li (200601 and standard 8 lots) show similar K1c in L-T at –320 deg F at similar L UTS, regardless of rolling practice, in uni–dr. or in two-direction. Two plates containing 1.2% Li (682321 & 682311) show significant improvement- higher K1c values at similar LUTS or similar K1c values at much higher LUTS.



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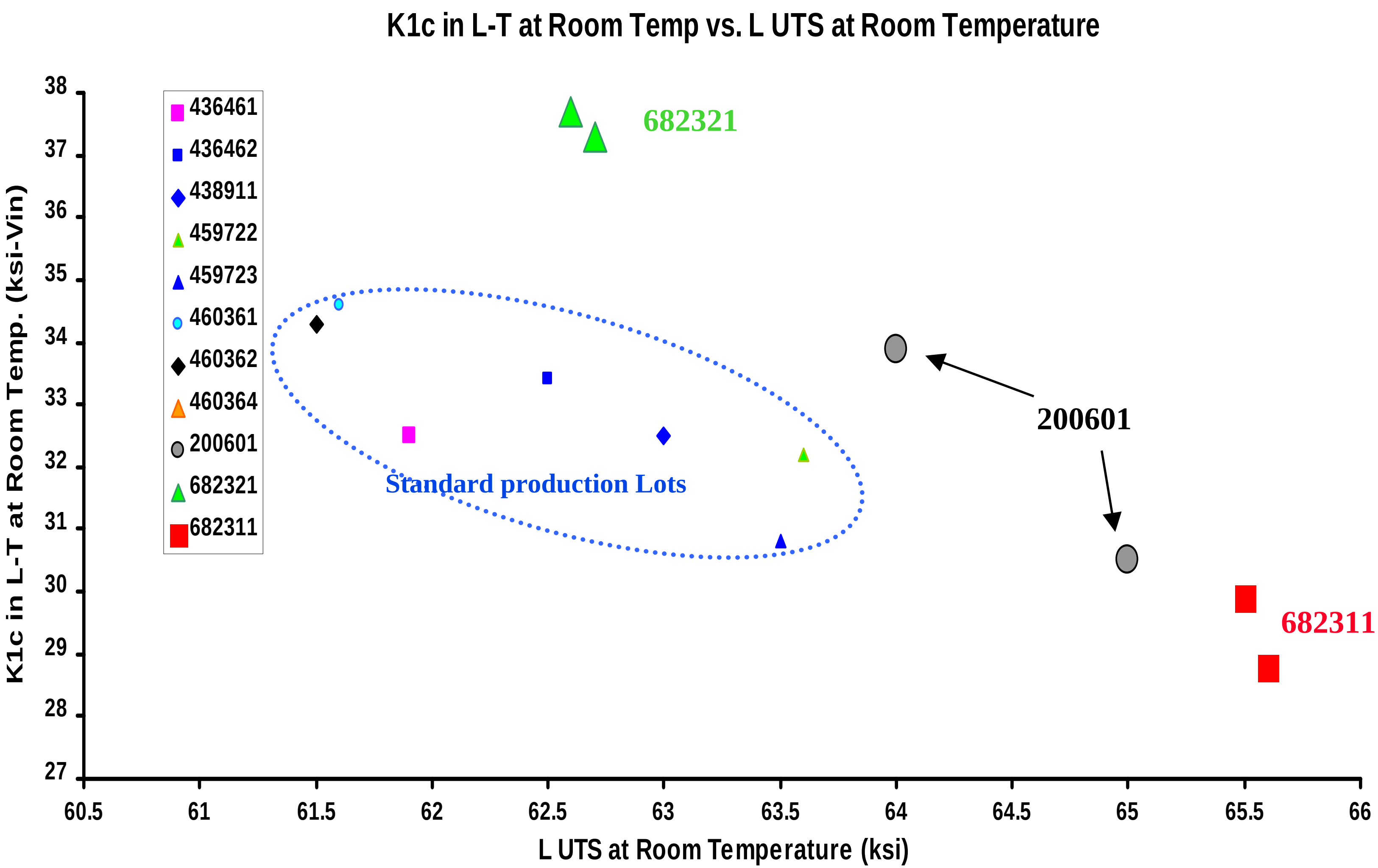
PECHINEY ROLLED PRODUCTS

Lot No.	% Li	Hot Roll	Cold Work
Std. 8 lots	1.3	One-dir.	Stretch only
200601	1.3	Two-dir.	Stretch only
682321	1.2	Two-dir.	Stretch only
682311	1.2	Two-dir.	Cold Roll+Str.

Except Lot 682321, two-directionally rolled plate (200601 & 682311) do not show improvement on K1c in L-T direction compared to the uni-directionally rolled standard production plate, even though two-directionally rolled plate show higher L UTS values at the comparable K1c in L-T. In most applications, K1c in L-T direction is usually sufficiently higher than the specification requirement and additional improvement of K1c in L-T is not necessary.



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PECHINEY ROLLED PRODUCTS

Summary of Property Test Results:

1. Alternate processing did not affect tensile properties in LT direction significantly.
2. Two-directional rolling improved L UTS values
3. Two-directional rolling improved S-L Fracture Toughness
4. “Cold rolling prior to Stretch” improved strength and Fracture Toughness in S-L relative to L-UTS
5. Two-directional rolling did not improve K1c in L-T direction
6. Excessive Cold Rolling prior to Stretch would adversely affect K1c in L-T direction.

Mechanical Properties of Uni-directionally rolled 2.4” gage 2297-T8 Plate

	Limits	RT	30	26	19	61	55	6	65	59	6	62	58	2	63	56	4
		-320	30	26	18												
	Age		Fracture			L Direction			Lt Direction			St Direction			45 Direction		
Lot #	Time	Location	L-T	T-L	S-L	L-Uit	L-Yld	L-Ein	Lt-Uit	Lt-Yld	Lt-Ein	St-Uit	St-Yld	St-Ein	45-Uit	45-Yld	45-Ein
436461	48	N	32.5	29.3	18.5	61.9	57.1	9.8	68.0	61.5	8.8	68.6	61.4	6.3	65.4	58.2	8.7
436461	48	NE				59.8	55.2	10.5									
436461	48	NW				62.9	58.9	9.9									
436461	48	N-320	33.6	32.5	19.4	74.6	65.7	17.0	82.2	70.4	9.5	81.2	67.2	5	79	66.5	17
436461	48	NE-320			25.2												
436461	48	NW-320			16.7												
436462	40	N	33.4	29.1	21.8	62.5	58.6	11.0	67.5	61.0	9.5	68.5	59.7	7.3	65.4	58.3	11.3
436462	40	NE				62.2	58.1	11.0									
436462	40	NW				62.3	58.2	11.0									
436462	40	N-320	30.9	29.1	18.0	76.1	67.4	19.0	83.6	72.6	12.0	83.3	67.2	8.0	79.4	67.9	17.0
436462	40	NE-320			19.1												
436462	40	NW-320			17.0												
438911	48	N	32.5	29.1	21.5	63.0	58.4	11.0	68.6	60.9	8.7	70.0	61.9	6.3	65.7	58.1	11.0
438911	48	NE				62.7	58.4	11.0									
438911	48	NW				62.7	58.1	10.0									
438911	48	N-320	32.5	29.0	17.7	76.7	67.8	16.0	83.6	72.0	12.0	83.9	69.4	6.0	81.0	68.8	14.0
438911	48	NE-320			19.9												
438911	48	NW-320			17.3												
459722	48	N	32.2	28.1	20.8	63.6	58.8	10.2	69.0	62.9	8.5	71.3	61.8	6.3	67.1	59.2	11.2
459722	48	NE				64.4	59.7	11.0									
459722	48	NW				63.5	59.4	11.0									
459722	48	N-320	31.6	29.3	18.6	78.2	68.8	16.0	85.1	73.2	11	83.7	69.2	4	82.7	69.7	15
459722	48	NE-320			17.9												
459722	48	NW-320			17.1												
459723	48	N	30.8	28.2	21.8	63.5	59.5	11.0	69.0	62.3	8.5,8,7.5	70.4	61.4	5.8	67.2	62.6	10.7
459723	48	NE				64.1	59.9	11.5									
459723	48	NW				62.6	58.5	10.0									
459723	48	N-320	29.6	28.4	18.4	77.4	68.7	15	85.6	74.5	9	83	69.6	3	82	69.8	15
459723	48	NE-320			20												
459723	48	NW-320			19.6												
460361	48	N	34.6	29.6	21.6	61.6	57.1	11.7	67.5	60.6	8.5	68.1	59.7	6.6	65.3	58.2	11.0
460361	48	NE				61.6	57.3	10.5									
460361	48	NW				62.0	57.9	11.5									
460361	48	N-320	31.6	29.9	18.5	74.9	66	16.0	83.3	71.2	11	82.8	67.2	5	79.3	67.3	15
460361	48	NE-320			19.6												
460361	48	NW-320			20.9												
460362	40	N	34.3	27.9	20.9	61.5	56.7	11.2	67.1	60.3	8.7	69.2	60.6	6.1	64.9	57.4	10.3
460362	40	NE				61.8	57.6	11.5									
460362	40	NW				62.3	57.9	10.5									
460362	40	N-320	31.7	29.6	19.6	75.2	66.1	18.0	83.3	71.9	12.0	83.0	68.0	4.0	79.7	67.4	14.0
460362	40	NE-320			21.5												
460362	40	NW-320			20.0												
460364	50	N	34.2	30.8	24.0	61.1	56.7	11.8	67.0	60.7	8.3	68.9	59.9	7.0	64.6	56.9	11.3
460364	50	NE				61.6	57.5	11.0									
460364	50	NW				61.4	57.3	11.0									
460364	50	N-320	33.1	30.4	21.1	74.6	66.1	17.0	83.5	71.6	10.0	83.4	66.7	4.0	79.7	67.1	15.0
460364	50	NE-320			21.2												
460364	50	NW-320			20.8												

6. Comparison of crystallographic texture of 2297-T8 plate at t/6 location (Uni- direction Rolling vs Two-direction Rolling)

Material:

To investigate the effect of hot rolling practice on crystallographic texture of 2297-T8 plate at t/6 locations, two lots of uni-directionally rolled standard production plate (125334 & 459724), and three lots (682321, 682311 & 200601) of two-directionally rolled plate were measured for CODF(crystallographic orientation distribution function) at t/6 plane locations.

Chemistry of 2.4 inch gage 2297-T8 plate (in weight %)

Lot No.	Cu	Li	Mn	Mg	Zr	Ti	Si	Fe
125334(1 dir HR,Stretch)	3.07	1.28	0.32	0.01	0.10	0.02	0.03	0.04
459724(1 dir HR,Stretch)	3.00	1.28	0.32	0.01	0.11	0.02	0.04	0.06
682311(2 dir HR,CR+Stretch)	2.94	1.18	0.32	0.01	0.10	0.02	0.04	0.04
682321(2-dir.HR,Stretch)	2.94	1.20	0.31	0.01	0.10	0.03	0.04	0.06
200601(2 dir HR,Stretch)	3.04	1.28	0.33	0.01	0.10	0.02	0.03	0.04

6. Comparison of crystallographic texture of 2297-T8 plate at t/6 location (Uni-direction Rolling vs Two-direction Rolling)

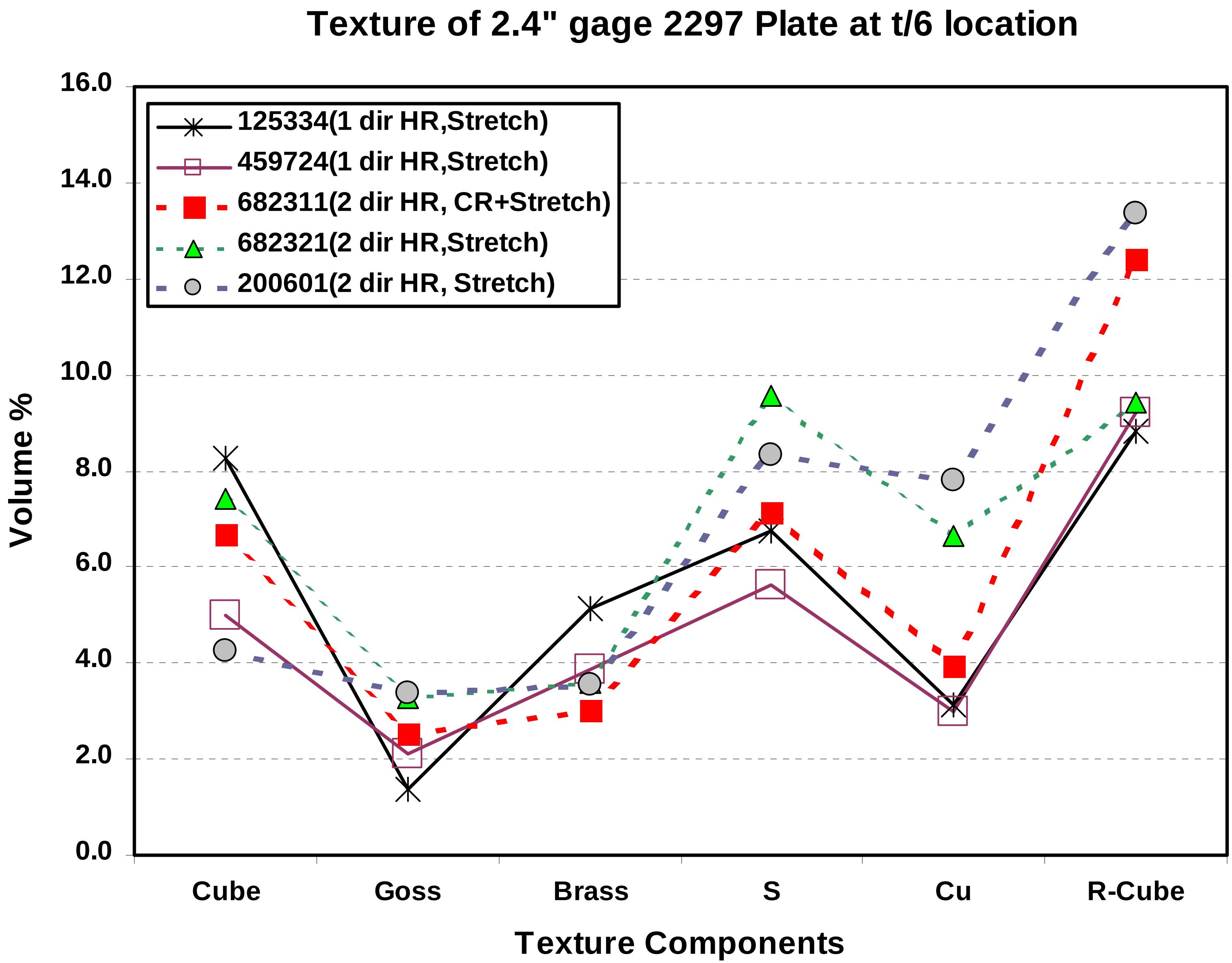
- Texture measurement results from the five lots at t/6 location are presented by volume % of each texture components as follows:

Cube: {001} <100>
Goss: {011} <100>
Brass: {011} <211>
S: {123} <634>
Cu: {112} <111>
rotated Cube: {001} <110>

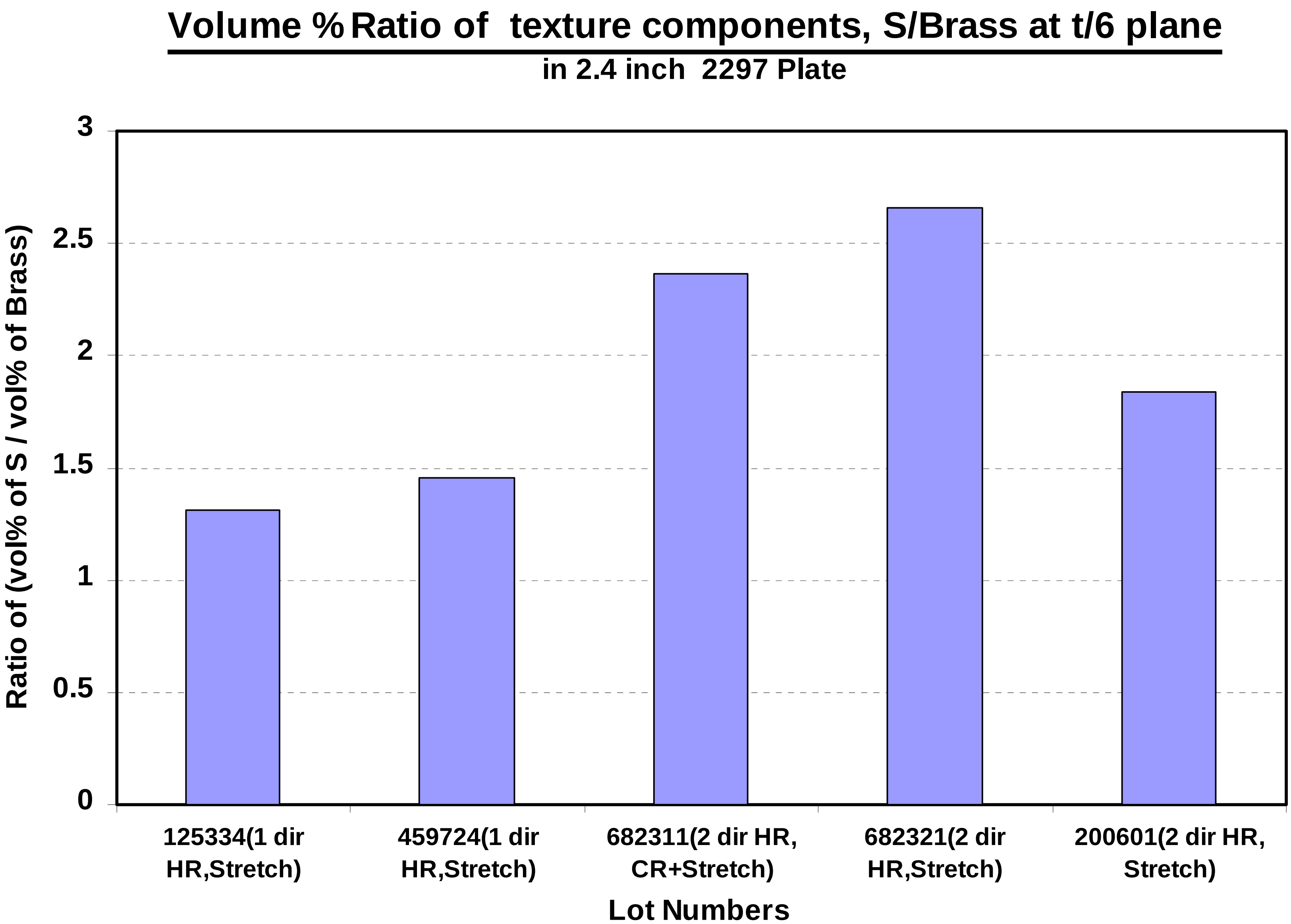
Crystallographic Texture of 2.4 inch gage 2297-T8 plate at t/6 location (in volume %)

Lot No	Cube	Goss	Brass	S	Cu	R-Cube	S/Br	Cu+ R.Cube
125334(1 dir HR,Stretch)	8.28	1.37	5.14	6.74	3.13	8.84	1.31	11.97
459724(1 dir HR,Stretch)	4.98	2.11	3.86	5.62	2.98	9.21	1.46	12.19
682311(2 dir HR, CR+Stretch)	7.43	3.26	3.60	9.57	6.66	9.43	2.36	16.36
682321(2 dir HR,Stretch)	6.69	2.53	3.02	7.14	3.94	12.42	2.66	16.09
200601(2 dir HR, Stretch)	6.25	3.56	3.78	6.96	5.12	13.68	1.84	18.80

- Two-directionally rolled plate shows higher volume % of S, Cu and Rotated Cube components, with slightly lower volume % of Brass component compared to the uni-directionally rolled plate



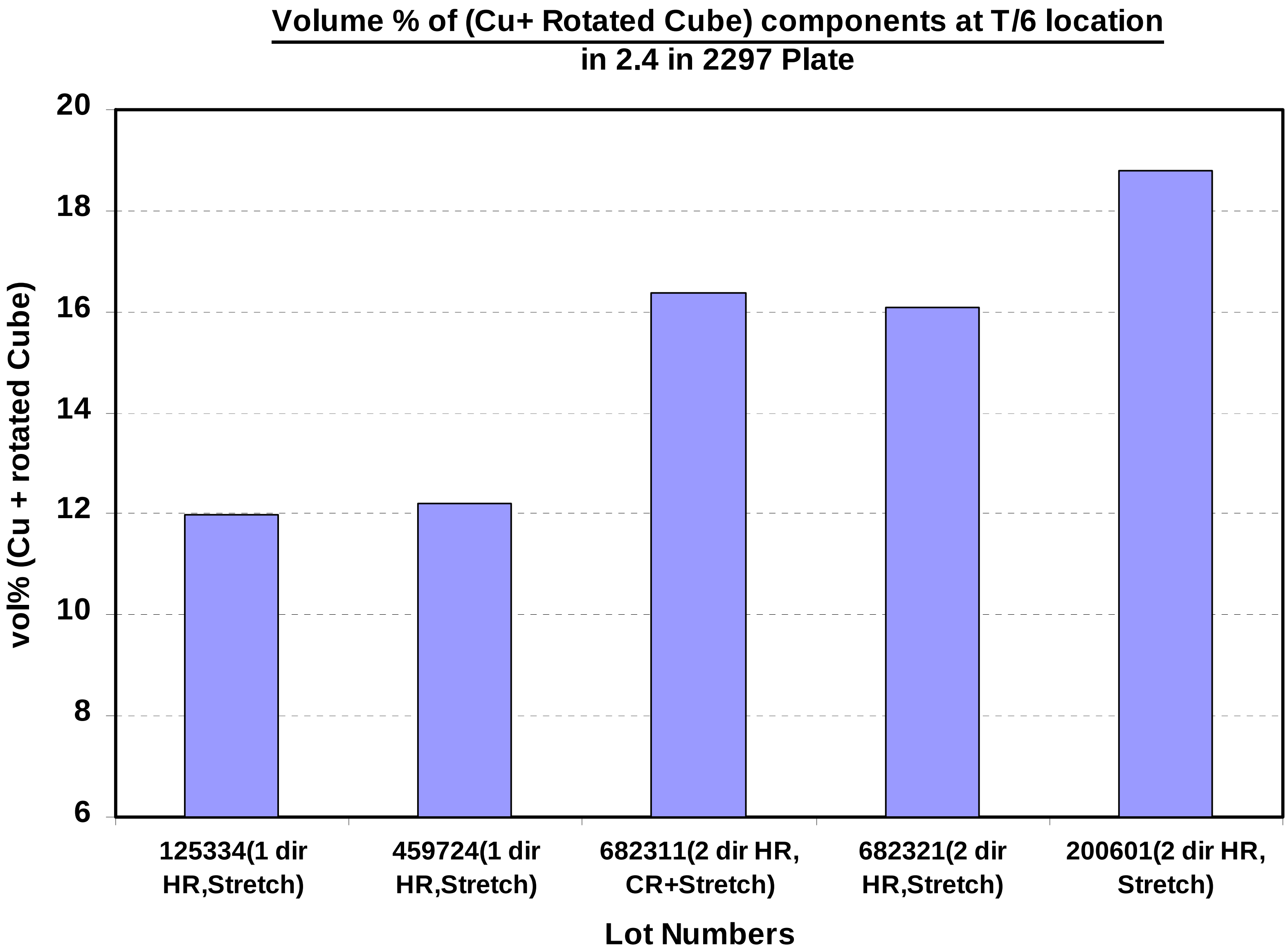
The ratio of S/Brass components of the three lots of two-directionally rolled plate (682321, 682311 & 200601) are higher than those of uni-directionally rolled plate (125334 & 459724), which is one of the primary texture characteristics of two-directionally rolled plate



Alex Cho (304-273-7038), Pechiney Rolled Products LLC, Aug.09, 2005 NASA Contract no. NNL04AB64T with AS&M Inc.

PECHINEY ROLLED PRODUCTS

The sum of Cu & rotated Cube components of the two-directionally rolled plate (682321, 682311 & 200601) is higher than those of uni-directionally rolled plate (125334 & 459724), which is one of the texture characteristics of two-directionally rolled plate



Summary of texture measurement on 2.4 inch gage 2297-T8 plate

1. All three lots of two-directionally rolled 2.4 inch gage 2297-T8 plate show a higher ratio of S/Brass components and greater value of the sum of the volume % of Cu and rotated Cube components compared to uni-directionally rolled plate. These are interesting observations because these were unique characteristics of crystallographic texture of two-directionally rolled 1.575 inch gage 2195-T8 plate at the t/6 location from prior studies .

7. Correlation of Crystallographic Texture and Tensile properties in L & LT direction in 2.4 inch gage 2297-T8 plate

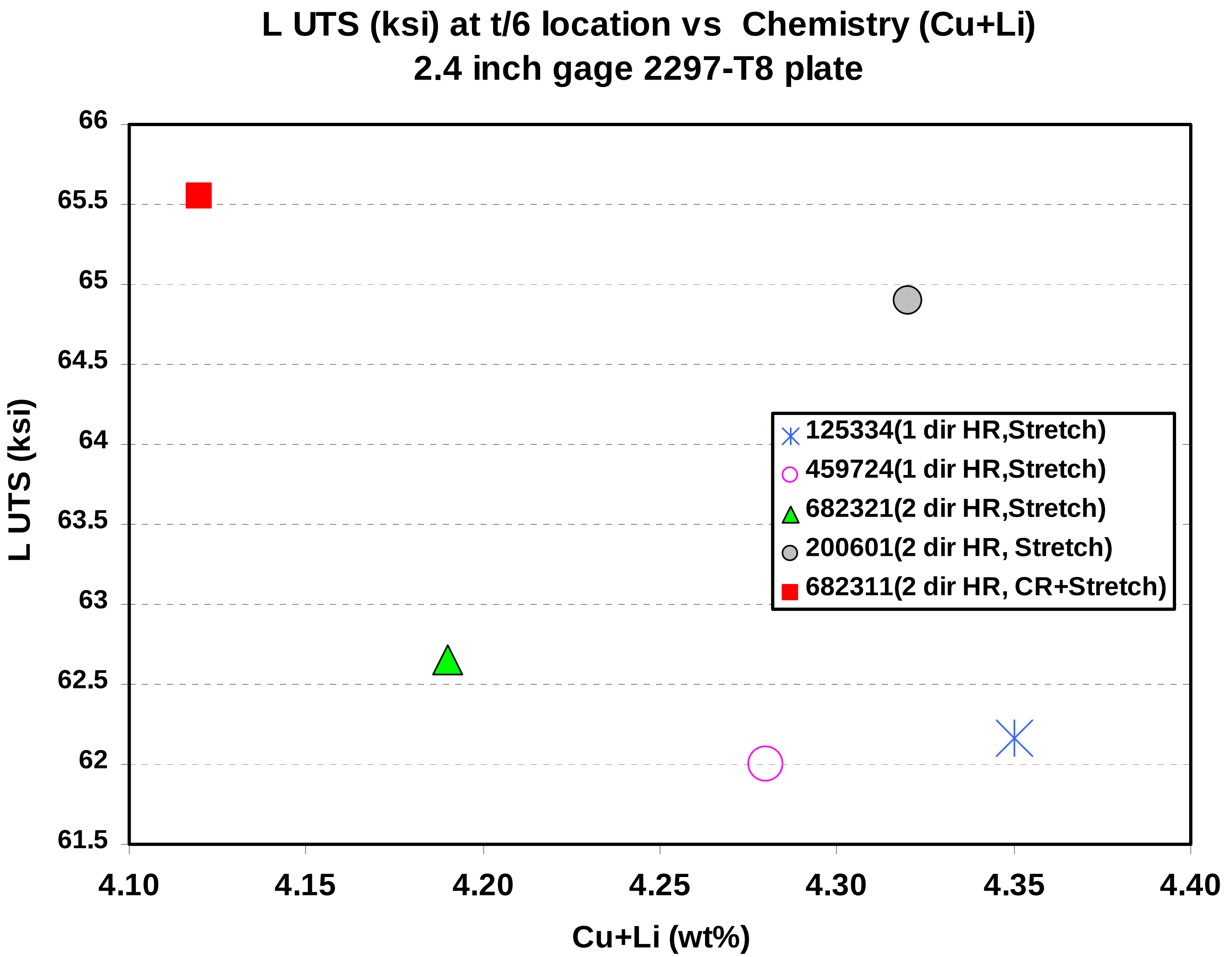
Tensile Properties of 2.4 inch gage 2297-T8 plate at t/6 location

Lot No	L UTS	L TYS	L EL	LT UTS	LT TYS	LT EL	LT UTS/L UTS	LT TYS/L TYS
125334(1 dir HR,Stretch)	62.2	57.2	10.3	67.2	60.1	8.2	1.080	1.051
459724(1 dir HR,Stretch)	62.0	57.6	10.0	67.0	60.9	8.3	1.081	1.057
682311(2 dir HR, CR+Stretch)	65.6	63.2	8.0	67.2	63.9	8.5	1.024	1.010
682321(2 dir HR,Stretch)	62.7	57.4	9.4	63.8	58.3	9.2	1.018	1.016
200601(2 dir HR, Stretch)	64.9	60.1	9.0	67.6	62.0	8.6	1.042	1.032

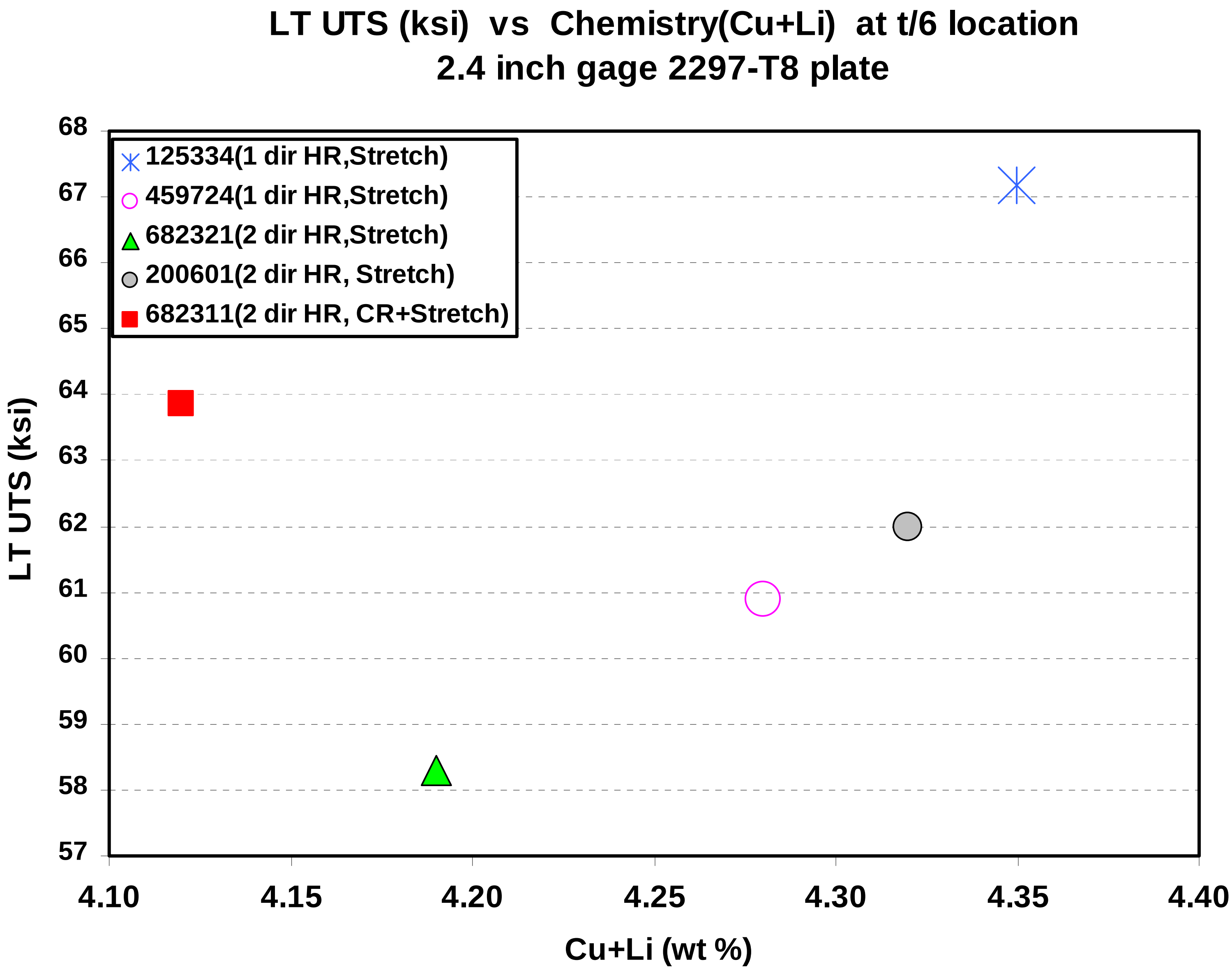
Note: UTS & TYS values are in ksi, and elongation values are in %.

Note: All tensile tests were conducted at t/6 thickness location on flat tensile specimens with 0.125” x 1” gage cross section and 2.0” gage length

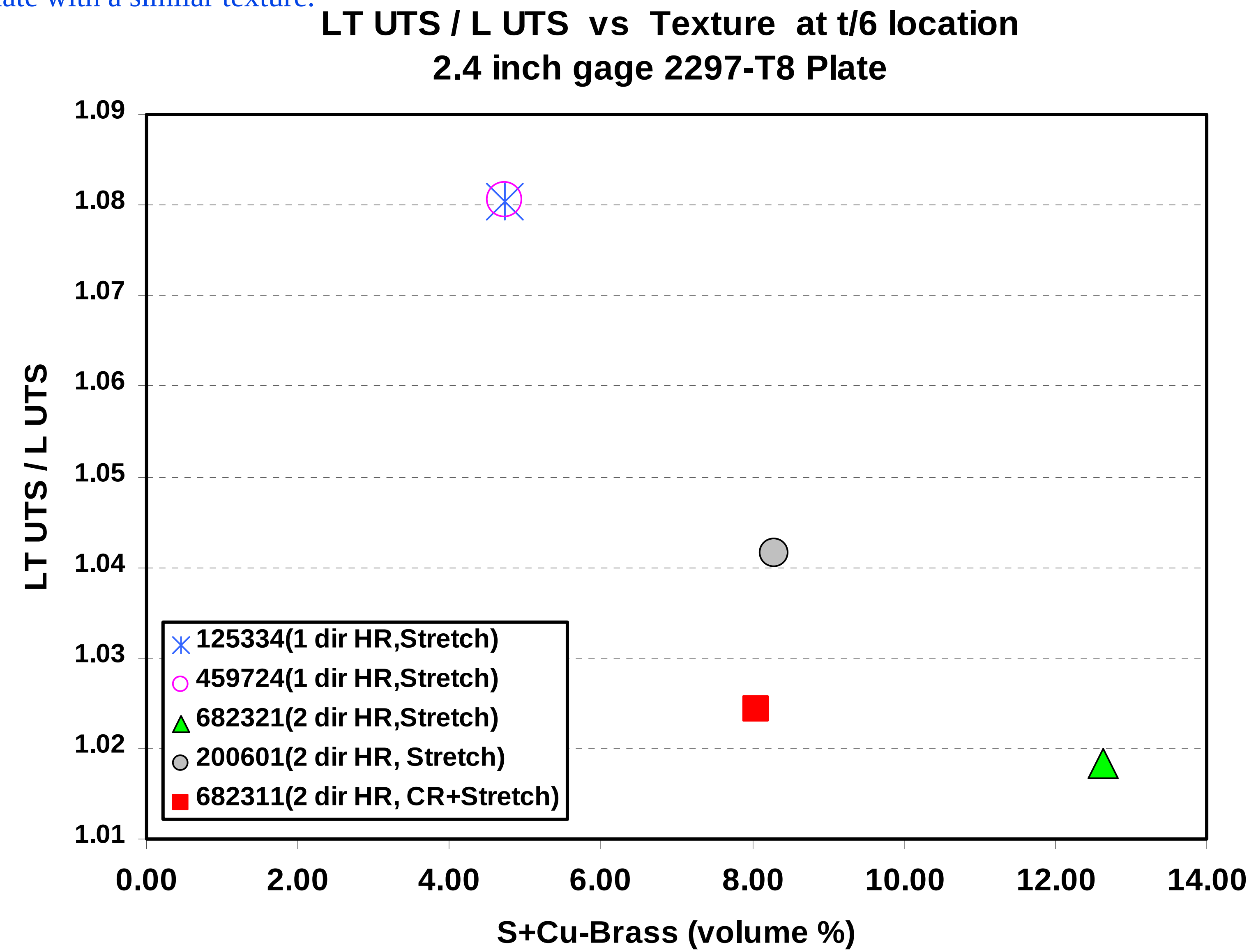
No correlation can be observed between chemistry and L UTS values.



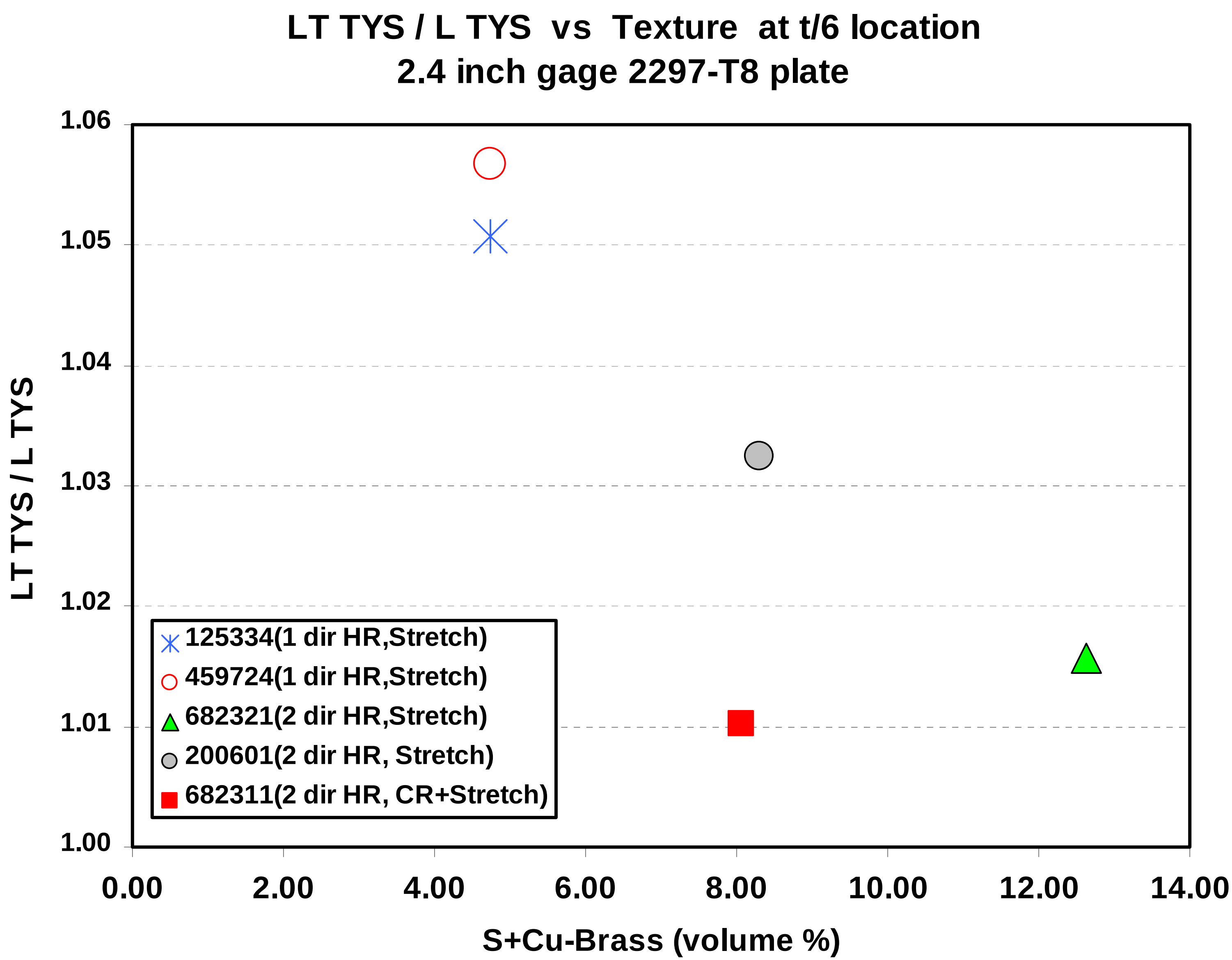
Except lot 682311 (cold rolled & stretched prior to age), LT UTS values appear to correlate with chemistry for the other four plate (stretched only prior to age) regardless of uni–dir. or two-dir. rolling. Previously, it was observed that two-directional rolling appeared to increase L-UTS values at t/6 location and affect little on LT UTS.



The ratio of LT UTS & L UTS shows good correlation with texture combination of S+Cu-Brass components except Lot 682311. It appears that 5.3% of cold rolling reduces degree of strength anisotropy for the the plate with a similar texture.



The ratio of LT TYS & L TYS shows good correlation with texture combination of S+Cu-Brass components except Lot 682311. It appears that 5.3% of Cold Rolling reduces degree of strength anisotropy for the plate with similar texture.



Summary on Texture vs. Tensile Properties

1. It appears that L UTS at t/6 location can not be correlated with plate chemistry.

2. Except lot 682311 (cold rolled & stretched prior to age), LT UTS values appear to correlate with chemistry among other four plate (stretched only, prior to age) regardless of uni–dir. or two-dir. rolling. It has been observed on 2195-T8 plate that two-directional rolling appears to increase L UTS values at t/6 location and affect little on LT UTS.

3. The ratio of LT UTS / L UTS and LT TYS/L TYS showed good correlation with texture combination of (S+Cu-Brass) components except Lot 682311. It appears that 5.3% of Cold Rolling reduces degree of strength anisotropy in the plate with similar texture in the plate lot. 682311.

8. Conclusions

a. Two-directionally rolled 2.4” gage 2297-T8 plate shows higher L UTS at t/6 location and higher K1c in T-L & S-L directions at both room temperature and at –320 deg F, compared to the uni-directionally rolled plate.

b. Two-directionally rolled plate shows a unique crystallographic texture, more favorable isotropic behavior and exhibits a smaller difference between L UTS & LT UTS values.

c. Two-directional rolling improves L UTS but does not affect LT UTS. Both LT UTS of uni-directionally & two-directionally rolled plate correlate with chemistry (Cu+Li).

Development of Al-Cu-Mg-Ag Alloy Plate

Alex Cho

Pechiney Rolled Products
Ravenswood WV

NASA Contract No. NNL04AB64T
with AS&M Inc.

Contents

I. BACKGROUND

Damage Tolerance Capability of 2xxx alloys

When 2xxx alloys are strengthened by artificial aging to –T6 or –T8 type temper for higher strengths, their damage tolerance capabilities are compromised as a result of weakened grain boundaries caused by grain boundary precipitation and PFZ's

2xxx –T3xx type temper for DT applications

By applying high levels of cold work (cold roll and/or cold stretch),

W temper (i.e. as-heat- treated-and-quenched) results in T3xx type temper, having higher strength as a result of natural aging and strain hardening.

This could achieve the desirable balance of strength and Fracture Toughness

example:

2024-T351, 2524-T351 for Aircraft Fuselage skin sheet

cold work practice; 2-4% stretch

2324-T39 for Aircraft Lower Wing skin plate

cold work practice; 10% cold roll + 2% stretch

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.
- 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

Age Hardening characteristics of 2xxx Alloys in High Strength Temper

alloy system	example alloys	strengthening phase	nucleation mode	required cold work?
Al-Cu;	2219, 2519	θ'(Al2Cu)	heterogeneous	yes
Al-Cu-Mg,	2024, 2014	S' (Al2CuMg)	heterogeneous	yes
Al-Cu-Mg-Ag	2139, 2039	Ω (Al2Cu)	homogeneous	no

Homogeneous nucleation mechanism of Ω phase **would allow more uniform distribution of precipitates without relying on dislocations, sub-grain and grain boundaries as nucleation sites. Therefore, Al-Cu-Mg-Ag alloy would be less prone to inter-granular and inter-sub-granular fracture after artificial age**

Homogeneous nucleation mechanism of Ω phase **would allow Al-Cu-Mg-Ag based alloys to achieve high strength without high level of cold work prior to artificial age.**

III. Evaluation of Al-Cu-Mg-Ag alloy plate product

-Two ingots were cast to evaluate Al-Cu-Mg-Ag based alloy

-To examine the effect of dispersoid forming elements, the following two chemistries were selected.

- Plate products were evaluated at two different gages

Chemistry of two Al-Cu-Mg-Ag based alloy ingots:

	Cu	Mg	Ag	Mn	Zr	Ti
Alloy A (Mn)	4.90	0.46	0.38	0.32	0.002	0.09
Alloy B (Zr)	4.81	0.45	0.39	0.01	0.14	0.02

Each ingot was hot rolled to two different gage plates for evaluation

1) 0.28 inch gage

2) 1.0 inch gage

Mechanical Properties of 0.28 inch gage plate product

Tensile Properties of 0.28 inch gage plate in T8 temper

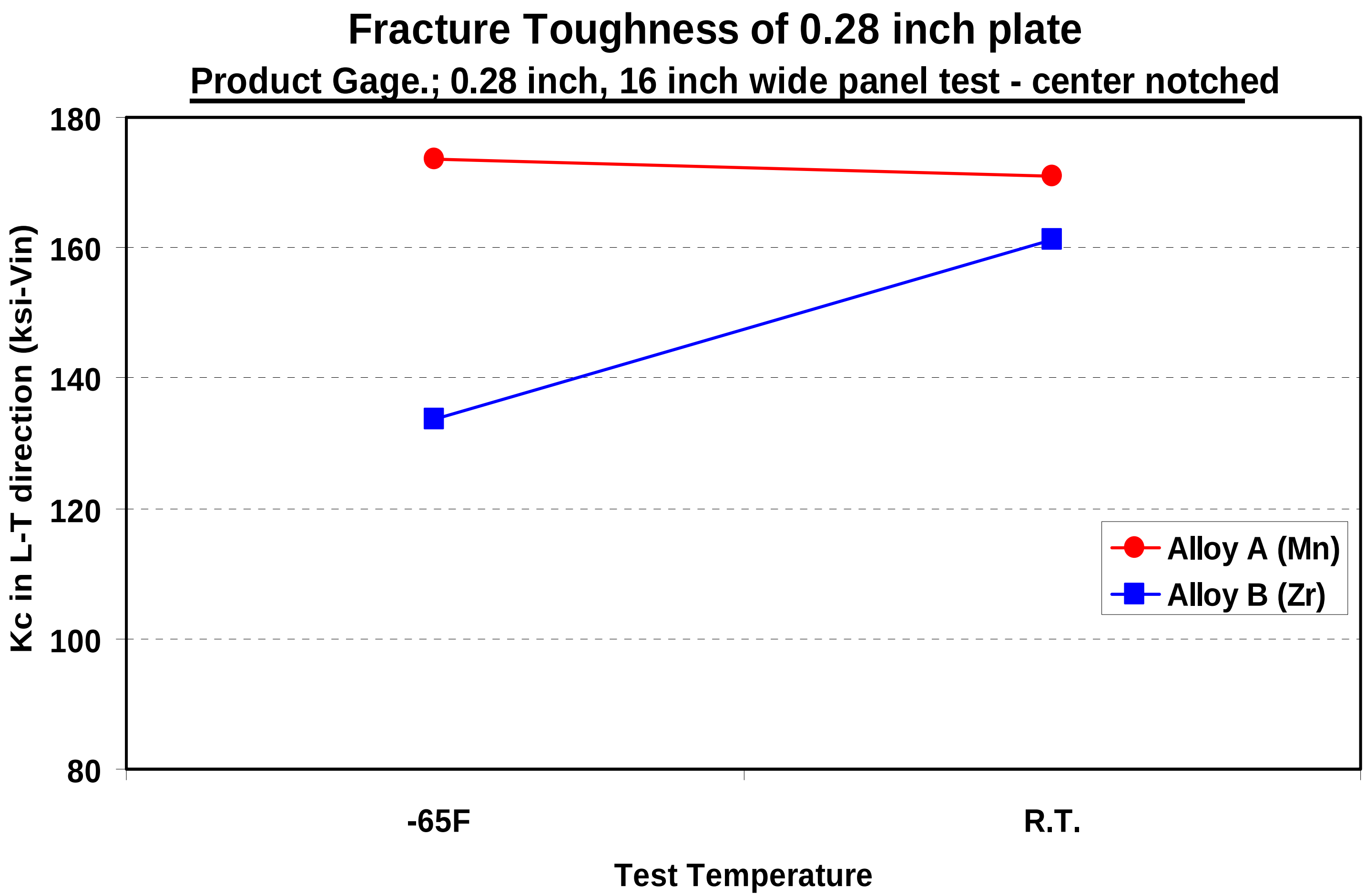
Lot number	Gage (in)	Direction	UTS (ksi)	TYS (ksi)	Elong (%)	Average UTS (ksi)	Average TYS (ksi)	Average Elong (%)
Alloy A	0.277	L	72	67.5	13.3	71.9	67.2	13.3
	0.277	L	71.7	66.8	13.3			
	0.279	LT	71.8	65.1	12.6	72.9	66.1	12.7
	0.271	LT	74	67	12.8			
	0.272	L-45-LT	73.4	65.5	13.5	73.5	66.1	13.6
	0.271	L-45-LT	73.6	66.6	13.6			
Alloy B	0.262	L	72.2	66.9	12.1	72.2	66.8	12.0
	0.262	L	72.1	66.7	11.9			
	0.263	LT	72.3	65.3	11.3	72.3	65.4	11.1
	0.262	LT	72.2	65.4	10.9			
	0.263	L-45-LT	71.8	64.6	12.2	71.6	64.3	11.9
	0.263	L-45-LT	71.4	63.9	11.6			

Evaluation of Al-Cu-Mg-Ag alloy plate product

Plane Stress Fracture Toughness of 0.28” gage Al-Cu-Mg-Ag alloy plate :

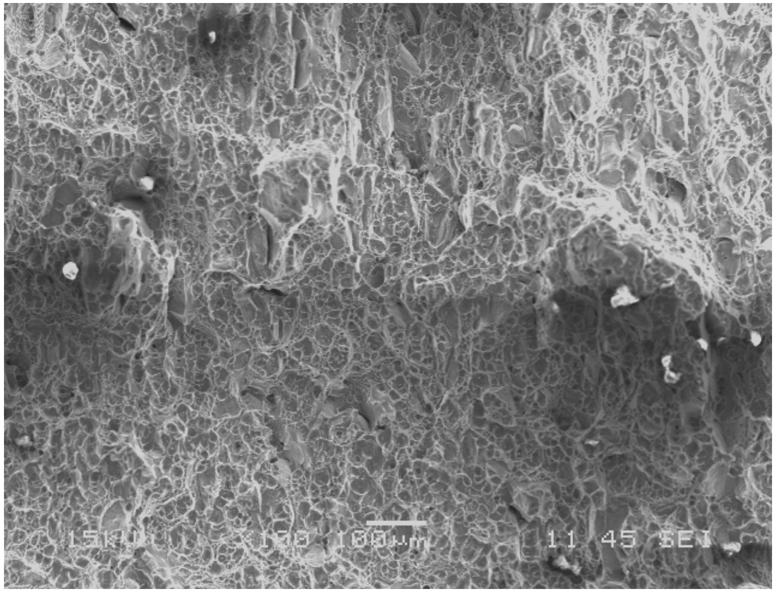
Lot Number	direction	Temp(deg F)	Kc (ksi-in $^{1/2}$)	Kapp(ksi-in $^{1/2}$)	Validity
Alloy A	L-T	+75	171	118.8	Invalid
Alloy B	L-T	+75	161.3	109.9	Invalid
Alloy A	L-T	-65	173.6	116	Invalid
Alloy B	L-T	-65	133.7	94.5	Valid

Difference in Fracture Toughness between alloy A(w/Mn) and alloy B(w/Zr) becomes larger at –65 deg F than that at room temperature



SEM Fractography after fracture tests at –65 deg F

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



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

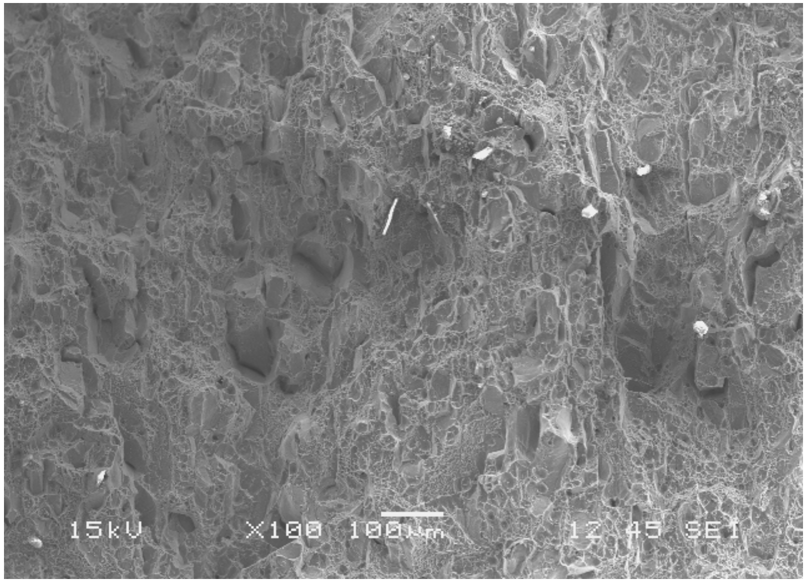


Figure 1. Fractography of A sample tested at -65°F (showing ductile fracture mode)

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

Mechanical Properties of 1.00 inch gage Al-Cu-Mg-Ag alloy plate

Tensile Properties of 1.0 inch gage plate

Room Temp. Tensile Properties of 1 in. gage plate

Lot number	Test dir.	test location	UTS KSI	0.2% YS KSI	Elong %	Plastic Elong. at Failure(%)
831571	L	t/2	71.9	68.3	16	14.6
831571	L	t/2	72.2	68.5	16	14.5
831571	LT	t/2	73.2	66.9	15	13.5
831571	LT	t/2	72.5	65.6	15	14.1
831581	L	t/2	70.1	66.1	15	14
831581	L	t/2	70.4	66.4	15	13.2
831581	LT	t/2	71.6	65.1	14	12.3
831581	LT	t/2	71.7	65	13	11.8

Note: Lot no.831571 is from Alloy A, Lot No.831581 is from Alloy B

Mechanical Properties of 1.00 in gage plate product

Fracture Toughness of 1.0 inch gage plate

Plane Strain Fracture Toughness of 1" plate

Lot number	Test dir.	test location	Temp.	K1c KSI-Vin.	Kq KSI-Vin.	Validity
831571	L-T	t/2	Room		51.1	Invalid
831571	T-L	t/2	Room		46.4	Invalid
831581	L-T	t/2	Room		44.6	Invalid
831581	T-L	t/2	Room		40.5	Invalid

CT specimen; B=1.0", W=3.0

Plane Stress Fracture Toughness of 1" plate

Lot number	Test dir.	test location	Temp. deg F	Kc KSI-Vin.	Kapp KSI-Vin.	Validity
831571*	L-T	t/2	+75	180.3	125.2	Invalid
831581*	L-T	t/2	+75	171.5	116.2	Invalid
831571**	L-T	t/2	-65	225.4	155.1	Invalid

*CCT(MT), precracked, B=0.25",W=16", ** B=0.25", W=30"

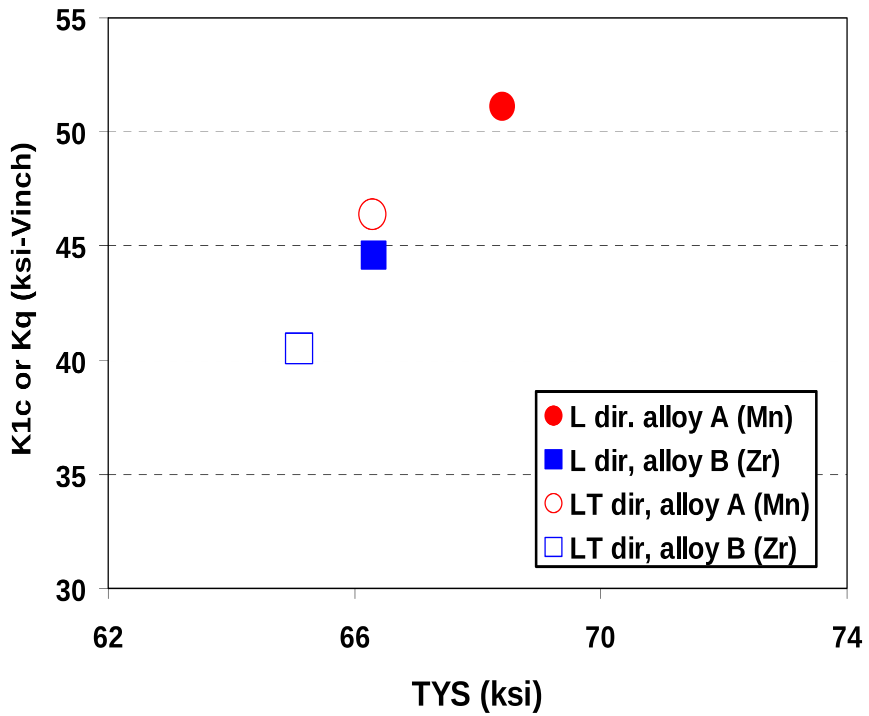
Note: Lot No.831571 is from Alloy A, Lot No.831581 is from Alloy B

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

1 inch gage Al-Cu-Mg-Ag alloy plate in T8 temper

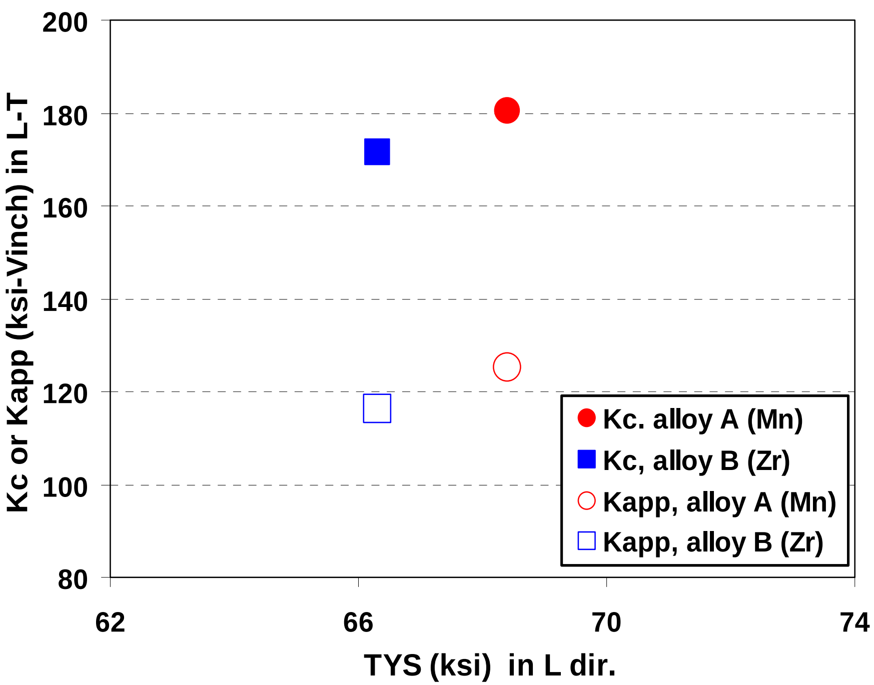
Effect of Dispersoid ; Mn vs. Zr

CT specimen B=1 in. W=3 in.



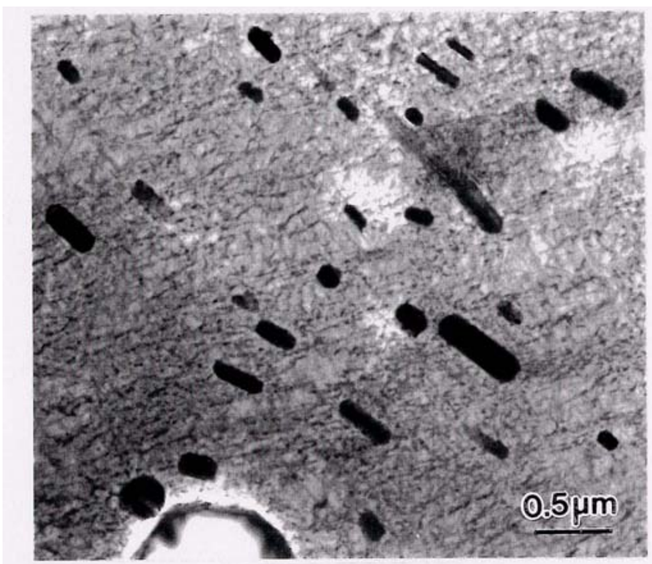
Effect of Dispersoid ; Mn vs. Zr

, M(T) specimen B=0.25 in. W=16 in.

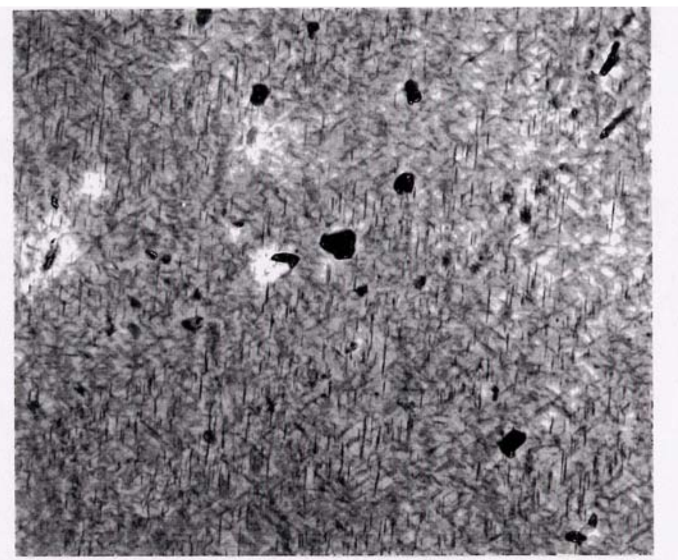


Large particles of Mn containing dispersoids in Al-Cu-Mg-Ag-Mn alloy

Particle Morphology (TEM) in Alloy A and Alloy B

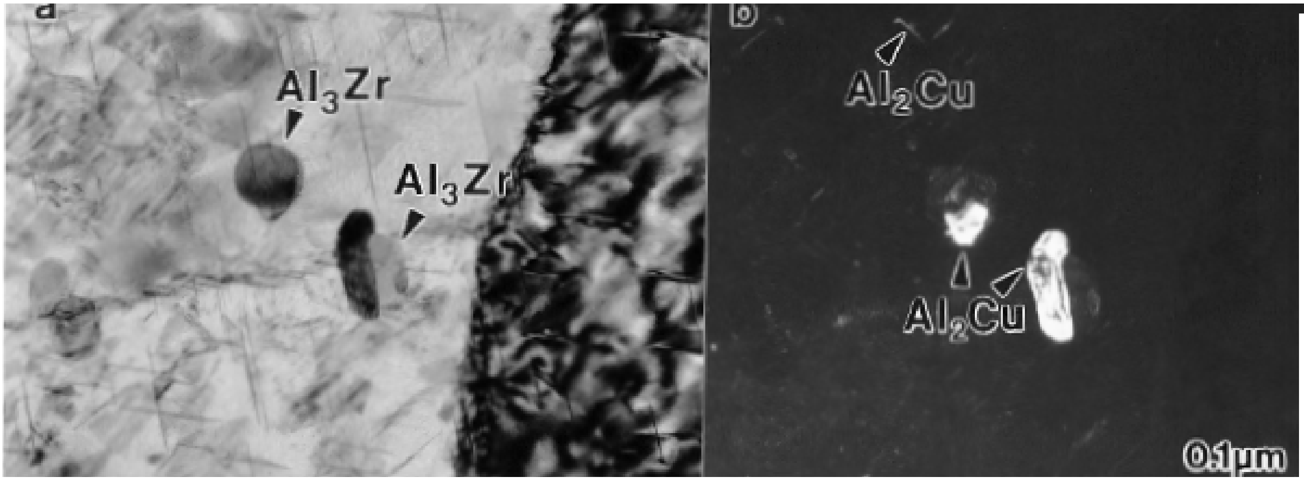


Al-Cu-Mg-Ag-Mn alloy



Al-Cu-Mg-Ag-Zr alloy

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



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

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

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

Fatigue Resistance of Al-Cu-Mg-Ag alloys and 2324-T39 Plate

Notch Fatigue Tests on 1 inch gage Plate

Notched Fatigue Tests on 1.0 in. gage Al-Cu-Mg-Ag-Mn (Alloy A & B) Plate in T8

L -dir. at t/2 Max. Stress; 39 ksi, R-Ratio; 0.1 Freq.; 15 Hz Lot No. 831571

Alloy A(Lot No.831571)		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	1,500,000	Discont.
3	1,500,000	Discont.
4	1,500,000	Discont.
5	158,968	Gage Sec.

Avg. 957,492

Alloy B(Lot No.831581)		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	223,747	Gage Sec.
3	1,500,000	Discont.
4	1,500,000	Discont.
5	455,387	Gage Sec.

Avg. 807,760

2324-T39;(Lot 980Y667A)		
S.N.	Cycle to Fail	Fail. Loc.
1	162,653	Notch
2	157,222	Gage Sec.
3	157,360	Gage Sec.
4	164,409	Gage Sec.
5	183,183	Gage Sec.

Avg. 164,701

Fatigue Resistance of Al-Cu-Mg-Ag alloys and 2324-T39 Plate

Double Open Hole Fatigue Tests on 1 inch gage Plate

Double Open Hole Axial Fatigue on 1.0" gage Al-Cu-Mg-Ag-Mn (Alloy A & B)plate in T8

L -dir. at t/2 Max. Stress; 20 ksi, R-Ratio; 0.1 Freq.; 15 Hz Lot No. 831571

Alloy A(Lot No.831571)		
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

Alloy B(Lot .831581)		
S.N.	Cycle to Fail	Fail. Loc.
1	1,500,000	Discont.
2	950,829	A-Hole
3	1,500,000	Discont.
4	278,594	A-Hole
5	1,500,000	Discont.

Avg. 977,844

2324-T39;(Lot 980Y667A)		
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

Corrosion Resistance of 1.0 inch gage 2139-T8 Plate

- **Alloy A(Lot no. 831571); 1.0 inch gage Plate**

  SCC: Passed at 30, 35, and 40 ksi for 20 days
  when tested in ST direction
  per ASTM G47 by ASTM G-38-01

- **Alloy B(Lot no. 831581); 1.0 inch gage plate**

  SCC: Passed at 30, 35, and 40 ksi for 20 days
  when tested in ST direction
  per ASTM G47 by ASTM G-38-01

IV. Conclusions

1. Al-Cu-Mg-Ag based alloys show very high potential for use in aerospace vehicle structures for aircraft, space transportation and space applications.
2. Al-Cu-Mg-Ag based alloys demonstrated excellent combinations of Strength and Fracture Toughness capabilities.
3. Al-Cu-Mg-Ag alloy with Mn-containing dispersoids showed higher fracture toughness and fatigue resistance compared to Zr –containing dispersoids.
4. Al-Cu-Mg-Ag alloys, having excellent Fracture Toughness, SCC Resistance and Fatigue resistance, would be most suitable for DT & D applications.
5. Two ingots of Al-Cu-Mg-Ag-Mn alloy have been cast to explore thicker gage product.

The Effect of Hot Rolling Processes on the Texture and Mechanical Properties of 7050 Plate

Alex Cho

Pechiney Rolled Products

Ravenswood WV

NASA Contract No. NNL04AB64T

With AS&M Inc.

The Effect of Hot Rolling Processes on the Texture and Mechanical Properties of 7050 Plate

Content

I. Objective

II. Background information of 7050-T7451 plate

III. Approach

IV. Examine the effect of hot rolling process and solution heat treatment on texture development and degree of recrystallization at various gages

V. Compare one and two-directionally rolled 7050 Plate at the intermediate gage range on texture development and mechanical properties

VI. Conclusions

I. Objective:

- Investigate the effect of hot rolling on the crystallographic texture and mechanical properties of 7050 plate.
- Evaluate the processing variables afftecting texture and mechanical properties to identify the cause for the low longitudinal ultimate tensile strength (L UTS) values in the intermediate plate gages (3- 4 inches)

II. Background Information on 7050-T7451 Plate

- 7050-T7451 Plate is the most widely used aluminum based alloy for high strength-high fracture toughness-high corrosion resistance application in aircraft structures today.
- Alloy 7050 is a versatile alloy produced in a wide range of thicknesses. 7050-T7451 plate is manufactured in the gage range of 1.5 – 8.5 inch, most commonly at 2.00 – 6.00 inch gage range.
- The recovery rate could be further improved if there was better understanding of the metallurgical manifestation of the product at the intermediate gage range (notably between 2 – 4” gages), and adjust processing accordingly.
- Ultimate tensile strength in longitudinal direction (L UTS) could be improved without detrimentally affecting fracture toughness and corrosion resistance.

III. Approach

Examine the evolution of texture in 7050 plate during hot rolling and identify the variables affecting mechanical properties

- Examine the effect of hot rolling process and solution heat treatment on texture development and degree of recrystallization at various gages
- Compare uni–directional rolling and two-directional rolling of 7050 plate at the intermediate gage range on texture development and mechanical properties.

The Effect of Hot Rolling Processes on the Texture and Mechanical Properties of 7050 Plate

IV: Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

a. Description of sample plate

b. Degree of recrystallization during solution heat treatment

c. Effect of plate thickness location on texture during rolling

d. Tensile properties of plant processed 7050-T7451 plate at t/4 location

e. Summary

IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

a. Description of Sample plate:

- **Six lots of 7050-F temper samples were selected to measure texture in F-temper and W-temper conditions**
- **W-temper samples were solution heat treated using a laboratory furnace to simulate the plant heat treat process**
- **Both F-temper and W-temper texture measurements were conducted at t/4 and t/2 thickness locations**

Sample	Ga.(in)	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
185781	5.157	0.04	0.05	2.09	0.02	2.29	0.00	6.09	0.03	0.09
177341	5.125	0.06	0.09	2.11	0.01	2.09	0.01	6.20	0.04	0.09
196661	3.8	0.05	0.08	2.16	0.01	2.23	0.01	6.35	0.04	0.09
177873	3.1	0.05	0.08	2.14	0.01	2.17	0.01	6.27	0.04	0.09
190921	2.125	0.06	0.08	2.11	0.01	2.18	0.01	6.29	0.03	0.11
209641	1.5	0.04	0.07	2.06	0.00	2.14	0.01	6.31	0.03	0.10

IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

a. Description of Sample plate – results of texture measurement for six lots at t/2 & t/4 locations in F & W temper

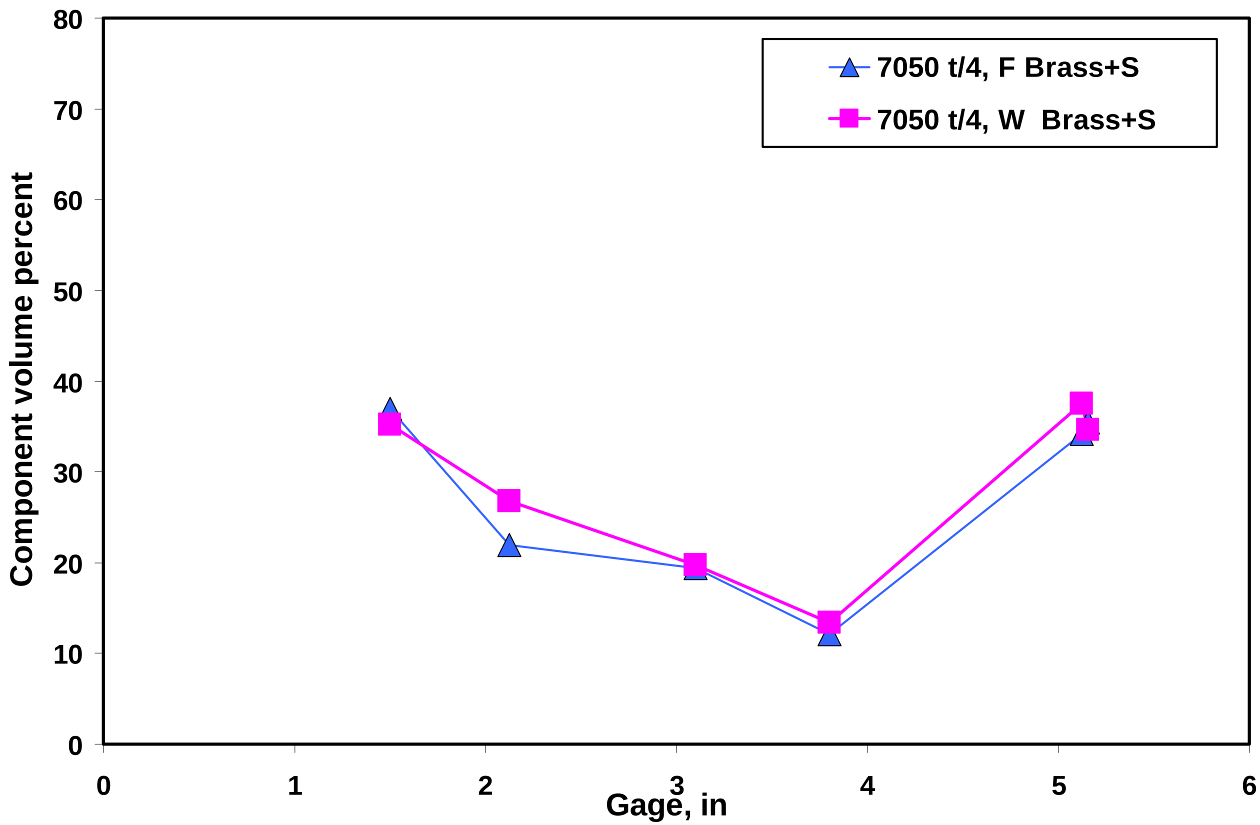
Lot	Alloy	Gage	Temper	Loc.	Cube	R-Cube	Brass	S	Goss	Cu	S+Cu+B	Brass+S	Cube+R-Cube
209641	7050	1.5	F	t/2	4.29	0.99	28.66	35.41	2.27	10.98	75.05	64.07	5.28
190921	7050	2.125	F	t/2	5.16	1.69	27.05	26.68	2.54	8.65	62.38	53.73	6.85
177873	7050	3.1	F	t/2	4.37	1.83	18.74	21.85	4.44	8.75	49.34	40.59	6.2
196661	7050	3.8	F	t/2	3.68	1.19	22.76	28.1	3.43	11.33	62.19	50.86	4.87
177341	7050	5.125	F	t/2	2.74	1.44	14.49	18.36	5.23	9.36	42.21	32.85	4.18
177341	7050	5.125	F	t/2	2.2	1.8	13.4	16.3	5.7	7.3	37	29.7	4
177341	7050	5.125	F	t/2	3.06	1.79	15.84	15.9	5.22	6.39	38.13	31.74	4.85
185781	7050	5.157	F	t/2	4.31	1.33	26	13.93	2.08	2.16	42.09	39.93	5.64
209641	7050	1.5	F	t/4	4.03	3.84	16.61	20.32	2.44	4.03	40.96	36.93	7.87
190921	7050	2.125	F	t/4	5.42	4.61	8.73	13.24	2.94	4.88	26.85	21.97	10.03
177873	7050	3.1	F	t/4	4.91	5.29	8.6	10.81	3.39	3.83	23.24	19.41	10.2
196661	7050	3.8	F	t/4	4.71	7.13	5	7.16	3.16	3.06	15.22	12.16	11.84
177341	7050	5.125	F	t/4	3.37	1.67	15.36	18.86	4.02	8.66	42.88	34.22	5.04
185781	7050	5.157	F	t/4	4.72	1.75	15.88	19.54	4.37	8.26	43.68	35.42	6.47
209641	7050	1.5	W -lab	t/2	3.74	0.79	35.66	38.38	2.27	9.37	83.41	74.04	4.53
190921	7050	2.125	W -lab	t/2	3.27	1.4	25.87	29.56	3.05	11.11	66.54	55.43	4.67
177873	7050	3.1	W -lab	t/2	3.31	1.6	19.97	25.46	3.32	10.17	55.6	45.43	4.91
196661	7050	3.8	W -lab	t/2	3.63	0.9	22.09	29.43	3.54	10.78	62.3	51.52	4.53
177341	7050	5.125	W -lab	t/2	2.53	1.49	15.56	19.41	4.23	7.5	42.47	34.97	4.02
185781	7050	5.157	W -lab	t/2	5.26	0.94	27.51	15.18	1.99	1.91	44.6	42.69	6.2
209641 (1.5")	7050	1.5	W -lab	t/4	4.92	4.52	14.47	20.76	2.6	6.89	42.12	35.23	9.44
190921 (2.125")	7050	2.125	W -lab	t/4	5.85	5.05	11.21	15.62	2.91	6.66	33.49	26.83	10.9
177873 (3.1")	7050	3.1	W -lab	t/4	5.49	5.85	9	10.74	3.24	4.17	23.91	19.74	11.34
196661 (3.8")	7050	3.8	W -lab	t/4	4.63	7.95	5.93	7.46	2.72	3.42	16.81	13.39	12.58
177341 (5.125")	7050	5.125	W -lab	t/4	3.09	1.55	15.57	21.93	2.77	9.82	47.32	37.5	4.64
185781 (5.25")	7050	5.157	W -lab	t/4	4.52	1.54	17.5	17.13	4.07	6.72	41.35	34.63	6.06

IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

b. Degree of recrystallization during Solution Heat treatment (SHT)

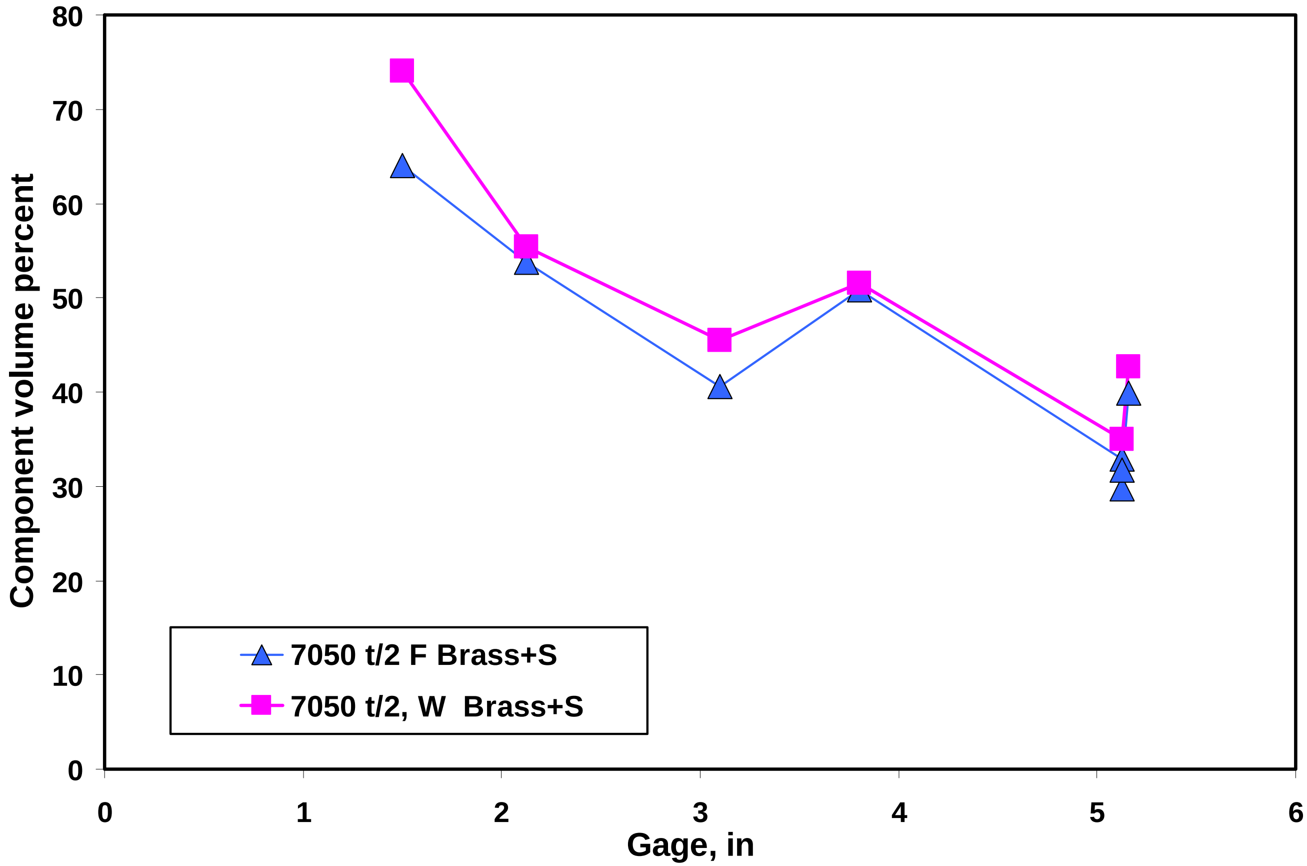
Deformation Texture at t/4 location in 7050-F & 7050-W plate

- Unchanged deformation texture indicates that no recrystallization occurred during SHT



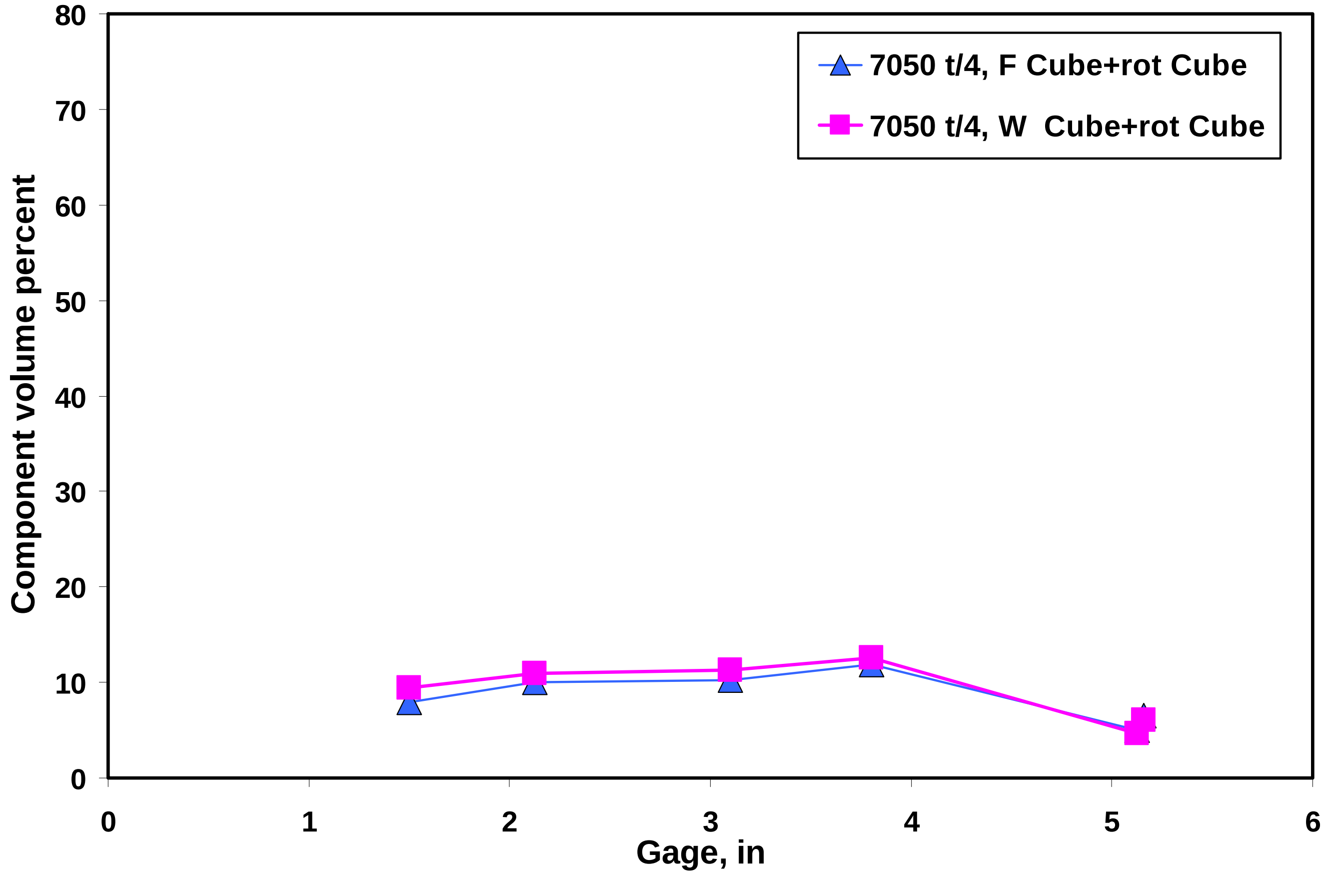
Deformation Texture at t/2 location in 7050-F & 7050-W plate

- Unchanged deformation texture indicates that no recrystallization occurred during SHT



Recrystallization Texture at t/4 location in 7050-F & 7050-W plate -

Unchanged texture indicates that no recrystallization occurred during SHT

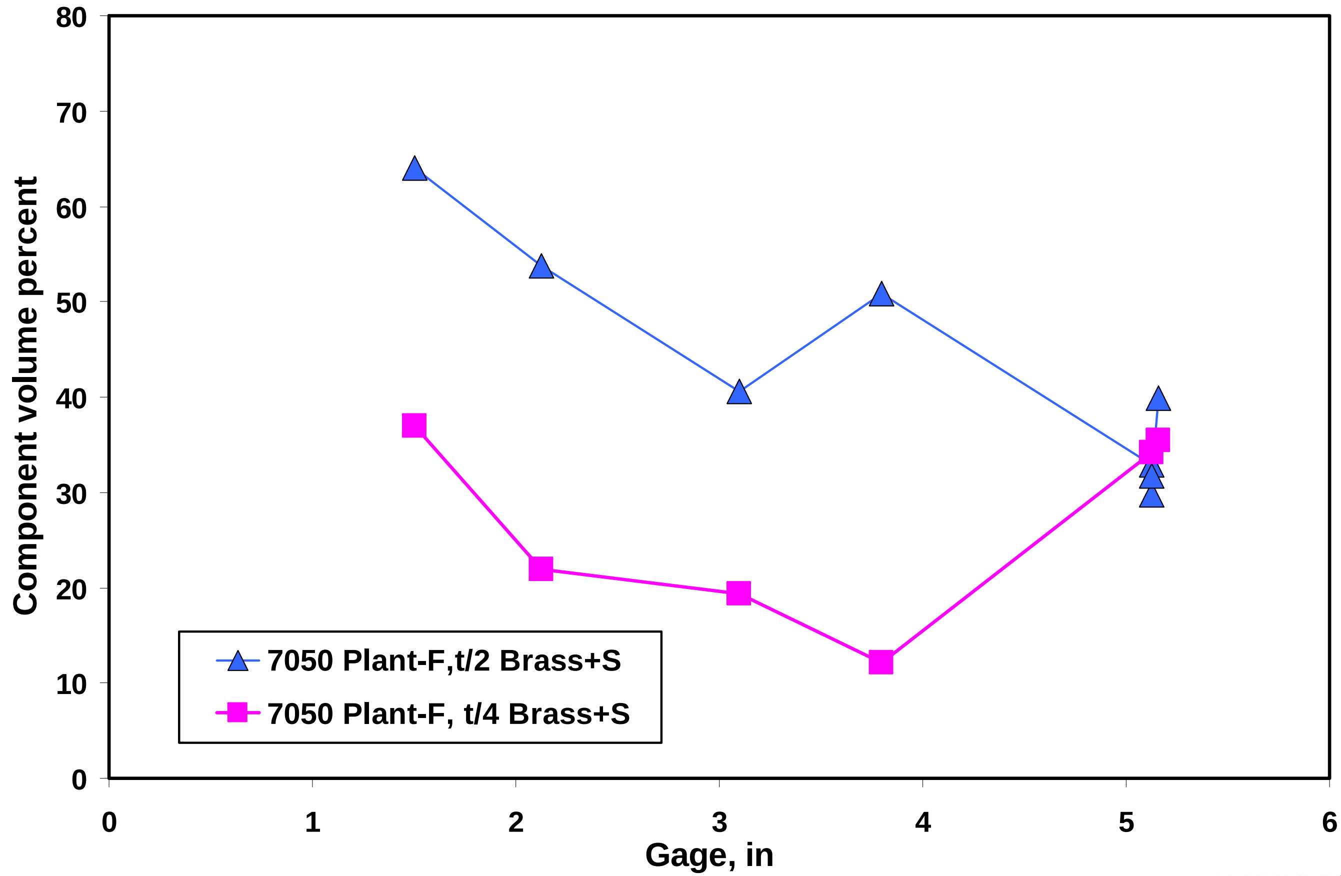


IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

c. Effect of plate thickness location on texture evolution during rolling

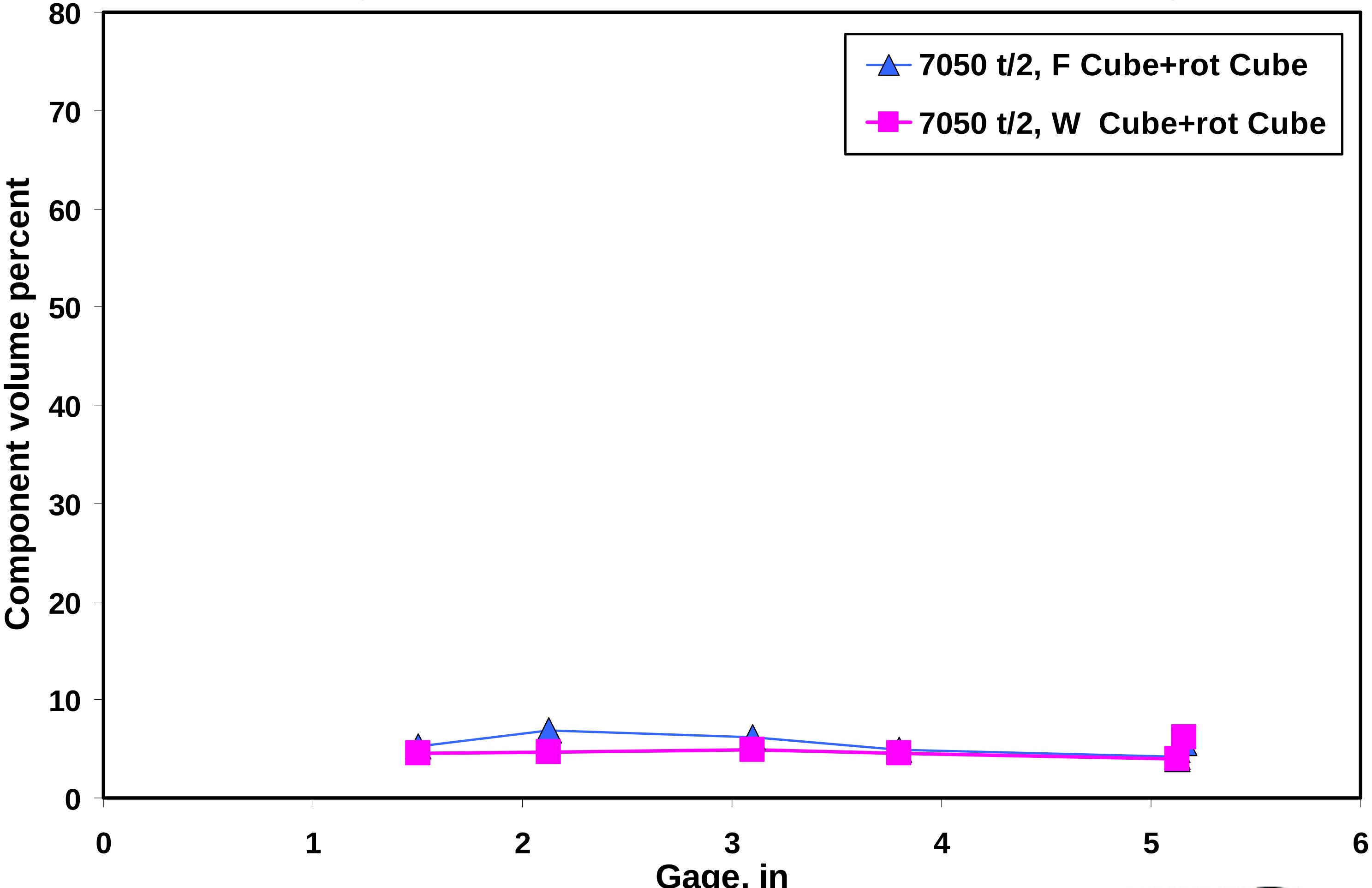
Deformation Texture at t/2 & t/4 in Various Gages of 7050-F Plate

–As gage decreases, deformation texture at t/4 decreases, then increases again . Much higher deformation texture at t/2 than at t/4



Recrystallization Texture at t/2 Location in 7050-F & 7050-W plate

-no change in recrystallization texture components during SHT

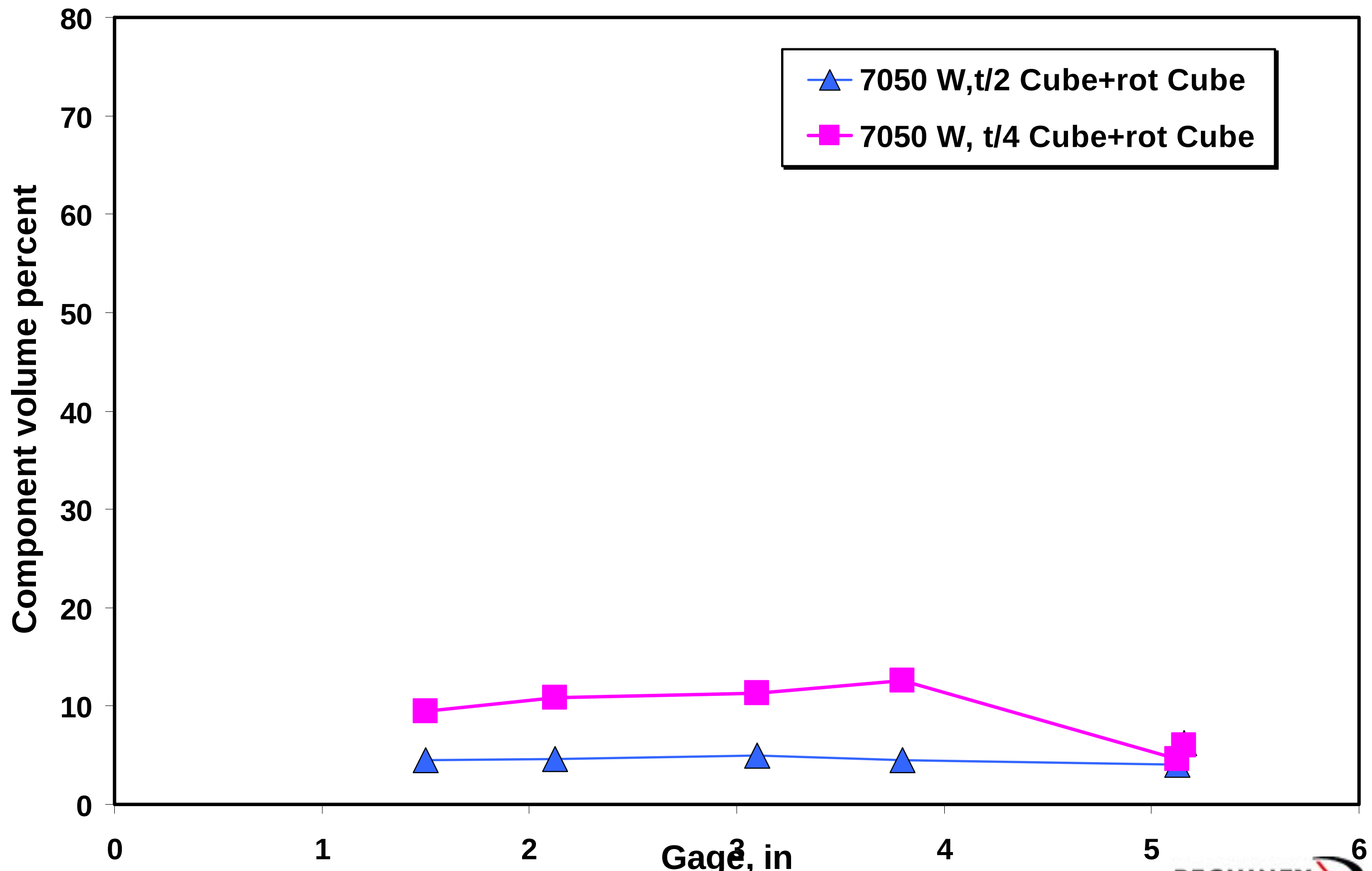


IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

c. Effect of plate thickness location on texture evolution during rolling

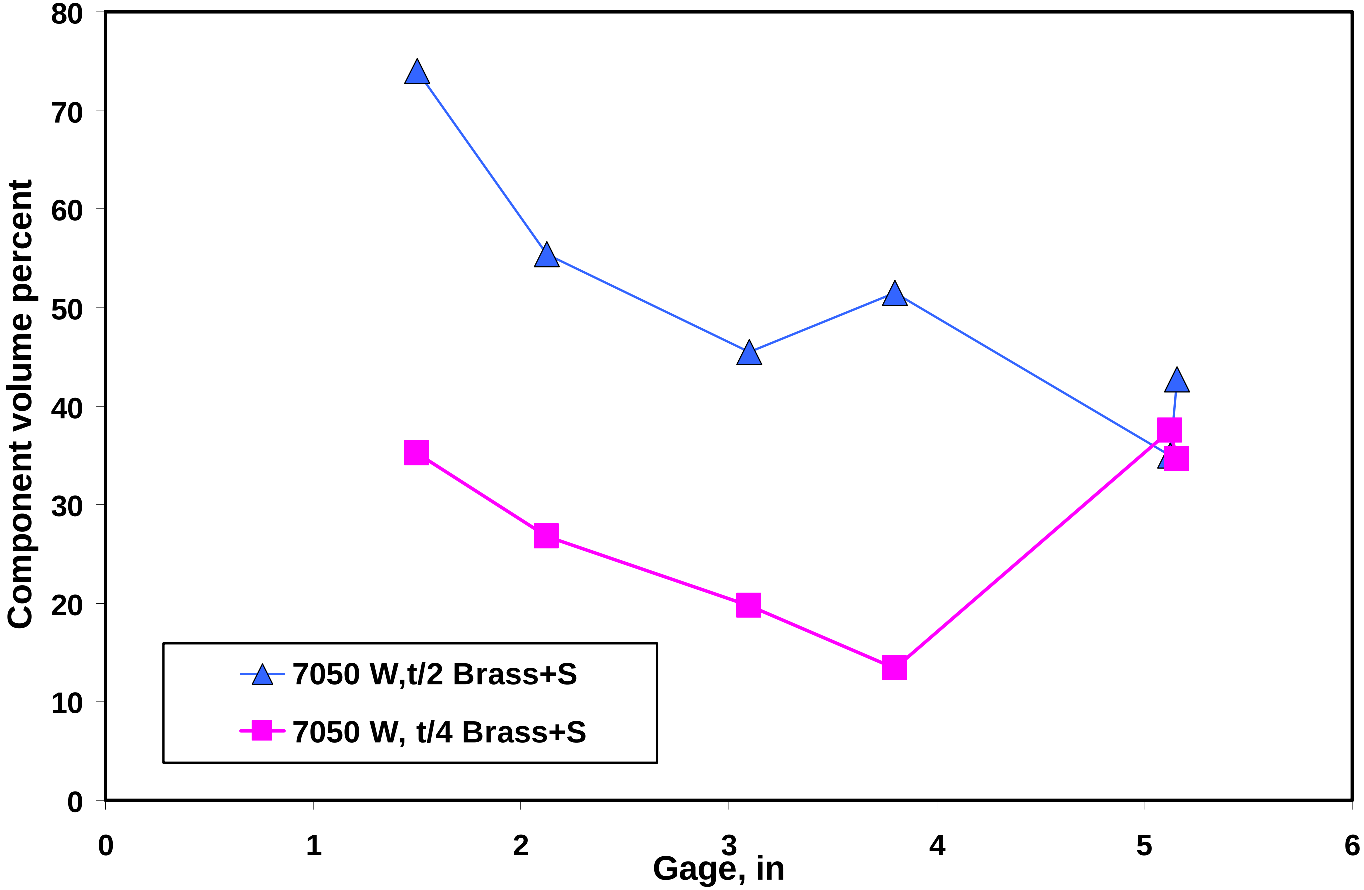
Recrystallization Texture in 7050-F Temper Plate at Various Gages

- Slightly higher vol% of recrystallization texture at t/4 than at t/2



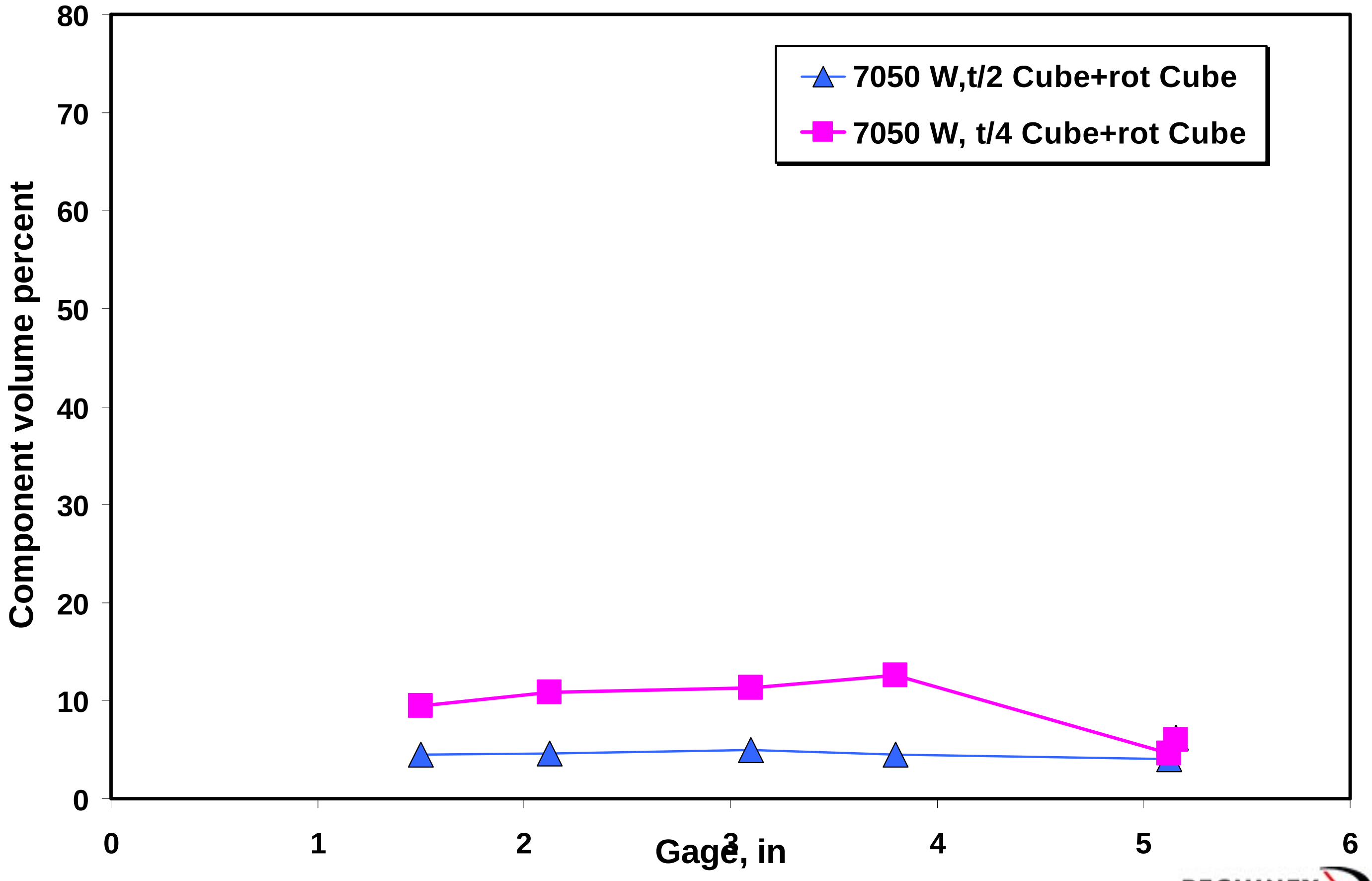
Deformation Texture at t/2 & t/4 in various gage 7050-W plate

–As gage decreases, deformation texture at t/4 decreases, then increases again .
Much higher deformation texture at t/2 than at t/4



Recrystallization Texture at t/2 & t/4 in various gage 7050-W plate

- Slightly higher vol% of recrystallization texture at t/4 than at t/2



IV. Examine the effect of hot rolling on the texture and degree of recrystallization on 7050 plate for various gages

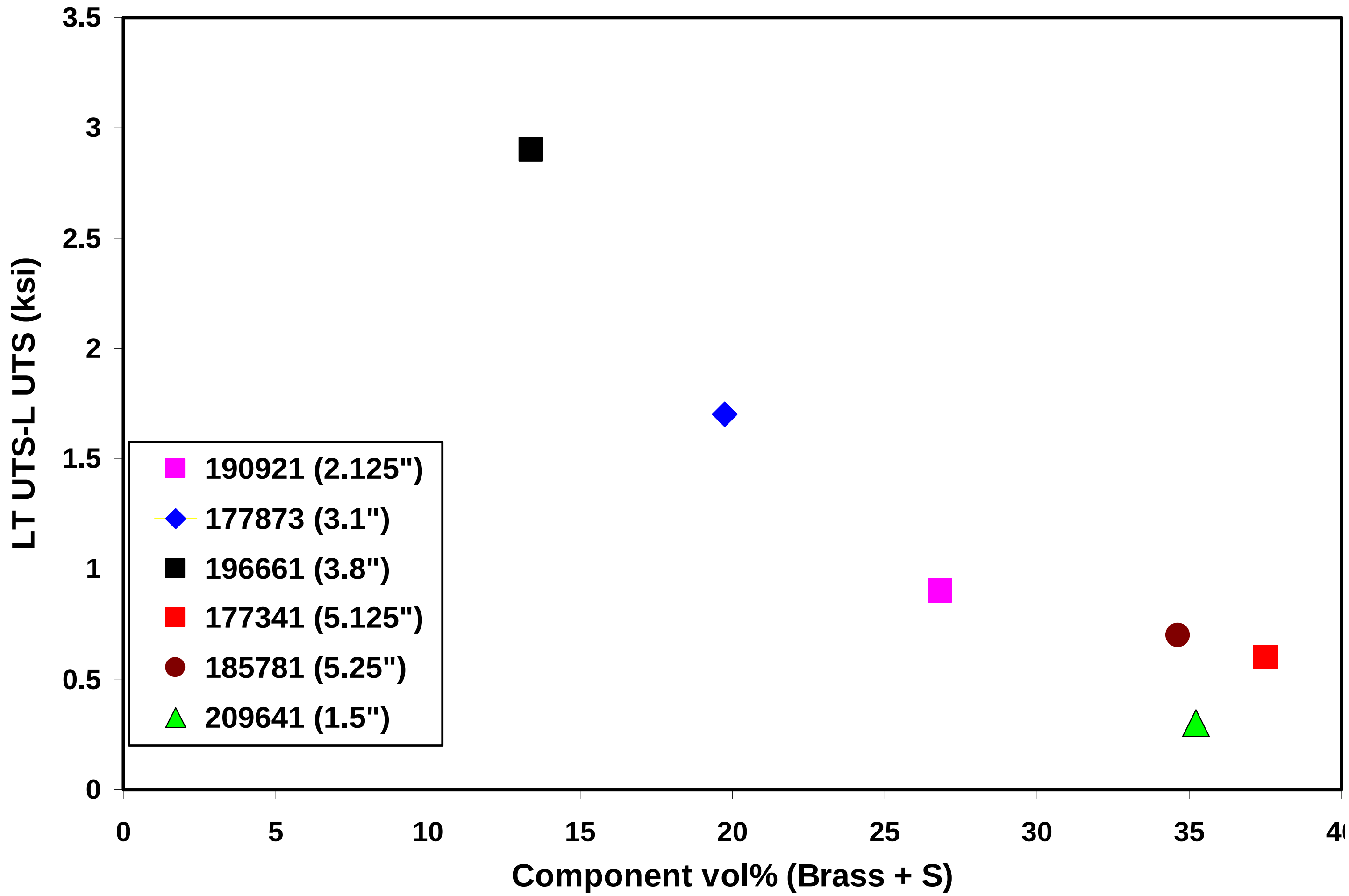
d. Tensile properties of plant processed 7050-T7451 plate at t/4 location

Plates at 3.0 - 3.5 inch gages show more strength anisotropy than other gages.

Lot	Gage	L UTS	L TYS	el	LT UTS	LT TYS	el	UTS (LT/L)	TYS(LT/L)	UTS(LT-L)	TYS(LT-L)
	INCH	KSI	KSI	%	KSI	KSI	%			KSI	KSI
209641	1.5	75	64.1	15	75.3	65.7	12.7	1.004	1.024961	0.3	1.6
190921	2.125	76.4	68.4	15	77.3	68.3	12.1	1.0117801	0.998538	0.9	-0.1
177873	3.1	76.6	70.3	14.7	78.3	71.2	11.1	1.0221932	1.0128023	1.7	0.9
196661	3.8	76.5	71.1	13	79.4	71.6	9.7	1.0379085	1.0070323	2.9	0.5
177341	5.125	74.7	67.3	11.5	75.3	66.2	9.1	1.0080321	0.9836553	0.6	-1.1
185781	5.157	74.6	67.5	10.1	75.3	67.5	9	1.0093834	1	0.7	0

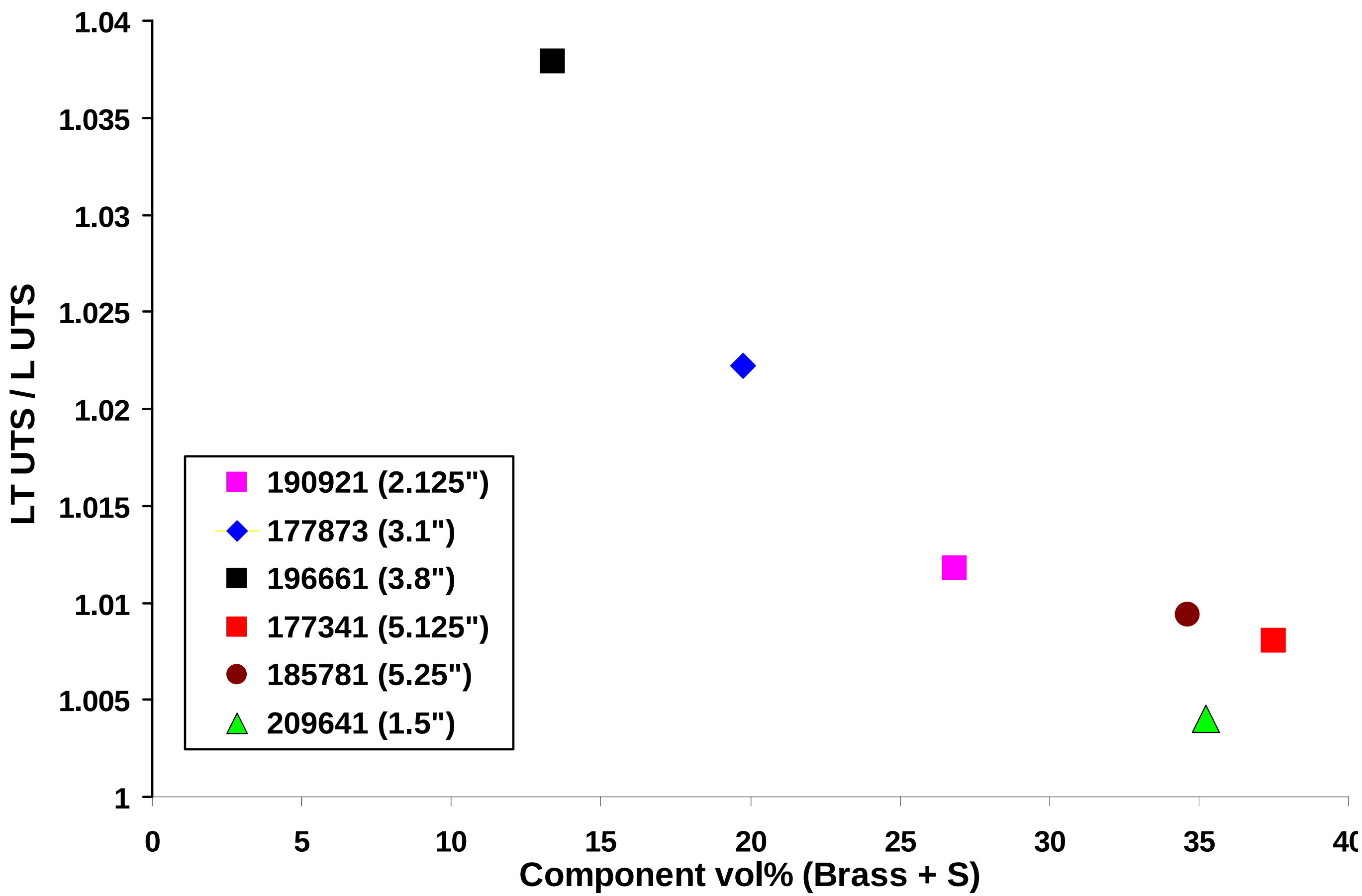
The difference between LT UTS and L UTS decreases as the deformation texture components (Brass + S) increase

Deformation Texture (Brass+S) vol% vs. (LT UTS - L UTS) at t/4



The ratio of LT UTS/L UTS decreases as the volume % of deformation texture components (Brass & S) increases

Deformation Texture (Brass+S) vol% vs. (LT UTS / L UTS) at t/4



IV. Examine the effect of hot rolling on the texture and degree of recrystallization , on 7050 plate for various gages

e. Summary

- Degree of recrystallization after solution heat treatment is minimal. W-temper plate is essentially unrecrystallized at t/4 thickness location for the plate samples examined.
- As the hot rolled gage decreases from 5-6 inch range to 3 – 4 inch range, volume % of deformation texture decreases at t/4 location
- As the hot rolled gage decreases from 3 inch range to 1.8 - 2 inch range, volume % of deformation texture increases at t/4 location
- Ratio of L UTS to LT UTS correlates with volume % of deformation texture

The Effect of Hot Rolling Processes on the Texture and Mechanical Properties of 7050 Plate

V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

a. Description of sample plate

b. Crystallographic texture at t/4 location from 7050-T7451 plate

c. Correlation of plate gage, crystallographic texture and tensile properties of uni- and two-directionally rolled plate

d. Summary

V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

a. Description of Sample Plate

Chemistry of uni –directionally rolled plate samples

Lot No.	Gage inch	Width inch	Si (%)	Fe (%)	Cu (%)	Mg (%)	Zn(%)	Ti (%)	Zr (%)	Cu+Mg+Zn (%)
196661	3.8	48	0.05	0.08	2.16	2.23	6.35	0.04	0.09	10.74
836681	3.75	48	0.07	0.10	2.10	2.07	6.24	0.03	0.08	10.41
368262	3.5	48	0.03	0.06	2.10	2.23	6.33	0.03	0.09	10.66
401261	3.5	48	0.04	0.08	2.30	2.10	6.19	0.03	0.09	10.59
371441	3.5	48	0.06	0.08	2.12	2.12	6.19	0.04	0.09	10.43
177873	3.1	48	0.05	0.08	2.14	2.17	6.27	0.04	0.09	10.58
375922	3	48	0.03	0.07	2.30	2.13	6.44	0.03	0.09	10.87
190921	2.125	48	0.06	0.08	2.11	2.18	6.29	0.03	0.11	10.58

Chemistry of two-directionally rolled plate samples

Lot No.	Gage inch	Width inch	Si (%)	Fe (%)	Cu (%)	Mg (%)	Zn(%)	Ti (%)	Zr (%)	Cu+Mg+Zn (%)
383001	3.5	96	0.03	0.07	2.19	2.21	6.25	0.03	0.09	10.65
383002	3.5	96	0.03	0.07	2.19	2.21	6.25	0.03	0.09	10.65
383231	2	72	0.05	0.08	2.22	2.07	6.37	0.03	0.09	10.66

V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

a. Description of Sample Plate

Tensile properties of uni –directionally rolled plate samples

Lot No.	Gage inch	Width inch	L UTS, ksi	L TYS, ksi	L E, %	LT UTS, ksi	LT TYS, ksi	LT el, %	LT UTS / L UTS	LT TYS / L TYS
196661	3.8	48	76.5	71.1	13	79.4	71.6	9.7	1.038	1.007
836681	3.75	48	73.6	67.1	15	75.9	67.3	11	1.031	1.003
368262	3.5	48	76	68.9	14.5	78.3	69.6	11.5	1.030	1.010
401261	3.5	48	74.1	67.3	15.5	76.9	68	11.5	1.038	1.010
371441	3.5	48	74	66.8	15.5	76.1	66.8	11.5	1.028	1.000
177873	3.1	48	76.6	70.3	14.7	78.3	71.2	11.1	1.022	1.013
375922	3	48	77.5	71.1	13.5	79.4	71.1	11	1.025	1.000
190921	2.125	48	76.4	68.4	15	77.3	68.3	12.1	1.012	0.999

Tensile properties of two-directionally rolled plate samples

Lot No.	Gage inch	Width inch	L UTS, ksi	L TYS, ksi	L E, %	LTUTS ksi	LT TYS, ksi	LT el, %	LT UTS / L UTS	LT TYS / L TYS
383001	3.5	96	74.4	67.4	14	77.1	69.2	8.5	1.036	1.027
383002	3.5	96	76.2	69.7	12	79.5	71.2	10.5	1.043	1.022
383231	2	72	77.7	69.9	13	78.9	70.2	12	1.015	1.004

V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

a. Description of Sample Plate

Crystallographic texture of uni –directionally rolled plate

Lot No.	Gage inch	Width inch	Cube (vol%)	Goss (vol%)	Brass (vol%)	S (vol%)	Cu (%)	R-Cube (vol%)	Brass+S (vol%)	S+Cu+Br (vol%)
196661	3.8	48	4.63	2.72	5.93	7.46	3.42	7.95	13.39	16.81
836681	3.75	48	4.66	1.87	3.96	8.03	3.83	7.87	11.99	15.82
368262	3.5	48	4.43	2.38	4.5	8.67	3.79	6.23	13.17	16.96
401261	3.5	48	5.34	2.31	5.99	10.26	4.76	5.14	16.25	21.01
371441	3.5	48	4.52	2.45	5.28	10.43	4.73	6.57	15.71	20.44
177873	3.1	48	5.49	3.24	9	10.74	4.17	5.85	19.74	23.91
375922	3	48	4.15	3.1	7.5	12.47	5.3	4.9	19.97	25.27
190921	2.125	48	5.85	2.91	11.21	15.62	6.66	5.05	26.83	33.49

Crystallographic texture of two-directionally rolled plate samples

Lot No.	Gage inch	Width inch	Cube (vol%)	Goss (vol%)	Brass (vol%)	S (vol%)	Cu (%)	R-Cube (vol%)	Brass+S (vol%)	S+Cu+Br (vol%)
383001	3.5	96	4.21	2.43	3.5	8.25	5.33	10.34	11.75	17.08
383002	3.5	96	4.87	2.59	4.12	9.8	5.97	6.52	13.92	19.89
383231	2	72	4.69	2.81	9.23	13.35	5.91	4.7	22.58	28.49

V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

a. Description of Sample Plate

Hot rolling reduction ratio of L vs. LT direction in uni –directionally rolled plate

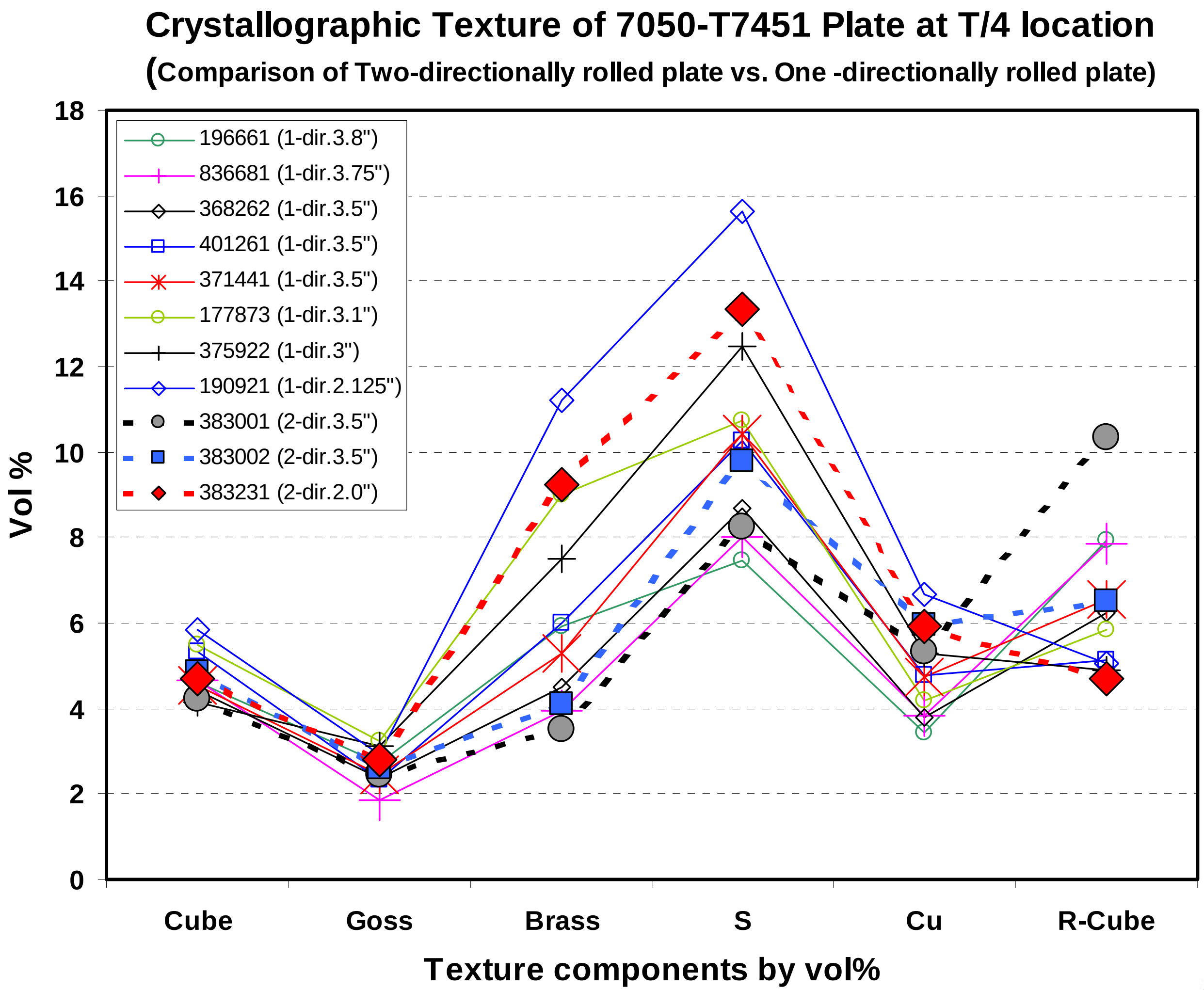
Lot No.	Ingot thickness (inch)	Ingot Width (inch)	Ingot Length (inch)	Plate Gage (inch)	Plate Width (inch)	Plate Length (inch)	Redution Ratio L vs. LT
196661	14.4	55	189	3.79	55	729	3.86 vs. 1
836681	14.6	56	190	3.85	56	729	3.84 vs. 1
368262	14.4	56	160	3.59	56	650	4.06 vs. 1
401261	14.4	56	180	3.58	56	732	4.07 vs. 1
371441	14.4	56	190	3.58	56	771	4.06 vs. 1
177873	14.4	55	167	3.065	55	803	4.81 vs. 1
375922	14.4	56	170	3.067	56	804	4.73 vs. 1
190921	14.4	55	130	2.098	55	821	6.32 vs. 1

Hot rolling reduction ratio of L vs. LT direction in two –directionally rolled plate

Lot No.	Ingot thickness (inch)	Ingot Width (inch)	Ingot Length (inch)	Plate Gage (inch)	Plate Width (inch)	Plate Length (inch)	Redution Ratio L vs. LT
383001	14.6	56	155	3.625	108.4	326	1.086 vs.1
383002	14.6	56	155	3.61	108	328	1.097 vs.1
383231	14.4	56	160	2.106	84.9	741	3.054 vs.1

V - b. Crystallographic Texture at t/4 thickness location from 7050-T7451 plate

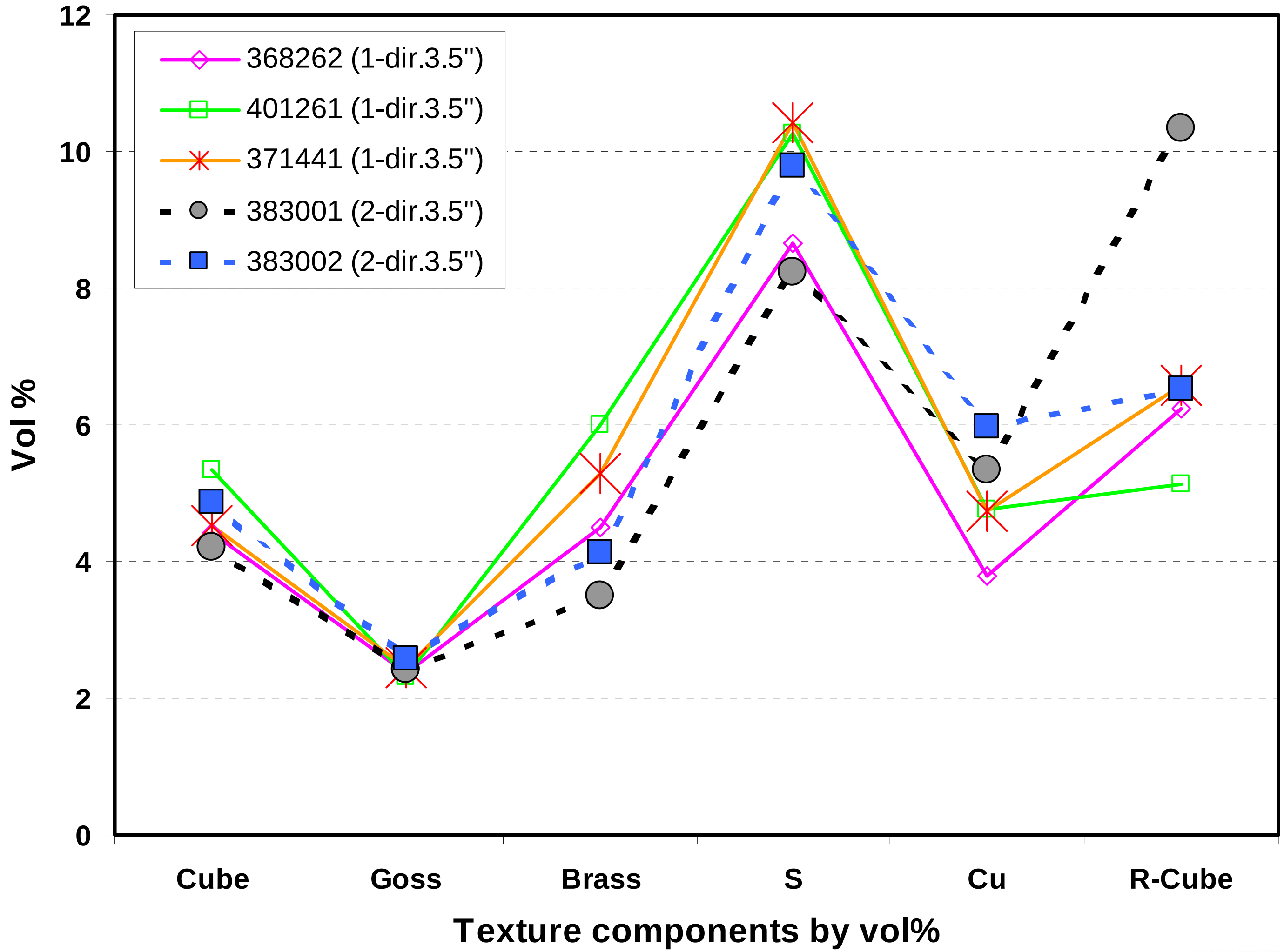
Brass and S components of two-directionally rolled plate tend to be lower compared to uni-directionally rolled plate. However, texture of two-directionally rolled 2” gage plate (Lot no.383231)is very similar to that of uni-directionally rolled plate, because the rolling reduction ratio of L vs .LT direction is not significantly different from that of uni- directionally rolled plate



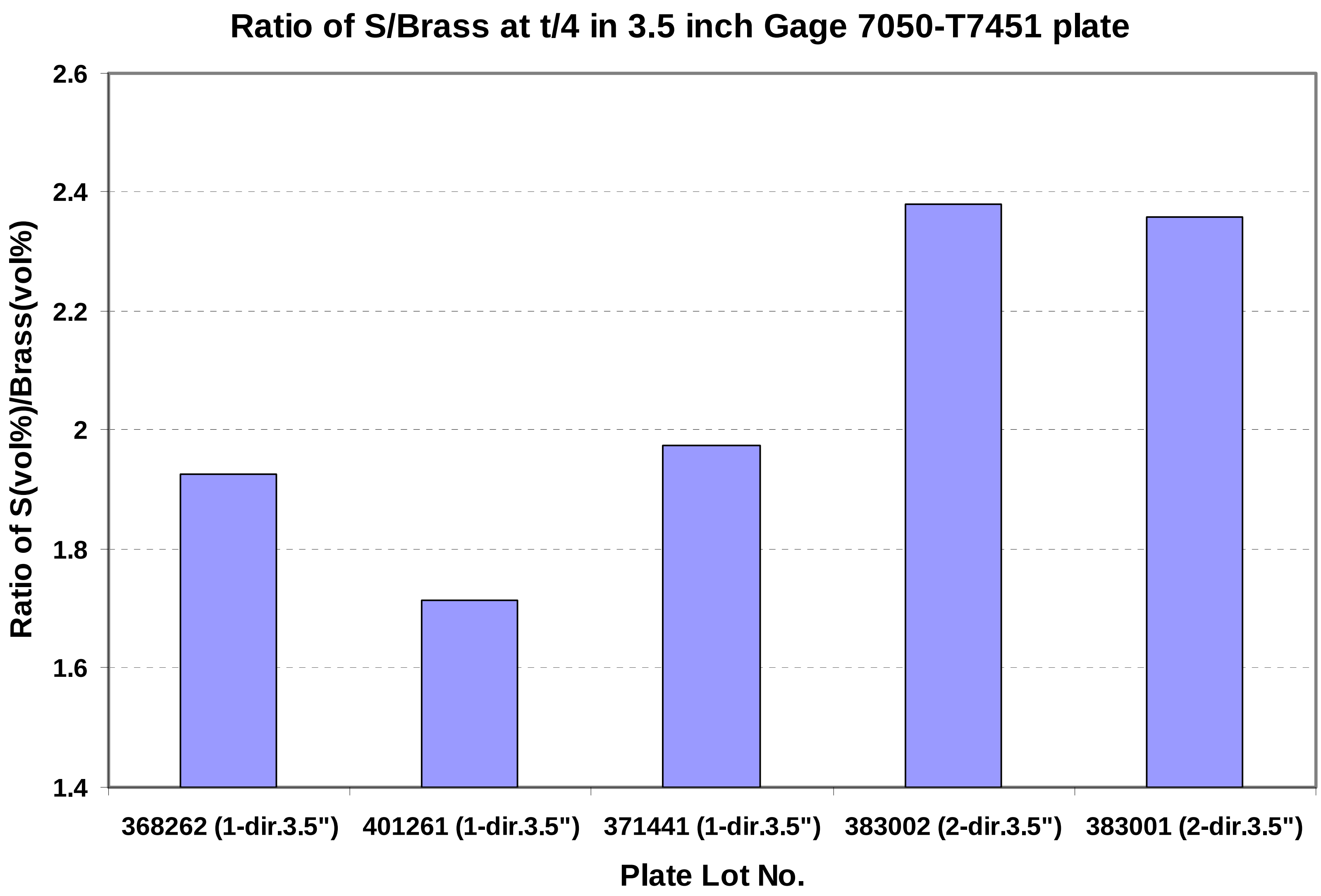
Texture of Two-directionally rolled plate does not appear vastly different from that of uni–directionally rolled plate. However, having lower volume % of Brass component compared to uni-directionally rolled plates, these two plates still show unique characteristics of the two-directionally rolled plate texture

Crystallographic Texture of 3.5 inch gage 7050-T7451 Plate at t/4

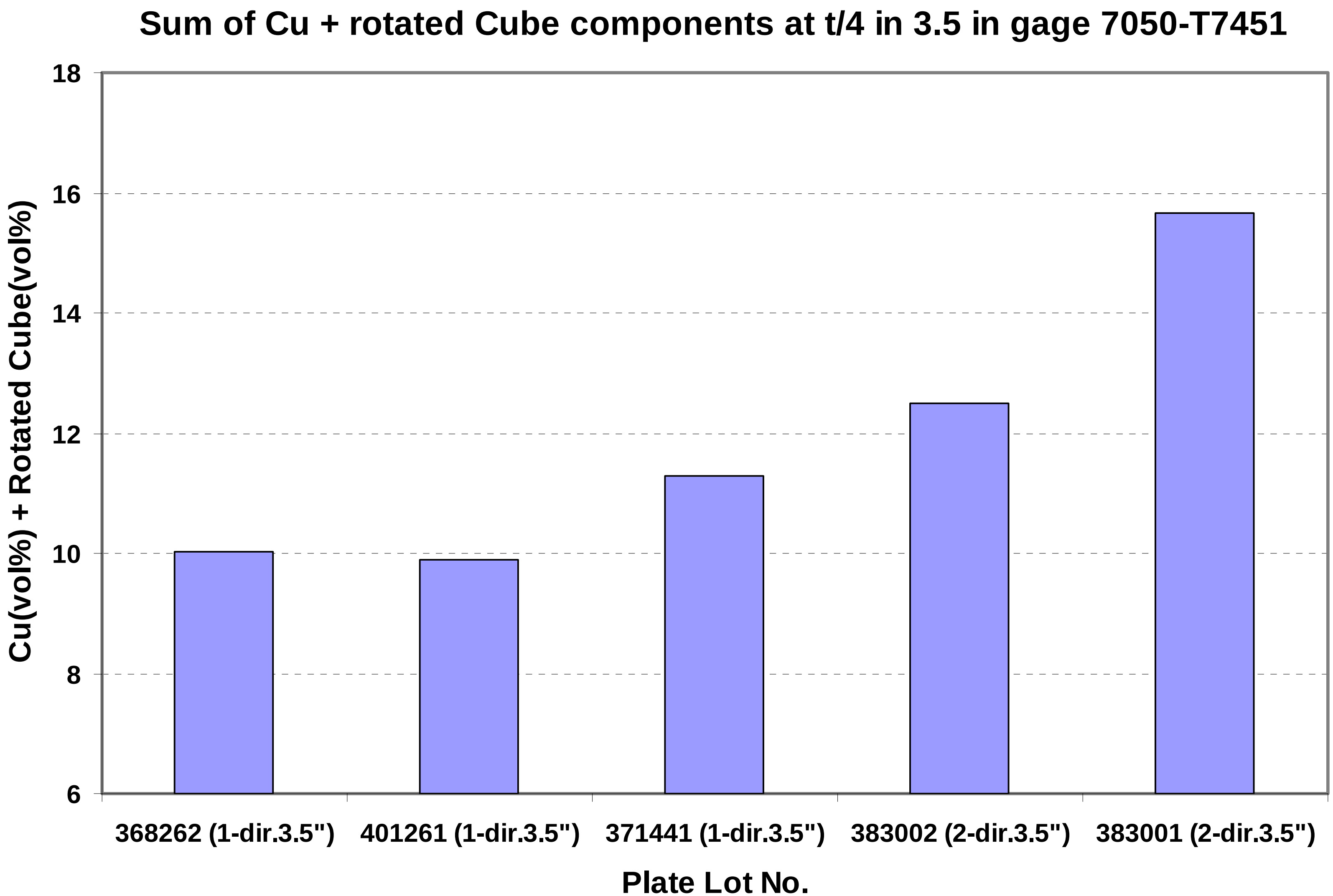
(Comparison of two-directionally rolled plate vs. uni-directionally rolled plate)



Higher ratio of S/Brass components are observed in the two-directionally rolled plate, which is one of the unique charateristics of two-directionally rolled plate



Sum of the Cu & rotated Cube components of the two-directionally rolled plate are greater than that of uni-directionally rolled plate, which is one of the unique characteristics of two directionally rolled plate



V. Compare uni- and two-directionally rolled 7050 Plate at the intermediate gage range on texture development and mechanical properties

b. Crystallographic Texture at t/4 location from 7050-T7451 plate

SUMMARY:

1. Because the rolling reduction ratio of L vs,.LT direction in lot 383321 is not significantly different from that of uni-directionally rolled plate, texture of two-directionally rolled 2" gage plate (Lot no.383231) is very similar to that of uni-directionally rolled plate

2. Texture of two-directionally rolled 3.5 inch gage plate does not appear vastly different from that of uni–directionally rolled plate. By a detailed examination, these two plates still show unique characteristics of two-directionally rolled plate texture

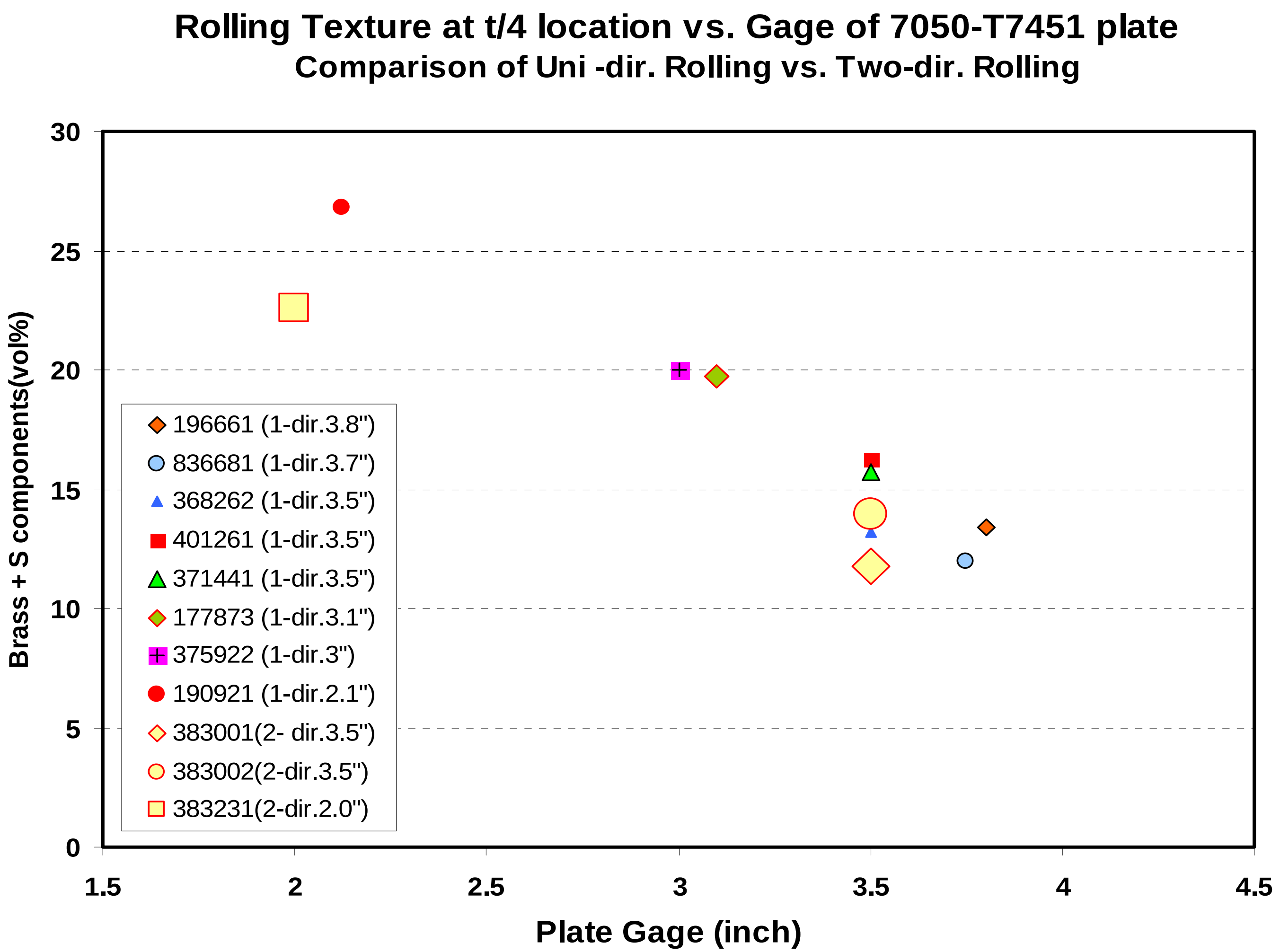
3. The two-directionally rolled 3.5 inch gage plate showed a lower volume % of Brass component and a higher volume % of Cu component while having a similar volume % of S component compared to uni-directionally rolled plate. Therefore, a higher ratio of S/Brass component is observed which is one of the characteristics of two-directionally rolled plate

4. The sum of the Cu & rotated Cube components of the two-directionally rolled 3.5 inch gage plate is greater than that of uni-directionally rolled 3.5 inch gage plate. This is one of the characteristics of two-directionally rolled plate.

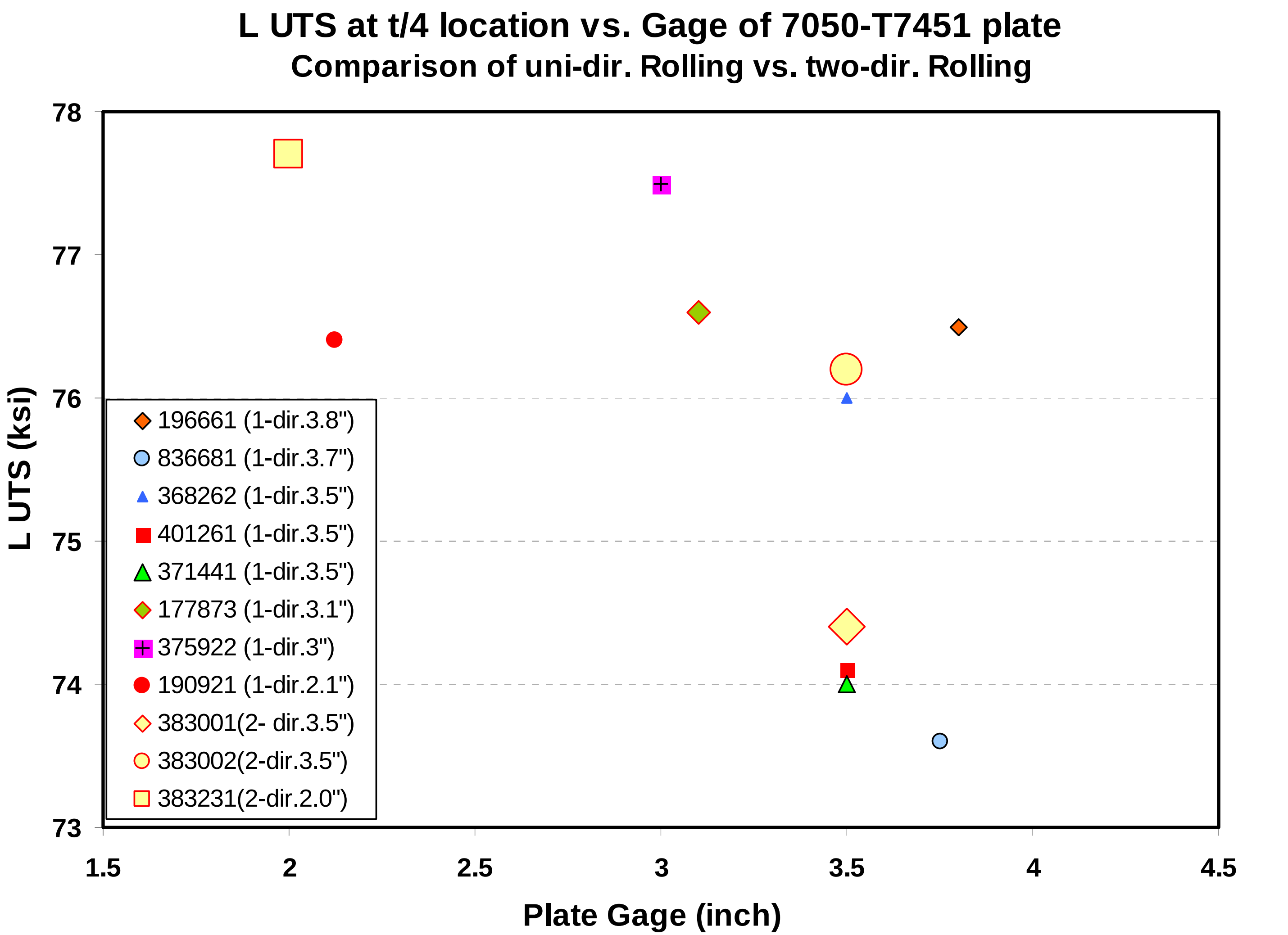
V. Compare uni- and two-directionally rolled 7050 Plate at the intermediate gage range on texture development and mechanical properties

c. Correlation of Plate gage, Crystallographic Texture and Tensile Properties of uni-directionally rolled and two-directionally rolled plate

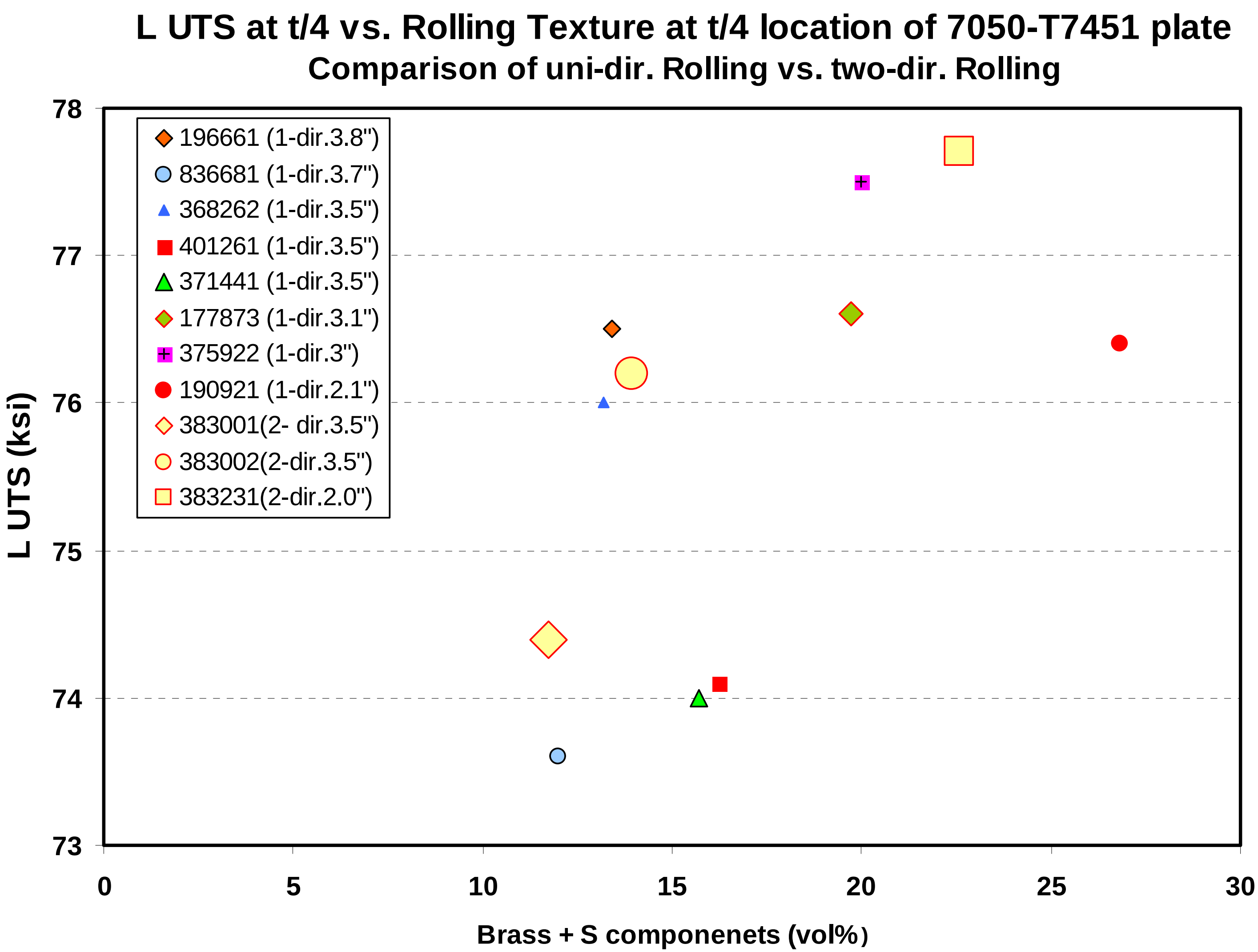
- For the plate gage range from 2 inch to 3.8 inch, deformation texture components (S and Brass components) correlate with the plate gage by increasing the sum of S and Brass components as the plate gage decreases
- Deformation texture (represented by sum of Brass and S components) of the two-directionally rolled plates is very similar to that of the uni-directionally rolled plate



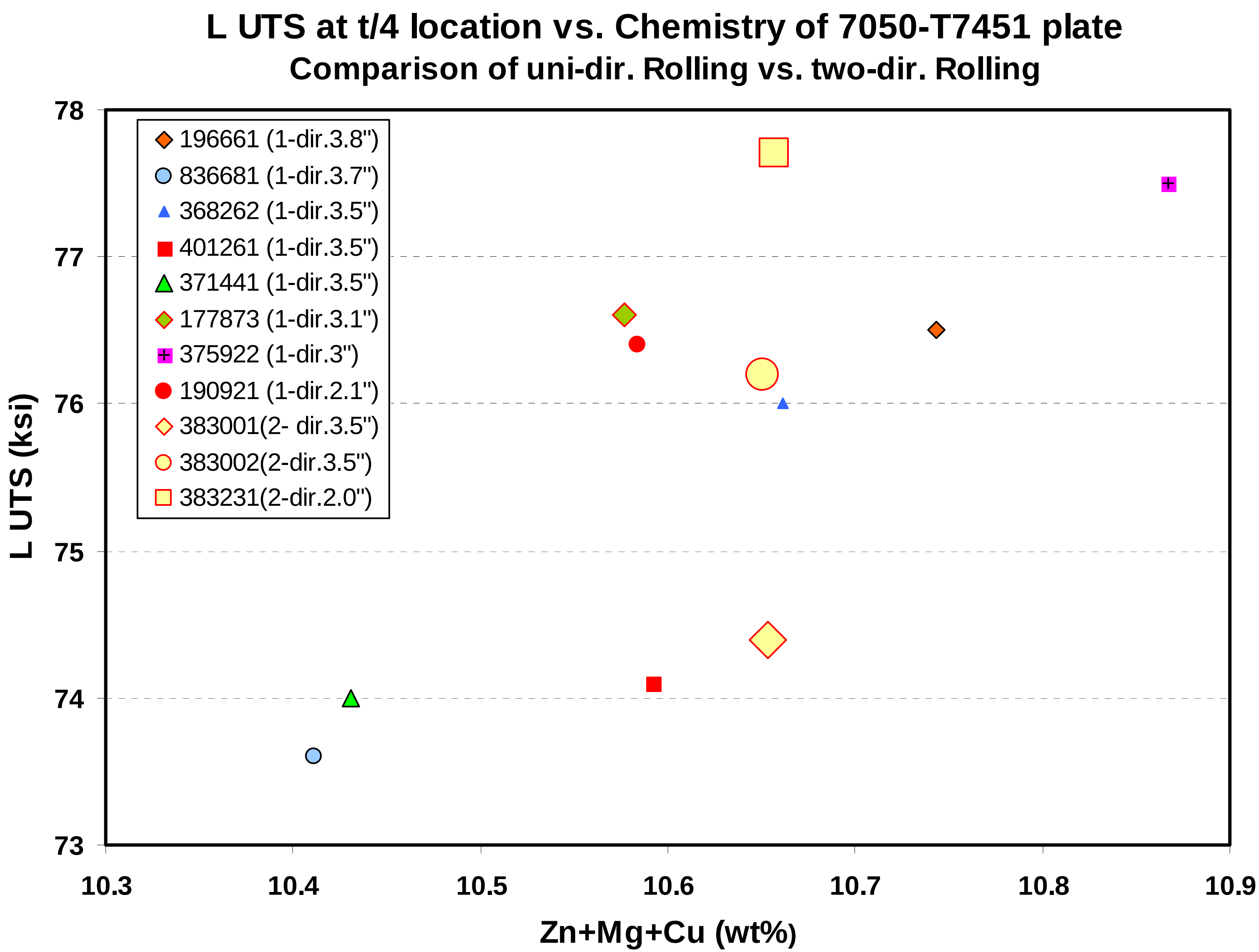
Except for the 2.0-2.125 inch gage plate, L UTS values show poor correlation with plate gage variation.



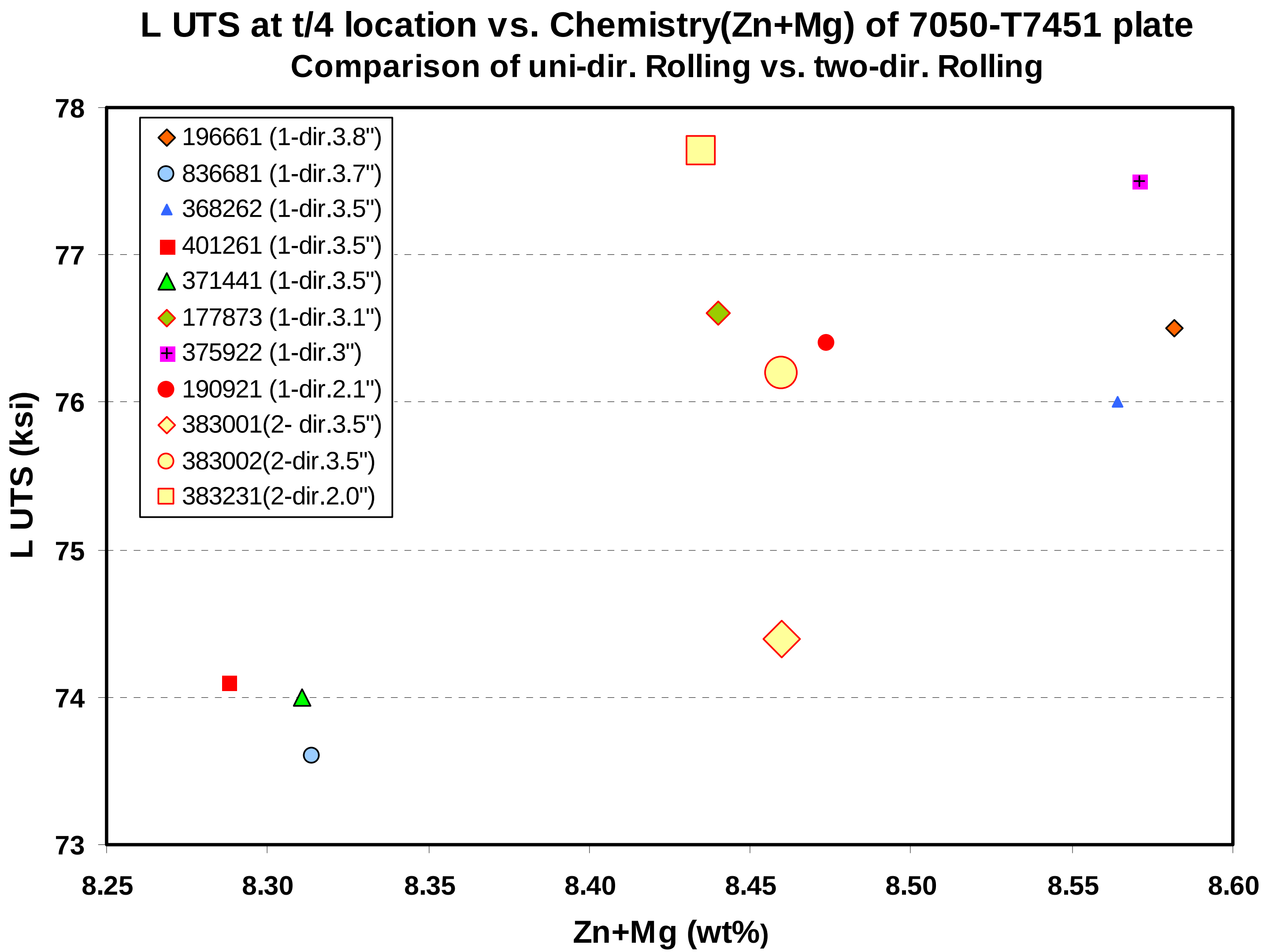
L UTS values do not correlate with deformation texture components represented by the sum of Brass & S components



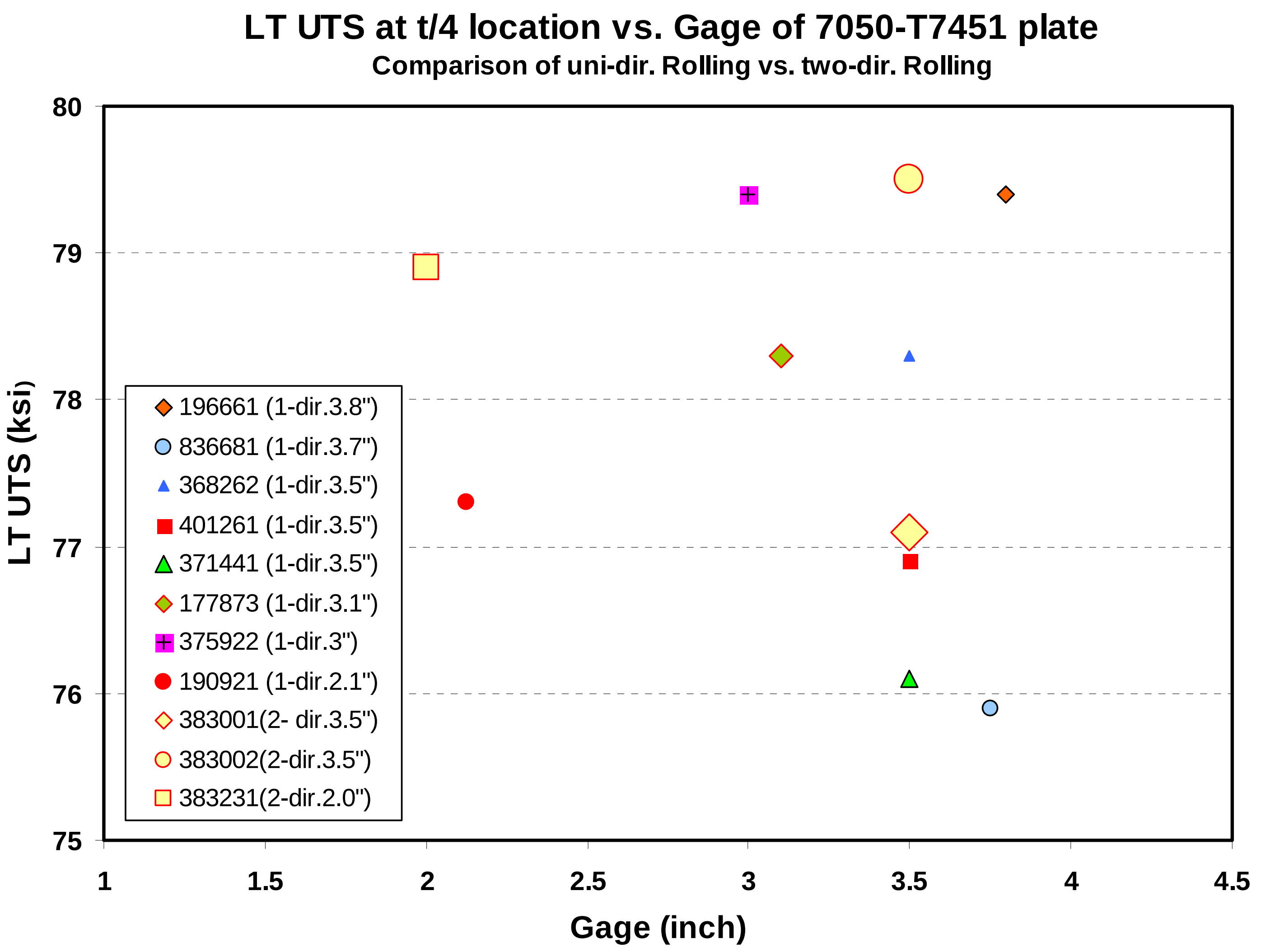
Except for the two-directionally rolled plate, L UTS values correlate with the sum of major alloying elements (Zn+Mg+Cu)



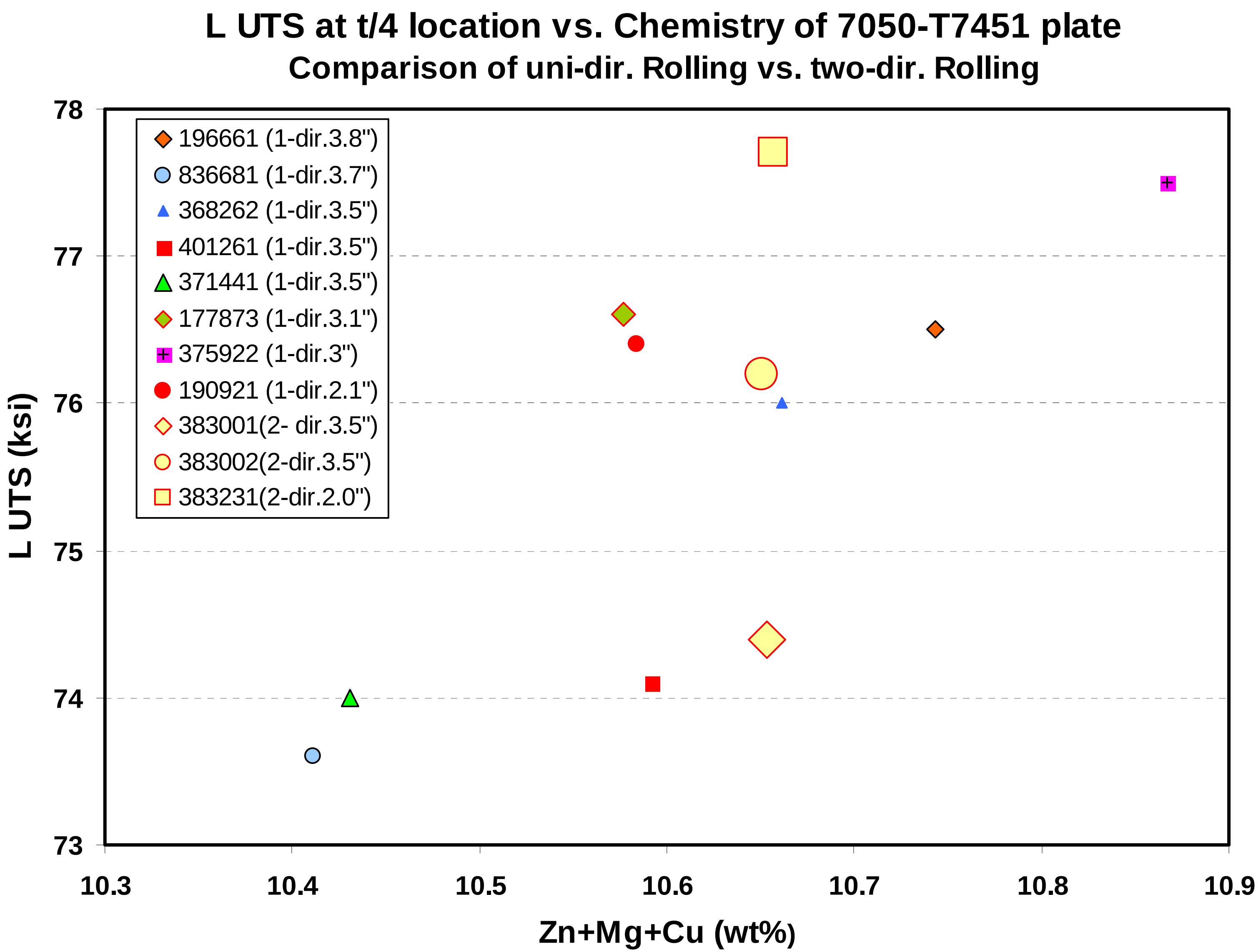
Except for the two-directionally rolled plate, L UTS values correlate with the sum of major alloying elements (Zn+Mg)



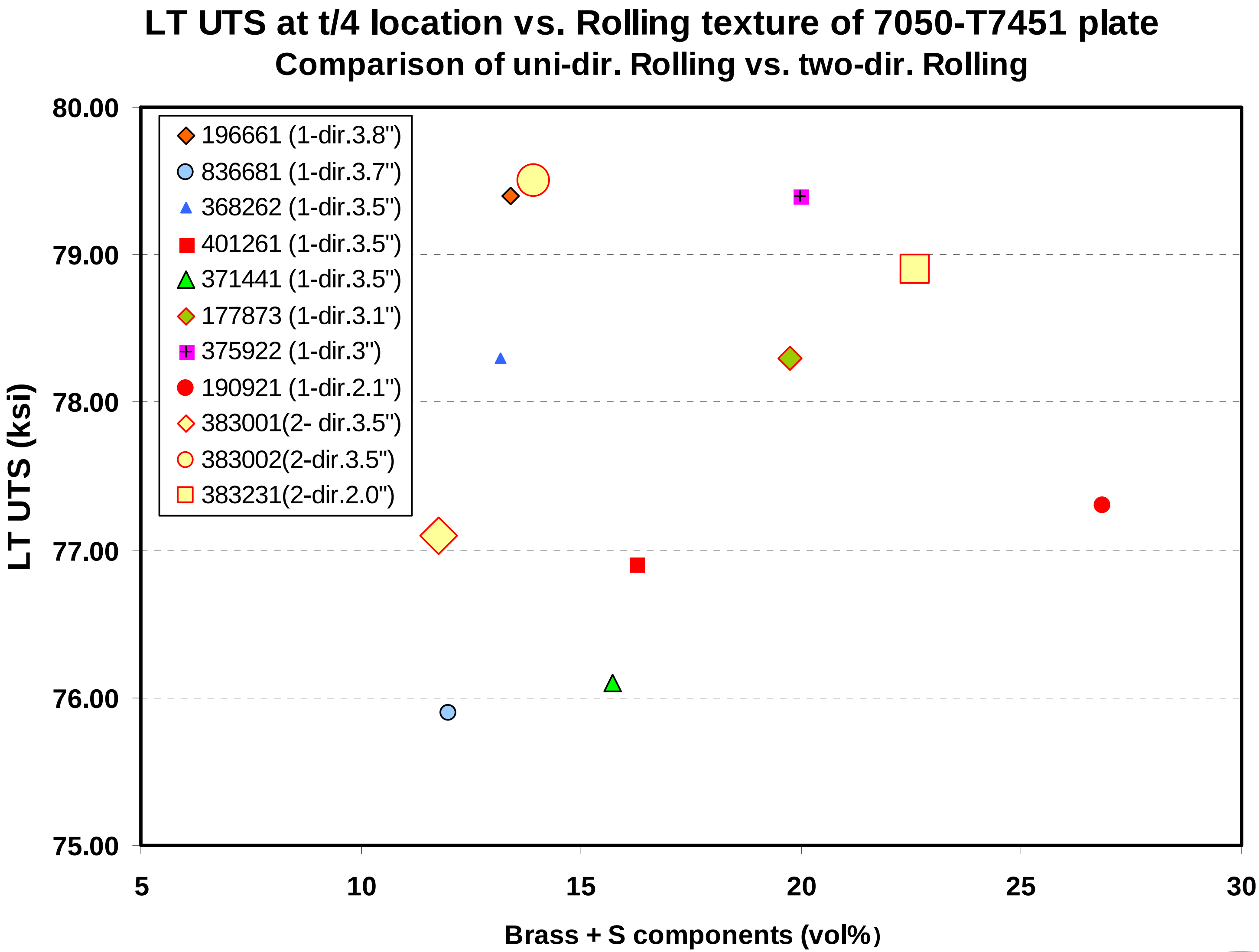
LT UTS values do not correlate with plate gages within 2.0 to 3.8 inch gage range



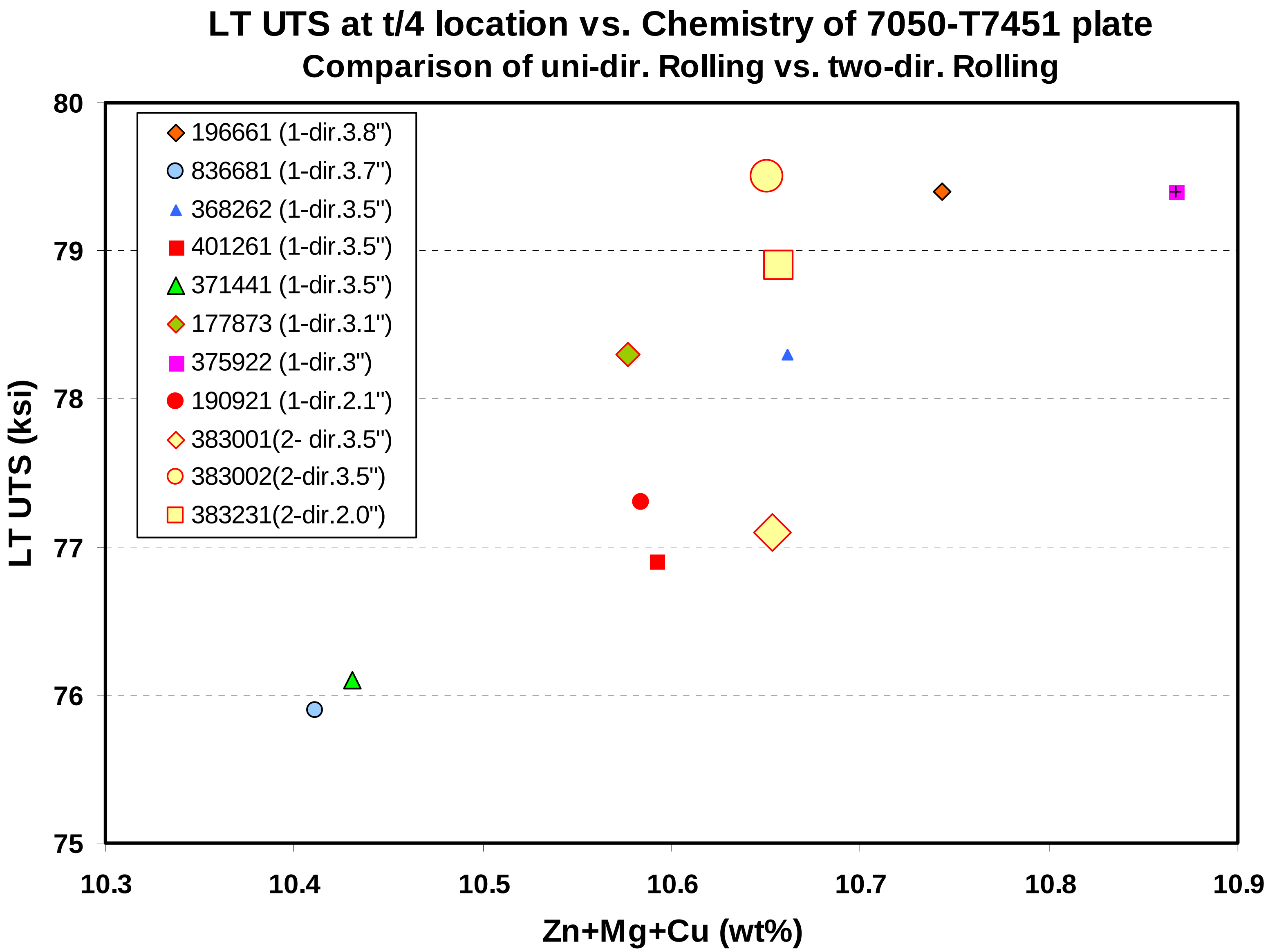
Except for the two-directionally rolled plate, L UTS values correlate with the sum of two major alloying elements (Zn+Mg+Cu)



LT UTS values do not correlate with the deformation texture represented by the sum of Brass and S components.



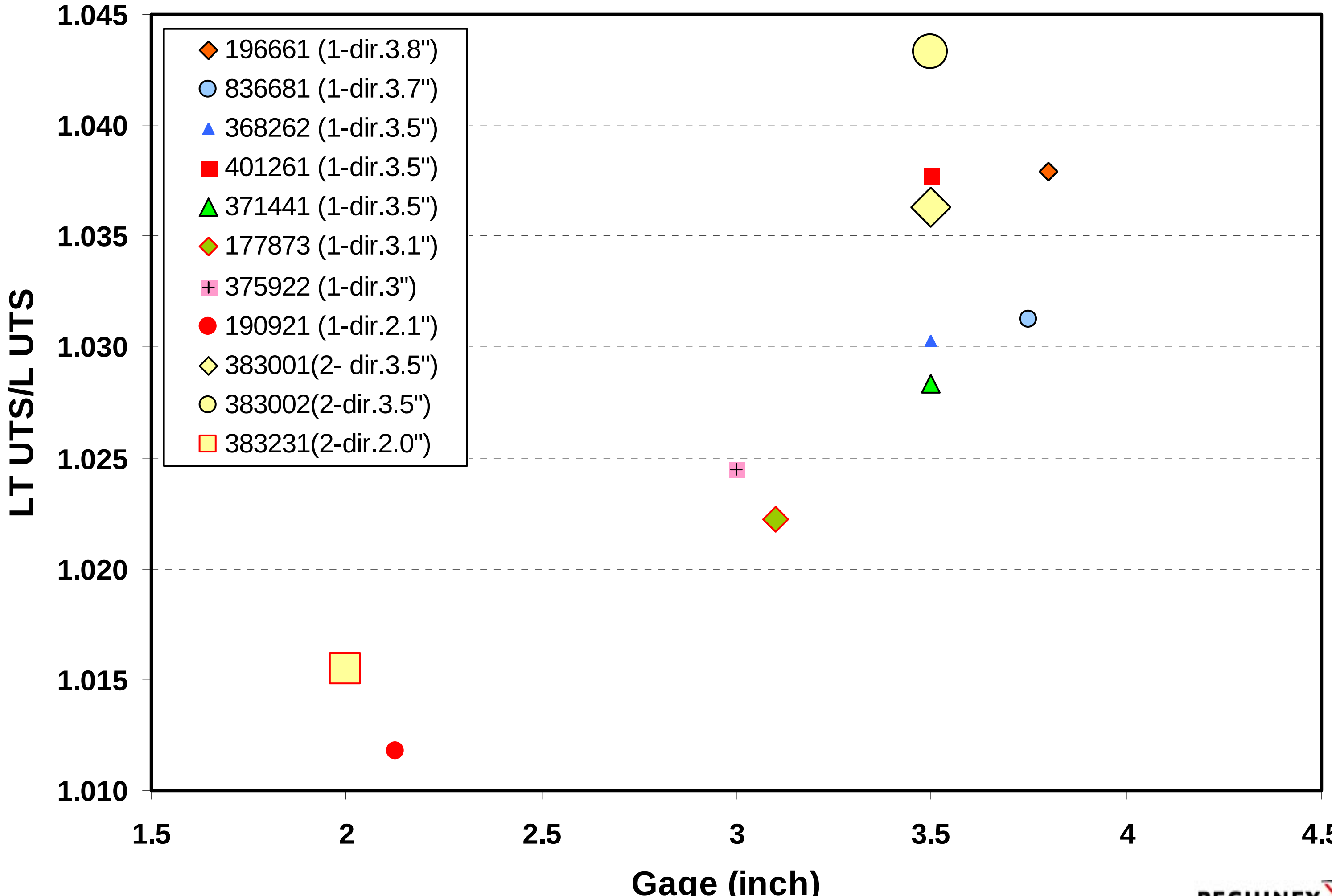
Except for the two-directionally rolled plate, LT UTS values correlate with the sum of major alloying elements (Zn+Mg+Cu)



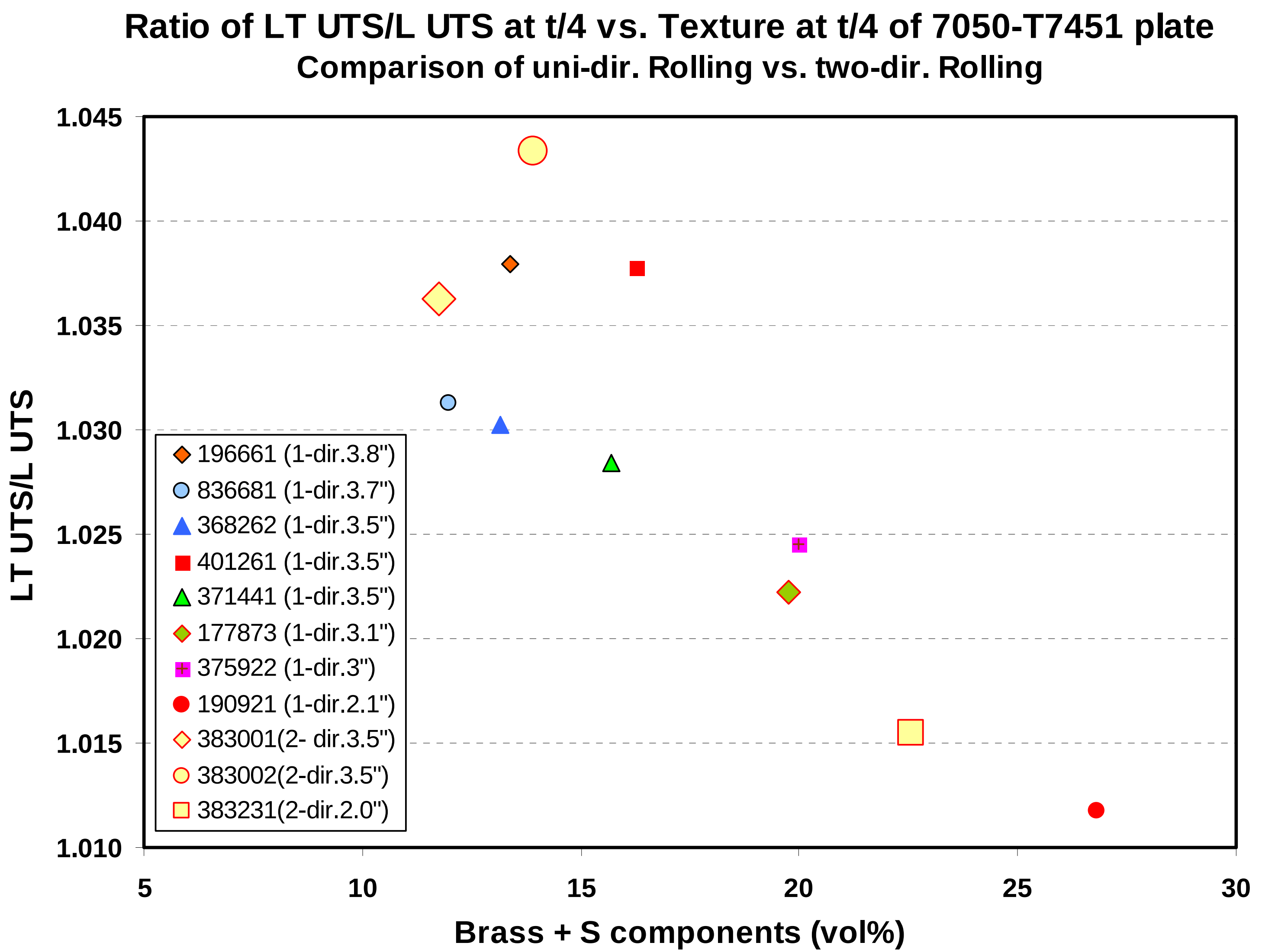
The ratio of LT UTS/L UTS correlates with plate gage within the range of 2.0 to 3.8 inch. As the plate gage decreases, the ratio of LT UTS/L UTS decreases. Uni-directionally rolled plate and two-directionally rolled plate shows no significant differences.

Ratio of LT UTS/L UTS at t/4 location vs. Gage of 7050-T7451 plate

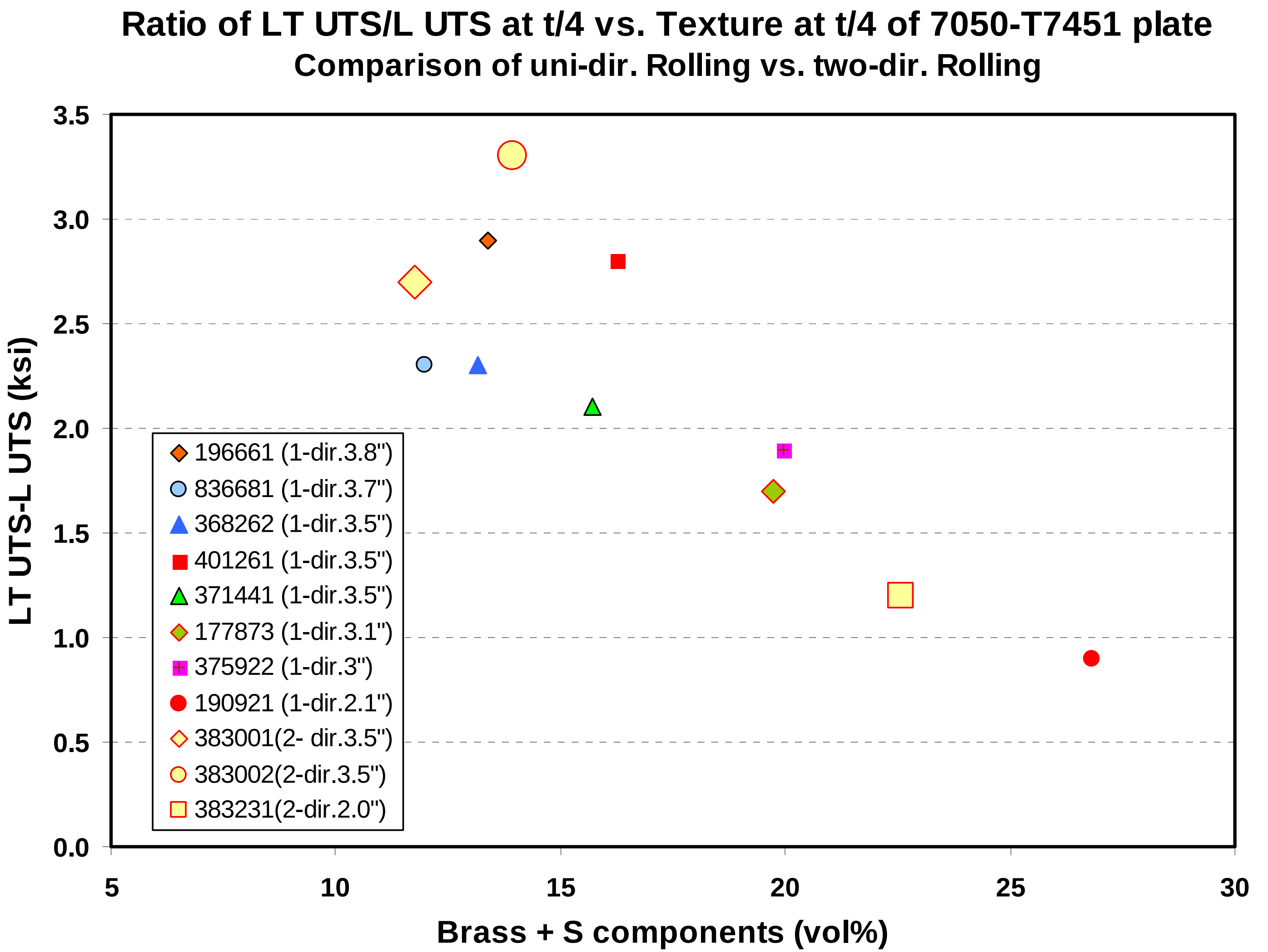
Comparison of uni -dir. Rolling vs. two-dir. Rolling



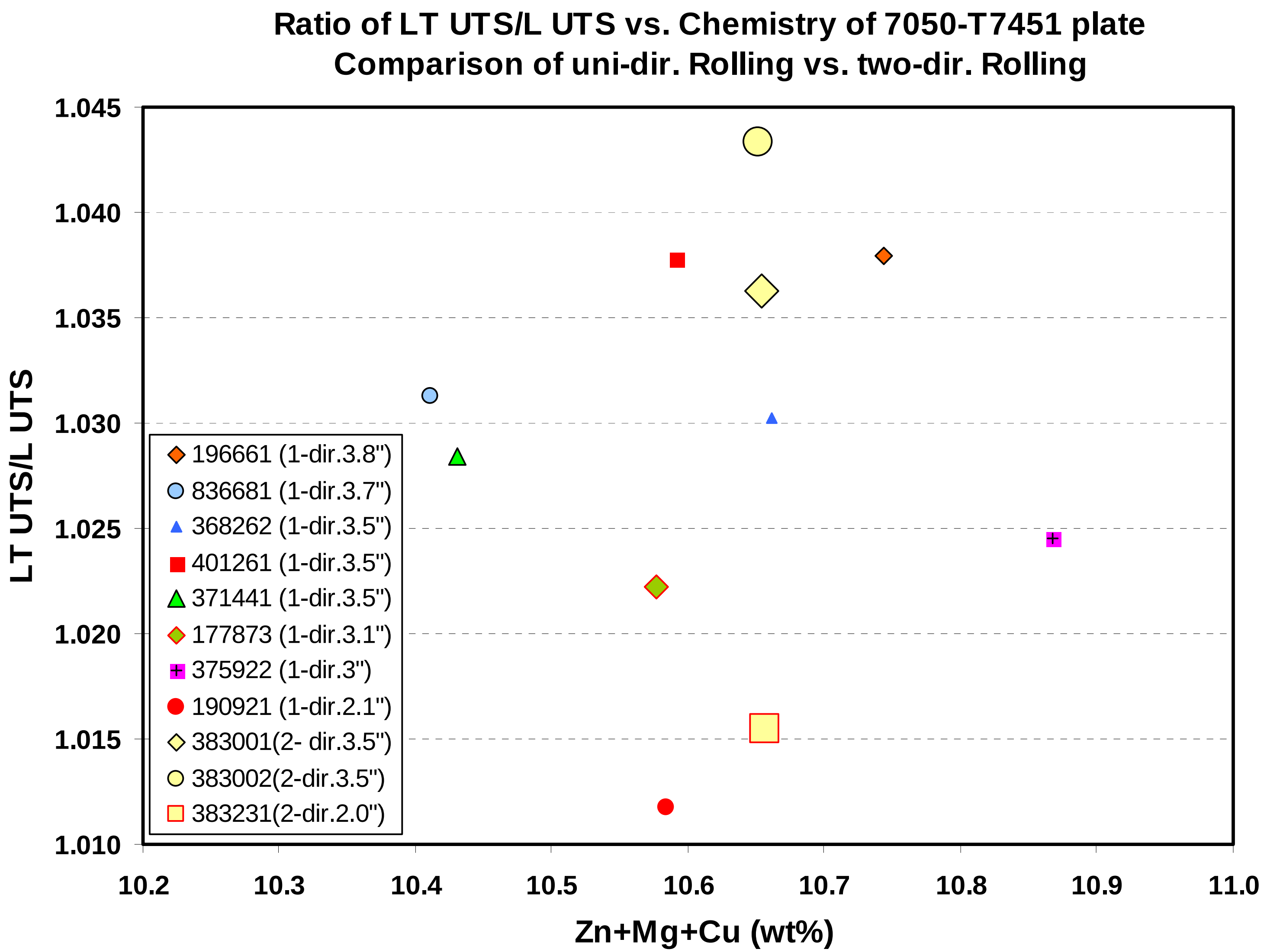
The ratio of LT UTS/L UTS correlates with the deformation texture within the range of 2.0 to 3.8 inch. As deformation texture increases, the ratio of LT UTS/L UTS decreases.



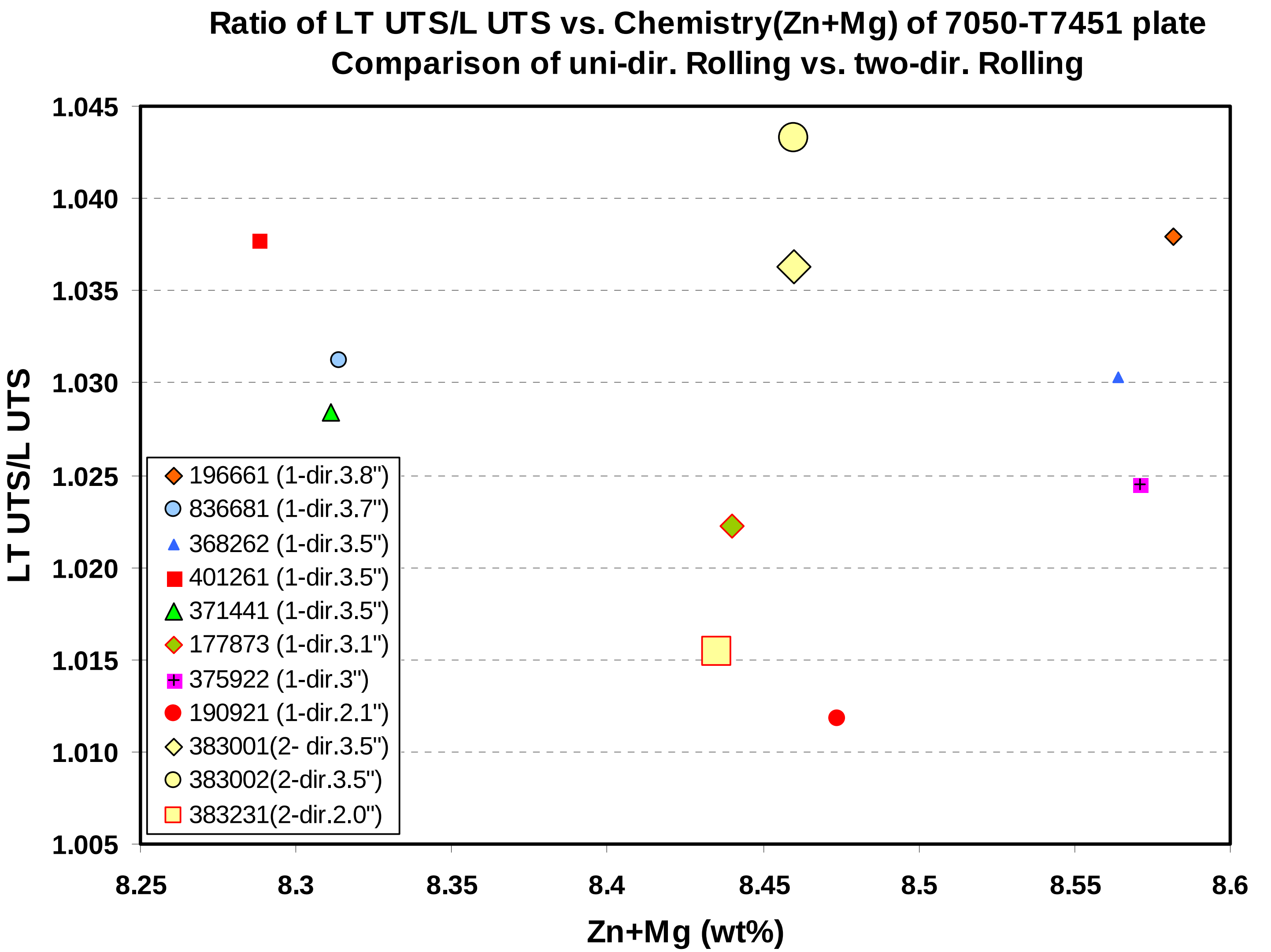
The difference between LT UTS & L UTS correlates with the deformation texture for the range of 2.0 to 3.8 inch. As the deformation texture increases, the difference between LT UTS andL UTS decreases.



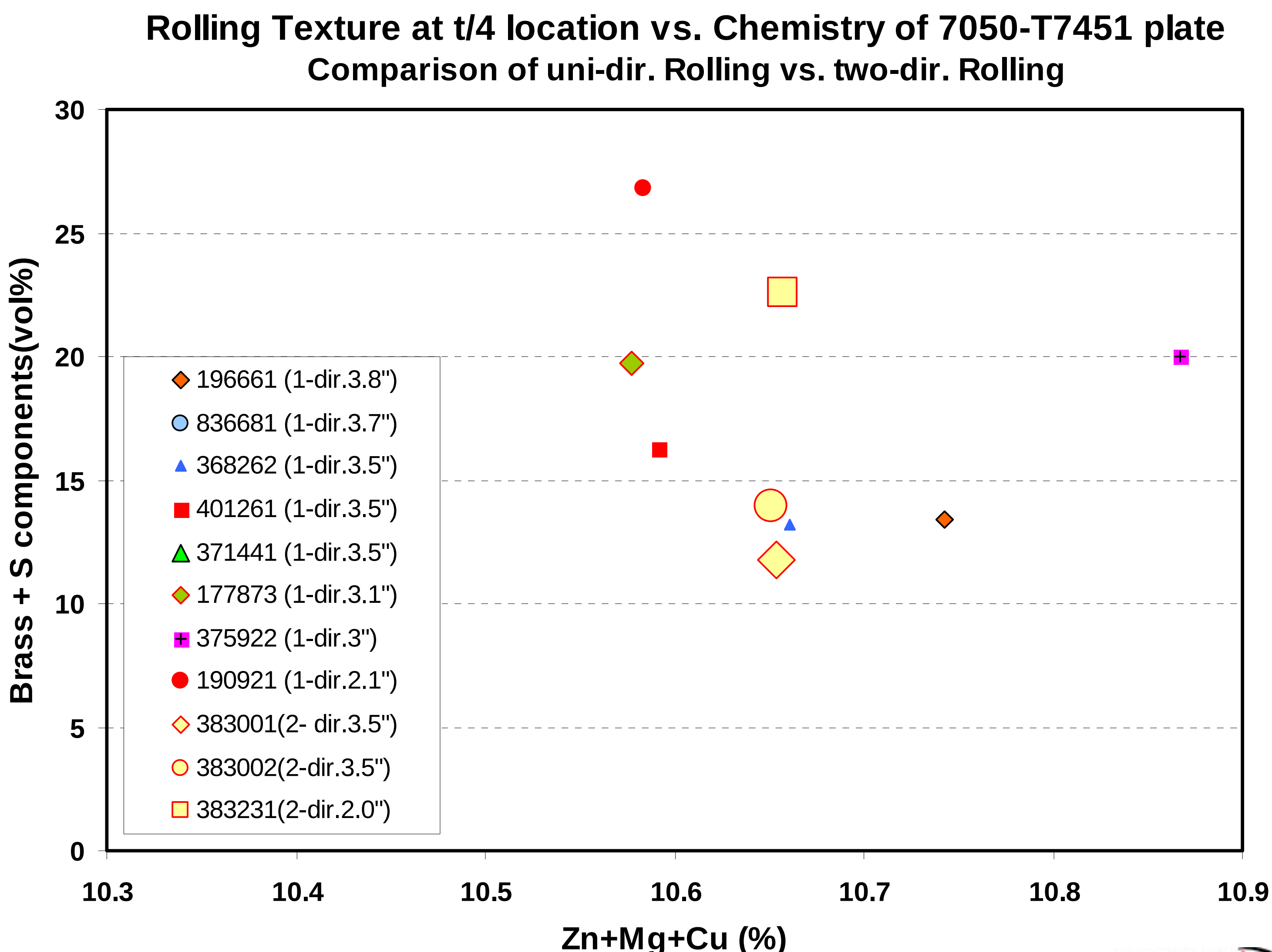
No correlation can be observed for the ratio of LT UTS/ L UTS and plate chemistry (Zn+Mg+Cu)



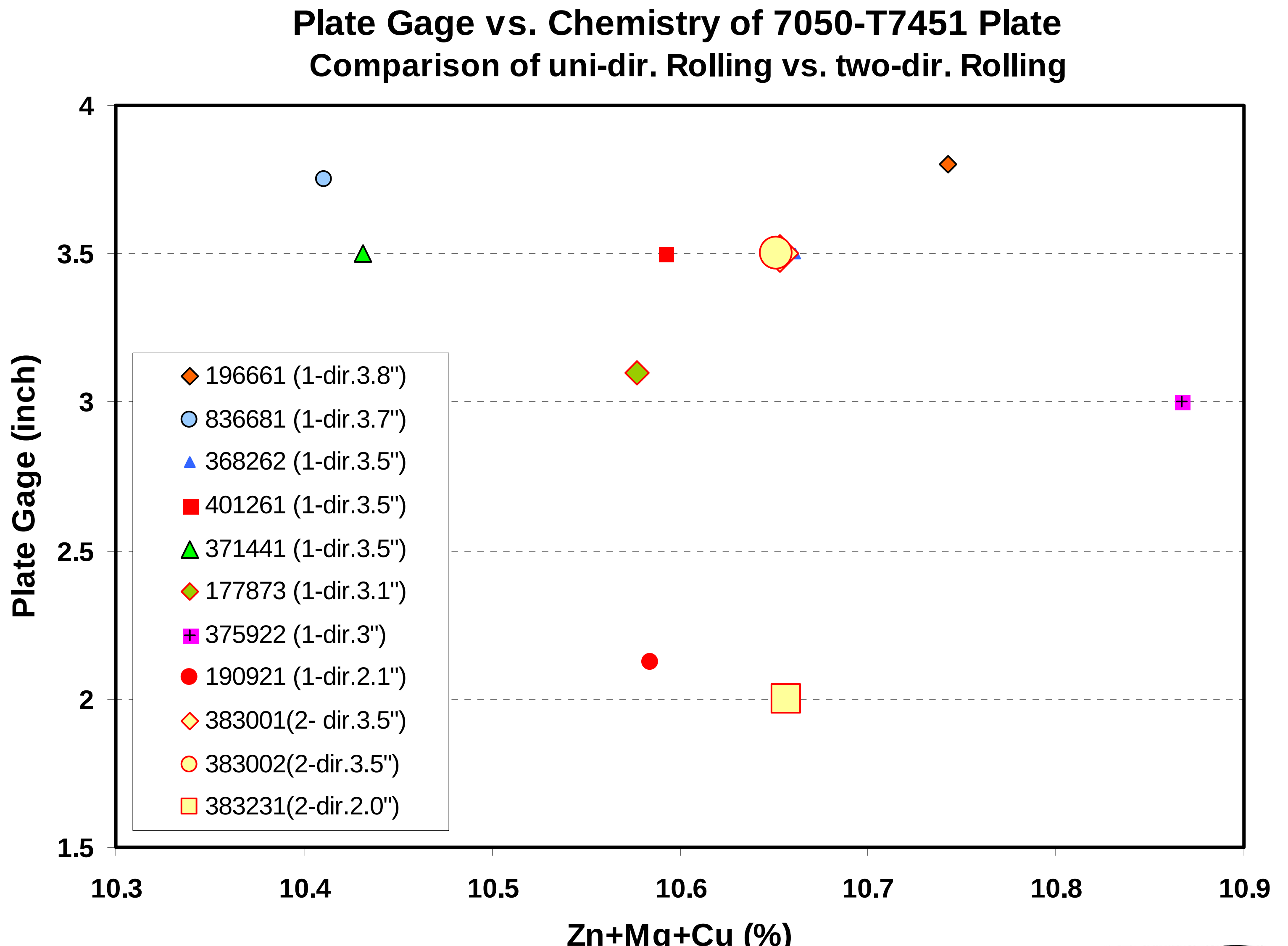
No correlation can be observed for the ratio of LT UTS/ L UTS and plate chemistry (Zn+Mg)



No correlation between chemistry and texture was observed. This validates the effect of chemistry on mechanical properties independent of texture effect.



No correlation between chemistry and texture was observed. This validates the effect of chemistry on mechanical properties independent of plate gage effect.



V. Compare uni- and two-directionally rolled 7050 plate at the intermediate gage range on texture development and mechanical properties

c. Correlation of plate gage, crystallographic texture and tensile properties of uni-directionally rolled and two-directionally rolled plate

Summary

1. Deformation texture volume % increases as plate gage decreases within the gage range of 2 to 4 inches.
2. L UTS and LT UTS values correlate with chemistry more strongly than any other variables examined.
3. The ratio of LT UTS/ L UTS does not show correlation with plate chemistry. Instead, the ratio shows a strong correlation with deformation texture and plate gage
4. The difference between L UTS and LT UTS values due to anisotropy caused by texture is relatively small compared to the overall variation of L UTS values due to chemistry
5. Two-directionally rolled plate showed only marginally different texture compared to the uni-directionally rolled plate
6. Two-directionally rolled plate did not show improvement in L UTS values. Test results showed that two-directional rolling did not improve the ratio of LT UTS / L UTS.

The Effect of Hot Rolling Processes on the Texture and Mechanical Properties of 7050 Plate

VI. Conclusions

1. Degree of recrystallization after solution heat treatment is minimal. W- temper plate is essentially unrecrystallized at t/4 location for the plate samples examined
2. Two-directionally rolled plate showed only marginally different texture compared to the uni-directionally rolled plate. The plate gage appears to correlate strongly with texture
3. Two-directionally rolled plate did not show improvement in L UTS values. Test results showed that two-directional rolling appeared to be detrimental to achieve isotropic strengths between LT UTS and L UTS.
4. L UTS and LT UTS values correlate with chemistry more strongly than any other variables examined
5. The difference between L UTS and LT UTS values due to anisotropy caused by texture is relatively small compared to the overall variation of L UTS values due to chemistry variation
6. The ratio of LT UTS/ L UTS shows a strong correlation with deformation texture and plate gage within 2 inch – 4 inch range

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14. ABSTRACT
This final report, in multiple presentation format, describes a comprehensive multi-tasked contract study to improve the overall property response of selected aerospace alloys, explore further a newly-developed and registered alloy, and correlate the processing, metallurgical structure, and subsequent properties achieved with particular emphasis on the crystallographic orientation texture developed. Modifications to plate processing, specifically hot rolling practices, were evaluated for Al-Li alloys 2195 and 2297, for the recently registered Al-Cu-Ag alloy, 2139, and for the Al-Zn-Mg-Cu alloy, 7050. For all of the alloys evaluated, the processing modifications resulted in significant improvements in mechanical properties. Analyses also resulted in an enhanced understanding of the correlation of processing, crystallographic texture, and mechanical properties.

15. SUBJECT TERMS
Alloys; Plate processing; Mechanical properties; Texture

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