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Effect of Stretch Orientation and Rolling Orientation on the Mechanical Properties of 2195 Al-Cu-Li Alloy

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Sheets of 2195 aluminum-lithium alloy were solution-treated at 507 °C for 30 min. One set was stretched to 3-5% in the 0°, 45°, and 90° angle with respect to the original rolling direction. Two other sets were rolled 6% reduction in thickness and 24% reduction in thickness in the 0°, 45°, and 90° angle with respect to the original rolling direction. All specimens were aged at 143 °C for 36 h. A second group of samples was rolled at 24 and 50% reduction in thickness after a solution treatment of 507 °C for 1 h prior to aging at 190 °C for 24 h. Tensile specimens were machined from each sheet at 0°, 45°, and 90° angles to the original grain orientation. Tensile testing was used to determine the mechanical properties and anisotropic behavior of each condition. Rolling 6% reduction in thickness in the 45° orientation yielded anisotropy of 7.6% in the yield strength.

Keywords 2195 Al-Li, anisotropy, rolling orientation, stretch orientation

1. Introduction

Aluminum-lithium 2195 is of great interest to the aerospace industry due to its superior physical and mechanical properties. It offers an improvement over the conventional 2219 alloy with an increased strength of 30-40% and a reduced density of 5% (Ref 1, 2). It was actually used in the fabrication of the super lightweight external tank of the Space Transportation System, NASA's mission STS-91. It provided a mass reduction of over 3000 kg and 50% increase of the payload capability (Ref 1-6).

Much research has been done on this alloy system. Li et al. (Ref 1) studied the effects of stretch prior to aging on the mechanical properties of the 2195 alloy. Hall and Sisk (Ref 7) studied the effects of reversion aging, Langan et al. (Ref 8) researched the environmentally assisted cracking and localized corrosion susceptibility, Hou et al. (Ref 9). Thompson (Ref 10), Bastias et al. (Ref 11), and Diwan et al. (Ref 12) researched the effects of welding, and Dyer et al. (Ref 13) studied the effect of near-net forging, Jiang et al. (Ref 4) studied the microstructure evolution of the 2195 alloy undergoing commercial production and Hales and Hafley (Ref 14) studied the structure-property correlations of the 2195 alloy in integrally "T" stiffened extruded panels.

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As with most aluminum-lithium alloys, one of the major concerns associated with the 2195 alloy is the mechanical strength anisotropy, (Ref 15, 16). The origin of anisotropy results from interactions among crystallographic texture, grain size and shape, cold deformation, and the precipitates developed during aging. This anisotropic behavior led to the inclusion of testing data at 45° with respect to the rolling direction as part of the MIL-HDBK-5 design minimal requirements (Ref 17). The T_1 phase (Al_2CuLi) is the major source of strengthening in this alloy system. This precipitate occurs as plates on {111} planes. Kim and Lee (Ref 18) have shown that there is an inhomogeneous distribution of the T_1 precipitates among the four {111} habit planes after stretching and aging of a 2090 aluminum-lithium alloy. It was further reported that this inhomogeneous distribution had a direct effect on the mechanical anisotropy of the material. Samples pulled at orientations parallel to the rolling direction had high strength because a high density of T_1 precipitates intercepted the slip plane resulting in homogenous deformation. Samples pulled at 60° orientation with respect to the rolling direction were weaker because the density of the T_1 precipitates was lower and were insufficient to influence the deformation behavior.

Among the methods of reducing the anisotropy of tensile properties was stretching or cold rolling in different directions, (Ref 17). Many attempts to minimize the mechanical anisotropy were successful when off-axis deformation was conducted on aluminum-lithium alloys (Ref 19-22). The philosophy was that off-axis deformation would change the morphology of the dislocation structure which the T_1 precipitates nucleate on. The objective of this study is to further research the effects of stretch orientation and rolling orientation on the mechanical tensile properties and anisotropy of the 2195 Al-Cu-Li alloy.

2. Experimental Procedure

The composition of the 2195 Al-Cu-Li alloy used in this investigation is presented in Table 1 (Ref 23).

The material was received from Reynolds, Richmond, Virginia as 0.318-cm thick sheets in the F-temper. Samples were solution heat-treated at 507 °C for 30 min and water quenched. Groups of samples were rolled to 6% reduction in thickness, 24% reduction in thickness, and stretched 2.5-3.0% at 0, 45, and 90° angles to the original rolling direction, respectively. The samples were then aged at 143 °C for 36 h and air-cooled. Tensile specimens were machined from each sheet at 0°, 45°, and 90° angles to the original grain orientation. A flowchart showing the sequence of processing is shown in Fig. 1.

Table 1 Nominal chemical composition of 2195 Alloy

Cu	Li	Ag	Zr	Mg	Al
4.1	1.41	0.4	0.13	0.35	Balance

A second group of samples was solution-treated at 507 °C for 1 h and water quenched. Following the solution treatment, the samples were cold-rolled either 24 or 50% reduction in

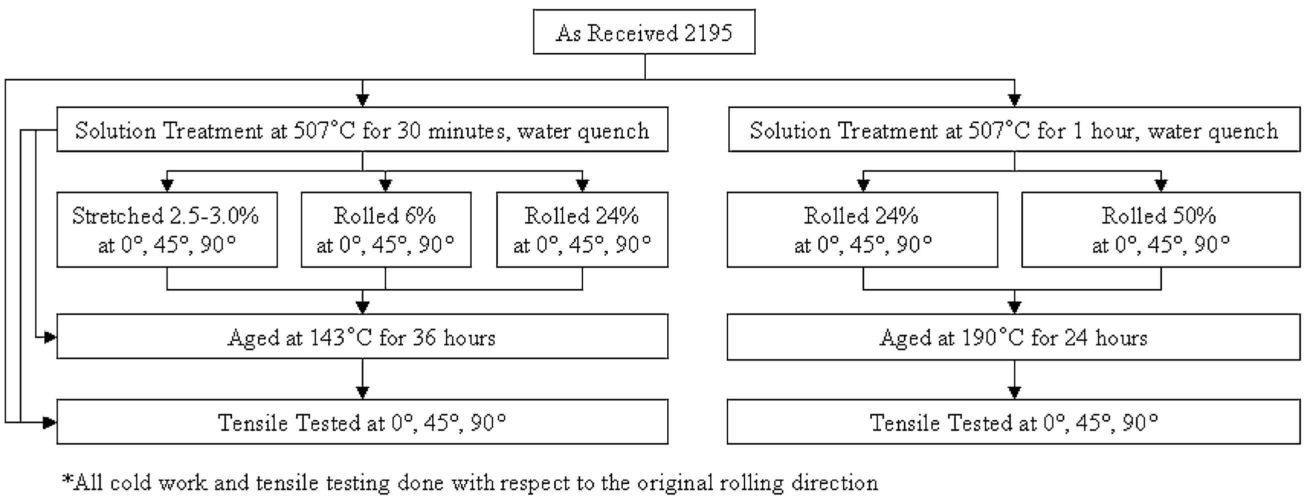


Fig. 1 The flow chart of the thermomechanical processing of the 2195 aluminum alloy

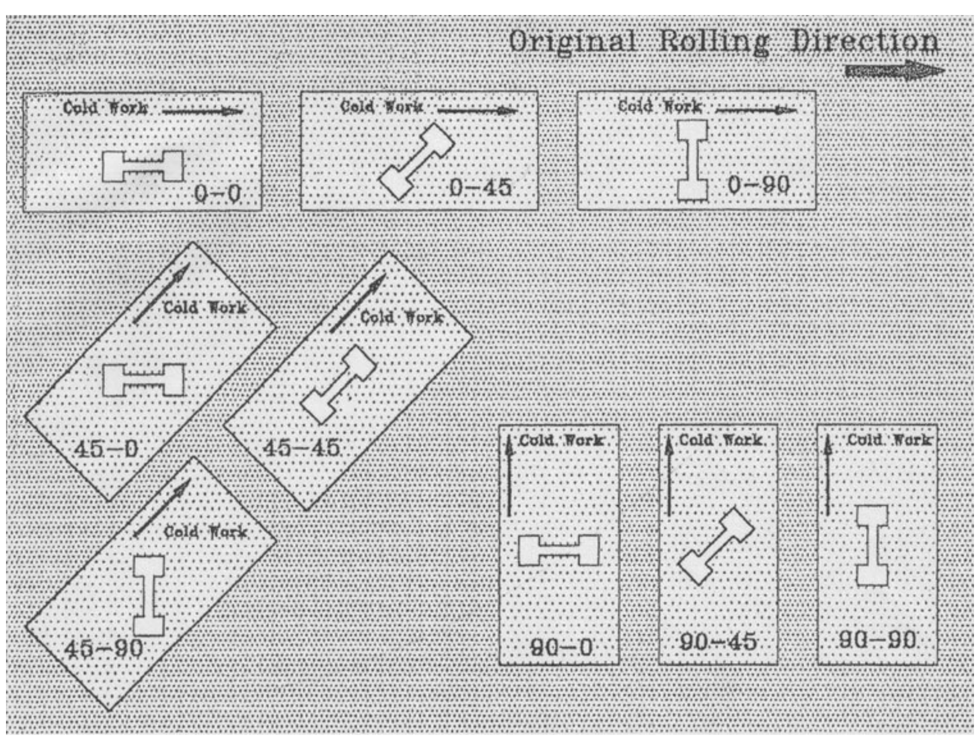


Fig. 2 Cold work and machining orientations in relation to original rolling direction. First number: angle of cold work (stretching or rolling) in relation to original rolling direction, second number: angle of cut tensile sample in relation to original rolling direction

thickness in the 0°, 45°, and 90° directions. Following the rolling, the samples were aged at 190 °C for 24 h and air-cooled. The samples were subsequently machined into tensile specimens at 0°, 45°, and 90° angles to the original grain direction and tested in tension. The solution treatment and aging were similar to those used by Li et al. (Ref 1).

A schematic diagram showing the stretching and rolling and machining orientations with respect to the original rolling direction is shown in Fig. 2. In it, for example, a 0-45 sample means that it is stretched or rolled along the rolling direction (0°) and machined at 45° to the rolling direction.

Tensile specimens were prepared and tested in accordance with ASTM standard E8. The tensile samples were rectangular plate specimens, with 203.2 mm (8.0 in) total length, 50.8 mm (2.0 in) gauge length, 12.7 mm (0.5 in) width, 57.15 mm (2.25 in) length of reduced section, and 12.7 mm (0.5 in) radius of fillet. The thickness of the samples was reduced to 6.35 mm (0.25 in). The grips had 50.8 mm (2.0 in) length and 19.05 mm (0.75 in) width. Specimens were machined using standard milling machines and a CNC machine. Tensile test was performed on an Instron 4505 test frame at a constant cross head speed of 1.27 mm/min (0.05 in/min). Three specimens were tested at each test condition with each data point representing the mean of three tests.

3. Results and Discussion

The effect of solution treatment (507 °C for 30 min and water quenching) and the effect of solution treatment and aging (143 °C for 36 h and air cooling) on the yield and tensile strengths are shown in Fig. 3. The mechanical strengths increase after solution treatment due to solid solution hardening and after aging due to the effect of the T1 (Al_2CuLi) precipitates. The yield strength of the aged samples in the 0° direction (354 MPa) is lower than that of the 2195 material (500 MPa) studied by Li et al. (Ref 1), however, and the ultimate strengths were comparable (~524-537 MPa). The anisotropy (difference between highest and lowest value/highest value) also increased with solution treatment and subsequent aging (7-12.7%).

The effect of stretching 2.5-3% and rolling 6% reduction in thickness is shown in Fig. 4(a) and (b). Stretching increases the yield strength slightly while rolling increases it significantly when compared to the as aged condition, Fig. 3. However, the ultimate tensile strengths are slightly higher in rolled samples versus stretched samples, Fig. 4(b). The anisotropy in yield strength is a minimum (7.6%) after 45° rolling and after 90° stretching (9.5%) which accords with the results of previous

Yield Strengths (MPa)

	AR	AR + ST	AR + ST + AG
0°	172	305	354
45°	163	267	309
90°	160	297	330
Anisotropy	7.0%	12.5%	12.7%

Ultimate Strengths (MPa)

	AR	AR + ST	AR + ST + AG
0°	236	484	538
45°	231	416	450
90°	246	459	484
Anisotropy	6.2%	14.1%	16.4%

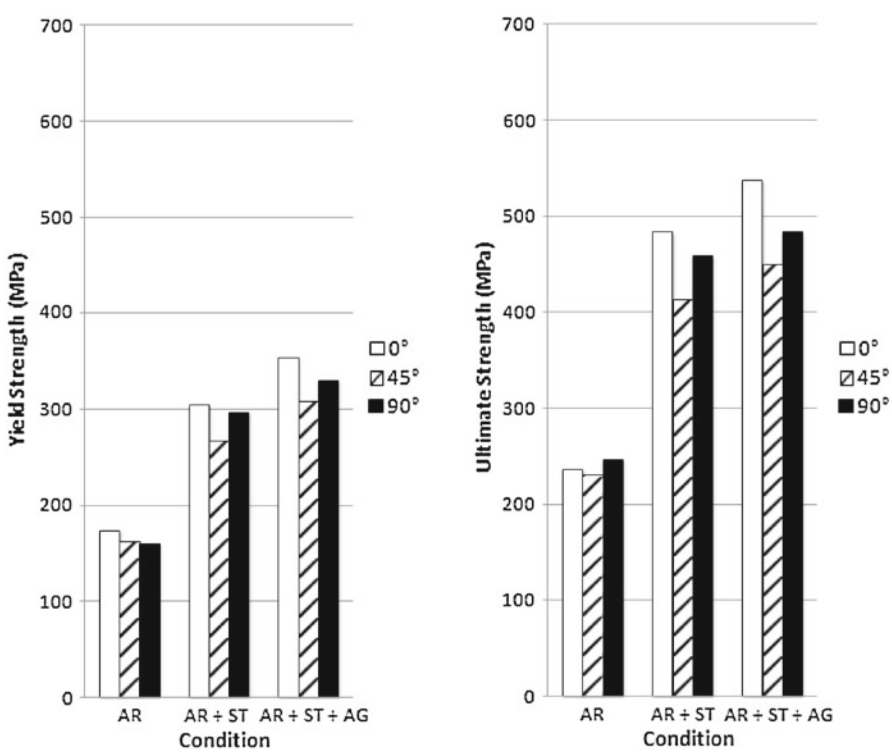


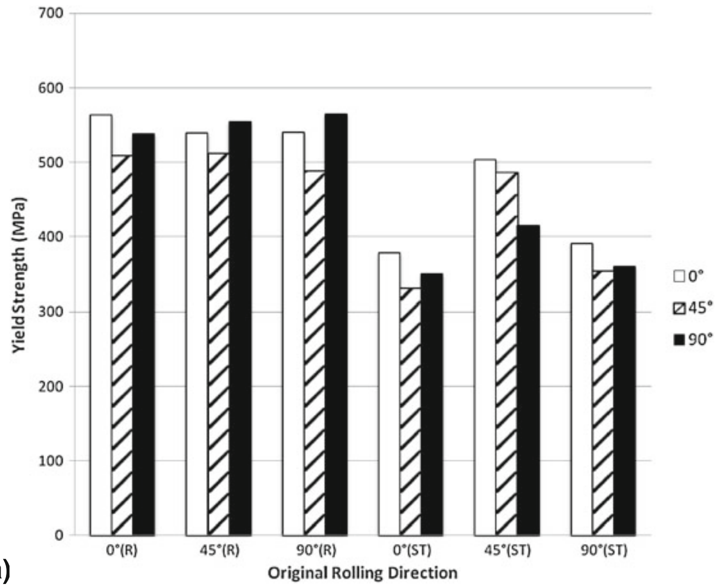
Fig. 3 Comparison of yield and ultimate strengths and anisotropies for as-received, solution treated, and aged 2195 alloy

Yield Strengths (MPa) R 6%

		angle of cold work		
		0° (R)	45°(R)	90° (R)
angle of tensile testing	0°	564	539	540
	45°	509	512	488
	90°	538	554	565
	Anisotropy	9.8%	7.6%	13.6%

Yield Strengths (MPa) ST 2.5-3%

	angle of cold work		
	0° (ST)	45° (ST)	90° (ST)
0°	378	504	391
45°	331	486	354
90°	350	415	360
Anisotropy	12.4%	17.7%	9.5%



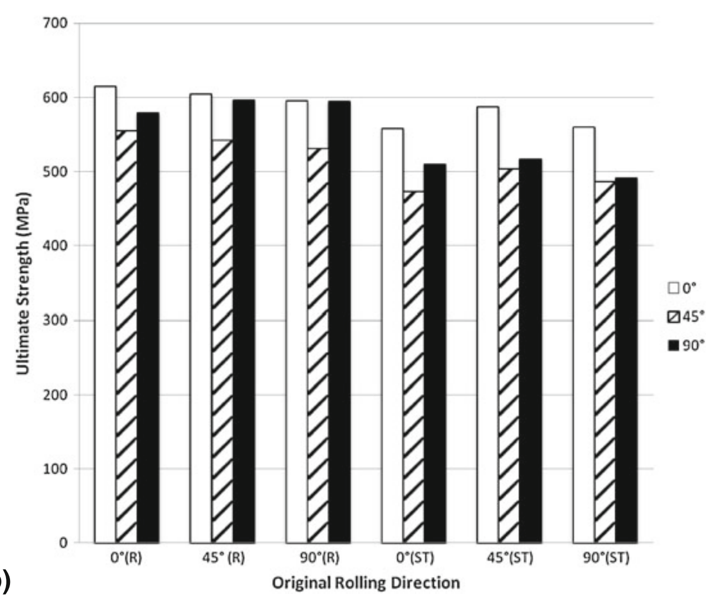
(a)

Ultimate Strengths (MPa) R 6%

		angle of cold work		
		0° (R)	45° (R)	90° (R)
angle of tensile testing	0°	615	604	595
	45°	555	542	531
	90°	579	596	594
	Anisotropy	9.8%	10.3%	10.8%

Ultimate Strengths (MPa) ST 2.5-3%

	angle of cold work		
	0° (ST)	45° (ST)	90° (ST)
0°	557	587	560
45°	473	504	486
90°	510	517	491
Anisotropy	15.1%	14.1%	13.2%



(b)

Fig. 4 Comparison of yield strengths (a) and ultimate strengths (b) for rolling 6% and stretching 2.5-3%

work (Ref 21, 24), while 45° stretching maximizes (17.6%) the anisotropic behavior (Ref 21). The anisotropy in ultimate strength is higher in stretched samples (13-15%) as compared to rolled samples (9-11%), Fig. 4(b). Again, the yield strength of the 2.5-3% stretched material in the 0° direction (378 MPa) is lower than that reported by Li et al. (Ref 1) (510 MPa), the ultimate tensile strengths however are comparable (∼551 MPa).

The effect of increasing the reduction in thickness from 6 to 24% after solution treatment and prior to aging is shown in Fig. 5(a) and (b). The strength values increased slightly in both yield and ultimate strengths. However, the anisotropy in yield strengths is more than doubled from 9-13.7% to 14.8-26%, Fig. 5(a).

In the study by Li et al. (Ref 1), specimens were solution-treated at 507 °C for 1 h, and quenched in ice water. The samples were immediately stretched parallel to the rolling direction (0° orientation) from 3 to 15% prior to aging at 190 °C for 24 h. The maximum yield strength after 15% stretch at (0-0) position (stretched and machined parallel to the original rolling direction) is ∼572 MPa and at the (0-90) position (stretched parallel to the rolling direction and machined perpendicular to it) is ∼537 MPa, Fig. 2. The ultimate strengths are 613 and 579 MPa, respectively. The values obtained from this study for the (0-0) orientation after rolling 6% are 564 and 615 MPa in yield and in ultimate strengths, and 598 and 665 MPa after 24% rolling, respectively, Fig. 5(a) and (b). Those obtained for the (0-90) orientation are 538 and 579 MPa in yield and in ultimate strengths after 6% reduction and 601 and 619 MPa after 24% reduction in thickness, respectively. The strength values obtained after 6% reduction are similar to the 15% pre-stretching (Ref 1) while 24% rolling are significantly superior. The percent elongation of the aged samples exhibited a constant value of ∼10% irrelevant of the amount of pre-stretch for both (0-0) and (0-90) orientations, (Ref 1). Also, in this study the percent elongation was always high, Table 2(a) to (d) even after 24% reduction in thickness prior to aging, Table 2(d). This alloy possesses significant improvement in ductility as compared to the 2090 and 2095 alloy systems (Ref 21).

An attempt was made to introduce 24 and 50% reduction in thickness by rolling after 507 °C, hour-long solution treatment and prior to 190 °C, 24 h aging. In 24% reduction in thickness process, many samples were badly curled and could not be machined, however, in the 50% reduction in thickness process, samples were straightened and machined into tensile bars. The results shown in Table 3(A) to (D) clearly indicated the onset of microcracking and most of the samples fractured outside the gauge length. It should be noted that applying a rolling deformation of 24% reduction in thickness to the previous solution and aging treatments retained the ductility of the material to high values of percent elongation, Table 2(d).

In a previous study (Ref 25), one group of samples used in this study was evaluated for crystallographic texture analysis. Three sets of samples were solution-treated at 507 °C for 30 min, water quenched, and rolled to 24% reduction in thickness in the 0°, 45°, and 90° directions to the original rolling direction, aged at 143 °C for 36 h (Fig. 5(a) and (b)) and were used for texture evaluation. Pole figures were generated and orientation distribution functions (ODF) were derived for this group as well as for the as-received sample (Ref 25).

The as-received sample exhibited a reasonable amount of typical FCC rolling texture. The texture indicates a large component of Brass {110}⟨112⟩ texture with an intensity of 20× random. Aluminum-lithium alloys have high intensity of the brass texture component which is directly proportional to the degree of mechanical anisotropy (Ref 17). It is not clear why grains with {110}⟨112⟩ lead to a high degree of anisotropy in the aluminum-lithium alloys, (Ref 22). Smaller Copper {112}⟨111⟩ and shear {111}⟨112⟩ components with an intensity of 5× random were also observed. Recrystallization texture components of Goss {110}⟨001⟩ with a texture intensity of ∼15× random, R {124}⟨211⟩ ∼10× random and P {110}⟨122⟩ 5× random were also apparent in the results. The texture components are significantly different when compared to those of the 2095 aluminum-lithium alloy (Ref 22). However, these components are typical deformation and recrystallization components present in Al-Li alloys (Ref 26-28).

Figure 6(a) shows the variation in the deformation texture for the as-received samples and samples rolled 24% reduction in thickness along the rolling direction (0°), and at 45° and 90° directions. The variation in recrystallization texture is shown in Fig. 6(b). The results indicate that rolling along the 0° orientation produces the largest Brass and Copper components. Rolling along the 0° direction also produced a relatively large (10× random) X {110}⟨111⟩ component and a lesser Rotated Brass component {110}⟨223⟩, ∼6× random. Rolling along the 90° produced a larger (10× random) Rotated Brass component than other orientations. The Brass component did not change (20× random), whereas the Copper was reduced to a minimum value. Rolling along the 45° resulted in the lowest Brass component.

Samples rolled at 0° produced higher Brass and Copper components and are associated with higher yield strength values, Fig. 5(a) and (b). In contrast, samples rolled at 45° resulted in lower Brass and Copper components and were associated with lower yield strength values, and samples rolled at 90° showed large variations in the Brass components and in the strength values.

These results are not in accord with the results of other researches (Ref 27, 28). The in-plane anisotropy in tensile stress is strongly influenced by the intensity of the Brass texture, {110}⟨112⟩. From Fig. 6(a), the Brass intensity is highest in the samples rolled along the 0° direction followed by the 90° rolling and the 45° rolling. The latter was expected to have the least anisotropy; however, it had the highest anisotropy (26.7%) in yield strength, Fig. 5(a).

4. Summary

Aluminum-lithium alloys exhibit strong crystallographic texture and are typically anisotropic. The anisotropic behavior of aluminum-lithium alloys during plastic forming is important and needs to be understood more clearly in all production and design steps (Ref 29, 30). Anisotropy is caused by several factors. These include elongated grains and the presence of second phase particles (Ref 17).

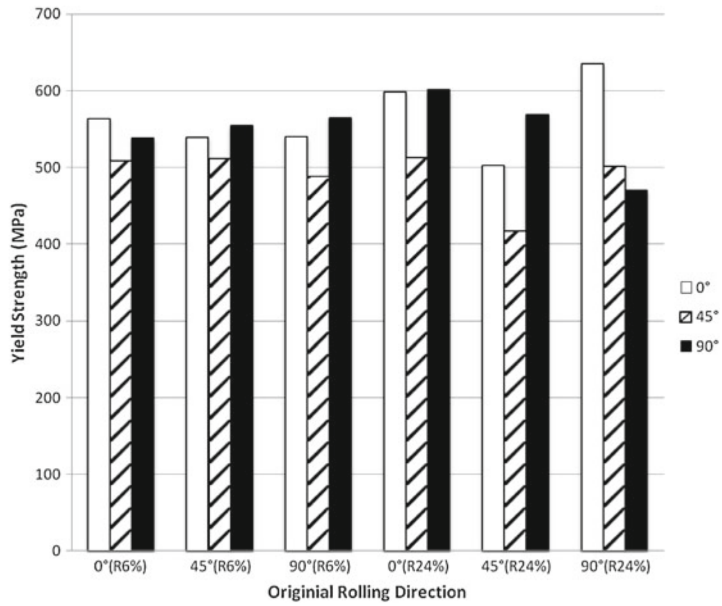
Crystallographic texture results from thermomechanical treatments like hot or cold rolling or stretching and is most directly responsible for anisotropy in metals (Ref 29-31). Kim and Lee (Ref 18) studied the effect of the inhomogeneous distribution of the T1 plate precipitates (Al_2CuLi) among four {111} habit planes after stretching and aging on the tensile properties of a 2090 aluminum-lithium alloy. Es-Said and Lee

Yield Strengths (MPa)
R 6%

angle of tensile testing	angle of cold work 0° (R)	45° (R)	90° (R)
0°	564	539	540
45°	509	512	488
90°	538	554	565
Anisotropy	9.8%	7.6%	13.6%

Yield Strengths (MPa)
R 24%

angle of tensile testing	angle of cold work 0° (R)	45° (R)	90° (R)
0°	598	503	635
45°	513	417	502
90°	601	569	470
Anisotropy	14.8%	26.7%	26.0%



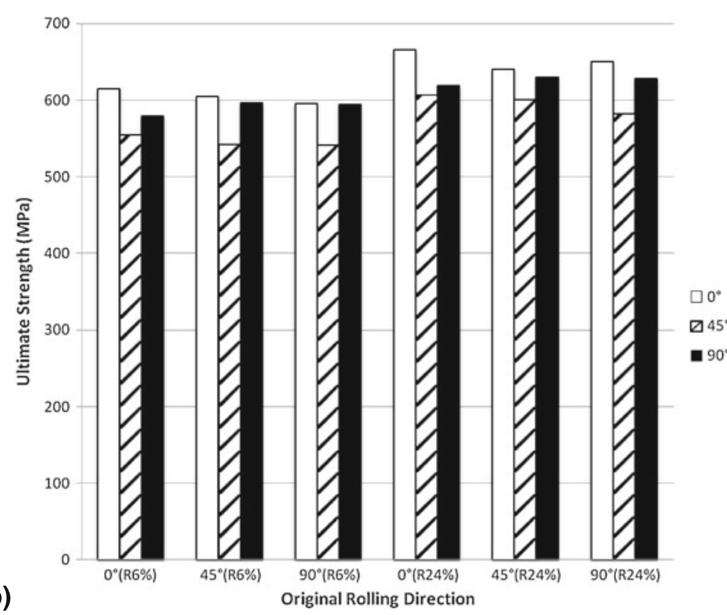
(a)

Ultimate Strengths (MPa)
R 6%

angle of tensile testing	angle of cold work 0° (R)	45° (R)	90° (R)
0°	615	604	595
45°	555	542	541
90°	579	596	594
Anisotropy	9.8%	10.3%	10.8%

Ultimate Strengths (MPa)
R 24%

angle of tensile testing	angle of cold work 0° (R)	45° (R)	90° (R)
0°	665	640	650
45°	607	600	582
90°	619	630	628
Anisotropy	8.7%	6.3%	10.5%



(b)

Fig. 5 Comparison of yield strengths (a) and ultimate strengths (b) for rolled 6% and rolled 24%

Table 2 Percent elongations of different conditions

Angle of tensile testing	AR, %	AR + ST, %	AR + ST + AG, %
(a) As-received, solution-treated, and aged samples			
0°	14.1	12.8	20.8
45°	17.9	32.2	35.4
90°	14.6	30.8	29.0

	Angle of cold work		
Angle of tensile testing	0°, %	45°, %	90°, %
(b) Stretched 2.5-3% samples			
0°	25.4	21.6	23.0
45°	34.8	28.5	33.3
90°	28.0	23.6	24.5
(c) Rolled 6% samples			
0°	14.7	11.7	8.4
45°	20.0	18.7	20.4
90°	12.0	16.8	11.4
(d) Rolled 24% samples			
0°	14.0	7.0	10.3
45°	17.2	14.5	16.4
90°	13.3	12.8	5.6

Table 3 Yield and ultimate strengths for rolling 24% and rolling 50%, solution treatment: 507 °C for 1 h and water quenched aging: 190 °C for 24 h and air-cooled

	Angle of cold work		
Angle of tensile testing	0°	45°	90°
(A) Yield strength (MPa) rolled 24%			
0°	617	450	613
45°	(a)	501	(a)
90°	569	(a)	430
(B) Ultimate strength (MPa) rolled 24%			
0°	661	516	642
45°	(a)	577	(a)
90°	615	(a)	430
(C) Yield strength (MPa) rolled 50%			
0°	351	254	617
45°	532	223	425
90°	570	366	400
(D) Ultimate strength (MPa) rolled 50%			
0°	387	553	633
45°	540	497	425
90°	588	481	400

(a) All samples were badly curled and unable to be machined into tensile samples

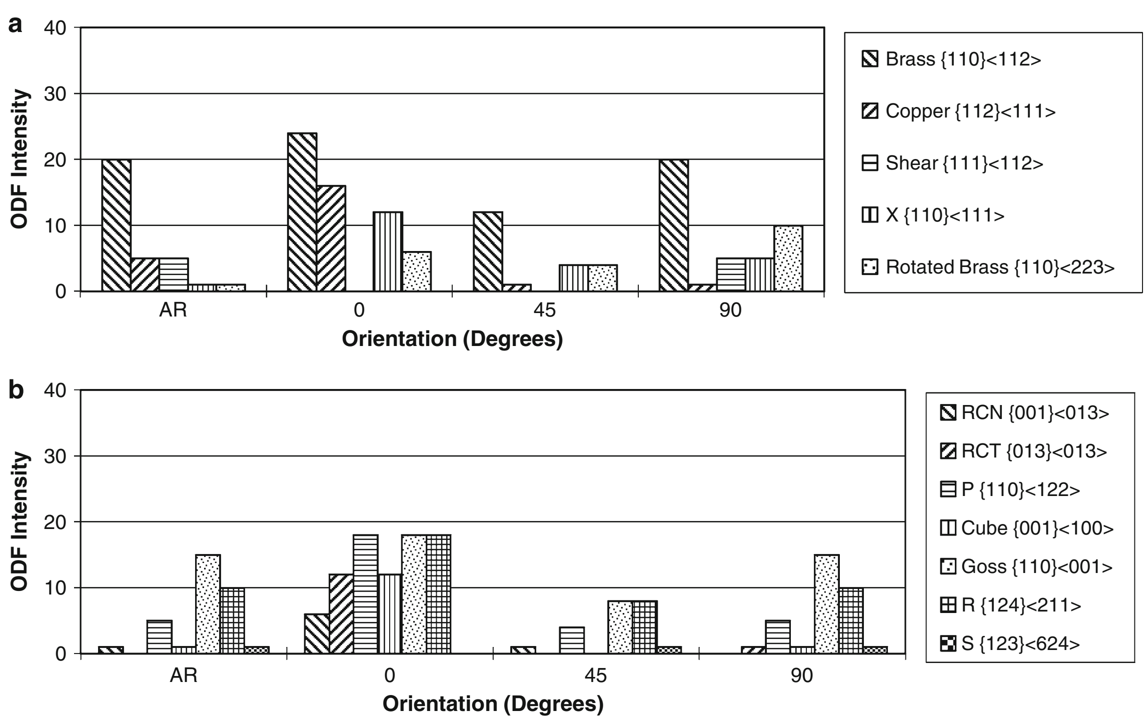


Fig. 6 Variation in texture components for the as-received and rolled in 0°, 45°, and 90° orientations. Deformation texture components are shown in (a). The recrystallization texture components are shown in (b) (Ref 16)

(Ref 21) studied the effect of stretching 2095 aluminum-lithium alloy at different angles with respect to the rolling direction prior to aging. They also studied the effect of 45° rolling prior to aging.

Their results (Ref 21) indicated that stretching along the 60° and 90° were more effective than other direction stretches in reducing the tensile anisotropy. The 45° rolling prior to aging was the most effective in reducing the tensile anisotropy. These results are also confirmed in this study. It appears that off-axis deformation produces a heterogeneous distribution of the primary strengthening T1 precipitates on specific habit planes. It is not clear why a 45° rolling or a 90° stretch would reduce the anisotropy. It might be that these off-axis deformations after aging treatments help produce favorable orientations in the T1 precipitates which prevent planar slip and results in homogenous deformations. A controlled stretch prior to aging is essential to accelerate precipitation of the strengthening phases to bring the yield strength to peak age levels (Ref 27); however, it appears that off-axis deformation has the potential of significantly reducing anisotropy. Probably these improvements in mechanical anisotropy will be brought about by the parts fabricators rather than the mil product producers (Ref 17). A fundamental study of characterizing the dislocation structure morphology after off-axis deformation prior to aging in aluminum-lithium alloys would clarify the origin of reduction in mechanical anisotropic behavior.

5. Conclusions

1. Solution treatment at 507 °C for 30 min and the subsequent aging at 143 °C for 36 h increases the strength but also increases the anisotropic mechanical behavior.
2. Stretching (2.5-3%) and rolling (6%) prior to aging increases the strength values. The anisotropy in yield strength is a minimum after 45° rolling and 90° stretching and maximum after 45° stretching.
3. Increasing the rolling deformation from 6 to 24% reduction in thickness increases the strength slightly at the expense of increasing the anisotropy significantly, however, ductility is retained.
4. Applying a rolling deformation of 24% (and 50%) reduction in thickness after a solution treatment at 507 °C for 1 h and prior to aging at 190 °C for 24 h induced microcracking.
5. The yield strength anisotropy for samples rolled at 24% reduction in thickness was highest for the 45° rolling, followed by the 90° rolling, and then by the 0° rolling. This was in a reverse trend to the increase of the Brass deformation texture component.

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