Characterizations of Aluminum Alloy Sheet Materials
Numisheet 2005

John C. Brem, Alcoa Laboratories, Material Science Research Division
Frederic Barlat, Alcoa Laboratories, Material Science Research Division
Robert E. Dick, Alcoa Laboratories, Rigid Packaging Division Technology
Jeong-Whan Yoon, Alcoa Laboratories, Material Science Research Division

Samples of aluminum alloys 6022-T43 (t = 1.000-mm) and 5182-O (t = 1.625-mm) were provided by Alcoa. Evaluations to determine the material characteristics of these sheet samples were performed at Alcoa Laboratories.

The equal biaxial mechanical behaviors were assessed using the instrumented hydraulic bulge test system. All tests were conducted at a constant true strain rate = 0.005/second with the extensometer oriented at 45° to the rolling direction of the sheet. The maximum values of stress and strain measured in these tests are summarized in Table 1, along with the Hollomon and Voce descriptions of the true membrane stress – true thickness strain (σ–ε) behaviors determined for each material.

Uniaxial tension tests were conducted using specimens taken at 0°, 15°, 30°, 45°, 60°, 75°, and 90° to the rolling direction of each sheet material. The 0.2% offset yield strength (YS), ultimate tensile strength (UTS), uniform and total elongations, and plastic strain ratios (r values) that were measured in the directional tests that were conducted for each material are listed in Table 2. The optimized Hollomon and Voce constants that describe the directional true stress – true plastic strain (σ–ε) behaviors of the materials are listed in Table 3. Microsoft Excel worksheets listing the directional engineering and true stress-strain relationships for each material are being sent in separate attachments.

Analyses of the elastic region of the engineering stress-strain curves measured in a separate series of tests in uniaxial tension for the longitudinal (0°) and transverse (90°) test directions were conducted to determine the modulus of elasticity and Poisson's ratio. These results are shown in Table 4.

Disk compression tests were performed for each sample using nominal 12.7-mm diameter x t specimens. Table 5 lists the biaxial r value (ε_{TD} / ε_{RD}) that was determined for each of the materials.

The mechanical behavior characteristics that were experimentally determined for each material in the various modes of deformation were used as input to yield criteria developed by F.Barlat, Alcoa in 2000 (Yld2000-2d) [1] and, most recently, in 2004 (Yld2004-18p) [2]. The material constants that describe the respective anisotropic yield surface shapes that were calculated for each sample based on the Yld2000-2d [1] yield function are shown in Table 6, while those for the Yld2004-18p [2] yield criterion are listed in Table 7. Additionally, Tables 8 and 9 list the material constants that define the yield surface shapes per Yld89 [3] using both stress-based and r value-based calculations. The stress-based and r value-based constants determined using Yld91 [4] are shown in Tables 10 and 11, respectively. The material constants determined with the Yld96 [5] criterion are shown in Table 12. See the attached Appendix for the material constants that are associated with each of the respective yield functions. In all cases, the reference stress state used to compute the yield function coefficients is the balanced biaxial state (i.e. $\sigma_b/\bar{\sigma}=1$).

The yield surface shape, as described by the Yld2000-2d [1] yield function, and the instantaneous strain hardening behavior measured experimentally in balanced biaxial tension for each respective sample were used as input to calculate a forming limit diagram (FLD). The limit strains that comprise each FLD were calculated according to the Marciniak-Kuczynski (MK) imperfection theory for strain localization [6]. The forming limit diagrams are illustrated in terms of true strains in Figures 1 and 2. The raw data are being sent separately as a Microsoft Excel attachment.

Standard x-ray techniques were used to assess the crystallographic texture attributes of each material. The Al(111), Al(200), and Al(220) pole figures and phi-sections that were measured in these analyses are shown in Figures 3 and 4, respectively, for each of the sheet materials. Collections of orientations (1000 grains) that are representative of the microstructures for these materials are being sent separately. The Euler angles, expressed in Bunge notation (phi-1, phi, and phi-2), that are contained in these files can be used for polycrystal-based modeling.

REFERENCES

[1] Barlat, F., Brem, J.C., Yoon, J.W., Chung, K., Dick, R.E., Lege, D.J., Pourboghrat, F., Choi, S.-H., Chu, E., 2003. Plane Stress Yield Function for Aluminum Alloy Sheets– Part I: Theory. Int. J. Plasticity 19, 1297-1319.

[2] Barlat, F., Aretz, H., Yoon, J.W., Karabin, M.E., Brem, J.C., Dick, R.E., 2004. Linear Transfomation-Based Anisotropic Yield Functions. Int. J. Plasticity, in press.

[3] Barlat, F., Lian, J., 1989. Plastic Behavior and Stretchability of Sheet Metals. Part I: A Yield Function for Orthotropic Sheets Under Plane Stress Conditions, Int. J. Plasticity 5, 51-66.

[4] Barlat, F., Lege, D.J., Brem, J.C., 1991. A Six-Component Yield Function for Anisotropic Materials, Int. J. Plasticity 7, 693-712.

[5] Barlat, F., Maeda, Y., Chung, K., Yanagawa, M., Brem, J.C., Hayashida, Y., Lege, D.J., Matsui, K., Murtha, S.J., Hattori, S., Becker, R.C., Makosey, S., 1997. Yield Function Development for Aluminum Alloy Sheets, J. Mech. Phys. Solids 45, 1727-1763.

[6] Marciniak, Z., Kuczynski, K., 1967. Limit Strain in the Process of Stretch Forming Sheet Metal. Int. J. Mech. Sci. 9, 609-620.

APPENDIX: YIELD FUNCTIONS

YLD89

$$\phi = a\left|K_1 + K_2\right|^m + a\left|K_1 - K_2\right|^m + c\left|2K_2\right|^m + = 2\bar{\sigma}^m$$

where

$$K_1 = \frac{\sigma_{xx} + h\sigma_{yy}}{2}$$
$$K_2 = \sqrt{\left(\frac{\sigma_{xx} - h\sigma_{yy}}{2}\right)^2 + p^2\sigma_{xy}^2}$$

The anisotropy coefficients are *a*, *c*, *h* and *p*. The exponent *m* is 6 for bcc materials and 8 for fcc materials.

YLD91

$$\phi = \phi(\tilde{\mathbf{s}}) = \left|\tilde{s}_1 - \tilde{s}_2\right|^m + \left|\tilde{s}_2 - \tilde{s}_3\right|^m + \left|\tilde{s}_3 - \tilde{s}_1\right|^m = 2\bar{\sigma}^m$$

where $\tilde{s}_k$ are the principal values of the tensor $\tilde{\mathbf{s}}$ defined by a linear transformation on the stress tensor $\boldsymbol{\sigma}$

$$\tilde{\mathbf{s}} = \mathbf{L}\boldsymbol{\sigma} = \frac{1}{3}\begin{bmatrix} b+c & -c & -b & 0 & 0 & 0 \\ -c & c+a & -a & 0 & 0 & 0 \\ -b & -a & a+b & 0 & 0 & 0 \\ 0 & 0 & 0 & 3f & 0 & 0 \\ 0 & 0 & 0 & 0 & 3g & 0 \\ 0 & 0 & 0 & 0 & 0 & 3h \end{bmatrix}\boldsymbol{\sigma}$$

The anisotropy coefficients are *a*, *b*, *c*, *f*, *g* and *h*. The exponent *m* is 6 for bcc materials and 8 for fcc materials.

YLD96 (plane stress)

$$\phi = \phi(\tilde{\mathbf{s}}) = \alpha_1\left|\tilde{s}_2 - \tilde{s}_3\right|^a + \alpha_2\left|\tilde{s}_3 - \tilde{s}_1\right|^a + \alpha_3\left|\tilde{s}_1 - \tilde{s}_2\right|^a = 2\bar{\sigma}^a$$

where $\tilde{s}_k$ are the principal values of the tensor $\tilde{\mathbf{s}}$ defined by a linear transformation on the stress tensor $\boldsymbol{\sigma}$

$$\tilde{\mathbf{s}} = \mathbf{L}\boldsymbol{\sigma} = \frac{1}{3}\begin{bmatrix} c_2+c_3 & -c_3 & -c_2 & 0 & 0 & 0 \\ -c_3 & c_3+c_1 & -c_1 & 0 & 0 & 0 \\ -c_2 & -c_1 & c_1+c_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3c_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3c_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3c_6 \end{bmatrix}\boldsymbol{\sigma}$$

The coefficient α_k are defined by

$$\alpha_k = \alpha_x p_{1k}^2 + \alpha_y p_{2k}^2 + \alpha_z p_{3k}^2$$
$$\alpha_z = \alpha_{z0}\cos^2 2\beta + \alpha_{z1}\sin^2 2\beta$$

where $\alpha_{z0} = 1$, the p_{ij} are the components of the transformation matrix from the principal axes of anisotropy (**x**, **y**, **z**) to the principal axes of $\tilde{\mathbf{s}}$ (**1**, **2**, **3**), and β represents the angle between the rolling direction **x** and the direction associated with the principal value of $\tilde{\mathbf{s}}$, $\tilde{s}_1$ and $\tilde{s}_3$ ($\tilde{s}_1 \geq \tilde{s}_3 \geq \tilde{s}_3$)

$$\cos\beta = \begin{cases} \mathbf{x}\cdot\mathbf{1} \; if \; |\tilde{s}_1| \geq |\tilde{s}_3| \; or \\ \mathbf{x}\cdot\mathbf{3} \; if \; |\tilde{s}_1| < |\tilde{s}_3| \end{cases}$$

Here, the dot denotes the scalar product. The anisotropy coefficients are the c_i, α_x, α_y and α_{z1}. The exponent a is 6 for bcc materials and 8 for fcc materials.

YLD2000-2D

$$\phi = \phi(\tilde{\mathbf{s}}', \tilde{\mathbf{s}}'') = |\tilde{s}_1' - \tilde{s}_2'|^a + |2\tilde{s}_2'' + \tilde{s}_1''|^a + |2\tilde{s}_1'' + \tilde{s}_2''|^a = 2\bar{\sigma}^a$$

where $\tilde{s}_k'$ and $\tilde{s}_k''$ are the principal values of the tensor $\tilde{\mathbf{s}}'$ and $\tilde{\mathbf{s}}''$ defined by two linear transformations on the stress deviator **s**

$$\tilde{\mathbf{s}}' = \mathbf{A}'\mathbf{s} = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_7 \end{bmatrix}\mathbf{s} \quad \text{and} \quad \tilde{\mathbf{s}}'' = \mathbf{A}''\mathbf{s} = \begin{bmatrix} \alpha_3 & 2\alpha_4 & 0 \\ 2\alpha_5 & \alpha_6 & 0 \\ 0 & 0 & \alpha_8 \end{bmatrix}\mathbf{s}$$

The anisotropy coefficients are the eight α_k. The exponent a is 6 for bcc materials and 8 for fcc materials.

YLD2004-18P

$$\phi = \phi(\tilde{\mathbf{s}}', \tilde{\mathbf{s}}'') = |\tilde{s}_1' - \tilde{s}_1''|^a + |\tilde{s}_1' - \tilde{s}_2''|^a + |\tilde{s}_1' - \tilde{s}_3''|^a + |\tilde{s}_2' - \tilde{s}_1''|^a + |\tilde{s}_2' - \tilde{s}_2''|^a + |\tilde{s}_2' - \tilde{s}_3''|^a + |\tilde{s}_3' - \tilde{s}_1''|^a + |\tilde{s}_3' - \tilde{s}_2''|^a + |\tilde{s}_3' - \tilde{s}_3''|^a = 4\bar{\sigma}^a$$

where $\tilde{s}_i'$ and $\tilde{s}_j''$ are the principal values of the tensors $\tilde{\mathbf{s}}'$ and $\tilde{\mathbf{s}}''$ defined by two linear transformations on the stress deviator **s**

$$\tilde{\mathbf{s}}' = \mathbf{C}'\mathbf{s} = \mathbf{C}'\mathbf{T}\boldsymbol{\sigma} = \mathbf{L}'\boldsymbol{\sigma}$$
$$\tilde{\mathbf{s}}'' = \mathbf{C}''\mathbf{s} = \mathbf{C}''\mathbf{T}\boldsymbol{\sigma} = \mathbf{L}''\boldsymbol{\sigma}$$

$\boldsymbol{\sigma}$ is the Cauchy stress tensor. $\mathbf{C}'$ and $\mathbf{C}''$ are the tensors containing the anisotropy coefficients

$$\mathbf{C}' = \begin{bmatrix} 0 & -c_{12}' & -c_{13}' & 0 & 0 & 0 \\ -c_{21}' & 0 & -c_{23}' & 0 & 0 & 0 \\ -c_{31}' & -c_{32}' & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44}' & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55}' & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66}' \end{bmatrix} \quad \mathbf{C}'' = \begin{bmatrix} 0 & -c_{12}'' & -c_{13}'' & 0 & 0 & 0 \\ -c_{21}'' & 0 & -c_{23}'' & 0 & 0 & 0 \\ -c_{31}'' & -c_{32}'' & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44}'' & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55}'' & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66}'' \end{bmatrix}$$

T is the transformation used to get the stress deviator from the stress tensor, i.e.,

$$\mathbf{T} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 \end{bmatrix}$$

The 18 anisotropy coefficients are the nine c_{pq}' and the nine c_{pq}''. The exponent a is 6 for bcc materials and 8 for fcc materials.

TABLE 1. 45° Equal Biaxial Tension Test Data (True Strain Rate = 0.005/s)						
Maximum Values		Hollomon: $\sigma = K \varepsilon^n$		Voce: $\sigma = A - B \exp(-C\varepsilon)$		
σ, MPa	ε	n	K, MPa	A, MPa	B, MPa	C
6022-T43 --- t = 1.000-mm						
362.5	0.516	0.255	448.58	363.44	234.67	7.278
5182-O --- t = 1.625-mm						
431.8	0.508	0.315	555.88	437.28	312.26	6.179

TABLE 2. Uniaxial Tension Test Data						
Test Direction	YS, MPa	UTS, MPa	% Elongation		r Value	r-bar
			Uniform	Total		
6022-T43 --- t = 1.000-mm						
0°	136.0	256.9	22.2	27.2	1.029	0.705
15°	136.0	253.4	22.8	26.9	1.010	
30°	134.7	251.7	24.0	28.4	0.703	
45°	131.2	247.6	24.8	29.4	0.532	
60°	129.8	241.9	25.0	28.2	0.553	
75°	128.9	239.8	24.9	28.5	0.689	
90°	127.6	238.3	24.0	27.6	0.728	
5182-O --- t = 1.625-mm						
0°	130.0	281.1	19.9	23.4	0.957	0.971
15°	128.0	279.8	23.1	24.1	0.903	
30°	126.1	272.9	21.9	26.7	0.916	
45°	124.9	268.9	23.7	27.6	0.934	
60°	124.8	267.5	23.1	27.0	0.947	
75°	126.4	269.5	22.7	28.1	0.981	
90°	128.2	273.8	24.6	26.0	1.058	

NOTE: r-bar = $(r_{0°} + 2r_{45°} + r_{90°}) / 4$

TABLE 3. True Stress – True Plastic Strain Descriptions – Uniaxial Tension						
Test Direction	Max ε_P	Hollomon: $\sigma = K\,\varepsilon^{n}$		Voce: $\sigma = A - B\exp(-C\varepsilon)$		
		n	K, MPa	A, MPa	B, MPa	C
6022-T43 --- t = 1.000-mm						
0°	0.196	0.258	479.92	339.05	202.50	10.357
15°	0.201	0.253	468.71	336.05	198.74	10.053
30°	0.210	0.252	463.44	336.95	199.26	9.557
45°	0.217	0.254	455.00	335.40	199.29	8.975
60°	0.218	0.252	443.31	328.64	194.78	8.864
75°	0.218	0.256	442.72	325.09	194.23	9.042
90°	0.210	0.258	442.45	322.13	193.64	9.196
5182-O --- t = 1.625-mm						
0°	0.177	0.319	586.72	366.84	251.07	11.166
15°	0.202	0.320	574.24	366.87	252.76	10.462
30°	0.193	0.322	561.38	361.29	248.42	10.062
45°	0.208	0.322	550.75	358.74	247.11	9.719
60°	0.203	0.323	545.76	355.56	244.73	9.638
75°	0.200	0.323	553.45	360.91	248.76	9.569
90°	0.216	0.318	557.10	362.39	248.11	9.981

TABLE 4. Engineering Stress-Strain Curve Analyses (Elastic Region)						
Material	Modulus, GPa			Poisson's Ratio		
	L	T	Avg.	L	T	Avg.
6022-T43 (1.000-mm)	70.9	69.4	70.2	0.368	0.358	0.363
5182-O (1.625-mm)	70.2	70.9	70.6	0.338	0.344	0.341

TABLE 5. Disk Compression Test Data	
r Value (Biaxial)	
6022-T43 (1.000-mm)	**5182-O (1.625-mm)**
1.149	0.948

TABLE 6. Material Constants for Yield Function Yld2000-2d (Exponent a=8)

Material	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
6022-T43 (1.000-mm)	0.938049	1.045181	0.929135	1.029875	0.987446	1.035941	0.952861	1.101099
5182-O (1.625-mm)	0.936033	1.078701	0.966889	1.004853	1.002609	1.016975	1.032625	1.114336

TABLE 7. Material Constants for Yield Function Yld2004-18p (Exponent a=8)

Material						
6022-T43 (1.000-mm)	c'_{12}	c'_{13}	c'_{21}	c'_{23}	c'_{31}	c'_{32}
	0.949886	1.109946	1.064143	1.328061	1.143103	1.253713
	c'_{44}	c'_{55}	c'_{66}	c''_{12}	c''_{13}	c''_{21}
	1.003310	1.002471	1.275242	0.917019	0.846874	0.908558
	c''_{23}	c''_{31}	c''_{32}	c''_{44}	c''_{55}	c''_{66}
	0.621073	0.735854	0.797399	1.013388	0.988851	0.521901
5182-O (1.625-mm)	c'_{12}	c'_{13}	c'_{21}	c'_{23}	c'_{31}	c'_{32}
	0.983762	0.710760	0.902832	0.507562	0.979320	0.985270
	c'_{44}	c'_{55}	c'_{66}	c''_{12}	c''_{13}	c''_{21}
	1.005394	0.994062	0.897646	0.894861	1.123328	1.062105
	c''_{23}	c''_{31}	c''_{32}	c''_{44}	c''_{55}	c''_{66}
	1.155056	0.751489	0.763667	0.998866	1.000015	1.094181

TABLE 8. Material Constants for Yield Function Yld89 (Exponent m=8) - Stress-Based				
Material	**a**	**c**	**h**	**p**
6022-T43 (1.000-mm)	0.741864	0.858579	1.068256	1.039155
5182-O (1.625-mm)	0.867393	0.991319	1.033910	1.065923

TABLE 9. Material Constants for Yield Function Yld89 (Exponent m=8) - r Value-Based				
Material	**a**	**c**	**h**	**p**
6022-T43 (1.000-mm)	1.344046	1.155261	1.097167	0.961368
5182-O (1.625-mm)	1.073010	1.079018	0.975305	0.973394

TABLE 10. Material Constants for Yield Function Yld91 (Exponent m=8) - Stress-Based						
Material	**a**	**b**	**c**	**f**	**g**	**h**
6022-T43 (1.000-mm)	1.065043	0.931500	1.012250	Isotropic Values = 1		1.013459
5182-O (1.625-mm)	1.033370	0.965741	1.015540			1.059716

TABLE 11. Material Constants for Yield Function Yld91 (Exponent m=8) - r Value-Based						
Material	**a**	**b**	**c**	**f**	**g**	**h**
6022-T43 (1.000-mm)	1.052492	0.946928	0.954701	Isotropic Values = 1		0.890503
5182-O (1.625-mm)	0.984944	1.015011	1.001573			0.986544

TABLE 12. Material Constants for Yield Function Yld96 (Exponent a=8 and c_4=c_5=1=Isotropic Values)				
6022-T43 (1.000-mm)	c_1	c_2	c_3	c_6
	1.026169	0.887357	1.010265	1.055135
	α_{x0}	α_{y0}	α_{z0}	α_{z1}
	1.341650	1.488900	1.000000	0.441500
5182-O (1.625-mm)	c_1	c_2	c_3	c_6
	1.057924	0.920731	1.016333	1.092887
	α_{x0}	α_{y0}	α_{z0}	α_{z1}
	0.820400	1.440000	1.000000	0.637560

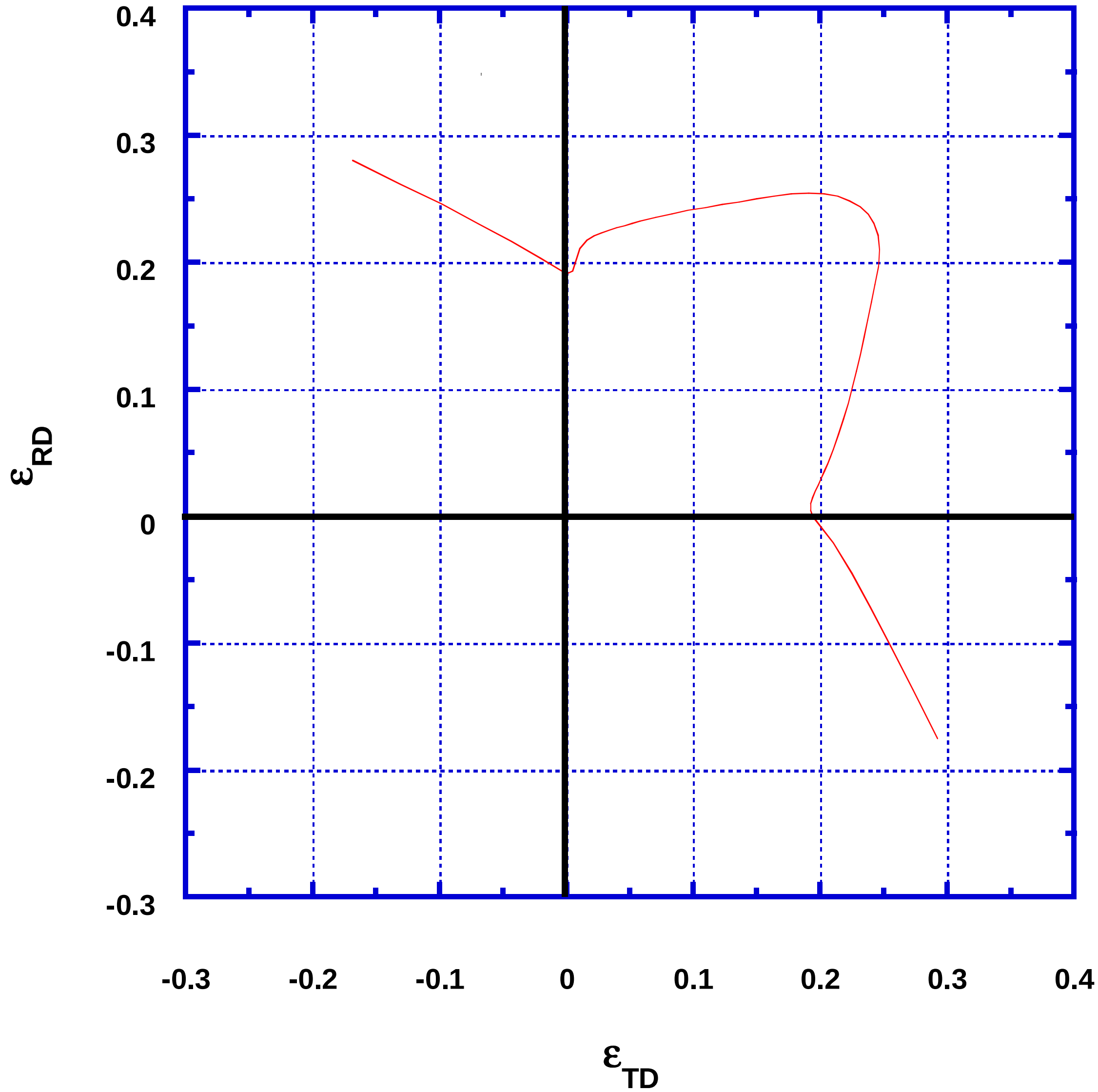


FIGURE 1. Predicted Forming Limit Diagram
Al Alloy 6022-T43 Sheet (t = 1.000-mm)

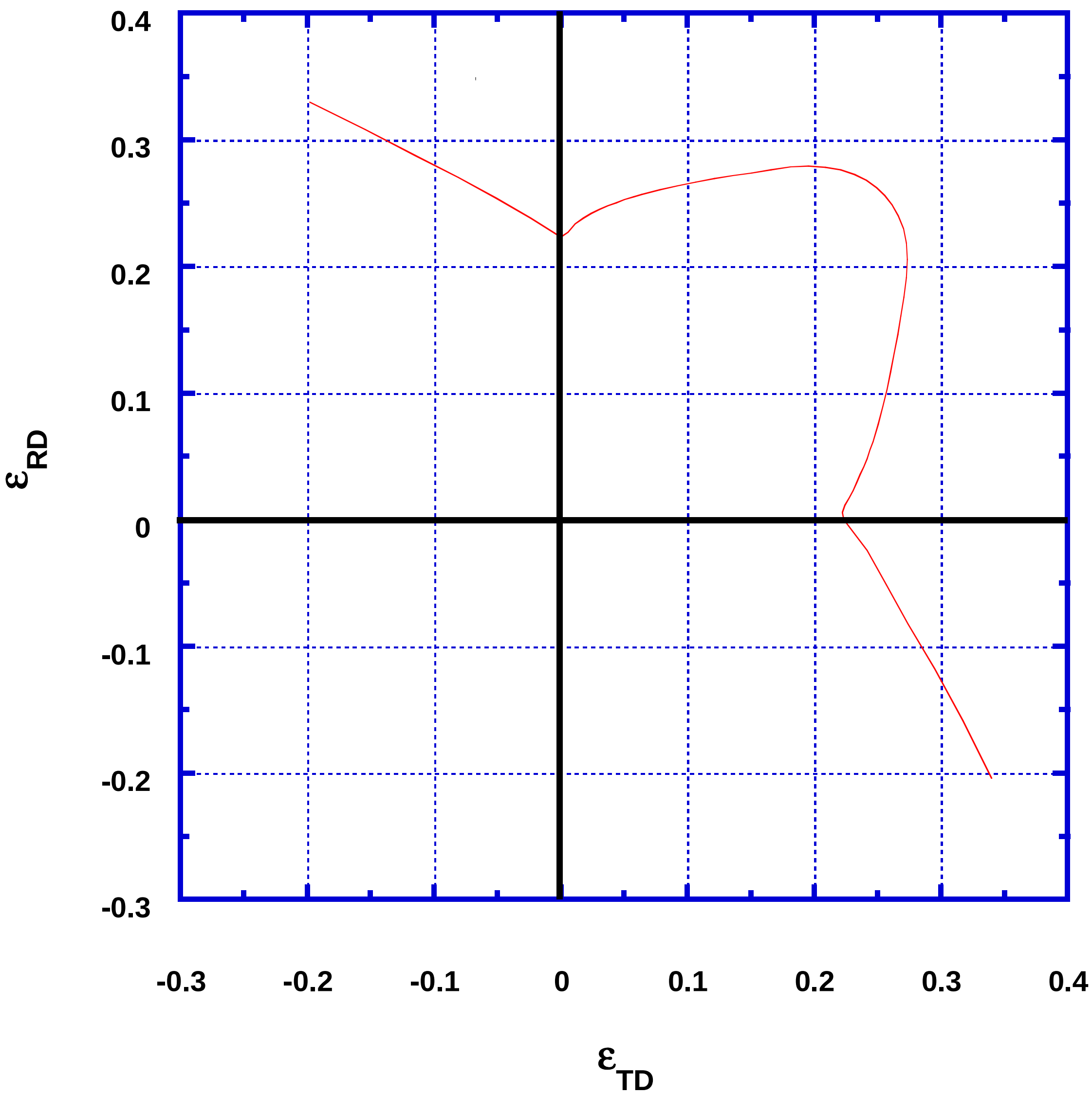
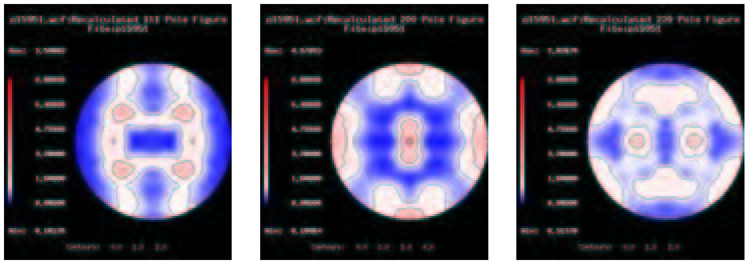


FIGURE 2. Predicted Forming Limit Diagram
Al Alloy 5182-O Sheet (t = 1.625-mm)

Recalculated Pole Figures

111 **200** **220**



Orientation Distribution Function

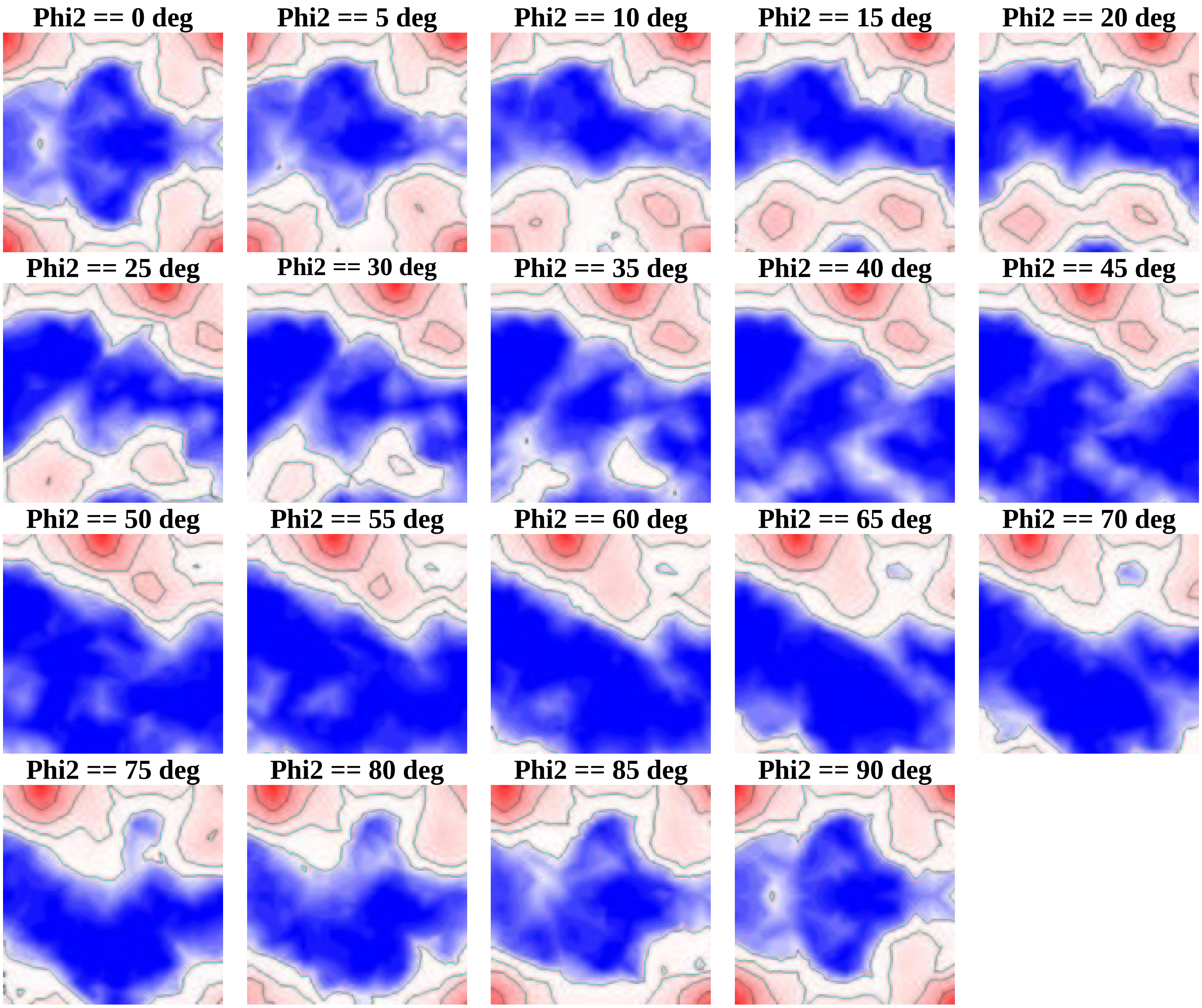


FIGURE 3. Crystallographic Texture
6022-T43 (t = 1.000-mm)

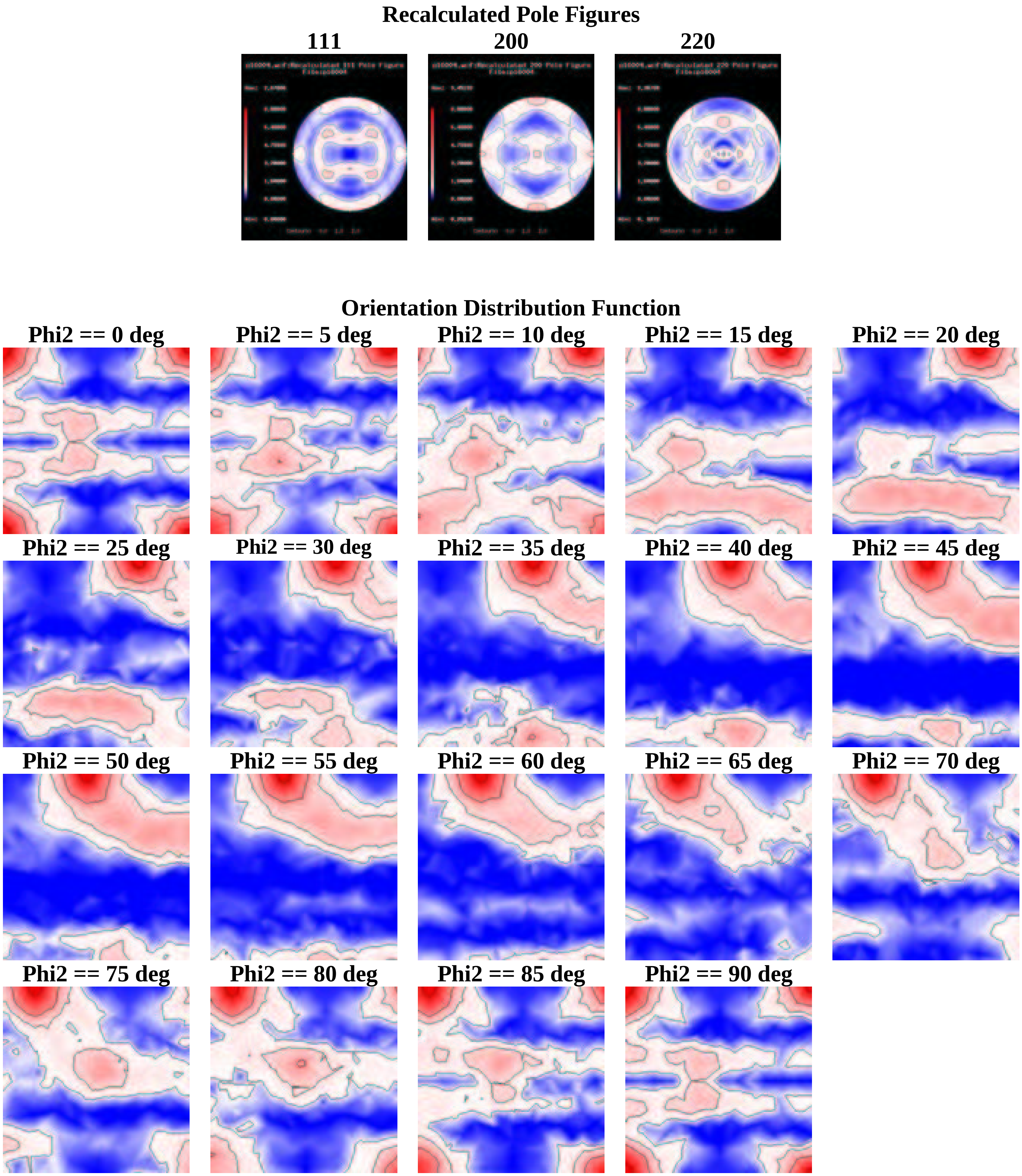


FIGURE 4. Crystallographic Texture
5182-O (t = 1.625-mm)