NASA TECHNICAL NOTE

NASA TN D-5413

c.1

NASA TN D-5413

CRYOGENIC FRACTURE PROPERTIES OF THIN AISI 301 60-PERCENT COLD-REDUCED SHEET AT VARIOUS ANGLES TO THE ROLLING DIRECTION

by Frederick D. Calfo

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1969

CRYOGENIC FRACTURE PROPERTIES OF THIN AISI 301 60-PERCENT COLD-REDUCED SHEET AT VARIOUS ANGLES TO THE ROLLING DIRECTION

By Frederick D. Calfo

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Fracture properties at various angles to the rolling direction in 0.022-in.-(0.056-cm-) thick AISI 301 60-percent cold-reduced stainless-steel sheet were determined. Specimens 3, 6, and 12 in. (7.6, 15.2, and 30.5 cm) wide were tested at -423°, -320°, and 70° F (20, 77, and 294 K). A gradual increase in yield and ultimate strengths was noted at all test temperatures as specimen orientation approached the transverse direction. Net fracture strength reductions of as much as 34 percent of the room temperature values were noted at cryogenic temperatures as the orientation of the cracked specimens approached the transverse direction.

CRYOGENIC FRACTURE PROPERTIES OF THIN AISI 301 60-PERCENT COLD-REDUCED SHEET AT VARIOUS ANGLES TO THE ROLLING DIRECTION

by Frederick D. Calfo
Lewis Research Center

SUMMARY

An experimental investigation was carried out to determine the fracture properties at various angles to the rolling direction in 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless-steel sheet. Specimens 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide were tested at -423°, -320°, and 70° F (20, 77, and 294 K). Critical crack lengths were measured with NASA continuity gages. The Griffith-Irwin theory was used to calculate fracture toughness values.

Fracture toughness values did not vary significantly with specimen width, which indicated that the small 3- by 12-inch (7.6- by 30.5-cm) specimens are of adequate size to determine fracture toughness for this material. No significant change in measured fracture toughness was noted for crack lengths varying from approximately 0.150 to 4.32 inches (0.381 to 10.98 cm). A gradual increase in yield and ultimate strengths was noted at all test temperatures as specimen orientation changed from the rolling direction to the transverse direction. Net fracture strength reductions of as much as 34 percent of the room temperature values were noted at cryogenic temperatures as the orientation of the cracked specimens approached the transverse direction.

INTRODUCTION

A number of austenitic stainless-steel alloys possess high strength-to-density ratios at very low temperatures. The 301 stainless-steel alloy in a cold-worked condition is such a high-strength material. It has good mechanical properties and corrosion-resistant characteristics. In view of its good formability, adequate weldability, and resistance to brittle fracture, the 301 stainless-steel alloy offers useful properties for engineering applications. Because of these properties, 301 stainless steel is used at subatmospheric temperatures in many applications such as liquid propellant tanks, storage vessels for natural gas, and equipment used in refrigeration and polymerization of hydrocarbons.

The usefulness of AISI 301 stainless steel for structural applications at cryogenic temperatures prompted the initiation of a research program at the NASA Lewis Research Center to study its fracture properties in 0.022-inch- (0.056-cm-) thick flat sheet in a 60-percent cold-reduced condition. The fracture toughness data were obtained at -320° and -423° F (77 and 20 K). Taken into consideration were such influential factors as sheet width, length of crack, and specimen orientation. Specimens 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide were tested to determine the minimum specimen size to ensure valid toughness values. Through-the-thickness slots of various lengths were fatigue cracked to simulate the most critical flaws the material would be expected to experience.

Previous investigations (refs. 1 and 2) disclosed that cold-rolled AISI 301 stainless-steel sheet is anisotropic, the transverse orientation being considerably more notch sensitive than the longitudinal orientation (rolling direction). Only the longitudinal and transverse orientations were studied. A previous NASA Lewis study (ref. 3) investigated AISI 301 stainless-steel tanks that were spiral welded with an 11° helix angle. In the present report, the effect of specimen orientation at various angles (including 11°) to the rolling direction on both notched and smooth properties was examined at 70°, -320°, and -423° F (294, 77, and 20 K).

The Griffith-Irwin theory (ref. 4) was used to determine the material toughness. At the present time, this theory appears to be the most appropriate method for calculating plane-stress fracture toughness.

MATERIAL

The test specimens were fabricated from AISI 301 stainless-steel 60-percent cold-reduced sheet with a nominal 0.022-inch (0.056-cm) thickness. The chemical analysis, as furnished by the material supplier, is given in table I.

TABLE I. - COMPOSITION OF AISI 301 60-PERCENT COLD-REDUCED STAINLESS STEEL

[Heat, 348 524.]

Composition, wt. %						
Carbon	Phospherus	Sulfur	Silicon	Chromium	Nickel	Manganese
0.11	0.23	0.009	0.60	17.26	7.10	1.44

The exact processing schedule for this heat of material is not available. However, the normal processing method employed by the material supplier for cold reducing this alloy is as follows: A continuous band of material 0.110 inch (0.279 cm) thick is normalized at 2050° F (1390 K) for approximately 60 seconds. A reversing mill is used to roll the material to 0.075 inch (0.191 cm) with three to four passes. Surface defects are removed by using a belt grinder. The material is then annealed at 1850° F (1278 K) for 30 seconds. Further thickness reduction is made by rolling the material to a nominal 0.060-inch (0.152-cm) thickness, followed by another annealing period of 30 seconds at 1850° F (1278 K). Final reduction to 0.022-inch- (0.056-cm-) thick sheet is made by passing the material through the reversing mill another four to seven times. The actual amount of cold reduction following the last annealing process was determined by the material supplier to be 64 percent.

TEST SPECIMENS

Sheet specimens for determining the effect of orientation to the rolling direction on mechanical properties and for determining fracture toughness properties are shown in figures 1 and 2. Both smooth and cracked tensile specimens for the directional study

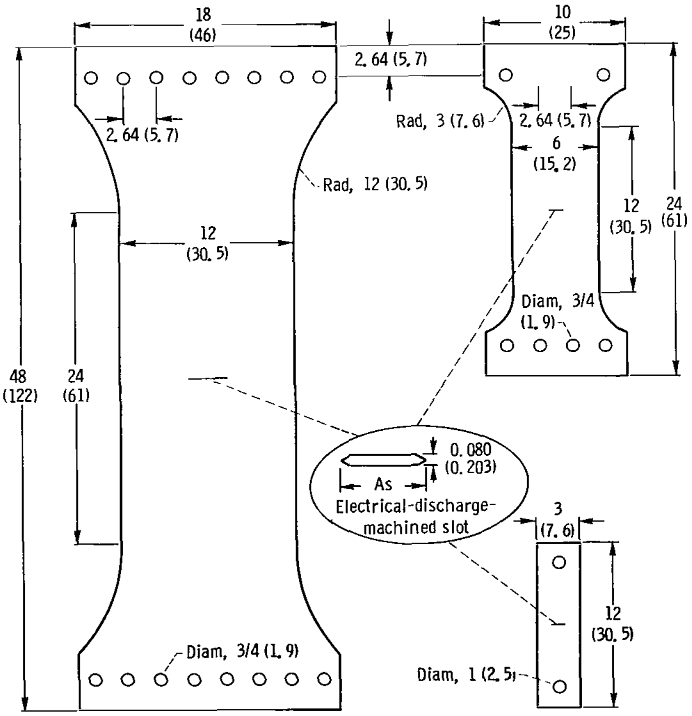
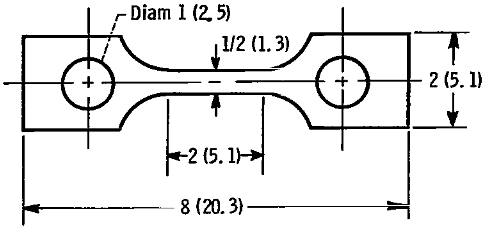
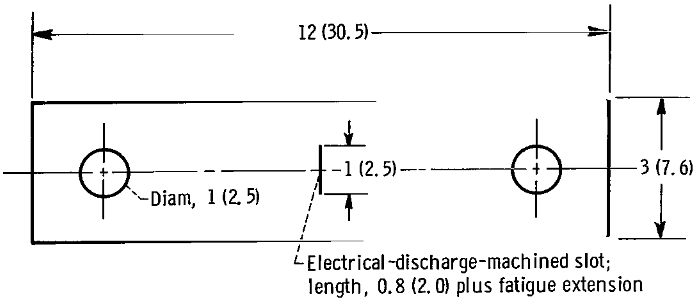


Figure 1. - Fracture toughness specimens. (All dimensions are in inches (cm).)



(a) Smooth specimen.



(b) Center-cracked specimen.

Figure 2. - Directional specimens. (All dimensions are in inches (cm).)

were machined at 0°, 11°, 28°, 45°, 62°, 79°, and 90° to the rolling direction. The 3-inch- (7.6-cm-) wide cracked tensile specimens were tested with nominal 1-inch (2.54-cm) cracks to determine the effect of specimen orientation on notch strength. Specimens tested to obtain fracture toughness values were 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide. Centrally located through cracks in these specimens ranged from 0.150 inch (0.381 cm) long to approximately one-third of the specimen width in length. The fracture toughness specimens were machined at 11° to the rolling direction of the material. This direction corresponded to the hoop direction in spiral-wound cylinders tested and reported in a previous NASA study (ref. 3). The cracked specimens were provided with various length center-through slots that were low-stress tension-tension fatigued to produce the desired crack lengths. The through slots were produced by electrical-discharge machining. The fatigue-cracking process followed the ASTM guideline (ref. 5) of less than 0.050-inch (0.127-cm) growth in the last 50 000 cycles. The fatigue crack length was controlled by using a single-element foil gage, as discussed in reference 3.

TEST APPARATUS AND PROCEDURE

The smooth directional specimens were tested in a 60 000-pound- (270 000-N-) capacity hydraulic tensile testing machine. Tests were conducted at 70°, -320°, and -423° F (294, 77, and 20 K). Cryogenic tests were conducted in a vacuum-jacketed

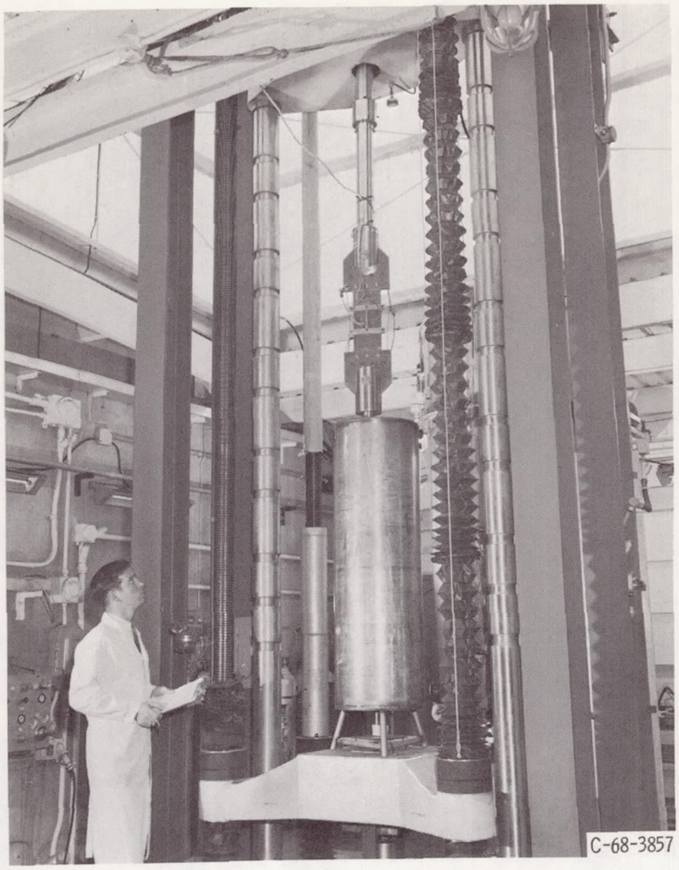
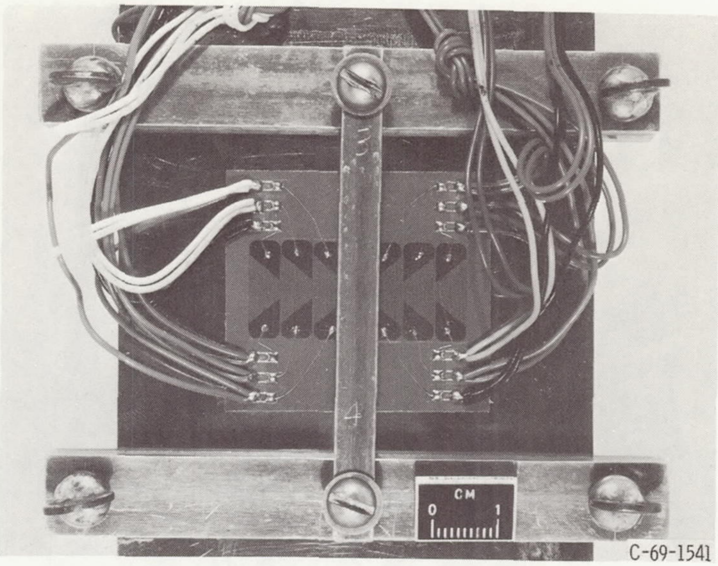


Figure 3. - 6-Inch- (15.2-cm-) wide specimen above cryogenic liquid container and 400 000-pound (1 780 000-N) testing machine.

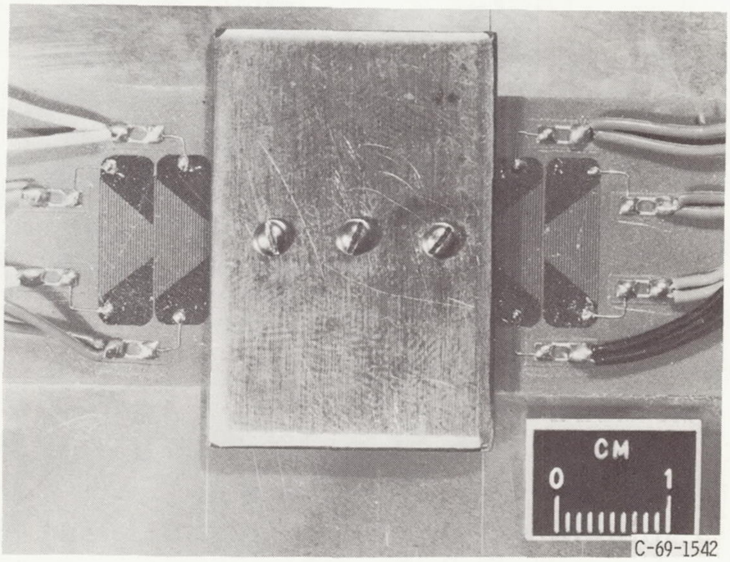
cryostat. Liquid level was maintained several inches above the upper specimen grip to ensure total immersion of the specimen in the cryogenic fluid. Each specimen was equipped with a differential transformer extensometer with a 2-inch (5.1-cm) gage length. The 3-inch- (7.6-cm-) wide specimens were tested at 70°, -320°, and -423° F (294, 77, and 20 K) in a 20 000-pound- (90 000-N-) capacity hydraulic tensile testing machine. The 6- and 12-inch- (15.2- and 30.5-cm-) wide specimens were tested at -320° and -423° F (77 and 20 K) in a 400 000-pound- (1 780 000-N-) capacity screw-powered tensile machine. The 400 000-pound (1 780 000-N) testing machine and the cryostat used for testing the 6-inch- (15.2-cm-) wide specimens are shown in figure 3.

Forman (ref. 6) found that measured plane-stress fracture toughness values were affected by lateral buckling of the edges of the crack out of the plane of the sheet. For this reason, an antibuckling fixture was clamped lightly to the surface of each specimen at the crack. This device minimized buckling of the plane of the sheet.

A vertical knife-edge fixture such as that shown in figure 4(a) was applied to the surface of the 3-, 6-, and 12-inch- (7.6-, 15.2-, and 30.5-cm-) wide specimens containing cracks less than 0.250 inch (0.64 cm) in length. The flat surface plate fixture, held to-



(a) For cracks less than 0.250 inch (0.64 cm) long.



(b) For cracks greater than 0.250 inch (0.64 cm) long.

Figure 4. - Antibuckling fixture.

gether with screws located through the machined slot, is shown in figure 4(b). This fixture was used for specimens containing cracks greater than 0.250 inch (0.64 cm) in length. The data points indicated by footnote b in table II were obtained with the fixture shown in figure 4(a), although the crack lengths were greater than 0.25 inch (0.64 cm). Insufficient crack support for these specimens is believed to have caused out-of-plane buckling, which resulted in premature fracture. Therefore, these data are not included in the calculation of plane-stress fracture toughness K_c.

Subcritical crack growth was measured by means of a multiple-element electrical

TABLE II. - FRACTURE PROPERTIES OF 3-, 6-, and 12-INCH- (7.6-, 15.2-, AND 30.5-CM-) WIDE SPECIMENS OF 0.022-INCH- (0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS STEEL

[Specimen orientation, 11° to the rolling direction.]

(a) U. S. Customary Units

Test temperature, °F	Specimen width, W, in.	Initial crack length, $2a_o$, in.	Critical crack length, 2a, in.	Critical crack length-to-width ratio, 2a/W	Gross fracture stress, σ, ksi	Net fracture strength,[a] σ_{ns}, ksi	Ratio of net fracture strength to yield strength, σ_{ns}/σ_{ys}	Nominal fracture toughness, K_{cn}, ksi $\sqrt{in.}$	Fracture toughness, K_c, ksi$\sqrt{in.}$	Indicated crack length, $2a_g$, in.
-320	2.948	0.498	0.752	0.255	159	214	0.895	166	217	0.893
	2.948	.488	.690	.234	157	205	.859	161	200	.807
	2.973	1.024	1.298	.437	110	196	.819	166	206	1.392
	2.974	1.027	1.322	.445	110	199	.831	167	211	1.419
	2.973	1.039	1.329	.447	110	200	.836	169	213	1.427
	5.998	.114	.150	.025	248	254	1.062	154	177	.618
	5.998	.258	----	----	198	---	-----	156	---	----
	5.999	1.007	1.344	.224	114	146	.612	156	[b]184	1.424
	5.999	2.006	2.418	.403	76.9	129	.539	153	[b]176	2.482
	12.00	.983	1.343	.112	126	142	.596	171	201	1.443
	12.00	1.998	2.343	.195	100	124	.518	189	207	2.442
	12.00	3.969	4.301	.358	68.1	106	.444	188	199	4.383
-423	3.006	0.135	-----	-----	232	---	-----	137	---	-----
	3.007	.267	0.340	0.080	192	216	0.815	146	166	0.489
	3.006	.263	.385	.128	192	220	.831	146	179	.572
	3.010	.264	.356	.118	194	220	.830	148	174	.519
	2.948	.496	.614	.208	156	197	.744	157	177	.748
	2.948	.515	.639	.217	149	190	.716	150	171	.760
	2.947	1.024	1.131	.384	106	172	.648	156	168	1.229
	2.947	1.024	1.258	.427	110	192	.726	163	194	1.387
	2.948	1.028	1.162	.394	110	182	.686	164	181	1.275
	5.999	.244	.340	.057	194	205	.775	140	166	.490
	6.000	.482	.739	.123	158	180	.680	153	191	.897
	5.999	1.014	1.197	.200	109	136	.513	147	[c]161	1.293
	5.999	2.027	2.232	.372	75.4	120	.453	150	[c]160	2.319
	12.00	.510	.731	.061	158	169	.636	157	188	.884
	12.00	.999	1.190	.099	120	133	.501	159	174	1.306
	12.00	1.973	2.219	.185	91.5	112	.424	170	181	2.337
	12.00	4.001	4.324	.360	64.3	101	.379	177	187	4.438

[a] Based on critical crack length.

[b] Insufficient crack support.

[c] No crack support.

TABLE II. - Concluded. FRACTURE PROPERTIES OF 3-, 6-, AND 12-INCH- (7.6-, 15.2- AND 30.5-CM-) WIDE SPECIMENS OF 0.022-INCH- (0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS STEEL

[Specimen orientation, 11° to the rolling direction.]

(b) SI Units

Test temperature, K	Specimen width, W, cm	Initial crack length, $2a_o$, cm	Critical crack length, 2a, cm	Critical crack length-to-width ratio, 2a/W	Gross fracture stress, σ, kN/cm^2	Net fracture strength[a], σ_{ns}, kN/cm^2	Ratio of net fracture strength to yield strength, σ_{ns}/σ_{ys}	Nominal fracture toughness, K_{cn}, kN $\sqrt{m}/m^2$	Fracture toughness, K_c, MNm$^{-3/2}$	Indicated crack length, $2a_g$, cm
77	7.488	1.265	1.910	0.255	109	148	0.895	182	238	2.268
	7.488	1.240	1.753	.234	108	141	.859	177	220	2.050
	7.551	2.601	3.297	.437	75.8	135	.819	182	226	3.536
	7.554	2.609	3.358	.445	75.8	137	.831	184	232	3.604
	7.551	2.639	3.376	.447	75.8	138	.836	186	234	3.625
	15.235	.290	.381	.025	171	175	1.062	169	195	1.570
	15.235	.655	----	----	137	---	-----	171	---	------
	15.237	2.558	3.414	.224	78.6	101	.612	171	[b]202	3.617
	15.237	5.095	6.142	.403	53.0	88.9	.539	168	[b]193	6.304
	33.00	2.497	3.411	.112	86.9	97.9	.596	188	221	3.665
	33.00	5.075	5.951	.195	69.0	85.5	.518	208	227	6.203
	33.00	10.081	10.925	.358	47.0	73.1	.444	207	219	11.133
20	7.635	0.343	------	-----	160	-----	-----	151	----	------
	7.638	.678	0.864	0.080	132	149	0.815	160	182	1.242
	7.635	.668	.978	.128	132	152	.831	160	197	1.453
	7.645	.671	.904	.118	134	152	.830	163	191	1.318
	7.488	1.260	1.560	.208	108	136	.744	173	195	1.890
	7.488	1.308	1.623	.217	103	131	.716	165	188	1.930
	7.485	2.601	2.873	.384	73.1	119	.648	171	185	3.122
	7.485	2.601	3.195	.427	75.8	132	.726	179	213	3.523
	7.488	2.611	2.951	.394	75.8	125	.686	180	199	3.239
	15.237	.620	.864	.057	134	141	.775	154	182	1.245
	15.240	1.224	1.877	.123	109	124	.680	168	210	2.278
	15.237	2.576	3.040	.200	75.2	93.8	.513	162	[c]177	3.284
	15.237	5.149	5.670	.372	52.0	82.7	.453	165	[c]176	5.890
	33.00	1.295	1.857	.061	109	117	.636	173	207	2.245
	33.00	2.537	3.023	.099	82.7	91.7	.501	175	191	3.317
	33.00	5.011	5.636	.185	63.1	77.2	.424	187	199	5.936
	33.00	10.163	10.983	.360	44.3	69.6	.379	195	206	11.273

[a] Based on critical crack length.

[b] Insufficient crack support.

[c] No crack support.

resistance continuity gage mounted at the tip of the crack. Reference 7 gives more detailed information concerning the NASA continuity gage. The analytical correction equation given in equation (1) of this reference was used to correct all crack-length data.

ANALYTICAL PROCEDURE

The Griffith-Irwin expression (ref. 4) for the relation between fracture toughness and failure stress for an infinitely wide sheet with a central crack is

$$K_c = \sigma\sqrt{\pi a} \tag{1}$$

where σ is the gross failure stress normal to the crack, and a is one-half the critical crack length. A modified Griffith-Irwin expression can be used to account for the finite width of the sheet and for the plastic zone that is usually present at the crack tip. Using the secant width correction factor presented by Feddersen in the discussion portion of reference 5 gives the equation

$$K_c = \sigma\sqrt{\pi\bar{a} \sec\frac{\pi\bar{a}}{W}} \tag{2}$$

where

$$\bar{a} = a + \frac{1}{2\pi}\left(\frac{K_c}{\sigma_{ys}}\right)^2$$

In equation (2), W is the specimen width, and σ_{ys} is the 0.2-percent offset yield strength of the material. When the critical crack length is not known, a nominal fracture toughness is sometimes determined by using the initial half-crack length a_o. The equation for such a nominal fracture toughness is

$$K_{cn} = \sigma\sqrt{\pi\bar{a}_o \sec\frac{\pi\bar{a}_o}{W}} \tag{3}$$

where

$$\bar{a}_o = a_o + \frac{1}{2}\left(\frac{K_{cn}}{\sigma_{ys}}\right)^2$$

RESULTS AND DISCUSSION

Smooth Properties

The 0.2-percent yield and ultimate strength properties of the material are shown in figure 5. The yield and ultimate strengths are plotted as a function of angle to the rolling direction for tests at -423°, -320°, and 70° F (20, 77, and 294 K).

The average values of yield and ultimate strength were determined from at least three tests at the given specimen orientation for each test temperature. Table III gives the individual test results. The yield strengths, in general, show a gradual increase as the specimen orientation approaches the transverse direction. Comparing the average longitudinal yield strength at -423° F (20 K) of 258 ksi (178 kN/cm^2) with the average transverse (90°) value of 293 ksi (202 kN/cm^2) shows a 12-percent increase. A similar comparison of the -320° F (77 K) data shows an 11-percent increase. Only slight variations appeared in the room temperature data for those orientation tested.

Ultimate strengths varied less with specimen orientation than did the yield strengths. Examination of the results presented in figure 5 shows a minimum value occurring at about 45°. However, for some unexplained reason, the scatter of the data at this orientation was considerably greater than that for the other orientations and may account for the low average value. The average transverse strength at -423° F (20 K) exceeded the

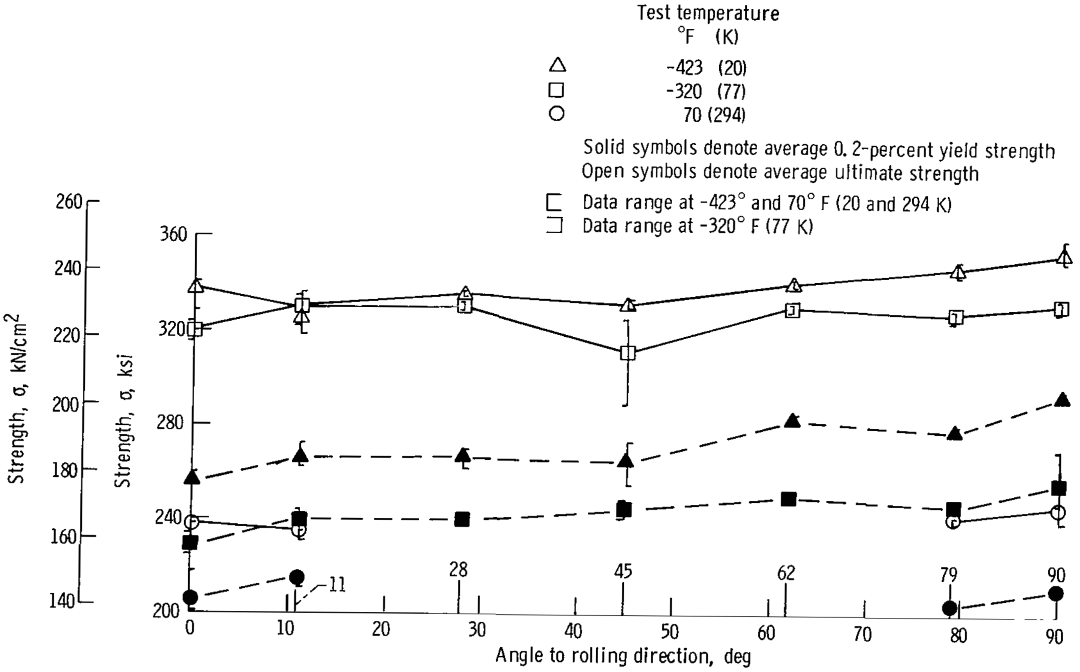


Figure 5. - Variation of yield strength and ultimate strength with angle to rolling direction for 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless-steel sheet.

TABLE III. - SMOOTH PROPERTIES OF 0.022-INCH- (0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS-STEEL SHEET AT VARIOUS ANGLES TO ROLLING DIRECTION

(a) U. S. Customary Units

Test temperature, °F	Angle to rolling direction, deg	0.2-Percent yield strength, σ_{ys}, ksi	Ultimate strength, σ_u, ksi
70	0	198	239
		202	239
		219	238
Average		206	239
70	11	217	239
		212	231
		216	238
Average		215	236
70	79	204	241
		199	239
		205	240
Average		203	240
70	90	212	247
		212	245
		211	245
Average		212	246
-320	0	235	324
		228	320
		226	317
Average		230	320
-320	11	234	331
		242	329
		243	328
Average		239	329
-320	28	239	330
		239	330
		241	329
Average		240	330
-320	45	248	288
		243	327
		242	321
Average		244	312
-320	62	250	330
		250	329
		250	329
Average		250	329
-320	79	246	327
		243	329
		249	329
Average		246	328
-320	90	240	333
		254	329
		271	332
Average		255	331
-423	0	261	329
		256	341
		256	341
Average		258	337
-423	11	257	324
		275	321
		263	324
		267	320
Average		265	322
-423	28	261	334
		270	336
		267	334
Average		266	335
-423	45	274	329
		255	329
		268	334
Average		266	331
-423	62	282	341
		281	339
		286	339
Average		283	340
-423	79	277	344
		279	344
		279	350
Average		278	346
-423	90	292	349
		293	359
		294	352
Average		293	353

TABLE III. - Concluded. SMOOTH PROPERTIES OF 0.022-INCH-(0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS-STEEL AT VARIOUS ANGLES TO ROLLING DIRECTION

(b) SI Units

Test temperature, K	Angle to rolling direction, deg	0.2-Percent yield strength, σ_{ys}, kN/cm^2	Ultimate strength, σ_u, kN/cm^2
294	0	137	165
		139	165
		151	164
Average		142	165
294	11	150	165
		146	159
		150	164
Average		148	163
294	79	141	166
		137	165
		141	165
Average		140	165
294	90	146	170
		146	169
		145	169
Average		146	170
77	0	162	223
		157	221
		156	219
Average		159	221
77	11	161	228
		167	227
		168	226
Average		165	227
77	28	165	228
		165	228
		166	227
Average		165	228
77	45	171	199
		168	225
		167	221
Average		168	215
77	62	172	228
		172	227
		172	227
Average		172	227
77	79	170	225
		168	227
		172	227
Average		170	226
77	90	165	230
		175	227
		187	229
Average		176	228
20	0	180	227
		177	235
		177	235
Average		178	232
20	11	177	223
		190	221
		181	223
		184	221
Average		183	222
20	28	180	230
		186	232
		184	230
Average		183	231
20	45	190	227
		176	227
		185	230
Average		183	228
20	62	194	235
		194	234
		197	234
Average		195	234
20	79	191	237
		192	237
		192	241
Average		192	239
20	90	201	241
		202	248
		203	243
Average		202	243

average longitudinal value by 5 percent. At -320° F (77 K), the difference was only 3 percent.

The effect of specimen orientation on both yield and ultimate strength seemed to be more pronounced at cryogenic temperatures. This effect may be associated with the martensitic formation that has been found to accompany tensile strain at low temperatures in this material. This phenomenon, which tends to strengthen the material, varies with specimen orientation.

Net Fracture Strength

Resistance to brittle fracture appears to be highly directional. The data presented in figure 6 were obtained from 3-inch- (7.6-cm-) wide specimens with nominal 1-inch (2.54-cm) center cracks. Examination of the room temperature data shows an apparent maximum net fracture strength at about 28° to the rolling direction, with the lowest value in the transverse direction. The specimens tested at -320° and -423° F (77 and 20 K) retained approximately 90 percent of the room temperature net fracture strength at the rolling direction orientation. However, the net fracture strengths at cryogenic temperature for the transverse direction were only about 65 percent of the room temperature values. Based on these data, a helix angle of up to 28° appears to be suitable for the spiral-weld tank configuration without a significant loss in notch strength being suffered.

This high transverse notch sensitivity is believed to be associated with two important factors. The first, previously mentioned with regard to the smooth tensile properties, is the anisotropy that is manifested in the material properties. Commonly referred to as crystallographic anisotropy, it deals with the arrangement of atoms or crystals that occur

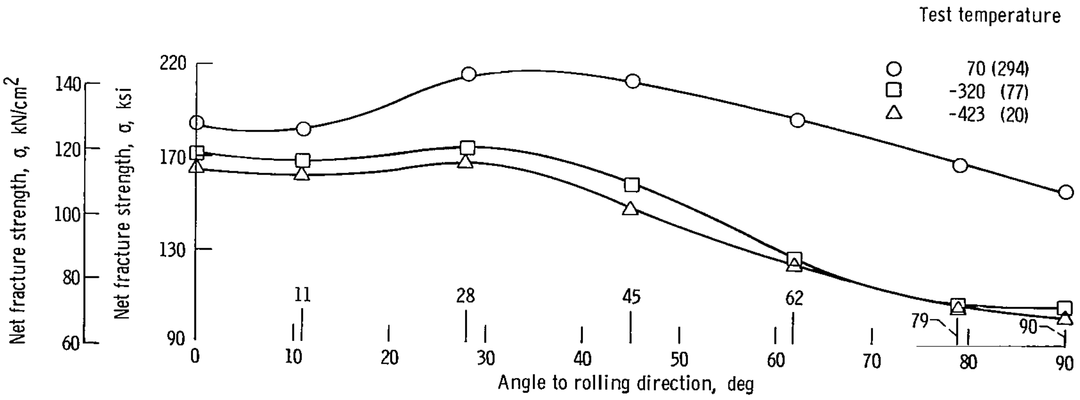


Figure 6. - Variation of net fracture strength (based on initial crack length) with angle to rolling direction for 0.022-inch- (0.056-cm-) thick AISI 301 for 60-percent cold-reduced stainless-steel 3-inch- (7.6-cm-) wide specimens with nominal 1-inch (2.54-cm) cracks.

TABLE IV. - FRACTURE PROPERTIES OF 3-INCH- (7.6-CM-) WIDE SPECIMENS OF 0.022-INCH- (0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS STEEL AT VARIOUS ANGLES TO ROLLING DIRECTION

(a) U. S. Customary Units

Test temperature, °F	Angle to rolling direction, deg	Thickness, in.	Initial crack length, $2a_0$, in.	Gross fracture stress, σ, ksi	Net fracture strength,[a] σ_{ns}, ksi	Ratio of net fracture strength to yield strength, σ_{ns}/σ_{ys}
70	0	0.0226	1.003	122	184	0.855
	11	.0227	.966	123	182	.846
	28	.0223	1.016	136	206	.958
	45	.0227	1.006	135	203	.944
	62	.0224	1.018	124	187	.869
	79	.0224	1.020	111	168	.781
	90	.0226	1.026	104	158	.734
-320	0	0.0225	0.992	115	171	0.715
	11	.0229	1.027	110	168	.702
	28	.0224	1.029	114	174	.728
	45	.0226	1.014	105	159	.665
	62	.0224	1.010	84.2	127	.531
	79	.0225	1.012	71.1	107	.447
	90	.0225	1.025	70.7	107	.447
-423	0	0.0225	1.017	109	165	0.622
	11	.0227	1.024	106	162	.611
	28	.0223	1.034	110	168	.633
	45	.0224	1.010	98.1	148	.558
	62	.0224	1.009	82.7	125	.471
	79	.0224	1.010	71.5	107	.403
	90	.0226	1.034	67.4	103	.388

[a] Based on initial crack length.

TABLE IV. - Concluded. FRACTURE PROPERTIES OF 3-INCH- (7.6-CM-) WIDE SPECIMENS OF 0.022-INCH- (0.056-CM-) THICK AISI 301 60-PERCENT COLD-REDUCED STAINLESS STEEL AT VARIOUS ANGLES TO ROLLING DIRECTION

(b) Si Units

Test temperature, K	Angle to rolling direction, deg	Thickness, cm	Initial crack length, $2a_0$, cm	Gross fracture stress, σ, kN/cm^2	Net fracture strength,[a] σ_{ns}, kN/cm^2	Ratio of net fracture strength to yield strength, σ_{ns}/σ_{ys}
294	0	0.0574	2.547	84.1	127	0.855
	11	.0577	2.454	84.8	125	.846
	28	.0566	2.581	93.8	142	.958
	45	.0577	2.555	93.1	140	.944
	62	.0569	2.586	85.5	129	.869
	79	.0569	2.591	76.5	116	.781
	90	.0574	2.606	71.7	109	.734
77	0	0.0572	2.520	79.3	118	0.715
	11	.0582	2.609	75.8	116	.702
	28	.0569	2.614	78.6	120	.728
	45	.0574	2.576	72.4	110	.665
	62	.0569	2.565	58.1	87.6	.531
	79	.0572	2.570	49.0	73.8	.447
	90	.0572	2.604	49.7	73.8	.447
20	0	0.0572	2.583	75.2	114	0.622
	11	.0577	2.601	73.1	112	.611
	28	.0566	2.626	75.8	116	.633
	45	.0569	2.565	67.6	102	.558
	62	.0569	2.563	57.0	86.2	.471
	79	.0569	2.565	49.3	73.8	.403
	90	.0574	2.626	46.5	71.0	.388

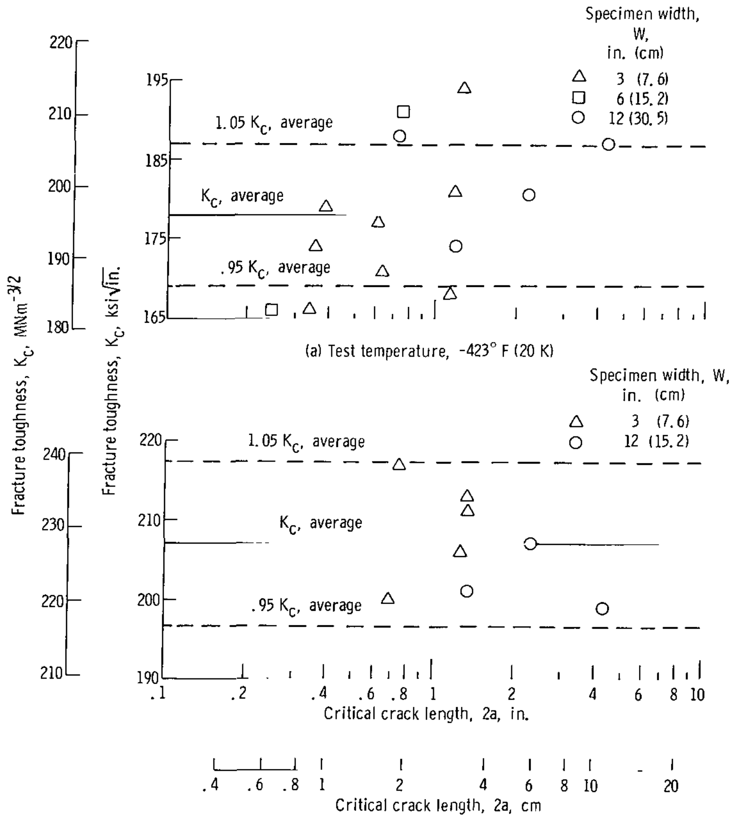
[a] Based on initial crack length.

in multiphase microstructures. Differences in the longitudinal and transverse ductilities in steels have been related to this metallurgical characteristic. The second factor that may influence resistance to brittle fracture is concerned with the extent of high stress concentration near the crack tip and its relation to the transformation of the austenitic phase to martensite in this metastable alloy when tested at cryogenic temperatures. These factors, along with the variation of crack orientation to rolling direction and grain boundaries, produce a complex interrelation that affects the directional properties of this sheet material.

The ratios of net fracture strength to yield strength are given in table IV. This ratio is sometimes used as an indication of notch toughness. By this measure, a relatively high degree of toughness is maintained up to about 45° to the rolling direction for all test temperatures.

Fracture Toughness Data

The fracture test data are listed in table II. In figures 7(a) and (b), the plane-stress



(a) Test temperature, -423° F (20 K)

(b) Test temperature, -320° F (77 K).

Figure 7. - Fracture toughness as function of critical crack length for 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless steel. Specimen orientation, 11° to rolling direction.

fracture toughness K_c is plotted as a function of the critical crack length $2a$ for -320° and -423° F (77 and 20 K), respectively. An average fracture toughness of 178 ksi$\sqrt{\text{in.}}$ (195 $\text{MNm}^{-3/2}$) was determined from the test data at -423° F (20 K), excluding specimens that had no notch support to prevent buckling (see table II). Examination of the test results indicates that the K_c values tend to increase somewhat as the value of crack length $2a$ increases from 0.150 to 4.32 inches (0.381 to 10.98 cm). The data, however, do not vary excessively, as indicated by a variation of less than ±9 percent from the average fracture toughness value. Although the data are insufficient for a clear definition of a similar trend for tests conducted at -320° F (77 K) and presented in figure 7, the data fall within ±5 percent of the average calculated value of 207 ksi$\sqrt{\text{in.}}$ (227 $\text{MNm}^{-3/2}$). The result of one test was not included in the average for the -320° F (77 K) data because the net fracture stress exceeded the yield strength of the material as can be seen in table II.

The ratios of net fracture strength to yield strength for the data reported at both test temperatures of -320° and -423° F (77 and 20 K) listed in table II show values exceeding the 0.80 criterion recommended in reference 8. However, the values of K_c calculated were within acceptable scatter limits when compared with the results of tests that pro-

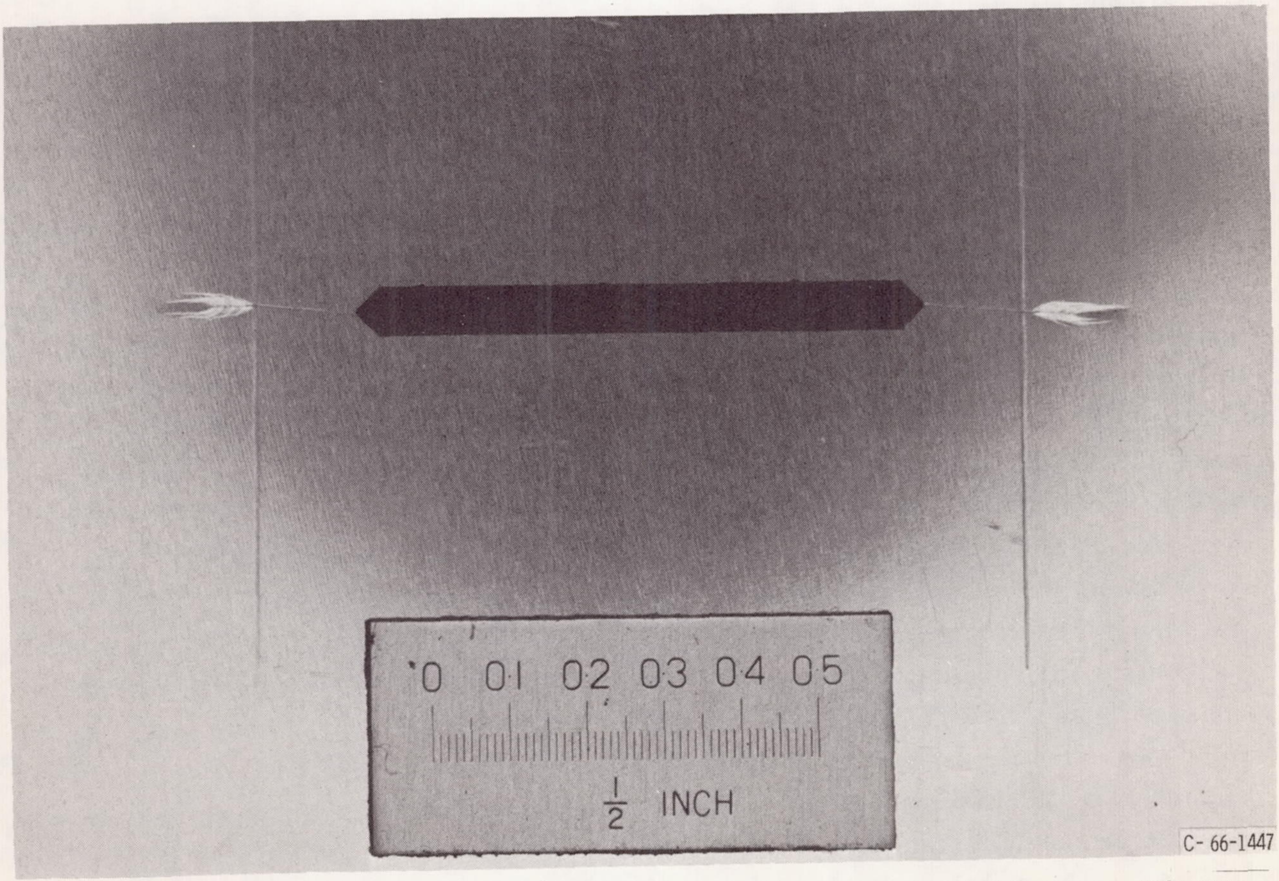


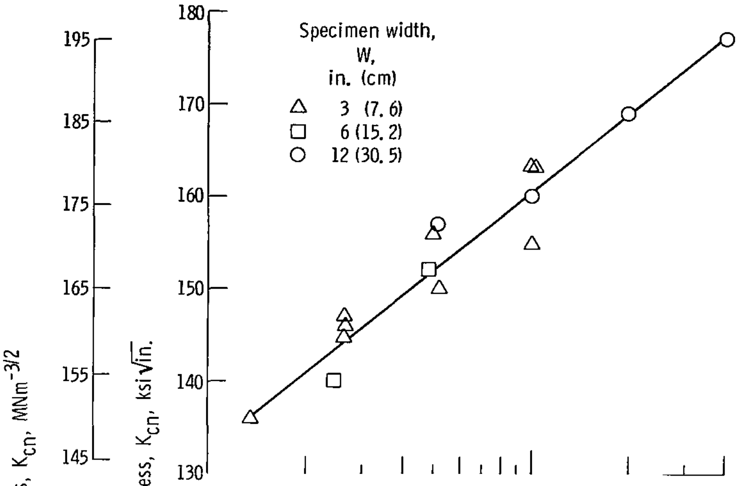
Figure 8. - Yield zone in 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless steel. Test temperature, -423° F (20 K).

duced ratios of net fracture strength to yield strength less than 0.8. The criterion (based on plastic zone size and discussed in ref. 5) to determine appropriate specimen size for plane-strain fracture toughness testing is believed to be a more reasonable method for deciding the validity of a plane-stress toughness test also. This method, unfortunately, requires extensive testing of the particular alloy to determine the required relations between specimen width, crack length, and plastic zone size $(K_c/\sigma_{ys})^2$ for valid fracture toughness specimens. Figure 8 shows the yield zone at the crack tip of a 301 stainless-steel specimen tensile loaded in a liquid-hydrogen environment to a stress level of 147 ksi (101 kN/cm^2). This yield zone was of sufficient size for tests at -320° and -423° F (77 and 20 K) to cause premature failure of the continuity gage elements used to measure crack growth. The analytical calibration for AISI 301 stainless steel in reference 7 accounts for this premature failure. This narrow line of yielding at the crack tip referred to as "catastrophic shear" is discussed in reference 9.

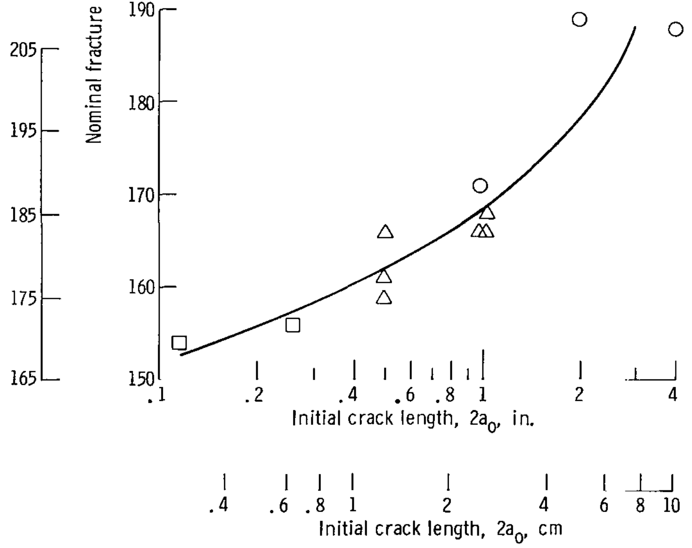
In figure 9, the nominal fracture toughness K_{cn}, computed by using equation (3), is plotted as a function of the initial crack length $2a_o$ for both test temperatures. The results at -423° and -320° F (20 and 77 K) show that the values of K_{cn} increase with increasing crack length. Thus, it is impossible to pick a constant K_{cn} to be used for design purposes.

The curves in figure 10(a) are the result of applying the average value of K_c, calculated by using equation (2), to predict the gross fracture stress of specimens having various combinations of crack length and width. The tests were conducted at a temperature of -423° F (20 K). Curves are drawn for 3-, 6-, 12-inch- (7.6-, 15.2-, and 30.5-cm-) wide sheet specimens. The agreement between predicted and experimental values of fracture stress is good (even for short crack lengths where fracture stress approaches the yield strength), except for the two 6-inch- (15.2-cm-) wide specimens that were tested with no crack support (indicated by footnote c in table II).

The dashed curve in figure 10(a) is the result of calculating fracture stress from equation (1), which is for an infinitely wide cracked sheet; the crack length is not corrected for the presence of a yield zone at the crack tip. An examination of this curve, which predicts fracture stress by neglecting the influence of the plastic zone and width correction terms in the calculation, discloses unconservative stress values. In figure 10(b), similar curves are presented using test data obtained at -320° F (77 K). The agreement between predicted and experimental values is good except for the two 6-inch- (15.2-cm-) wide specimens that were tested with insufficient crack support, as mentioned in the section TEST APPARATUS AND PROCEDURES. These data are indicated by footnote b in table II. Curves to predict fracture stress by using K_{cn} were not drawn in figure 11 because the values of K_{cn} shown in figure 9 were continuously varying (and therefore no constant value was determinable) at both the -320° and -423° F (77 and 20 K)

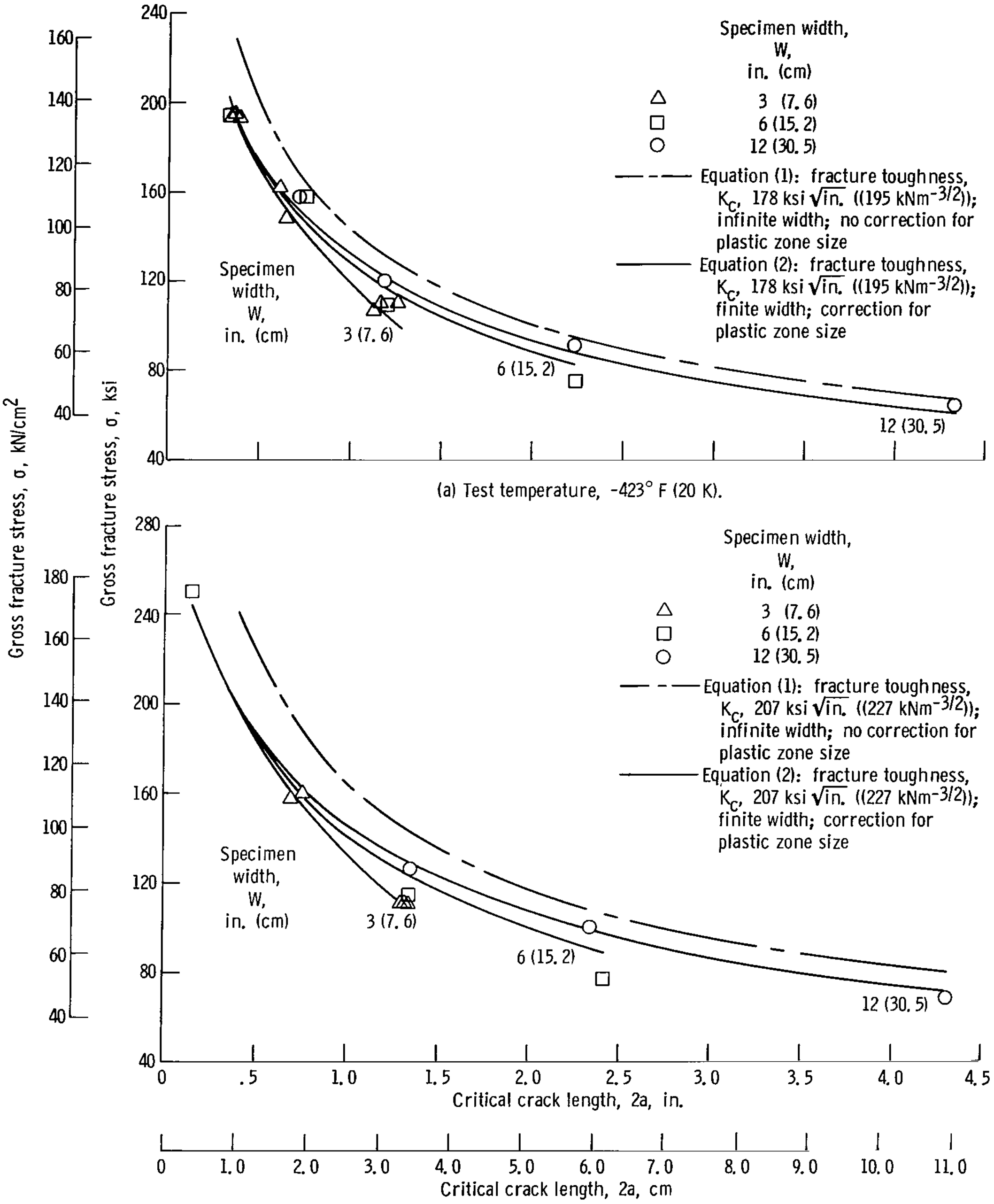


(a) Test temperature, -423° F (20 K).



(b) Test temperature, -320° F (77 K).

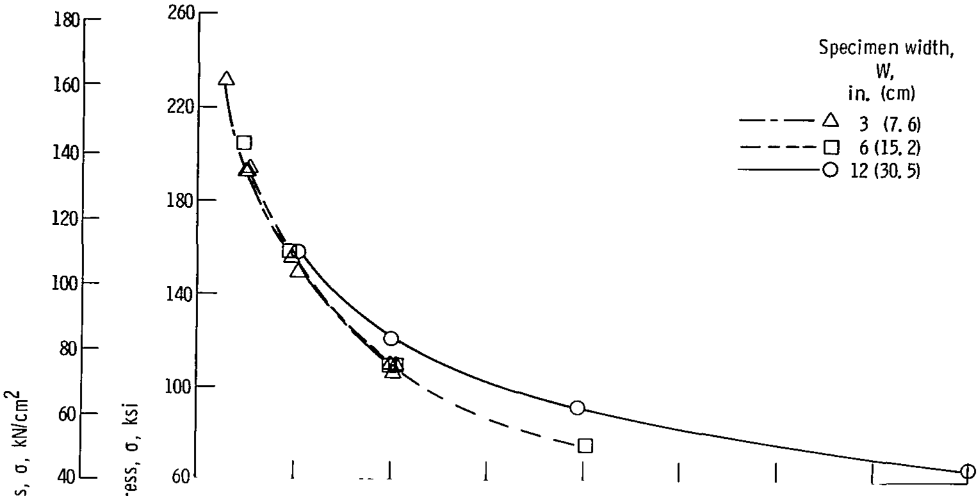
Figure 9. - Nominal fracture toughness as function of initial crack length for 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless steel. Specimen orientation, 11° to rolling direction.



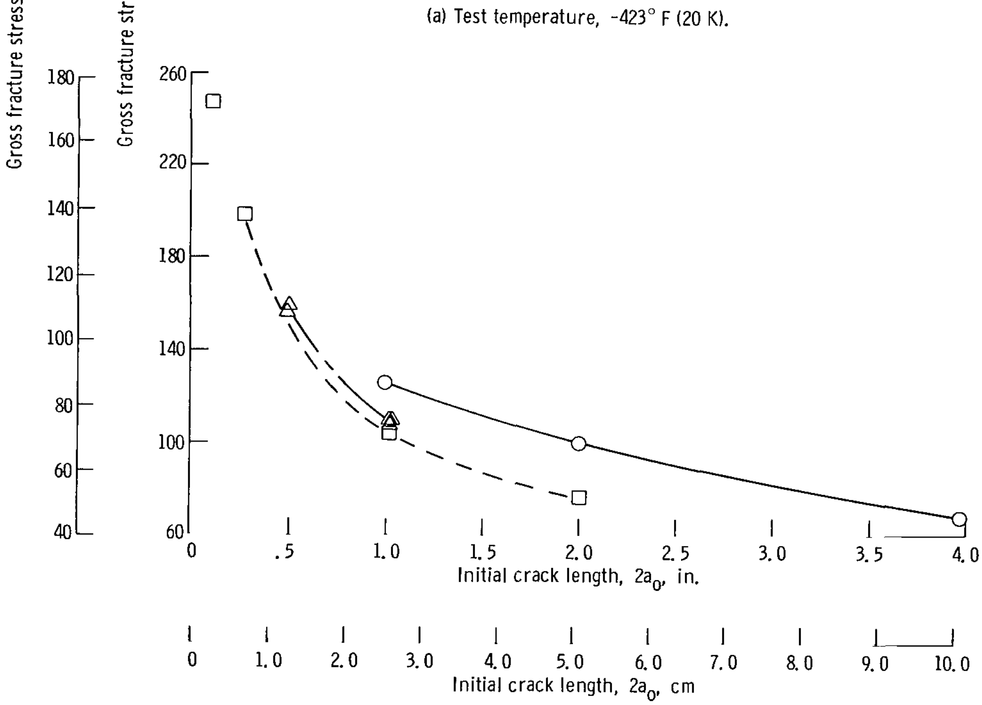
(a) Test temperature, -423° F (20 K).

(b) Test temperature, -320° F (77 K).

Figure 10. - Fracture stress as function of critical crack length for 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless steel. Specimen orientation, 11° to rolling direction.



(a) Test temperature, -423° F (20 K).



(b) Test temperature, -320° F (77 K).

Figure 11. - Fracture stress as function of initial crack length for 0.022-inch- (0.056-cm-) thick AISI 301 60-percent cold-reduced stainless steel. Specimen orientation, 11° to rolling direction; curves faired through data points.

test temperatures. However, curves were faired through the data points. The data for the 6-inch- (15.2-cm-) wide specimens with the longer cracks are seen to be relatively low, which is believed to be, at least in part, the result of insufficient crack support.

SUMMARY OF RESULTS

The measured fracture toughness values of AISI 301 stainless-steel 60-percent cold-reduced 0.022-inch- (0.056-cm-) thick sheet at -320° and -423° F (77 and 20 K) did not vary significantly with specimen widths from 3 to 12 inches (7.6 to 30.5 cm) or with crack lengths from 0.150 to 4.32 inches (0.381 to 10.98 cm). It is thus reasonable to conclude that a 3-inch- (7.6-cm-) wide specimen is sufficient to determine a valid plane-stress fracture toughness for this material and thickness. The average toughness at 11° to the rolling direction was 207 ksi $\sqrt{\text{in.}}$ (227 $\text{MNm}^{-3/2}$) at -320° F (77 K) and 178 ksi $\sqrt{\text{in.}}$ (195 $\text{MNm}^{-3/2}$) at -423° F (20 K).

Investigation of the effect of varying specimen orientation with respect to rolling direction showed variations in mechanical properties. As the specimen orientation approached the transverse direction, the yield and ultimate strengths, in general, showed a gradual increase. The average transverse yield strength at -423° F (20 K) was determined to be 293 ksi (202 kN/cm^2), which represented a 14-percent increase when compared with the average longitudinal value of 258 ksi (178 kN/cm^2). A similar comparison of the -320° F (77 K) data resulted in a 11-percent increase when the longitudinal value of 230 ksi (159 kN/cm^2) was compared with 255 ksi (176 kN/cm^2) for the transverse direction. Only slight variations appeared in the room temperature data for those orientations tested.

However, of more significance was the effect of angle to rolling direction on net fracture strength of the cracked specimens. The longitudinal net fracture strength of 165 ksi (114 kN/cm^2) at -423° F (20 K) represents approximately 90 percent of the room temperature value. However, a decrease to 103 ksi (71.0 kN/cm^2), representing only 65 percent of the room temperature value, was noted for the transverse direction. When compared with the room temperature results, the trends for the data obtained at -320° F (77 K) were analogous to those obtained at -423° F (20 K).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 28, 1969,
124-08-08-19-22.

REFERENCES

1. Christian, J. L.; and Hurlich, A.: Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment, Part II. Rep. AE63-0090, General Dynamics/Astronautics (ASD-TDR-62-258, pt. 2), Apr. 1963.
2. Espey, G. B.; Repko, A. J.; and Brown, W. F., Jr.: Effect of Cold Rolling and Stress Relief on the Shart Edge Notch Tensile Characteristics of Austenitic Stainless Steel Sheet Alloys. Proc. ASTM, vol. 59, 1959, pp. 816-836.
3. Calfo, Frederick D.: Effect of Residual Stress on Fracture Strength of AISI 301 Stainless-Steel and Ti-5Al-2.5 Sn ELI Titanium Cracked Thin-Wall Cylinders. NASA TN D-4777, 1968.
4. ASTM Special Committee on Fracture Toughness Testing of High-Strength Metallic Materials: Fracture Testing of High-Strength Sheet Materials. Part I. Bull. No. 243, ASTM, Jan. 1960, pp. 29-40.
5. Brown, W. F., Jr.; and Srawley, J. E.: Plane Strain Crack Toughness Testing of High Strength Metallic Materials. Spec. Tech. Publ. No. 410, ASTM, 1967, p. 51.
6. Forman, Royce G.: Experimental Program to Determine Effect of Crack Buckling and Specimen Dimensions on Fracture Toughness of Thin Sheet Materials. Rep. AFFDL-TR-65-146, Air Force Systems Command, Jan. 1966. (Available from DDC as AD-483308.)
7. Sullivan, Timothy L.; and Orange, Thomas W.: Continuity Gage Measurement of Crack Growth on Flat and Curved Surfaces at Cryogenic Temperatures. NASA TN D-3747, 1966.
8. ASTM Special Committee on Fracture Testing of High-Strength Materials: Progress in Measuring Fracture Toughness and Using Fracture Mechanics. Materials Res. Standards, vol. 4, no. 3, Mar. 1964, pp. 107-119.
9. Wessel, E. T.: Some Exploratory Observations of the Tensile Properties of Metals at Very Low Temperatures. ASM Trans., vol. 49, 1957, pp. 149-172.

NASA-Langley, 1969 —— 17 E-5066

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> — NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546