CR 54614

[redacted]

GENERAL DYNAMICS

Convair Division

[redacted]

A2136-1 (REV. 5-65)

CR 54614

The Effects of Cold Rolling on the Mechanical Properties of Type 310 Stainless Steel at Room and Cryogenic Temperatures

by

J. L. Christian
Staff Scientist

J. D. Gruner
Engineering Metallurgist

and

L. D. Girton
Design Specialist

General Dynamics/Astronautics
A Division of General Dynamics Corporation

AR-592-1-365

The Effects of Cold Rolling on the Mechanical Properties of Type 310 Stainless Steel at Room and Cryogenic Temperatures

by

J. L. Christian, J. D. Gruner and L. D. Girton

ABSTRACT

N66-22934

The purpose of this investigation was to determine the applicability of cold rolled Type 310 stainless steel for structural uses at cryogenic temperatures. Yield and tensile strengths, elongation and notched toughness were determined as a function of cold rolling from 0 to 92% reduction and of temperatures from 78° to -423°F.

The results indicate that high strengths may be achieved by cold rolling and that the toughness is adequate for structural applications at -423°F for the 0 - 85% cold rolled tempers. An evaluation was also made on the room temperature formability of annealed and cold rolled 310 stainless steel and was found to be acceptable for the 0 - 37.5% cold rolled tempers. As a result of this, and previous investigations, it is believed that cold rolled Type 310 stainless steel is an excellent material for structural applications at cryogenic temperatures.

Author

INTRODUCTION

The advent of the Space Age has placed an increasing demand upon materials' engineers to provide materials with improved properties for construction of missiles and space vehicles. The properties of foremost importance are high strength, in particular the strength-to-density ratio, and adequate toughness over the entire spectrum of the operating environments. In addition, the materials must be weldable and formable, posses adequate resistance to corrosion, and be readily available in various forms and sizes at a reasonable cost. The necessity for these properties is due to the immediate need of reliable, light-weight, inexpensive flight vehicles to achieve the goals of the national space program.

Toughness, as used herein, is defined as the ability of a material to resist brittle failure under severe conditions of loading, stress concentrations and temperature. Normal loading conditions may include bi- and tri- axial loading, vibrational or impact loading, as well as very high operating stresses (up to 90% of the yield strength of the material). Stress concentration may be caused by several factors. These include non-axial loading, discontinuities (such as found at welds), mechanical joints and re-entrant angles of formed parts, surface imperfections caused by machining, tooling marks and handling, and discontinuities such as inclusions, stringers and large intermetallic precipitates within the material. Depending upon the vehicle, and location within the vehicle, temperatures may vary from very high temperatures (e.g., leading edges of re-entry vehicles, engine components, etc.) to very low temperatures. The very low temperatures result from the use of liquid oxygen (-297°F) and liquid hydrogen (-423°F) as propellants and under certain conditions in outer space. Due to the extensive use of liquified gases as propellants and because materials are inherently more brittle at lower temperatures, the knowledge of the properties of structural materials at cryogenic temperatures is of prime importance.

One class of materials which appears to possess the requisite properties for missile and space vehicle structures is the cold rolled austenitic stainless steels. As a result, extensive investigations have been conducted to determine the properties of the 300 series stainless steels (Ref. 1-10). In particular, and primarily as a consequence of its use in the Atlas and Centaur vehicles, Type 301 stainless steel has received considerable attention and has been evaluated as a function of form, temper (amount of cold work), and temperature. The results of these investigations have shown that cold rolled (1/4 hard to extra full hard) Type 301 stainless steel possesses excellent properties for liquid oxygen (-297°F) tankage and therefore is ideal for construction of vehicles, such as Atlas, which are fueled with RP-1 (high grade kerosene) and liquid oxygen. However, it has been found that many heats of cold rolled Type 301 stainless lack adequate toughness for welded structures at the temperature of liquid hydrogen, -423°F (Ref. 1, 4, 10). The reasons for the partial embrittlement of 301 at -423°F is primarily attributed to the presence of martensite, in particular that martensite which transforms from the meta-stable austenite as a result of plastic deformations at cryogenic temperatures. (Ref. 10,11).

Because of the partial embrittlement of 301 at -423°F, attention has been focused on the higher nickel, and therefore more stable, stainless steels such as Types 304 and 310. Type 310 stainless steel appears to be the most promising since it has been found to be fully stable (no occurrence of martensitic transformation) due to cold rolling or application of stress (to failure) at -423°F (Ref. 4, 10, 12). The primary disadvantages of 310 as compared to 301 are a lower strength to density ratio of the extra full hard cold rolled material and a decrease in the formability of the 1/4 to 3/4 hard cold rolled material. The purpose of this investigation was, therefore, to determine the properties, primarily strength, toughness and formability, of Type 310 stainless steel as a function of cold rolling and temperature.

MATERIALS AND PROCEDURE

Two heats of Type 310 stainless steel were evaluated in this investigation. The chemical analysis of these heats is given in Table I. The cold rolling of heat 84074 and of the 75% CR condition of heat 43631 was performed by the suppliers. The remainder of the cold rolling was performed at room temperature on a six inch wide, two high - four high laboratory rolling mill at GD/A.

Drawings of the tensile and notched tensile specimens are shown in Figure 1. The notched tensile specimens had a stress concentration factor (K_t) of 6.3 as determined by $\sqrt{a/r}$, where a is equal to 1/2 of the width between the notches and r is the radius at the root of the notch. Tensile tests were performed at 78°F (room temperature), -100°F by immersion in a bath of dry ice and alcohol, -320°F by immersion in liquid nitrogen and -423°F by immersion in liquid hydrogen. A full description of the testing apparatus and experimental procedure is given in Reference 13.

As an indication of the approximate formability of the cold rolled 310 stainless steel, standard ductility cup tests were performed at room temperature. The test consisted of drawing a cup in the metal by a 1.5 inch diameter hemispherical punch which is hydraulically activated. The hydraulic pressure and cup height are determined by means of pressure and dial gauges upon onset of failure. Specimen sizes and typical failures are shown in Figure 10.

DISCUSSION OF RESULTS

The results of the tensile and notched tensile tests are given in Table 2 and Figures 2-4. Although only the longitudinal data are presented in the figures, there does not appear to be much of a directional effect in Type 310 stainless steel as a function of cold rolling or temperature. As would be expected, the yield and tensile strengths increase with an increase in the amount of cold rolling and with a decrease in the testing temperature. Type 310 stainless steel has been found to be a fully stable austenitic material with no martensitic transformations occurring as a result of cold working or thermal cycling (Ref. 10, 11). Therefore, the increase in strength which results from cold rolling is due solely to the work hardening of the austenite and thus explains why much higher strengths (F_{ty} of 180-200 Ksi and F_{tu} of 200-240 Ksi at 78°F) are obtained by cold rolling Type 301 stainless steel which undergoes an austenite to martensite transformation (Ref. 1, 4, 10). The large increase in tensile strength with reduction in temperature (60-100% increase from 78° to -423°F) are typical of face-centered cubic lattice (austenitic) structures. However, the large increases in yield strength, 60-180% from 78° to -423°F, are atypical (Ref. 14, 15). Similar behavior has previously been noted for some high strength aluminum alloys and is explained on the basis of a highly strained lattice structure which results from the large amount of alloying elements present in solid solution (Ref. 16).

The elongation of Type 310 stainless steel decreases with an increase in the amount of cold rolling, but increases with a reduction in temperature, at least to -320°F with a small decrease from -320° to -423°F. At room temperature the elongation decreases rapidly from the annealed (40% elongation) to the 40% cold rolled condition (about 5% elongation), and then gradually decreases to about 1-2% elongation for the 90-92% cold worked material. At -320°F the elongation is much greater for the annealed material, about 70%, and decreases in a more linear manner, to about 10%, for the 80% cold rolled condition. At -423°F the elongation decreases nearly linear from 50% for the annealed material to about 5% for the 92% cold rolled material. Based upon elongation, the ductility of annealed or cold rolled Type 310 stainless steel is greater at cryogenic temperatures than at room temperature.

It has been found that the notched tensile strengths and resulting notched/ unnotched tensile strength ratios provide a good indication of a material's toughness or resistance to brittle failure (Ref. 10, 12). Analysis of the notched tensile data indicate the following. At room temperature, the notch toughness is slightly improved by cold rolling to about 30-40% reduction and then gradually decreases upon further cold rolling so that beyond 90% reduction the notched/unnotched tensile strength ratio is below unity. At -320°F, the same improvement in notch toughness by cold rolling to about 40% reduction is witnessed, and the toughness does not appear to be further affected upon cold rolling to 80% reduction. At -423°F, the notch toughness is improved by cold rolling to about 75% reduction; however, a sharp decrease in the notched tensile strength beyond 80% reduction results in a significant decrease in the notched/unnotched tensile strength ratio with values below unity resulting beyond about 85% reduction. A possible explanation for this decrease in toughness at -423°F is due to the presence of a large number of carbide stringers in the severely cold worked material (see Figures 6-9). It is recommended that 310 stainless steel which is to be used for structural applications at -423°F not be cold rolled beyond about 80% reduction.

Mechanical properties of fusion and resistance welds of cold rolled 310 stainless were not determined in this study due to the lack of material; however these properties have been thoroughly evaluated for the 75% cold rolled condition and are reported in References 4 and 10.

Another property of the material which was required in order to evaluate its applicability for liquid hydrogen and liquid oxygen tankage was formability, in particular the ability of the alloy to be stretch formed into gore or pie sections which are subsequently welded to make bulkheads (see Figure 11). Because of material limitations and in order to minimize costs, cup tests were used to evaluate the formability of annealed and cold rolled Type 310 stainless steel. The data obtained on five conditions of 310 are given in Table 3 and Figure 5. In addition, cupping test data are also presented for four cold rolled conditions of Type 301 stainless steel. From the vast amount of experience obtained in stretch forming Type 301 stainless steel for the Atlas and Centaur bulkheads, it has been found that 1/2 hard and 3/4 hard 301 may be easily stretch formed over the most severe bulkhead forming tool which has a 60-inch by 30-inch compound radius. On the other hand, the extra full hard 301 cannot be successfully stretch formed, and the full hard 301 is stretch formable only to a limited extent involving mild curvatures. From this information and the data in Table 3, it was ascertained that a cup height of 0.350 inches or greater at failure, using a 1.5 inch diameter hemispherical punch, was required in order to have the desired formability.

From the cupping test data it appears that 0-37.5% cold rolled 310 stainless possesses adequate formability to meet the stretch forming requirements. Because of the limited width of the material rolled on the laboratory mill, it was not possible to actually stretch form some of the 37.5% cold rolled material. However, several sheets of 60% cold rolled 310 were partially annealed by heating to 1400-1500°F, and the resultant tensile properties approximated those for the 10 to 20% cold rolled material. These sheets were successfully stretch formed and are shown in Figure 11. Although the cupping tests were performed primarily to determine the ability of the material to be stretch formed, it is believed that these data may also be useful for evaluating other forming applications.

SUMMARY

The tensile and notched tensile properties were determined on Type 310 stainless steel as a function of temper (0-92% reduction by cold rolling) and temperature (78°, -320° and -423°F). Also, the formability of several tempers of Type 310 stainless steel at room temperature was evaluated by means of cup tests. From the data obtained in this investigation the following conclusions and recommendations are made:

1. The yield and tensile strength of 310 stainless steel increases with an increase in the amount of cold work and a decrease in the testing temperature.

2. The ductility, as measured by elongation, decreases with increased amount of cold working. However, the ductility at cryogenic temperatures is greater than at room temperature for 310 stainless steel at a given temper.

3. The toughness, as determined by notched tensile strengths and resulting notched/unnotched tensile strength ratio, is not severely affected by cold work at 78° or -320°F but is significantly impaired at -423°F for tempers beyond 80-85% cold work.

4. The formability, as determined by cup tests, is decreased by increased amounts of cold rolling, but remains comparable to 1/2 and 3/4 hard Type 301 stainless steel to about 35-40% reduction by cold rolling.

5. It is recommended that Type 310 stainless steel cold rolled beyond 85% reduction not be used for structural applications at -423°F.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of their associates who contributed to this paper and, in particular, to A. Hurlich, who supplied technical counsel throughout the course of this investigation. The work was performed under the sponsorship of General Dynamics/Astronautics, whose permission to publish this paper is gratefully acknowledged.

REFERENCES

1. Watson, J. F. and Christian, J. L., "Mechanical Properties of High Strength 301 Stainless Steel Sheet at 70°, -320° and -423°F in the Base Metal and

Welded Joint Configurations", ASTM Special Technical Publication No. 287, February 1961.

2. Espey, G. B., Repko, A. J. and Brown, W. F., "Effect of Cold Rolling and Stress Relief on the Sharp Edge Notch Tensile Characteristics of Austenitic Stainless Steel Sheet Alloys", Proceedings ASTM, Vol. 59, 1959.

3. Krivobok, V. N. and Talbot, A. M., "Effect of Temperatures on the Mechanical Properties, Characteristics and Processing of Austenitic Stainless Steel", Proceedings ASTM, Vol. 50, 1950.

4. Watson, J. F. and Christian, J. L., "Properties of Cold Rolled AISI Types 301, 302, 304 ELC and 310 Stainless Steel Sheet", ASTM Special Technical Publication No. 287, February 1961.

5. Krivobok, V. N., "Properties of Austenitic Stainless Steels at Low Temperatures", NBS Circular No. 520, Washington, D.C., 1952.

6. Hoke, J. H., Mabus, P. G. and Goller, G. N., "Mechanical Properties of Stainless Steels at Sub Zero Temperatures", Metal Progress No. 55, 1949.

7. Mangone, R. J., Roach, D. B. and Hall, A. M., "Properties of Certain Cold Rolled Austenitic Stainless Sheet Steels", DMIC Report No. 113, Batelle Memorial Institute, Columbus, Ohio, 1959.

8. Rice, L. P., Campbell, J. E. and Simmons, W. F., "The Evaluation of the Effects of Very Low Temperatures on the Properties of Aircraft and Missile Metals", WADD-TR-60-254, Wright-Patterson AFB, Ohio, 1960.

9. Durham, T. F., et al, "Cryogenic Materials Data Handbook", NBS-CEL Report No. PB 171809, February 1962.

10. Christian, J. L., "Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment", ASD-TDR-62-258, Wright-Patterson AFB, Ohio, 1962.

11. Kulin, S. A. and Cohen, M., "On the Martensitic Transformation at Temperatures Approaching Absolute Zero", Journal of Metals, Vol. 188, September 1950.

12. Watson, J. F., Christian, J. L., Tanalski, T. T., and Hurlich, A., "The Correlation of Notch: Unnotch Tensile Ratios with Tensile Fatigue Properties of Complex Welded Joints in High Strength 300 Series Stainless Steels at Cryogenic Temperatures". ASTM Special Publication No. 302, June 1961.

13. Watson, J. F. and Christian, J. L., "Cryostat and Accessories for Tensile Testing at -423°F", ASTM Bulletin, February 1961.

14. Lorig, C. H., "Influence of Metallurgical Factors", Behavior of Metals at Low Temperatures, pp. 71-105, ASM, Cleveland, 1953.

15. Low, J. R., Jr., "The Influence of Mechanical Variables", Behavior of Metals at Low Temperatures, pp. 39-70, ASM, Cleveland, 1953.

16. Christian, J. L. and Watson, J. F., "Properties of the 7000 Series Aluminum Alloys at Cryogenic Temperatures", Advances in Cryogenic Engineering, Vol. 6, Plenum Press, Inc., New York, 1961.

TABLE 1

Chemical Analysis of Type 310 Stainless Steel

	310 CRES 40-75% C.R.	310 CRES 0-92% C.R.	
Heat No.	84074	43631	
Coil No.	-	44942	
Supplier	Allegheny-Ludlum	Washington	
Gauge (In.)	0.020	0.006-0.080	
Content (Wt. %)			Specification AMS 5521B
C	0.04	0.060	0.08 Max.
Cr	25.26	24.62	24.0-26.0
Cu	-	0.23	0.50 Max.
Fe	Bal.	Bal.	Bal.
Mn	1.66	1.60	2.00 Max.
Mo	-	0.32	0.50 Max.
Ni	19.58	19.66	19.0-22.0
P	-	0.030	0.040 Max.
S	-	0.011	0.030 Max.
Si	0.70	0.58	0.75 Max.

TABLE 2

Mechanical Properties of Type 310 Stainless Steel at Various Degrees of Cold Rolling

Heat No.	% Cold Work	Test Temp. (°F)	Grain Direct.	F_{ty} (KSI)	F_{tu} (KSI)	Elong. %	Notch T.S. K_t = 6.3 (KSI)	Notched/Unnotched Tensile Ratio
43631	0	78	Long.	40.3	85.8	46	93.9	1.09
		78	Trans.	34.8	86.8	46	91.6	1.05
		-320	Long.	86.5	164	71	155	0.95
		-320	Trans.	89.8	165	71	151	0.92
		-423	Long.	113	196	52	182	0.93
		-423	Trans.	117	197	44	179	0.91
43631	12.5	78	Long.	87.6	100	24	115	1.15
		78	Trans.	88.9	101	22	120	1.19
		-320	Long.	131	182	51	186	1.02
		-320	Trans.	123	180	54	187	1.04
		-423	Long.	156	221	43	213	0.96
		-423	Trans.	144	215	42	211	0.98
43631	37.5	78	Long.	125	139	9	167	1.20
		78	Trans.	126	140	9	167	1.19
		-320	Long.	162	208	31	237	1.14
		-320	Trans.	165	208	31	235	1.13
		-423	Long.	191	243	27	261	1.07
		-423	Trans.	187	243	32	263	1.08
84074	40	78	Long.	138	153	4	168	1.10
		-100	Long.	156	170	13	-	-
		-100	Trans.	151	180	12	-	-
		-320	Long.	182	221	24	236	1.07
		-423	Long.	200	276	28	276	1.00
			Trans.	218	263	25	294	1.11
84074	60	78	Long.	153	174	3	180	1.03
		-320	Long.	205	233	17	248	1.06
		-423	Long.	232	278	18	296	1.06
			Trans.	226	285	16	308	1.08
43631	62.5	78	Long.	161	167	4	181	1.09
		78	Trans.	150	181	5	181	1.00
		-320	Long.	210	236	18	263	1.11
		-320	Trans.	197	247	16	297	1.20
		-423	Long.	240	270	10	296	1.10
		-423	Trans.	224	280	16	321	1.15
84074	75	78	Long.	160	179	3	197	1.10
		-320	Long.	215	242	13	269	1.11
		-423	Long.	254	281	14	312	1.11
		-423	Trans.	247	298	2	301	1.01

TABLE 2 (Continued)

Mechanical Properties of Type 310 Stainless Steel at Various Degrees of Cold Rolling

Heat No.	% Cold Work	Test Temp. (°F)	Grain Direct.	F_{ty} (KSI)	F_{tu} (KSI)	Elong. %	Notch T.S. K_t = 6.3 (KSI)	Notched/Unnotched Tensile Ratio
43631	75	78	Long.	157	181	2	194	1.07
		78	Trans.	163	199	4	193	0.97
		-100	Long.	190	204	3	220	1.08
		-100	Trans.	192	225	8	236	1.05
		-320	Long.	223	251	10	278	1.11
		-320	Trans.	225	273	11	292	1.07
		-423	Long.	261	290	5	329	1.12
		-423	Trans.	280	317	10	328	1.03
43631	80	78	Long.	168	189	2	198	1.05
		78	Trans.	162	210	4	210	1.00
		-320	Long.	236	256	9	267	1.05
		-320	Trans.	246	286	10	318	1.11
		-423	Long.	254	296	9	320	1.08
		-423	Trans.	261	316	8	355	1.13
43631	85	78	Long.	167	191	2	197	1.03
		-423	Long.	253	300	7	307	1.02
43631	90	78	Long.	170	198	1	198	1.00
		-423	Long.	264	308	5	300	0.97
43631	92	78	Long.	169	200	2	196	0.98
		-423	Long.	270	313	5	290	0.93

TABLE 3

Results of Cupping Tests on Types 301 and 310 (Heat No. 43631) Stainless Steel

Material	Condition	Thickness (in.)	TENSILE PROPERTIES: Direction	F_{ty} (KSI)	F_{tu} (KSI)	El. (%)	CUP HEIGHT (in.) (1.5" Dia): No. of Tests	Average	Minimum
301 S.S.	XFH (60% CR)	0.026	Long. Trans.	205 190	220 225	3 4	6	0.200	0.185
301 S.S.	FH (50% CR)	0.022	Long. Trans.	180 -	205 -	6 -	6	0.307	0.295
301 S.S.	3/4 H (40% CR)	0.023	Long. Trans.	165 155	190 190	18 10	6	0.368	0.355
301 S.S.	1/2 H (30% CR)	0.023	Long. Trans.	125 120	170 170	24 20	6	0.408	0.402
310 S.S.	Annealed	0.080	Long. Trans.	40.3 34.8	85.8 86.8	46 46	3	0.703	0.692
310 S.S.	12.5% CR	0.070	Long. Trans.	87.6 88.9	100 101	24 22	2	0.503	0.500
310 S.S.	37.5% CR	0.050	Long. Trans.	125 126	139 140	9 9	4	0.360	0.350
310 S.S.	62.5% CR	0.030	Long. Trans.	161 150	167 181	4 5	4	0.203	0.190
310 S.S.	80% CR	0.016	Long. Trans.	168 162	189 210	2 4	4	0.170	0.140

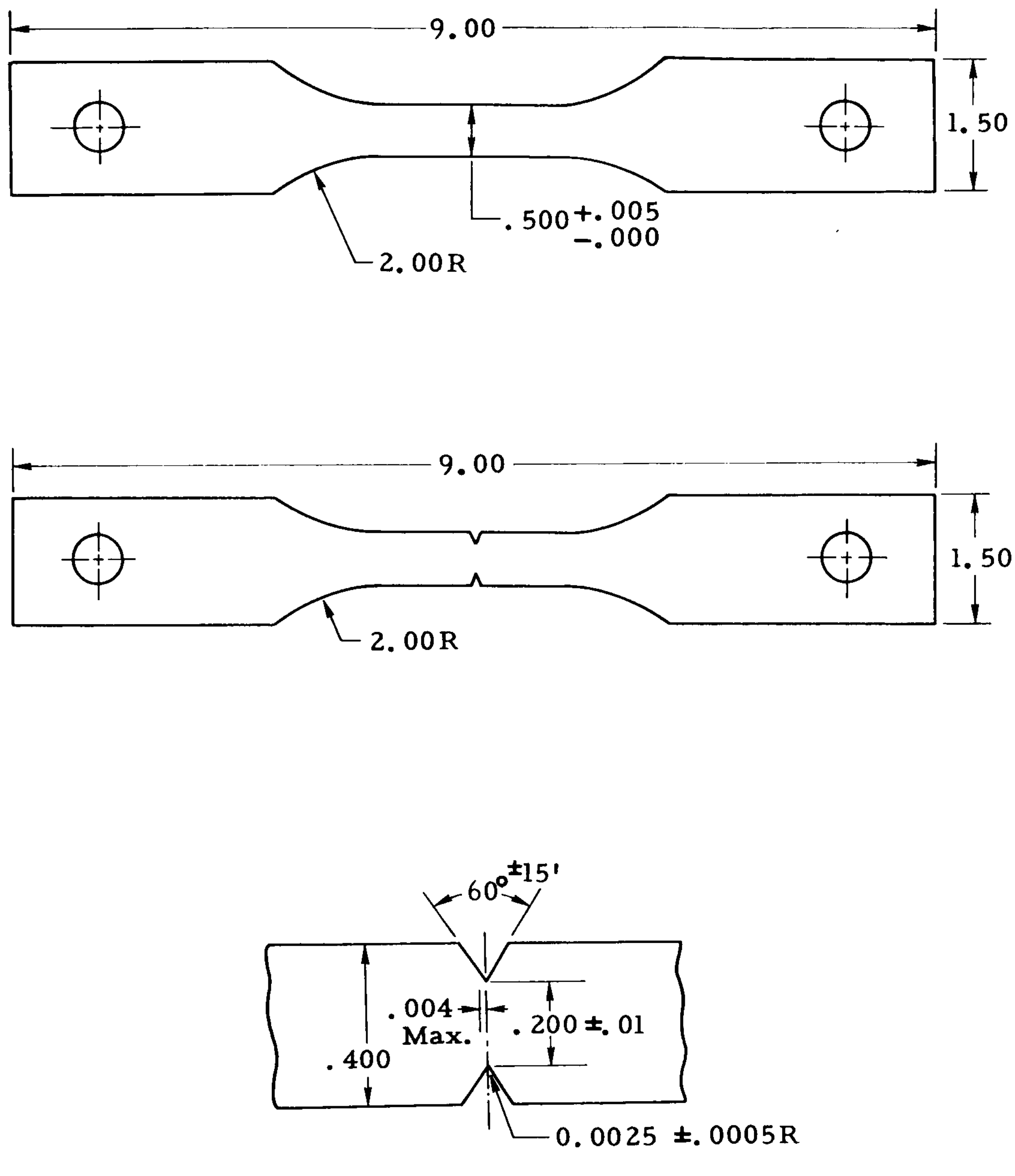


Figure 1. Tensile specimens for cryogenic testing (all dimensions in inches).

Mechanical Properties (Long. Dir.) at 78° F.

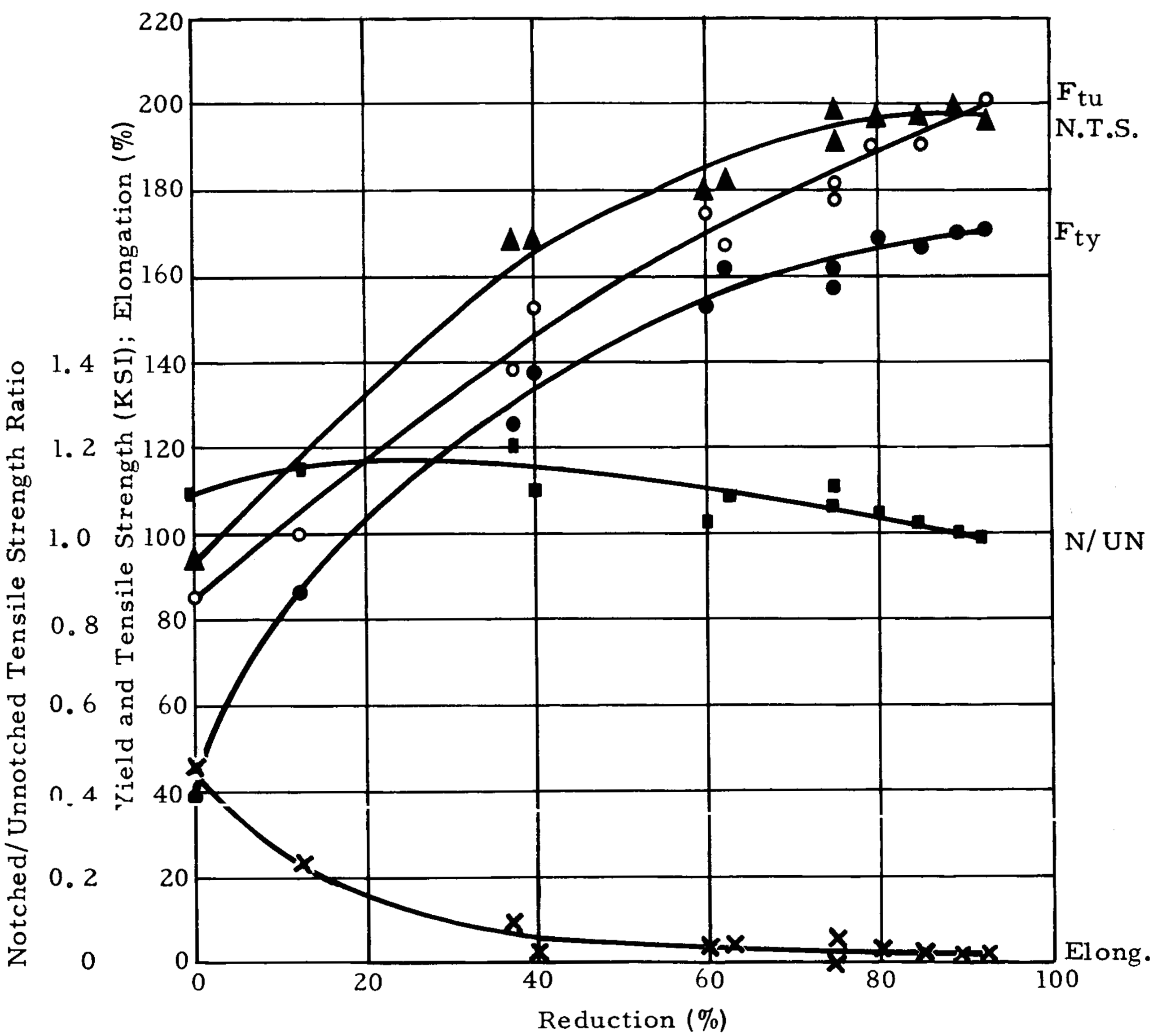


Figure 2.

Mechanical Properties (Long. Dir.) at -320° F.

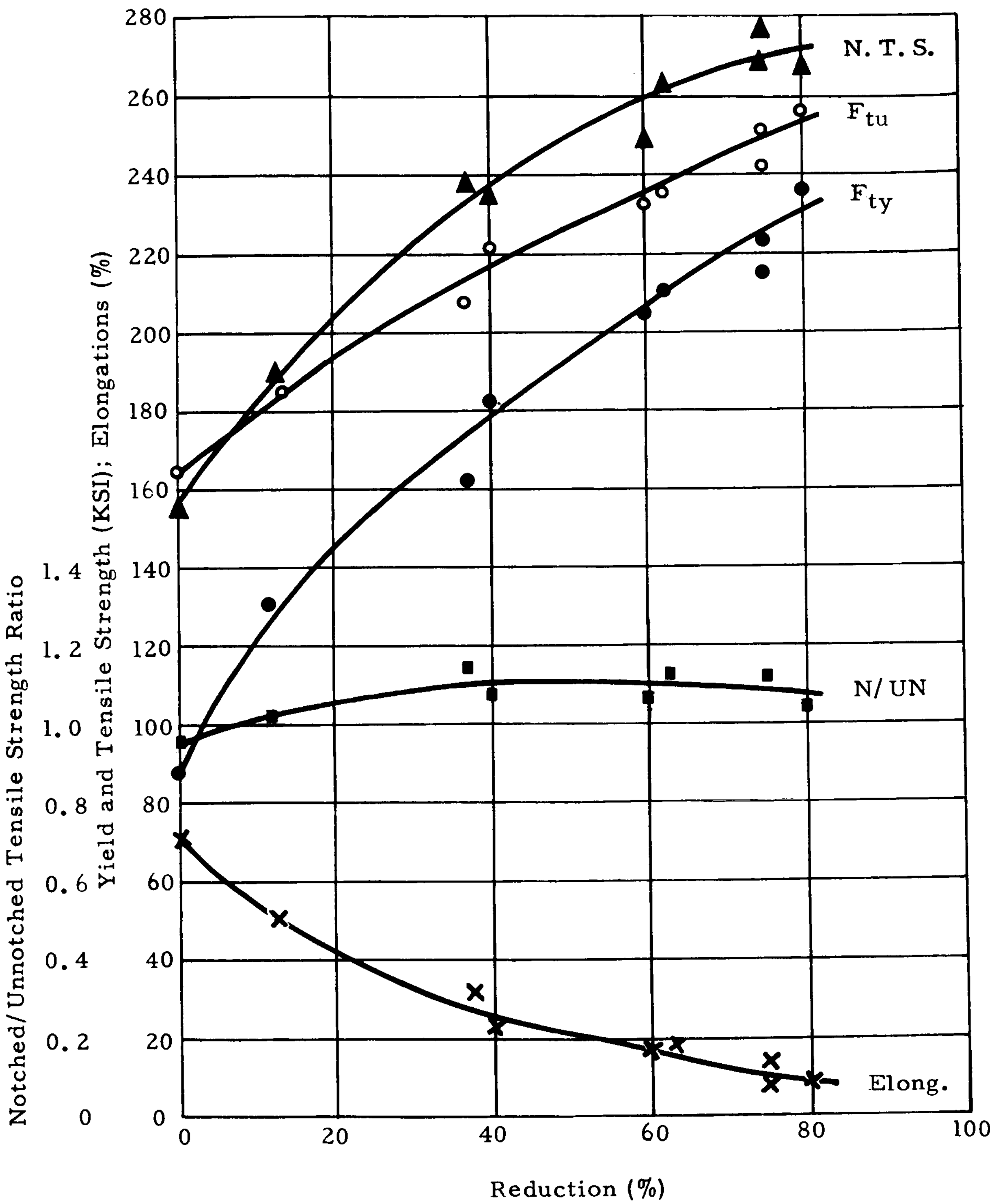


Figure 3.

Mechanical Properties (Long. Dir.) at -423° F.

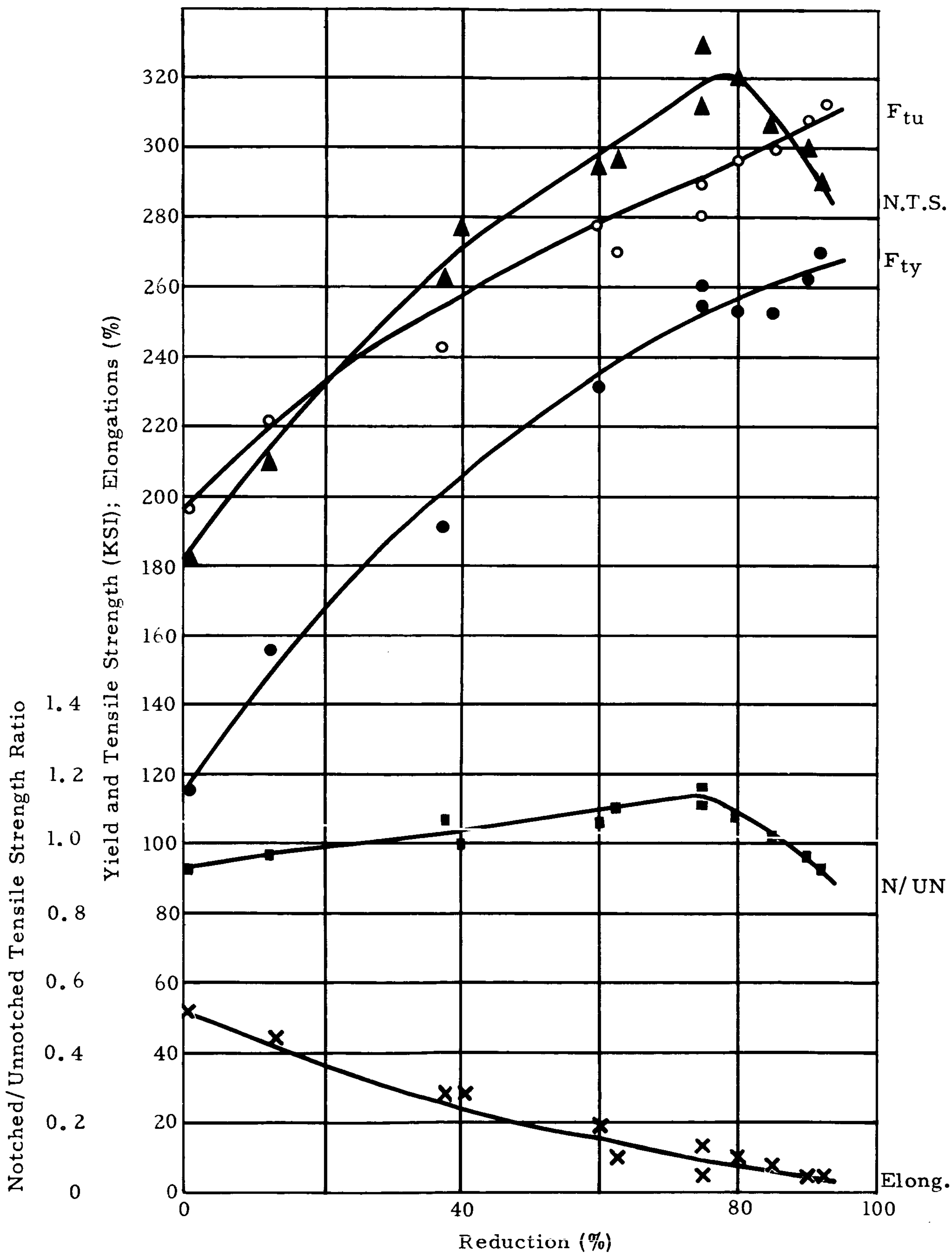
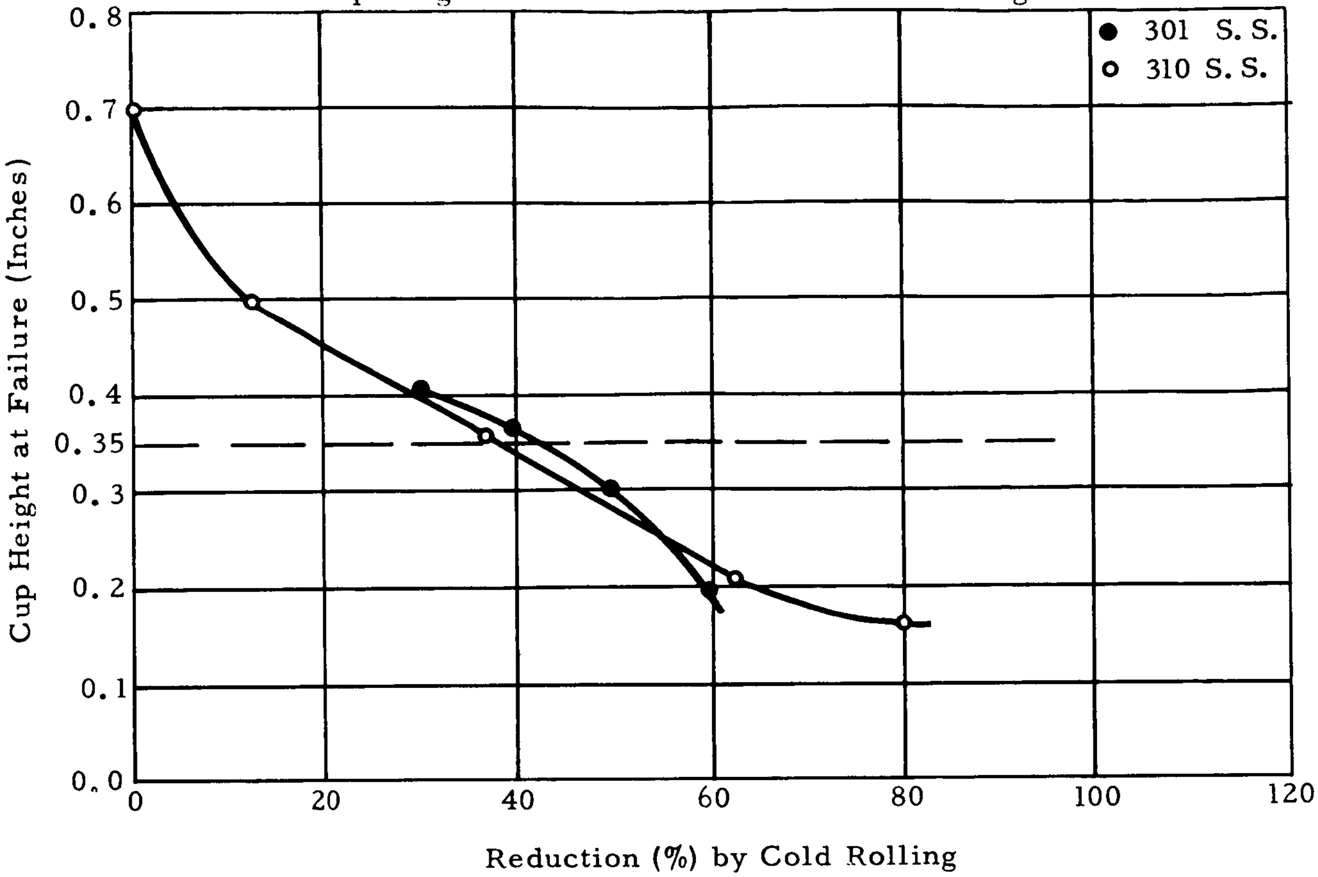


Figure 4.

Cup Height vs. Cold Work and Tensile Elongation



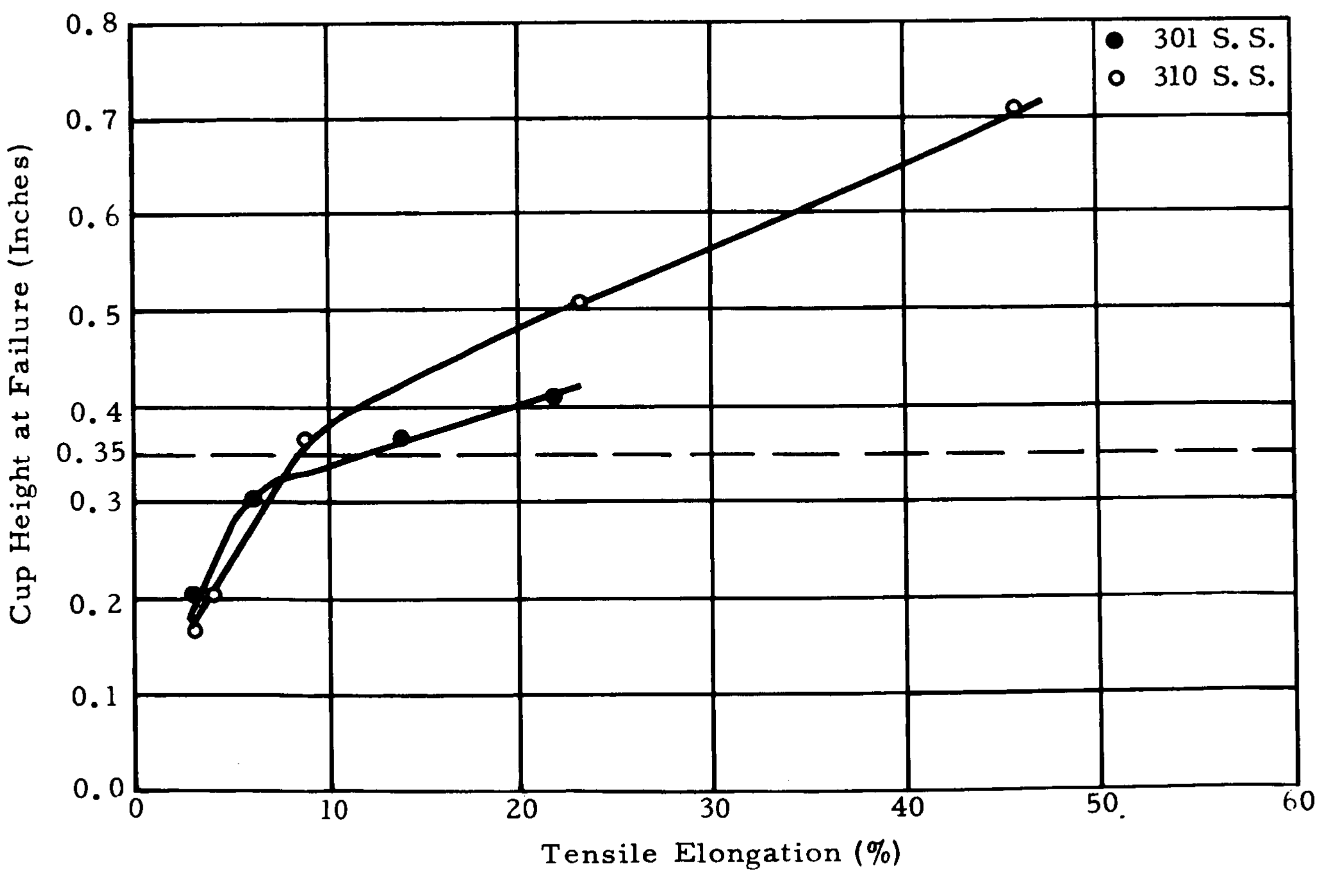
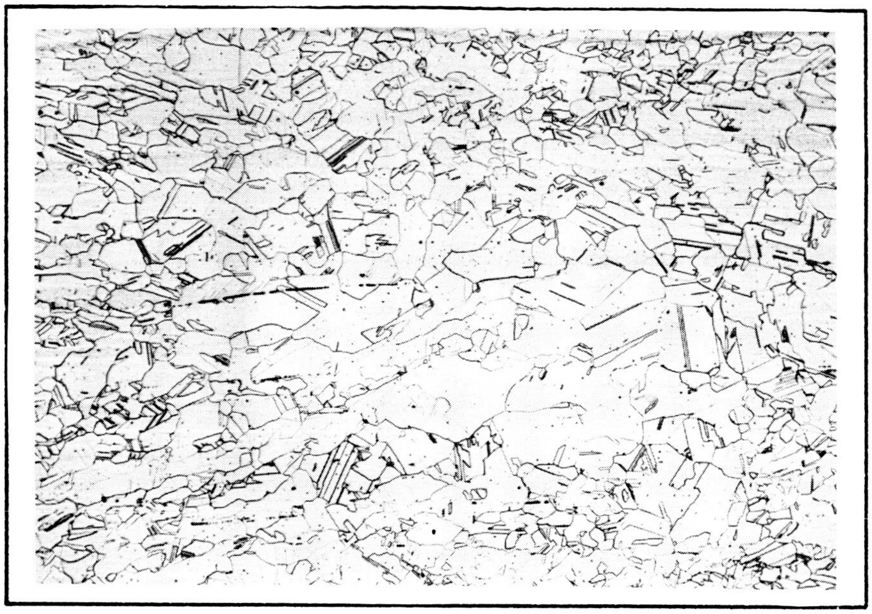
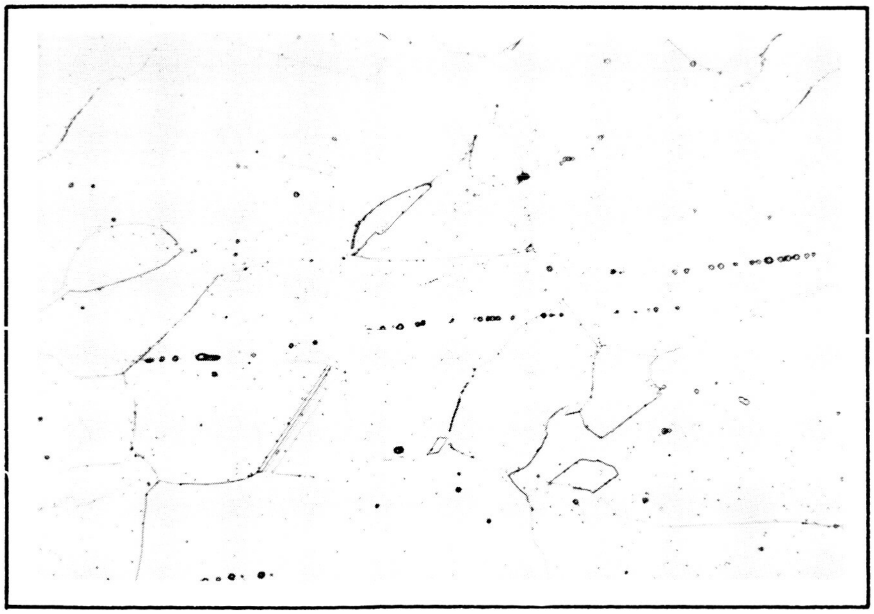


Figure 5



100 X Etchant: Oxalic Acid

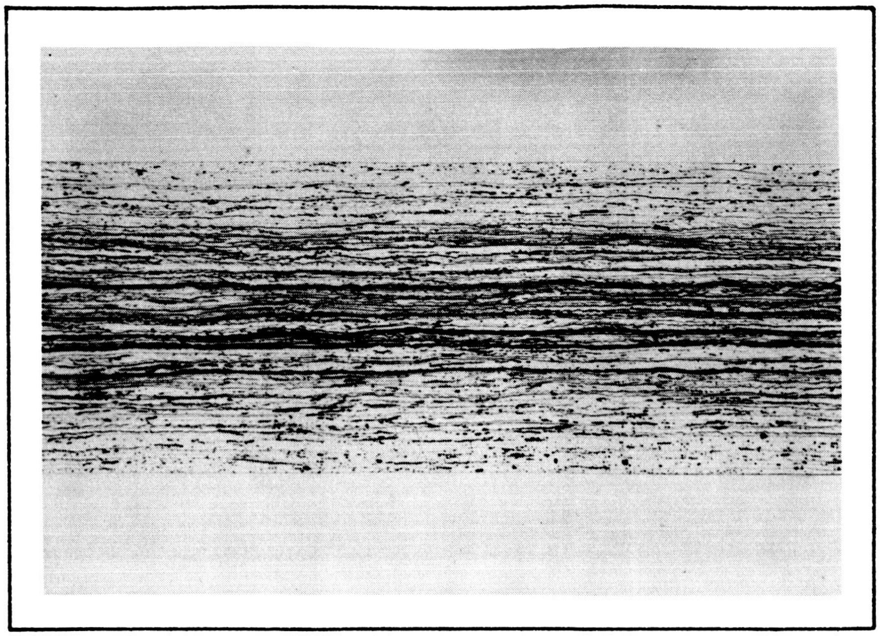
The microstructure of a longitudinal section of the annealed 0.080" thickness material. A relatively small amount of inclusions and foreign particles are visible in a recrystallized austenitic matrix.



500 X Etchant: Oxalic Acid

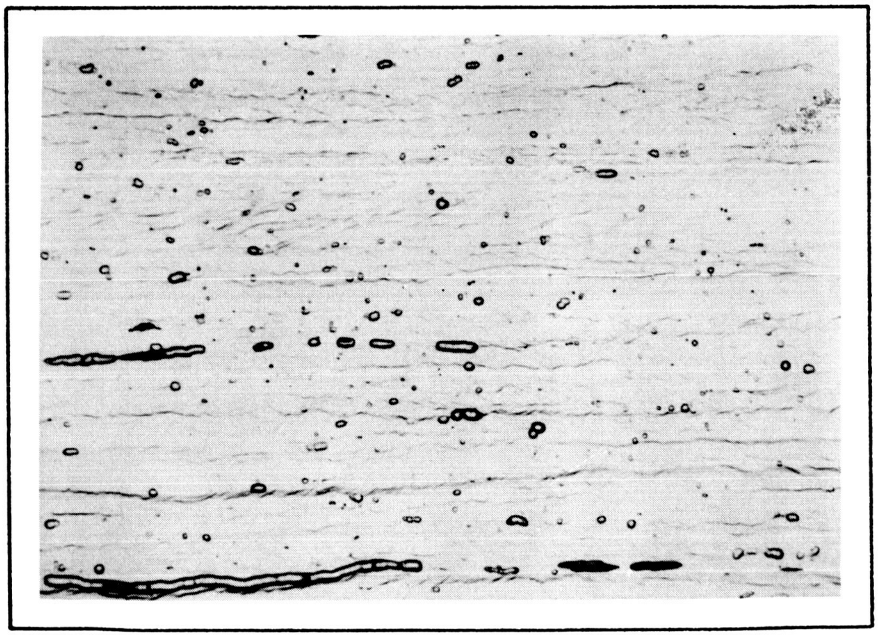
A higher magnification view of the microstructure from the annealed .090" thickness material.

Figure 6.



100 X Etchant: Oxalic Acid

The microstructure of a longitudinal section of the 0.016" thickness material. This material has been severely cold worked (80% reduction)



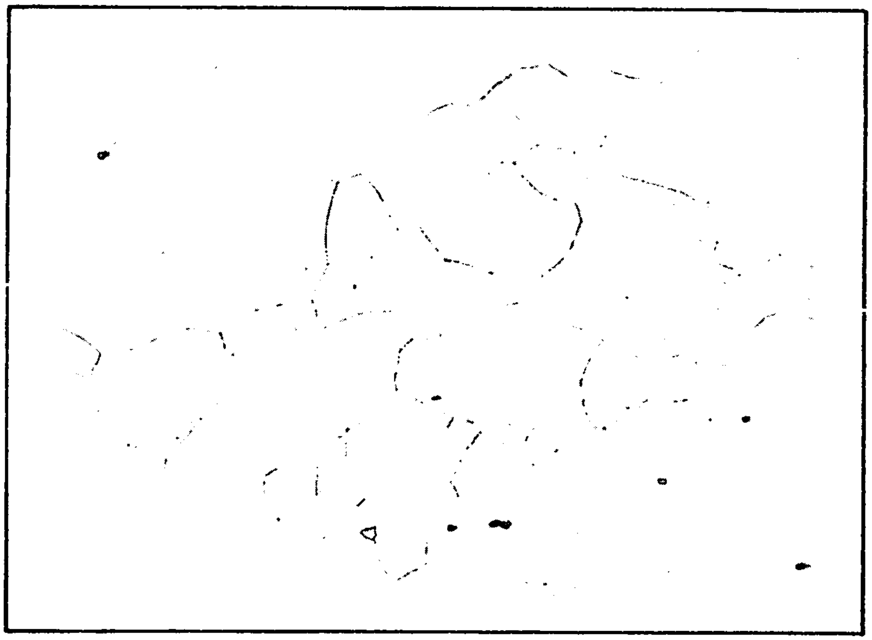
500 X Etchant: Oxalic Acid

A higher magnification of the microstructure of the 0.016" thickness material.

Figure 7.

100 X Etchant: Sodium Cyanide-Electrolytic

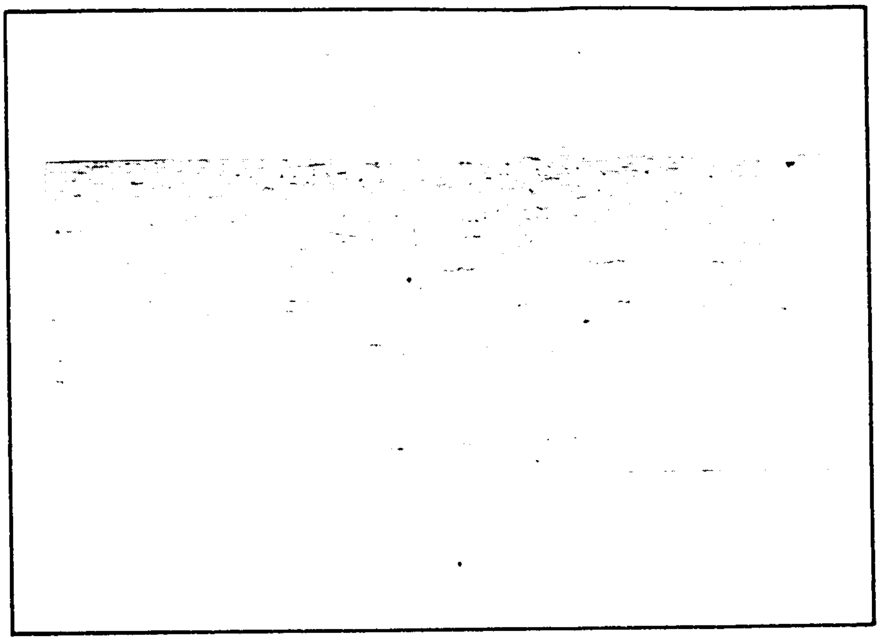
The presence of a discontinuous network of grain boundry carbides, shown as dark lines, was determined by electrolytically etching with sodium cyanide.



500 X Etchant: Sodium Cyanide-Electrolytic

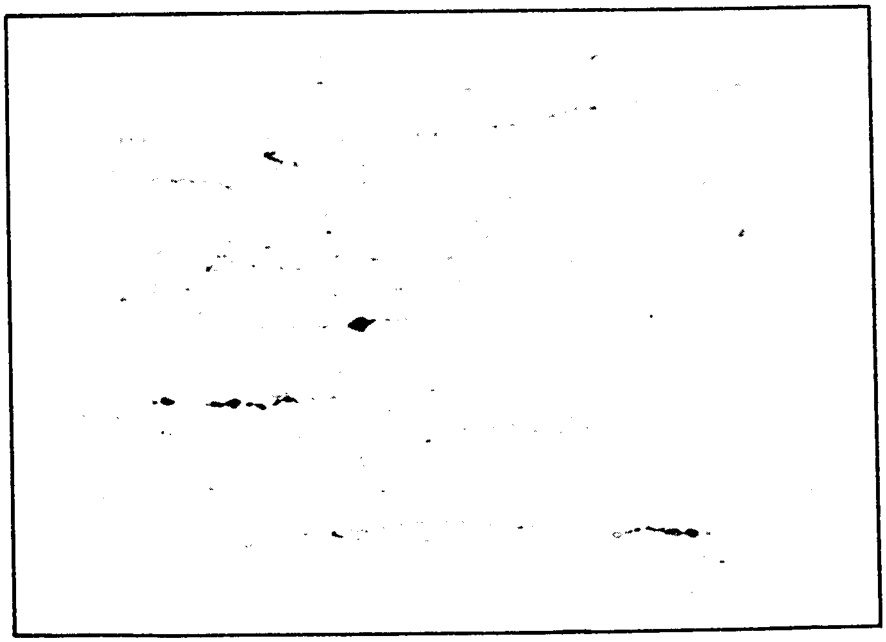
A higher magnification of the discontinuous network of grain boundry carbides revealed by the electrolytic sodium cyanide etch.

Figure 8.



100 X Etchant: Sodium Cyanide-Electrolytic

A longitudinal cross section of the 0.016" material electrolytically etched with sodium cyanide. The network of globular carbides has been elongated in the direction of cold work.



500 X Etchant: Sodium Cyanide-Electrolytic

A higher magnification of the elongated network of globular carbides in the 0.016" material.

Figure 9.

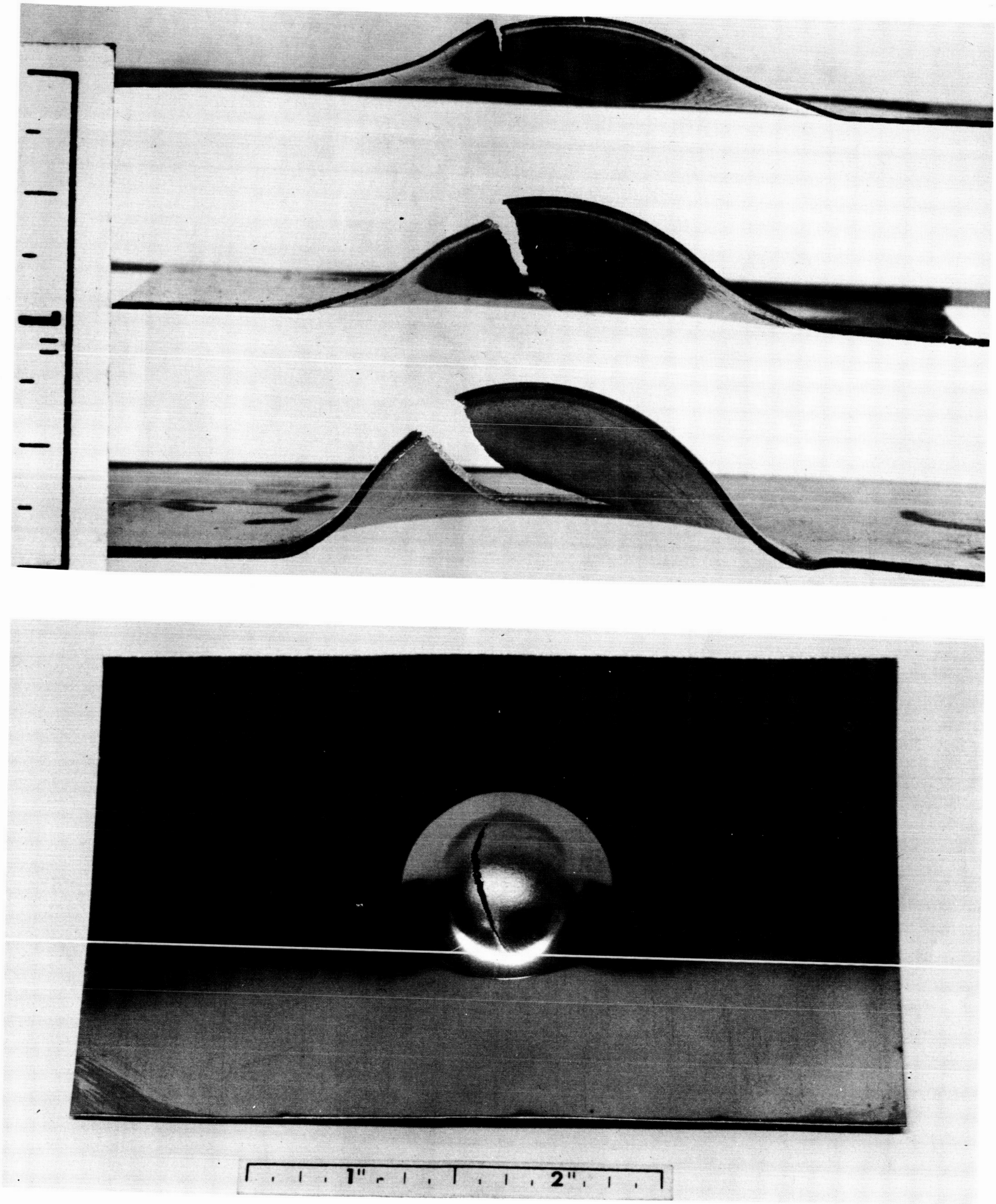


Figure 10. Examples of Cupping Test Specimens

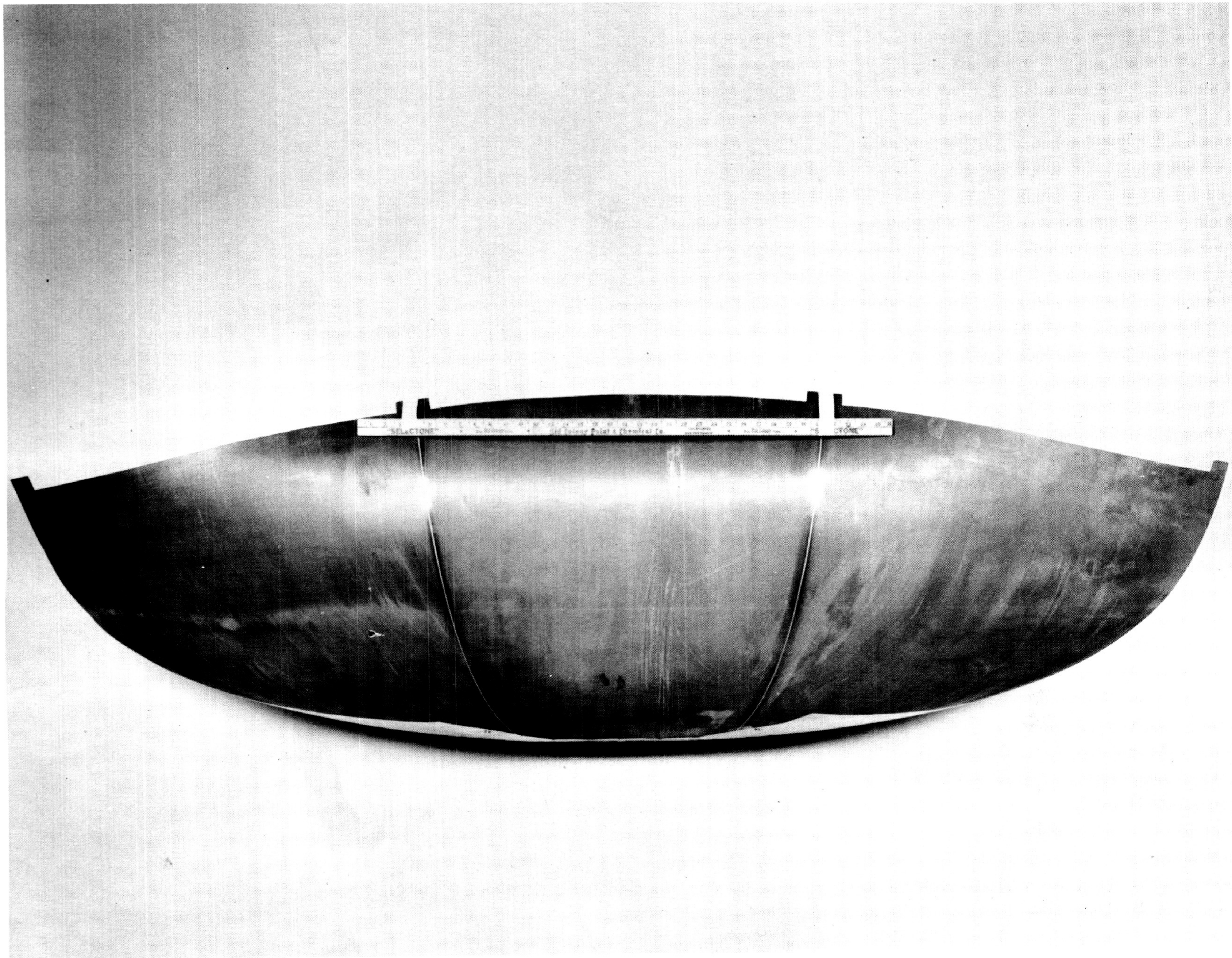


Figure 11. Stretch Formed and Fusion Welded 310 Stainless Steel

lost pg.

AR-592-1-365

27 November 1962

OK

SUBJECT: The Effects of Cold Rolling on the Mechanical Properties of Type 310 Stainless Steel at Room and Cryogenic Temperatures.

Prepared by: J. L. Christian
J. L. Christian
Staff Scientist

Prepared by: J. D. Gruner
J. D. Gruner
Engineering Metallurgist

Prepared by: L. D. Girton
L. D. Girton
Design Specialist

APPROVED BY: A. Hurlich
A. Hurlich
Chief of MATERIALS RESEARCH

Distribution:

V. A. Babits	592-0
H. F. Dunholter	590-0
W. M. Sutherland	967-4
A. Hausrath	592-3
R. Bradley	374-6
W. Morris	541-3
W. Beyers	290-2
H. E. Micken	290-3
W. M. Gross	563-1
J. A. Fager	541-3
R. S. Shorey	597-3

GENERAL DYNAMICS

Convair Division