RTD-TDR-63-4236

THE DEVELOPMENT OF OPTIMUM MANUFACTURING METHODS FOR COLUMBIUM ALLOY SHEET

TECHNICAL DOCUMENTARY REPORT NO. RTD-TDR-63-4236

Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

Project No. 7-784

(Prepared under Contract AF33(600)-39942, by E. I. du Pont de Nemours & Company, Inc., Baltimore, Maryland, authors: James S. Clark, Albert L. Mincher, and George N. Villee.)

NOTICES

FOREWORD

This technical documentary report covers work performed by sub-contract with E. I. du Pont de Nemours & Company, Inc., Baltimore, Maryland under Items 8 and 9 of Contract No. AF33(600)-39942. This work was initiated under the Manufacturing Methods Project No. 7-784, "The Development of Optimum Manufacturing Methods for Columbium Alloy Sheet". It was accomplished under the technical direction of Mr. W. E. Smith of the Manufacturing Technology Division, AF Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio.

This work covers a period of work conducted from 15 September 1962 to 31 October 1963.

The Technical Engineering Report (1)* for Items 1 through 7 of the contract was issued by the prime contractor, Crucible Steel Company of America.

The program for the development of a manufacturing process for D-43 sheet was conducted through the coordinated efforts of many persons at the Du Pont Metals Center. Mr. A. L. Mincher, Development Engineer, and Mr. G. N. Villee, Production Supervisor, were the engineers directly responsible for the work. Others who contributed to the development program were

E. M. Mahla, W. S. Wartel, and J. S. Clark - technical supervision

A. W. Dana, Jr. - production and technical supervision

R. W. Heckel - physical metallurgy

A. Brunner, W. F. Bumgarner, R. W. Felber, J. P. Hodges, and A. L. Larsen, Jr. - production supervision

H. O. Boord, Jr. - Quality control supervision

J. A. Crane - metallography and mechanical testing

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*Numbers in parentheses refer to bibliography

ABSTRACT

DEVELOPMENT OF OPTIMUM MANUFACTURING METHODS FOR COLUMBIUM ALLOY SHEET

James S. Clark
Albert L. Mincher
George N. Villee
E. I. du Pont de Nemours & Company, Inc.

This technical documentary report describes the development of a manufacturing process for D 43 columbium alloy sheet (Cb 10W 1Zr-0.1C, formerly called X-110). Du Pont performed the work as subcontractor to Crucible Steel in Contract AF33(600) 39942.

Six thousand pounds of second-melt electrodes were melted into eight-inch diameter ingots. The ingots were converted by extrusion and rolling to twenty-four inch wide sheets in three gages, 0.012", 0.018", and 0.030". The material was dispersion-strengthened by solution treatment at penultimate gage and aging at final gage. Sheets of all three gages had consistently high tensile strength at elevated temperature. The sheet processing is described.

Sheet quality was emphasized. The gage control was excellent, the majority of sheets being within one-half of the standard tolerances. The results of the quality control inspection are given. Various mechanical and physical properties of final product sheet are also given.

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PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER

Melvin E. Fields

MELVIN E. FIELDS, Colonel, USAF
Chief, Manufacturing Technology Division
AF Materials Laboratory

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I. INTRODUCTION

Contract AF33(600)-39942 for the development of optimum manufacturing methods for columbium alloy sheet was administered for the Air Force by the Crucible Steel Company of America, the prime contractor. The contract was originally divided into nine items as follows:

Items 1 & 2	- State-of-the-Art Survey and Selection of Alloys
Item 3	- Comparison of Ingot Consolidation Techniques
Items 4 & 5	- Evaluation of Ingot Integrity
Items 6 & 7	- Development of Sheet Rolling Process on 24" x 24" sheets
Item 8	- Reproducibility of Optimum Sheet Rolling Process, using 30" x 36" sheets
Item 9	- Production Reproducibility using 30" x 96" Sheet Panels

Work performed by Crucible on the F-48 and D-31 alloys under Items 1 through 7 has been summarized in the Interim Technical Engineering Report (1). After completion of the first seven items program changes were made as follows (Figure 1):

1. Items 8 and 9 were sub-contracted to E. I. du Pont de Nemours & Company, Inc.

2. Due to the difficulty of sheet processing of the F-48 alloy and the relatively low high temperature strength of the D-31 alloy, the D-43 alloy (previsouly designated X-110) was selected for production scale development.

Accordingly, work on this contract was continued at Du Pont and proceeded as far as completion of the rolling of sheet panels against Item 1 (original Item 8) requirements. At this point, work on the contract was temporarily halted pending renegotiation for the rolling of thinner gage material than originally specified. Revised program objectives are shown in Figure 1.

Transcript released by authors for publication on December 20, 1963.

THE DEVELOPMENT OF OPTIMUM MANUFACTURING METHODS FOR COLUMBIUM ALLOY SHEET

ORIGINAL PROGRAM
(Crucible Steel Company of America)

- Item 8-Reproducibility of sheet process on 30" x 36" panels of F-48 alloy at three gages 0.020", 0.040", 0.063"
- Item 9-Production reproducibility of sheet process on 30" x 96" panels of F-48 alloy at three gages 0.020", 0.040", 0.063"

REVISED TO →

NEW PROGRAM
(Sub-contracted to E. I. du Pont de Nemours & Company by Crucible Steel Company of America)

- Item 1-Development of sheet process for producing 30" x 36" panels of D-43 alloy at three gages 0.020", 0.040", 0.063"
- Item 2-Production reproducibility of sheet process for 30" x 96" panels of D-43 alloy at three gages 0.020", 0.040", 0.063"

REVISED TO ↓

- Item 1-Development of sheet process for producing 24" x 36" panels of D-43 alloy at three gages 0.012", 0.018", 0.030"
- Item 2-Production reproducibility of sheet process for 24" x L panels of D-43 alloy at three gages 0.012", 0.018", 0.030"

Figure 1. Program Revisions

The requirements of the sub-contract against the prime contract AF33(600)-39942 were the development of processing techniques and demonstration of reproducibility for the production of sheet in columbium alloy D-43 (Cb-10W-1Zr-0.1C, previously designated X-110). The program consisted of two items.

Item 1. Processing of 600 pounds of second-melt electrodes to sheet panels 24" x 36" at three gages:

0.012"
0.018"
0.030"

Item 2. Processing of 5400 pounds of second-melt electrodes of the D-43 alloy to sheet panels 24" x L at the three gages manufactured by the optimum processing schedule developed in Item 1.

Efforts were directed to producing the D-43 alloy to satisfactory sheet quality regarding gage uniformity, flatness, and surface finish. This final report summarizes all work performed by Du Pont on this sub-contract.

II. SUMMARY

A total of ten 3" diameter ingots of the D-43 alloy were prepared by arc-melting. The first two ingots were melted to 8" diameter x 22" long x ~ 300 lb. for processing against Item 1 contract requirements. Subsequent ingots for Item 2 were melted to 45" long x ~ 600 lb. and sectioned to obtain two billets from each ingot. A total of approximately 6000 lbs. of second-melt electrodes was consumed in the program.

Initial breakdown to 2" x 6" sheet bar was by the extrusion route. The sheet bars were hot rolled to 1/4" plate after which the alloy proved readily amenable to cold reduction.

In processing to original Item 1 contract requirements, sheet rolling was conducted by a low temperature route in that all working and annealing was at or below 2200°F. The D-43 sheet panels produced in this manner are listed in Table 1.

Processing against revised contract requirements necessitated re-rolling of these panels to thinner gage, and techniques developed at Du Pont expense under its refractory metals program were applied to the contract work. Strain induced precipitation hardening was effected by introducing a high temperature (3000°F) solution treatment at penultimate gage followed by limited cold work and aging. The sheet processing schedule is given in Figure 2. In view of the satisfactory results obtained by this technique, all material processed against Item 2 contract requirements was made via this high temperature route. Sheet panels were produced to 24" widths in three gages - 0.012", 0.018" and 0.030". The compilation of sheets produced under Item 2 appears in Table 1.

The emphasis on Item 1 processing was on the development of the high temperature solution treatment route for the production of D-43. In processing the major portion of the contract material against Item 2 requirements, emphasis was on the improvement of rolling and conditioning procedures to effect satisfactory sheet quality.

There were 1390 pounds of sheet panels produced in this development program. The yield of finished product from the 6000 pounds of second-melt electrode stock was 23%. The material consumed in process development and extensive sheet evaluation affected the yield.

The gage control was excellent on the final and largest batch of sheets processed. Over half the sheets were within one-half of the standard tolerances for each gage. The mechanical properties of these sheets were consistent from gage to gage. The 2200°F tensile strength was in the range 35 - 40,000 psi.

The sheet flatness averaged 6 - 7%. End curl of the sheets due to the stretch-leveling operation was the main factor in out-of-flatness.

TABLE 1

SHEET PANELS PRODUCED AGAINST CONTRACT REQUIREMENTS

Gage	Item 1 (Original) 28" wide		Item 1 (Revised) 24" wide		Item 2 24" wide		Total	
	Pieces	Wt.	Pieces	Wt.	Pieces	Wt.	Pieces	Wt.
0.008"	1	5.2					1	5.2
0.012"	1	5.0	6	38.5	46	320.0	53	363.5
0.018"			3	35.1	58	561.0	61	596.1
0.020"	1	3.8					1	3.8
0.030"			4	61.4	30	323.0	34	384.4
0.040"	1	4.0					1	4.0
0.062"	2	31.7					2	31.7
Total	6	49.7	13	135.0	134	1204.0	153	1388.7

Figure 2

D-43 Sheet Processing Schedule

Ingot 8" diameter x L

|

Extruded (2000°F) to 2" x 6" x L Sheet Bar

|

Cross Rolled (2200°F) to 1/4" Plate

|

Flattened and Conditioned

|

Annealed 2200°F/1 Hr.

|

Cold Rolled to 0.100"

|

Annealed 2200°F/1 Hr.

|

Cold Rolled to Penultimate Gage

|

Solution Heat Treated, 3000°F/10 min.

|

Cold Rolled to Final Gage

|

Annealed 2600°F/1 Hr.

|

Flattened

III. PROCESSING

A. MELTING AND EXTRUSION

All ingots were prepared by double consumable electrode arc-melting (direct current-straight polarity) under high vacuum. The alloy blend was prepared to nominal D-43 composition (Cb-10W-1Zr-0.1C) and isostatically compacted to 3" diameter bars.

Six inch diameter ingots were made on first melting, and remelted into an 8-1/4" diameter mold. The ingots were checked ultrasonically for soundness and then cropped, sectioned and machined to billets 7.57" diameter x ~ 22" L. The billets were canned in steel and extruded from 2000°F to 2" x 6" sheet bar (4:1 extrusion ratio). Extrusion details appear in Table 2. Proprietary glass lubrication techniques developed by Sejournet were used.

The extruded sheet bars had a satisfactory surface with no nose bursting or surface checking. Typical extrusions are shown in Figure 3.

B. ROLLING

Rolling was conducted on the Schloemann Mill at the Du Pont Metals Center, Figure 4. Initial breakdown rolling from the 2" thick extruded bar to 1/4" plate was conducted on the 2 Hi set-up (35" diameter work rolls). The pieces were cross-rolled from 2100°F, using reductions of 10 - 15% per pass. Intermediate reheats were inserted as required.

The 1/4" plate was conditioned and annealed then returned to the 2 Hi set-up for cold-rolling to approximately 0.1". After annealing at 0.1", cold-rolling was conducted on either the single cluster (6" diameter work rolls) or the 4 Hi (16-1/2" diameter work rolls) configuration. A yield loss was experienced in the 1/4" and 0.1" plate due to 45° surface cracks. The cracking was apparently caused by residual surface contamination from the warm rolling step.

In rolling to original contract requirements in Item 1 (0.020", 0.040" and 0.063" gage) all pieces were tension rolled from 0.1" to final gage on the single cluster set-up. In rolling to revised contract requirements (0.012", 0.018" and 0.030"), individual panels were hand rolled to final gage on the 4 Hi mill after the high temperature solution treatment. Rolling was satisfactory, with only minor cracking being experienced. For final rolling of the last, and largest, batch of sheets in Item 2, emphasis was placed on rolling close to the target gages of 0.012", 0.018", and 0.030" with minimum gage variation. Comparatively

TABLE 2

EXTRUSION DETAILS

Billet Diameter:	7.57" diameter x 20" L canned to 7.88" diameter in Mild Steel
Billet Temp:	2000°F
Die:	2" x 6", flat faced, 750°F
Reduction Ratio:	4 to 1
Liner:	8" diameter, 900°F
Lubrication:	Pad - "D" Glass
	Table - "E" Glass

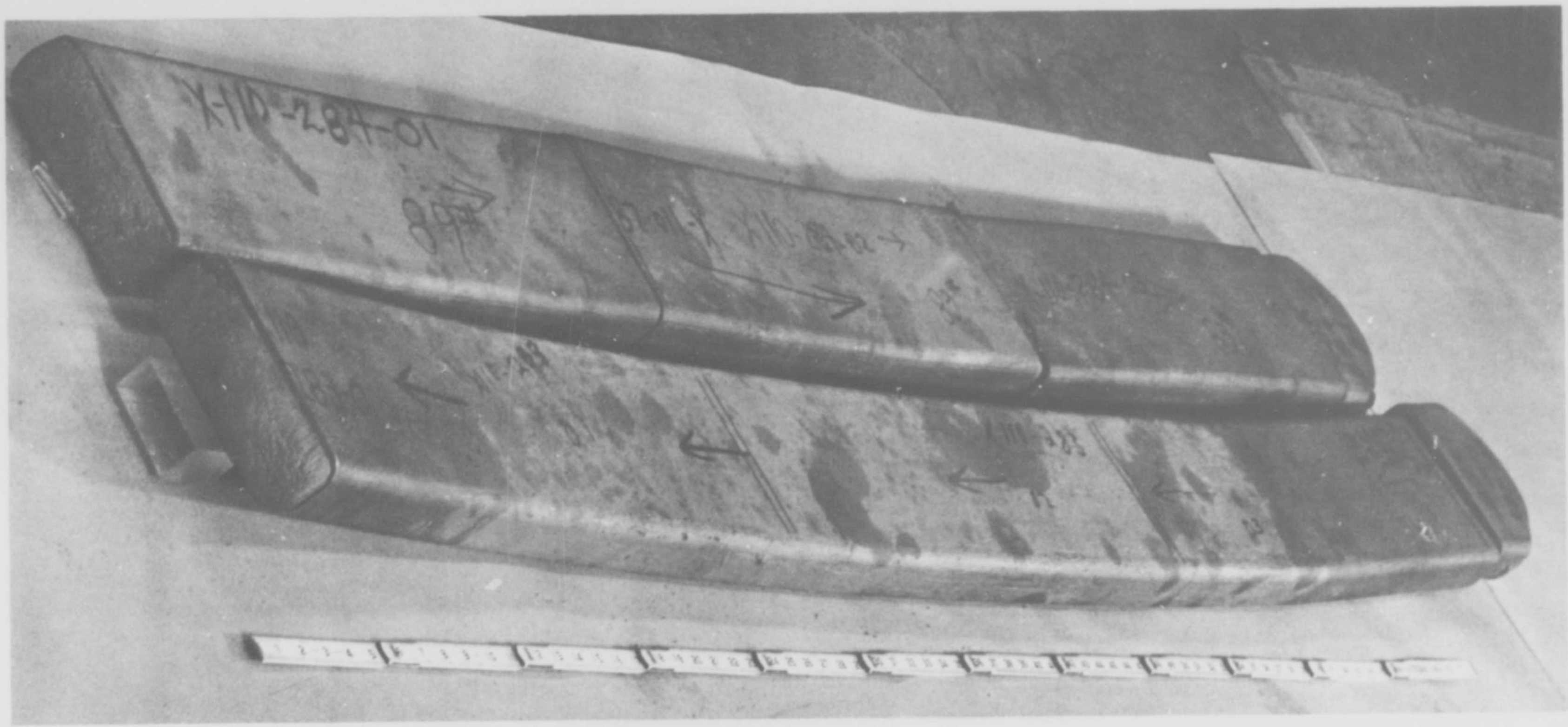


Figure 3. Extruded Sheet Bars

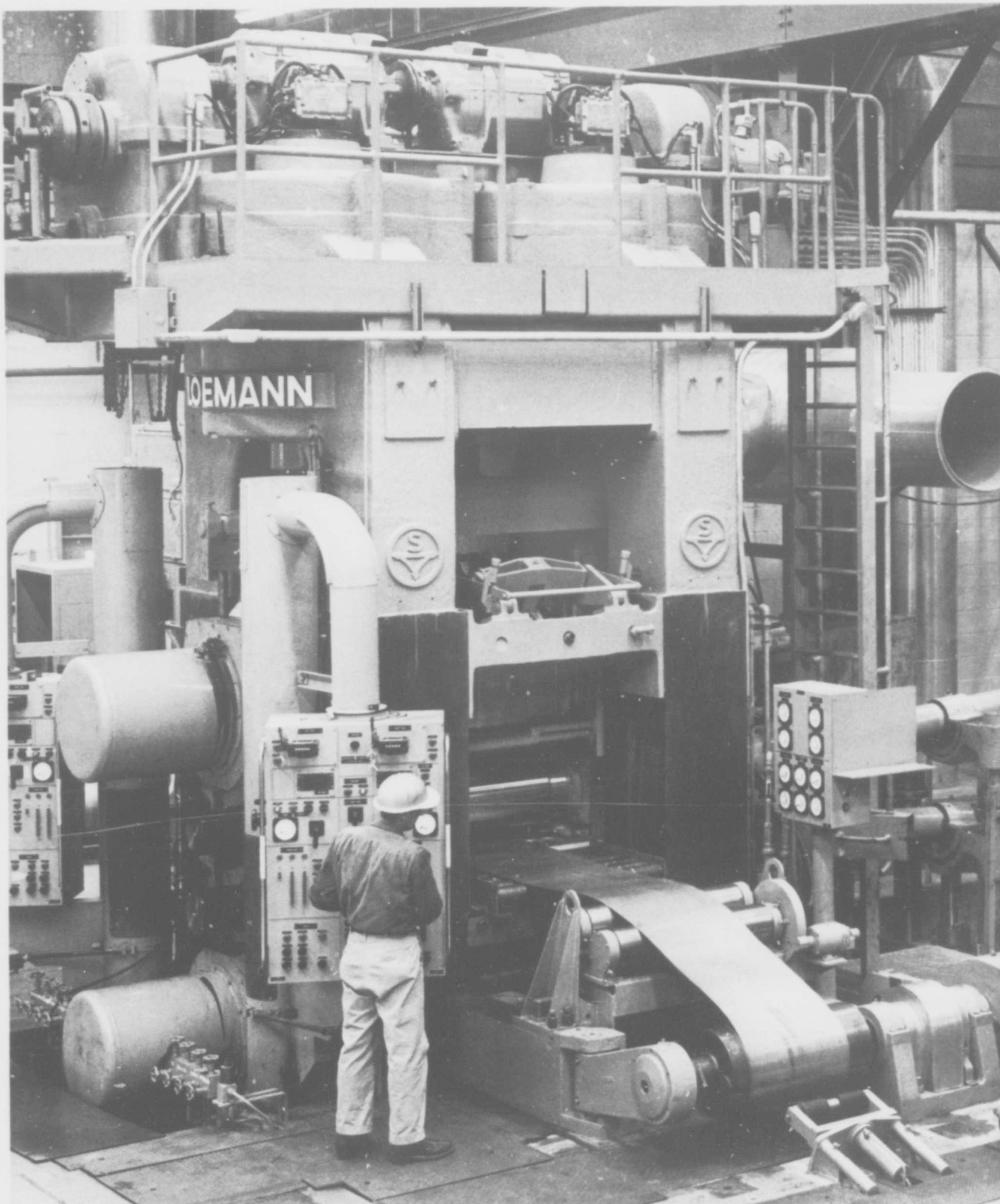


Figure 4. Rolling Mill

light reductions were taken to effect this greater dimensional control. Light reductions/pass were achieved by a combination of light crown on the work rolls and light mill loading. The gage survey of this final batch of sheets is described under "Inspection" below.

C. HEAT TREATMENT

Annealing at the various stages to penultimate gage was conducted in the Du Pont sheet furnace, Figure 5, under a vacuum of 0.1 micron. Intermediate stress reliefs were controlled at 2175 - 2200°F. Sheet lengths in this furnace are limited to 96".

The critical processing of D-43 sheet to get high hot strength is in the final working and annealing stage. Experimentation by Du Pont showed that a wide range of properties could be obtained in D-43 by strain-induced precipitation hardening. Solutionizing was studied in the 2800 - 3200°F range, the objective being to obtain the effective solution of dispersoids without excessive grain growth. The experimental parameters were kept within the capabilities of commercial furnaces. The amount of final rolling reduction and the final aging treatment was also investigated.

The selection of process conditions was based on an optimum combination of hot strength and ductility. Short-time solutionizing at 3000°F followed by 25% final reduction and aging achieved a balance of properties.

Accordingly, all panels at penultimate gage were given a 3000°F solution treatment under vacuum in the Du Pont strip furnace, Figure 6. Typical microstructures after solution treatment (Figure 7) show full recrystallization (ASTM 4-6) with a coarse Widmanstatten precipitate. Following the solution anneal the sheets were cold-rolled approximately 25% to final gage.

Final aging of sheets to develop optimum elevated temperature strength was performed at 2600 - 2700°F for 1 hour in the sheet furnace (Figure 5). The selection of a final aging temperature for the D-43 sheet panels was based on a compromise among

1) Satisfactory 2200°F strength

2) Adequate ductility and formability at room temperature

3) Thermal stability at elevated temperature

Aging at lower temperatures, e.g., 2200°F, produced exceptionally high strength sheet but cup tests of the sheet indicated a tendency toward brittle fracture under biaxial stress despite reasonable cup depth.

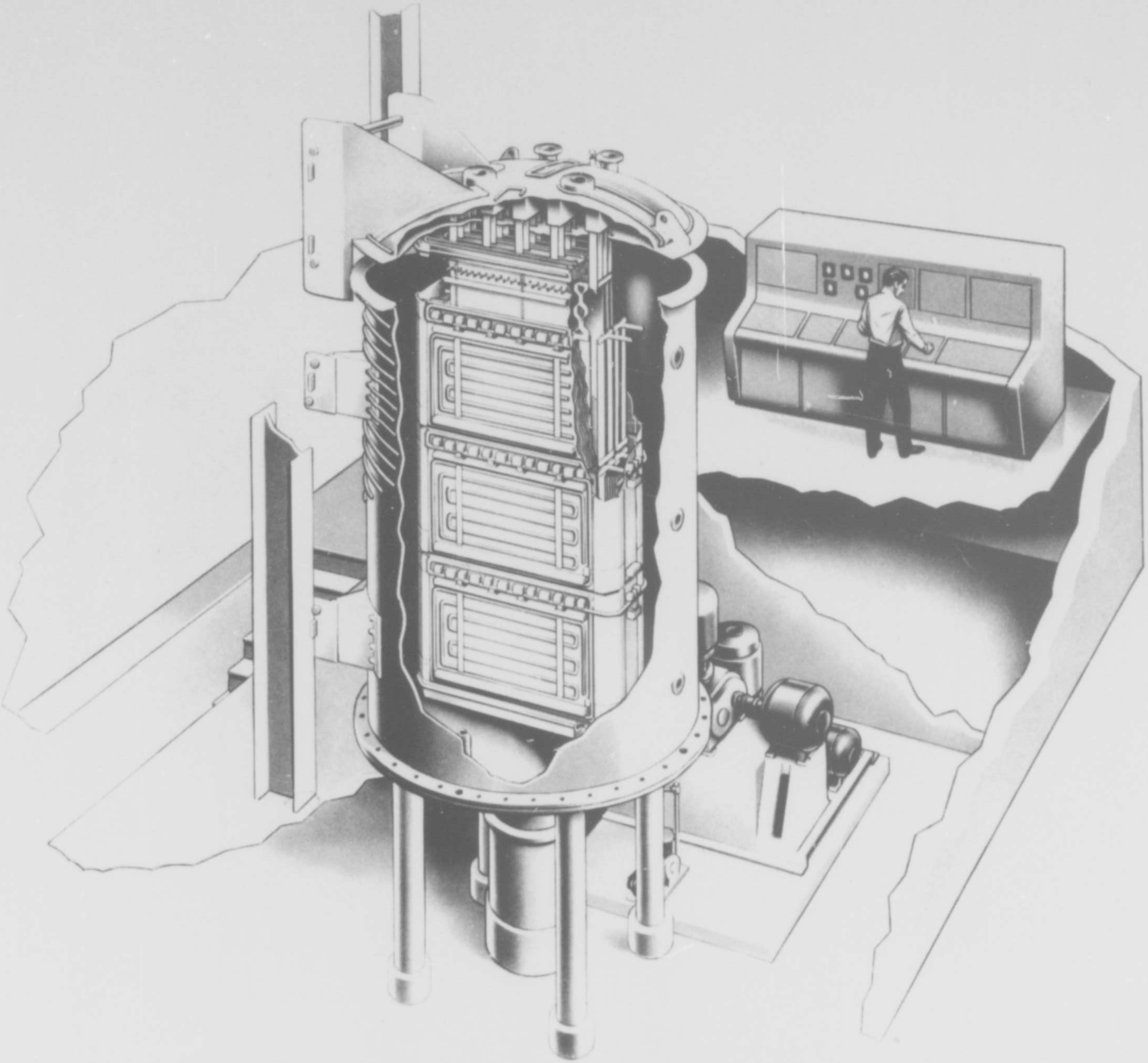


Figure 5. Vacuum Sheet Furnace

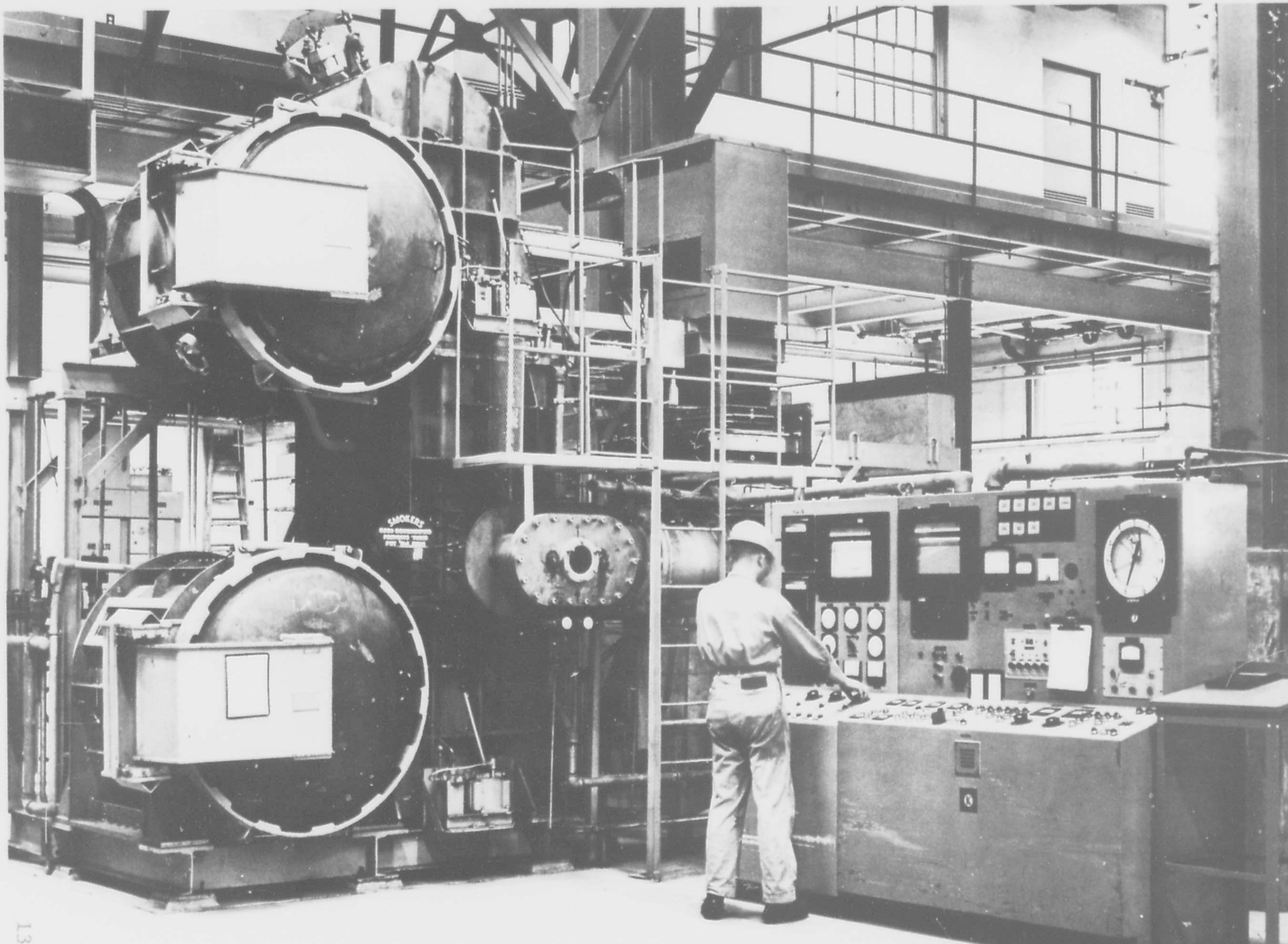
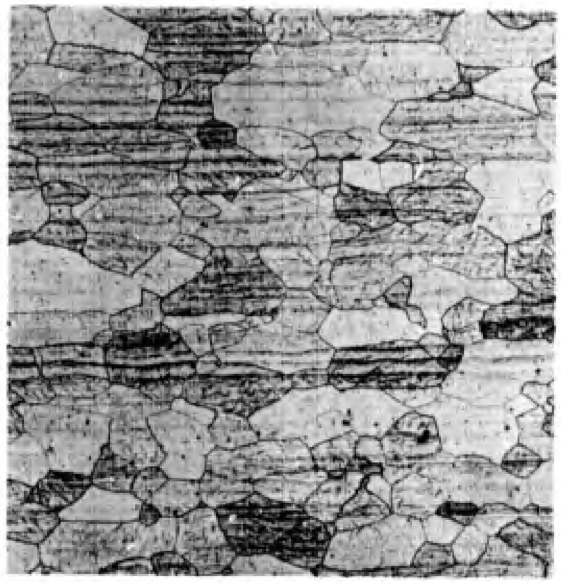
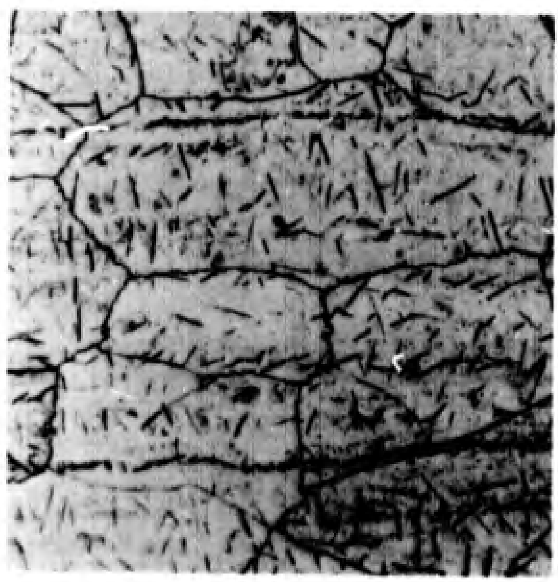


Figure 6. Vacuum Strip Furnace



X100



X500

Figure 7. Microstructures of 0.040" D-43 Sheet Solution Treated at 3000°F.

D. LEVELING

Leveling was required at two stages in the process. The 1/4" plate, as hot-rolled, was not sufficiently flat to allow uniform conditioning. Accordingly, the hot-rolled plates were flattened by warm (~ 800°F) roller leveling. Some yield loss was incurred on Item 2 plates which were roller leveled below ~ 800°F (down to ambient temperature), resulting in fine 45° surface cracks.

Leveling of final sheet product was performed by stretching at ambient temperature on the Du Pont Metals Center stretch straightener to a maximum 1% elongation. Serrated jaw type grips were used. Fracture of a small number of sheets occurred during the stretching operation. Fracture was attributed to fine edge cracks from the final rolling operation. Edge shearing virtually eliminated this problem.

E. CONDITIONING

Various methods were attempted to optimize conditioning procedures throughout the processing. The following sequence was devised:

1) Fully condition 1/4" warm-rolled plate by automatic wet grinding of leveled plates

2) Spot grind in-process sheet as required prior to each rolling operation

3) Belt sand finished sheet all over

The final wide-belt sanding was done to produce a smooth uniform surface free of processing defects.

IV. INSPECTION AND TESTING

In process quality control was on the basis of ingot chemistry (as determined from extrusion slices) and inspection for surface and lamination defects at intermediate gage thicknesses during rolling.

All final sheet panels produced in both Item 1 and Item 2 were submitted to standard Du Pont quality control inspection for gage, flatness, and surface. In addition, randomly selected sheets were closely surveyed for gage by means of a "Vidigage" ultrasonic measuring instrument, the measurements being made on 6" centers over the entire sheet.

Lot testing of samples of all final product for chemistry, room- and elevated temperature tensile strengths, and ductility by cup test was performed at the Du Pont Metals Center Laboratory. The individual lots of final product were on the basis of "ingot (heat) by gage by final heat-treatment batch".

The final batch of sheet produced in Item 2 - the major portion of sheet produced in the contract - represented the closest control of processing variables achieved. Therefore the properties and quality of this batch, which amounted to approximately 1050 pounds of sheet product, are reported in detail in this section.

A. MECHANICAL PROPERTIES

The comprehensive evaluation of mechanical and physical properties of D-43 sheet produced in Item 1 of the contract is presented as Appendix I of this report. One panel of each gage was tested for various physical and mechanical properties in order to characterize D-43 sheet.

The results of standard tensile tests both at room temperature and 2200°F of Item 2 samples appear in Table 3. The results of Erichson cup tests (1" diameter ball) are also shown. The tensile specimens, 1/4" wide x 1" gage length, were tested at the following strain rates:

Room Temperature: 0.005"/"/min. to yield, 0.05"/"/min. to fracture

2200°F: 0.05"/"/min. throughout

The agreement in strength levels among the three gages is excellent. One exception is the group of results for 0.018" gage product listed separately in the table. The 2200°F tensile strength level of this group is 3000 - 5000 psi lower than the remainder of the

TABLE 3

TENSILE AND ERICHSON CUP TEST RESULTS - ITEM 2 MATERIAL

		Tensile Tests												Cup Tests
		2200°F						RT						
		L			T			L			T			Cup Depth
Gage	Ht.No.	UTS	YS	%E	UTS	YS	%E	UTS	YS	%E	UTS	YS	%E	(mm across 1" dia.)
.012"	396-12	37.9	36.2	14.5	41.0	38.8	11.6	82.1	65.4	18.5	85.0	63.4	15.0	6.50(B)[1]
	388-23	34.7	32.7	14.8	39.9	37.5	14.8	81.7	61.0	17.0	88.9	63.0	17.0	4.90(B)
	389-22	34.9	30.0	24.0	39.6	35.4	12.8	82.1	63.2	20.0	86.5	62.8	18.0	3.66(B)
	396-13	37.3	34.6	15.6	41.4	38.6	12.5	82.7	66.7	20.0	85.6	61.7	15.5	5.04(B)
	388-21	37.4	35.2	17.5	38.6	35.2	11.6	82.6	66.2	20.0	86.0	63.2	16.0	6.40
	396-22	34.1	31.2	20.2	37.9	35.1	14.5	85.9	64.0	20.0	89.0	64.2	17.0	5.89(B)
	388-22	35.8	33.5	15.6	39.6	36.4	16.4	86.0	65.2	15.0	89.6	65.4	14.5	6.50
.018"	397-21	39.3	37.2	17.6	40.6	36.8	17.0	87.4	71.9	22.0	91.5	61.1	20.0	6.50(B)
	395-11	35.9	32.3	25.5	42.2	37.5	13.0	89.1	67.2	17.5	98.9	71.3	20.0	7.10(B)
	395-13	37.9	36.3	16.4	39.6	34.2	13.3	80.6	62.9	18.3	83.9	63.6	17.5	6.90(B)
	397-22	35.2	33.3	16.8	39.8	36.7	13.4	81.5	64.1	20.8	85.0	63.9	17.0	7.00(B)
	397-23	34.7	33.2	11.1	38.7	36.4	17.1	84.7	68.1	14.0	87.8	64.9	15.5	6.00
	395-23	35.5	33.2	18.5	40.2	37.2	14.5	84.7	68.1	19.4	87.1	64.3	19.0	6.80(B)
	396-21	35.2	33.2	20.2	39.2	37.4	15.5	80.8	63.2	22.5	86.4	64.1	17.0	5.04(B)
	396-23	34.9	33.3	21.3	40.1	37.9	18.2	82.3	62.5	25.0	88.0	63.2	19.0	6.61
.030"	394-12	37.2	35.5	18.8	39.0	34.9	14.0	85.3	71.2	18.0	89.4	64.2	15.5	5.50(B)
	394-21	35.8	34.5	17.1	40.7	38.6	13.4	85.1	66.2	22.5	89.1	65.0	18.0	5.03(B)
	398-22	34.8	32.2	19.5	39.2	37.0	16.3	82.5	61.3	26.8	87.1	64.4	25.0	8.15(B)
.018"[2]	397-13	32.2	30.7	26.7	36.4	33.6	21.6	79.2	58.2	26.0	85.3	60.6	19.0	7.95
	388-11	32.9	30.2	27.1	35.7	32.2	22.3	80.3	58.4	25.5	84.4	58.3	22.6	7.67
	395-22	31.2	28.2	27.2	32.8	29.9	21.0	77.5	57.0	23.0	82.6	54.7	20.0	7.20
	388-12	34.0	32.0	20.8	37.7	35.0	17.1	83.7	62.5	22.8	89.0	64.2	22.0	7.39
	395-12	31.8	28.5	26.5	36.2	32.7	24.4	80.3	57.6	22.0	84.2	57.5	20.0	7.26

1 (B) indicates brittle-type fracture
2 This material processed separately from above

material. This is the result of a lower solution temperature (~ 100°F lower) during heat treatment at penultimate gage.

The tensile strength data in Table 3 for all gages were submitted to a statistical analyses. (The group of "low" strengths in 0.018" gage were omitted). The results appear in Table 4. The average tensile and elongation values for each gage - 0.012", 0.018", and 0.030" - agree quite closely. The number of samples, n, is indicated. The agreement is more clearly seen by comparing the average value for each gage with the overall average of all gages. The standard deviation, s, and the 95% confidence limits appear in the table.

B. CHEMICAL ANALYSIS

The results of chemical analysis of lot samples (final product) from all ingots produced in this contract are presented in Table 5. The composition limits in the Du Pont D-43 sheet specification (DPC-1101-1) are included in the table. All of the final product samples reported in the table are within specification. Contamination from oxygen was slight despite the high temperature processing. A yield loss was incurred in the first batch of Item 2 product because a portion of one heat was above the Du Pont specification limit for tungsten - 14.2% vs. 11% maximum.

C. GAGE

The objective regarding gage in the Item 2 product was twofold -

1) to minimize gage variation, and

2) to attain each of the three target gages

All finished sheets were surveyed for gage using the "Vidigage" ultrasonic instrument. A minimum of 15 readings were taken on each sheet - 5 along both edges and 5 along the center line. In addition randomly selected sheets were measured at 6" centers over the entire sheet. The summary of gage control in relation to the three target gages appears in Table 6. The results are presented in terms of the percentages of sheets at each gage which are within the given tolerances. The gage control of the 0.012" material (46 sheets) was excellent; 89% of the sheets were within ± .001" of the target gage. The gage control of 0.018" and 0.030" stock was also good, especially when gage variation is expressed as a percentage of thickness. The data in Table 6 reveal that the absolute deviation from target gage increased with increasing gage. The major deviation was measured at the edges and ends of the sheets. No attempt was made

TABLE 4

STATISTICAL ANALYSIS OF TENSILE STRENGTH[1] DATA

		2200°F						RT					
		L			T			L			T		
Gage		UTS	YS	%E	UTS	YS	%E	UTS	YS	%E	UTS	YS	%E
(n=7)	.012"	36.01	33.26	17.46	39.71	36.71	13.46	83.30	64.53	18.64	87.23	63.39	16.14
(n=8)	.018"	36.08	34.00	18.41	40.05	36.76	15.25	83.89	66.00	19.94	88.58	64.55	18.13
(n=3)	.030"	35.93	34.07	18.47	39.63	36.83	14.57	84.30	66.23	22.43	88.53	64.53	19.50
18	All	36.03	33.72	18.05	39.85	36.76	14.44	83.73	65.47	19.85	88.04	64.09	17.58
s		1.45	1.84	1.10	1.06	1.36	1.95	2.39	3.07	3.20	3.35	2.10	2.81
95% conf.limits		33.1/ 38.9	30.0/ 37.4	15.8/ 20.2	37.7/ 42.0	34.0/ 39.5	10.5/ 18.3	78.9/ 88.5	59.3/ 71.6	13.5/ 26.3	81.3/ 94.7	59.9/ 68.3	12.0/ 23.2

[1] all strength values x 1000 psi.

TABLE 5

SHEET CHEMISTRY, ITEM 2

Heat Number Du Pont Spec.	Sheet Thickness DPC(P)-1101	W (%) 9.0-11.0	Zr (%) 0.75-1.25	C (ppm) 800-1200	O (ppm) 400	H (ppm) 20	N (ppm) 100
387-2	0.030"	9.4	1.00	1070	136	3	40
-3	0.030"	9.3	1.10	1090	141	3	40
388-1	0.018"	9.5	.96	885	202	8	38
-2	0.012"	9.7	.94	1065	352	2	58
389-1	0.018"	10.5	.99	990	137	4	37
-2	0.012"	10.9	1.00	1000	186	3	48
394-1	0.030"	9.9	.93	940	264	5	40
-2	0.030"	9.8	.91	995	266	5	37
395-1	0.018"	9.5	.95	940	298	4	33
-2	0.018"	9.9	.92	965	197	5	42
396-1	0.012"	9.7	.95	950	290	8	52
-2	0.018"	9.6	.95	980	180	4	38
397-1	0.018"	9.9	.92	995	183	2	41
-2	0.018"	9.6	1.00	875	224	8	40
398-2	0.030"	9.9	.95	925	93	10	32

TABLE 6

FINAL GAGE INSPECTION

% Of Pieces Within	THICKNESS Of 0.012" (46 pcs.)	Of 0.018" (53 pcs.)	Of 0.030" (10 pcs.)
± 0.0005"	22%	6%	0%
± 0.0010"	89	53	30
± 0.0015"	98	91	60
± 0.0020"	100 "S"*	96 "S"*	80
± 0.0025"	100	100	100 "S"*

* "S" denotes standard Du Pont thickness tolerance

to shear back edges or ends for minimum gage variation. Sheets were trimmed for maximum width only. The results of individual detailed gage surveys of randomly selected sheets in Item 2 are presented graphically in Figure 8A through 8F.

D. FLATNESS

The Item 2 sheets were inspected for percent flatness as measured by 1/2 H/L, where H is the height of a bow in the sheet from a flat surface and L is the length over which the bow extends. Figure 9 is a bar graph showing the percentage of sheets at each gage with maximum percent flatness in incremental ranges. The majority of sheets at all gages were flatter than 6%. The end curl and/or corner curl of the sheets were the principal contributing shapes to the out-of-flatness. Trimming of sheet ends can eliminate certain cases of out-of-flatness. The end curl of the 0.018" gage D-43 sheet in Figure 10-A was eliminated simply by shearing approximately 6" from the end, Figure 10-B. The amount of corner curl of the 0.030" gage D-43 sheet in Figure 11-A was not changed by shearing approximately 2 feet from the end, Figure 11-B.

Several Item 1 sheets were checked for the approximate area flatter than 3%. The inspection results appear in Table 7. Seven of the ten sheets could possibly have been brought within 3% flatness by shearing with a total yield loss of 26%. The estimated yield loss is 25 - 50% to achieve 3% flatness in the contract sheets by shearing.

88" × 24"

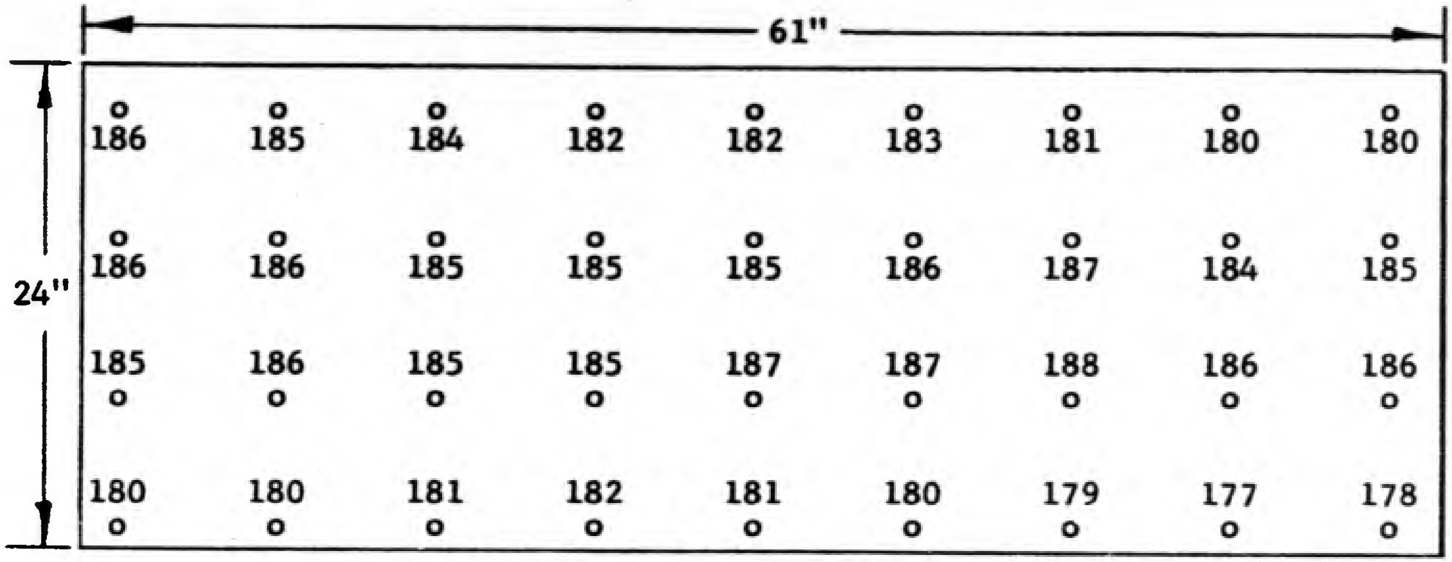
127	127	129	127	128	128	128	129	129	129	130	130
123	126	126	126	128	128	128	128	127	127	128	127
122	124	123	123	125	125	125	124	124	124	125	123
119	123	123	124	125	125	126	124	124	124	125	122

Mean Gage = 0.0125"

Range = 0.0119" - 0.0130"

Deviation = ± 0.0006" 5%

Figure 8A. Thickness Survey of 0.012" Sheet (389-21)



Mean Gage = 0.0182"

Range = 0.0177" - 0.0187"

Deviation = $\pm$ 0.0005" 3%

Figure 8B. Thickness Survey of 0.018" Sheet Panel (389-13)

95" × 24"

308	304	296	302	305	301	297	300	299	295	295	292	290
311	308	306	306	308	303	304	305	304	301	301	301	295
310	305	303	304	306	302	304	307	302	301	301	302	298
307	303	303	302	300	298	301	305	304	302	303	304	298

Mean Gage = 0.0300"

Range = 0.0292" - 0.0308" (Excluding Ends)

Deviation = ± 0.0008"   2-1/2%

Figure 8C. Thickness Survey of 0.030" Sheet Panel (387-31)

94"

24"

119	123	122	121	122	122	123	122	123	123	124	124	126	127	126	125
120	123	121	123	123	123	124	123	124	124	125	125	124	127	126	124
118	119	119	119	120	120	121	121	121	122	121	122	123	123	122	123
115	119	119	119	120	120	121	121	122	122	123	123	123	124	123	122
112	119	118	119	120	120	120	120	122	124	123	124	123	124	123	121

Mean Gage = 0.0123"

Range = 0.0119" - 0.0127" (Excluding Ends)

Deviation = ± 0.0004" 3%

Figure 8D. Thickness Survey of 0.012" Sheet Panel (396-23)

91" × 24"

175	180	182	182	186	186	184	186	186	185	186	185	185	183	184	184
181	182	187	186	189	189	190	189	190	190	191	191	188	188	189	186
179	182	185	186	189	190	189	189	190	189	190	188	188	187	188	188
180	184	184	186	188	190	189	190	189	188	189	188	189	188	188	188
169	183	184	182	184	185	184	185	185	185	183	185	185	184	183	181

Mean Gage = 0.0185"

Range = 0.0180" - 0.0191" (Excluding Ends)

Deviation = ± 0.0006" 3%

Figure 8E. Thickness Survey of 0.018" Sheet Panel (395-13)

54"

24"

301	300	298	301	301	305	305	308	310	310
305	302	303	307	308	310	310	310	312	315
305	303	303	306	307	308	310	311	312	316
303	303	301	303	305	308	310	309	308	310
297	297	296	296	298	300	301	301	303	301

Mean Gage = 0.0306"

Range = 0.0296" - 0.0316"

Deviation = ± 0.001" 3%

Figure 9F. Thickness Survey of 0.030" Sheet Panel (394-21)

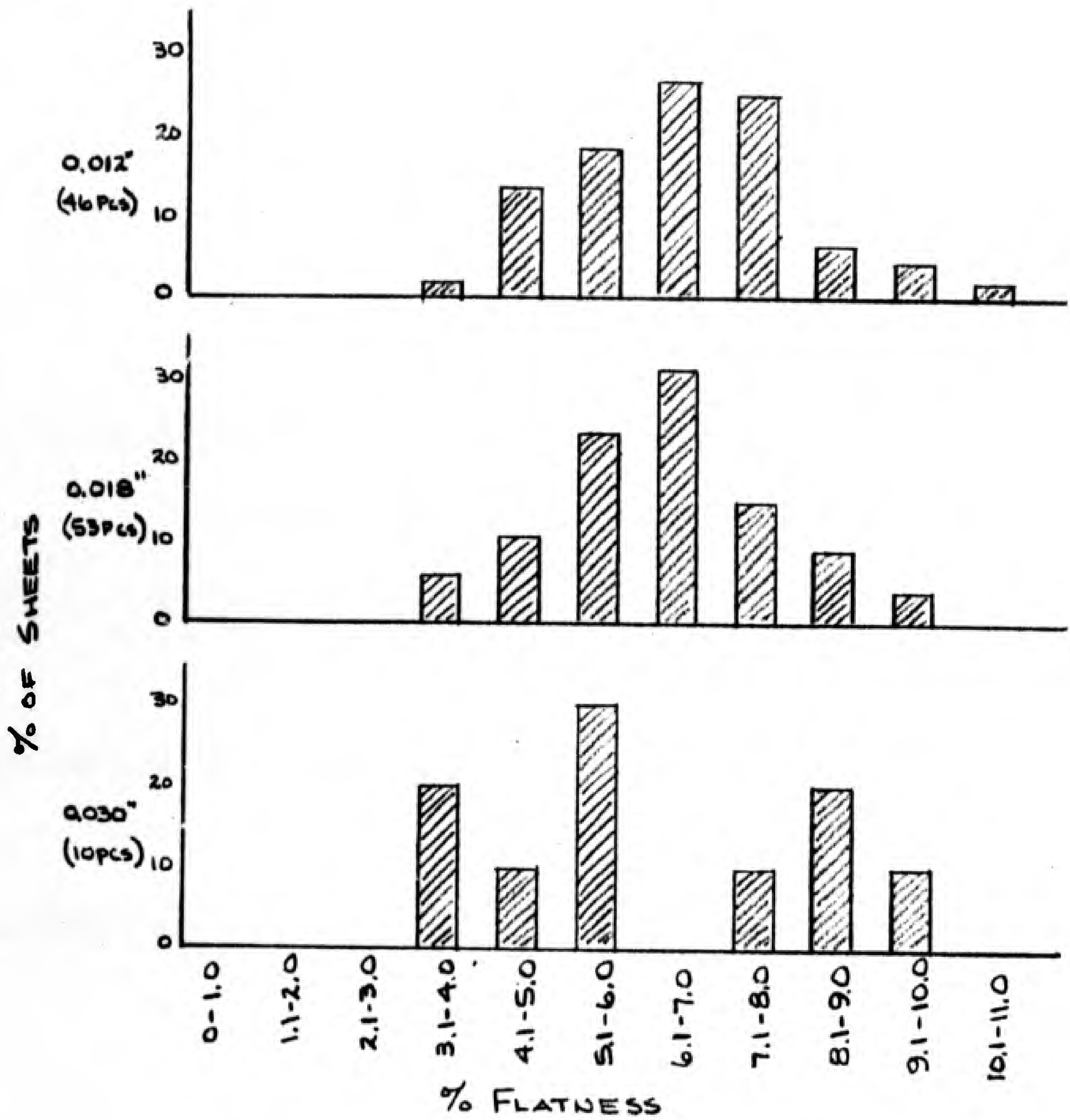


Figure 9. D-43 Crucible Sub-contract Final Inspection Data, Flatness

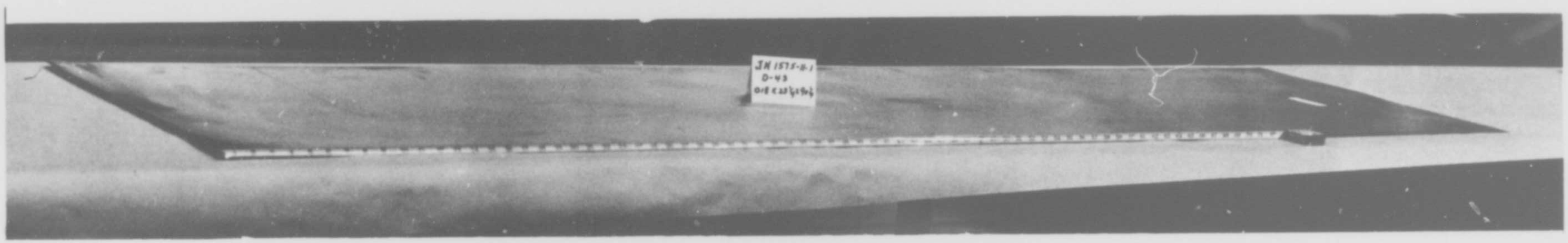


Figure 10A. D-43 Sheet 0.018" Gage Before Shearing

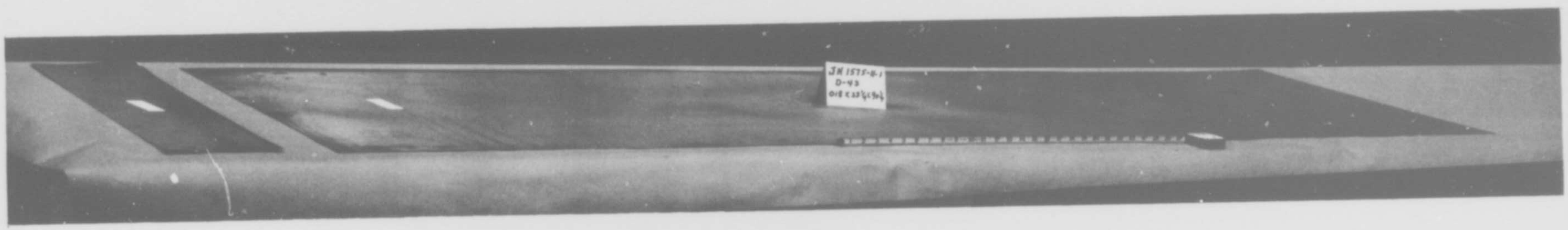


Figure 10B. D-43 Sheet 0.018" Gage After Shearing

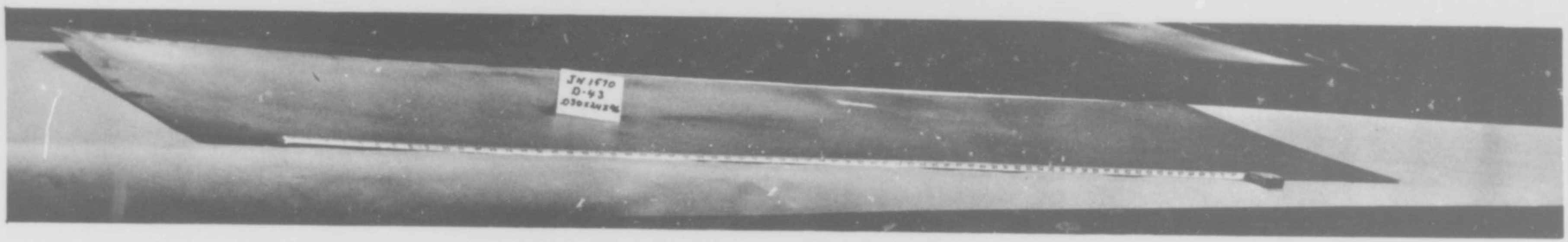


Figure 11A. D-43 Sheet 0.030" Gage Before Shearing

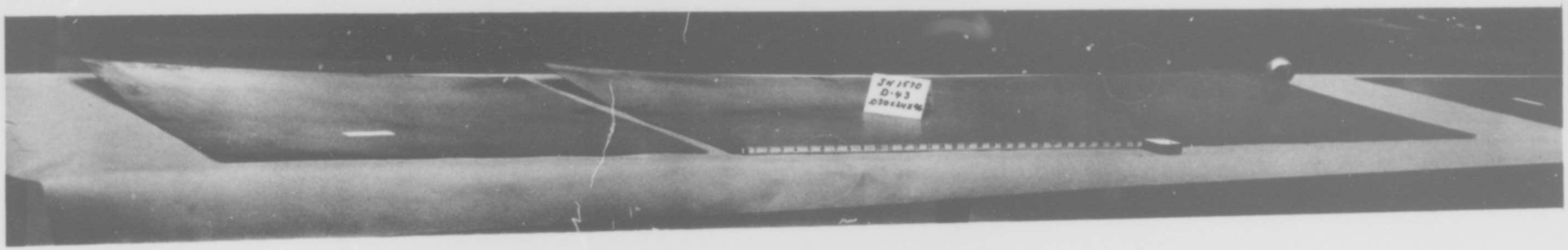


Figure 11B. D-43 Sheet 0.030" Gage After Shearing

TABLE 7

FLATNESS OF ITEM 1 SHEETS

Panel	Gage	Length (inches)	Flatness Deviation(%)	Estimated Sheet Area(%) Within 3% Flatness
284-02	0.030	41	8	0
283-01	0.030	61	6.3	67
283-02	0.030	60	4.4	73
283-01	0.018	59	5.4	59
283-02	0.018	93	8	81
284-03	0.013	71	7.8	70
284-03	0.013	76	7.6	0
284-03	0.013	66	5	82
284-01	0.013	64	10	0
284-03	0.013	69	6.5	81

V. MATERIALS DISPOSITION

The materials disposition under Items 1 and 2 of the sub-contract are summarized in Table 8.

TABLE 8

MATERIALS DISPOSITION

A SHIPMENTS

Company	Heat No.	Size(in.)	Wt.(lb.)	Proposed Evaluation
T.R.W.	283	0.020"x25"x22"*	3.8	Welding
	283	0.030"x14"x12"	1.7	
	283	0.030"x24"x12"	2.8	
	283	0.030"x24"x12"	2.7	
AEC (Oak Ridge)	284	0.062"x28"x42"*	24.9	Liquid Metal Studies
	283	0.062"x28"x12"*	6.8	
University of Dayton	283	0.020"x24"x12"	2.1	Coating
	283	0.020"x24"x12"	2.0	
	283	0.020"x24"x11"	1.8	
Battelle	284	0.030"x24"x21"	4.9	Notch Sensitivity as affected by coating
	283	0.030"x24"x91"	21.0	
McDonnell Aircraft	284	0.030"x24"x21"	4.9	Mechanical Testing Weldability
	283	0.030"x24"x61"	14.5	
	283	0.020"x24"x94"	14.5	
	284	0.012"x24"x71"	7.4	
Solar	284	0.012"x24"x76"	7.4	Coating
	284	0.012"x24"x66"	6.8	
	284	0.012"x24"x12"	1.4	
	284	0.012"x24"x12"	1.3	
	284	0.012"x24"x16"	1.8	
Watertown Arsenal	284	0.040"x28"x12"*	4.0	High Temp Strength
Metals and Controls	284	0.012"x24"x67"	7.2	Foil Rolling

B DU PONT EVALUATION

	Heat No.	Size(in.)	Wt.(lb.)	Proposed Evaluation
	283	0.030"x10"x 8"	0.8	Comprehensive Testing of Physical and Mechanical Properties
	283	0.030"x24"x12"	2.7	
	283	0.020"x24"x12"	2.0	
	283	0.012"x24"x12"	1.4	

C HOLDING

	Heat No.	Size(in.)	Wt.(lb.)	Proposed Evaluation
	284	0.012"x28"x54"*	5.0	For Re-rolling to 0.002"
	284	0.008"x29"x64"*	5.2	
	283	0.012"x24"x34"	3.6	
	283	0.020"x24"x75"	11.4	For Re-rolling to 0.006"

*Made by Low-Temp. Route. All other material processed by High-Temp. Route

TABLE 8 (CONT'D.)

MATERIALS DISPOSITION

A SHIPMENTS

Company	Gage	No. Panels	Weight
Martin Co.-Baltimore	0.030	13	131.8
	0.018	24	278.0
	0.012	18	141.8
Martin Co.-Denver	0.030	1	14.3
	0.018	3	26.7
	0.012	1	7.2
Metals and Controls	0.030	6	99.3
	0.018	4	50.4
McDonnel Aircraft Company	0.030	6	40.9
	0.018	7	51.2
North American Aviation	0.018	5	42.1
	0.012	7	53.4
ASD(ASRCE-21 D. Watson)	0.030	1	11.8
NASA-Lewis Research Center	0.030	1	4.4
TRW	0.030	1	3.0
Standard Pressed Steel	0.030	1	8.5
	0.012	1	3.4
University of Dayton	0.018	1	6.4
	0.012	1	4.8
The Pfaudler Company	0.030	2	7.7
	0.018	3	6.3
Douglas Aircraft Company	0.018	1	8.3
	0.012	6	36.0
General Dynamics	0.018	1	5.7
	0.012	4	28.0
AFML(MAMD) F. Osterman	0.030	1	7.4
RTD(MATB) C. S. Cook	0.018	1	1.1

VI. BIBLIOGRAPHY

(1) J. B. Guernsey, "The Development of Optimum Manufacturing Methods for Columbium Alloy Sheet", Interim Technical Engineering Report No. ASD TR 7-784 (VII), Air Force Contract No. AF33(600)-39942, December 1962.

APPENDIX I

D-43 SHEET - PHYSICAL AND MECHANICAL PROPERTIES

A comprehensive evaluation was conducted to characterize the sheet produced by the "high temperature" route in Item 1 of the contract. Testing was conducted on all three gages (0.012", 0.018", and 0.030") to determine the following properties:

1) Microstructure

2) Physical Properties (Thermal Conductivity, Specific Heat Thermal Expansion)

3) Short Time Tensile Properties for

   a) Variation with temp. to 3000°F

   b) Strain-rate sensitivity

   c) Directionality

4) Tensile Modulus to 2500°F

5) Thermal Stability

6) Creep-rupture

7) Ductility (Bend and Cup Testing)

Specimens for testing at D.M.C. were prepared as follows:

Standard Tensile: 1/4" wide, 1" gage length

Notched Tensile: Gage width 0.5", Notched width 0.25", 60° angle, 0.005" notch radius

All tensile specimens, unless otherwise noted, were tested at the following strain rates -

To 1500°F: 0.005"/"/min. to yield, 0.05"/"/min. to fracture

1500°F +: 0.05"/"/min. throughout

All elevated temperature testing at D.M.C. was conducted in a vacuum of 10^{-5} mm.

MICROSTRUCTURE

Initiation of recrystallization is indicated in the microphotograph (250X) in Figure 12. The structure indicates partial retention of the carbide platelets induced by the high temperature treatment. The morphology of the dispersed phase shown in the electron photomicrograph (8000X) in Figure 12 indicates a particle size of 0.2 microns.

PHYSICAL PROPERTIES

The physical properties were determined at the Southern Research Institute. The results of thermal expansion, thermal conductivity, and specific heat measurements are presented in Figure 13.

1) Thermal Expansion

The plot indicates linear behavior in the temperature range 1000 - 2500°F, and the coefficient of expansion in this range is calculated at 4.3×10^{-6} in/in/°F.

2) Thermal Conductivity

In the temperature range 500 - 2500°F, conductivity shows only a slight increase from 420 to 432 BTU/Hr/Ft^2/°F/in.

3) Specific Heat

In the temperature range 500 - 2500°F, specific heat increased some 50% from 0.06 to 0.09 BTU/Lb/°F.

TENSILE PROPERTIES

Tensile properties over the temperature range of -80° to 3000°F are reported in Table 9. Duplicate samples were obtained from opposite quarters of the particular sheet panel used in this evaluation.

DIRECTIONALITY

The data for RT and 2200°F testing in Table 9 indicate directionality in that transverse strengths are some 5000 psi higher than in the longitudinal direction. The 45° strength levels are slightly higher than in the longitudinal direction. Satisfactory elongation figures were obtained in all directions.

EFFECT OF SHEET THICKNESS

The effect of sheet thickness appears to be slight on short-time properties, all three gages showing virtually equivalent properties at all test temperatures.

TABLE 9

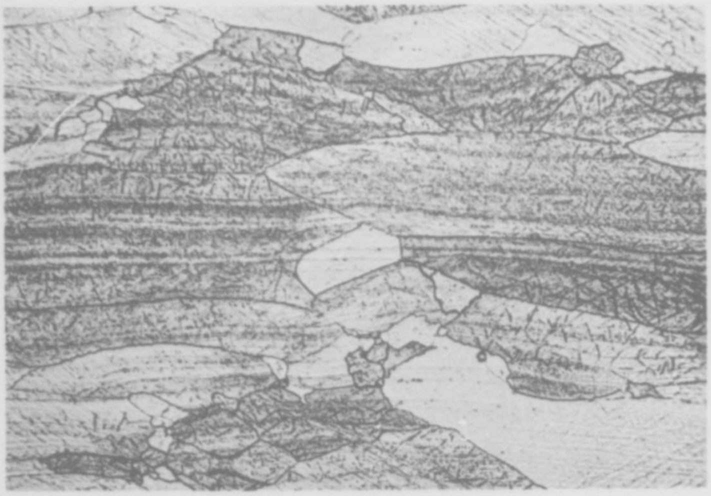
D-43 SHEET - VARIATION OF TENSILE PROPERTIES WITH TEMPERATURE

Test Temp (°F)	Test Direction	Panel	0.012" Sheet YS (ksi)	0.012" Sheet UTS (ksi)	0.012" Sheet El (%)	0.018" Sheet YS (ksi)	0.018" Sheet UTS (ksi)	0.018" Sheet El (%)	0.030" Sheet YS (ksi)	0.030" Sheet UTS (ksi)	0.030" Sheet El (%)
-80	L	B	79.9	97.4	18	81.2	98.3	18	85.3	100.9	20
		D	86.5	104.7	19	83.0	98.7	22	84.7	100.8	20
R.T.	L	B	68.8	86.4	22.0	69.2	86.0	20.5	72.9	88.6	22.5
		D	69.2	86.0	19.2	71.1	86.6	21.8	71.7	87.5	20.5
R.T.	T	B	61.7	92.3	17.5	63.9	92.2	17.8	65.5	95.4	17.5
		D	61.2	92.5	17.5	62.2	92.4	17.5	63.4	94.2	18.0
R.T.	45°	B	67.4	85.9	22.5	65.8	85.2	22.5	70.5	89.5	23.0
		D	65.9	85.2	19.8	69.7	87.4	20.0	68.9	87.8	22.5
600		B	54.9	69.0	11.8	55.1	69.2	14.0	56.3	68.3	17.1
		D	54.9	67.8	11.4	57.2	68.4	13.0	55.2	69.1	15.3
1000		B	54.2	69.5	8.4	59.1	71.0	6.6	62.3	70.4	17.5
		D	53.4	69.7	7.2	60.9	72.0	7.2	58.8	68.4	9.7
1500		B	50.2	61.9	6.8	52.1	61.1	8.9	56.9	62.0	9.8
		D	52.6	60.9	7.9	55.0	61.8	7.1	53.7	61.3	9.0
2000		B	45.6	47.3	11.8	43.6	45.6	13.2	43.6	47.0	12.2
		D	43.5	46.2	9.7	44.8	46.4	10.6	45.4	47.0	11.5
2200	L	B	34.5	35.8	15.6	32.7	34.4	18.0	33.7	35.7	18.7
		D	31.4	34.4	16.1	31.1	34.0	18.0	31.2	35.0	19.6
2200	T	B	38.6	40.3	11.0	36.2	40.0	15.6	38.1	40.5	11.7
		D	35.1	39.9	11.4	35.0	39.4	14.7	36.1	40.0	11.5
2200	45°	B	34.6	36.9	15.0	32.8	35.0	18.3	35.3	37.2	18.4
		D	32.8	36.2	18.5	32.1	36.1	17.1	33.3	37.6	17.5
2400		B	25.3	27.4	22.0	23.1	25.0	26.3	25.0	27.6	24.6
		D	24.6	27.0	23.2	22.9	25.6	28.7	24.3	27.3	26.0
									23.6*	27.8	23
2600		B	17.8	20.1	29.4	16.3	18.2	37.6	17.7	19.7	35.2
		D	17.2	18.6	29.7	16.0	18.2	36.9	18.1	20.3	36.0
2800*		B	10.2	13.0	67	11.4	13.0	60	9.8	13.1	50
		D	8.2	15.2	62	12.3	15.0	44	10.1	11.1	62
3000*		B	4.7	7.7	78	6.2	6.6	86	5.1	5.9	69
		D	3.9	4.6	62	5.3	5.5	72	7.3	7.8	90

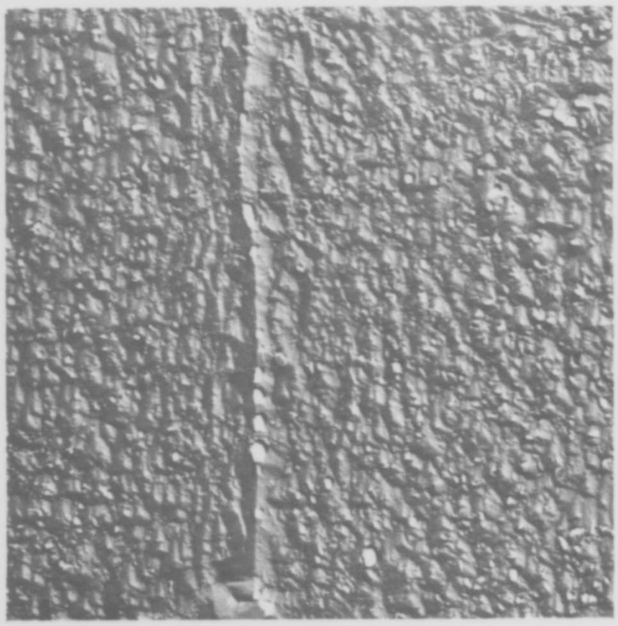
*Tested at Metcut

Strain Rate: R.T. - 1500°F 0.005" to Y.P. 0.05" to Fracture
1500°F - 2600°F 0.05" Throughout Test
2800°F - 3000°F (Metcut) 0.05" Throughout

All testing in longitudinal direction, except where indicated



X250



X8000

Figure 12. Typical Microstructure of D-43 Sheet

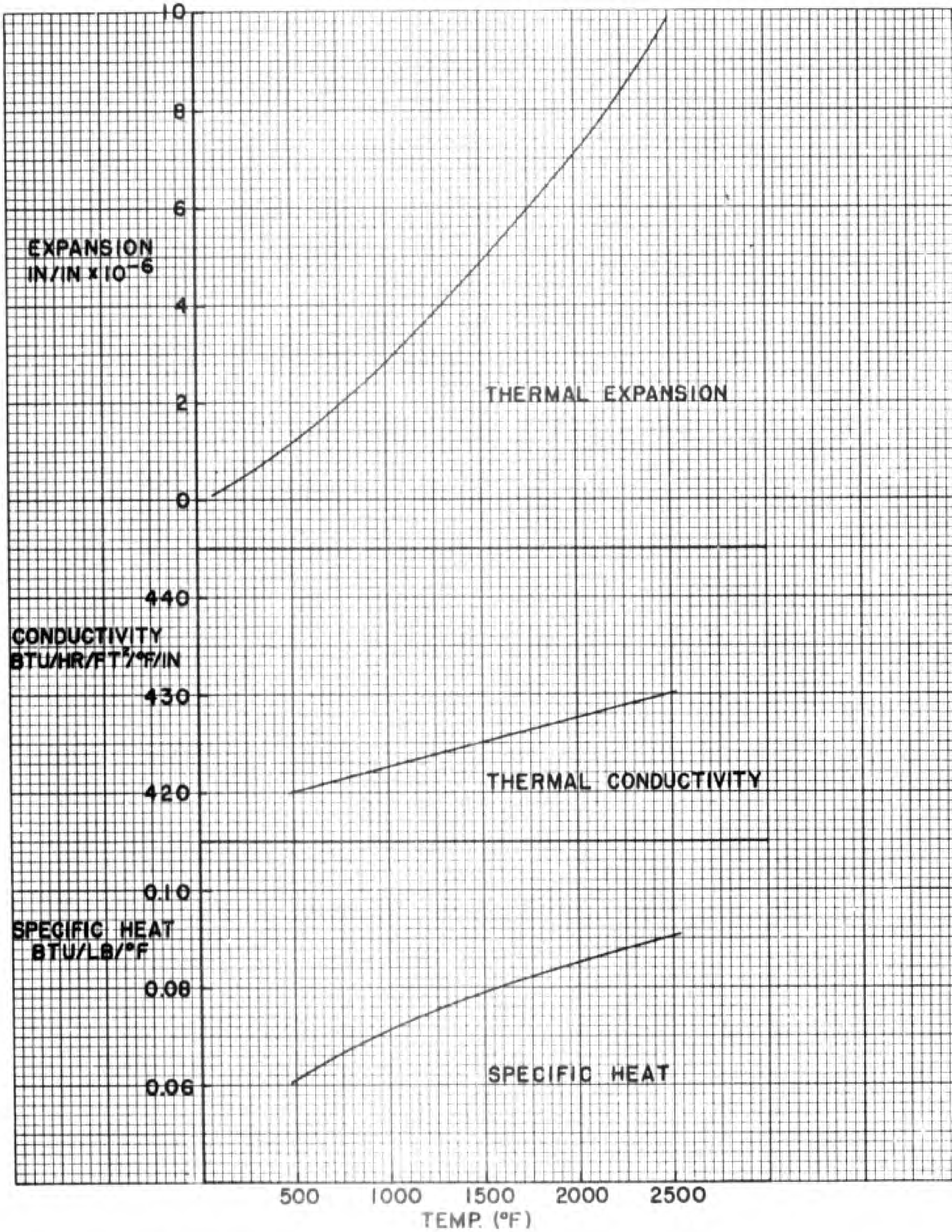


Figure 13. Variation of Physical Properties with Temperature

SHEET UNIFORMITY

The consistency of results obtained in duplicate testing at each temperature indicates satisfactory sheet uniformity.

EFFECT OF TEMPERATURE

The variation of longitudinal properties with temperature is shown in the composite plot. Strain aging is indicated in the 1000°F range, accompanied by reduced ductility, (Figure 14).

FORMABILITY

Both bend testing and Erichsen cup testing at room temperature were conducted on D-43 sheet, with the results shown below. All three gages passed a 1T bend test without fracture. On cup testing, brittle type fracture was indicated under conditions of bi-axial stress. This was evident in the thicker gage material (0.030") only. In all cases, good cup depth was obtained.

BEND AND CUP TESTING

Gage	Cup Depth (mm across 1" dia.)	Longitudinal Bend Radius
0.012"	5.1 - 6.5	1T (N.F)
0.018"	6.2 - 7.0	1T (N.F)
0.030"	6.9 - 7.2	1T (N.F)

N.F - No fracture

MODULUS

Modulus of elasticity was determined from tensile testing on 0.030" sheet at the Southern Research Institute. The variation of modulus with temperature was reported as shown in the plot Figure 15. The results indicate that D-43 maintains a modulus of approximately 16.5 x 10^6 psi up to 2000°F, dropping to 6 x 10^6 psi at 3000°F.

STRAIN-RATE SENSITIVITY

Variation of strain-rate on room temperature testing gave results as follows:

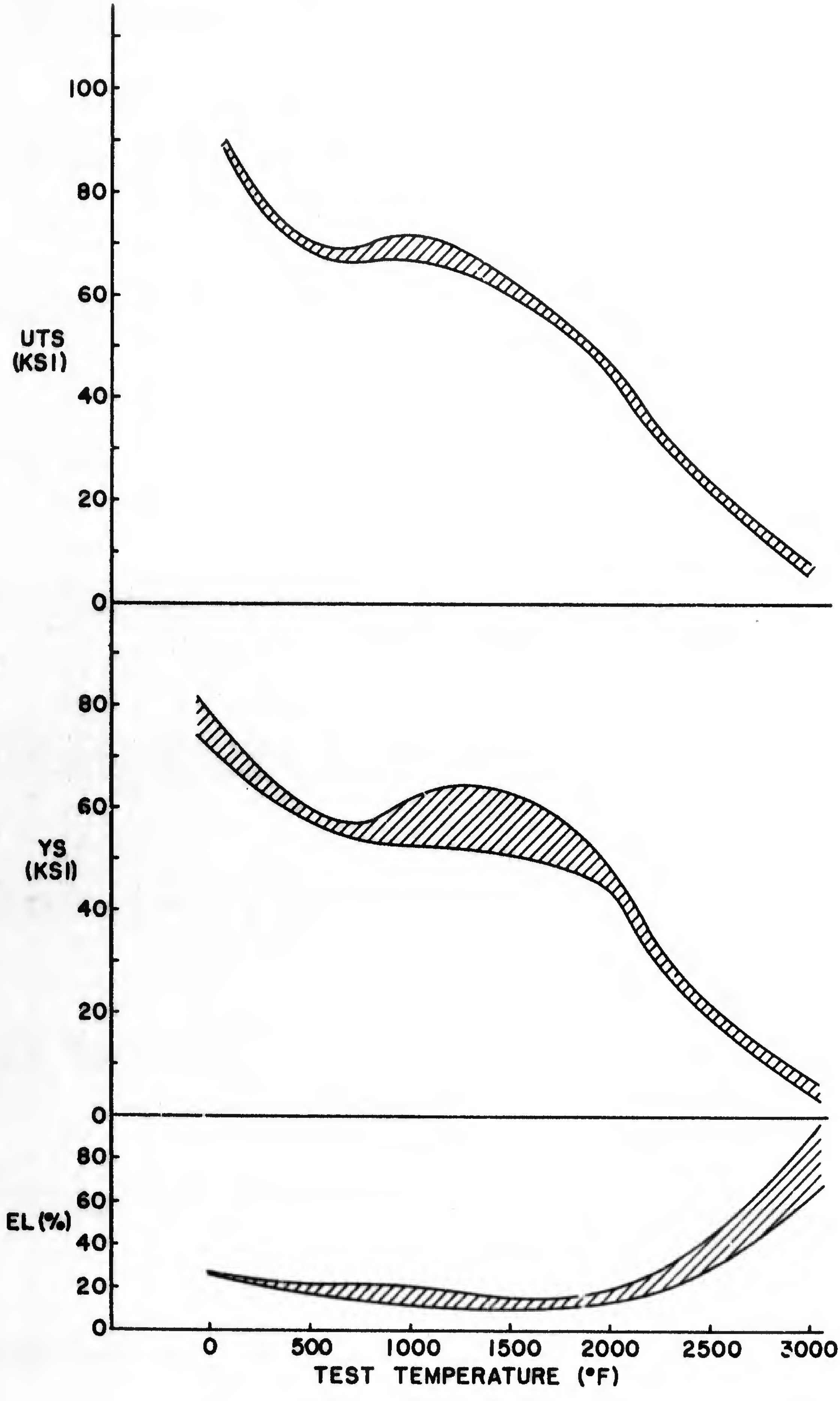


Figure 14. D-43 Sheet-Variation of Longitudinal Tensile Properties with Temperature. (Composite Plot for all Three Gages)

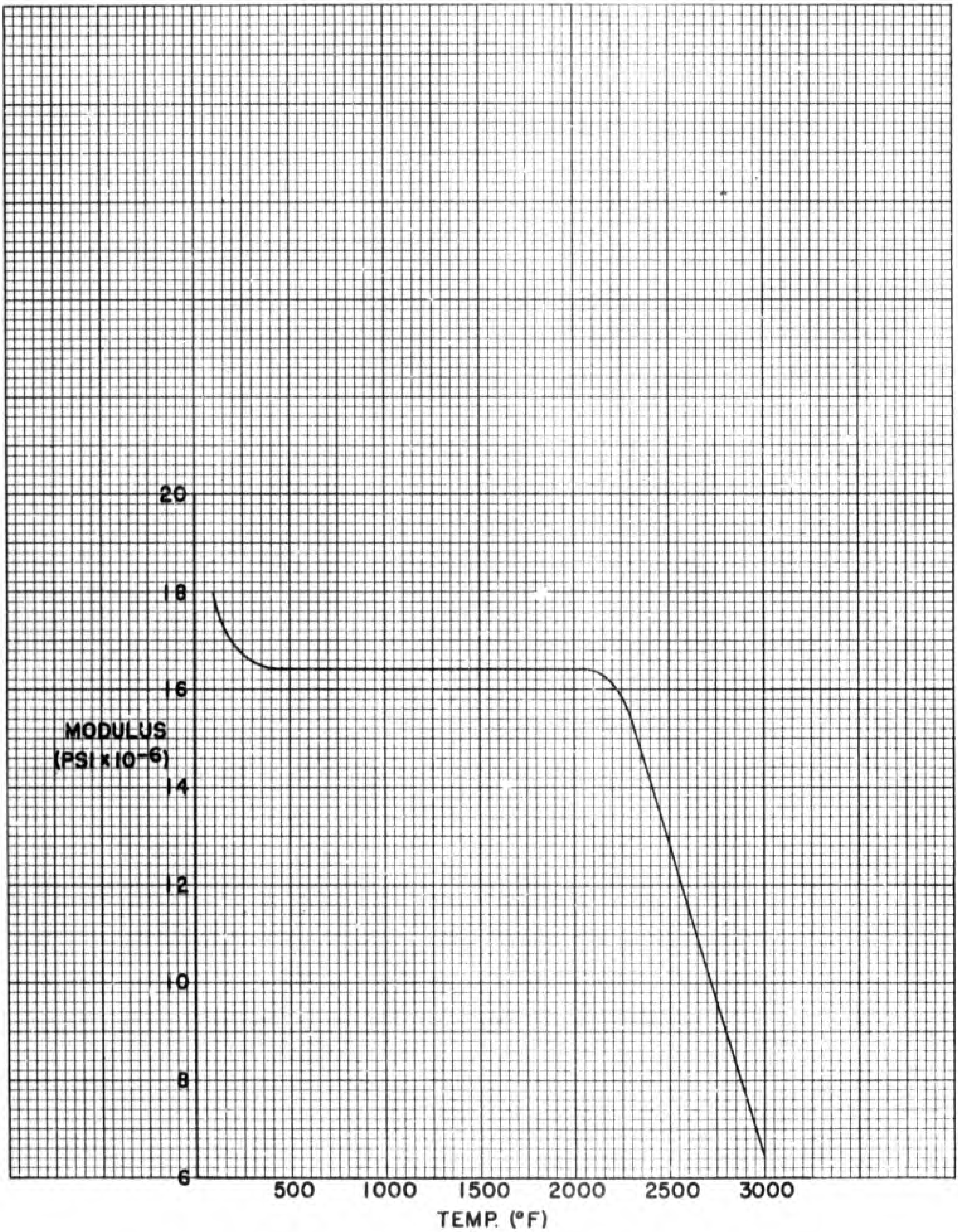


Figure 15. Variation of Modulus with Temperature

Strain Rate (in/in/min)		Panel	0.012" Sheet YS (ksi)	UTS (ksi)	El (%)	0.018" Sheet YS (ksi)	UTS (ksi)	El (%)	0.030" Sheet YS (ksi)	UTS (ksi)	El (%)
0.001	to Y.P.	B	64.6	81.0	17	66.0	82.7	20	73.1	86.8	20
0.01	to Fracture	D	67.5	83.0	17	70.6	85.2	20	68.8	84.9	20
0.01	to Y.P.	B	67.3	84.8	17	66.0	83.5	20	72.9	88.1	19
0.10	to Fracture	D	68.5	85.8	17	69.6	84.7	19	70.0	86.9	19
0.10	to Y.P.	B	66.0	83.8	17	72.1	83.4	20	78.2	88.7	20
0.10	to Fracture	D	67.0	84.3	17	71.1	85.9	20	71.1	86.8	20
0.005	to Y.P.	B	68.8	86.4	22	69.2	86.0	20	72.9	88.6	22
0.05	to Fracture	D	69.2	86.0	19	71.1	86.6	21	71.7	87.5	20

Increasing strain rate gave only a slight effect on yield strength. The plot (Figure 16) indicates the low strain-rate sensitivity in the range investigated (0.001 to 0.100"/"/min).

CREEP RUPTURE

Tests were conducted in vacuum up to 100 Hr., to evaluate the stress rupture and creep characteristics of the D-43 alloy. The results of testing on all three sheet gages are shown in Figure 17. Rupture life at elevated temperature is indicated as follows:

Temp. (°F)	Rupture Time (1 Hr.)	Rupture Stress (psi)	Min. Creep Rate (in/in/hr.)
2000	1	37,000 - 30,000	
2000	10	31,000 - 26,000	
2000	100	25,000 - 22,000	0.0007 - 0.0017
2200	1	23,000 - 21,000	
2200	10	18,000 - 16,000	
2200	100	12,000 - 11,000	0.0006 - 0.0017
2400	1	16,000 - 14,000	
2400	10	12,000 - 9,000	
2400	100	7,000 - 5,000	0.0013 - 0.0050

The ranges shown for rupture stress and creep rate, indicate the effect of gage thickness, with the thicker sheet (0.030") exhibiting higher rupture strength and lower creep rate than the thinner gages.

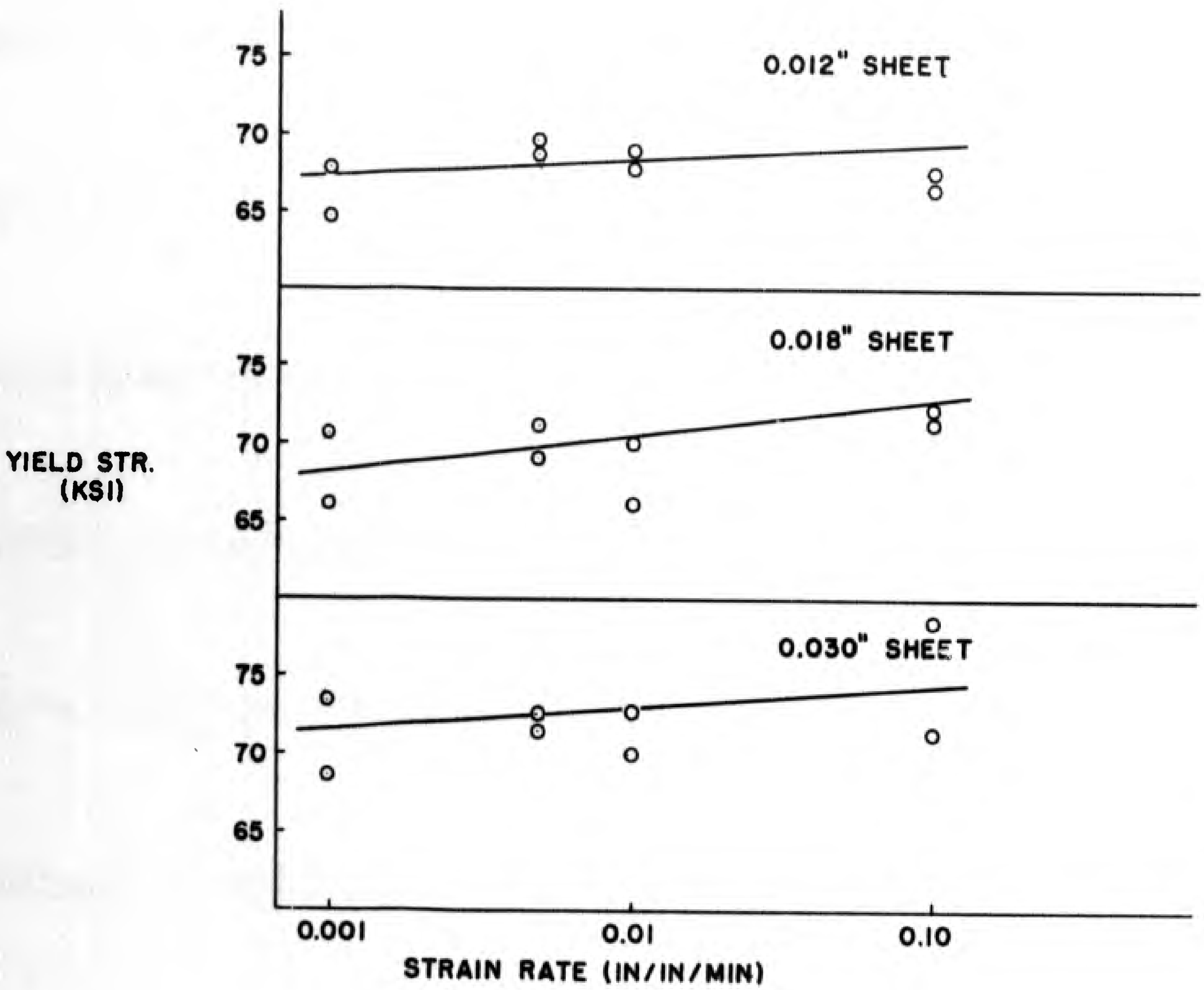


Figure 16. Effect of Strain Rate on Room Temperature Tensile Strength

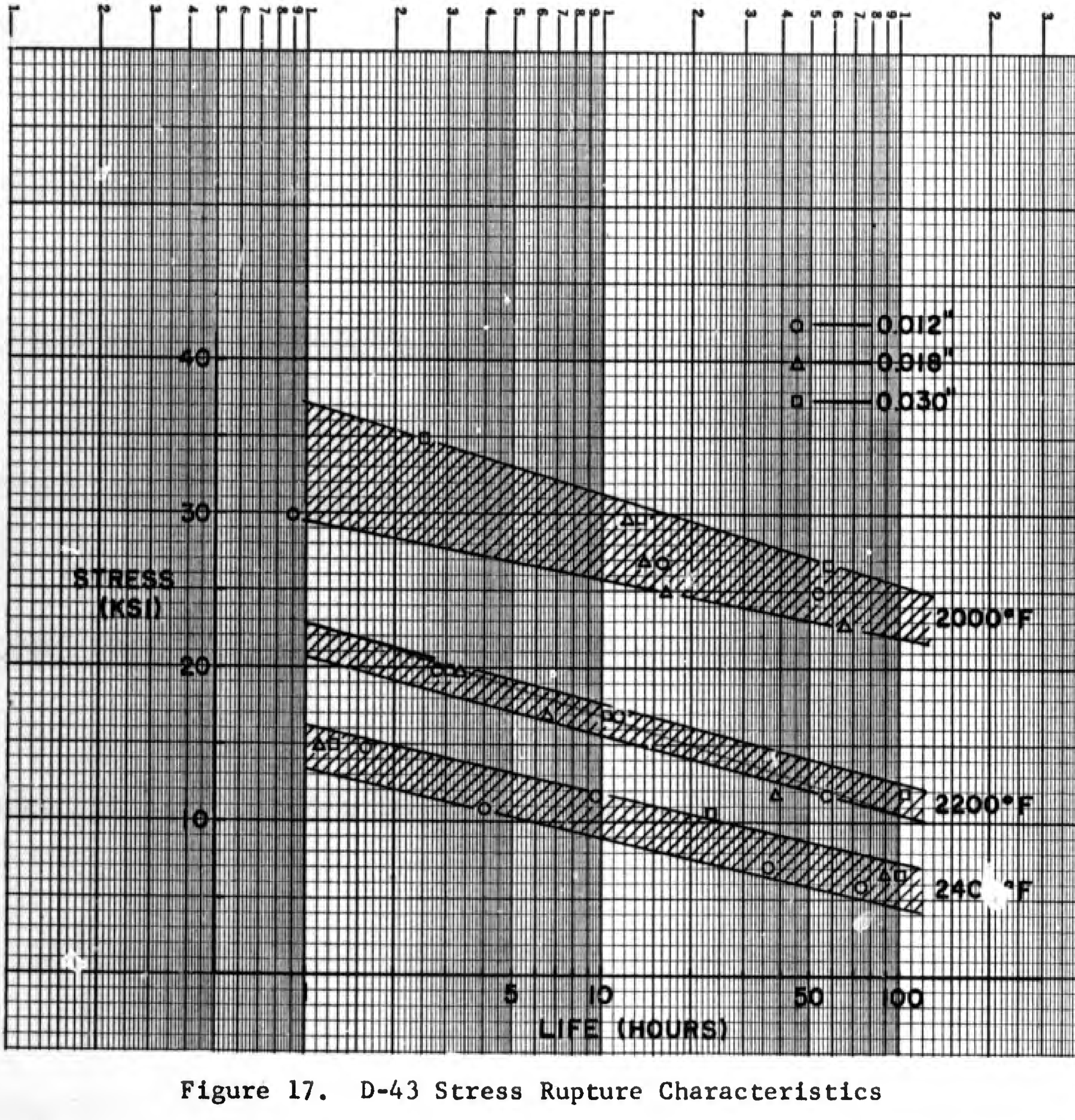


Figure 17. D-43 Stress Rupture Characteristics

THERMAL STABILITY

Tests were conducted on D-43 sheet after 1 Hr. exposures in the 2000 - 3000°F range. Thermal stability was evaluated on the basis of RT and 2200°F properties after exposure. All testing was conducted in the longitudinal direction; composite plots for all three sheet gages are shown in Figure 18 for RT and Figure 19 for 2200°F.

The room temperature properties indicate reasonable stability on exposure to 2600°F, although the yield strength data indicate a softening effect in the 2000 - 2400°F range and an aging effect in the 2400 - 2600°F range. Aging effects are also indicated in the 2200°F properties, both at 2600°F and 3000°F. Exposures in the 2000 - 2400°F range effect slight degradation of both yield and ultimate strength levels on 2200°F testing. In general, satisfactory thermal stability is indicated on exposures up to 2600°F, the temperature of the final anneal on as-produced D-43 sheet. On exposures above 2600°F, additional stress relief is balanced by aging mechanisms to give reasonable stability up to 3000°F.

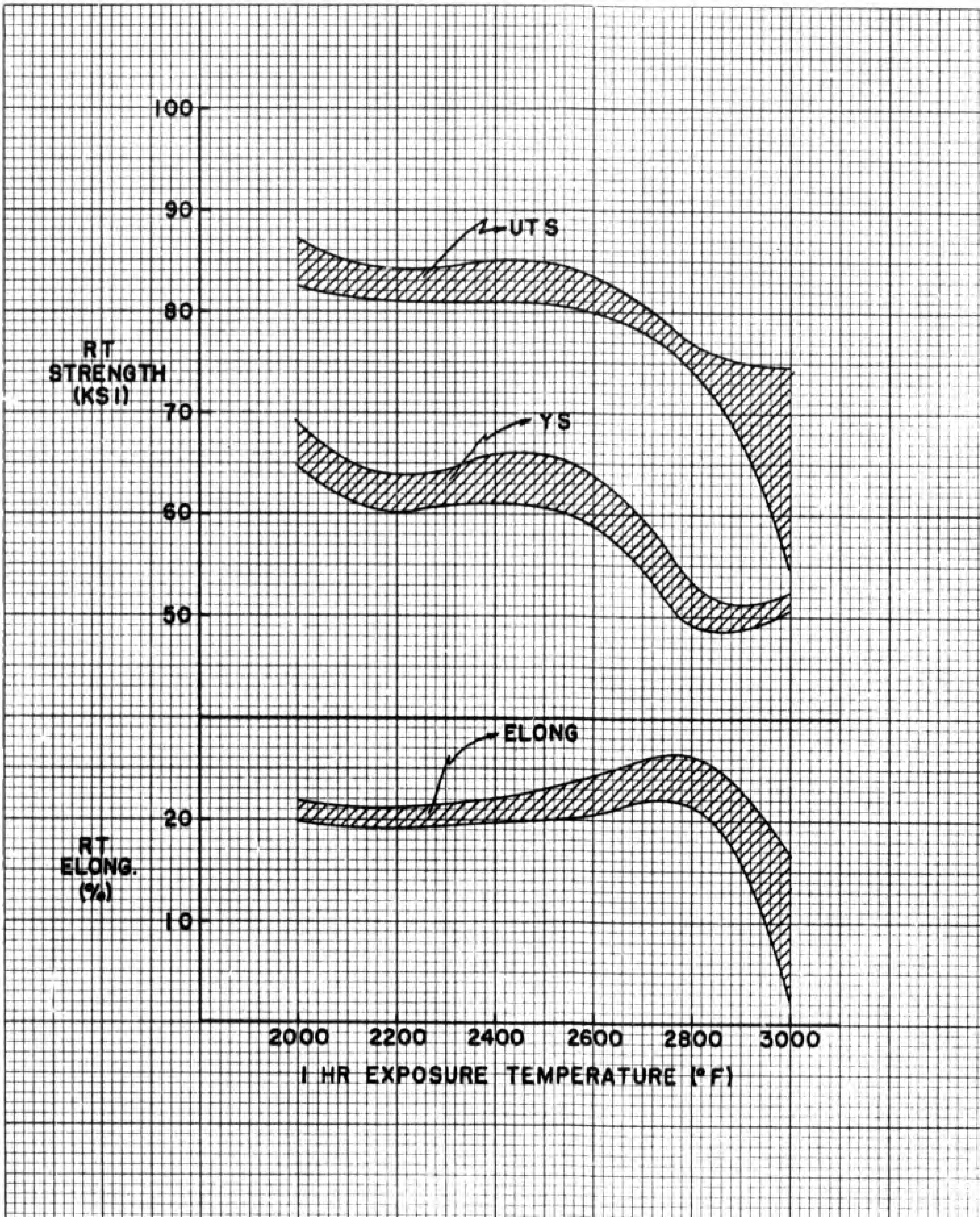


Figure 18. Effect of High Temperature Exposures on Room Temperature Longitudinal Properties (Composite Plot for all Three Sheet Gages)

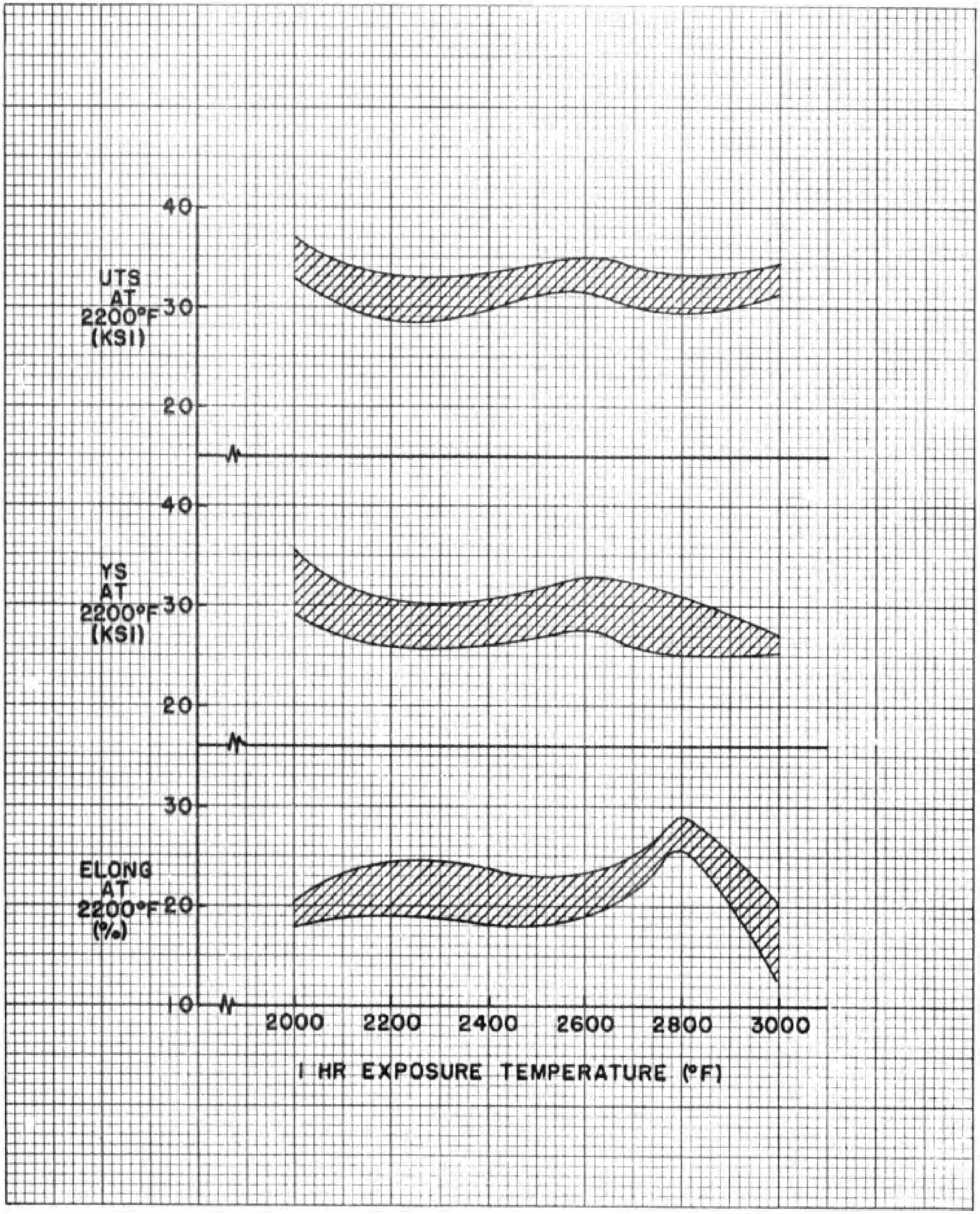


Figure 19. Effect of High Temperature Exposures on 2200°F Longitudinal Properties (Composite Plot for all Three Sheet Gages)

APPENDIX II

QUALITY CONSIDERATIONS IN D-43 SHEET MANUFACTURE

A corollary study on the attainment of sheet gage control and flatness was conducted during the processing of Item 2 sheets. The purpose of this study was simply to determine the additional costs incurred in producing D-43 sheet to smaller gage tolerances and smaller percent-flatness than normal. The normal case was taken from Du Pont specification DPC(G)-01 as 6% flatness (1/2 H/L) and the following gage tolerances:

Gage	Tolerance
.012"	± 0.002"
.018"	± 0.002"
.030"	± 0.0025"

The additional costs, in $/lb. to meet tighter specification than those shown above would presumably be made up of both increased processing costs and lower overall yields due to fallout. The relative effect of these two elements in product cost was evaluated in this contract by producing and inspecting sheet to the higher quality specifications. The results of this study on improved gage tolerance and flatness are presented below:

Gage Tolerance

The final rolling of the major portion of Item 2 sheets was performed in a manner which would minimize gage variation at the three nominal gages - 0.012", 0.018", and 0.030". Very light reductions/pass were taken in the final 4-Hi hand-rolling, as described above under "Processing", to insure rolling closer to the nominal target thicknesses. Approximately 12C0 lbs. of sheet was rolled in this manner. Despite the greater number of passes taken per sheet, this large batch of material permitted effective programming. Roll setting changes and delays between passes were minimized. The increase in processing time for rolling in this manner, i.e., many passes at light reductions, was considered insignificant.

The results on gage tolerance for this batch of final product sheets are summarized in Table 6 in the "Inspection" section of the report. The table is reproduced below for convenience. The percentage of sheets of each of the three gages are given which are within several stated tolerances of the nominal gage.

TABLE 6 (REPEAT)

FINAL GAGE INSPECTION

Percent of Sheets Within	Gage, in. .012"	.018"	.030"
± 0.0005"	22%	6%	0%
± 0.0010"	89	53	30
± 0.0015"	98	91	60
± 0.0020" (std. for .012" & .018" gages)	100	96	80
± 0.0025" (std. for .030" gage)	100	100	100

The data on gage control in Table 6 are indicative of the drop in yield which would be experienced if tighter tolerances than standard were required. If, for example, sheet at .018" with a tolerance of ± .001" were required, one would anticipate a drop in product yield to 53%, this percentage being the amount which met the ± .001" tolerance on the contract material. The cost for producing sheet to this tighter tolerance would be indicated by dividing the standard sheet cost by the percentage yield of acceptable sheets taken from the table.

The table of data on gage control applied to the first (and only) batch of sheets rolled in the manner described earlier to achieve close gage control. Although a large number of sheets - 106 pieces which weighed approximately 1200 lbs. total - were processed in this batch, additional batches of sheet would have to be processed similarly in order to establish gage control performance more closely.

Flatness

All final product sheets were stretch-leveled, permanent elongation being <1%. Three sheets of each gage from Item 2 were stretched by the customary procedure, removed, and given an in-process check for flatness (approximate). The pilot sheets were re-inserted and stretched an additional amount - but still <1% - which the operator judged would improve flatness. The increase in processing cost which would result from this slight amount of additional time in stretching was considered negligible.

The maximum out-of-flatness (%) of the pilot sheets, as measured in final inspection, was essentially similar to the bulk of sheets stretched in the standard manner. The major contributing shape to out-of-flatness in both cases was end curl and corner curl. (See Figure 10 and 11 in "Inspection" section). This shape apparently is characteristic of the stretching operation employed. Shearing of ends would almost certainly reduce the out-of-flatness to <3% on the majority of sheets. The shearing would result in considerable yield loss. For this reason the selective shearing of sheets to meet 3% flatness was not resorted to on contract material.

The cost of sheet produced to within 3% flatness would be indicated by dividing the standard sheet cost by the percentage yield of flat sheet (<3%) sheared from the standard sheet, similar to the case for gage. This study did not establish the yield figure. The estimated range of yield in shearing to achieve 3% flatness in the D-43 sheets if 50 - 75%.

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