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THE FABRICATION OF BERYLLIUM ALLOYS - VOLUME II: FORMING TECHNIQUES FOR BERYLLIUM ALLOYS

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THE FABRICATION OF BERYLLIUM ALLOYS-VOLUME II.

FORMING TECHNIQUES FOR BERYLLIUM ALLOYS

ABSTRACT

This report documents the forming techniques investigated and developed for the fabrication of beryllium aerospace vehicle structures. It is Volume II of a six volume set of technical reports entitled "The Fabrication of Beryllium." Time-temperature relationships are established for the forming of straight bends, compound curved channels, and hemispherical segments. The flow of the material is determined, and the resulting dimensional changes are measured. The feasibility of the extreme forming of cross-rolled beryllium sheet material is demonstrated.

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THE FABRICATION OF BERYLLIUM ALLOYS - VOLUME II.

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The other Volumes of Technical Memorandum X-53453 are:

Vol. I.	A Survey of Current Technology
Vol. III.	Metal Removal Techniques for Beryllium Alloys
Vol. IV.	Surface Treatments for Beryllium Alloys
Vol. V.	Thermal Treatments for Beryllium Alloys
Vol. VI.	Joining Techniques for Beryllium Alloys

MANUFACTURING ENGINEERING LABORATORY

ACKNOWLEDGEMENT

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Mr. R. F. Williams, NASA Advanced Manufacturing Programs, was the Project Manager of this effort under the management of Mr. J. T. Hart, Manager, NASA Advanced Development Programs, Lockheed Missiles and Space Company. The work was performed under the technical direction of Mr. S. E. Ingels assisted by Mr. C. Fruth in preparation of the final report.

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THE FABRICATION OF BERYLLIUM ALLOYS - VOLUME II.

FORMING TECHNIQUES FOR BERYLLIUM ALLOYS

SECTION I. INTRODUCTION

The objectives of this task are the investigation, development, and documentation of the beryllium fabrication methods classified as "Forming" in the Beryllium Fabrication Methods Development Program Plan.

The availibility of cross-rolled beryllium sheet material of uniform quality, in sizes compatible with design requirements, now makes possible the full realization of the potential advantages of beryllium in the fabrication of aerospace vehicle structures. Although large radius, simple curved panels are being formed on a routine production basis, the lack of suitable production techniques for the forming of minimum bends and compound curves still inhibits the extensive utilization of beryllium in the fabrication of large space vehicle structures.

The several tasks accomplished during this study included the experimental forming of both simple and compound configurations as follows:

1. Straight Bends

   Angles

   Channels

   Zee Sections

   Hat Sections

2. Compound curved configurations

Spherical Segments

Channel Ring Segments

3. Joggles

Angles

The accomplishment of these tasks, directed toward the development of both engineering and production information and data, included the documentation of the optimum forming temperature, the establishment of minimum bend radii, and the verification of the feasibility of forming abrupt dimensional changes in the plane of the material.

SECTION II. GENERAL

The material utilized in the accomplishment of the tasks included in this phase of the program was commercial quality cross-rolled beryllium sheet purchased from the Brush Beryllium Company of Cleveland, Ohio. This material was purchased in accordance with the specification requirements and contained the following minimum specific properties:

a. Ftu - 70,000 psi

b. Fty - 50,000 psi

c. Elongation - 5% in 1.0 inch

Table I presents the chemical analyses and the mechanical properties of the material.

With the exception of the joggle dies, all of the tooling used during this program was fabricated of "Glassrock," a ceramic material with very stable thermal characteristics. Either 11 or 14-gage nichrome wire heating elements, spaced 1/2-inch apart. were imbedded in the material 1/2-inch from the

TABLE I

CHEMICAL ANALYSES AND MECHANICAL PROPERTIES - MATERIAL FOR FORMING SPECIMENS

VENDOR DATA

Vendor: The Brush Beryllium Company

Gases: 0.020 Inch 0.030 Inch 0.060 Inch AND 0.120 Inch

CHEMICAL ANALYSES - %

Lot No.	Be Assay	BeO	Fe	Si	Al	Mg	C
9967	98.29	1.66	0.138	0.05	0.095	0.011	0.12
1033	98.19	1.60	0.129	0.045	0.07	0.021	0.11
2469	98.50	1.83	0.12	0.03	0.008	0.009	0.10
3516	98.21	1.70	0.14	0.04	0.11	0.008	0.13

NOTE: Cr, Mn, Ni, LESS THAN 0.04% EACH.

TABLE I (Con't)

MECHANICAL PROPERTIES

Lot No.	Sheet No.	Fty - Psi		Ftu - Psi		Elongation - % in 1"	
		Long	Trans.	Long.	Trans.	Long.	Trans.
9967	447A	57,400	58,100	78,300	86,200	11.5	14
1033	456A	56,700	54,900	81,100	74,000	12.8	12.8
2469	734	51,300	50,300	79,700	70,000	16.5	6.5
3516	1064A1	63,300	60,400	85,000	82,100	18	18
3516	1064A2	63,300	60,400	85,000	82,100	18	18
3516	1065A1	61,400	60,300	81,100	82,100	10	18
3516	1065B1	62,200	59,700	84,600	80,300	16	15
3516	1065B2	62,200	59,700	84,600	80,300	16	15
3516	1066A1	60,900	58,400	84,600	80,000	18	10
3516	1066A2	60,900	58,400	84,600	80,000	18	10
3516	1067A2	58,600	61,100	80,200	80,200	12	18
3516	1067B2	58,600	61,100	80,200	80,200	12	18
3516	1068A	61,800	58,700	82,900	81,000	10	23
3516	1069A	61,000	60,700	79,900	81,100	10	24
3516	1069B1	61,000	60,700	79,900	81,100	10	24
3516	1070B	62,500	59,900	85,300	80,300	15	15
3516	1071B	60,000	58,100	82,700	79,700	24	25
3516	1072A1	60,500	60,100	84,200	82,200	15	18
3516	1072A2	60,500	60,100	84,200	82,200	15	18
3516	1072B	60,500	60,100	84,200	82,200	15	18

the working surface.

Although the low fabrication cost of this "tooling" material makes its use particularly attractive for limited "runs", the applications must be selected with care to avoid overstressing of the "Glassrock." Analyses of the several tooling failures, experienced during the accomplishment of this program, are included in the discussion of the pertinent forming task.

SECTION III. FORMING PROCESSES

A. STRAIGHT BENDS

The most basic forming operation, required during the fabrication of structural components, is the straight bend. The object of this first phase of the program was the determination of the time-temperature parameters required for the consistent and reliable production of minimum radius bends.

1. Minimum Radius Bend Investigation. This initial phase of the program included not only the establishment of the basic forming parameters, but the determination of the minimum radius bends that could be consistently produced. In order to obtain representative comparative data, a set of thirty-six 90-degree angle specimens was formed of each of the four material gages. All of the specimens were formed of each of the four material gages. All of the specimens were formed at the desired radii of 4, 5, and 6t, and the selected forming temperatures of 1050°F, 1250°F, and 1350°F. The forming temperatures were recorded by means of chromel-alumel thermocouples, installed on control specimens, and a Honeywell 20 channel strip recorder. A "feedback loop" to the electric power supply provided the necessary control of the forming temperatures.

Current production procedures were utilized for the preparation of the basic 1.0 by 3.5 inch uniform test specimens. All of the specimens were identified during the initial layout on full size vellum sheets, and this identification was maintained throughout the program. The layout, including the identifying numbers, was transferred to the sheet material, and the parts were cut to size on the precision abrasive cut-off saw.

The forming of the minimum radius bend specimens was accomplished in the "Universal" type punch and die set, consisting of heated, "Glassrock" die segments and a conduction heated punch mounted between the upper segments, illustrated in Figure 1. The nichrome heating wires and the stainless steel buffer plates, installed to prevent the excessive wearing away or breakage of the "Glassrock" die blocks, are clearly visible. A different stainless steel punch, with an appropriately "radiused" edge, was installed as required, for the forming of the various test specimens.

The specimen blanks were placed in position on the die, heated by conduction from the hot die, and formed as soon as the desired material temperature had been attained. The nominal forming time for each specimen was 1 minute; slight, though negligible, variations in forming time did occur due to the manual control of the press. After the forming operations were completed, all of the specimens were etched in a solution consisting of 3 percent HF (hydrofluoric acid) and 45 percent HNO_3 (nitric acid) to remove approximately 0.001-inch of material from all surfaces in preparation for microscopic examination. The bend area of all of the specimens was cricially examined, both visually and microscopically, to ascertain the quality of the bend itself.

Summaries of the grain orientation, forming temperatures, bend radii and types of failure for the 0.020, 0.030, 0.060 and 0.120-inch gage specimens are presented in Tables II through V respectively. The several categories of bend quality, illustrated in Figures 2 through 11 were as follows:

a. No defect

b. Questionable - strainlines visible, but no open cleavage

c. Incipient failure - minor cleavage visible at 50X

d. Moderate cleavage - visible to unaided eye

e. Gross failure - visual fractures

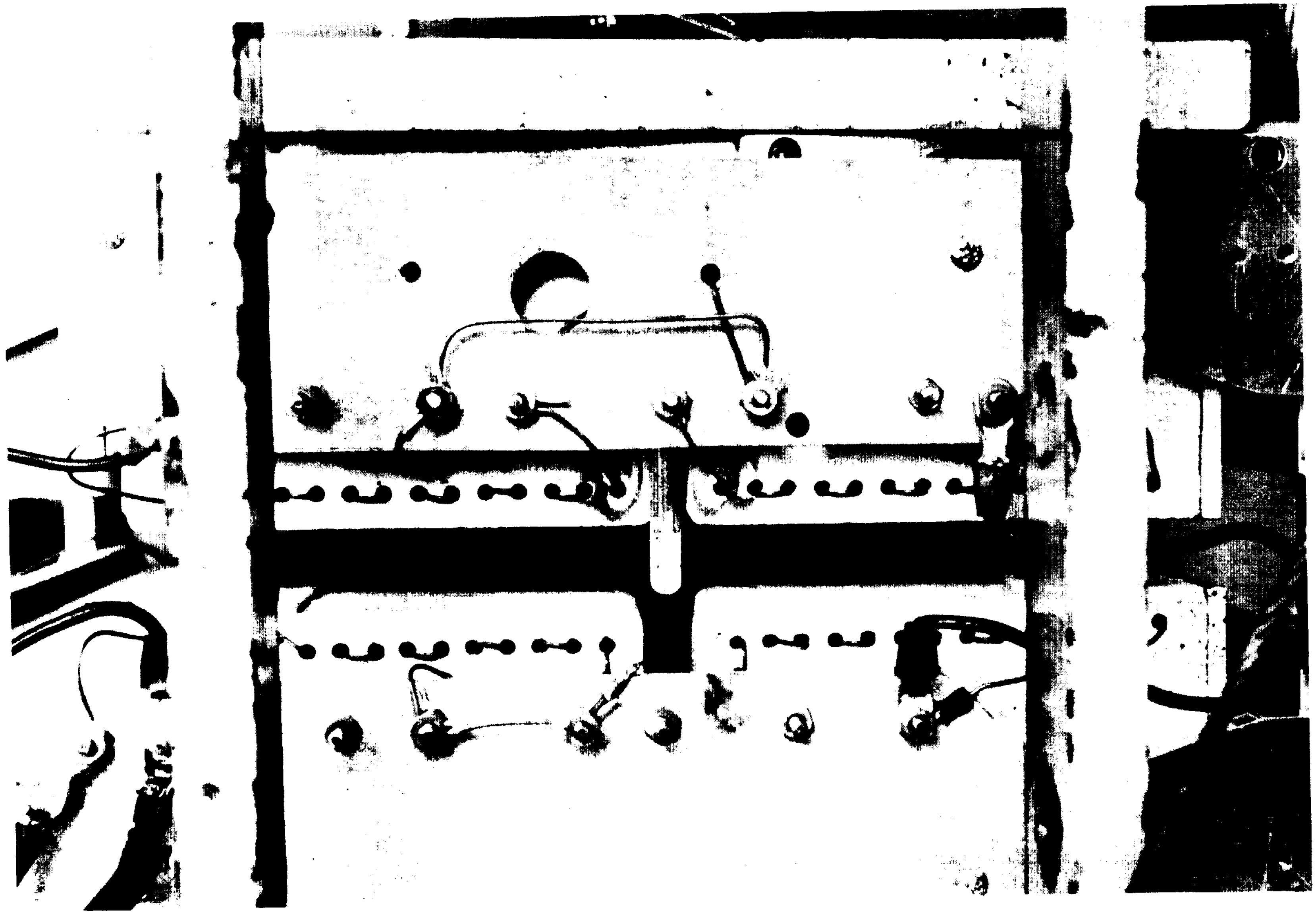


FIGURE 1. UNIVERSAL FORMING DIE
NOTE. THE HEATING ELEMENTS AND STAINLESS STEEL BUFFER PLATES.

TABLE II

SUMMARY - MINIMUM RADIUS BENDS - 0.020-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
2-5-1-02L	1072A2	L	1050	4			X		
2-5-1-03T	1072A2	T	1050	4		X			
2-1-1-04L	1071B	L	1050	5			X		
2-1-1-01T	1071B	T	1050	5				X	
2-5-1-08L	1072A2	L	1050	6			X		
2-5-1-21T	1072A2	T	1050	6			X		
2-5-1-16L	1072A2	L	1250	4	X				
2-5-1-17T	1072A2	T	1250	4	X				
2-5-1-04L	1072A2	L	1250	5	X				
2-5-1-05T	1072A2	T	1250	5		X			
2-5-1-10L	1072A2	L	1250	6		X			
2-5-1-27T	1072A2	T	1250	6			X		
2-1-1-06L	1071B	L	1350	4	X				
2-1-1-02L	1071B	L	1350	4		X			
2-5-1-28L	1072A2	L	1350	4			X		
2-5-1-14L	1072A2	L	1350	4	X				
2-1-1-05T	1071B	T	1350	4	X				
2-5-1-23T	1072A2	T	1350	4	X				
2-1-1-07T	1071B	T	1350	4	X				
2-5-1-07T	1072A2	T	1350	4	X				

TABLE II (Con't.)

SUMMARY - MINIMUM RADIUS BENDS - 0.020-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
2-5-1-12L	1072A2	L	1350	5	X				
2-5-1-24L	1072A2	L	1350	5	X				
2-5-1-22L	1072A2	L	1350	5		X			
2-5-1-20L	1072A2	L	1350	5	X				
2-5-1-09T	1072A2	T	1350	5			X		
2-5-1-13T	1072A2	T	1350	5	X				
2-5-1-18T	1072A2	T	1350	5	X				
2-5-1-11T	1072A2	T	1350	5	X				
2-1-1-06L	1071B	L	1350	6	X				
2-5-1-26L	1072A2	L	1350	6	X				
2-1-1-10L	1071B	L	1350	6	X				
2-1-1-08L	1071B	L	1350	6			X		
2-5-1-01T	1072A2	T	1350	6	X				
2-1-1-03T	1071B	T	1350	6			X		
2-5-1-19T	1072A2	T	1350	6	X				
2-5-1-15T	1072A2	T	1350	6	X				

TABLE III

SUMMARY - MINIMUM RADIUS BENDS - 0.030-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
3-1-1-02L	1070B	L	1050	4				X	
3-1-1-07T	1070B	T	1050	4			X		
3-1-1-04L	1070B	L	1050	5			X		
3-1-1-03T	1070B	T	1050	5			X		
3-5-1-04L	1069B1	L	1050	6	X				
3-1-1-01T	1070B	T	1050	6	X				
3-1-1-08L	1070B	L	1250	4			X		
3-5-1-01T	1069B1	T	1250	4				X	
3-1-1-06L	1070B	L	1250	5	X				
3-5-1-27T	1069B1	T	1250	5	X				
3-1-1-05T	1070B	T	1250	6	X				
3-1-1-10L	1070B	L	1250	6	X				
3-5-1-02L	1069B1	L	1350	4					X
3-5-1-16L	1069B1	L	1350	4	X				
3-5-1-06L	1069B1	L	1350	4	X				
3-5-1-08L	1069B1	L	1350	4	X				
3-5-1-03T	1069B1	T	1350	4	X				
3-5-1-05T	1069B1	T	1350	4	X				
3-5-1-07T	1069B1	T	1350	4	X				
3-5-1-09T	1069B1	T	1350	4	X				

TABLE III (Con't.)

SUMMARY - MINIMUM RADIUS BENDS - 0.030-INCH MATERIAL

IDENTIFICATION NUMBERS		ORIENTATION	FORMING	R/t	BEND QUALITY				
SPECIMEN	SHEET		TEMP (°F)		(1)	(2)	(3)	(4)	(5)
3-5-1-12L	1069B1	L	1350	5	X				
3-5-1-18L	1069B1	L	1350	5	X				
3-5-1-20L	1069B1	L	1350	5	X				
3-5-1-22L	1069B1	L	1350	5	X				
3-5-1-25T	1069B1	T	1350	5	X				
3-5-1-21T	1069B1	T	1350	5	X				
3-5-1-19T	1069B1	T	1350	5	X				
3-5-1-17T	1069B1	T	1350	5	X				
3-5-1-14L	1069B1	L	1350	6	X				
3-5-1-24L	1069B1	L	1350	6	X				
3-5-1-26L	1069B1	L	1350	6	X				
3-5-1-28L	1069B1	L	1350	6	X				
3-5-1-23T	1069B1	T	1350	6	X				
3-5-1-15T	1069B1	T	1350	6	X				
3-5-1-13T	1069B1	T	1350	6	X				
3-5-1-11T	1069B1	T	1350	6	X				

TABLE IV

SUMMARY - MINIMUM RADIUS BENDS - 0.060-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
6-2-1-23L	540A	L	1050	4		X			
6-2-1-20T	540A	T	1050	4			X		
6-2-1-02T	540A	T	1050	5		X			
6-2-1-05L	540A	L	1050	5		X			
6-2-1-35L	540A	L	1050	6	X				
6-2-1-36T	540A	T	1050	6			X		
6-2-1-13L	540A	L	1250	4		X			
6-2-1-08T	540A	T	1250	4			X		
6-2-1-03L	540A	L	1250	5	X				
6-2-1-04T	540A	T	1250	5		X			
6-2-1-33L	540A	L	1250	6		X			
6-2-1-28T	540A	T	1250	6			X		
6-2-1-15L	540A	L	1350	4			X		
6-2-1-19L	540A	L	1350	4	X				
6-2-1-17L	540A	L	1350	4		X			
6-2-1-21L	540A	L	1350	4	X				
6-2-1-10T	540A	T	1350	4			X		
6-2-1-16T	540A	T	1350	4			X		
6-2-1-14T	540A	T	1350	4		X			
6-2-1-12T	540A	T	1350	4			X		

TABLE IV (Con't.)

SUMMARY - MINIMUM RADIUS BENDS - 0.060-INCH MATERIAL

IDENTIFICATION NUMBERS		ORIENTATION	FORMING		BEND QUALITY				
SPECIMEN	SHEET		TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
6-2-1-01L	540A	L	1350	5	X				
6-2-1-05T	540A	T	1350	5		X			
6-2-1-07L	540A	L	1350	5	X				
6-2-1-09L	540A	L	1350	5	X				
6-2-1-11L	540A	L	1350	5	X				
6-2-1-30T	540A	T	1350	5		X			
6-2-1-32T	540A	T	1350	5	X				
6-2-1-34T	540A	T	1350	5	X				
6-2-1-29L	540A	L	1350	6	X				
6-2-1-25L	540A	L	1350	6	X				
6-2-1-27L	540A	L	1350	6	X				
6-2-1-31L	540A	L	1350	6	X				
6-2-1-26T	540A	T	1350	6	X				
6-2-1-18T	540A	T	1350	6	X				
6-2-1-22T	540A	T	1350	6	X				
6-2-1-24T	540A	T	1350	6	X				

TABLE V

SUMMARY - MINIMUM RADIUS BENDS - 0.120-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
12-3-1-12L	1064A2	L	1050	4					X
12-3-1-11T	1064A2	T	1050	4					X
12-1-1-02L	1065B	L	1050	5					X
Lost	1064A1	T	1050	5			X		
Lost	1064A1	L	1050	6			X		
12-1-1-06T	1065B	T	1050	6			X		
12-3-1-10L	1064A2	L	1250	4	X				
12-3-1-09T	1064A2	T	1250	4		X			
12-1-1-06L	1065B	L	1250	5	X				
Lost	1064A1	T	1250	5	X				
Lost	1064A1	L	1250	6	X				
Lost	1064A1	T	1250	6	X				
12-3-1-02L	1064A2	L	1350	4	X				
12-3-1-04L	1064A2	L	1350	4	X				
12-3-1-06L	1064A2	L	1350	4		X			
12-3-1-08L	1064A2	L	1350	4	X				
12-3-1-01T	1064A2	T	1350	4		X			
12-3-1-03T	1064A2	T	1350	4		X			
12-3-1-05T	1064A2	T	1350	4		X			
12-3-1-07T	1064A2	T	1350	4		X			

TABLE V (Con't.)

SUMMARY - MINIMUM RADIUS BENDS - 0.120-INCH MATERIAL

IDENTIFICATION NUMBERS			FORMING		BEND QUALITY				
SPECIMEN	SHEET	ORIENTATION	TEMP (°F)	R/t	(1)	(2)	(3)	(4)	(5)
12-3-1-16L	1064A2	L	1350	5	X				
12-1-1-08L	1065B	L	1350	5		X			
12-1-1-04L	1065B	L	1350	5	X				
12-3-1-14L	1064A2	L	1350	5		X			
12-3-1-21T	1064A2	T	1350	5	X				
12-1-1-05T	1065B	T	1350	5	X				
12-3-1-15T	1064A2	T	1350	5		X			
12-3-1-13T	1064A2	T	1350	5	X				
Lost	1064A1	L	1350	6	X				
Lost	1064A1	L	1350	6	X				
Lost	1064A1	L	1350	6	X				
Lost	1064A1	L	1350	6	X				
Lost	1064A1	T	1350	6		X			
12-1-1-07T	1065B	T	1350	6		X			
12-1-1-01T	1065B	T	1350	6	X				
12-1-1-03T	1065B	T	1350	6	X				

The material gages, the bend radii, and the forming temperatures are presented with the illustrations of the several categories of defects.

Visual examination of a category 1 specimen, illustrated in Figure 2, revealed little or no appreciable change in surface texture of the specimen. Critical microscopic examination of a cross-section of the same specimen at 500X, illustrated in Figure 3, revealed only the typical surface condition of slight undulations; there were no sharp notches or other indications of potential failure.

Visual examination of a category 2 specimen illustrated in Figure 4, revealed fine lines or a very slight orange peel appearance of the outer fibers of the specimen. The microscopic examination of the cross section at 500X, illustrated in Figure 5, verified the presence of the fine lines as a series of slight, but sharply defined, indentations.

The surface conditions of the category 3 specimen, illustrated in Figure 6, are very similar to that of the category 2 specimen, except that the lines are more pronounced and clearly visible. The microscopic examination of the specimen at 500X, illustrated in Figure 7, verified the presence of moderate surface cleavage. The slight separation of particles of beryllium from the basic material may be noted in the illustrations. Although an additional etching operation to remove approximately 0.002-inch of material from the surface would result in the removal of these defects, the overall condition is considered to be marginal.

The fracture in the bend area of the category 4 specimen is clearly visible in Figure 8. The 500X magnified cross-section of the specimen, illustrated in Figure 9, clearly shows the magnitude of the fracture. The sharply defined indentations adjacent to the fracture clearly indicate the progressive strain condition existing in the surface of the beryllium.

No magnification was required for the examination and evaluation of the category 5 type of specimen defect. The cleavage of the beryllium in the bend area, clearly illustrated in Figure 10, may be easily observed with the unaided eye. The microscopic cross-section of the specimen at 100X (not

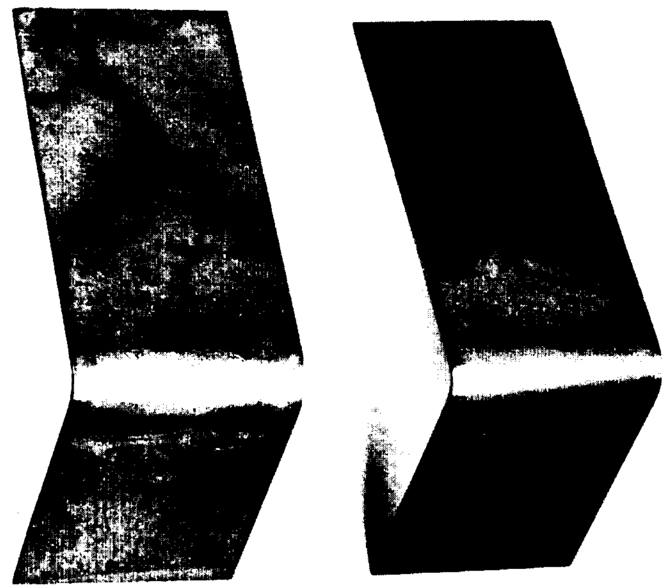


FIGURE 2. MINIMUM RADIUS (4t) BEND - 0.020-INCH MATERIAL - 1350°F.
CATEGORY 1 QUALITY - NO DEFECTS.

500X

FIGURE 3. CROSS-SECTION: MINIMUM RADIUS (4t) BEND - 0.020-INCH MATERIAL - 1350°F. CATEGORY 1 QUALITY - NO DEFECTS.

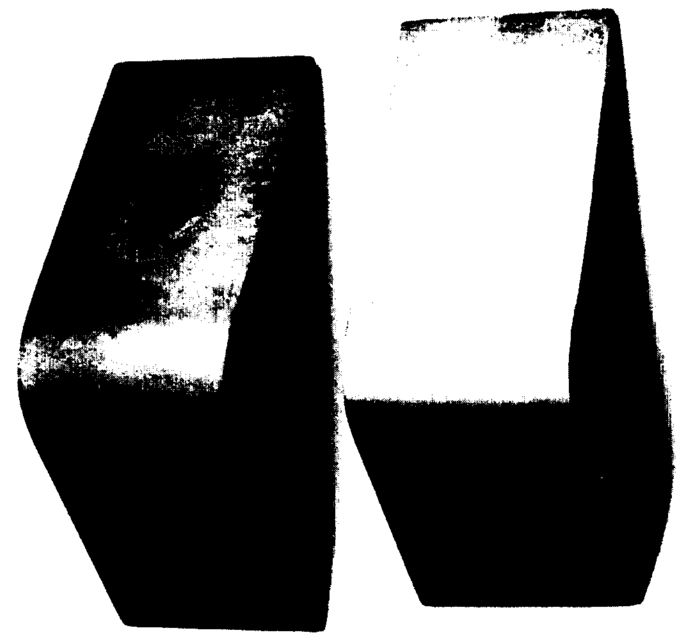


FIGURE 4. MINIMUM RADIUS (4t) BEND - 0.060-INCH MATERIAL - 1350°F. CATEGORY 2 QUALITY - QUESTIONABLE; STRAIN LINES VISIBLE, BUT NO OPEN CLEAVAGE,

500X

FIGURE 5. CROSS-SECTION; MINIMUM RADIUS (4t) BEND - 0.060-INCH MATERIAL - 1350°F. CATEGORY 2 QUALITY.

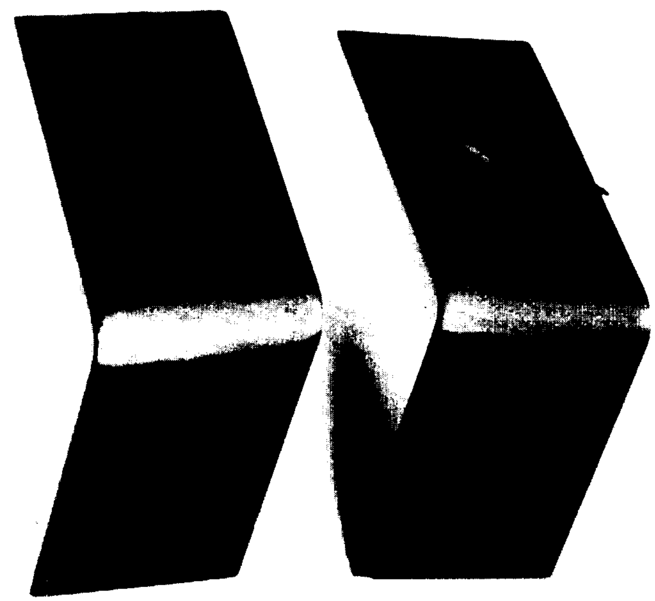


FIGURE 6. MINIMUM RADIUS (4t) BEND - 0.030-INCH MATERIAL - 1050°F. CATEGORY 3 QUALITY - INCIPIENT FAILURE, MINOR CLEAVAGE.

500X

FIGURE 7. CROSS-SECTION; MINIMUM RADIUS (4t) BEND -0.030-INCH MATERIAL - 1050°F. CATEGORY 3 QUALITY.

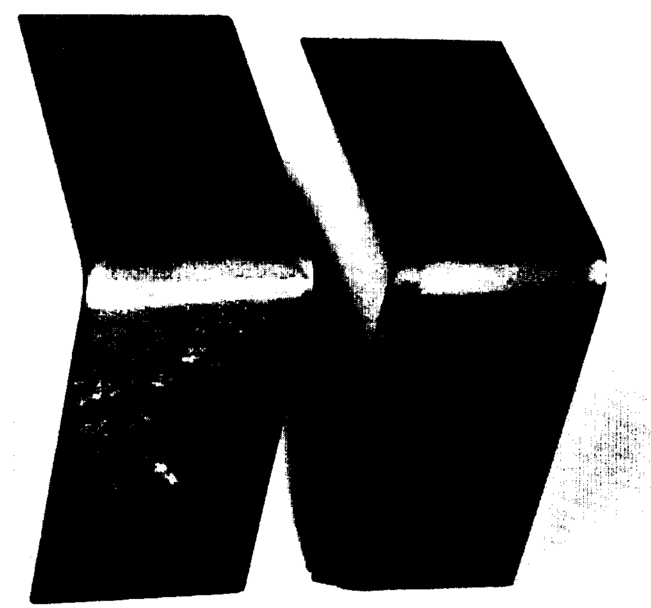


FIGURE 8. MINIMUM RADIUS (4t) BEND - 0.030-INCH MATERIAL - 1050°F. CATEGORY 4 QUALITY - MODERATE CLEAVAGE VISIBLE TO THE UNAIDED EYE.

FIGURE 9. CROSS-SECTION; MINIMUM RADIUS (4t) BEND - 0.030-INCH MATERIAL - 1050°F. CATEGORY 4 QUALITY.

FIGURE 10. MINIMUM RADIUS (4t) BEND - 0.120-INCH MATERIAL - 1050°F. CATEGORY 5 QUALITY - GROSS FAILURE, VISIBLE FRACTURES.

500X as heretofore), illustrated in Figure 11, clearly reveals the sharp cleavage of the beryllium, the potential progressive failure on the bottom of the crack, and other potential failures adjacent to the main fracture.

The analysis of the information and data presented in the tables and figures indicated that 5t radius bends could be consistently and reliably produced in all gages of material at a forming temperature of 1350°F. The results of the tests conducted at 1250°F were very inconsistent, and those at 1050°F were so inconsistent as to be considered unsatisfactory. In addition, only the 0.020 and 0.030-inch gage specimens could be reliably formed at the 4t radius at the 1350°F forming temperature.

Therefore, a minimum radius of 5t and a forming temperature of 1350°F were utilized during all of the subsequent forming operations.

2. Channels. In order to evaluate the effect of the bend radius during actual forming operation, several different procedures were used for the shaping of the channel test specimens. The methods utilized for this investigation included a conventional punch and die, a "Leaf" brake, and a standard press brake. Due to the basic differences in the respective procedures, the results and pertinent discussions are presented individually.

a. Conventional Punch and Die Method. The successful forming of beryllium requires the close control of the pertinent forming parameters, including: close dimensional control, even temperature distribution within the die segments, and even stress distribution. The conventional punch and die appeared to meet all of these requirements.

The "Universal" Forming Die, modified by the substitution of a heated "Glassrock" punch for the stainless steel punch, was used for this evaluation.

Although channel sections were successfully formed, the typically galled condition of the surface, illustrated in Figure 20, was very unacceptable. Beryllium is inherently extremely abrasive, particularly at elevated temperatures, and

100X

FIGURE 11. CROSS-SECTION; MINIMUM RADIUS (4t) BEND - 0.120-INCH MATERIAL - 1050°F. CATEGORY 5 QUALITY.

therefore very resistant to flow across other surfaces. During this phase of the program, various lubricants were tried, but as to yet no satisfactory material has been found which will maintain its lubricating properties at the required forming temperature, and simultaneously will not "build up" on the tool itself.

An alternate method is the use of "buffer" sheets of stainless steel or molybdenum foil. The use of such sheets does result in the forming of satisfactory channels, but at greatly increased cost as the foil is expendable, and considerable additional time is required for its placement in the die.

The discussion of the results is presented in Section III, paragraph A5, Metallographic Analyses.

b. **Leaf Brake Die.** This die, which utilizes the "folding" principle, was designed and fabricated to permit the evaluation of this forming method. In addition, this method eliminates all need for lubricant and thus would eliminate the galling problem.

The "Leaf" die, illustrated in Figure 12, consisted of the basic frame, the center heated "Glassrock" hold-down block and two heated "Glassrock" leaves -- one on either side. As illustrated in Figure 13, several hold-down blocks, incorporating different radius edges, were provided to permit the forming of several configurations.

Prior to the actual forming, the specimen blanks were preheated to 1350-1400°F in a furnace. The blanks then were transferred into the die and the consecutive "folding" of the two sides of the channel was manually accomplished in approximately 30 seconds per side.

Although the principle of the die was sound and the galling problem was solved, various mechanical problems occurred with this experimental tool during the program. These problems, which would be eliminated in the design of a production tool, included insufficient clearance at the ends of the "Glassrock" die blocks for the heating wires, inadequate support of the long slender die blocks along their length and uneven heat distribution due to the open nature of the die. The lack of even temperature

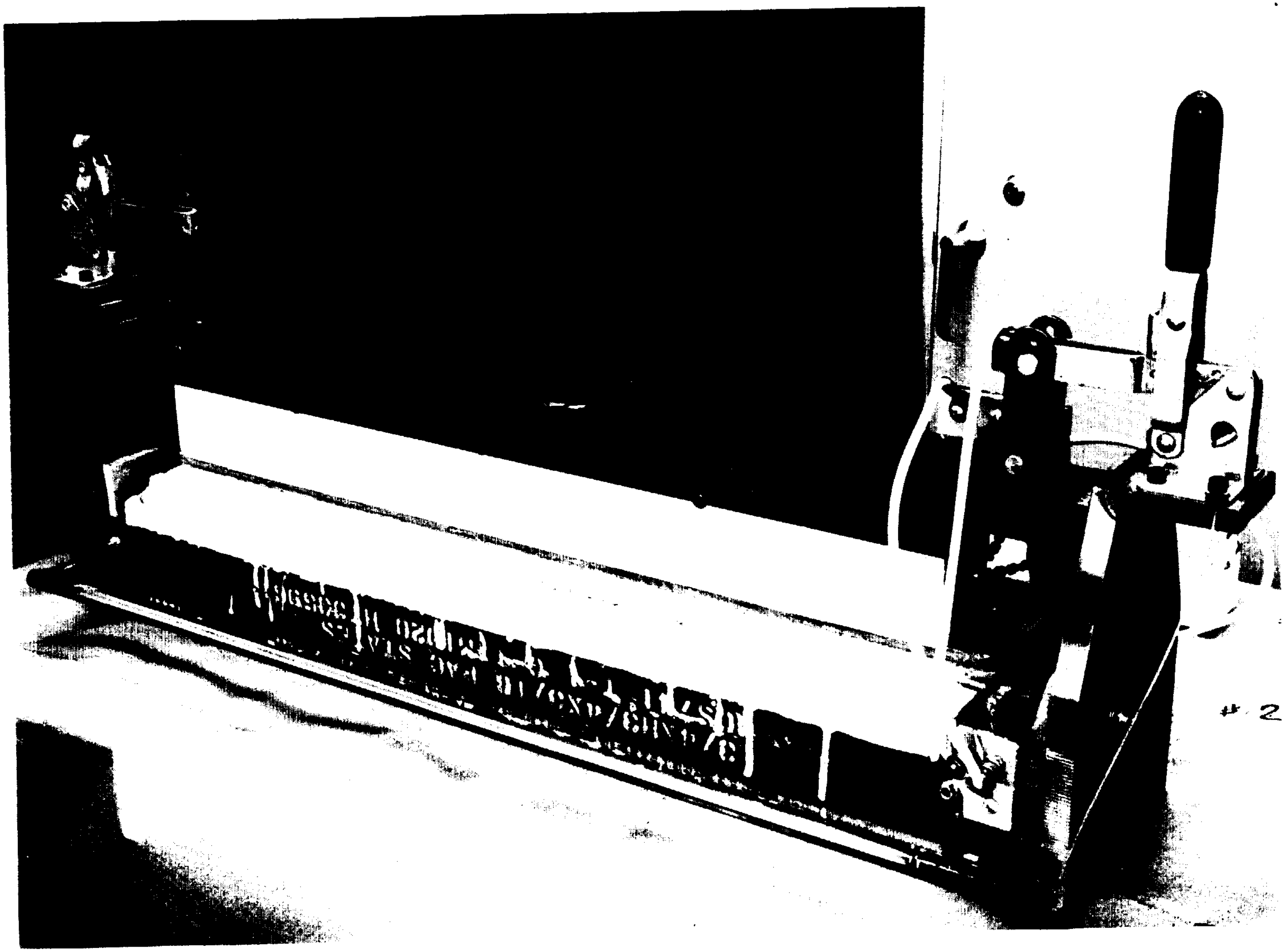


FIGURE 12. ASSEMBLED LEAF BRAKE DIE.
NOTE THE STEEL FRAME AND THE "GLASSROCK"DIE BLOCKS.

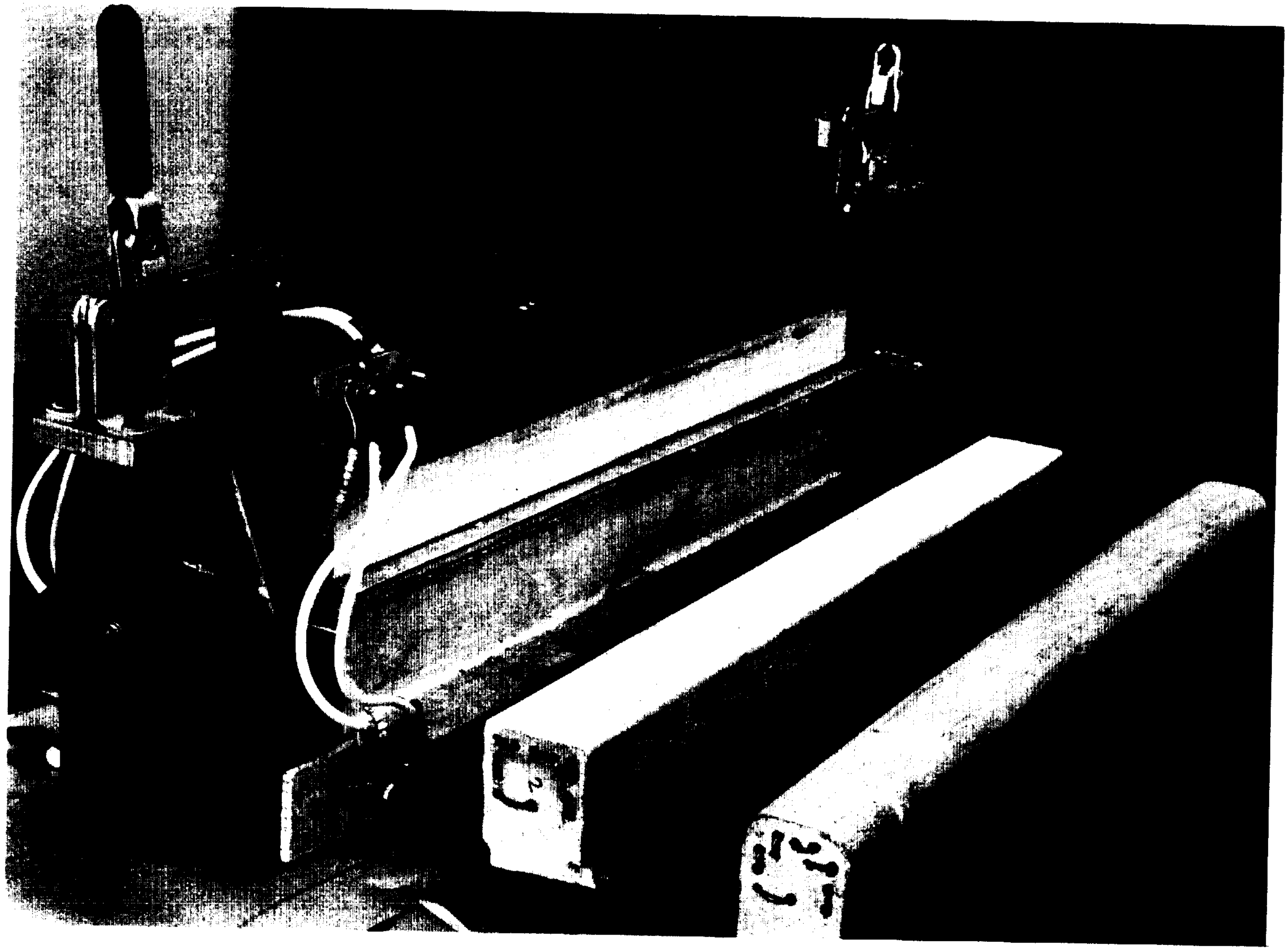


FIGURE 13. LEAF BRAKE DIE WITH 0.10-INCH AND 0.60-INCH RADIUS DIE BLOCKS. THE 0.30-INCH RADIUS DIE BLOCK IS INSTALLED.

along the die blocks resulted in severe warpage of the specimens, particularly with the thinner gages of material as illustrated in Figure 14. Subsequent resizing and stress relieving of the specimens in the Universal Forming Die at a temperature of 1350°F for approximately 20 minutes resulted in the production of smooth straight channel sections as illustrated in Figure 15.

c. Standard Press Brake. a standard 60-ton Pacific hydraulic brake, equipped with heated platens, was used for the forming of the 0.120-inch channel specimens. Due to the limited capacity of the power supply and the heating elements (1000°F maximum temperature), supplementary heat was supplied by quartz lamps in order to attain the required forming temperature of 1350°F. The 0.120-inch beryllium blank was "sandwiched" between 0.060-inch mild steel plates during the forming operation to avoid galling the surface of the beryllium. This forming operation, illustrated in Figure 16, was unsuccessful. The thermal characteristics of the beryllium and the large mass of the press brake acting as a heat sink, precluded the maintenance of the required temperature in the beryllium blank. This forming activity was discontinued after two attempts, made at a material temperature of approximately 1100°F, resulted in the catastrophic type of failure illustrated in Figure 17.

3. Zee Sections. No unanticipated problems were encountered during the forming of the Zee Sections on the Leaf brake die. All forming was, of necessity, accomplished in two steps, i.e., the blank was heated to 1350°F, placed in the die, and the first leg of the Zee was formed. The specimen then was reheated, placed in the die "upside down" from the previous position and the final leg of the Zee was formed. As occurred during the forming of the channel sections, the uneven temperature along the die resulted in the formation of warped specimens. However, a subsequent straightening and stress relieving operation, conducted in the Universal Forming Die at 1350°F for approximately 20 minutes, corrected this condition. This operation is illustrated in Figure 18. Representative stress relieved and straightened Zee sections are illustrated in Figure 19.

4. Hat Sections. As four separate operations would have been required for the forming of the hat sections in the leaf die, the "Glassrock" die segments were installed in the Universal Forming Die, as illustrated in Figure 18, which

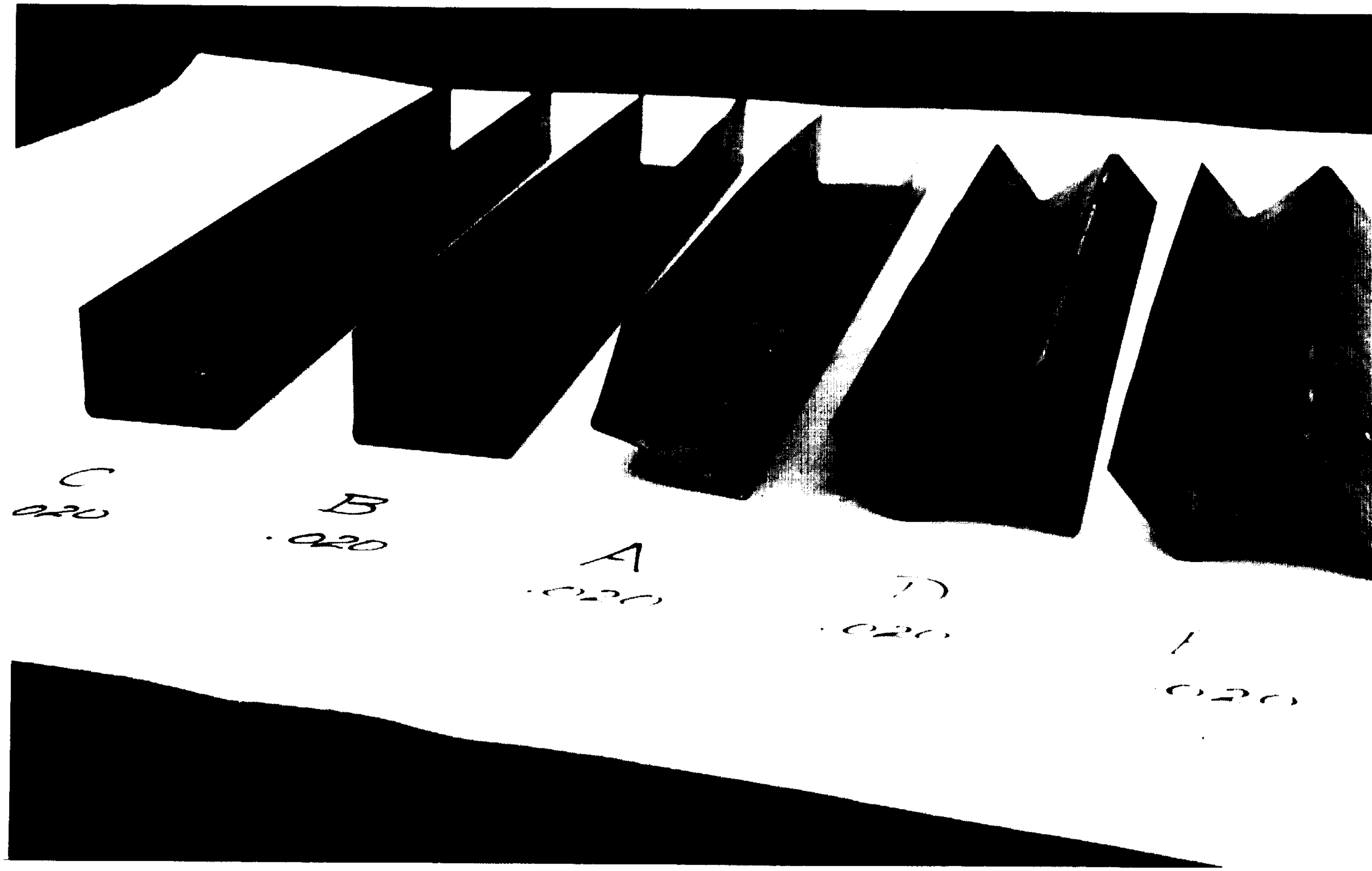


FIGURE 14. "AS FORMED" SPECIMENS.
WARPED DUE TO UNEVEN TEMPERATURE.

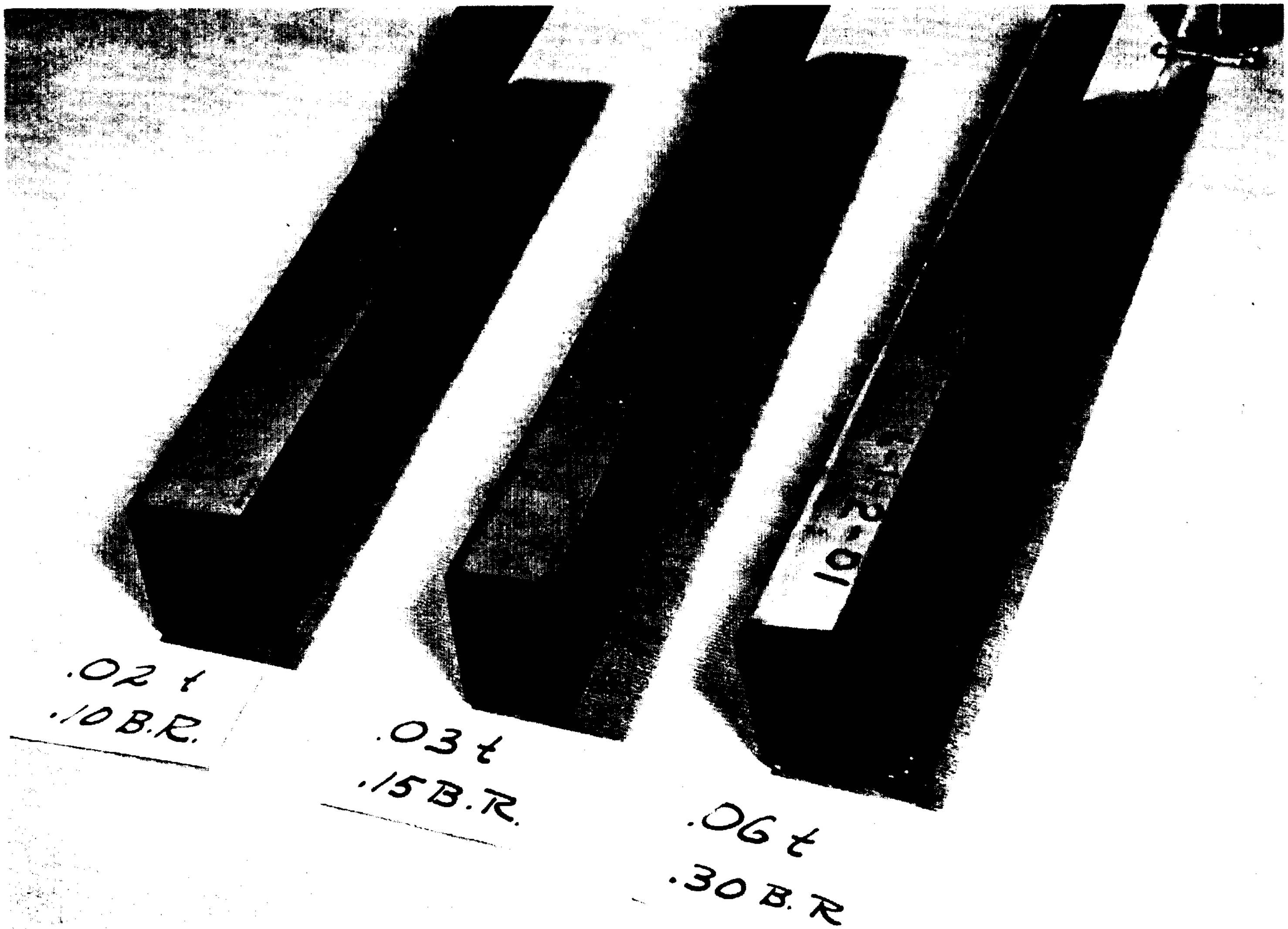


FIGURE 15. REPRESENTATIVE CHANNEL SECTIONS FORMED ON THE LEAF BRAKE. STRESS RELIEVED AND STRAIGHTENED.

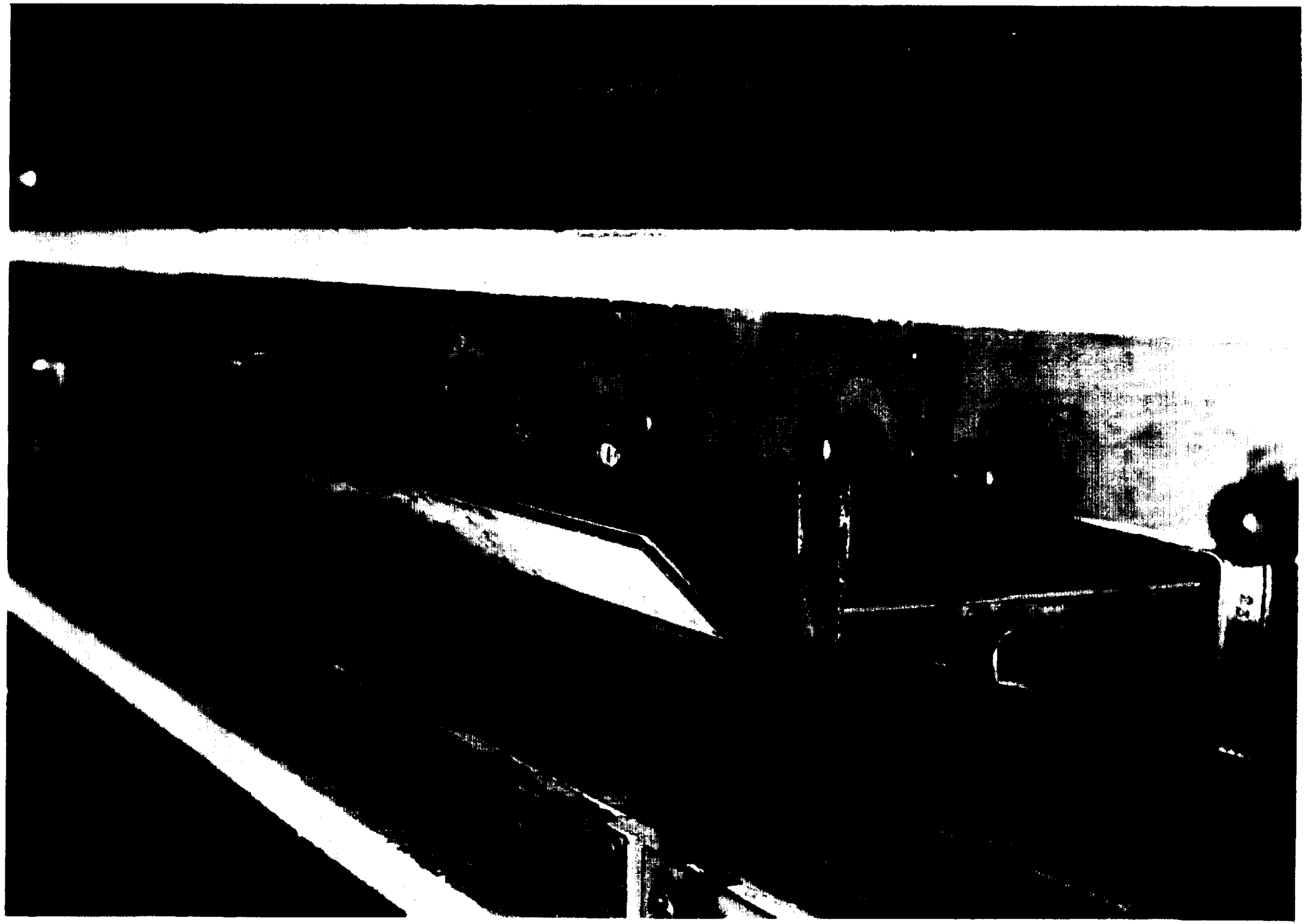


FIGURE 16. CHANNEL BEING FORMED ON THE PRESS BRAKE.
NOTE THE STEEL PLATES ON BOTH SIDES OF THE BERYLLIUM SPECIMEN.

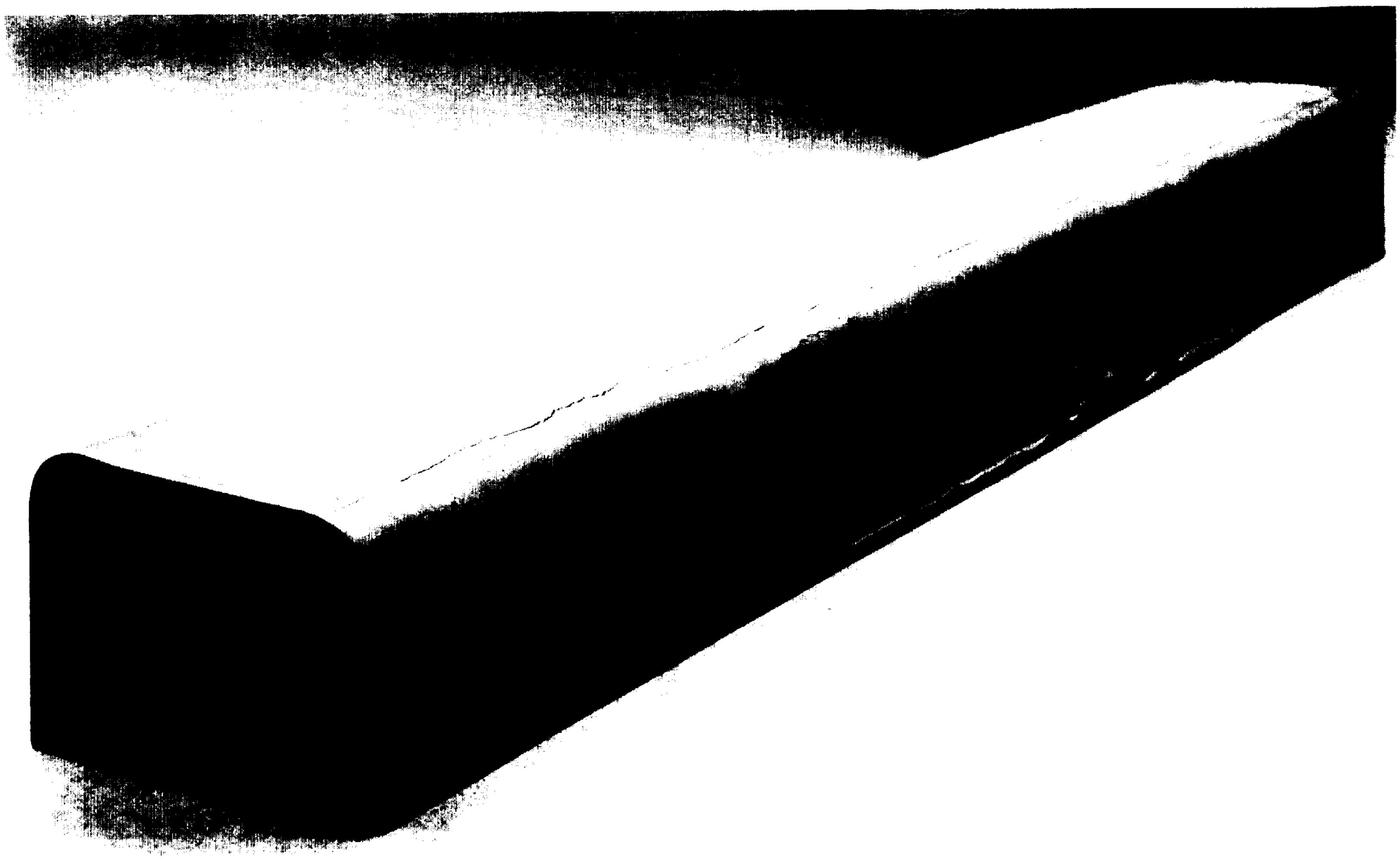


FIGURE 17. CHANNEL FORMED ON THE PRESS BRAKE AT 1100°F.
NOTE THE CATASTROPHIC FAILURE.

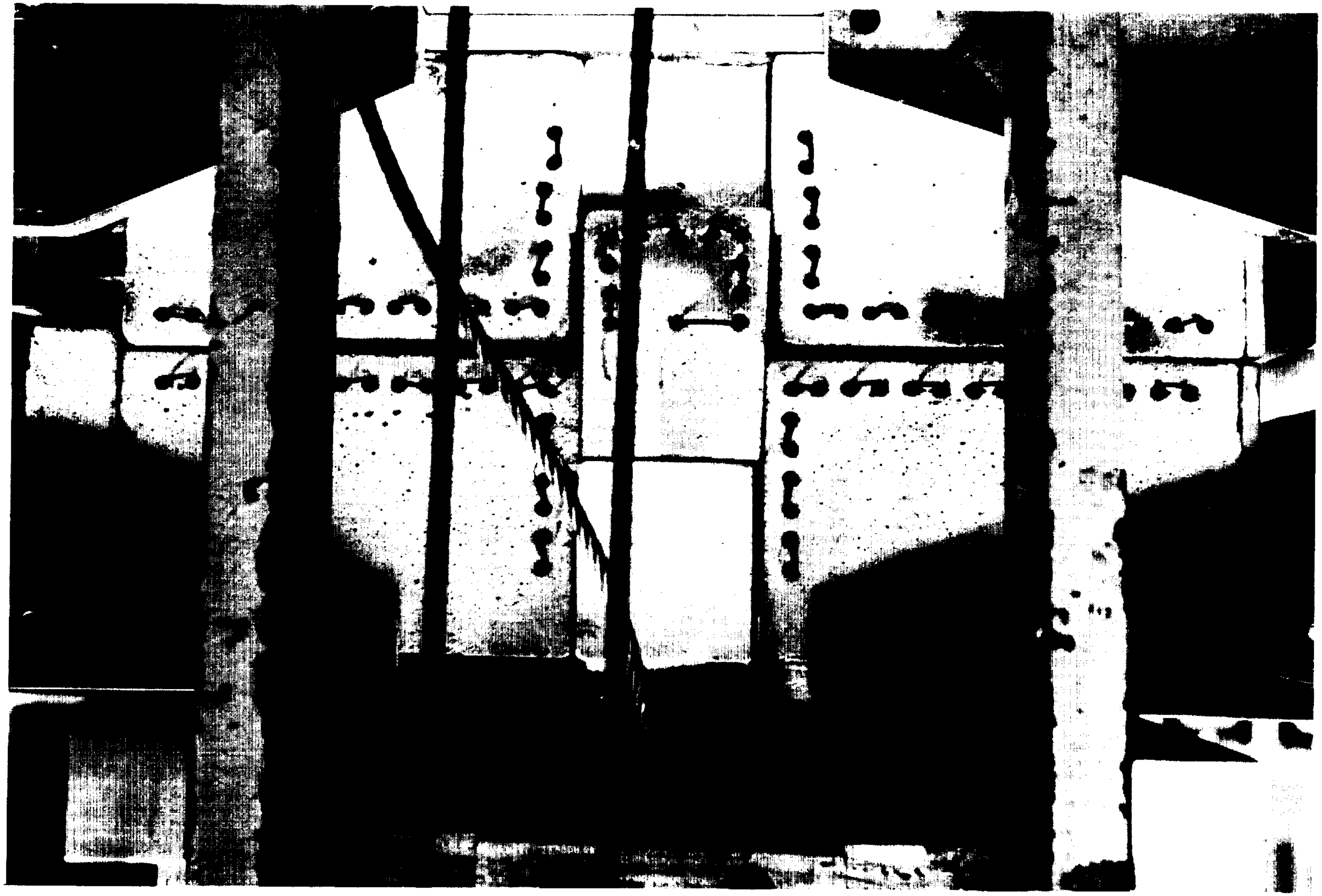


FIGURE 18. ZEE SECTION BEING RELIEVED IN THE UNIVERSAL FORMING DIE. NOTE THE STAINLESS STEEL BUFFER PLATES AND THE 1 1/2-DEGREE SPRINGBACK ALLOWANCE ON THE LEFT SIDE OF THE PUNCH BLOCK.

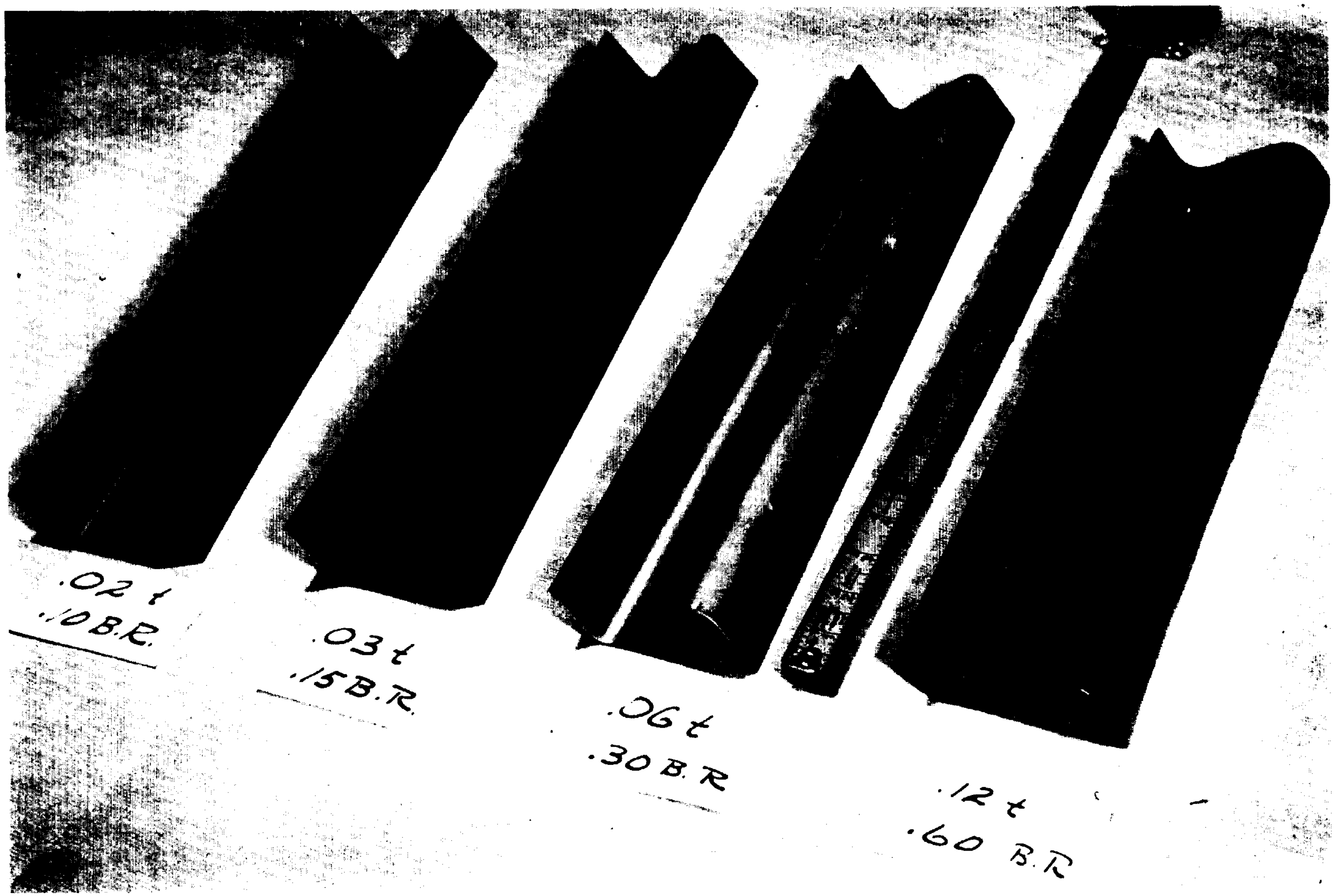


FIGURE 19. REPRESENTATIVE ZEE SECTIONS FORMED ON THE LEAF BRAKE STRESS RELIEVED AND STRAIGHTENED.

permitted the forming of the hat sections in one operation. The 1 1/2-degree springback clearance, visible on the left side of the punch, provided an undesirable unsupported area along this face of the block. This allowance is not required for normal forming operations at 1350°F.

The initial forming operations, conducted without buffer strips resulted in the severe galling of the surface of the material as illustrated in Figure 20. The subsequent installation of stainless steel buffer strips, visible in Figure 18, alleviated this condition. Representative hat sections are illustrated in Figure 21.

5. Metallographic Analyses. In order to permit the comparative evaluation of the merits of the several forming methods utilized during this investigation, the bend radius areas of representative specimens were prepared for microscopic and metallographic analyses.

Due to the impossibility of attaining the proper forming temperature, and the catastrophic failures experienced, no "press brake" specimens were prepared.

Critical examination of representative cross-sections of the hat sections formed during the "punch and die" investigation, and illustrated in Figures 22, 23, and 24 revealed severe subsurface delamination and twinning too far below the surface of the material to permit their removal during the normal 0.002-inch etching operation. The combination of the experimental tool, uneven temperature distribution, and the forced forming of the three bends of the "hat" simultaneously are believed to have caused these deleterious effects. The use of a double acting die with exact temperature control should result in the production of acceptable parts.

Examination of the microphotographs of the channel section, formed on the Leaf brake, revealed a vastly improved grain structure. As may be noted in Figures 25, 26, and 27, very little deformation "twinning" occurred, although considerable shallow sub-surface delamination is visible. However, it should be emphasized that the routine 0.002-inch etching operation will remove the delamination defects.

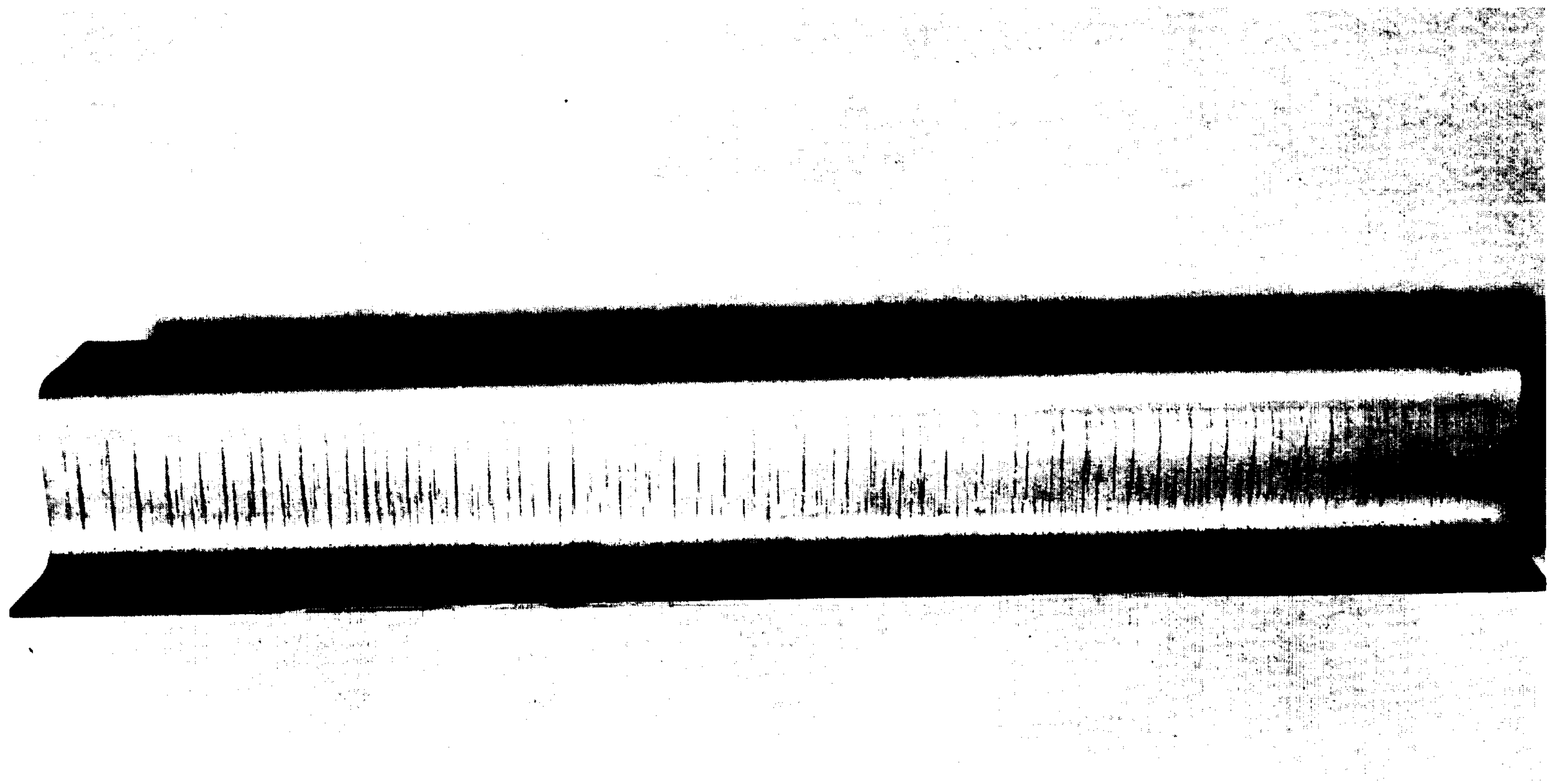


FIGURE 20. HAT SECTION FORMED IN THE UNIVERSAL FORMING DIE WITHOUT BUFFER STRIPS OR LUBRICANT.
NOTE THE SEVERE GALLING.

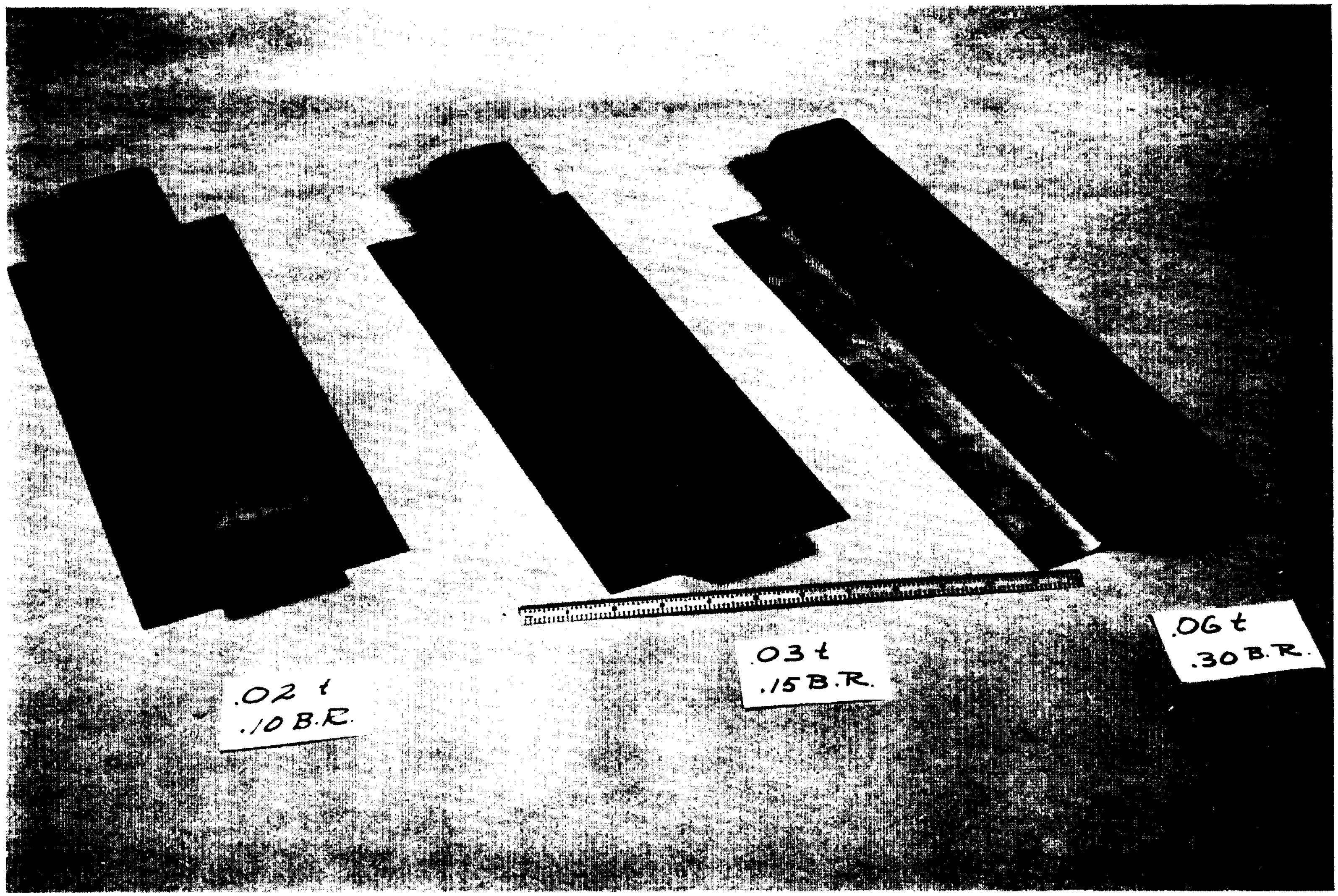
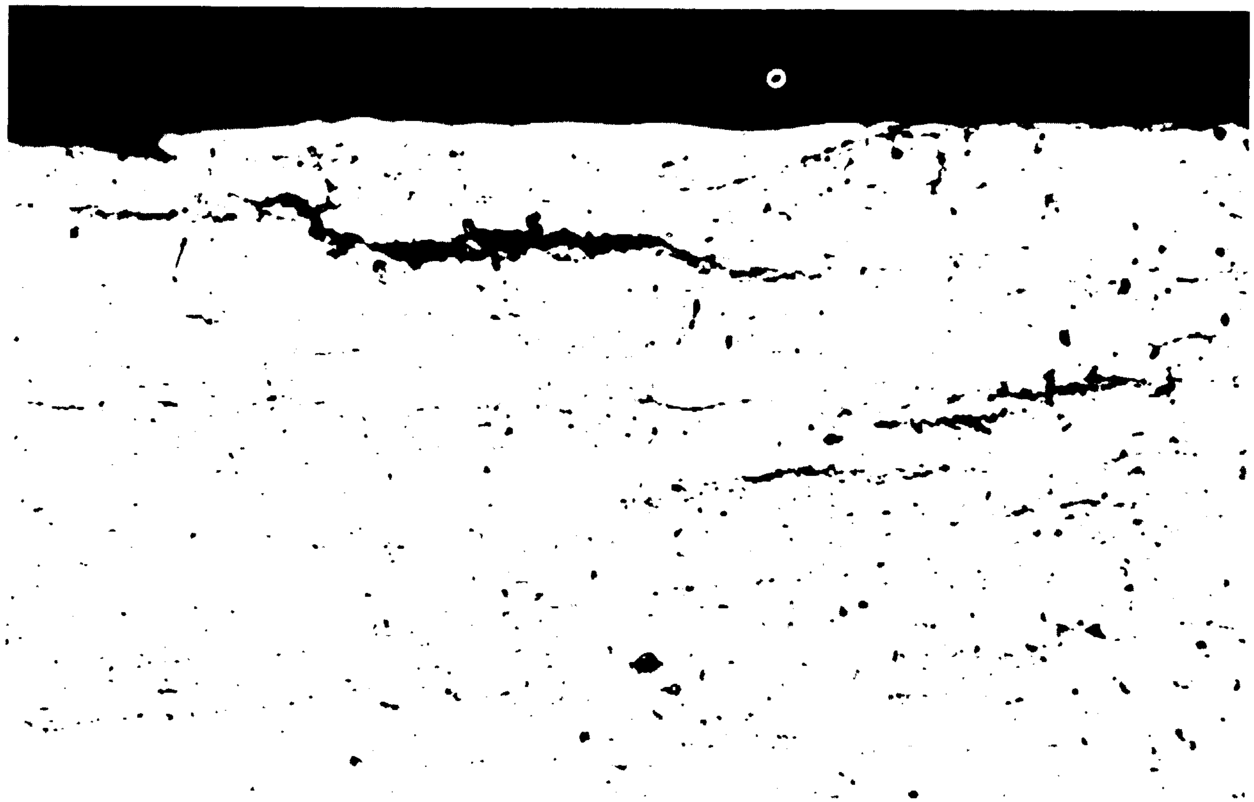


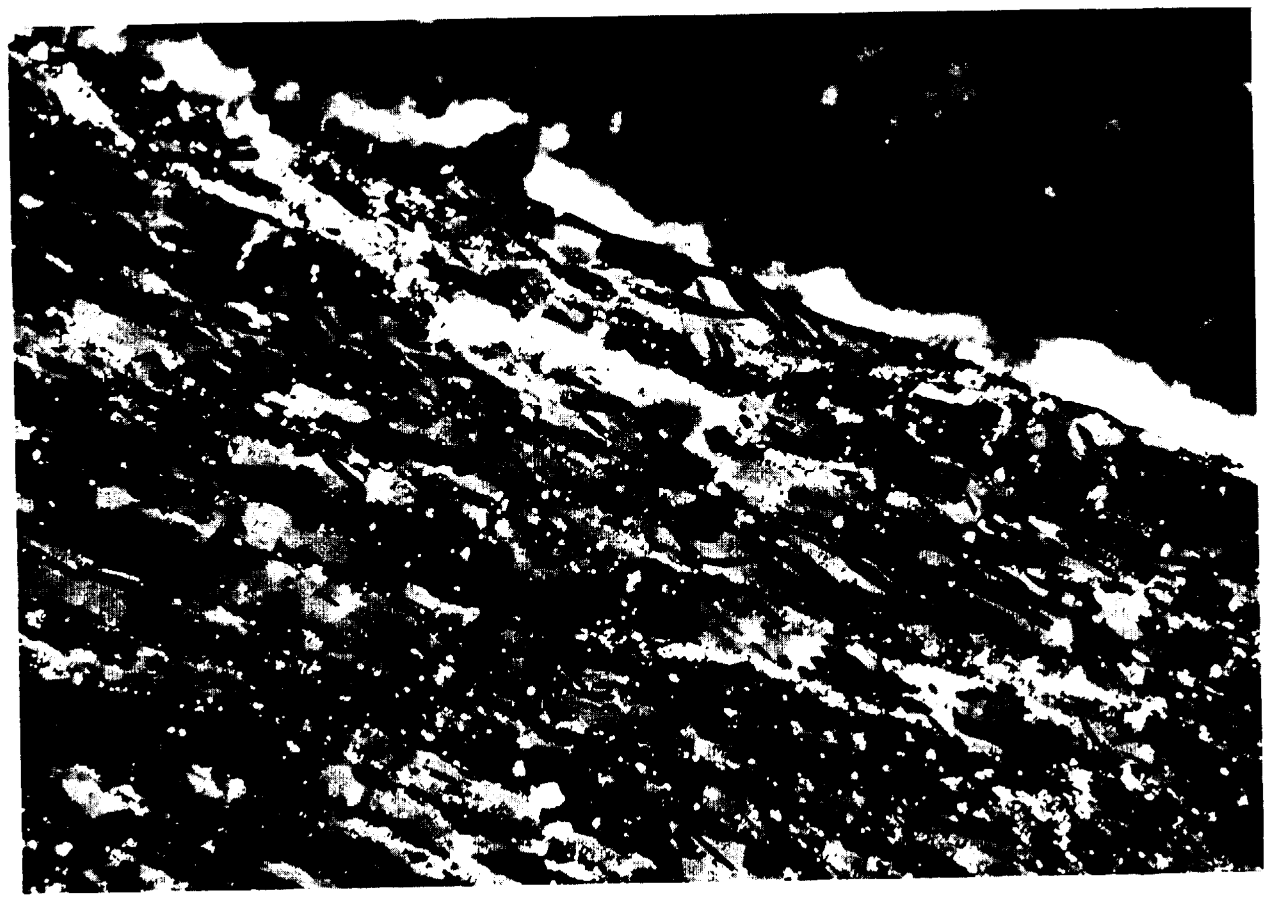
FIGURE 21. REPRESENTATIVE HAT SECTIONS FORMED ON THE UNIVERSAL FORMING DIE.

FIGURE 22. REPRESENTATIVE CROSS-SECTION OF "PUNCH AND DIE" FORMED HAT SECTION - 0.060-INCH MATERIAL.



500X

FIGURE 23. TYPICAL DELAMINATION IN BEND AREA OF "PUNCH AND DIE" FORMED HAT SECTION - 0.060-INCH MATERIAL .



500X

FIGURE 24. TYPICAL TWINNING IN BEND AREA OF "PUNCH AND DIE" FORMED HAT SECTION - 0.060-INCH MATERIAL.

FIGURE 25. REPRESENTATIVE CROSS-SECTION OF CHANNEL FORMED ON THE LEAF BRAKE - 0.060-INCH MATERIAL.

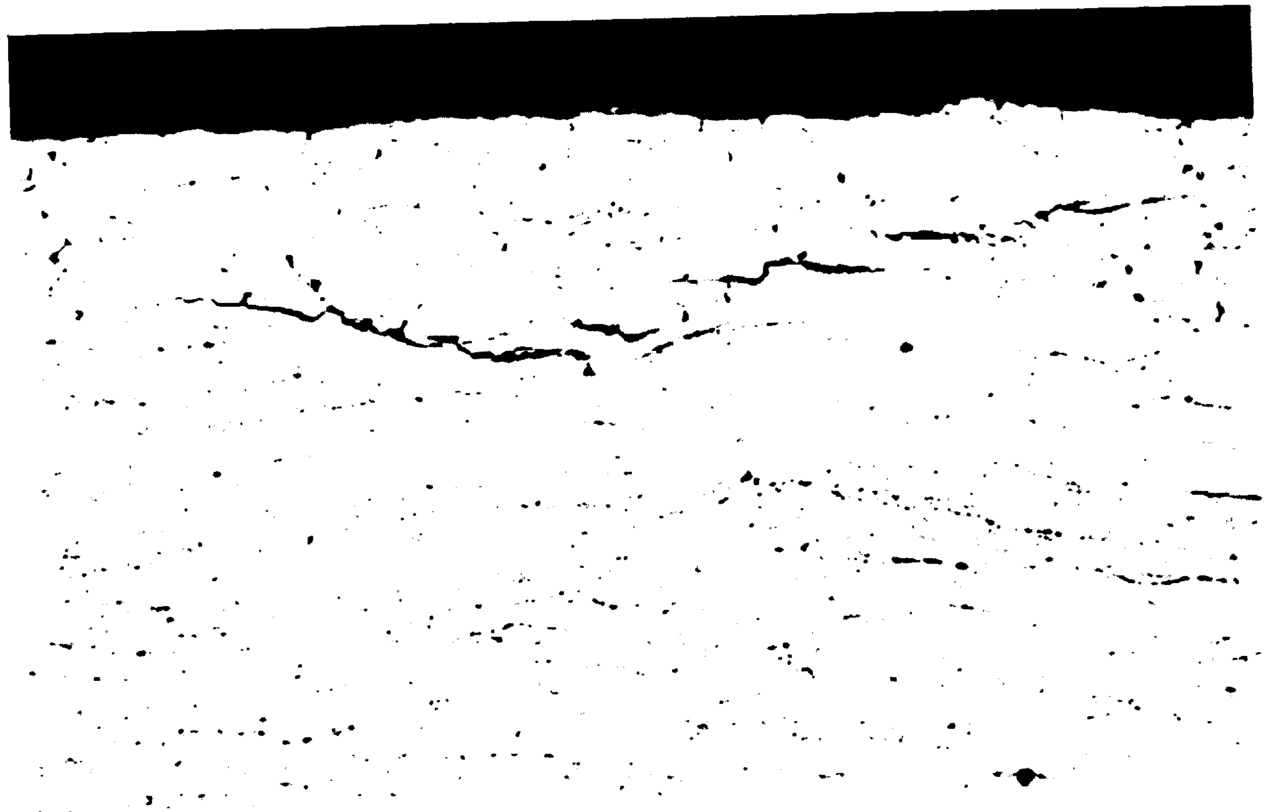


FIGURE 26. TYPICAL DELAMINATION IN BEND AREA OF CHANNEL FORMED ON THE LEAF BRAKE - 0.060-INCH MATERIAL.
ROUTINE 0.002-INCH ETCHING SUBSEQUENT TO FORMING WILL REMOVE THIS DEFECT.

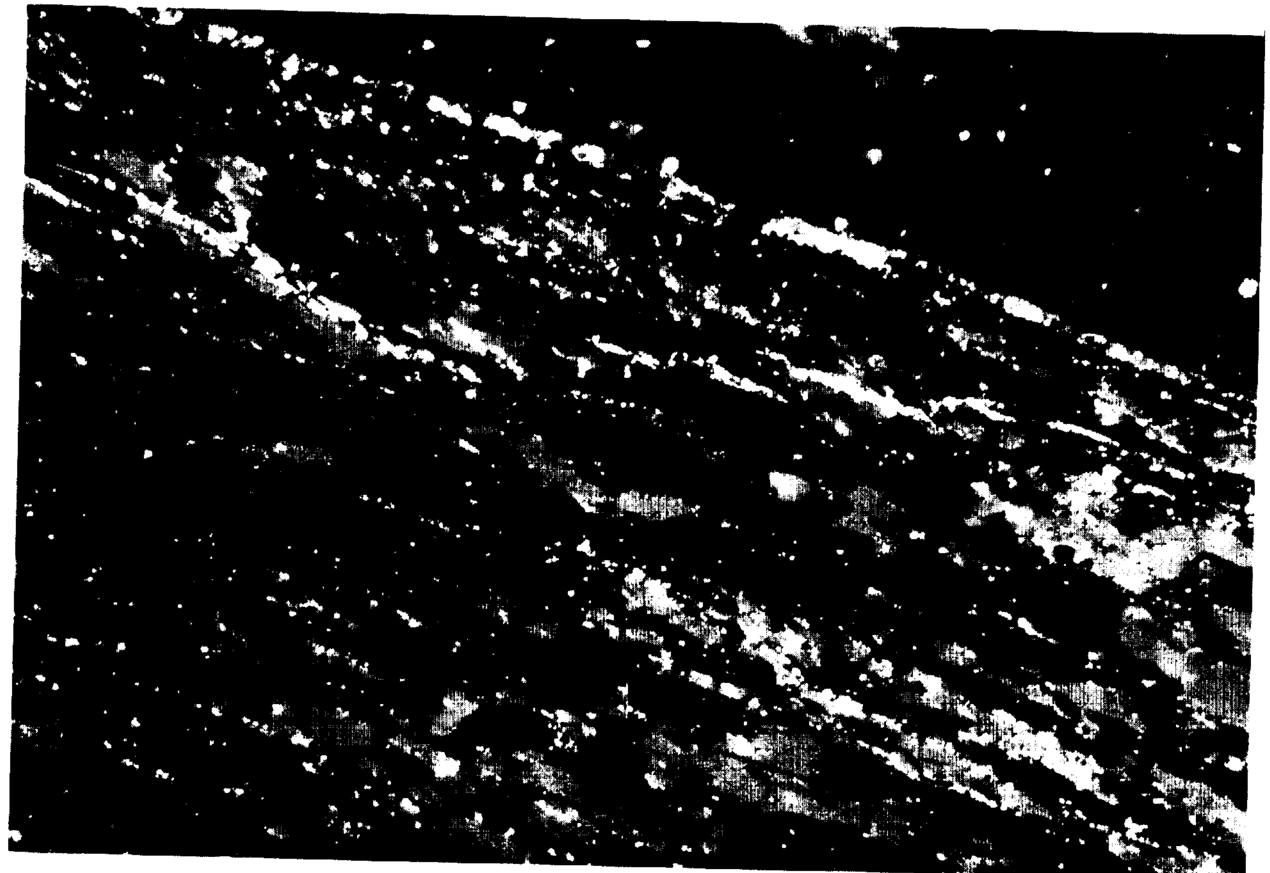


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FIGURE 27. TYPICAL TWINNING IN BEND AREA OF CHANNEL FORMED ON THE LEAF BRAKE - 0.060-INCH MATERIAL.
VERY LITTLE TWINNING OCCURRED.

The microphotographs of the Zee section, also formed on the Leaf brake, exhibited the best grain structure of all. No twinning, sub-surface delamination, or other defects may be seen in Figures 28, 29, and 30. The difference in the grain structures exhibited by the two specimens, formed in the Leaf brake, are believed due to slight variations in the forming parameters including the actual forming temperature, the time to form, and the double heating required for the forming of the Zee Section.

The results of the analyses of these three specimens indicate that the "punch and die" forming method subjected the material to appreciably higher stresses than the "folding" method inherent in the operation of the Leaf brake die. The "drag" forces, or resistance of the material as it is being drawn over a die surface, tend to cause the type of damage exhibited in Figures 23 and 24. The "folding" method of forming subjects only the radius area to bending deformation stresses, without the additional tensile or "drag" stresses inherent in the "punch and die" forming method.

6. Roll Forming. The forming of cross-rolled beryllium sheet material can be performed in conventional three-roll equipment under carefully controlled conditions. However, due to the limited application of this process, and the inherent manufacturing problems, no additional work was included in this development program. Only previous experience, as stated in the Program Plan, is reported.

During one development program, conducted approximately 2 years ago, several sheets of beryllium 0.060-inch by 17 by 25 inches were individually formed, to a 30-inch radius in one pass through the rolls

Each sheet was "sandwiched" between 0.060-inch thick mild steel plates, preheated to 1100-1200°F, manually transferred to the rolls, and passed through the equipment. The actual forming temperature is not known; the "sandwich" temperature dropped approximately 50-100°F during the transfer from the oven to the adjacent rolls, and the unheated rolls acted as a heat sink during the actual forming operation. The panels then were stress relieved at 1229-1290°F for 20 minutes. No damage

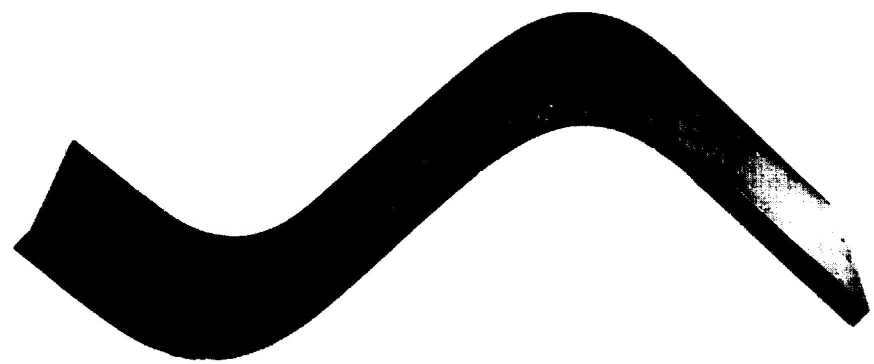
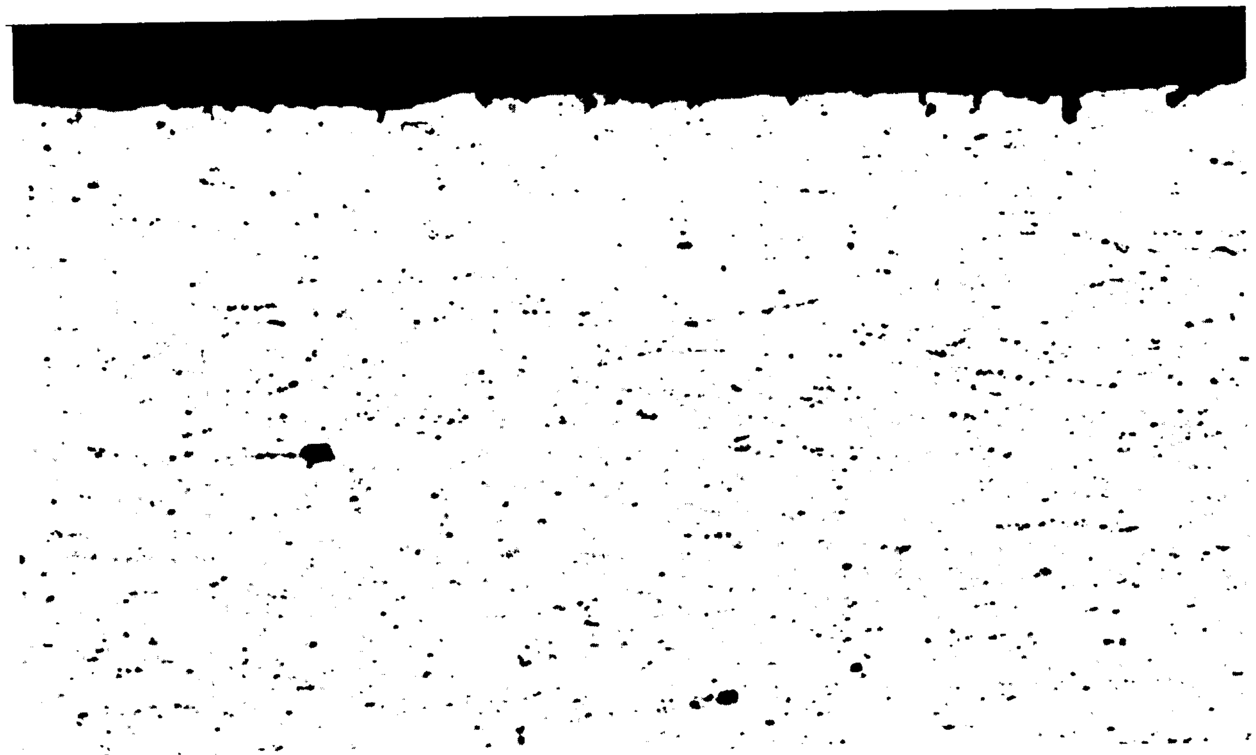
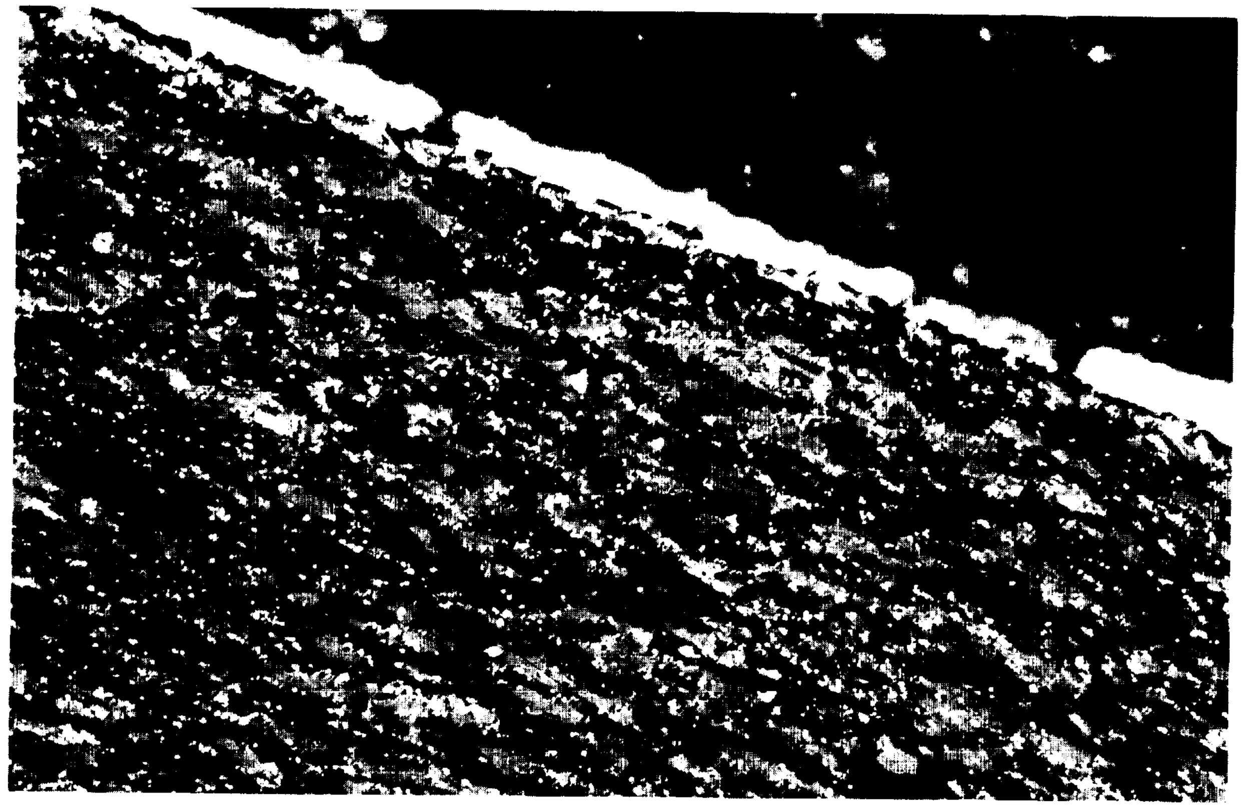


FIGURE 28. REPRESENTATIVE CROSS-SECTION OF ZEE SECTION FORMED ON THE LEAF BRAKE - 0.120-INCH MATERIAL.



500X

FIGURE 29. TYPICAL CROSS-SECTION OF THE BEND AREA OF THE ZEE SECTION FORMED ON THE LEAF BRAKE - 0.120-INCH MATERIAL.
NOTE ABSENCE OF SUBSURFACE DELAMINATION.



500X

FIGURE 30. TYPICAL CROSS-SECTION OF THE BEND AREA OF THE ZEE SECTION FORMED ON THE LEAF BRAKE - 0.120-INCH MATERIAL.
NOTE ABSENCE OF TWINNING.

was detected during the visual inspection, and the formed contour was well within the acceptable limits.

However, during the subsequent drilling of the attachment holes, radial cracking or major failure through the holes resulted in a high rejection rate. In an effort to determine the cause, or causes for this unacceptable failure rate, the effects of various stress relieving time/temperature schedules were investigated. In addition, cross-sectional hardness surveys were made on 0.070-inch thick "as received" sheet material, and on "roll formed plus stress relieved" 30-inch radius panels. The hardness data, measured at 0.005-inch increments across the edges of the specimens from the tension to the compression side of the curved panel, are presented in Table VI. As anticipated, the hardness numbers were highest at the two surfaces of the curved specimens and decreased to the minimum level near the center of the sheet.

It was concluded that, due to the low rolling temperatures and the less-than-optimum stress relieving procedure utilized at that time considerable unrelieved residual stress remained in the material which caused the high rejection rate. The ultimate result of this early development work was the establishment of the "hot die plus stress relief" production procedures currently utilized for the forming of panels. The careful control of the forming and stress relieving parameters has resulted in the reduction of the rejection rate to a negligible level.

Although beryllium sheet material can be formed by rolling, the process is not easily controlled, and several inherent disadvantages preclude its widespread use as a production process, and are listed as follows:

a. Approximately 3-4 inches of additional material must be provided at each end of the piece to be rolled; the leading and trailing edges are not formed. This additional very costly material normally becomes scrap.

b. Heated rolls, with precise temperature control, should be used in order to maintain the proper material forming temperature. This requirement indicates the need for specialized equipment.

TABLE VI

HARDNESS SURVEY OF CURVED SPECIMENS

Vendor: The Brush Beryllium Company
Lot No: 1942
Sheet No: 541A
Material Gage: 0.070-Inch

Distance from Tension Surface inch	Vickers Hardness Number: 300 gram load	
	Flat Sheet "As Received"	Roll Formed "Stress Relieved"
0.005	208	216
0.010	207	214
0.015	206	212
0.020	239	206
0.025	216	197
0.030	203	195
0.035	196	200
0.040	197	204
0.045	199	209
0.050	192	211
0.055	193	219
0.060	218	211
0.065	202	203

c. The beryllium must be "sandwiched" between mild or stainless steel sheets to aid in the maintenance of even temperature and to provide support for the beryllium during the actual forming process.

d. Subsequent to the forming operation, the parts must be stress relieved. This additional operation not only results in increased costs due to the time and equipment required for its accomplishment, but also increases the possibility of damage during the additional necessary handling of the parts.

B. COMPOUND CURVES

The lack of suitable production procedures for the forming of compound curved sections still inhibits the utilization of beryllium in many space vehicle structural applications.

The objectives of this phase of the program were the establishment of the basic forming parameters including the allowable radius/thickness ratio, the deformation limits including both stretch and shrink limits, and the forming temperature.

1. <u>Spherical Segments</u>. Prior to the forming of the full scale task specimens, subscale 3.0-inch spherical radius specimens were formed in the experimental punch and die equipment illustrated in Figure 31. A split "Glassrock" heating unit provided the necessary heat for the forming operation. During the forming operation, the temperature was recorded by means of thermocouples and a "Honeywell" 20-channel strip recorder.

Three circular blanks, 0.020 by 9.0-inches, 0.030 by 8.0-inches, and 0.060 by 7.0-inches were formed at the nominal forming temperature of 1350°F. Since the radius of the punch remained constant (3.0-inch), the Radius/thickness (R/t) rates of the formed hemispherical segments were 150, 100, and 50 respectively. The results of these preliminary experiments, illustrated in Figures 32 and 33, indicated that a R/t radio of approximately 50 appeared to be satisfactory for the forming of unsupported hemispherical segments. The severe edge crippling that occurred at higher R/t ratios is clearly visible in the illustrations. It should be emphasized that these results were very preliminary, to be used only as a guide for the subsequent forming operations.

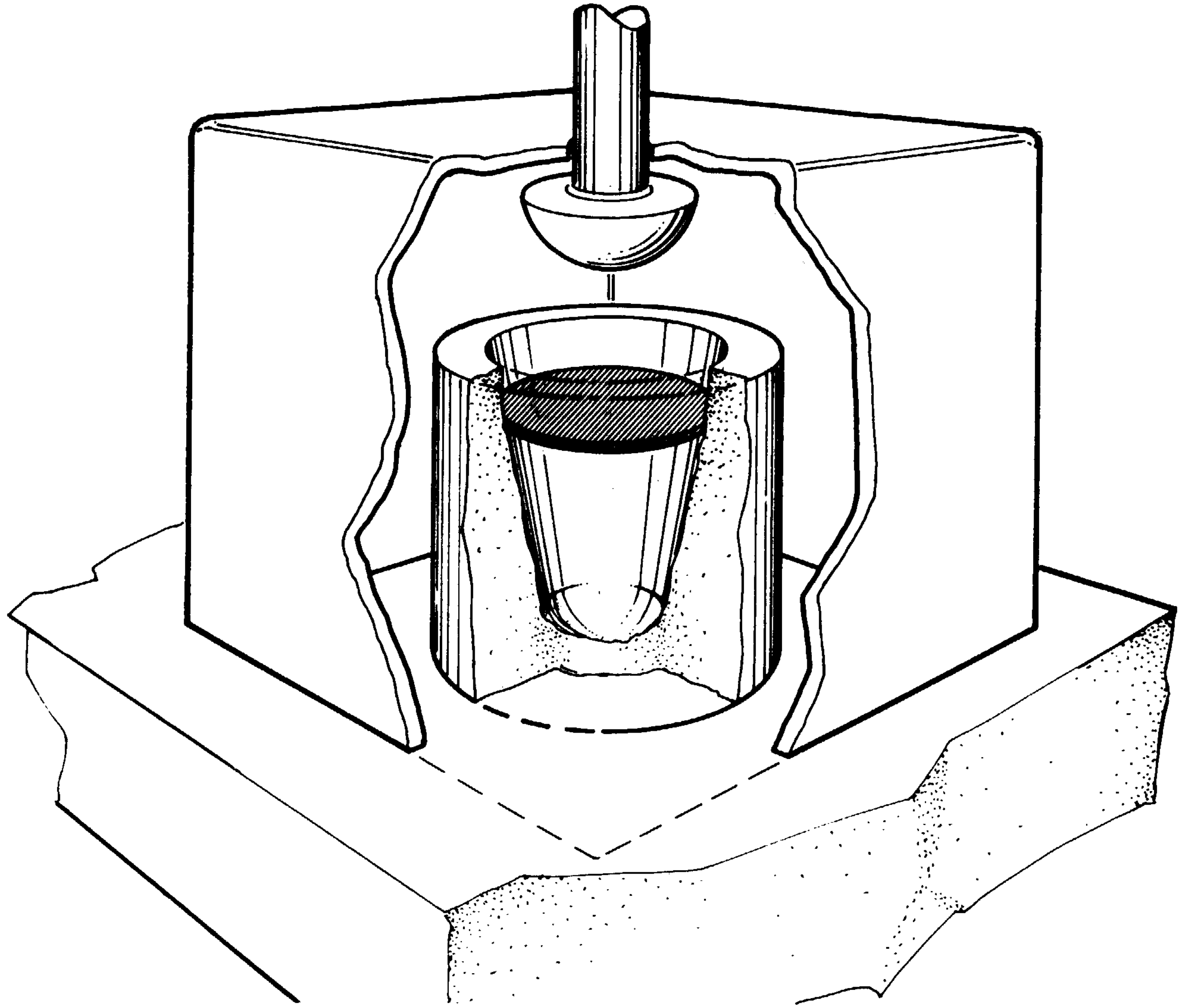
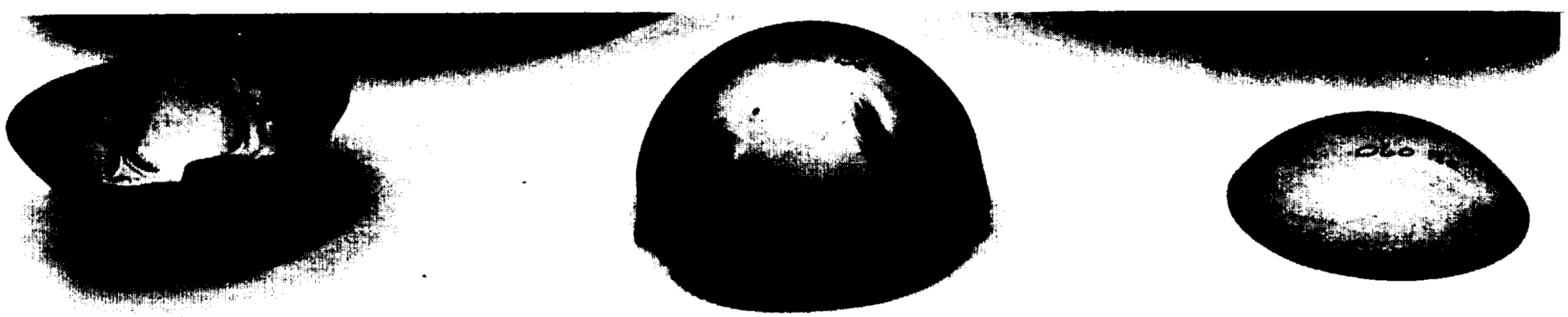


FIGURE 31. EXPERIMENTAL PUNCH AND DIE - PRELIMINARY SPHERICAL RADIUS FORMING - 3.0-INCH RADIUS.



Gage:	0.020-INCH	0.030-INCH	0.060-INCH
R/t:	150	100	50

FIGURE 32. EXPERIMENTAL HEMISPHERICAL SEGMENTS - PRELIMINARY FORMING. NOTE WRINKLING OF THE 0.020-INCH AND 0.030-INCH SEGMENTS.

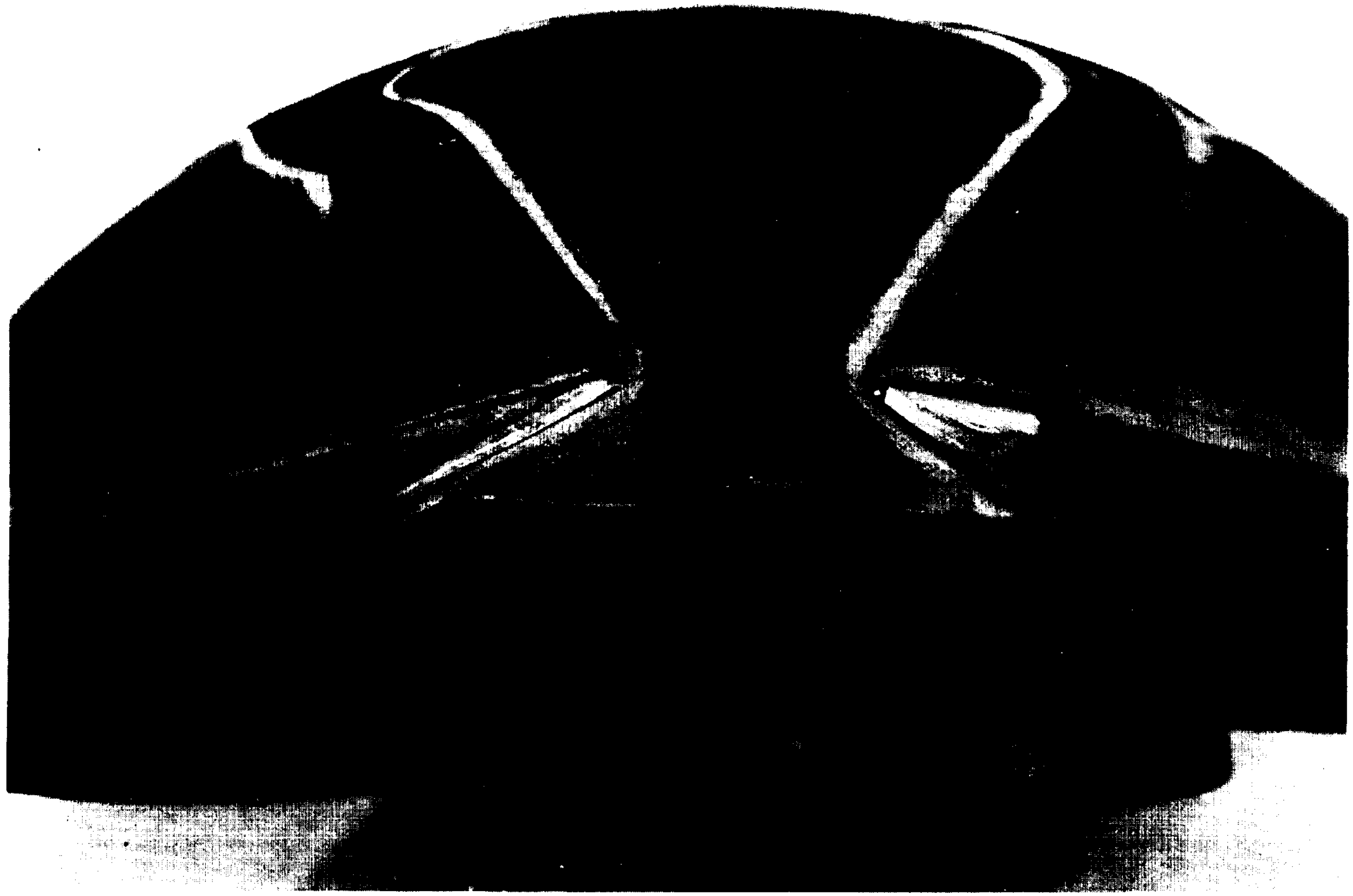


FIGURE 33. EXPERIMENTAL HEMISPHERICAL SEGMENT - 0.020-INCH MATERIAL. NOTE SEVERE FOLDING OF THE MATERIAL.

Due to the size of the specimens to be formed and the results of the initial investigation, a 12.0-inch spherical radius, internally heated, "Glassrock" die was fabricated for use during this phase of the program. The completed punch and die set is illustrated in Figure 34.

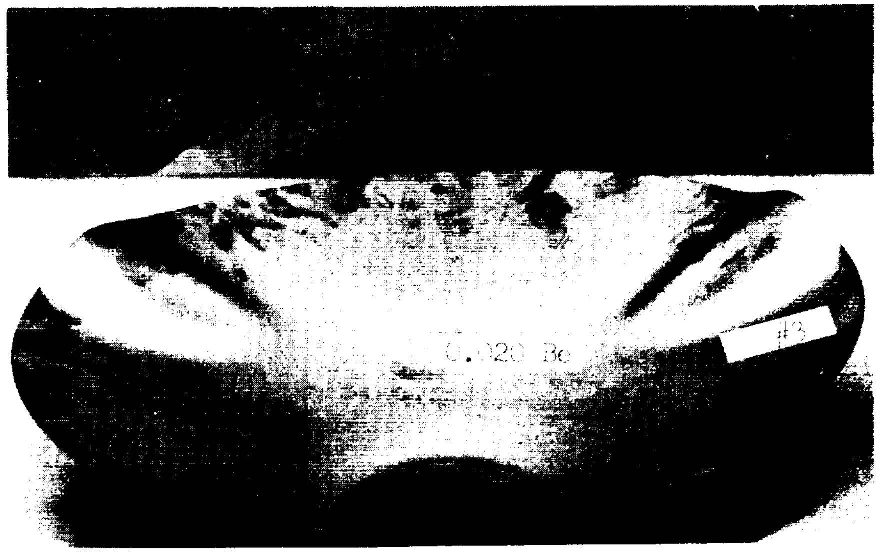
Prior to the forming of any beryllium test specimens, a "tool try" was made at room temperature with a 0.060 by 18.0-inch 61SO aluminum blank. The room temperature characteristics and properties of 61SO aluminum are very similar to those of beryllium at 1350°F; the use of the aluminum provides an inexpensive means for checking the operation of tooling to be used for the forming of beryllium. The aluminum hemispherical test segment, and a 0.020-inch beryllium segment are illustrated in Figure 35. The similarity of the wrinkles in the edges of the two specimens should be noted.

All of the 18.0-inch diameter beryllium blank specimens were preheated to 1350°F in an oven, located adjacent to the forming die, before being manually transferred to the preheated forming die. During the forming operations, the temperatures were recorded by means of thermocouples and a Honeywell 20-channel strip recorder.

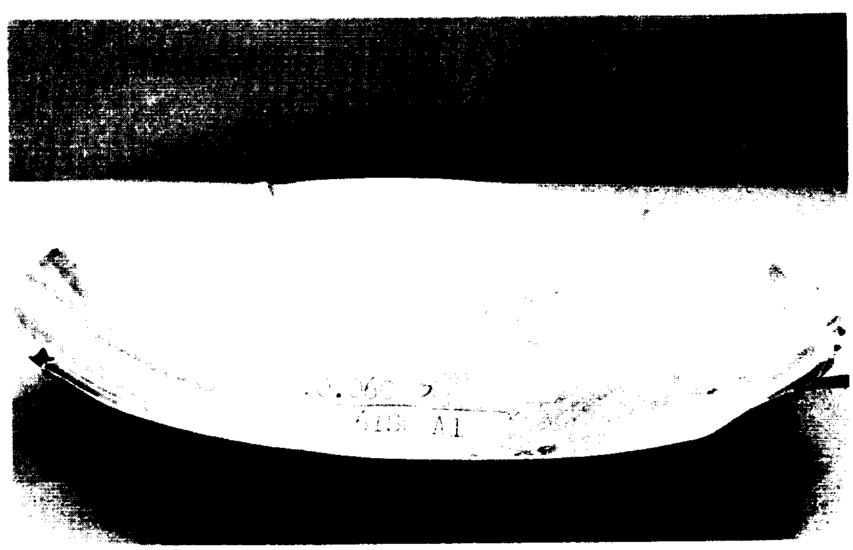
The wrinkling in the edges of the 0.020-inch, 0.030-inch and 0.060-inch test specimens was very similar to that exhibited by the preliminary test specimens, but was progressively less severe. Prior to the forming of the 0.120-inch thick specimen, a 1.00-inch grid was scribed lightly on one side of the blank in order to permit the measurement of the relative shrinkage and stretching of the material. The 18.00-inch diameter blank and the formed spherical segment are illustrated in Figure 36; the scribed inner surface of the spherical segment is illustrated in Figure 37. It should be noted that the roughness of the edge of the material, visible in the illustrations, was due to the chemical process used in cutting the circular blank, and not due to any forming reaction.

Critical visual examination of the 0.120-inch thick formed specimens revealed no wrinkles or other deleterious effects from the forming operation. The 0.120-inch thickness of the material provided a Radius/thickness (R/t) radio such that any slight wrinkling that may have occurred during the forming

FIGURE 34. "GLASSROCK" SPHERICAL FORMING DIE - 12.0-INCH RADIUS.



NOTE: 0.020-INCH BERYLLIUM



NOTE: 0.060-INCH 61SO ALUMINUM

FIGURE 35. SPHERICAL SEGMENTS
0.020-INCH BERYLLIUM AND 0.060-INCH 61SO ALUMINUM
FORMED AT 1350°F AND ROOM TEMPERATURE, RESPECTIVELY.
NOTE THE SIMILARITY OF THE WRINKLES AT THE EDGES
OF THE SPECIMENS.

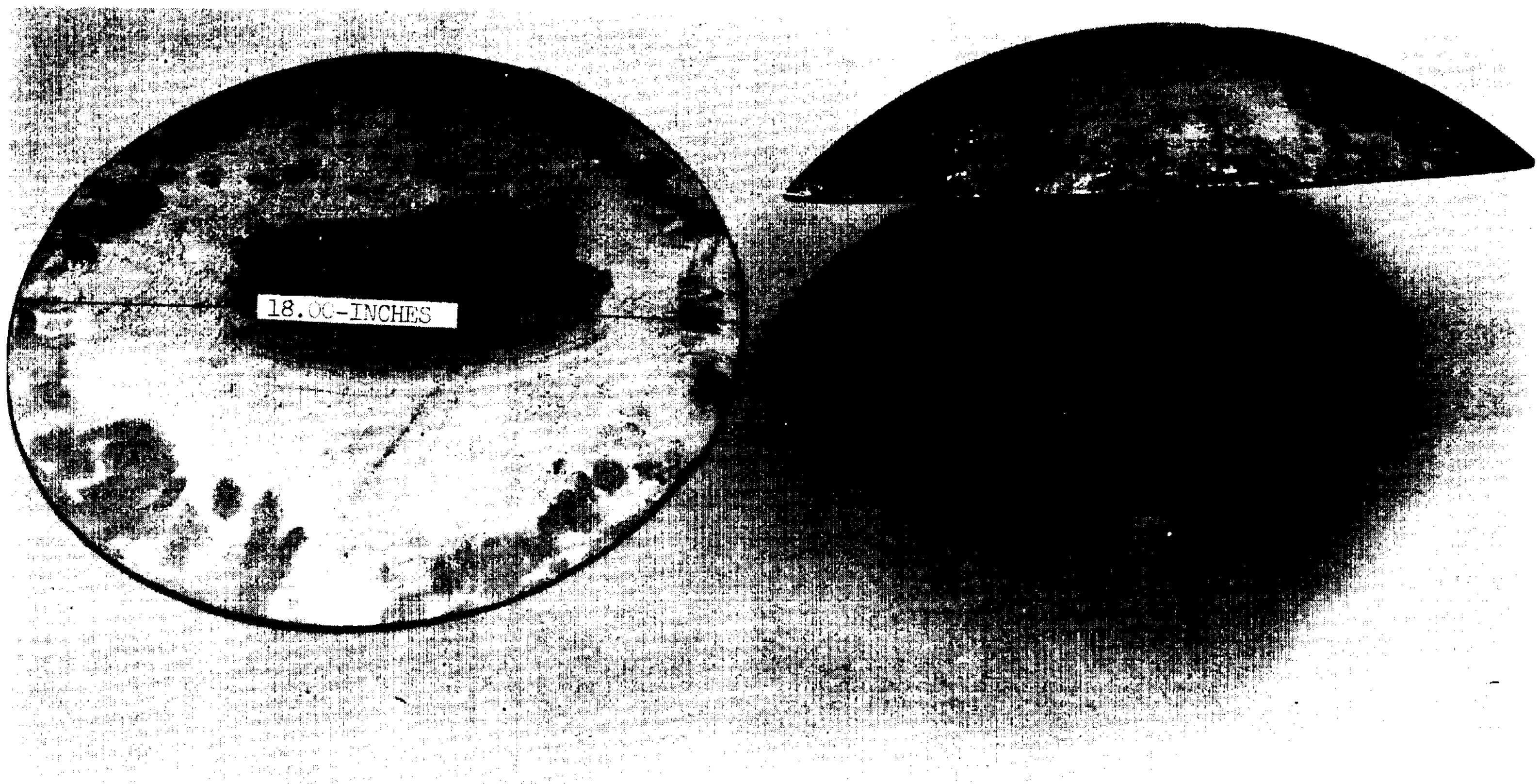


FIGURE 36. SPECIMEN BLANK AND FORMED SPHERICAL SEGMENT - 0.120-INCH MATERIAL - 12.0-INCH RADIUS - 100 R/t.

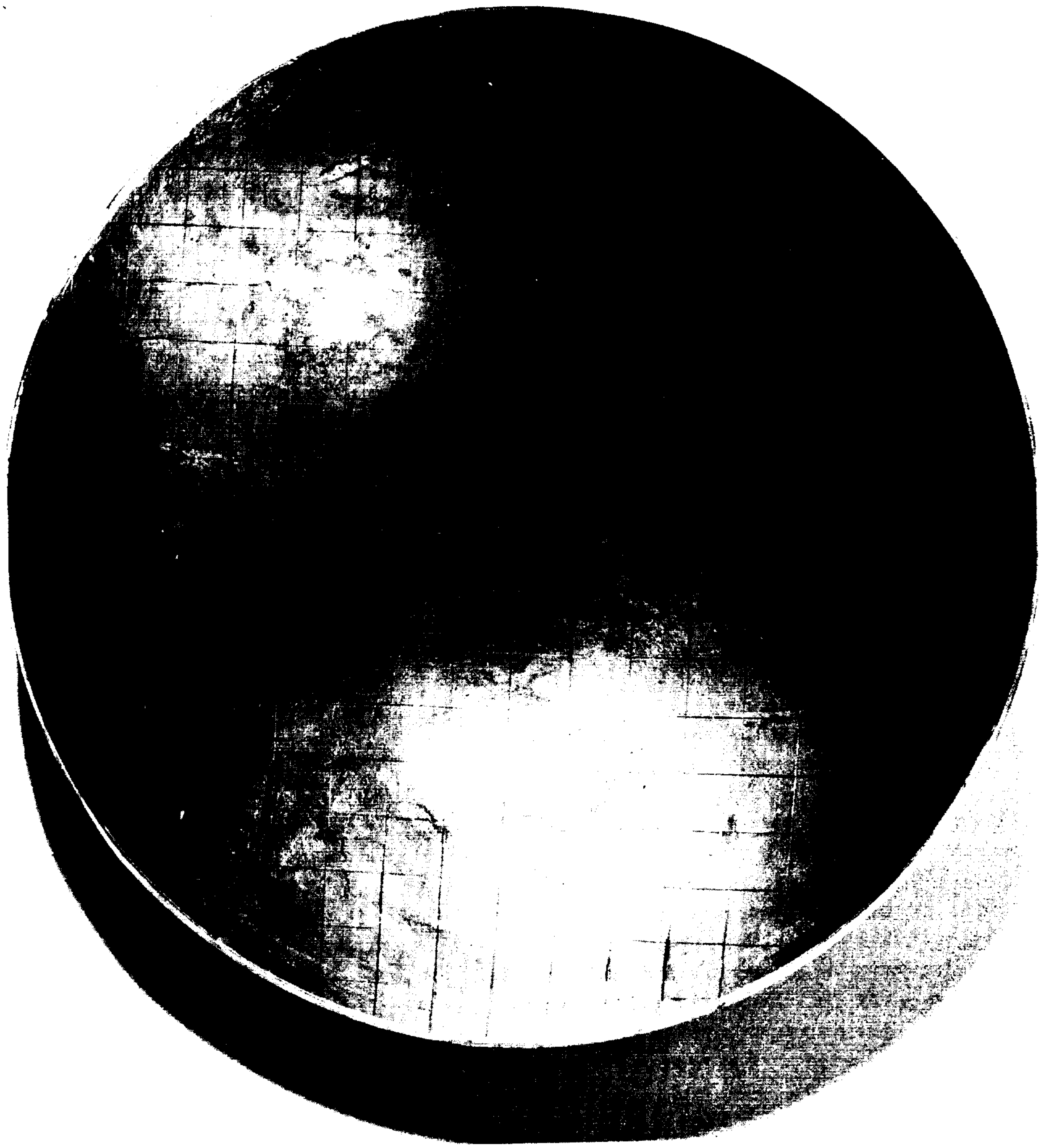


FIGURE 37. SCRIBED INNER SURFACE OF THE FORMED SPHERICAL SEGMENT - 1.00-INCH GRID - 0.120-INCH MATERIAL - 12.0-INCH RADIUS - 100 R/t.

operation was "ironed out" by the punch as the die was completely closed.

Unfortunately, the failure of the die set, due to the fusing together of the punch and die during a preheating cycle in the closed position, precluded the forming of the balance of the specimens.

A summary of the results of this investigation is presented in Table VII. Both the initial 3.0-inch radius and the final 12.0-inch radius data are included.

The measurement of the grid on the 0.120-inch thick spherical specimens revealed the maximum shrinkage and elongation of the forming operation, were 6 and 5.5 percent respectively.

The limited results of this preliminary study indicate that for the forming of compound curves involving multi-directional material flow and unrestrained edges, the maximum R/t ratio and shrinkage appear to be 100 and 6 percent respectively. The establishment of firm R/t ratios and shrink and stretch values for all gages of material and a representative series of diameters would require the accomplishment of a comprehensive specialized development program which is not believed to be within the scope of this study.

Following the completion of the forming of the spherical segment specimens, the hemispherical gore segments were to be formed in the same 12.0-inch radius punch and die set. The complete failure of the tool precluded the accomplishment of this minor portion of the program. However, since a hemispherical gore is a sector of a hemisphere, and after careful analysis and evaluation of the material flow pattern indicated by the grid on the 0.120-inch thick specimens, it is believed that the R/t ratios and shrinkage values would be comparable to those for the spherical segments.

2. Channel Ring Segments. Due to the combined forming requirements of minimum radius bends and compound curvature, the development of suitable procedures for the forming of curved channel segments was the next logical step in this forming program.

TABLE VII

SUMMARY - SPHERICAL SEGMENTS

GAGE INCH	RADIUS INCHES	R/t RATIO	REMARKS
0.020	3.0	150	Severe wrinkling - unacceptable
	12.0	600	Severe wrinkling - unacceptable
0.030	3.0	100	Severe wrinkling - unacceptable
	12.0	400	Severe wrinkling - unacceptable
0.060	3.0	50	No wrinkling - excellent
	12.0	200	Severe wrinkling - unacceptable
0.120	3.0	--	No effort.
	12.0	100	Slight wrinkling - "ironed out" - very good.

Again, due to the limited number of specimens to be formed, the curved punches and the die were fabricated of "Glassrock" and supported in steel frames for installation in the press. Two punches, with bend radii of 0.30-inch and 0.60-inch, were fabricated for the forming of the four gages of material. The 0.30-inch radius punch was used for forming the 0.020, 0.030, and 0.060-inch material; the 0.60-inch radius punch was used for forming the 0.120-inch material. The resulting cross-section bend radii, therefore, were 15t, 10t, 5, and 5t, respectively for the four gages of material.

The configuration and nominal dimensions of the curved channels are illustrated in Figure 38. The completed die and one of the punch blocks, ready for the installation of the heating elements, are illustrated in Figure 39. The punch and die clearances were nominal for the 0.060 and 0.120-inch materials; copper sheets of appropriate thickness, placed on the die with the beryllium blanks, compensated for the excess clearance that would have existed during the forming of the 0.020 and 0.030-inch specimens.

The blanks were preheated to 1350°F in an oven, located adjacent to the forming die, before being manually transferred to the preheated forming die. During the forming operations, the temperatures were recorded by means of thermocouples and a Honeywell 20-channel strip recorder. The forming of one of the 0.120-inch specimens is illustrated in Figure 40. A specimen blank and representative curved channels are illustrated in Figure 41.

The effects of excessive clearance or lack of die support are clearly visible in this figure. The 0.020-inch thick channel was formed with the proper 0.040-inch thickness of copper sheet material. The slight waviness of the edge of the outer flange was due to lack of support at the very edge; the flange extended slightly above the tangent of the die radius. The same condition is exhibited by the 0.060-inch thick channel specimen. As illustrated by the 0.120-inch thick specimen, this edge is removed during the final trimming operation. The effect of excessive punch -die clearance is illustrated by the 0.030-inch thick channel specimen. This particular channel was formed with an 0.018-inch thick spacer sheet rather than the required 0.030-inch thick sheet. The utilization of a spacer of the proper

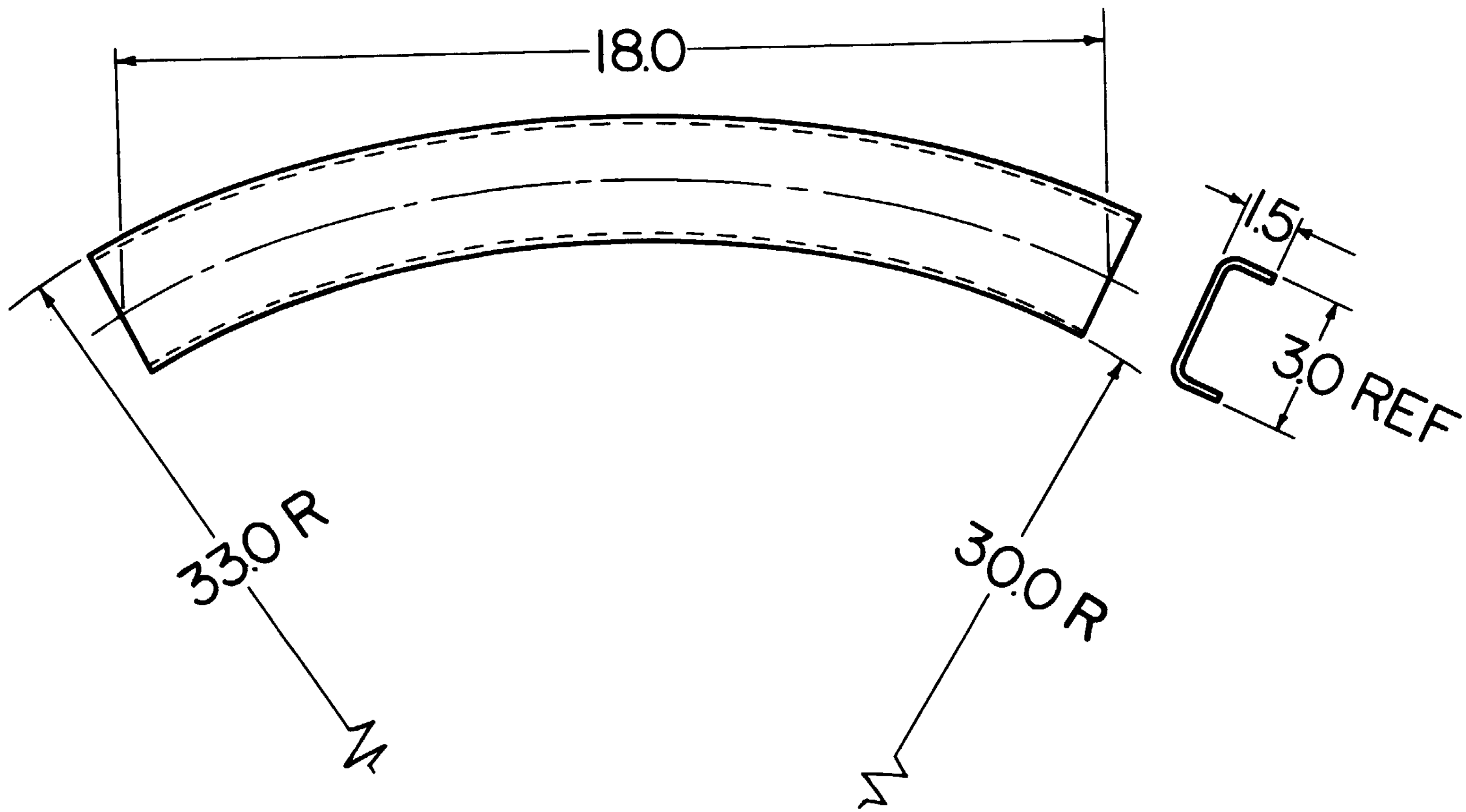


FIGURE 38. CURVED CHANNEL CONFIGURATION - NOMINAL DIMENSIONS.

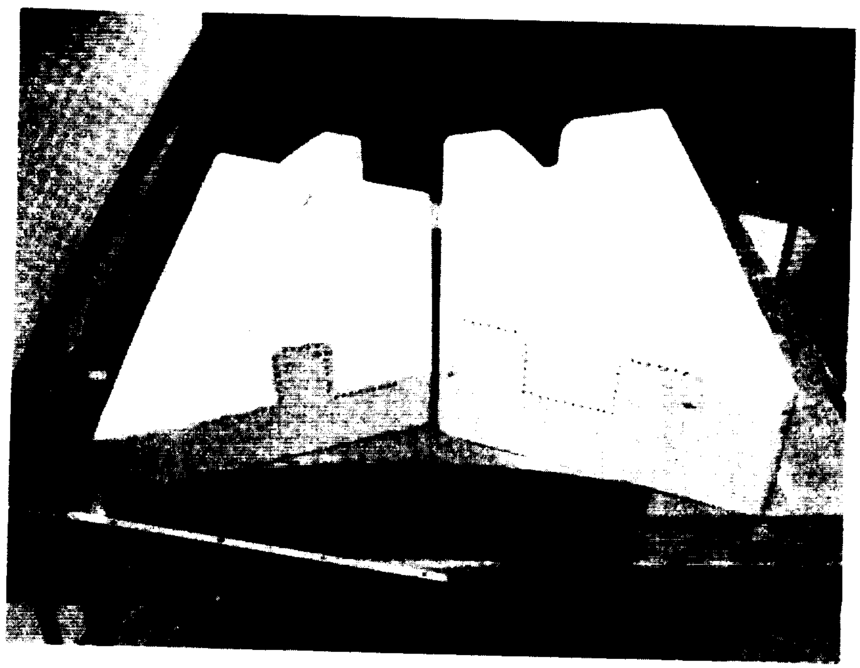


FIGURE 39. "GLASSROCK" CURVED CHANNEL FORMING DIE BLOCKS.

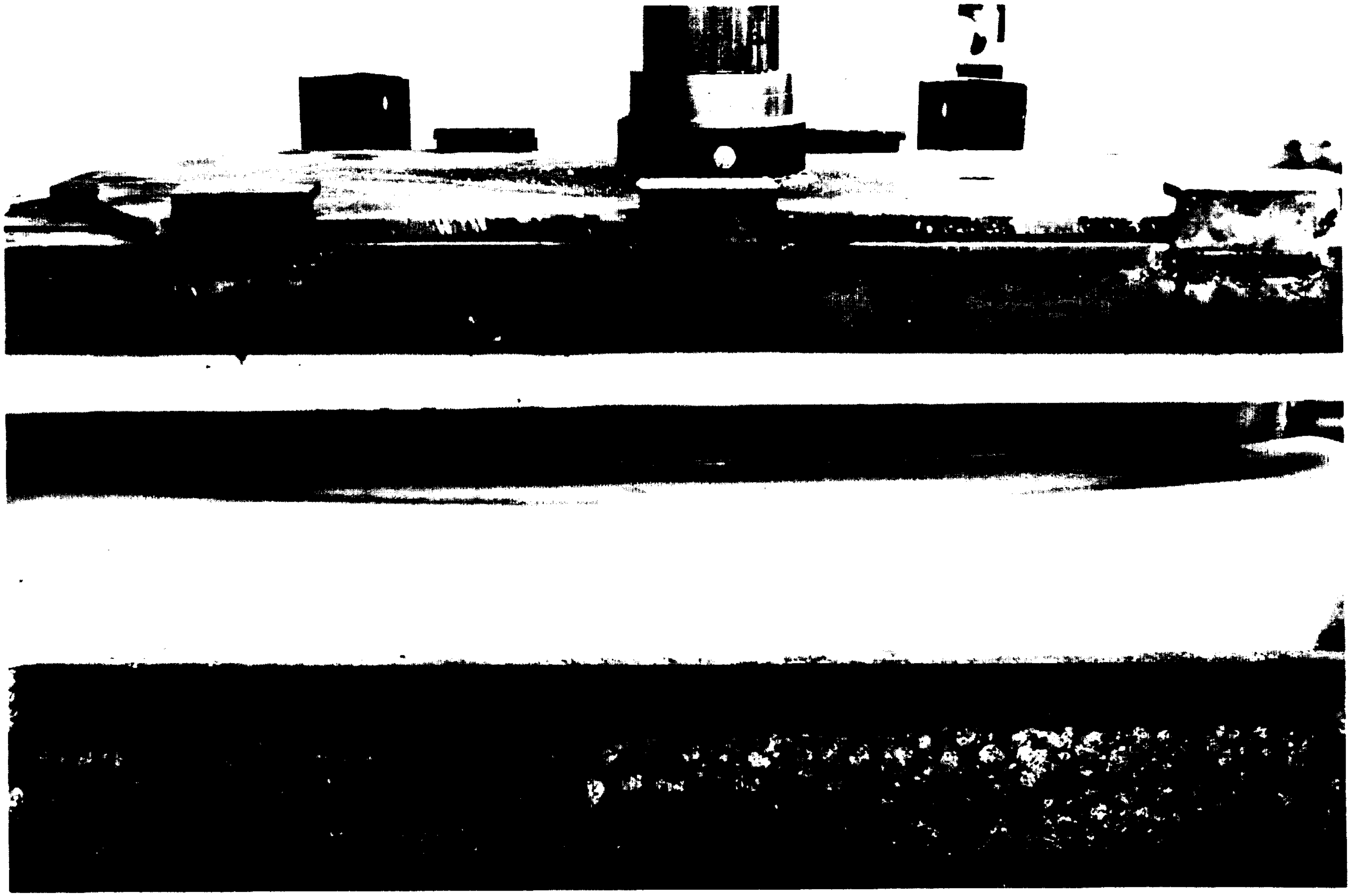


FIGURE 40. CURVED CHANNEL BEING FORMED - 0.120-INCH MATERIAL.

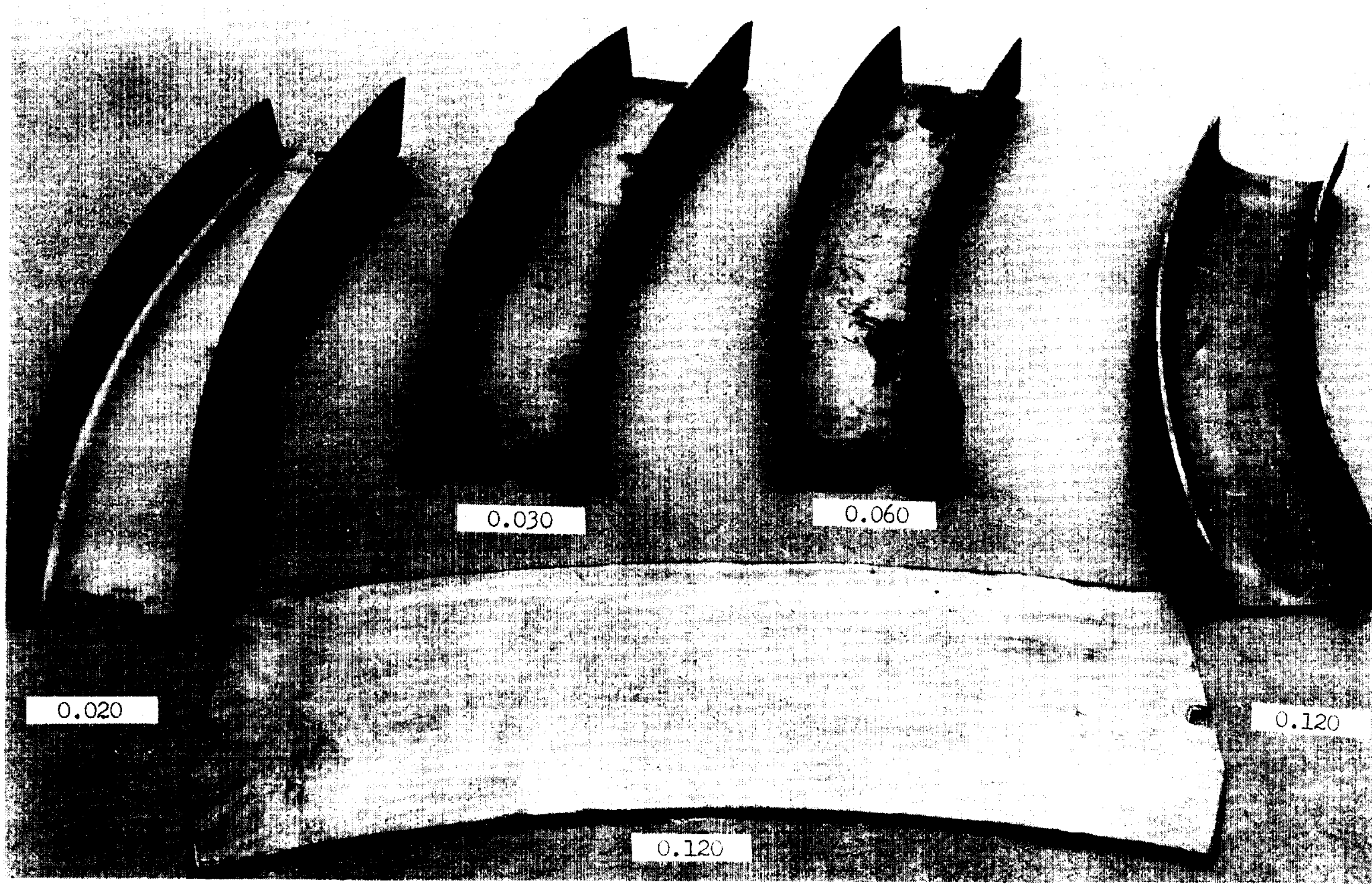


FIGURE 41. SPECIMEN BLANK AND REPRESENTATIVE CURVED CHANNELS.

thickness alleviates this problem.

It should be noted that the slight unevenness of the curved edges of the blank was due to the chemical process used in cutting them.

In order to determine the material flow pattern, a 1.00-inch grid was scribed lightly on one side of one of the 0.120-inch blanks prior to the forming operation. The displacement of the grid lines and the appreciable variation in the height of the flanges is clearly visible in Figure 42. It should be stated that a portion of this variation in flange height is believed due to the shearing of the punch locating pins during the forming operation; the beryllium blank was displaced slightly during the actual forming cycle. The shrinkage and elongation of the material decreased progressively from the maximum of 4 percent of the midpoint (midlength), to less than 1 percent at the ends.

The results of this portion of the forming development program indicate that the forming of curved channel segments on a production basis is entirely feasible, and that existing punch and die sets may be utilized if spacer sheet material is used to compensate for any excessive clearance that may exist. The maintenance of the nominal forming temperature of 1350°F throughout the forming operation is mandatory. A steady punch travel rate, not exceeding 1 inch per minute, is suggested.

Furthermore, the low shrinkage and elongation indicate that the forming of curved channels of smaller arc radii is entirely feasible. Since most of the required material flow is in the plane of the sheet material, where slippage along the basal planes is most readily accomplished, significant dimensional changes may be anticipated.

3. Deep Drawing. The drawing of beryllium can be accomplished on a limited basis under carefully controlled conditions. However, the extreme abrasiveness of the material at forming temperatures, the lack of a suitable lubricant, and the availability of other more suitable forming methods preclude its extensive use at the present time. Therefore, due to its limited application and the inherent manufacturing problems, no

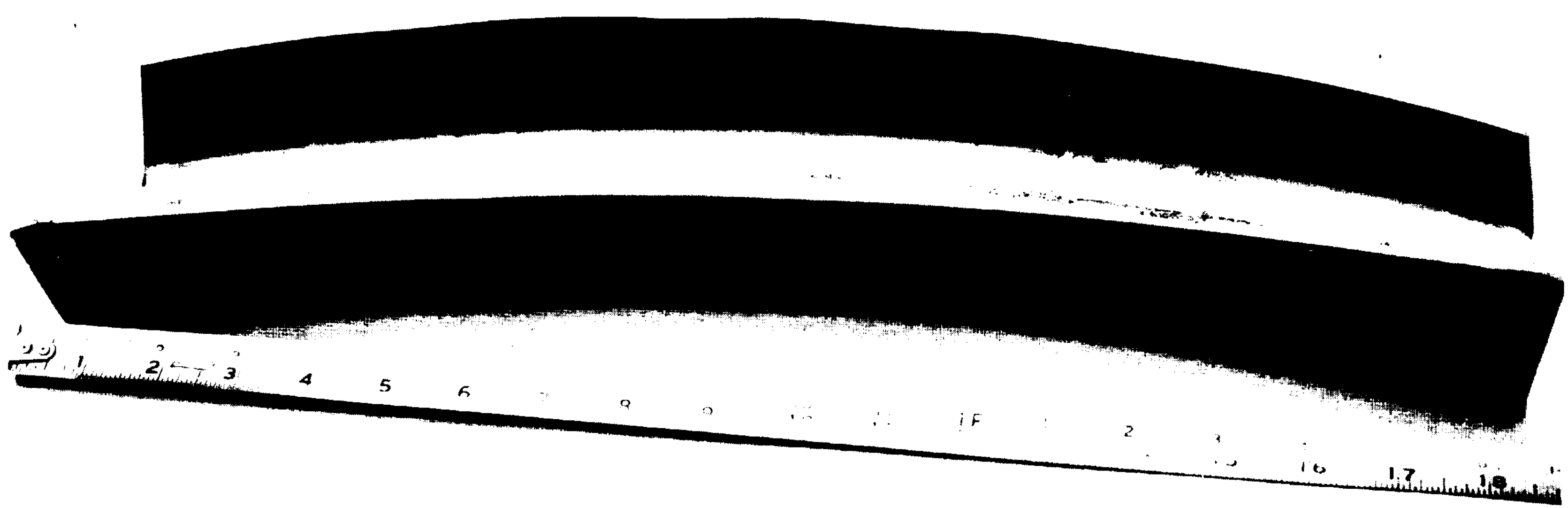


FIGURE 42. CURVED CHANNEL SPECIMEN - 1.00-INCH GRID - 0.120-INCH MATERIAL. NOTE THE DISPLACEMENT OF THE GRID LINES AND THE VARIATION IN FLANGE HEIGHT.

additional work was included in this development program. Only previous experience, as stated in the Program Plan, is reported.

During a very limited development program, conducted approximately 2 years ago, the feasibility of limited drawing of beryllium was demonstrated. During the initial forming operation, the oven heated (1300°F) 0.290-inch thick by 9.5-inch diameter vacuum hot pressed block blank was successfully "cupped" 1.36-inch deep at a rate of approximately 0.3-inch depth of draw per minute.

An improved die, incorporating integral heating units, was fabricated for use during the subsequent forming operations. Several specimens, cut from 0.064-inch thick cross-rolled sheet material were successfully formed. The 9.5-inch diameter blanks were heated in an oven to a temperature of 1300°F manually transferred to the die and drawn at rates of approximately 0.2 to 0.4 -inch per minute. The nominal final diameter and maximum depth attained were 6 inches and 2.87 inches respectively. It should be stated that this depth was accomplished in two stages; the maximum depth attained without failure, during a single stage was 1.3 inches. Unfortunately, severe galling occurred on the external surfaces of all of the specimens. The effects of various lubricating materials, were investigated. Although a slight improvement was observed, none of these materials was satisfactory, and as stated before, a suitable lubricant for beryllium has yet to be developed.

The results of this early development work indicate that beryllium can be moderately formed by drawing, i.e., hemispheres can be formed by this method. However, the inherent characteristics of the material at high temperatures, the lack of a suitable lubricant, the necessity for extremely close control of drawing pressures, and the subsequent development of the simpler more straightforward forming procedures reported herein appear to preclude further development of the drawing process as a beryllium method.

C. JOGGLING

Although the joggling of aluminum, steel, etc., angle has long since become a routine production forming process, the inherent characteristics of beryllium have inhibited the application of the process to this material. The joggling of the angle stock normally is a re-strike operation during which areas of the part are shaped by the displacement and repositioning of the material. The requirement for dimensional changes in the plane of the material has presented the greatest deterrent, and little or no development work has been accomplished.

The objectives of this portion of the development program, therefore, were the verification of the feasibility of the process, as applied to beryllium, and the establishment of preliminary forming parameters.

Due to the previous failure of the "Glassrock" dies and the availability of the hydraulic press brake and standard adjustable steel joggle dies, this portion of the program was accomplished on this standard production equipment. Since the nominal 1000°F limit of the standard conduction heated joggle dies was too low, high intensity quartz lamps with "Glassrock" reflectors were utilized to provide the necessary supplementary heating to raise the temperature of the dies to the required beryllium forming temperature of 1350°F. However, due to the heat loss by radiation, the heat sink effect of the steel die blocks, and the necessity for withdrawing the lamps several inches to provide clearance for the ram during actuation of the press, the maintenance of the desired temperature of 1350°F was extremely difficult. Even the momentary withdrawal of the lamps during the actuation cycle of the press frequently resulted in a specimen temperature drop of 50-100°F, at the actual instant of joggling. During the joggling operations, the temperatures were recorded by means of thermocouples and a Honeywell 20-channel strip recorder. The press platen, adjustable joggle die blocks, the quartz lamps and a pair of beryllium angle specimens ready for forming are illustrated in Figure 43.

In order to establish acceptable joggle depth to transition ratios, a transition length was arbitrarily selected for each material gage and the joggle depth was varied. A summary of the results of this investigation are presented in Table VIII.

The analysis of the information and data presented in the table verified the feasibility of joggling as a beryllium forming process. The fractures that occurred during the joggling operations were due either to incorrect material temperature

FIGURE 43. BERYLLIUM ANGLES IN PLACE IN JOGGLE DIE.SUPPLEMENTARY HEATING PROVIDED BY QUARTZ LAMPS. NOTE THE SCALE ON THE DIE BLOCKS

TABLE VIII

SUMMARY - JOGGLED ANGLES

MAT'L GAGE (in)	SPECIMEN NO. (1)	TRANSITION LENGTH(in)	JOGGLE DEPTH(in)	UPSTANDING LEG DEFLECT-ION(2) (in)	TEMP. (°F)	REMARKS
0.020	1	0.20	0.020	0.006-0.014	1220	No defect
0.020	1A	0.20	0.021	0.007-0.013	1220	No defect
0.020	2	0.20	0.031	0.010-0.025	1140	No defect
0.020	2A	0.20	0.036	0.011-0.030	1140	No defect
0.020	3	0.20	0.045	0.010-0.026	1160	Moderate fracture @ bend radius
0.020	3A	0.20	0.050	0.018-0.037	1160	No defect
0.020	4	0.20	0.062	0.016-0.034	1180	No defect
0.020	4A	0.20	0.071	0.024-0.037	1180	Moderate fracture @ bend radius
0.020	5	0.20	0.096	0.026-0.045	1240	No defect
0.020	5A	0.20	0.101	0.025-0.055	1240	Moderate fracture @ bend radius
0.030	6	0.30	0.050	0.000-0.001	1200	Severe fracture @ bend radius
0.030	6A	0.30	0.059	0.002-0.004	1200	Severe fracture @ bend radius
0.030	7	0.30	0.038	0.017-0.036	1240	No defect
0.030	7A	0.30	0.069	0.021-0.044	1240	No defect
0.030	8	0.30	0.054	0.000-0.000	1220	No defect

TABLE VIII (Con't.)

MAT'L GAGE (in)	SPECIMEN NO. (1)	TRANSITION LENGTH (in)	JOGGLE DEPTH(in)	UPSTANDING LEG DEFLECTION (2)(in)	TEMP. (°F)	REMARKS
0.030	8A	0.30	0.060	0.009-0.014	1220	No defect
0.030	9	0.30	0.059	0.002-0.005	1220	Severe fracture @ bend radius
0.030	9A	0.30	0.061	0.008-0.019	1220	Severe fracture @ bend radius
0.030	10	0.30	0.045	0.004-0.004	1210	Severe fracture @ bend radius
0.030	10A	0.30	0.055	0.003-0.009	1210	Severe fracture @ bend radius
0.030	11	0.30	0.052	0.010-0.020	1240	Minor fracture @ bend radius
0.030	11A	0.30	0.056	0.015-0.022	1240	Minor fracture @ bend radius
0.030	12	0.30	0.045	0.015-0.031	1245	Moderate fracture @ bend radius
0.030	12A	0.30	0.049	0.015-0.048	1245	Moderate fracture @ bend radius
0.030	13	0.30	0.049	0.015-0.031	1195	No defect (3)
0.030	13A	0.30	0.062	0.033-0.053	1195	Moderate fracture @ bend radius (4)
0.060	14	0.75	0.062	0.001-0.004	1320	Fractured from bend radius into leg
0.060	15	0.75	0.057	0.000-0.004	1300	No defect
0.060	16	0.75	0.085	0.011-0.021	1330	No defect
0.060	17	0.75	0.076	0.004-0.015	1340	No defect

NOTES: (1) JOGGLE IN PAIRS - BACK-TO-BACK, I. E., #1 and 1A
(2) RANGE -FROM TRANSITION TO END OF ANGLE
(3) UPSTANDING FLANGE TRIMMED TO 0.75-INCH
(4) UPSTANDING FLANGE TRIMMED TO 0.50-INCH

(substantially less than the optimum forming temperature of 1350° F), or to insufficient displacement of the leg of the angle during the joggling operation. In the majority of the cases, if the displacement was less than 25 percent of the depth of the joggle, failure occurred in the bend radius of the angle. This lack of leg displacement is believed due to the scale that formed on the die segments, which interferred with the free movement of the leg during the joggling operation, and resulted in the "pinching" of the bend radius. The effect of this insufficient movement of the leg of the angle and the resulting pinching of the bend radius angle are illustrated in Figure 44. The use of stainless steel matched die sets, instead of the standard adjustable die set used during this program, should alleviate this problem. Representative satisfactory joggled specimens are illustrated in Figure 45. The smooth transition and lack of bend radius "pinching" should be particularly noted.

In conclusion, the results of this phase of the program indicate that the joggling of beryllium angles on a production basis is entirely feasible, and that existing equipment can be utilized if nominal transition lengths and joggle depths of approximately 10-12t and 1-2t, repsectively are utilized. The maintenance of the nominal forming temperature of 1350°F throughout the forming operation is mandatory. In addition, the use of stainless steel matched die sets, rather than a standard adjustable die set, is highly recommended.

SECTION IV. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation clearly verified the feasibility of forming structural shapes of cross-rolled beryllium sheet material. Both "straight bend" and "compound curvature" forming can be successfully accomplished if the details of the processes are carefully observed.

The maintenance of the proper material temperature during the entire forming cycle is mandatory. Even relatively small variations that would be of little or no importance in the forming of "conventional" materials, may inhibit the successful forming of beryllium.

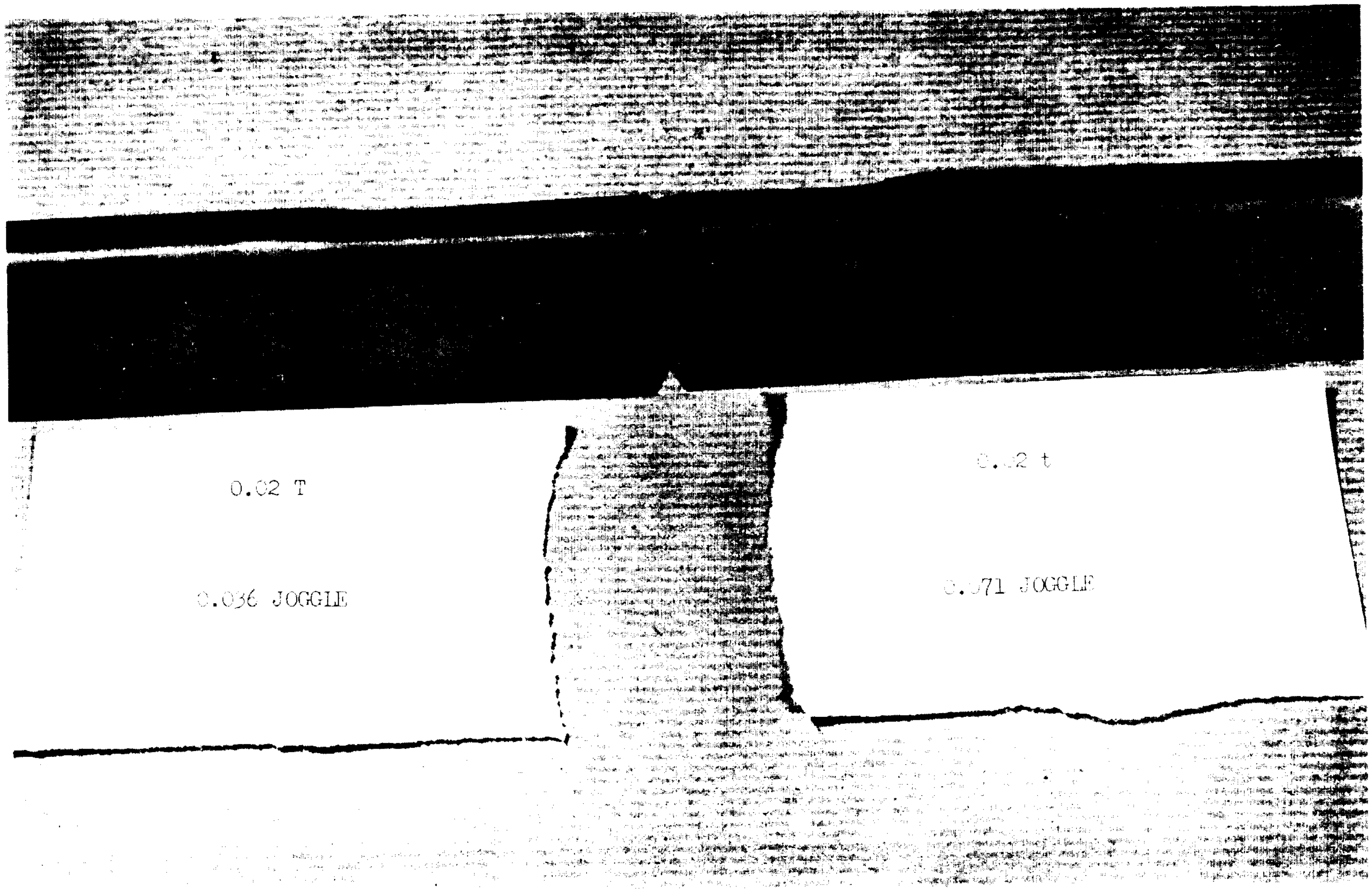


FIGURE 44. TYPICAL JOGGLE ANGLES WITH "PINCHED" ANGLE BEND RADIUS.

0.02 t 0.071 JOGGLE

0.02 t 0.036 JOGGLE

0.03 t 0.060 JOGGLE

0.03 t 0.038 JOGGLE

FIGURE 45. REPRESENTATIVE SATISFACTORY JOGGLED ANGLES.
NOTE THE SMOOTH TRANSITION AND LACK OF BEND RADIUS "PINCHING".

The results of these limited investigations indicate the following conclusions and recommendations:

a. The optimum forming temperature appears to be 1350 ± 25°F.

b. The minimum radius bend for all gages of beryllium sheet material up to 0.120-inch in thickness is 5t.

c. Although very thin gages of beryllium up to approximately 0.030-inch in thickness can be formed to a 4t radius, this radius is not recommended.

d. The use of the conventional "punch and die" type of equipment for the forming of channel sections is acceptable if the temperature is carefully controlled throughout the length of the die, and if appropriate means, such as stainless steel buffer plates, are utilized to prevent the galling of the surface of the beryllium.

e. In order to avoid high stress levels, the double-action type of "punch and die" equipment is recommended for the forming of hat sections.

f. It is believed that the use of appropriately designed "folding type" equipment will be the most economical means for the production forming of straight bend sections including angles, channels, zee and hat sections. The maintenance of even temperature throughout the workpiece during the entire forming cycle is mandatory.

g. Additional "straight bend" forming work is recommended. Although the forming of representative sections by various methods has been demonstrated, the establishment of firm minimum bend radii for all gages of material, and the determination and refinement of the most appropriate method for the production of each specific cross-section, are required.

h. Due to the necessity for heated rolls with precise temperature control, the difficulty of maintaining the proper forming temperature throughout the workpiece, the high cost of the "scrap ends" and of the steel sandwich material, and the subsequent stress-relieving operation in specialized equipment, rolling is not recommended as a forming procedure.

i. The use of a heated die press is recommended for the forming of parts having a large radius.

j. The maximum permissable R/t ratio and shrinkage appear to be 100 and 6 percent respectively for the forming of compound curves, involving multi-directional material flow and unrestrained edges.

k. The forming of hemispherical sections on a production basis is entirely feasible with properly designed "punch and die" type of equipment. Exact temperature control and precise clearance tolerances must be incorporated in the equipment.

l. The forming of curved channel sections on a production basis is entirely feasible with existing "punch and die" sets if the correct thickness of spacer sheet material is used to compensate for any excessive clearance that may exist. The maintenance of the proper temperature throughout the workpiece during the forming cycle is mandatory. A steady punch travel rate, not exceeding 1 inch per minute, is recommended.

APPROVAL NASA TM X- 53453

THE FABRICATION OF BERYLLIUM ALLOYS - VOLUME II.

FORMING TECHNIQUES FOR BERYLLIUM ALLOYS

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission Programs has been made by the MSFC Security Classification Officer.

This report, in its entirety, has been determined to be unclassified.

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m. Additional compound curvature forming work is recommended. Although the feasibility of forming various compound curves has been demonstrated, the establishment of firm R/t ratios and shrink and stretch values, for all gages of material and a representative series of diameters or sizes, have not yet been accomplished.

n. Deep drawing is not recommended for the forming of beryllium.

o. The feasibility of joggling beryllium angles has been demonstrated. The use of stainless steel matched die sets is highly recommended to avoid the "pinching" of the bend radius. Heating equipment, with precise temperature control, must be an integral part of the die set.

p. The use of similar stainless steel matched die sets should permit the joggling of channel sections.

q. Additional joggling development work is recommended. Although the feasibility of joggling angles has been demonstrated and the feasibility of joggling channel sections is indicated, further investigation and development of the processes are required. The determination of firm transition lengths for all gages of material and representative sizes of sections, the development of exact controls, the establishment of routine production procedures, and the design of suitable stainless steel matched die sets have not yet been accomplished.