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INGOT BERYLLIUM—MICROSTRUCTURAL AND MECHANICAL
PROPERTY CHANGES DURING CAN-ROLLING

Clinton R. Heiple

L. Frank Dolechek

DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

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Clinton R. Heiple

Research and Ecology
PHYSICAL METALLURGY GROUP

L. Frank Dolechek

GENERAL FABRICATION GROUP

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DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

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INGOT BERYLLIUM—MICROSTRUCTURAL AND MECHANICAL PROPERTY CHANGES DURING CAN-ROLLING

Clinton R. Heiple and L. Frank Dolechek

Abstract. Microstructural and mechanical property observations of ingot-source beryllium at selected points in the can-rolling process are reported. Recrystallization occurs concurrently with rolling at temperatures above 1800 °F (982 °C), and only partial recrystallization is observed during reheats at 1400 °F (760 °C). Most grain refinement induced by the present rolling schedule occurs in the first 15 rolling passes. These represent 88 percent reduction from the ingot. A relatively small contribution comes from the final six passes which bring the total reduction from the ingot to 95 percent. Information was also obtained on the effects of the rolling schedule on the properties of the stainless steel can.

INTRODUCTION

Development of processes to produce beryllium sheet from cast ingots has been under way for several years. The present procedure involves casting ingots, welding a 0.625-inch thick Type-304 stainless steel can around the ingot, and rolling the composite. The process and its development have been described in detail in related reports.^{1,2} The current investigation of the microstructure and mechanical properties of the beryllium at selected points in the can-rolling process was undertaken so future problems associated with rolling might be more easily solved and so the effects of modifications in the rolling schedule might be anticipated. The mechanical properties of the stainless can were

also measured at various points in the rolling schedule to determine if the reheats affected the properties of the can.

DISCUSSION

Procedures:

The rolling schedule in use for the can rolling of beryllium at Rocky Flats Plant is given in Table I, and the sampling points are indicated by arrows in the table. Passes 4, 13, 15, and 17 are, respectively, the last rolling passes at nominal rolling temperatures of 1900 (1038), 1800 (982), 1600 (871), and 1500 °F (816 °C). Canned billets were removed from the rolling stream at the indicated points and air-cooled. In addition, part of the sample removed after Pass 4 was annealed at 1800 °F (982 °C) for one hour (to simulate the condition present prior to Pass 5) and re-examined. The mechanical properties of the stainless cans were also measured.

Results:

The microstructures of the beryllium at the selected points in the rolling process are shown in Figures 1 through 8,³ and the corresponding mechanical properties of the beryllium are given in Table II. All the micrographs were taken using polarized light, and the designations longitudinal (L) and transverse (T) refer to tensile axes or polishing sections parallel or perpendicular, respectively, to the last rolling direction. It is apparent from Figures 1, 2,

¹J. L. Frankeny and D. R. Floyd. "Ingot-Sheet Beryllium Fabrication." RFP-910. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. February 9, 1968.

²Dennis R. Floyd, William W. Leslie, and Leon F. Dolechek. *Can Rolling of Beryllium Ingots*. RFP-2041. Rocky Flats Division, Dow Chemical U.S.A., Golden, Colorado. October 15, 1973.

³Figures are included at end of text.

TABLE I. Production Can-Rolling Schedule for Beryllium Ingots.

Pass No. or Thermal Treatment	Nominal Thickness of Canned Billet after Pass	Percent Reduction (this Pass)	Cumulative Percent Reduction at this Nominal Rolling Temperature	Cumulative Percent Reduction from Original Thickness
Heat at 1900 °F (8 to 10 hours)	4.750	—	—	—
1	4.450	6.3	6.3	6.3
2	4.150	6.7	12.6	12.6
3	3.850	7.2	18.9	18.9
4	3.550	7.8	25.3	25.3
→ Anneal 1800 °F (45 to 60 minutes)				
5	3.250	8.5	8.5	31.6
6	2.950	9.2	16.9	37.9
7	2.650	10.2	25.4	44.2
8	2.350	11.3	33.8	50.5
→ Anneal 1800 °F (30 to 45 minutes)				
9	2.050	12.8	42.3	56.8
10	1.800	12.2	49.3	62.1
11	1.550	13.9	56.3	67.4
→ Anneal 1800 °F (30 to 45 minutes)				
12	1.300	16.1	63.4	72.6
13	1.100	15.4	69.0	76.8
→ Anneal 1600 °F (25 to 40 minutes)				
14	0.900	18.2	18.2	81.1
15	0.750	16.7	31.8	84.2
→ Anneal 1500 °F (25 to 40 minutes)				
16	0.650	13.3	13.3	—
→ Anneal 1500 °F (25 to 40 minutes)				
17	0.550	15.4	26.7	88.4
→ Anneal 1400 °F (20 to 35 minutes)				
18	0.450	18.2	18.2	90.5
→ Anneal 1400 °F (25 to 40 minutes)				
19	0.360	20.0	34.5	92.4
→ Anneal 1400 °F (25 to 40 minutes)				
20	0.280	22.2	49.1	94.1
→ Anneal 1400 °F (25 to 40 minutes)				
21	0.240	14.3	56.4	94.9
→ Anneal 1400 °F (~16 hours)				

TABLE II. Mechanical Properties of Ingot-Source Beryllium at Selected Points in the Production Can-Rolling Process.

Condition ¹	Direction	Percent Reduction (this Pass)	Percent Total Reduction from Ingot	^c Yield (ksi) (0.2 percent)	Ultimate (ksi)	Elongation Percent
After Pass 13	^a L	15	77	24.8	28.0	0.8
	^b T	15	77	26.4	28.5	0.6
1600 °F (45 minutes)	L	—	—	24.4	27.7	0.75
	T	—	—	25.0	26.4	0.5
After Pass 15	L	17	84	33.5	35.0	0.4
	T	17	84	33.3	33.3	0.2
1500 °F (65 minutes)	L	—	—	24.1	30.8	1.5
	T	—	—	24.4	30.5	1.5
After Pass 17	L	15	88	35.3	35.8	0.3
	T	15	88	34.4	36.5	0.5
1400 °F (30 minutes)	L	—	—	31.7	36.6	1.3
	T	—	—	31.4	33.7	0.7
After Pass 21	L	14	95	42.	45.	0.2
	T	14	95	36.	39.	0.1
1400 °F (16 hours)	L	—	—	28.	36.	1.5
	T	—	—	27.	30.	1.1

^aL — longitudinal.^bT — transverse.^cA ksi is 1000 pounds per square inch or in SI (metric) units: 1 ksi = 7 megapascals.

and 3(a) and (b) that recrystallization occurs concurrently with rolling at nominal rolling temperatures above 1800 °F (982 °C). No evidence was noted of cold work in the microstructures of beryllium after Pass 4 or Pass 13, such as bend planes or flattened grains. The anneal following Pass 13 produces essentially no change in mechanical properties. This also indicates that the material is in the fully annealed condition prior to the reheat. The as-cast columnar microstructure has mostly disappeared by the end of the fourth pass because of recrystallization. A comparison of Figures 3(a) and (b) and 4(a) and (b) shows that substantial grain growth occurs during reheats at 1600 °F (871 °C).

The partial recrystallization occurring during rolling at 1600 °F (871 °C) can be seen in Figures 5(a) and (b). A 65-minute anneal at 1500 °F (816 °C)

produces complete recrystallization, but does not coarsen the structure [Figures 6(a) and (b)]. The yield strength of the recrystallized beryllium after the 1500 °F (816 °C) anneal preceding Pass 16 is essentially the same as that of beryllium in the recrystallized state earlier in the rolling schedule, however the ultimate strength and elongation are greater, reflecting the reduced grain size.

A limited amount of recrystallization also occurs during rolling at 1500 °F (816 °C) [Figures 7(a) and (b)]. Uniform recrystallization does not occur during reheats at 1400 °F (760 °C) [Figures 8(a) and (b)]. Even a 16-hour anneal at 1400 °F (760 °C) following Pass 17 produces a duplex, irregular structure with some evidence of cold work and with a larger average grain size than material following Pass 15 [Figures 9(a) and (b)].

TABLE III. Mechanical Properties of Type-304 Stainless Steel Cover Plates at Selected Points in the Beryllium Can-Rolling Process.

Condition	Percent Reduction (this Pass)	Percent Total Reduction from Ingot	*Yield (ksi) (0.2 percent)	Ultimate (ksi)	Elongation Percent
As-received	—	—	45.0	85.0	60.0
After Pass 4	25	25	48.8	92.0	74.0
1800 °F (60 minutes)	—	—	31.1	91.4	78.0
After Pass 13	15	77	66.5	101.7	54.5
1600 °F (45 minutes)	—	—	38.9	95.1	65.0
After Pass 15	17	84	73.7	103.7	42.5
1500 °F (65 minutes)	—	—	35.7	93.3	55.5
After Pass 17	15	88	74.6	99.7	31.0
1400 °F (30 minutes)	—	—	68.5	102.7	34.0

*A ksi is 1000 pounds per square inch or in
SI (metric) units: 1 ksi = 7 megapascals.

Presumably, not enough strain energy remains in the material following Pass 17 to produce uniform recrystallization at 1400 °F (760 °C). The incomplete annealing produced by the reheat following Pass 17 is reflected by the high yield strength and fairly low elongation of the beryllium at this stage in rolling.

By the end of the last rolling pass, enough work appears to have accumulated in the structure so that reasonably uniform recrystallization occurs during anneals at 1400 °F (760 °C). The structure following the standard 16-hour anneal after Pass 21 is shown in Figures 10(a) and (b).

The mechanical properties of the stainless-steel cover plates at the selected points in the rolling schedule are given in Table III. The steel is apparently received in a partially worked condition, since its yield is reduced and elongation increased by the 1800 °F (982 °C) anneal following Pass 4.

Reheats at lower temperatures do not restore the as-annealed properties, but they significantly lower the yield strength, raise the ductility, and thus contribute to maintaining the integrity of the can [only a small effect is seen at 1400 °F (760 °C) in 30 minutes].

Both the structure and mechanical properties of the beryllium immediately before Pass 16 indicate that the sheet is suitable for bare rolling at this point in the rolling schedule. Unfortunately, sheet decanned at this point had severe surface cracks, which extended about one third the way through the sheet thickness, and which made bare rolling impossible. These cracks heal during subsequent can-rolling stages in the production schedule. However, the relatively small decrease in grain size that occurs during Passes 17 through 21 in sheet suggests that improved rolling parameters (such as temperature and reduction per pass) may be possible in this part of the rolling schedule.

ILLUSTRATIONS

Figures 1 through 10

FIGURE 1. After Pass 4, 25 Percent Reduction from Ingot, Last Pass at 1900 °F. (Photograph from a montage.) Magnification 50X.

FIGURE 2. Before Pass 5, 25 Percent Reduction from Ingot, Last Pass at 1900 °F. Annealed at 1800 °F for One Hour. (Photograph from a montage.) Magnification 50X.

FIGURES 3(a) and (b). After Pass 13, 77 Percent Reduction from Ingot, Last Pass at 1800 °F. Grain Size, Longitudinal (a), 150 Micrometers; Transverse (b), 164 Micrometers. Magnification 50X.

FIGURES 4(a) and (b). Before Pass 14, 77 Percent Reduction from Ingot, Last Pass at 1800 °F, Annealed 45 Minutes at 1600 °F. Grain Size, Longitudinal (a), 267 Micrometers; Transverse (b), 254 Micrometers. Magnification 50X.

FIGURES 5(a) and (b). After Pass 15, 84 Percent Reduction from Ingot, Last Pass at 1600 °F, Longitudinal (a) and Transverse (b). Magnification 50X.

FIGURES 6(a) and (b). Before Pass 16, 84 Percent Reduction from Ingot, Last Pass at 1600 °F, Annealed 1500 °F for 65 Minutes. Grain Size, Longitudinal (a), 89 Micrometers; Transverse (b), 96 Micrometers. Magnification 50X.

FIGURES 7(a) and (b). After Pass 17, 88 Percent Reduction from Ingot, Last Pass at 1500 °F, Longitudinal (a) and Transverse (b). Magnification 50X.

FIGURES 8(a) and (b). Before Pass 18, 88 Percent Reduction from Ingot, Last Pass at 1500 °F, Annealed 30 Minutes at 1400 °F, Longitudinal (a) and Transverse (b). Magnification 50X.

FIGURES 9(a) and (b). Before Pass 18, 88 Percent Reduction from Ingot, Last Pass at 1500 °F, Annealed 16.75 Hours at 1400 °F, Grain Size, about 134 Micrometers, Longitudinal (a), and about 110 Micrometers, Transverse (b). Magnification 50X.

FIGURES 10(a) and (b). After Pass 21, 95 Percent Reduction from Ingot, Last Pass at 1400 °F, Annealed 16 Hours at 1400 °F. Grain Size, about 61 Micrometers, Longitudinal (a) and 60 Micrometers, Transverse (b). Magnification 50X.