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THE ROLLING OF URANIUM

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ABSTRACT

Uranium rods and strips were rolled under various rolling conditions and the roll-separating force measured. The roll load increased with decreasing rolling temperature so that at 300 C, the loads were three to five times as great as at 600 C. The rolling speed between 61 and 122 feet per minute had little effect on the roll load, and the effect of the initial structure of the metal was also small. A temperature rise of 6 to 12 C per pass occurred in the work on rolling at 600 C and a 35 to 44 C rise occurred at 300 C. Rods rolled at 400 C and lower had cracks and other rolling defects.

Mild steel rolled at 1030 C (1900 F) produced nearly the same roll load as uranium at 600 C, and the spread of uranium and steel strip also was nearly the same.

The specific resistance to deformation or yield strength of uranium during rolling was calculated by the method of Orowan and varied from 26,000 psi at 600 C to 81,000 psi at 300 C.

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INTRODUCTION

Uranium has been fabricated by rolling since early in the history of the Manhattan Project, and a large amount of practical information on rolling has been accumulated. However, when new rolling facilities were being designed specifically for uranium, it was found that there were few numerical data on the roll-separating forces to be expected under various rolling conditions.

An investigation was therefore started to obtain specific data on these forces. Round bars as well as flat strips were rolled at temperatures between 250 and 800 C. The effect of the initial structure of the metal, rate and amount of reduction, and method of heating on the roll load was determined. A low-carbon steel was rolled to provide a standard for comparison with the uranium.

In addition to the data on roll-separating forces, information was also obtained on the temperature rise in uranium resulting from the work introduced in the rolls, and data were obtained on the oxidation losses during rolling at various temperatures.

EXPERIMENTAL WORK

Equipment and Materials

The rolling was done in an 8 x 12-inch two-high mill. Open passes designed for rolling steel were used to roll the rods. Figure 1 shows the shape and size of the eleven passes used to reduce a 1.55-inch-diameter casting to a 1/2-inch-diameter rod. The percentage reduction per pass and other data on these rolls are shown in Table 1. The flat strips were rolled on flat, chilled-iron rolls.

The uranium was bar stock which was melted in an induction furnace in a graphite crucible and cast into 1-5/8-inch-diameter x 8-inch-long bars. These castings were scalped to 1.55 inch in diameter to remove the rough surface and to obtain a standard starting size.

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FIGURE I. DESIGN OF ROLLS

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TABLE 1. DATA ON GROOVED ROLLS

Groove Number	Roll Number	Shape of Groove	Area of Bar, sq in.	Reduction Per Pass		Total Reduction, per cent	Projected Area of Contact, ⁽²⁾ sq in.
				Sq In.	Per Cent		
1	2	Diamond	1.50	0.39 ⁽¹⁾	21 ⁽¹⁾	21 ⁽¹⁾	1.26
2	2	"	1.25	0.25	17	34	1.20
3	2	"	1.12	0.13	10	41	0.73
4	2	Oval	0.90	0.22	20	52	1.21
5	2	1" Round	0.78	0.12	13	59	0.70
6	2	Oval	0.69	0.09	12	64	0.72
7	2	7/8" Round	0.60	0.09	13	68	0.52
Roll Change		-	-				
3	1	Oval	0.40	0.20	33	79	1.04
4	1	Diamond	0.32	0.08	20	83	0.90
5	1	Oval	0.24	0.08	25	87	0.62
6	1	1/2" Round	0.20	0.04	17	90	0.28

(1) Based on a starting size of 1.55-inch diameter.

(2) Contact Area between rolls and work projected in a horizontal plane.

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Gamma-extruded uranium was also rolled to determine the effect of initial structure on the roll load. The analysis of this metal also is shown in Table 2. The extruded bars were 1-3/8 inch diameter and were rolled as extruded.

The metal used for the flat-strip rolling tests was forged at 600 C directly from the bar stock. The forged strips were heat treated and finally machined to the required dimensions. Most of the strips were annealed one hour at 600 C and furnace cooled, but samples also were quenched after five minutes at 700 C in a lead pot, and others were annealed one hour at 800 C and furnace cooled. Several cast strips were also rolled.

The roll-separating force was measured by means of strain gages attached to the screw-down blocks of the mill. These steel blocks were 4 inches in diameter and 4 inches long and fit between the end of the screw-down and the upper bearings. A smaller steel block was placed on top of the pressure block to engage the screw and distribute the load. Figure 2 shows the blocks with attached strain gages and Figure 3 shows the blocks in place in the mill.

The strain gages were connected into an alternating-current Wheatstone bridge. A Type 1A David Taylor Model Basin strain analyzer was first used in conjunction with a Miller oscillograph to record the roll loads. A Brush strain analyzer and oscillograph were later used because this direct-inking oscillograph eliminated the inconvenience of developing the photographic film required by the Miller instrument. Figure 4 shows this circuit schematically.

The system was calibrated by applying known loads to the pressure blocks in a hydraulic press. The response to an applied load was practically instantaneous, and the results during calibration were reproducible.

Rolling Results on Round Bars

The 1.55-inch-diameter billets were heated in an electric muffle furnace in an argon atmosphere for one hour prior to rolling and were reheated ten minutes in the same muffle after each pass. The bars were rolled to 1/2-inch-diameter rod in eleven passes at temperatures of 250, 300, 400, 500, and 600 C. The bars were quenched after the seventh pass, because a roll change was necessary at this size. After the roll change, the bars were reheated for 1/2 hour before rolling was resumed. The finished rods were quenched after the last pass.

Table 3 shows the roll-separating force observed in each pass under the various rolling conditions. Duplicate samples were rolled in each

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FIGURE 2. SCREW-DOWN BLOCKS WITH ATTACHED STRAIN GAGES FOR MEASURING ROLL LOADS

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FIGURE 3. ROLLING MILL WITH LOAD-MEASURING EQUIPMENT IN PLACE

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FIGURE 4. SCHEMATIC ARRANGEMENT OF CIRCUIT FOR MEASURING ROLL-SEPARATING FORCE

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TABLE 3. THE EFFECT OF TEMPERATURE AND OTHER ROLLING VARIABLES
ON THE ROLL-SEPARATING FORCE WITH ROUND BARS

Bar No.	Mate- rial	Starting Structure	Initial Diam- eter, in.	Rolling Temp, C	Heating Method	Roll Speed, rpm	Roll-Separating Force, 1000 pounds										
							Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Pass 6	Pass 7	Pass 8	Pass 9	Pass 10	Pass 11
44	U	Cast	1.55	250	Muffle	40	147	--	--	120	--	82	61	109	83	67	51
50	"	"	"	"	"	"	151	--	--	--	--	84	57	112	82	67	49
49	"	"	"	300	"	"	139	114	96	130	68	83	59	109	70	63	50
51	"	"	"	"	"	"	147	117	--	132	69	82	64	114	75	79	52
47	"	"	"	400	"	"	91	69	51	72	36	--	34	76	52	42	29
48	"	"	"	"	"	"	92	70	49	69	37	46	--	79	54	42	42
45	"	"	"	500	"	"	80	69	44	53	27	31	19	49	31	25	21
46	"	"	"	"	"	"	82	55	42	55	29	34	17	54	36	--	20
37	"	"	"	600	"	"	46	28	22	--	--	19	12	30	26	--	--
40	"	"	"	"	"	"	48	29	20	--	16	18	10	32	23	23	10
41	"	"	"	"	"	"	45	28	18	33	20	19	12	31	25	18	13
1	U	Gamma extruded	1.375	250	"	"	--	--	--	--	--	90	62	--	90	73	61
2	"	"	"	"	"	"	120	--	--	--	75	81	67	114	93	85	--
3	"	"	"	300	"	31	79	101	92	--	66	79	57	111	70	65	46
4	"	"	"	"	"	"	77	102	93	120	67	76	51	115	78	72	43
1	"	"	"	"	"	40	76	98	84	110	65	80	56	106	69	--	39
2	"	"	"	"	"	"	76	100	83	110	64	80	53	115	70	--	47
3	"	"	"	600	"	31	28	39	24	31	15	19	14	31	24	20	9
4	"	"	"	"	"	"	28	37	22	28	16	18	13	32	27	18	9
1	"	"	"	"	"	60	--	33	20	30	15	20	13	32	26	22	11
2	"	"	"	"	"	"	27	37	23	31	16	19	--	32	26	22	12
1	"	"	"	300	Pb bath	40	74	88	80	120	71	86	63	101	77	65	55
2	"	"	"	"	"	"	71	96	81	117	69	85	63	108	75	67	60
1	"	"	"	600	"	"	31	31	26	26	22	15	10	37	27	22	12
2	"	"	"	"	"	"	--	30	26	23	21	16	--	34	27	22	16
1	Steel	Cold rolled	1.500	1038	Muffle	"	34	31	24	34	14	19	11	42	29	25	27
2	"	"	"	"	"	"	42	39	20	34	14	18	9	42	30	25	16
3	"	"	"	"	"	"	44	31	22	36	16	--	11	41	30	25	12
4	"	"	"	"	"	"	42	36	24	35	17	18	--	42	32	26	15

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case, and, in general, the results on both samples agreed fairly well. In the last pass, some difficulty was experienced in entering the bars through the guides into the rolls. This delay and the resulting decrease in temperature of the bar caused considerable spread in the loads observed in this groove. The variable tendency of the bars to turn in the guides was also a probable cause of some spread in the results on duplicate samples.

Figure 5 shows the effect of rolling temperature on the loads observed in the first five grooves. The roll load increased with decreasing rolling temperature. The increase in load was roughly proportional to the decrease in temperature between 600 and 400 C. A marked increase in roll load occurred between 400 and 300 C, but decreasing the temperature further to 250 C caused no additional increase in the roll load. However, the loads at 250 and 300 C approached the limiting strength of the rolls, and the collar of the eleventh pass was damaged during the 300 C rolling.

The roll load in each groove was roughly proportional to the projected contact area between the rolls and the work, and there were no consistent indications that the shape of the pass had a significant effect on the roll load.

The effect of rolling speed was not significant at roll speeds between 31 and 60 rpm (62 to 120 feet per minute). At 300 C, there was considerable spread in the results in the various passes but there was no consistent trend toward either higher or lower loads with increased rolling speed. At 600 C, the roll loads at the high and low speeds were the same within the limits of experimental error.

The method of heating also appeared to have little effect on the roll load. Samples heated in a lead-tin alloy bath produced nearly the same roll loads as samples heated in an argon atmosphere. At 600 C, the lead-tin alloy wet the uranium in spots and the alloy was carried into the rolls. This affected the coefficient of friction between the rolls and work and resulted in considerable variation in the roll load. At 300 C, the uranium was not wet by the alloy.

The gamma-extruded bars were smaller in diameter than the cast bars, and the resulting loads in the initial passes were lower. After the first three passes, however, the roll loads on both types of material were the same.

The quality of the bars rolled at 400 C and below was poor. The bars rolled at 250 and 300 C cracked at the corners of the diamond during the first three passes and these cracks became progressively worse as the amount of reduction increased. The 1/2-inch-diameter rods were severely cracked, and several split longitudinally as the bar left the rolls.

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FIGURE 5. EFFECT OF ROLLING TEMPERATURE ON THE ROLL-SEPARATING FORCE IN THE FIRST FIVE PASSES ON URANIUM ROD

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Only slight cracking was apparent after 90 per cent reduction at 400 C and bars rolled at 500 and 600 C were sound.

Weight Loss on Round Bars

A marked change in the character of the oxide occurred between 400 and 500 C on bars heated in the argon atmosphere. At 500 C, a loose fluffy oxide was formed; but at 400 C, the oxide was dense and adherent. Efforts to measure the weight loss during rolling at the various temperatures, however, were unsuccessful. At 400 C and below, the rolls frequently ground off the corners of the bar before a bite was obtained. This resulted in considerable metal loss and made the weight-loss data of little value as a measure of the oxidation loss.

Structure of Rolled Bars

Metallographic examination of the rolled bars which had been quenched immediately after the final pass showed that recrystallization had occurred in the bars rolled at 500 and 600 C. Some of the bars rolled at 400 C were partially recrystallized and others were severely cold worked. All of the 250 C and 300 C bars were severely cold worked.

Temperature Rise in Round Bars

The bars which were rolled at 600 C from an argon atmosphere appeared to be considerably hotter than the furnace when replaced in the furnace after each pass. This temperature rise was believed to be the result of either the work of rolling or the surface oxidation of the uranium. In order to measure the temperature rise during rolling, a 1.55-inch-diameter cast bar was rolled with a thermocouple fixed in the center of the bar. The glass insulated Chromel-Alumel thermocouple was inserted in an axial hole drilled to the center of the bar. The thermocouple bead was held in place by a copper plug upset on the bead through a radial hole. The thermocouple was connected to a recording potentiometer and the bar rolled through each of the various passes.

The temperature rise in each pass is shown in Table 4. At 600 C, the temperature rise in each of the first five passes varied from 6 to 12 degrees centigrade. The bar began to cool as soon as it was removed from the furnace and continued to cool after the momentary temperature rise during the passage through the rolls. It was observed, however, that when the bar was replaced in the muffle at 600 C, the temperature continued to rise as long as the door of the muffle remained on. A one-inch-diameter rod

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TABLE 4. TEMPERATURE RISE DURING ROLLING OF CAST URANIUM BARS

Sample Number	Rolling Temp, C	Temperature Rise, C						
		Pass No. 1	Pass No. 2	Pass No. 3	Pass No. 4	Pass No. 5	Pass No. 6	Pass No. 7
1	600	6	9	6	12	9	Shorted	
2	600	6	9	--	9	--	"	
3	300	35	41	24	47	41	44	53
4	300	44	35	Shorted		--	--	--

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TABLE 5. THE EFFECT OF ROLLING CONDITIONS ON THE ROLL-SEPARATING FORCE WHILE ROLLING URANIUM AND STEEL STRIPS⁽¹⁾

Initial Structure	Rolling Temperature, C	Roll Opening, inch	Roll Speed, rpm	Draft, inch	Per Cent Reduction	Roll-Separating Force, pounds	Number of Samples Averaged
Alpha-Annealed U	300	0.200	45	0.013	6	31,000	3
Ditto	"	"	"	0.033	13.5	58,000	3
"	"	"	"	0.063	22	88,000	3
"	"	"	"	0.110	33	117,000	3
"	"	"	"	0.168	42	155,000	3
"	400	"	"	0.015	7	22,000	3
"	"	"	"	0.039	15.5	47,000	3
"	"	"	"	0.068	24	69,000	3
"	"	"	"	0.118	35	87,000	3
"	"	"	"	0.177	44	118,000	3
"	500	"	"	0.018	8	19,000	3
"	"	"	"	0.044	18	33,000	3
"	"	"	"	0.075	26	52,000	2
"	"	"	"	0.124	37	73,000	1
"	"	"	"	0.183	46	86,000	3
"	< 600 ⁽²⁾	"	"	0.019	8.5	16,000	2
"	"	"	"	0.044	18	26,000	3
"	"	"	"	0.074	26	44,000	3
"	"	"	"	0.125	37	59,000	3
"	"	"	"	0.183	46	73,000	3
"	700	"	"	0.019	8.5	35,000	3
"	"	"	"	0.043	17	58,000	3
"	"	"	"	0.076	26	68,000	3
"	"	"	"	0.124	36.5	82,000	3
"	"	"	"	0.189	47	89,000	2
"	800	"	"	0.030	14	3,000	3
"	"	"	"	0.054	21	3,400	3
"	"	"	"	0.084	29.5	5,000	3
"	"	"	"	0.137	40.5	7,100	3
"	"	"	"	0.198	49.5	9,300	3
Cold-Rolled Steel	1038	"	"	0.045	18	20,000	3
Ditto	"	"	"	0.104	30	38,000	3
"	"	"	"	0.162	43.5	48,000	3
Alpha-Annealed U	600	"	"	0.075	26	39,000	3
Beta-Quenched U	< 600 ⁽²⁾	"	"	0.072	26	48,000	3
As-Cast U	600	"	"	0.073	26	34,000	2
Gamma-Annealed U	"	"	"	0.074	26	33,000	3
Alpha-Annealed U	"	0.100	30	0.035	24	30,000	1
Ditto	"	0.200	"	0.082	27	36,000	1
"	"	0.300	"	0.126	29.5	41,000	1
"	"	0.400	55	0.167	29	43,000	1
"	300	0.200	30	0.060	21	86,000	3
"	"	"	60	0.060	21	92,000	3
"	600	"	30	0.021	9	14,000	3
"	"	"	60	0.020	9	13,000	3
"	"	"	30	0.046	18	25,000	3
"	"	"	60	0.045	18	23,000	3
"	"	"	30	0.075	26	39,000	3
"	"	"	60	0.077	27	38,000	3
"	"	"	30	0.122	36	52,000	3
"	"	"	60	0.127	38	48,000	3
"	"	"	30	0.184	46	60,000	3
"	"	"	60	0.186	46.5	61,000	3

(1) Samples were 1-1/2 inch wide, rolled one pass and quenched.

(2) Controller failed, temperatures were low.

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TABLE 6. THE EFFECT OF ROLLING TEMPERATURE AND AMOUNT OF REDUCTION ON ROLL LOADS OBSERVED WHILE ROLLING URANIUM AND STEEL STRIPS(1)

Sample Number	Material	Rolling Temp, C	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll-Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi(2)	Total Spread, in.	Rockwell B Hardness As Rolled
311A	Alpha-Annealed U	300	0.223	0.012	5	32,700	0.328	99,700	88,000	0.006	96.5
312A	Ditto	"	0.222	0.013	6	30,500	0.339	90,000	78,000	0.005	
313A	"	"	0.223	0.013	6	31,100	0.338	92,000	80,000	0.007	
321A	"	"	0.251	0.034	13.5	55,600	0.554	100,500	78,000	0.016	
322A	"	"	0.251	0.035	14	56,700	0.560	101,200	76,000	0.017	
323A	"	"	0.250	0.032	13	60,600	0.537	105,600	87,000	0.017	
331A	"	"	0.287	0.065	23	89,200	0.766	116,400	81,000	0.032	100.5
332A	"	"	0.288	0.063	22	91,800	0.756	121,400	86,000	0.034	
333A	"	"	0.784	0.062	22	83,900	0.752	111,600	82,000	0.036	
341A	"	"	0.337	0.110	33	--	1.003	--	--	0.078	
342A	"	"	0.337	0.110	33	116,000	1.003	115,000	75,000	0.072	
343A	"	"	0.337	0.109	32	119,000	1.001	119,000	77,000	0.085	
351A	"	"	0.401	0.168	42	151,000	1.251	121,000	81,000	0.130	104.0
352A	"	"	0.402	0.168	42	156,500	1.277	123,000	75,000	0.142	
353A	"	"	0.401	0.168	42	158,500	1.272	125,000	76,000	0.134	
411A	Alpha-Annealed U	400	0.222	0.015	6.7	23,000	0.366	62,000	56,000	0.000	
412A	Ditto	"	0.222	0.013	5.8	22,000	0.339	64,000	60,000	0.005	
413A	"	"	0.222	0.017	7.6	21,000	0.392	55,000	47,000	0.010	
421A	"	"	0.252	0.039	15.4	47,000	0.593	79,000	59,000	0.015	
422A	"	"	0.251	0.039	15.5	46,000	0.593	77,000	57,000	0.023	
423A	"	"	0.252	0.040	16.0	49,000	0.601	81,000	60,000	0.029	
431A	"	"	0.284	0.068	24.0	--	0.790	--	--	0.048	
432A	"	"	0.285	0.068	24.0	69,000	0.789	88,000	60,000	0.046	
433A	"	"	0.285	0.069	24.0	69,000	0.797	87,000	59,000	0.050	
441A	"	"	0.338	0.119	35.0	87,000	1.053	83,000	52,000	0.081	
442A	"	"	0.338	0.118	35.0	91,000	1.050	87,000	55,000	0.082	
443A	"	"	0.336	0.117	35.0	82,000	1.045	79,000	48,000	0.082	
451A	"	"	0.402	0.177	44.0	119,000	1.316	91,000	54,000	0.167	
452A	"	"	0.402	0.177	44.0	114,000	1.317	87,000	52,000	0.163	
453A	"	"	0.403	0.178	44.0	120,000	1.311	92,000	55,000	0.146	
511A	Alpha-Annealed U	500	0.222	0.018	8.0	19,000	0.042	46,200	37,000	0.007	
512A	Ditto	"	0.222	0.018	8.0	18,000	0.042	42,600	33,000	0.011	
513A	"	"	0.222	0.018	8.0	19,000	0.042	46,000	37,000	0.010	
521A	"	"	0.251	0.043	17.0	37,000	0.063	59,000	43,000	0.031	
522A	"	"	0.252	0.045	18.0	33,000	0.064	52,000	38,000	0.029	
523A	"	"	0.249	0.044	18.0	30,000	0.063	48,000	34,000	0.032	
531A	"	"	0.286	0.075	26.0	54,000	0.083	65,000	43,000	0.061	
532A	"	"	0.287	0.076	26.5	50,000	0.084	60,000	40,000	0.063	
533A	"	"	0.285	0.074	26.0	45,000	0.082	55,000	36,000	0.055	
541A	"	"	0.337	0.123	36.5	73,000	0.108	68,000	42,000	0.124	

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TABLE 6. (Continued)

Sample Number	Material	Rolling Temp, C	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll - Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi(2)	Total Spread, in.	Rockwell B Hardness As Rolled
542A	Alpha-Annealed U	500	0.338	0.124	37.0	63,000	0.107	59,000	34,000	0.076	
543A	Ditto	"	0.337	0.125	37.0	63,000	0.109	58,000	36,000	0.097	
551A	"	"	0.402	0.180	45.0	85,000	0.132	64,000	38,000	0.147	
552A	"	"	0.402	0.184	46.0	91,000	0.137	66,000	37,000	0.228	
553A	"	"	0.401	0.184	46.0	83,000	0.134	62,000	36,000	0.171	
611A	Alpha-Annealed U	600	0.223	0.020	9.0	16,000	0.423	38,000		0.010	97 Controller failed, temperature was slightly low.
612A	Ditto	"	0.223	0.019	8.5		0.415			0.007	
613A	"	"	0.221	0.017	7.5	15,000	0.391	39,000		0.012	
621A	"	"	0.247	0.041	17.0	27,000	0.610	44,000		0.028	
622A	"	"	0.251	0.045	18.0	25,000	0.640	40,000		0.031	
623A	"	"	0.251	0.045	18.0	26,000	0.641	40,000		0.033	
631A	"	"	0.285	0.074	26.0	47,000	0.830	57,000		0.071	100
632A	"	"	0.284	0.074	26.0	42,000	0.831	54,000		0.055	
633A	"	"	0.282	0.073	26.0	43,000	0.824	53,000		0.060	
641A	"	"	0.337	0.124	36.5	62,000	1.087	57,000		0.120	
642A	"	"	0.338	0.126	37.5	59,000	1.094	54,000		0.113	
643A	"	"	0.337	0.125	37.0	55,000	1.094	51,000		0.120	
654A	"	"	0.402	0.186	46.0	77,000	1.369	56,000		0.208	102
655A	"	"	0.393	0.177	45.0	72,000	1.370	53,000		0.206	
656A	"	"	0.402	0.187	46.5	70,000	1.387	50,000		0.244	
711A	Alpha-Annealed U	700	0.223	0.020	9.0	33,000	0.426	78,000	64,000	0.020	97
712A	Ditto	"	0.222	0.018	8.0	36,000	0.403	89,000	69,000	0.027	
713A	"	"	0.223	0.019	8.5	37,000	0.416	89,000	74,000	0.025	
721A	"	"	0.251	0.043	17.0	55,000	0.626	88,000	63,000	0.042	
722A	"	"	0.251	0.043	17.0	57,000	0.630	91,000	66,000	0.052	
723A	"	"	0.251	0.043	17.0	62,000	0.630	99,000	71,000	0.051	
731A	"	"	0.288	0.077	26.5	58,000	0.846	69,000	45,000	0.067	98.5
732A	"	"	0.286	0.075	26.0	69,000	0.835	82,000	49,000	0.067	
733A	"	"	0.286	0.074	26.0	70,000	0.830	84,000	56,000	0.070	
741A	"	"	0.338	0.125	37.0	71,000	1.092	65,000	41,000	0.116	
742A	"	"	0.338	0.124	36.5	88,000	1.088	81,000	55,000	0.122	
743A	"	"	0.336	0.123	36.5	88,000	1.085	81,000	55,000	0.120	
751A	"	"	0.402	0.190	47.0	89,000	1.365	65,000	47,000	0.166	99
752A	"	"	0.402	0.188	47.0	88,000	1.363	65,000	46,000	0.172	
753A	"	"	0.403	0.198	49.0		1.391			0.158	

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TABLE 6. (Continued)

Sample Number	Material	Rolling Temp, C	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll-Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi(2)	Total Spread, in.	Rockwell B Hardness As Rolled
811A	Alpha-Annealed U	800	0.223	0.030	13.5	3,400	0.519	6,500	1,432	0.050	100
812A	Ditto	"	0.222	0.028	12.6	2,900	0.508	5,700	4,462	0.051	
813A	"	"	0.222	0.033	14.9	2,600	0.553	4,700	3,365	0.056	
821A	"	"	0.251	0.052	21.0	3,500	0.697	5,020	3,417	0.084	
822A	"	"	0.251	0.053	21.0	3,500	0.708	4,940	3,323	0.089	
823A	"	"	0.251	0.056	22.0	3,300	0.724	4,560	3,038	0.085	
831A	"	"	0.286	0.083	29.0	5,000	0.908	5,500	3,460	0.175	99
832A	"	"	0.284	0.084	29.5	4,900	0.915	5,350	3,339	0.172	
833A	"	"	0.284	0.084	29.5	5,000	0.915	5,460	3,411	0.170	
841A	"	"	0.338	0.137	40.5	6,800	1.191	5,710	3,313	0.256	
842A	"	"	0.337	0.136	40.3	7,100	1.194	5,950	3,768	0.270	
843A	"	"	0.337	0.137	41.0	7,500	1.200	6,250	3,613	0.270	
851A	"	"	0.402	0.199	49.5	9,200	1.461	6,300	3,441	0.313	99
852A	"	"	0.401	0.199	50.0	9,300	1.492	6,230	3,386	0.380	
853A	"	"	0.399	0.196	49.1	9,500	1.478	6,430	3,515	0.379	
S1	SAE 1020 Steel	1038	0.249	0.045	18	20,000	0.636	31,500	22,400	0.025	
S2	Ditto	"	0.249	0.045	18	19,500	0.635	30,700	21,800	0.023	
S3	"	"	0.249	0.045	18	21,800	0.636	34,300	24,400	0.024	
S4	"	"	0.312	0.103	30	38,200	0.975	39,200	24,500	0.085	
S5	"	"	0.313	0.104	30	37,700	0.980	38,500	22,800	0.084	
S6	"	"	0.312	0.104	30	37,900	0.980	38,700	24,200	0.085	
S7	"	"	0.372	0.162	43.5	47,400	1.243	38,100	22,300	0.154	
S8	"	"	0.372	0.161	43.5	47,400	1.241	38,200	22,400	0.154	
S9	"	"	0.374	0.163	43.5	48,700	1.253	39,900	22,700	0.168	

(1) Samples were machined strips 1-1/2 inches wide. Rolled one pass and quenched. Roll speed 45 rpm or 93 fpm. Constant roll opening of 0.200 inch.

(2) Calculated by the method of Orowan.

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TABLE 7. THE EFFECT OF INITIAL STRUCTURE ON THE ROLL LOAD OBSERVED WHILE ROLLING URANIUM STRIPS⁽¹⁾

Sample Number	Initial Structure	Rolling Temp, C	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi ⁽²⁾	Total Spread, in.	Rockwell B Hardness As Rolled
634AS	Alpha Annealed	600	0.286	.075	26.0	38,000	0.844	45,000	30,000	.055	100
635AS	Ditto	"	0.286	.076	26.5	41,000	0.847	49,000	32,000	.061	
636AS	"	"	0.285	.075	26.0	39,000	0.843	47,000	31,000	.064	
631B	Beta Quenched	<600	0.279	.069	25.0	48,000	0.800	60,000	40,000	.057	101 Temp control failed, temp was low
632B	Ditto	"	0.283	.073	26.0	48,000	0.836	58,000	39,000	.068	Ditto
633B	"	"	0.284	.074	26.0	48,000	0.839	58,000	38,000	.070	"
631C	As Cast	600	0.278	.070	25.1	34,000	0.802	43,000	27,000	.055	98
632C	Ditto	"	0.280	.074	26.4	34,000	0.827	41,000	26,000	.061	
633C	"	"	0.279	.074	26.5	29,000	0.824	35,000	22,000	.059	
631G	Gamma Annealed	"	0.282	.074	26.2	34,000	0.831	41,000	27,000	.072	95
632G	Ditto	"	0.283	.074	26.1	35,000	0.831	43,000	28,000	.073	
633G	"	"	0.283	.074	26.1	31,000	0.827	37,000	24,000	.058	

(1) Machined 1-1/2 inch wide strip, rolled one pass and quenched. Roll speed 45 rpm (93 fpm). Constant roll opening of 0.200 inch.

(2) Calculated by method of Orowan.

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TABLE 8. THE EFFECT OF ROLL OPENING ON ROLL LOAD WHILE ROLLING URANIUM STRIP⁽¹⁾

Sample Number	Material	Rolling Temp, C	Roll Opening, in.	Compression Rate, sec ⁻¹	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi ⁽²⁾	As-Rolled Hardness, VHN	Total Spread, in.
A1	Alpha Annealed	600	0.100	8.1	0.147	0.036	24.5	30,000	0.579	52,000	29,300	238	0.029
A2	Ditto	"	"	8.1	0.146	0.036	24.7	26,000	0.582	45,000	25,000	--	0.027
A3	"	"	"	8.0	0.143	0.033	23.0	25,000	0.558	45,000	26,000	--	0.035
B1	"	"	0.200	6.0	0.306	0.087	28.5	36,000	0.909	39,000	26,000	231	0.072
B2	"	"	"	5.9	0.299	0.079	26.4	33,000	0.868	38,000	25,000	--	0.066
B3	"	"	"	5.9	0.301	0.080	26.6	32,000	0.871	37,000	25,000	--	0.070
C1	"	"	0.300	7.6	0.430	0.126	29.3	41,000	1.102	37,000	26,000	242	0.104
C2	"	"	"	7.6	0.430	0.126	29.3	38,000	1.107	34,000	24,000	--	0.107
C3	"	"	"	--	0.430	--	--	--	--	--	--	--	--
D1	"	"	0.400	8.0	0.573	0.167	29.2	43,000	1.265	34,000	26,000	229	0.101
D2	"	"	"	8.0	0.572	0.166	29.1	39,000	1.258	30,000	23,000	--	0.100
D3	"	"	"	8.0	0.575	0.169	29.4	36,000	1.268	28,000	22,000	--	0.097

(1) Machined alpha-annealed uranium strip 1-1/2 inch wide.

(2) Calculated by method of Orowan.

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TABLE 9. THE EFFECT OF ROLL SPEED ON ROLL LOADS OBSERVED WHILE ROLLING URANIUM STRIPS⁽¹⁾

Sample Number	Material	Roll Speed, rpm	Rolling Temp, C	Initial Thickness, in.	Draft, in.	Per Cent Reduction	Roll- Separating Force, pounds	Projected Contact Area, sq in.	Mean Vertical Pressure, psi	Yield Strength, psi	Total Spread, in.
334AS	Alpha-Annealed U	30	300	0.285	0.060	21.0	80,000	0.485	108,000	77,000	0.034
335AS	Ditto	"	"	0.284	0.059	21.0	91,000	0.483	123,000	91,000	0.041
336AS	"	"	"	0.285	0.060	21.0	87,000	0.485	117,000	83,000	0.042
337AF	"	60	"	0.286	0.060	21.0	91,000	0.485	123,000	80,000	0.040
338AF	"	"	"	0.286	0.060	21.0	97,000	0.485	131,000	93,000	0.041
339AF	"	"	"	0.286	0.061	21.0	87,000	0.490	117,000	83,000	0.032
614AS	Alpha-Annealed U	30	600	0.225	0.021	9.3	14,000	0.434	33,000	27,000	0.009
615AS	Alpha-Annealed U	"	"	0.223	0.019	8.5	14,000	0.413	33,000	27,000	0.013
616AS	"	"	"	0.224	0.022	9.8	14,000	0.445	31,000	24,000	0.014
617AF	"	60	"	0.222	0.019	8.6	13,000	0.413	30,000	25,000	0.008
618AF	"	"	"	0.223	0.020	9.0	14,000	0.423	34,000	27,000	0.010
619AF	"	"	"	0.222	0.020	9.0	12,000	0.423	29,000	24,000	0.010
624AS	"	30	"	0.251	0.049	19.5	26,000	0.667	39,000	27,000	0.038
625AS	"	"	"	0.250	0.045	18.0	25,000	0.642	39,000	28,000	0.051
626AS	"	"	"	0.249	0.044	17.5	24,000	0.631	38,000	27,000	0.033
627AF	"	60	"	0.250	0.043	17.0	23,000	0.623	36,000	27,000	0.023
628AF	"	"	"	0.250	0.046	18.5	22,000	0.644	33,000	24,000	0.026
629AF	"	"	"	0.250	0.046	18.5	23,000	0.646	36,000	25,000	0.034
634AS	"	30	"	0.286	0.075	26.0	38,000	0.844	45,000	30,000	0.055
635AS	"	"	"	0.286	0.076	26.5	41,000	0.847	49,000	32,000	0.061
636AS	"	"	"	0.285	0.075	26.0	39,000	0.843	47,000	31,000	0.064
637AF	"	60	"	0.285	0.078	27.0	37,000	0.853	43,000	28,000	0.049
638AF	"	"	"	0.285	0.076	27.0	35,000	0.847	41,000	27,000	0.048
639AF	"	"	"	0.284	0.077	27.0	41,000	0.850	48,000	32,000	0.060
644AS	"	30	"	0.335	0.119	35.5	54,000	1.080	50,000	29,000	0.120
645AS	"	"	"	0.337	0.123	36.5	53,000	1.105	48,000	30,000	0.126
646AS	"	"	"	0.337	0.125	37.0	48,000	1.090	44,000	27,000	0.103
647AF	"	60	"	0.339	0.129	38.0	48,000	1.120	43,000	26,000	0.132
648AF	"	"	"	0.338	0.126	37.0	50,000	1.110	45,000	28,000	0.118
649AF	"	"	"	0.337	0.127	38.0	45,000	1.100	41,000	26,000	0.120
651AS	"	30	"	0.400	0.183	46.0	64,000	1.360	47,000	28,000	0.185
652AS	"	"	"	0.400	0.183	46.0	59,000	1.370	43,000	25,000	0.192
653AS	"	"	"	0.401	0.186	46.5	56,000	1.370	40,000	23,000	0.234
657AF	"	60	"	0.401	0.187	46.5	62,000	1.370	45,000	26,000	0.198
658AF	"	"	"	0.401	0.186	46.5	60,000	1.365	44,000	26,000	0.170
659AF	"	"	"	0.339	0.186	46.5	61,000	1.390	44,000	25,000	0.202

(1) Machined strip 1-1/2 inch wide.

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FIGURE 6. EFFECT OF ROLLING TEMPERATURE ON THE ROLL-SEPARATING FORCE WHILE ROLLING URANIUM STRIP WITH CONSTANT ROLL OPENING OF 0.200 INCH

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FIGURE 7. EFFECT OF TEMPERATURE AND AMOUNT OF REDUCTION ON THE ROLL-SEPARATING FORCE WHILE ROLLING $1\frac{1}{2}$ -INCH-WIDE URANIUM AND STEEL STRIP

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FIGURE 8. EFFECT OF ROLLING TEMPERATURE AND AMOUNT OF REDUCTION ON THE MEAN VERTICAL PRESSURE WHILE ROLLING URANIUM STRIPS

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FIGURE 9. APPEARANCE OF URANIUM STRIPS ROLLED AT 700 C
Nominal reductions (top to bottom): 30, 40, 50, 50, and 50 per cent

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surface of the gamma-rolled material was rough as a result of rapid oxidation, but no cracking occurred in the central section of the strips. The ends which were held by the tongs and cooled into the transformation range were cracked as indicated in Figure 10.

Spread of Flat Strips

The increase in width or "spread" of the samples rolled to various reductions at constant temperatures and at a constant roll opening of 0.2 inch is shown in Figure 11. In the alpha region, the spread was independent of the rolling temperature but increased as the amount of reduction increased. The spread of the low-carbon steel was nearly the same as that of alpha-rolled uranium.

In the gamma region at 800 C, the spread was much greater than in the alpha-temperature range. A sample reduced 50 per cent at 800 C increased 0.375 inch in width compared with a spread of 0.197 inch in a 46.5 per cent reduction at 600 C.

The spread was also dependent on the finish thickness of the strip. For a 30 per cent reduction, the spread increased from 0.030 inch at a finish thickness of 0.110 inch to 0.105 inch at a thickness of 0.304 inch.

Microstructure of Rolled Strip

The rolled and quenched samples were examined metallographically to determine the extent of recrystallization. All of the samples rolled at 500 C and below had cold-worked structures with no evidence of recrystallization. Samples rolled at 600 C to reductions of 30 per cent and less also had cold worked structures, but the samples reduced 40 and 50 per cent at 600 C had started to recrystallize. Figure 12 shows the extent of recrystallization in a sample reduced 50 per cent at 600 C.

A series of samples were rolled at 600 C to a reduction of 30 per cent in a single pass and quenched after time intervals of 1, 2, 4, 8, 16, and 32 seconds in order to determine the time necessary to permit recrystallization. Recrystallization had started after 4 seconds, but it was not completed until after 32 seconds.

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FIGURE 10. APPEARANCE OF URANIUM STRIP ROLLED AT 800 C

Nominal reduction (top to bottom): 30, 40, and 50 per cent

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FIGURE II. SPREAD OF ALPHA - AND GAMMA-ROLLED URANIUM AND SAE 1020 STEEL STRIP ROLLED ONE PASS WITH CONSTANT ROLL OPENING OF 0.200 INCH

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FIGURE 12. EXTENT OF RECRYSTALLIZATION IN A URANIUM STRIP REDUCED 50 PER CENT IN A SINGLE PASS AT 600 C AND QUENCHED IMMEDIATELY

Effect of Roll Opening

It has been observed in the rolling of steel that the mean vertical pressure, under otherwise identical conditions, increases as the thickness of the rolled material decreases. In order to determine the effect of strip thickness on the mean vertical pressure while rolling uranium, alpha-annealed samples were rolled at 600 C with roll openings of 0.1, 0.2, 0.3, and 0.4 inches. The initial thickness of the samples was varied so that a nominal reduction of 30 per cent was made on each sample. The roll speed was varied with the roll opening in an effort to obtain equal compression rates at the various drafts.

Table 9 shows the rolling conditions and the roll loads observed. Under these conditions, the total roll-separating force increased with increasing finish thickness, because the draft was increased to obtain equal percentage reductions. The mean-vertical pressure, however, decreased with increasing finish thickness. These effects are indicated in Figures 13 and 14.

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FIGURE 14. EFFECT OF FINISH THICKNESS ON THE MEAN VERTICAL PRESSURE FOR A NOMINAL 30 PER CENT REDUCTION ON URANIUM AT 600 C

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This decrease in average roll pressure with increasing strip thickness is probably the result of the decreasing effect of skin friction as the thickness of the strip increases. It also may be caused to some extent by the more rapid cooling of the thin strip.

Effect of Roll Speed

Samples of alpha-annealed metal were rolled at roll speeds of 30 and 60 rpm (61 to 122 fpm) at rolling temperatures of 300 and 600 C. The average roll loads observed are shown in Table 9. There was no consistent change in roll loads with increasing roll speeds. However, at nominal reductions of 10, 20, 30, and 40 per cent, the loads at the higher rolling speed were slightly lower than at 30 rpm. For reductions of 50 per cent, the opposite effect was observed. The change in roll load was slight, however, and the slightly higher loads at slow speeds may be the result of increased temperature drop in the strip at the lower rolling speed since an increase in the specific resistance to deformation or yield strength would normally be expected with increasing rate of deformation.

Initial Structure

Cast, gamma-annealed, beta-quenched, and alpha-annealed strips were rolled at 600 C to 30 per cent reduction with a constant roll opening of 0.2 mil.

The effect of initial structure was slight. The alpha-annealed samples produced slightly higher roll loads than either cast or gamma-annealed material. The temperature controller failed on the beta-quenched samples and the loads observed on these samples are not comparable to those obtained with other samples because the rolling temperature was low.

Yield Strength

As indicated in the preceding sections, the roll-separating force is dependent not only on those factors affecting the plasticity or resistance to deformation of the material but also on the geometry of the pass. In order to predict the roll load to be expected under a given set of conditions, it is necessary to find an expression correlating all of these factors.

The equation developed by E. Orowan appears to offer a fairly satisfactory method of calculating the roll loads for any given hot-rolling conditions, provided the specific resistance to deformation or yield strength of

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the material is known. Conversely the yield strength of the material can be calculated if the roll load is known. Figure 15 shows the calculated yield strength of uranium at various temperatures.

The method developed by E. Orowan⁽¹⁾ "A Simple Method of Calculating Roll Pressure and Power Consumption in Hot-Flat Rolling" appears to offer a fairly satisfactory method of calculating the roll loads under various conditions. This method is based on the assumption that there is no elastic deformation in the rolls, and that slip does not occur between the rolls and the work. A knowledge of the coefficient of friction is, therefore, not necessary. A simplified distribution of pressure between the rolls and work also is assumed. This results in the following equation for the roll-separating force "P" for stock, with a mean width " $\bar{b}$ " and a mean thickness of " $\bar{h}$ ", where "K" equals the yield stress in two-dimensional compression at rolling speeds, and "L" is the length of the projected arc of contact:

$$P = K\bar{b}L\left[0.8 + 0.5g - \frac{\bar{h}}{3\bar{b}g}(g - 0.2)^3\right]$$

The factor "g" is given by the following expression:

$$g = \frac{nL}{h_0}$$

in which "n" is the distance of the plane of maximum pressure from the exit plane and h_0 is the final thickness.

In the preceding tests in which the roll loads were measured, all of the factors in the above equation are known except the yield stress and the factor "n". The factor "n" is dependent on the amount of reduction but varies over only a small range. The value of this factor was assumed to be the same with uranium as in the case of steel and was obtained from Orowan's data.

The yield strength of uranium under the various rolling conditions was calculated and is shown in the tables with the other rolling data. Figure 15 shows the effect of rolling temperature on the yield strength of alpha-annealed uranium. At 600 C, an average value of 26,000 psi was obtained; and at 300 C, the average yield strength was 81,000 psi.

A sharp discontinuity occurs in the beta region, but the yield strength in the gamma region falls nearly on the extended curve of alpha yield strengths.

(1) Orowan, E., "The Iron and Steel Institute Special Report", No. 34, Iron and Steel Institute, London, 1946.

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FIGURE 15. CALCULATED YIELD STRENGTH OF URANIUM DURING FLAT-STRIP ROLLING (AVERAGED VALUES)

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The yield strength of the SAE 1020 steel rolled at 1038 C was 23,000 psi. This value is in close agreement with the value given by Trinks⁽¹⁾ for a similar steel and also with the yield strength calculated by Orowan from roll-load measurements on 0.28 per cent carbon steel.

HAS:JRK:RJD/hp
January 13, 1953

(1) Trinks, W., "Roll Pressures in Hot Rolling", Blast Furnace and Steel Plant, 25, p 1005, 1937.

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