Refractomet Division

UNIVERSAL-CYCLOPS STEEL CORPORATION

Technical Report

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BRIDGEVILLE, PENNSYLVANIA

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MANUFACTURING TECHNOLOGY LABORATORY

Directorate of Materials and Processes
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United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT
Fourth Interim Report

ASC INTERIM REPORT 7-786 (IV)
April, 1963

INFAB PROCESSING OF TZM SHEET

Refractomet Division
Universal-Cyclops Steel Corporation

Twenty-nine pieces of intermediate gage (mold out) TZM have been evaluated for soundness, contamination, recrystallization and tensile properties. Results show that mold out produced by rolling at 2400 and 2800°F are superior to mold out rolled at 2000 or 3200°F regardless of forging practice. Mold out properties are correlated with forging practice and results show that mold out produced from fine hot forged or partially hot forged sheet bar structures exhibit the heat combination of properties. This evaluation essentially completes the Phase IV program.

ASC TR 7-786 (IV)

ASC INTERIM REPORT 7-786 (IV)
April, 1963

INFAB PROCESSING OF TZM SHEET

Contract AF 33(657)-8495

Fourth Interim Technical
Engineering Report
15 January 1963 - 15 April 1963

Phase IV Report

Prepared By
F. R. Cortes

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NOTICES

FOREWORD

This Interim Technical Progress Report covers work performed under Contract AF 33(657)-8495 from 15 January 1963 to 15 April 1963. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with the Refractomet Division of Universal-Cyclops Steel Corporation, Bridgeville, Pennsylvania was initiated under ASC Aeronautical System Division, Project 7-786, "InFab Processing of TZM Sheet." It was administered under the direction of Mr. Hugh L. Black, Project Engineer, Basic Industry Branch, Manufacturing Technology Laboratory, Wright-Patterson Air Force Base, Ohio. F. R. Cortes of the Development Group, Refractomet Division, Universal-Cyclops Steel Corporation was the engineer in charge.

Since the nature of this work is of interest to so many fields of endeavor, your comments are solicited as to the potential utilization of the material produced under this contract. In this manner, it is felt that a full realization of the resultant material produced will be accomplished.

PUBLICATION REVIEW

Reviewed By W A McNeish

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I. Introduction

This program was designed to evaluate the potential of the InFab facility for the production of TZM alloy sheet. The evaluation consists of the following six phase program.

Phase I	Literature Survey
Phase II	Ingot Production and Evaluation
Phase III	Production of Sheet Bar
Phase IV	Intermediate Breakdown
Phase V	Production of Evaluation Sheets
Phase VI	Production of Sheets by Best Techniques

During this report period the Phase IV evaluation of intermediate gage was completed. This report covers the results of the Phase IV evaluation and the determination of the best sheet bar forging and mold out rolling practices for the Phase V program. The Phase V program was designed and billets were prepared for forging in InFab when operation resumes approximately May 1, 1963.

II. Phase IV Intermediate Breakdown and Evaluation

The previous interim report described sheet bar rolling procedures to nominal 0.125 mold out. Of the 34 sheet bar sections rolled, 29 pieces of mold out were produced for full evaluation.

A. Continuation of Mold Out Evaluation

Initial evaluation of 0.125" mold out was reported in the previous interim report. Included were the results of ultrasonic inspection, determination of surface contamination and hardness surveys. The remainder of this evaluation was completed during this report period.

1. Mold Out Contamination

Visible contamination layers were reported previously along with chemical analyses to determine surface iron pickup during rolling. Wrought surface layers on recrystallized mold out (attributed to interstitial contaminants) appeared on all mold out rolled at 2800°F and on a few sections rolled at 2400°F but not on all mold out rolled at 2000°F. Mold out rolled at 3200°F, exhibited lightly worked structures, and showed no wrought contamination layers either as-rolled or recrystallized as the high rolling temperature offset any effects of contamination on recrystallization during rolling and the lightly worked surface prevented any delineation between surface and sub strate after annealing. Chemical analyses revealed that surface iron pickup became a problem at rolling temperatures above 2800°F.

Interstitial analyses of mold out, during this report period (Table I) revealed that:

TABLE I

Mold Out Code	Rolling Temp.	Reheats	Gauge As Rolled	Chemistry of As-Rolled Cross Section Fe	C	N	0-Lab 1	0-Lab 2	Surface Removed (per side)	Chemistry of Surface Milled Cross Section Fe	C	N	O
T1	3200	6	.138	-	-	-	-	-	.025"			-	.0011
T9	3200	7	.151	.010	.054	.0005	.0048	.0050	.025"	.0018	.034	.0014	.0010
											.031		
T17	3200	-	.162	-	.055	-	.0040	.0070	.025"	-	.025		.0010
T10	2800	8	.131	.0025	.034	.0009	.0056	.0110	.020"	<.0015	.036	.0009	.0010
T14	2800	8	.129	-	-	-	-	-	.020"	-		-	.0014
T18	2800	-	.126	-	.029	-	.0059	.016	.020"		.027	-	.0008
T11	2400	10	.129	.0025	.030	.0006	.0050	.0080	.015"	<.0015	.032	.0014	.0005
T19	2400		.131	-	.032	-	.0055	.0080	.015"	-	.026	-	.0009
T12	2000	8	.133	<.0015	.031	.0006	.0118	.0070	.010"	<.0015	.033	.0012	.0012
					.034								
T20	2000	-	.131	-	.030	-	.0045	.021	.010"	-	.034	-	.0008

1. Nitrogen contamination did not occur as nitrogen contents did not differ in as-rolled and surface milled mold out.
2. Carbon contamination occurred only at the very highest rolling temperature, 3200°F. Mold out rolled at 3200°F showed carbon levels of .055% or almost double those for mold out rolled at the lower temperatures or for surface milled samples.
3. Oxygen contamination occurred in all cases but there was no correlation with rolling temperatures.

The graphite suscepter of the induction heating furnace is the known source of the carbon contamination. During this report period the induction furnace was replaced with a tungsten element resistance heated furnace which should prevent carbon contamination during future sheet rolling operations.

The source of the oxygen contamination at temperatures below 3200°F has not as yet been accurately determined but it is also believed to be a function of the induction furnace temperature though this was not necessarily indicated by analyses of the mold out. The difficulty in obtaining reproducible oxygen analyses between laboratories is readily apparent from Table I. Initial analyses (Lab-1) of as-rolled mold out cross sections showed oxygen levels of about 50 ppm regardless of the rolling temperature. After removing from .010 to .025" per side by milling and pickling the oxygen contents dropped to about 10 ppm. A recheck of the analyses (Lab 2) on as-rolled mold out showed oxygen levels to be from 50 to 300% greater than results obtained from Lab 1. In addition results from Lab 2 give some indication of increasing oxygen contamination with rolling temperature up to 2800°F. The lowest oxygen levels reported by both laboratories were for mold-out rolled at 3200°F. Since carbon contamination was at its peak at 3200° it may have been a factor contributing to the lower level of oxygen contamination.

2. Recrystallization and Structures of .125" Mold Out

The effects of rolling temperature and sheet bar forging practice on mold out structures, recrystallization temperatures and recrystallized grain size are summarized in Table II. As rolled mold out structures can

TABLE II

RECRYSTALLIZATION TEMPERATURES AND RECRYSTALLIZED GRAIN SIZE OF NOMINAL 0.125" MOLD OUT

Sheet Bar	Mold Out	Furnace or Rolling Temperature °F	As-Rolled Mold Out Structure	As Rolled Hardness	1 Hr. ReXL Temp. Est. From Micros 50%		100%	ReXL Grain Size (ASTM)
Extruded & Forged								
1098A1	T1	3200	Hot Rolled to Lightly Wo.	276	-	*	>3000°F	4.5
	T3	2400	Fibered	376	2750°F	*	2900°F	6.5
1098A2	T5	3200	Hot Rolled to Lightly Wo.	276	-		>3000	Non Uniform
	T6	2800	Fibered	327	2650		2850	7
	T8	2000	Fibered	405	2650		2850	7.5
1098A3	T9	3200	Hot Rolled to Lightly Wo.	281	-		>3000	Non Uniform
	T10	2800	Worked, Fibered Centered	289	2850	*	2900	4.5
	T11	2400	Fibered	348	2650		2900	7
	T12	2000	Fibered	373	2600		2850	7.7
1098B1	T13	3200	Hot Rolled to Lightly Wo.	262	-		>3000	3-6
	T14	2800	Fibered + Trace ReXL	333	2725	*	2850	6
	T15	2400	Fibered	373	2725	*	2800	6.5
1098B2	T17	3200	Worked, Not Fibered	257	2800		2950	3-6
	T18	2800	Worked, Fibered Center	289	2750		2900	Non Uniform
	T19	2400	Heavily Fibered	333	2600		2900	6-7
	T20	2000	Heavily Fibered	360	2550		2700	7.5
1098B3	T21	3200	Worked	297	2800		2950	3-6
	T22	2800	Worked, Fibered Center	312	2650		2725	4.5
	T23	2400	Fibered	330	2500		2650	7
	T24	2000	Heavily Fibered	354	2500		2600	7.5
1098B4	T25	3200	Worked	302	2625		2725	5
	T26	2800	Worked, Fibered Center	279	-	*	2900	Non Uniform
	T27	2400	Fibered	336	2500		2600	7.5
	T28	2000	Heavily Fibered	357	2475		2575	7.7
Cast and Forged								
1099A	T34	2800	Fibered + Trace ReXL	333	2725		2825	6.5
	T35	2400	Heavily Fibered	360	2600		2800	7.5
1099C	T38	2800	Heavily Worked	299	2750	*	2900	6
	T39	2400	Fibered	351	2625		2800	6.5
	T40	2000	Heavily Fibered	370	2575		2750	7.5

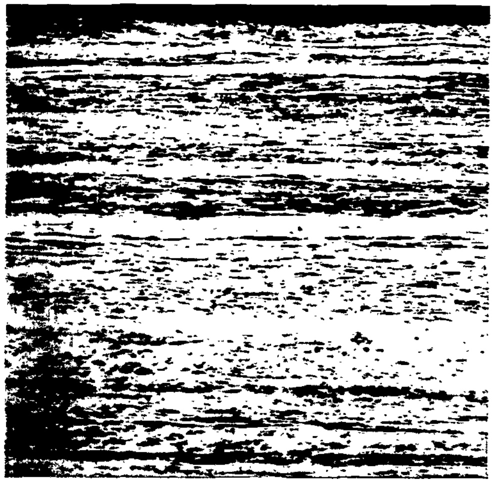
be grouped with rolling temperature into three classes as follows:

Rolling Temp °F	Structure
2000 & 2400	Fibered
2800	Worked & Fibered Center
3200	Hot Rolled to Lightly Worked

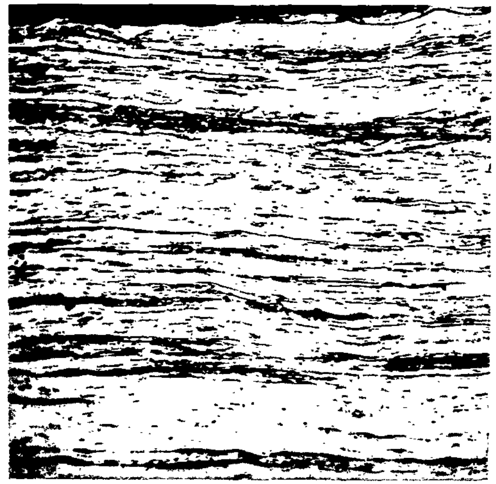
Structural variations were greatest in mold out rolled at 2800° as this temperature falls between the hot and cold working range for TZM. Figures 1 and 2 show typical structures for each group as well as some variations between mold out rolled at 2800°F.

The annealing response of TZM mold out rolled at 2000°F is shown in Figure 3. Hardnesses dropped to recrystallized values of 200-210 after a 1 hour anneal at 2600°F. Only six pieces of mold out were rolled successfully at 2000°F as 3 sections from hot forged sheet bars were not fabricable. Of the six produced mold out T8, from a hot forged sheet bar, maintained the highest annealed hardness and required 2850°F for 100% recrystallization.

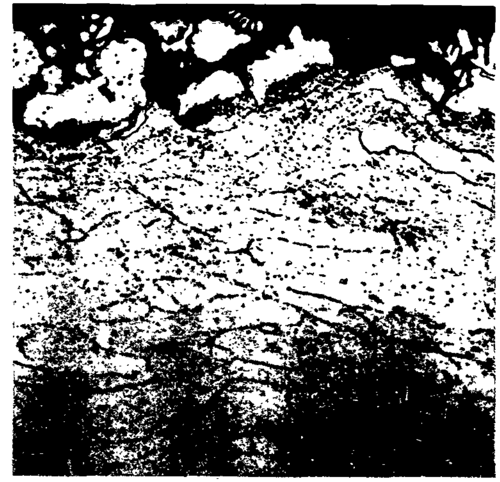
Though hardnesses dropped rapidly upon annealing at 2600°F the microstructures revealed



R12748 200X
MOLD OUT T-8
ROLLED AT 2000°F



R12752 200X
MOLD OUT T-15
ROLLED AT 2400°F



R12745 200X
MOLD OUT T-5
ROLLED AT 3200°F

FIGURE 1

AS ROLLED MOLD OUT STRUCTURES

R12747 200X
MOLD OUT T6
ROLLED FROM HOT FORGED
SHEET BAR 1098A2

R12755 200X
MOLD OUT T22
ROLLED FROM HOT-COLD FORGED
SHEET BAR 1098B3

R12757 200X
MOLD OUT T34
ROLLED FROM SHEET BAR 1099A
HOT FORGED FROM 6" DIA INGOT

FIGURE 2

AS ROLLED STRUCTURES OF MOLD OUT ROLLED AT 2800°F

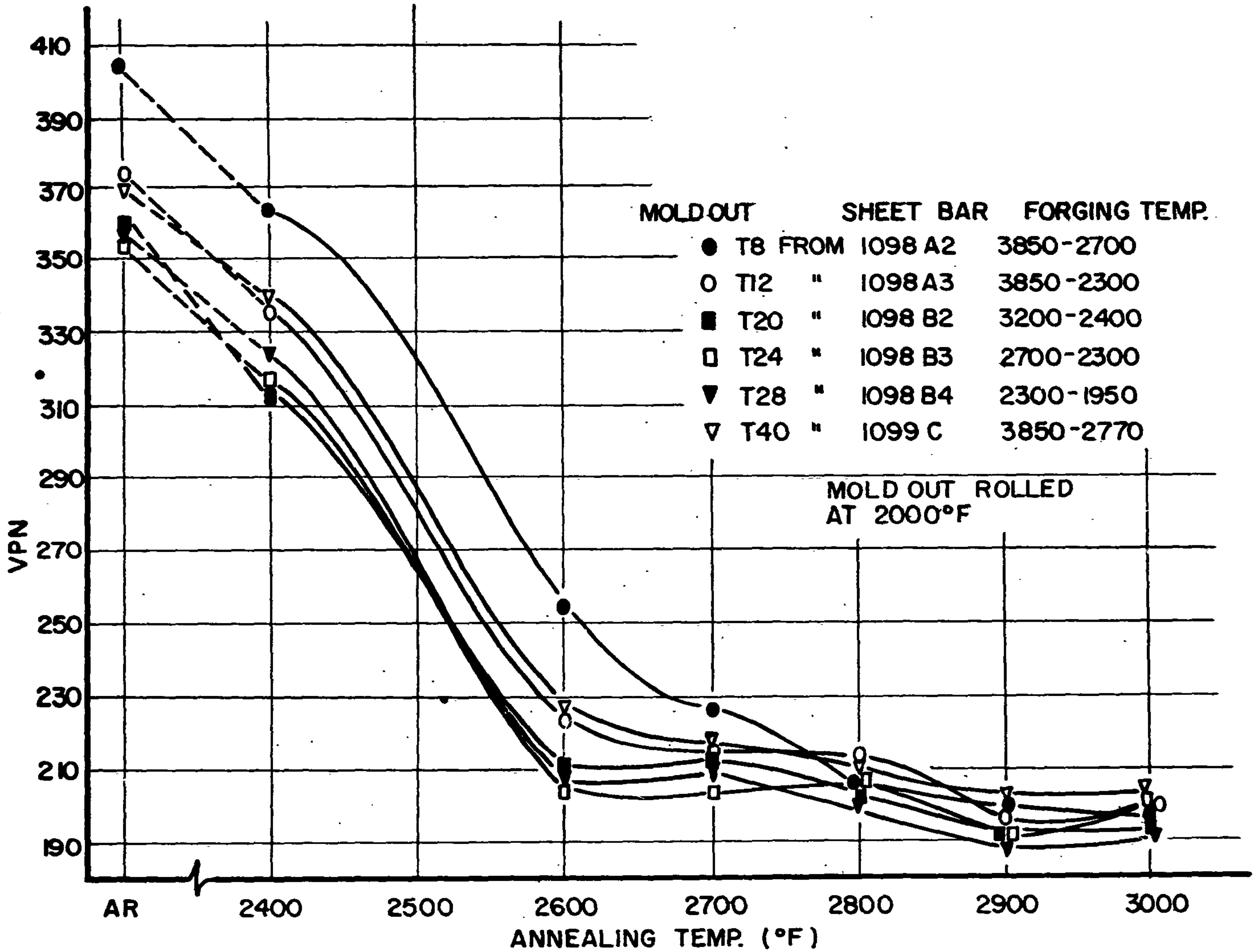


FIGURE 3

EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF NOMINAL 0.125" MOLDOUT ROLLED AT 2000°F

RTA-0310

that temperatures of 2700 to 2850°F were required for 100% recrystallization as shown in Table II except for mold out T24 and T28. These latter two, having been produced from heavily hot-cold forged sheet bars 1098Bc and 1098B4, were fully recrystallized at 2600°F. A fine recrystallized grain size of about ASTM 7.5 was produced in all mold out sections rolled at 2000°F indicating, as expected, finer grain size with lowest prior rolling temperature.

Except for sections T3 and T15, Figure 4 shows that hardness of mold out rolled at 2400°F also dropped close to recrystallized values after a 2600°F anneal. Sections T3 and T15 were rolled from primarily hot forged sheet bars and maintained worked hardness levels of 275 and 250 QPH up to 2700°F with microstructural evidence of 100% recrystallization at 2900 and 2800°F respectively. Progress of recrystallization in mold out T3 is shown in Figure 5.

The lowest recrystallization temperatures for mold out rolled at 2400°F occurred in sections T23 and T27 which were rolled from heavily cold forged sheet bar 1098B3 and 1098B4. Recrystallized grain sizes

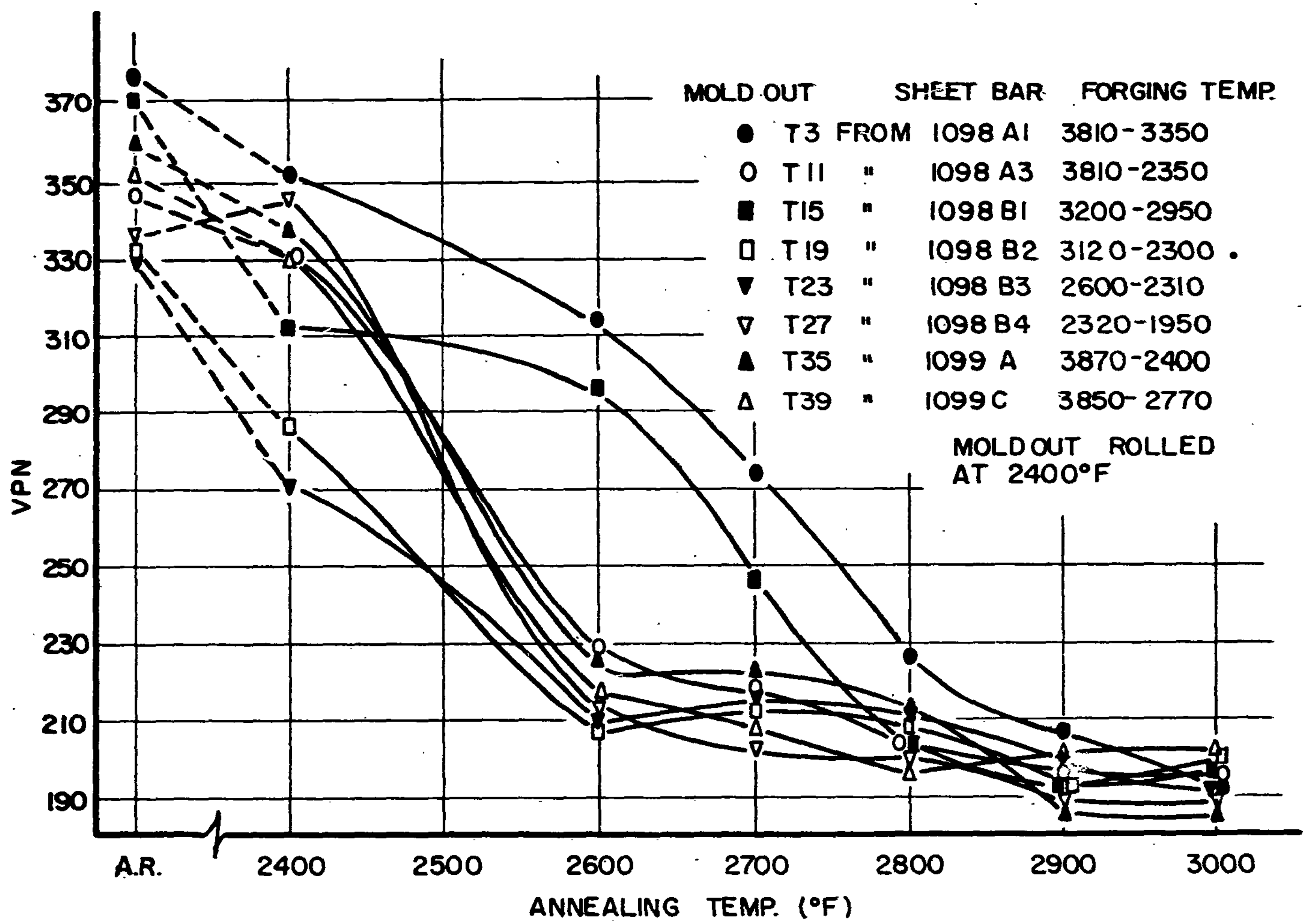
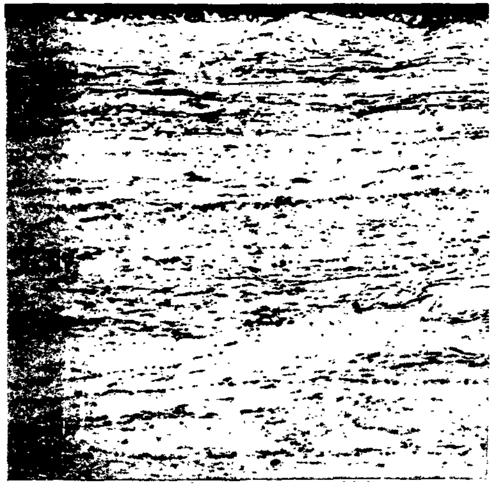


FIGURE 4

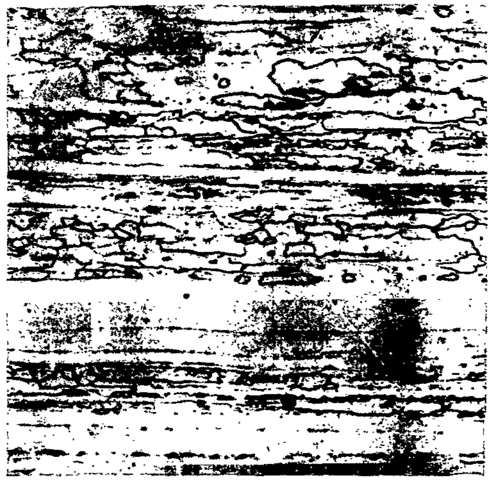
EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF NOMINAL 0.125" MOLDOUT ROLLED AT 2400°F

RTA-0311

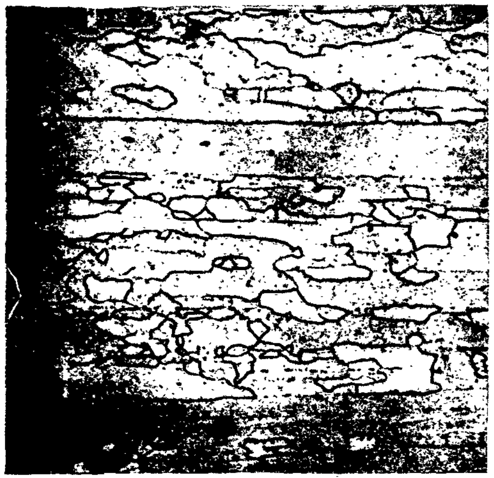


R12744 200X
AS-ROLLED

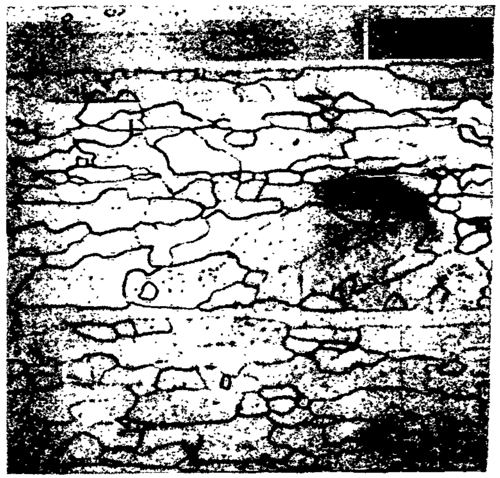
R12761 200X
1 Hr @ 2600°F



R12767 200X
1 Hr @ 2700°F



R12772 200X
1 Hr @ 2800°F



R12777 200X
1 Hr @ 2900°F

FIGURE 5

PROGRESS OF RECRYSTALLIZATION IN MOLD OUT T3 PRODUCED FROM HOT FORGED SHEET BAR BY ROLLING AT 2400°F for mold out rolled at 2400°F averaged about ASTM 6.9 and ranged from 6.5 to 7.5. Thus increasing the rolling temperature from 2000 to 2400°F resulted in only a slight coarsening of recrystallized gram size amounting to about one half an ASTM number.

Mold out rolled at 2800 and 3200°F developed as-rolled hardnesses ranging from 255 to 332 in comparison to hardness ranging from 330 to 400 for mold out rolled at 2000 and 2400°F. As a result softening upon annealing appeared more gradual, Figures 6 and 7, for mold out rolled at the higher temperatures. Annealing temperatures from 2750°F to 2800°F were necessary to produce recrystallized hardness levels in mold out rolled at 2800°F except for sections T18, T22 and T26. These sections were produced from hot cold forged sheet bar and softened at about 2650 to 2700°F. Softening temperatures for mold out rolled at 3200 were the same as for mold out rolled at 2800°F, about 2750 to 2800°F. The microstructures indicated that recrystallization was complete at temperatures ranging from 2725 to 2900°F for mold out rolled at 2800 and at temperatures

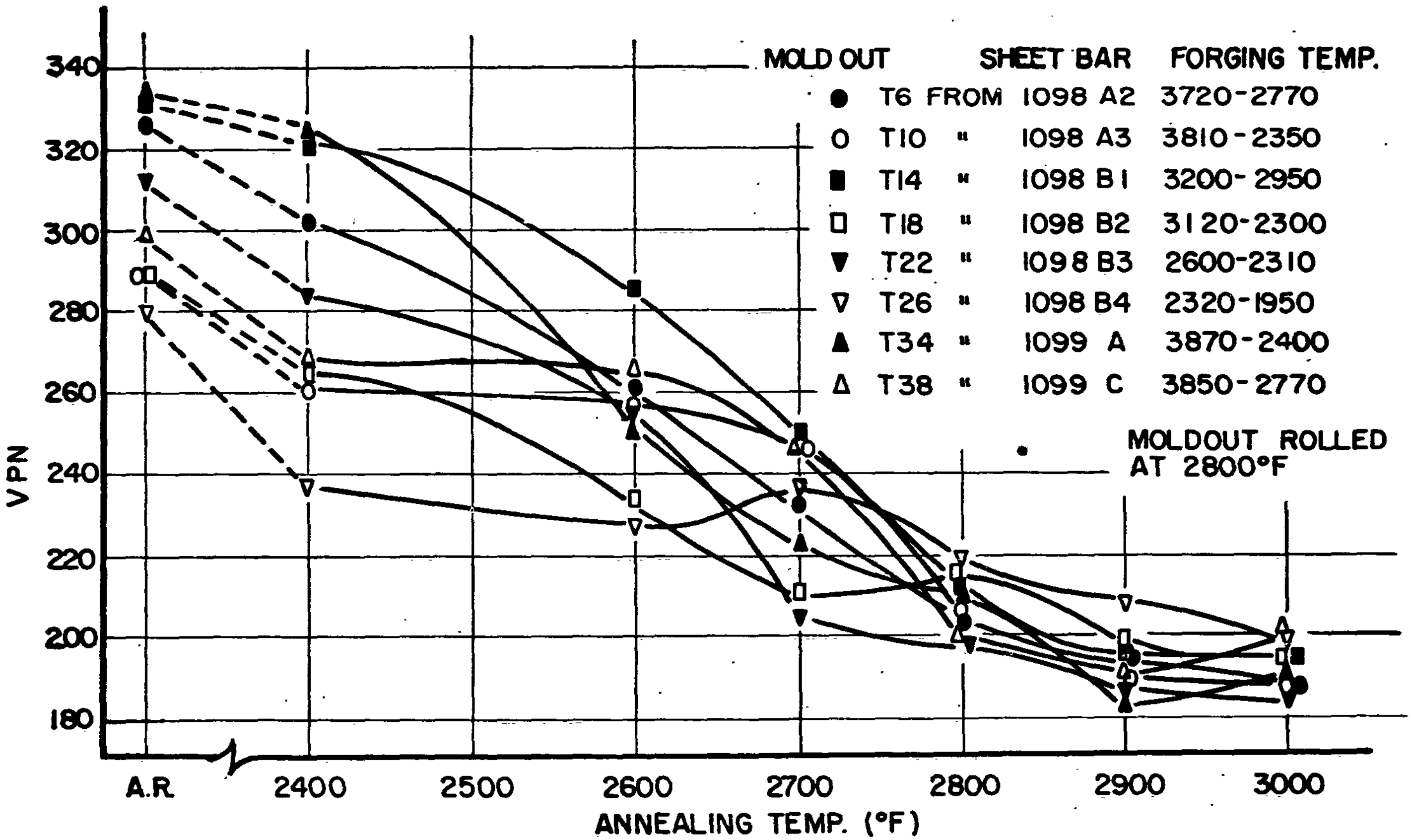


FIGURE 6

EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF NOMINAL 0.125" MOLDOUT ROLLED AT 2800°F

RTA-0312

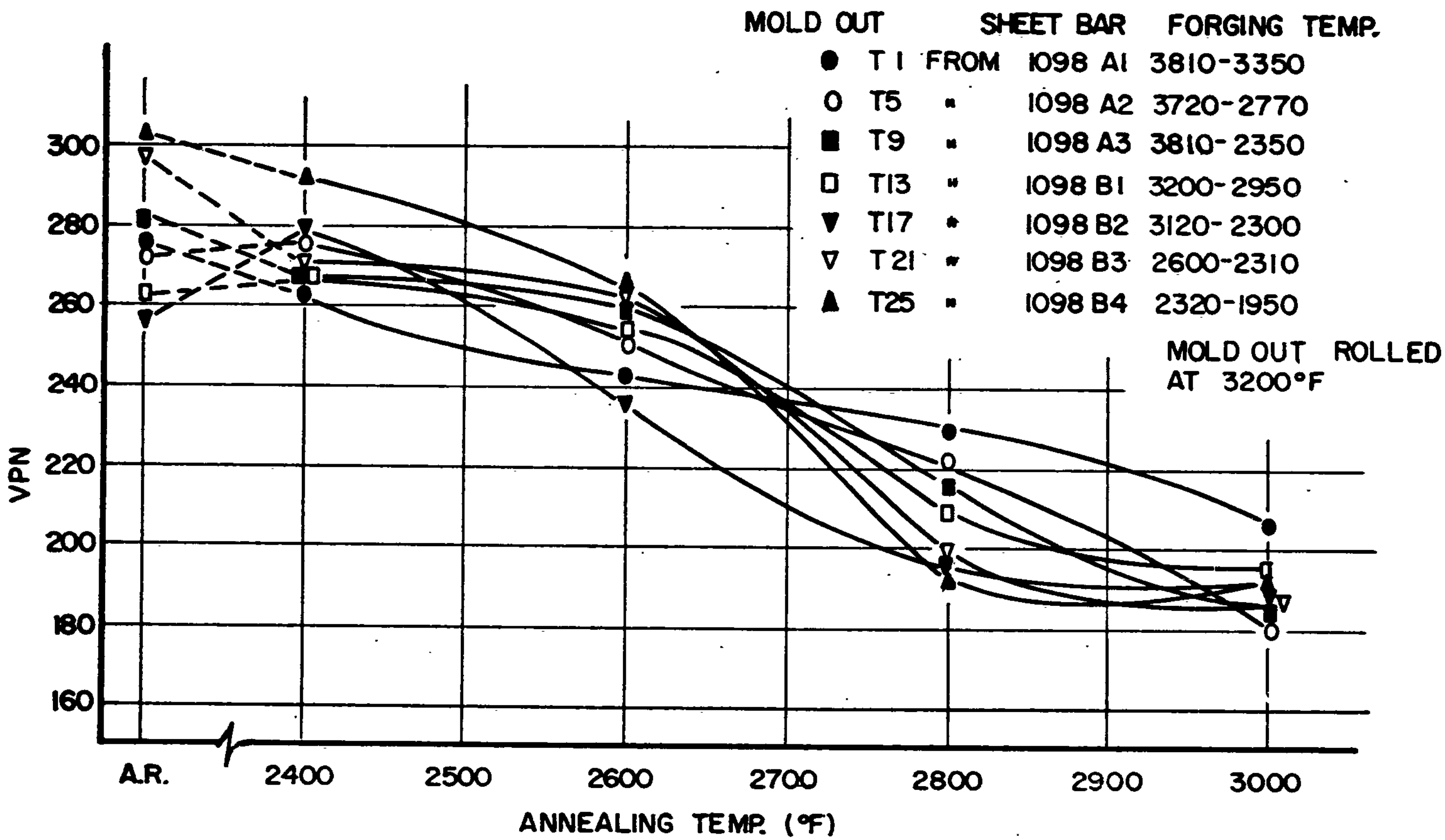


FIGURE 7

EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF NOMINAL 0.125" MOLDOUT ROLLED AT 3200°F

RTA-0313

from 2725 to >3000°F for mold out rolled at 3200°F. The very high (>3000°) recrystallization temperatures for mold out rolled at 3200°F resulted from the small amount of work retained at the high rolling temperature.

Recrystallized grain size of mold out rolled at 2800°F ranged from ASTM 4.5 to 7 with an average about 5.75 while mold out rolled at 3200 exhibited coarse, non uniform structures averaging about ASTM 4.5.

Mold out sections which exhibited the outstanding hardness stability with annealing temperatures are as follows:

Mold Out	Rolling Temp.	Rex. Temp.	Sheet Bar Source	Sheet Bar Forging Practice
T1	3200	2800	1098A1	3850°F to 3200 min.
T3	2400	2775	1098A1	3850°F to 3200 min.
T10	2800	2725	1098A3	3850°F to 2300 min.
T14	2800	2750	1098B1	3200°F to 2950 min.
T15	2400	2725	1098B1	3200°F to 2950 min.
T38	2800	2725	1099C*	3850°F to 2770 min.

* Forged directly from ingot

Significant observations are:

1. Outstanding hardness stability is exhibited by mold out rolled at either 2400 or 2800°F.
2. Sheet bars from which each mold out was rolled were primarily hot forged.

The supporting microstructural evidence for (50%) recrystallization is summarized in Figure 8. Mold out from cold forged sheet bar exhibit the lowest recrystallization temperatures while mold out from hot forged sheet bar showing good hardness stability (circled code nos.) exhibit the highest recrystallization temperatures. Mold out produced from directly forged ingots exhibit only average recrystallization temperatures.

3. <u>Tensile Properties of .125" Mold Out</u>

Room temperature tensile properties were obtained in the following conditions:

As-Rolled - Longitudinal Direction Only

As Rolled and Conditioned Surface - Longitudinal and Transverse

Stress Relieved and Conditioned Surface - Longitudinal and Transverse

Recrystallized and Conditioned Surface - Longitudinal and Transverse

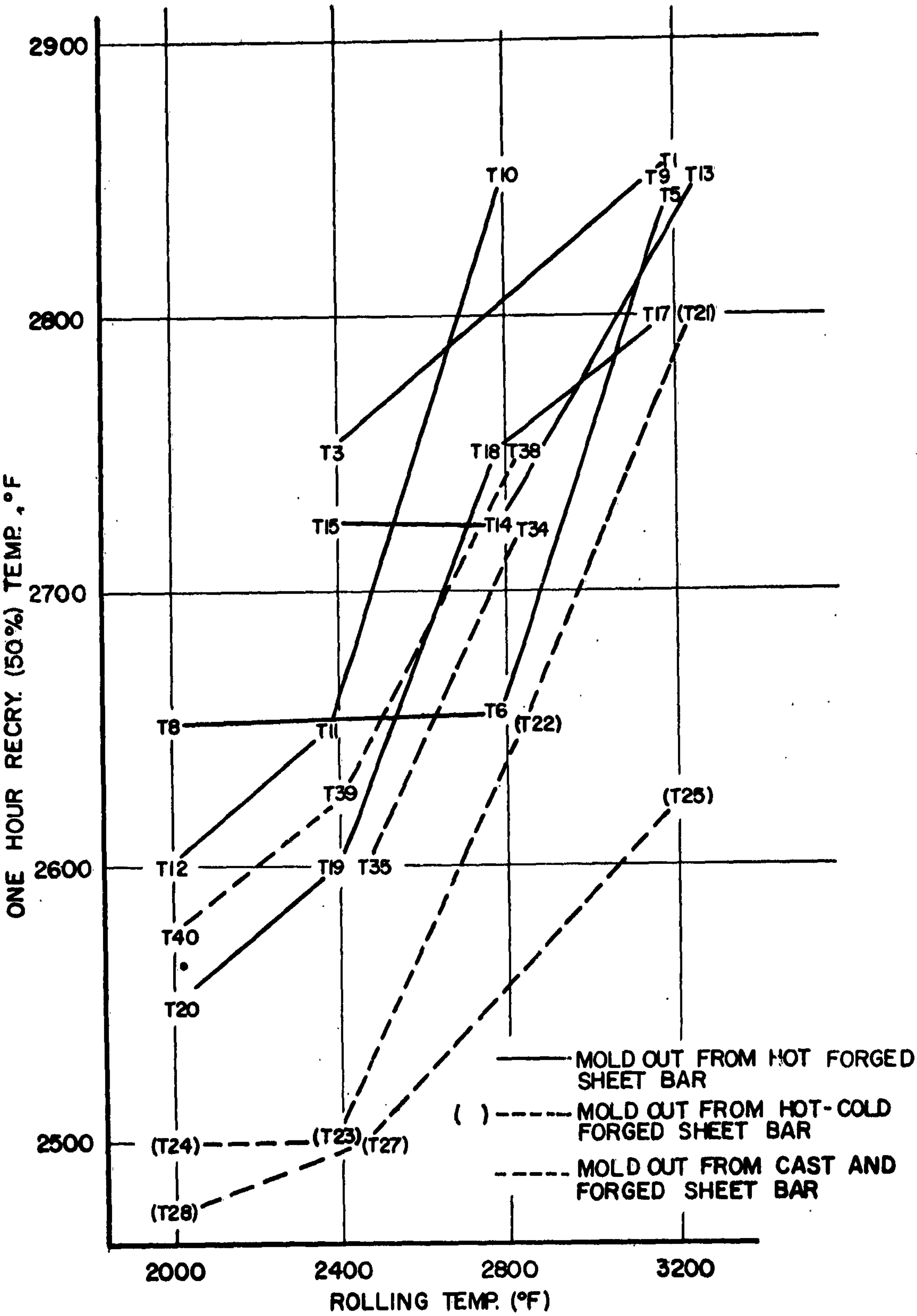


FIGURE 8

EFFECT OF ROLLING TEMPERATURE ON TEMPERATURE FOR 50% RECRYSTALLIZATION OF 0.125" MOLDOUT

Ultimate strength and elongation for each of the above conditions is summarized in Tables III and IV. Comparing longitudinal tensile properties of as-rolled mold out with as-rolled and conditioned mold out reveals the detrimental surface contamination effect. In particular, mold out rolled at 2400 and above exhibited no as-rolled tensile ductility, Table IV, in the longitudinal direction. (Transverse properties were not determined as-rolled.) However surface conditioning by belt grinding produced tensile elongations of 5 to 15% in the longitudinal direction and 2 to 10% transverse. Surface conditioning plus a stress relief further increased tensile ductility of most of the mold out sections. However, mold out sections T1 and T5 hot rolled at 3200°F from hot forged sheet bar showed no improvement in elongation with either the surface conditioning or stress relief treatment. Recrystallization anneals greatly improved tensile elongation in almost every case.

A technique for rating mold out ductility was devised giving equal weight to as-rolled and stress relieved elongations and one half weight

TABLE IV

TENSILE DUCTILITY OF .125" MOLD OUT AT ROOM TEMPERATURE

Sheet Bar	Mold Out	Rolling Temp.	Annealing Temp.	Longitudinal Elongation As.Ro.	As.Ro.&C.	Str.Re.&C.	ReXl&C	Transverse Elongation As.Ro.&C.	Str.Re.&C.	ReXl&C	Overall % EL. Rating	Average
1098A1	T1	3200	2600	0.0	0.7	0.8	14.3	1.8	0.0	1.9	.72	1.61
	T3	2400	2600	1.8	-	7.6	27.8	-	1.3	-	2.5	
1098A2	T5	3200	2600	0.0	-	0.6	1.0	-	.5	7.0	.6	1.75
	T6	2800	2500	.5	-	(18.2)	28.5	3.4	2.1	35.7	2.66	
	T8	2000	2500	.7	7.0	4.6	27.3	4.6	1.6	7.3	2.0	
1098A3	T9	3200	2600	.6	4.4	-	7.4	2.6	1.5	8.8	1.66	2.50
	T10	2800	2700	.2	7.8	-	23.1	7.6	1.4	17.2	2.33	
	T11	2400	2400	.6	(10.7)	13.9	24.4	6.6	7.8	18.1	2.86	
	T12	2000	2500	5.2	8.6	-	30.9	2.2	11.8	25.4	3.16	
1098B1	T13	3200	2600	-	2.5	-	19.4	2.1	0.7	0.1	1.4	2.08
	T14	2800	2600	-	9.4	14.6	25.0	4.7	1.8	27.7	2.84	
	T15	2400	2500	0.1	(10.2)	-		1.6	-	-	2.0	
1098B2	T17	3200	2600	-	15.0	6.8	27.7	1.8	0.9	19.5	2.5	3.35
	T18	2800	2600	0.6	8.0	(22.8)	26.2	8.9	3.3	7.0	2.72	
	T19	2400	2400	-	(15.6)	17.6	39.4	9.6	(19.5)	39.3	4.33	
	T20	2000	2400	5.8	11.7	24.0	43.3	3.9	11.8	34.7	3.86	
1098B3	T21	3200	2600	-	0.6	-	5.3	-	-	-	1.0	2.55
	T22	2800	2600	0.5	8.1	10.1	27.5	3.2	3.8	21.3	2.42	
	T23	2400	2400	0.5	(15.8)	(19.8)	.5	1.6	(20.0)	32.2	3.0	
	T24	2000	2400	9.1	8.6	18.1	39.0	-	-	37.0	3.8	
1098B4	T25	3200	2600	0.0	-	9.4	-	-	0.7	13.4	1.25	2.96
	T26	2800	2600	1.4	12.2	-	16.8	2.0	2.5	9.3	2.5	
	T27	2400	2400	-	(15.6)	(20.5)	36.7	11.5	(16.7)	39.8	4.66	
	T28	2000	2400	10.5	10.2	19.2	9.2	1.4	5.6	36.2	3.42	
1099A	T34	2800	2500	0.7	11.3	14.6	9.0	6.6	(11.9)	26.7	2.84	2.92
	T35	2400	2400	1.8	8.8	-	28.8	6.7	(11.8)	25.8	3.00	
1099C	T38	2800	2500	0.0	0.2	(15.7)	28.1	0.0	1.8	1.0	1.56	1.82
	T39	2400	2500	0.0	10.3	-	36.5	2.1	4.7	17.9	2.50	
	T40	2000	2400	0.0	7.8	.1	26.6	3.1	1.0	.6	1.42	

TABLE IV

TENSILE DUCTILITY OF .125" MOLD OUT AT ROOM TEMPERATURE

Sheet Bar	Mold Out	Rolling Temp.	Annealing Temp.	Longitudinal Elongation As.Ro.	Longitudinal Elongation As.Ro.&C.	Longitudinal Elongation Str.Re.&C.	Longitudinal Elongation ReXl&C	Transverse Elongation As.Ro.&C.	Transverse Elongation Str.Re.&C.	Transverse Elongation ReXl&C	Overall % EL. Rating	Average
1098A1	T1	3200	2600	0.0	0.7	0.8	14.3	1.8	0.0	1.9	.72	1.61
	T3	2400	2600	1.8	-	7.6	27.8	-	1.3	-	2.5	
1098A2	T5	3200	2600	0.0	-	0.6	1.0	-	.5	7.0	.6	
	T6	2800	2500	.5	-	(18.2)	28.5	3.4	2.1	35.7	2.66	1.75
	T8	2000	2500	.7	7.0	4.6	27.3	4.6	1.6	7.3	2.0	
1098A3	T9	3200	2600	.6	4.4	-	7.4	2.6	1.5	8.8	1.66	
	T10	2800	2700	.2	7.8	-	23.1	7.6	1.4	17.2	2.33	
	T11	2400	2400	.6	(10.7)	13.9	24.4	6.6	7.8	18.1	2.86	2.50
	T12	2000	2500	5.2	8.6	-	30.9	2.2	11.8	25.4	3.16	
1098B1	T13	3200	2600	-	2.5	-	19.4	2.1	0.7	0.1	1.4	
	T14	2800	2600	-	9.4	14.6	25.0	4.7	1.8	27.7	2.84	2.08
	T15	2400	2500	0.1	(10.2)	-		1.6	-	-	2.0	
1098B2	T17	3200	2600	-	15.0	6.8	27.7	1.8	0.9	19.5	2.5	
	T18	2800	2600	0.6	8.0	(22.8)	26.2	8.9	3.3	7.0	2.72	
	T19	2400	2400	-	(15.6)	17.6	39.4	9.6	(19.5)	39.3	4.33	3.35
	T20	2000	2400	5.8	11.7	24.0	43.3	3.9	11.8	34.7	3.86	
1098B3	T21	3200	2600	-	0.6	-	5.3	-	-	-	1.0	
	T22	2800	2600	0.5	8.1	10.1	27.5	3.2	3.8	21.3	2.42	
	T23	2400	2400	0.5	(15.8)	(19.8)	.5	1.6	(20.0)	32.2	3.0	2.55
	T24	2000	2400	9.1	8.6	18.1	39.0	-	-	37.0	3.8	
1098B4	T25	3200	2600	0.0	-	9.4	-	-	0.7	13.4	1.25	
	T26	2800	2600	1.4	12.2	-	16.8	2.0	2.5	9.3	2.5	
	T27	2400	2400	-	(15.6)	(20.5)	36.7	11.5	(16.7)	39.8	4.66	2.96
	T28	2000	2400	10.5	10.2	19.2	9.2	1.4	5.6	36.2	3.42	
1099A	T34	2800	2500	0.7	11.3	14.6	9.0	6.6	(11.9)	26.7	2.84	2.92
	T35	2400	2400	1.8	8.8	-	28.8	6.7	(11.8)	25.8	3.00	
1099C	T38	2800	2500	0.0	0.2	(15.7)	28.1	0.0	1.8	1.0	1.56	
	T39	2400	2500	0.0	10.3	-	36.5	2.1	4.7	17.9	2.50	1.82
	T40	2000	2400	0.0	7.8	.1	26.6	3.1	1.0	.6	1.42	

to recrystallized values. The resultant elongation rating is also listed in Table IV. On the basis of this rating, sheet bar 1098B2, forged between 3200 and 2300°F, produced the most uniformly ductile mold out. Of further significance is the fact that the best ductility rating for mold out from any one sheet bar occurred for the most part in sections rolled either at 2400 or 2800°F. Mold out rolled at 3200 showed the poorest overall ductility.

III Summary and Conclusions

The results obtained from the Phase III Sheet Bar Evaluation, reported in the last interim report, and the Phase IV Mold Out Evaluation of this report are summarized in Table V using an arbitrary rating system for the various properties. Sheet bar exhibiting the best quality rating of (18), (1098B1), was entirely hot forged at the low end of the hot work range for TZM which prevented excess grain growth. Sheet bars 1098A3 and 1098B2 exhibiting the next best quality ratings (15 and 16) were initially hot forged and then finish forged in the hot cold work range. Sheet bars produced by forging primarily at very high temperatures 3850°F, were low rated on the basis of grain size, carbide distribution and rollability while sheet bar forged at low temperatures 2000 to 2700 were low rated primarily because of low receystallization temperatures

TABLE V

PHASE III AND IV

QUALITY RATING FOR INFAB TZM

SHEET BAR Forging Practice	Yield (1-2)	Hardness Uniformity-As Forged	Grain Size Uniformity-Macro Disc (1-3)	Recrystallization Temp. (1-3)	Carbide Distribution (1-4)	Reliability (1-4)	Sub Total 1	Sub Total 2A Average	Sub Total 1	GRAND TOTAL
1098A1 3850-3200	2	2	2	3	2	2	13	16.61	13	29.61
1098A2 3850-2700	2	3	1	3	2	3	14	15.40	14	29.40
1098A3 3850-2300	2	3	1	3	2	4	(15)	(16.5)	15	31.5
1098B1 3200-2950	2	(4)	(3)	3	3	3	(18)	(18.41)	18	36.41
1098B2 3200-2300	2	3	2	1	4	4	(16)	(18.10)	16	33.85
1098B3 2700-2400	2	2	2	1	3	4	14	15.4	14	29.4
1098B4 2300-2000	2	1	2	1	3	4	13	14.5	13	27.50
1099A 3550-2400	2	2	2	2	1	3	12	16.92	12	28.92
1099C 3850-2770	1	3	1	3	1	4	13	15.82	13	28.82

Sheet Bar	HOLD OUT	Rolling Temp. x 10^2	Carbide Dist. (1-3)	Sonic Rating (1-3)	Recrystallization Temp. (1-10)	Recrystallized Grain Size (1-5)	Tensile Elongation Rating	Hardness Stability With Annealing Temperature	Sub Total 2
1098A1	T1	32	1	3	9	2	.72	1	16.72
1098A1	T3	24	1	1	7	4	2.5	1	16.5
1098A2	T5	32	1	3	9	2	.6		15.6
1098A2	T6	28	1	3	5	4	2.66		15.66
1098A2	T8	20	1	2	5	5	2.0		15.40
1098A3	T9	32	2	3	9	2	1.66		17.66
1098A3	T10	28	2	1	9	2	2.33	1	17.33
1098A3	T11	24	2	2	5	4	2.86		15.86
1098A3	T12	20	2	1	4	5	3.16		15.16
1098B1	T13	32	2	3	9	2	1.4		17.4
1098B1	T14	28	3	3	7	3	2.84	1	19.84
1098B1	T15	24	3	1	7	4	2.0	1	18.0
1098B2	T17	32	3	3	8	2	2.5		18.5
1098B2	T18	28	3	3	7	2	2.72		17.72
1098B2	T19	24	3	3	4	4	4.33		18.33
1098B2	T20	20	3	3	3	5	3.86		17.86
1098B3	T21	32	2	1	8	2	1.0		14.0
1098B3	T22	28	2	3	5	2	2.42		14.42
1098B3	T23	24	3	3	2	4	3.0		15.0
1098B3	T24	20	3	3	2	5	3.8		16.8
1098B4	T25	32	2	2	5	2	1.25		12.25
1098B4	T26	28	2	3	7	2	2.5		15.5
1098B4	T27	24	2	2	2	(5)	4.66		15.66
1098B4	T28	20	2	3	2	5	3.42		15.42
1099A	T34	28	1	3	7	4	2.84		17.84
1099A	T35	24	1	3	4	(5)	3.0		16.0
1099C	T38	28	2	2	7	3	1.56	1	16.56
1099C	T39	24	2	2	5	4	2.5		15.5
1099C	T40	20	2	3	4	5	1.42		15.4

which would undoubtedly be transmitted to finished sheet. Sheet bar produced by direct ingot forging were also low rated due to coarse non uniform carbides and structures. In addition sheet bar forged directly from ingot contained more surface contamination (both iron and interstitial) as many more forging blows and reheats were required. Though a rating was not applied for degree of contamination it is a factor in the choice of forging or rolling variables for the Phase V program.

Although the grain size of hot forged sheet bar was more coarse than the recrystallized grain size of hot-cold forged sheet bar, this difference had little effect on the grain size of recrystallized mold out (Table V). The recrystallized mold out grain size was instead more dependent upon rolling temperatures. However, the sheet bar forging practice did have considerable influence on other mold out properties such as recrystallization temperature, carbide distribution and tensile ductility. On the basis of these properties the three sheet bar rated as highest quality were also equal or superior to other sheet bar practices in mold out form, sub totals 2 and 2A of Table V.

Individual mold out sections with stand out ratings were T9 and 10, T14 and 15, and T17, 18, 19 and 20 all rolled from the three top quality sheet bars. The latter four in particular, all rolled from sheet bar 1098B2 (forged at 3200 to 2300°F) exhibited the most consistently good quality ratings for any one group of mold out sections. The mold out section exhibiting the very highest quality rating, T14, was rolled at 2800°F from sheet bar entirely hot forged in the 3200°F range.

A cursory examination of Table V for outstanding individual property ratings as indicated by check marks reveals that in almost every case the standout values for recrystallization, elongation, etc., occurred in mold out rolled either at 2400 or 2800°F. Of particular note, was the fact that tensile ductility of mold out improved as rolling temperatures decreased to 2400°F but a further decrease to 2000°F did not result in any further ductility improvement.

IV Phase V Program

The overall objective of this investigation is to develop an improved TZM alloy sheet product through the use of the InFab facility. Primarily this means the evaluation of higher processing temperatures then those available for present commercial TZM practice. The proposed Phase V Program design resulting from the Phase III and Phase IV evaluation is shown in Figures 9 and 10. A total of 35 variables to .040" sheet are incorporated. Evaluation of reductions is limited to two and there is no evaluation of intermediate anneals as both parameters have been fully evaluated on previous programs,[1] the results of which have been considered in this program design. Forging and rolling variables incorporated

(1) Navy Sheet Rolling Program Contract NOas 59-6142-C

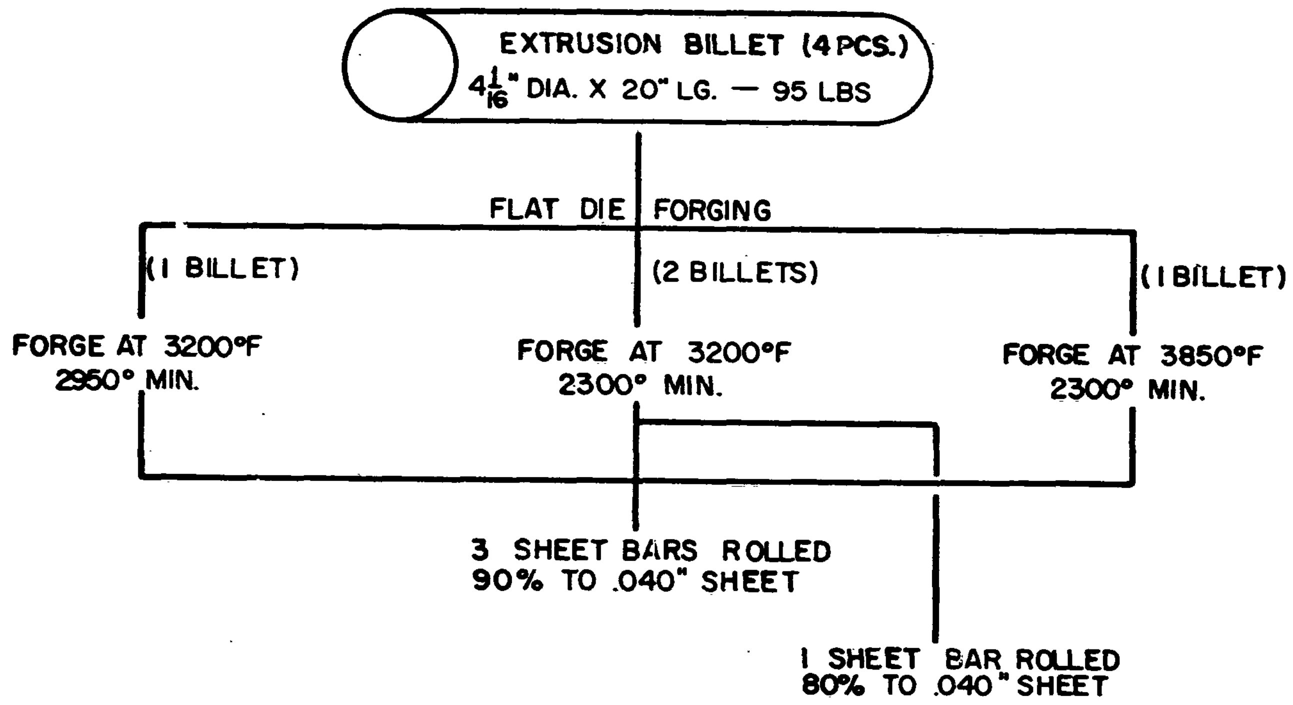


FIGURE 9

PHASE V FORGING VARIABLES

RTA-0315

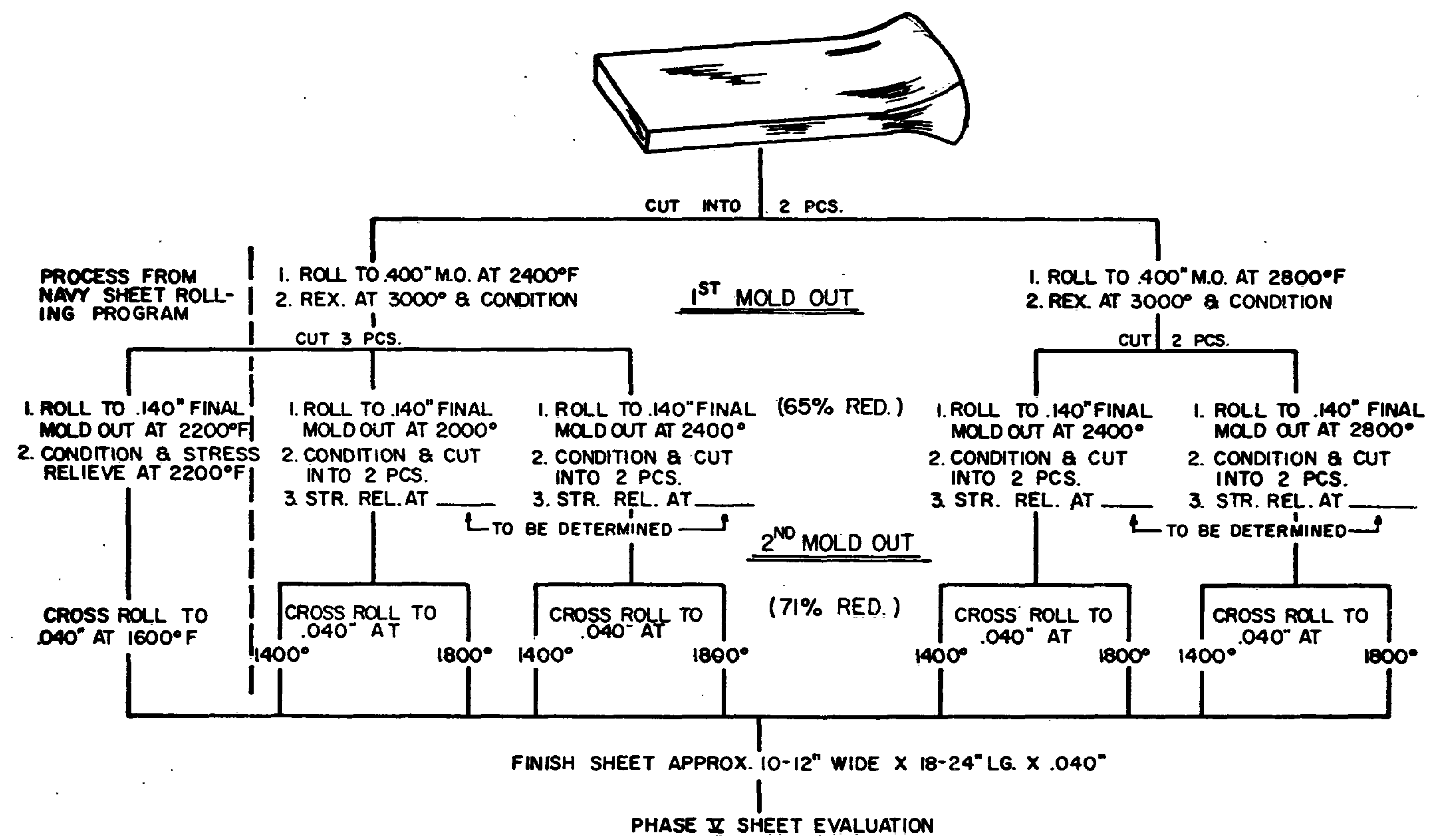


FIGURE 10

PHASE V SHEET ROLLING VARIABLES

RTB-0038

from Phase III and IV are as follows:

Sheet Bar - Three best practices from Phase III

1. 3250 start, 2950°F min. (2 pcs)
2. 3250 start, 2300°F Min. (1 pcs)
3. 3850 start, 2300°F Min. (1 pcs)

Mold Out - Two best Phase IV practices

1. 2400°F
2. 2800°F

Recrystallized mold out will then be rolled to final mold out at temperatures ranging from 2000 to 2800°F. Stress relief temperatures will be determined and final sheet produced at two temperatures 1400 and 1800°F. In addition one section from each sheet bar will be rolled to sheet according to the process developed on the Navy's Molybdenum Sheet Rolling Program. The .040" sheet produced from the 3 forging practices will contain a total of 90% reduction from recrystallized mold out. An additional reduction will be evaluated however by rolling a fourth sheet bar (from the 2nd forging practice Figure 9) to the same temperature schedule in Figure 9 but to a total of 80% reduction in .040" sheet.

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