NEW TECHNIQUES FOR PROCESSING METALS

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EXTRUSION OF HIGH TEMPERATURE MATERIALS

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Introduction

The activity and technological advancement in the field of refractory metals, that is, molybdenum, tungsten, columbium, and tantalum, during the past two years is quite evident, even though the inherent problem areas of oxidation, protective coatings, joining, and room temperature brittleness are far from solution.

In the development of refractory alloys, like other base metal systems, the quality of the raw material, or ingot, is one of the major factors that control the effectiveness of the end product. The advancements in this area have been most pronounced. Conversely, commercial extrusion capability has not kept pace with alloy development nor the increased size and quality of refractory metal ingots.

Complete details of the current extrusion techniques and the metallurgical evaluation of the effects of extrusion variables on the secondary workability of the TZM alloy and the Mo-25W-.1Zr-.02C alloy will soon be published (5). This work will be reported by Harvey Aluminum, Incorporated, who operate and maintain the extrusion facility at the Directorate of Materials and Processes. In addition to accomplishing their own program with the TZM and the Mo-25W-.1Zr-alloy, Harvey Aluminum personnel have performed "service type" extrusion work for the Directorate of Materials and Processes alloy development program contractors and a variety of work sponsored by other governmental agencies.

When reference is made to the Directorate of Materials and Processes, it encompasses the specific program being conducted by Harvey Aluminum and work generated by the various co-operative programs listed in table 1.

Commercial Production Capability

As a general rule, high temperature materials denote high temperature processing, particularly with regard to the initial breakdown of the as-cast structure of refractory metals. Materials Advisory Board Reports of the Committee on Refractory Metals have consistently stressed the need to raise extrusion temperature capabilities. Until the recent installation of a 200 KW, 3000 cycle, induction heating station at the E.I. duPont deNemours extrusion facility (2) and a 60 cycle, 7500 KW, unit being installed at Curtiss-Wright (2), commercial production facilities were generally limited to a 2300°F-2600°F billet heating capability. There are, however, many reasons for this delay to increase billet heating capabilities. The most prevalent reasons being: (a) only glass lubrication appeared to be practical above 2400°F, which required a financial burden for license rights (b) specific quantity requirements could not be ascertained for a reasonable cost analysis of equipment modification amortization (c) the high volume materials, unalloyed molybdenum, and Mo-.5Ti could be satisfactorily extruded with conventional equipment, and (d) the die problem appeared formidable for extrusion above 2500°F.

Some of the earliest molybdenum extrusion work was performed by the Babcock and Wilcox Company, Tubular Products Division. A condensed "recap" of extrusion data, pertaining to work performed during the period 1957-1959, is shown in table 2. Considering the fact that refractory metal extrusion was in its embryonic stage and makeshift material handling was utilized, a wide variety of alloys were successfully extruded. Most of these alloys were of an experimental nature and subsequently discarded; however, a great deal of knowledge was gained to advance the state of the art.

The Canton Drop Forge & Manufacturing Company has produced the greatest amount of refractory metal extrusions (1). Tons of unalloyed molybdenum and the Mo-.5Ti alloy have been extruded at Canton. Table 3 depicts the current capability with regard to billet size and extrusion ratio at 2300°F, the current temperature limitation. Although the 2300°F limitation dictated the extrusion of the "tougher" materials at lower extrusion ratios, this facility has served as the major producer of wrought refractory metals for several years. The successful extrusion of refractory metals into sheet bar was a highly desirable advantage for sheet rolling.

The new E. I. duPont deNemours extrusion facility has been in operation for a short time and the scope of the production capacity or specific refractory metals being extruded has not been determined. This facility certainly possesses a great potential in the extrusion of refractory metals as evidenced by the available information of the equipment already in operation (2,6):

a. 2500 Ton, high speed (10 in/sec), extrusion press

b. 200 KW, 3000 cycle, induction billet heater

c. 4000°F maximum billet temperature

d. 8.5" dia. x 24" long, maximum billet size

Work under the Columbium Extrusion Development Program sponsored by AF Contract 33(600)-40700 is being accomplished at this facility. Six ingots (7.75" dia. x 16-20" long) of the D-31 alloy (Cb-10Ti-10Mo) have been extruded at approximately a 5:1 ratio. The D-31 alloy has been extruded utilizing a .250-inch thick, mild steel can with very good results. It is anticipated that the final D-31 "T" shape will be extruded from a wrought billet. This facility is a Ugine-Sejournet licensee and details of lubrication are not available.

Pilot Plant and Research Laboratory Extrusion Facilities

The most significant advances in the high temperature extrusion (2500°F) of refractory metals has been accomplished in the pilot plant type facilities and/or research laboratories. The Allegheny Ludlum Steel Corporation (1,778 ton press) and the General Electric Research Laboratory (1,250 ton press) could be classified in a production category; however, insufficient detailed information regarding the production output is available. Most of the available literature of these two organizations pertains to extrusion work performed in container, liner sizes not greater than 4-inch I.D. and are considered as pilot plant type facilities in this presentation.

The Thompson Ramo Wooldridge Research Laboratory (700 ton high speed press) and the Directorate of Materials and Processes (700 ton high speed press), Aeronautical Systems Division, Wright-Patterson AFB, Ohio, are the two most active laboratory facilities engaged in the high temperature extrusion of refractory alloys. The Super Alloy Forge, Inc., Hamburg, Michigan, possesses mechanical presses of 1000 ton (horizontal) and 400 ton (vertical) capacity (1). Some very interesting work in the extrusion of refractory metals has been accomplished by Super Alloy Forge and warrants a rather detailed discussion. This will be presented as a separate item of discussion later in the text.

Although differences do exist in equipment size, operational limitations, and techniques utilized, several aspects of general operation are shared in common. Relatively high ram speeds, conical dies, refractory coated dies, and glass lubrication are used to varying degrees by all five organizations. The most significant accomplishments or pronounced differences will be presented for each of the organizations:

The Allegheny Ludlum Steel Corporation

The Allegheny Ludlum Steel Corporation is a Ugine-Sejournet licensee and most of the published information regarding their work is derived from technical reports under government sponsored contracts. The following are considered to be the most significant results obtained in the Air Force "Molybdenum Alloy Extrusion Development Program" with the Mo-.5Ti-.08Zr-.02C alloy:

	TEMP	RATIO	SHAPE
ARC CAST	3740°F	11.4:1	ROD
WROUGHT	2900°F	17.25:1	ROD

A detailed report regarding the above work will be published soon (7).

The room temperature hardness of the wrought material was 206 DPH; billet length was 4.5 inches in a 3 7/8-inch container liner; a flat face die was used. The ability to extrude a "T" shape approaching commercial tolerances required for steel and titanium by utilizing wrought billets is certainly promising with this approach. The successful extrusion of some of the high strength refractory alloys currently being developed may require the adoption of this approach at considerably lower extrusion ratios.

General Electric Company Research Laboratory, Schenectady, New York

The General Electric Research Laboratory has been actively engaged in the hot extrusion of refractory metals, intermetallic compounds, and a variety of proprietary materials. The major portion of their work is of a semi-proprietary nature and consequently has not been published with any great amount of detail. Unalloyed arc-cast tungsten has been extruded at 3000°F and a 5.5:1 reduction (8). The F-48 alloy is being extruded on a production basis in molybdenum cans and a 4:1 extrusion ratio at 2800°F. They have also extruded a considerable amount of the TZC alloy (Mo-1.25Ti-.1Zr-.018C). General Electric has extruded the Mo-W series of alloys in conjunction with the Air Force alloy development programs with Climax Molybdenum. Glass lubrication and conical shaped dies are used. The extent to which ceramic coated dies are utilized is not known. The General Electric Research Laboratory is active in many areas of material development and a considerable amount of press time is absorbed by internal programs.

Thompson Ramo-Wooldridge, Inc. Research Laboratory

The Thompson Ramo-Wooldridge Research Laboratory has been a pioneer in the hot (3000°F) extrusion of refractory metals. The utilization of ceramic coated dies has led to the successful extrusion of the 85W-15Mo alloy with negligible die wash at 4000°F and extrusion ratios of 5:1-8:1. TRW is actively engaged in the "Tungsten Forging Development Program", Contract AF 33(600)-41629 (9,10). A considerable amount of experience in the extrusion of tungsten and tungsten alloys was derived through an extrusion program with NASA. Most of the initial columbium alloy extrusion development for duPont was done by the TRW Research Laboratory. This phase of work included a large number of alloys for experimental screening.

The TRW Research Laboratory has always differed significantly from other research extruders in that they have been the pioneers in utilizing higher temperatures, greater extrusion ratios, and higher ram speeds, that is 4000°F, 6:1-10:1, and ram speeds greater than 10 in/sec under load. Considerable die wash was experienced in this approach during the early work. New developments in refractory metal and/or ceramic die coatings have resulted in negligible die wash (.010"-.015") in the extrusion of the 85W-15Mo alloy at 4000°F and extrusion ratios of 6:1 to 8:1.

One of the novel techniques used by TRW is the utilization of the oxide formed on the surface of the billet as a lubricant, during the transfer from the heating station to the press. A current report (10) indicates that a lubrication study is contemplated.

The Super Alloy Forge, Inc., Hamburg, Michigan

An extremely interesting report (11) by E.J. Dulis and A. Kasak, Central Research Laboratory, Crucible Steel Company, includes detailed information on the extrusion of a tungsten, tantalum, molybdenum, and columbium series of new alloys. All of the extrusion work was performed by The Super Alloy Forge, Inc. The techniques used in the extrusion work are not only novel but indicative of the current trend in the approach to the solution of high temperature extrusion. The detailed description of the procedures and techniques utilized is highly commendable. A list of the alloys included in this work is shown in table 4.

The work was performed in a 400 ton vertical mechanical press with a six-inch ram stroke. Ram speeds at no load averaged 1200 in/min. The average size of the extrusion blanks was 1-inch O.D. x 1.5-inch long. Extrusion ratios ranged from 2.7:1 to 4:1, the majority at approximately 3:1. Carbon blocks were used as back-up material for most extrusions and Armco iron blocks were used for the most difficult materials to extrude.

The induction heater station was powered by a 100 KW, 9600 cycle unit with high pressure water cooling of the induction coil. The furnace tube was made of "KT" silicon carbide insulated from the induction coil by a .250-in. thickness of high temperature felt. Woven "Fiberglas" covered the induction coil and temperatures greater than 4000°F could be attained. An argon atmosphere was maintained in the heating chamber and billet temperatures were based on a time and power basis obtained by previous experimentation. Oxidation during heating was sufficient to eliminate optical pyrometer readings for each extrusion blank. The billets extruded at lower temperatures (2500°F and 3100°F) were precoated with a glass lubricant. Billets heated from 3500°F to 4000°F were plasma flame sprayed with a molybdenum coating from .010 inch to .015 inch thick.

Hardened hot-work steel dies (H-12) were used for extrusions up to 3100°F. A .010-inch thick layer of tungsten plus a .015-inch thick layer of molybdenum was plasma flame sprayed on dies for the higher temperature extrusions. The dies were designed with a 70 degree included entrance angle.

During the initial work, the transfer time* was 6 to 10 seconds. The cooling rate of the extrusion blanks at 4000°F was estimated to be 160°F/sec. In order to circumvent this temperature drop, an automatic device was constructed that reduced the transfer time to 1 to 2.5 seconds.

The tungsten and tungsten-tantalum rich alloys were the most difficult to extrude above 3500°F and were prone to transverse cracking. Although the as-cast harness of the tungsten and tungsten-tantalum rich alloys ranged from 370 to 450 DPH, none of the extrusion blanks shattered under impact during the extrusion runs.

Directorate of Materials and Processes, ASD, Ohio

During the past two years, the development of new techniques for the extrusion of refractory metals has progressed from steel dies and grease lubrication, with optimum extrusion temperatures of 2400°F, to ZrO_2 coated dies and an all-glass lubrication with optimum extrusion temperatures of 3400°F to 3600°F. Two Mo-25W-.1Zr billets were extruded recently with a negligible die wash of .010 inch to .012 inch. The effectiveness of the glass lubrication at this temperature has not been determined, although surface conditions were comparable to some extrusions performed at lower temperatures. Front to back dimensions were within .010 inch to .015 inch.

The evolution of the extrusion techniques developed at the Directorate of Materials and Processes is described in detail in the progress and technical reports by Harvey Aluminum (5,12,13,14). Similar information is contained in the presentations being given at this technical conference and in a number of technical reports derived from refractory alloy development programs sponsored by the Air Force (15,16).

The operational capabilities and/or limits of the basic units of equipment and the glasses used for lubrication are shown in table 5. Flame sprayed Al_2O_3 coated dies are considered satisfactory up to 3400°F. Flame sprayed ZrO_2 coated dies have shown .010 inch to .015 inch die wash at 4100°F on two occasions and the temperature limitation has not been determined.

Molybdenum and Tungsten Base Alloys

More than 300 refractory metal billets have been extruded at the Directorate of Materials and Processes in the past two years. An effort has been made to determine a correlation of extrudibility to various properties of refractory metals, that is, hot hardness, recrystallization temperature, grain size, solid solution versus precipitation hardening type alloys, and others.

Analysis of available data has not substantiated any firm conclusion. This is not too surprising when one considers the many variables involved. The heterogeneous structure of the refractory metals and the many variables involved during the casting, conditioning, extruding, and even packing and shipping, tend to complicate the problems.

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* Elapsed time between removal from furnace and completion of the pressure stroke.

Table 6 lists some of the alloys extruded at various temperatures and extrusion ratios with the best weight percentage recoveries obtained. This is a representative sample of the general results obtained.

It can be stated that molybdenum base alloys are relatively easy to extrude; in fact, reproducible high weight percentage recoveries have been established for all molybdenum alloys extruded. The tungsten base alloys have been extruded with lower weight percentage recoveries and more difficulty. The two 85W-15Mo extrusions, identified as stickers in table 6, were partial extrusions of less than 50 percent. The W-.1Zr-.01C alloy could hardly be moved at temperatures up to 3600°F at a 4:1 extrusion ratio. Almost all of these difficult-to-extrude billets fractured when ejected from the container liner, indicative of brittleness at high temperatures. The capability of the ZrO_2 coated dies to withstand temperatures above 4000°F will result in an improvement for tungsten extrusions. Some work has already been done at 3600°F and 3750°F, but the analysis was not completed in time for inclusion in this report.

Sintered Molybdenum and Tungsten

Table 7 lists the sintered molybdenum, tungsten, and 50Mo-50W billets extruded at various temperatures and extrusion ratios. The extrusion of the 70 percent dense, unalloyed molybdenum billets was unsuccessful, although some sound material was salvaged from the back end of the 6:1 extrusion. It may be possible successfully to extrude the low density, sintered molybdenum (70 percent) at higher temperatures, greater extrusion ratios, and with the utilization of relatively cold (1400°F) steel nose plugs.

There was a remarkable difference in extruding the high density molybdenum. The extrusion planning to these billets was based on arc-melted material. The extruded surfaces were excellent, with practically no evidence of nose burst. No internal defects were found. Although the 50Mo-50W extruded rod had a rough surface due to die wash, the extrusion was sound.

Both of the commercially pure tungsten billets had good surfaces. The 93.3 percent dense material had an internal, non-closure, approximately seven inches long from one edge to the other in the transverse plane. This non-closure was approximately .250 inch away from the center of the extrusion. It is difficult to determine whether the defect was due to the difference in density or to the small defects indicated during inspection. Ultrasonic inspection prior to extrusion indicated two slight defects but at approximately .750 inch from each end of the billet and approximately in the center of the billet.

The difference between the two W + 1% ThO_2 billets was quite evident. The difference in extrusion temperature and ratio was expected to have its effects; however, the front end of the 89 percent dense extrusion was torn severely and pieces from the extrusion were lying in the run out tube.

The extruded section of the W + 1% ThO_2 (97.5% dense) exhibited complete recrystallization at the outer edge of the rod to a depth of approximately .060 inch. Three sections of the extrusion were side flattened with height reductions of 68 percent, 82 percent, and 85 percent at 2600°F on a hydraulic forge press. No defects were observed at the 68 percent reduction and minor cracks at the leading edge were evident on the pieces with 82 percent and 85 percent reduction. The recrystallization temperature of the forged material was 3200°F. This material exhibited good surfaces throughout the processing cycle. Sound specimens of the 89 percent dense (W + 1% ThO_2) and the 93.3 percent dense (C.P.-W) were forged under the same conditions at a 50 percent reduction in height. Gross cracking on all edges resulted. Additional work is being done and will include rolling of sound material. The workability of the high density (97.5%) W + 1% ThO_2 was quite pronounced.

REFERENCES

1. Santoli, P.A., "Molybdenum Alloy Extrusion Program," Allegheny Ludlum Steel Corporation. ASC* Interim Report 7-785(I), October 1960.
2. Dana, A.W., Jr., "Columbium Alloy Extrusion Program," E.I. duPont deNemours. ASC Interim Report #1 (Parts I and II), Contract AF 33(600)-40700, 30 June 1960.
3. "Tantalum Alloy Extrusion Program," Wah Chang Corporation. ASC Contract 33(600)-42369 (to be published soon).
4. "Tungsten Alloy Extrusion Program," Wah Chang Corporation. ASC Contract AF 33(600)-42395 (to be published soon).
5. Long, J.R., Tombaugh, R.W., and Green, R.C., "Development of Optimum Methods for the Primary Working of Refractory Metals," Harvey Aluminum, Inc. WADD Technical Report 60-418 Part II (to be published soon).
6. Dana, A.W., Jr., "Columbium Alloy Extrusion Program," E.I. duPont deNemours. ASC Technical Report 7-775(II), 16 February 1961.
7. Santoli, P.A., "Molybdenum Alloy Extrusion Program," Allegheny Ludlum Steel Corporation. ASC Interim Report 7-785 (II) (to be published soon).
8. Noesen, S.J., and Hughes, J.R., "Arc-Melting and Fabrication of Tungsten." Transactions of the AIME, Vol. 218, pp. 256-61, April 1960.
9. "Tungsten Forging Development Program," Thompson Ramo-Wooldridge. ASC Interim Report 7-797(I), 31 August 1960.
10. Lake, F.N., and Bresnyak, E.J., "Tungsten Forging Development Program," Thompson Ramo-Wooldridge. ASC Interim Report 7-797(III), March 1961.
11. Dulis, E.J., and Kasak, A., "Research on Workable Refractory Alloys of Tungsten, Tantalum, Molybdenum, and Columbium," Crucible Steel Company. WADD Technical Report 61-134, April 1961 (in preprint status).
12. Simonson, R.B., Long, J.R., Tombaugh, R.W., and Green, R.C., "Development of Optimum Methods for the Primary Working of Refractory Metals," Harvey Aluminum, Inc. WADD Technical Report 60-418, August 1960.

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* Metallic Materials Branch, Manufacturing and Materials Technology Division, Wright-Patterson AFB, Ohio.

REFERENCES (Cont'd)

13. Tombaugh, R.W., and Green, R.C., "Development of Optimum Methods for the Primary Working of Refractory Metals," Harvey Aluminum, Inc., Progress Report No. 3, WADD Contract AF 33(616)-6377, October 1960.

14. Tombaugh, R.W., and Green, R.C., "Development of Optimum Methods for the Primary Working of Refractory Metals," Harvey Aluminum, Inc., Progress Report No. 4, WADD Contract AF 33(616)-6377, February 1961.

15. Semchyshen, M., and Barr, R.Q., "Extrusion and Mechanical Properties of Some Molybdenum and Tungsten Base Alloys," Climax Molybdenum Company, WADD Technical Report 61-193, March 1961.

16. Ogden, H.R., and Maykuth, D.J., "Scale-Up of Tantalum-Base Alloys," Battelle Memorial Institute, Second Quarterly Progress Report, Contract AF 33(616)-7452, 15 January 1961.

17. Toaz, M.W., Davies, G.F., and Johnson, R.D., "Production of Extrusion Billets of High Temperature Aircraft Alloys by Powder Metallurgy," Clevite Corporation, ASC TR 60-7-764, December 1960.

TABLE I

LIST OF VARIOUS EXTRUSION WORK PERFORMED AT THE DIRECTORATE OF MATERIALS AND PROCESSES

NASA — C.P.—W, canned in steel

G.E. Lamp Division (Navy)
Sintered billets of: Mo, W, W + 1% ThO_2,
and 50 Mo – 50W, 4:1 – 8:1,
2100° F – 3400° F

Naval Research Laboratory
Ti – 1.5V – 15Al, and Ti – 8Mn
canned in mild and stainless steel

Kawecki Chemical Co. (AF)
C.P. Tantalum at 1800° F and
room temperature

Clevite Corporation (AF)
Ph 15–7Mo and Rene 41 unsintered,
70% dense

National Research Corp. (Navy)
90Ta–10W, 85Ta – 15 W, 80Ta–20W
from 2500° F to 3150° F

Westinghouse Electric (AF)
Cb – 1Ti – 1Zr – 5Hf
Canned in steel at 1800° F

Armour Research (Navy)
C.P.— Mo, 70 % dense

G.E., Evendale (AF)
TZC alloy, 7:1, 2900° F
Mo – .5Ti, 7:1, 2700° F

Republic Aviation (AF)
93 W – 7Mo, 5:1, 3400° F

Crucible Steel (AF)
F – 48, canned in Mo, Ti – 110AT, 316 stainless,
and mild steel at 3000° F, 2600° F, and
2300° F and 4:1

Universal Cyclops (AF)
C.P. – W at 3000° F, 4:1, bare and mild
steel can

Climax Molybdenum (AF–Navy)
W – Mo series, and TZC alloy
Mo–1.5 Cb–.5Ti–.3Zr–.3C
Mo–1.5 Cb–.5Ti–.3C

Bendix (AF)
Cerametalix 2400–30 (Cr base + MgO,
90% dense), 6:1, 8:1, 10:1, and 12:1,
and 2000° F and 2200° F

Manufacturing Laboratories (AF)
C.P. – Mo – C.P.–W, 2500° F – 3200° F

( ) – Sponsoring Government Agency

TABLE 2

THE BABCOCK AND WILSON COMPANY EXTRUSION DATA ON COMMERCIALLY PURE MOLYBDENUM AND MOLYBDENUM ALLOYS

MATERIAL	BILLET DIAMETER	REDUCTION RATIO	BILLET TEMP (°F)	EXT. PEAK	PRESSURE AVERAGE	EXT. RATE (I. P. S.)
C.P. – Mo	6.5	3.71/1	2460	1970	1600	—
C.P. – Mo	6.5	3.24/1	2540	1300	—	10.4
C.P. – Mo	7.0	3.74/1	2420	1650	1550	8.0 – 10.4
Mo + 1.25% V	6.970	2.91/1	2540 (est)	1820	1520	3.0
Mo + .7% V	6.5	3.24/1	2540	1970	1680	—
Mo + .7% V	6.5	2.84/1	2620	1500	—	10.8
Mo + .2% Zr	6.97	2.84/1	2550 (est)	2030	2030	—
Mo + .5% Ti	6.97	2.84/1	2550 (est)	1620	1530	—
Mo + 1.25% Ti	6.97	2.91/1	2550 (est)	1830	1640	2.6
Mo + 2.0% Ti	6.97	2.84/1	2550 (est)	1800	1600	—
Mo + .1% Co	6.97	2.91/1	2550 (est)	1520	1400	3.2
Mo + .6% Al	6.97	3.29/1	2550 (est)	1120	1120	3.6
Mo + 1.25% Cb	6.97	2.84/1	2550 (est)	1790	1680	—
Mo + 2% W + .04% Cr	6.97	2.84/1	2580	1380	1260	—

(Glass lubrication utilized for this work.)

TABLE 3

THE CANTON DROP FORGE & MFG. COMPANY EXTRUSION DATA

ALLOYS	RATIO TEMP(°F)	RAM SPEED	PRESSURE (Tons/in^2)	LUBRICANT	DIE MATERIAL	REMARKS
Toughest W alloy 85 W-15 Mo	2.8:1 2300	200 in/min	65	Fiske #604	H-12	Comparatively good surfaces. Very little nose cracking. Ultimate wt. % recovery not known
Largest W Billet Unalloyed W 5 5/8" dia.	4:1 2300	200 in/min	51	Fiske #604	H-12	
Toughest Mo alloy 50Mo-50W	4:1 2300	200 in/min	37	Fiske #604	H-12	Cracked practically full length.
Largest Mo Billet Unalloyed Mo 16" dia.	3:1 2300	150 in/min	30	Fiske #604	H-12	Good as extruded surface. Ultimate wt. % recovery not known.
Toughest Cb alloy 80 Cb-10Ti-10Mo	4.5:1 2300	150 in/min	50-60	Fiske #604	H-12	Good as extruded surface. Tail end cropping only. Ultimate wt. % recovery not known
Largest Cb Billet Cb-1%Zr 14 3/8" dia.	3.16:1 2300	150 in/min	30	Fiske #604	H-12	

1.9" x 5.5", 2.5 x 8", 3.1" x 8", and 3.5" x 8", and 3.75" x 8" sheet-bars have been extruded from 7 1/2", 9", and 11" diameter ingots of unalloyed molybdenum, Mo-.5Ti, and Cb-1% Zr. Maximum ratio was 5.9:1. Lubrication, ram speeds, and die materials were as shown above. Temperatures were 2200° F and 2300° F and pressures did not exceed 58 Tons / in^2

TABLE 4

REFRACTORY ALLOY COMPOSITIONS IN CURRENT DIRECTORATE OF MATERIAL AND PROCESSES ALLOY DEVELOPMENT PROGRAMS

Battelle Memorial Institute
Contract AF 33(616)-7452

Ta-10Hf-5W
Ta-30Cb-7.5V

Battelle Memorial Institute
Contract AF 33(616)-5888

Ta-30Cb-5V
Ta-30Cb-10V
Ta-1Zr
Ta-10V
Ta-10V-5W
Ta-10Hf-1Zr
Ta-10Hf-5Mo
Ta-30Ti-5Al
Ta-40Ti-5Al
Ta-40Ti-10Al
Ta-30Ti-5Al-5Cr

Westinghouse Electric Corp.
Contract AF 33(616)-6933

$W-2ThO_2$
$W-4ThO_2$
$W-5ThO_2$
W-1TaC
W-2WB
$W-.5B_4C$
W-.5ZrC
W-.5CbC
$W-.5HfO_2$
$W-.2TiO_2$
W-.15TiC
$W-1.0ZrO_2$

Crucible Steel Company
Contract AF 33(616)-6172

W	Ta	Mo	Cb
100	—	—	—
75.3	24.7	—	—
50.4	49.6	—	—
25.3	74.7	—	—
—	100	—	—
88.8	—	—	11.2
68.2	20.6	—	11.2
44.2	44.4	—	11.2
20.7	68.1	—	11.2
—	88.6	—	11.4
88.4	—	11.6	—
68.0	20.4	11.6	—
44.2	44.2	11.6	—
20.4	67.9	11.7	—
—	88.3	11.7	—
88.6	—	5.7	5.7
68.1	20.5	5.7	5.7
44.3	44.3	5.7	5.7
20.6	68.0	5.7	5.7
—	88.6	5.7	5.7

Westinghouse Electric Corp.
Contract AF 33(616)-6258

Cb-5Ti
Cb-7.5Ti
Cb-20Ti
Cb-10Zr
Cb-20Zr
Cb-10Hf
Cb-1.25Cr
Cb-2.5Cr
Cb-5Mo
Cb-10Mo
Cb-20Mo
Cb-10W
Cb-20W
Cb-2Re
Cb-10Re
Cb-18Re
Cb-.6Al
Cb-1.5Al
Cb-2.5Al
Cb-1Y
Cb-5V-5Mo
Cb-5V-5Mo-1Zr
Cb-5W-5V
Cb-5W-5V
Cb-5W-5V-1Zr
Cb-5Hf-5V
Cb-5Zr-5V
Cb-5W-5Hf-5V

TABLE 4 (Cont'd)

Climax Molybdenum Company
Contract AF 33(616)-7930

Mo-1.5Cb-.5Ti-.3Zr-.05C
Mo-2Ti-.3Zr-(.07C, .14C, and .21C)
Mo-3Ti-.5Zr-.3C
Mo-25W-1.25Ti-.3Zr-.15C
Mo-50W-1.25Ti-.3Zr-.15C
Mo-25W-1.25Ti-.3Zr-1.5Cb (.05C, .1C, and .15C)
Mo-50W-1.5Cb-1.25Ti-.3Zr-.15C
W-(.01-.03Zr)-.01C
W-5Ta - Zr to be
W-5Cb - determined
W-5Cb-5Ta-

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Mo-25W-.1Zr-.03C
Mo-1.25Ti-.3Zr-.15C
Mo-5Cb-.02C
Mo-50W-.01C
W-30Mo-.01C
W-10Mo-.01C
W-.01C

Mo-.01C
Mo-.5Zr-.02C
Mo-.5Ti-.07Zr-.02C
W-.1Zr-.01C
W-.5Cb-.01C
W-10Ta-.01C

TABLE 5

DIRECTORATE OF MATERIALS AND PROCESSES

EXTRUSION EQUIPMENT AND OPERATIONAL CAPABILITIES

High Speed Horizontal Extrusion Press

Rated Peak Capacity	700 Tons
Rated Working Capacity	600 Tons
Working System Pressure	3000 psi
Ram Speed	up to 900"/min
Container Size	3 1/16" I.D. — 15" long
Container Temperature	1000°F max
Stem Size	3"

Heating Stations

Ajax, Induction, 30KW, 4200 cycle	4000°F (argon)
Harrop, Globar, Semi-portable (Fire Curtain and Argon)	3000° F max 2800° F normal
Pereny, Globar (Argon)	2000°F max
Hevi Duty, Globar (Argon)	2500°F max

Glass Lubrication

Corning Glass No.	Ext. Temp. Range (°F)
7570	1100-1500
8871	1250-1900
0010	1900-2450
7052	2400-3100
1720	2500-3200
7740	2950-3600
7810	Under study
7900	Under study

TABLE 6

WEIGHT PERCENT RECOVERY OF REFRACTORY ALLOYS EXTRUDED AT VARIOUS TEMPERATURES AND RATIOS

Mo-.5Ti-.08Zr-.02C(d)			Mo-.5Ti-.08Zr-.02C(e)		
2800(a)	4:1(b)	81%(c)	2600	4:1	60.3%
3000	8:1	89.5%	2750	4:1	61.9%
3000	6:1	88.5%	2900	4:1	55.6%

Mo-25W-.1Zr-.03C			Mo-25W-.1Zr-.02C		
2600	4:1	70.5%	2600	4:1	76%
2800	5:1	63.9%	3000	5:1	79%
3000	6:1	94.5%	3200	6:1	89%
3200	7:1	80.1%	3600	8:1	89%
3200	8:1	87.1%			

50Mo-50W-.01C			W-30Mo-.01C		
2000	4:1	67.4%	2600	4:1	74.6%
2200	4:1	69.2%	3000	4:1	67.2%
3200	6:1	66.5%	3200	4:1	73.2%
			3200	5:1	51.4%

W-.01C			W-15Mo		
2800	4:1	81.6%	3000	4:1	79%
2800	4:1	55%	3000	4:1	71%
3000	5:1	70.3%	3200	4:1	Sticker
3000	6:1	69.2%	3400	4:1	Sticker

(a) Billet extrusion temperature (°F)
(b) Extrusion ratio
(c) Wt % recovery
(d) Harvey Aluminum report
(e) Giancola report

TABLE 7

EXTRUSION DATA FOR SINTERED Mo-W BILLETS

Material Identification	Ratio Temp (°F)	Press (Tons)	Ram Speed	Remarks
70% dense C.P.–Mo	6:1 2500	515	4.5 2.1	Broke in several pieces. Torn surface.
70% dense C.P.–Mo	4:1 2400	528	5.3 2.9	Severe tearing. Pine cone effect. Many small pieces.
70% dense C.P.–Mo	8:1 2400	620	3.1 Start	Stuck
97% dense C.P.–Mo	4:1 2100	474	7.0 5.4	Excellent surface. Sound rod.
97% dense C.P.–Mo	8:1 2400	633	16.8 5.2	Excellent surface. Sound rod.
97.5% dense W + 1% ThO_2	6:1 3400	512	5.5 2.7	Very smooth surface. Sound rod.
89% dense W + 1% ThO_2	4:1 3100	550	4.7 2.6	First half lateral cracking. Rough.
96.2% dense C.P.–W	4:1 3000	487	3.7 2.0	Smooth. Sound rod.
93.3% dense C.P.–W	4:1 3000	549	3.7 2.0	Smooth surface. Internal non-closure.
93% dense 50 Mo-50W	4:1 3000	571	11.8 5.9	Severe die wash. Sound rod.