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CLIMAX MOLYBDENUM CO.
OF MICHIGAN
Detroit, Michigan

a subsidiary of **AMERICAN METAL CLIMAX, INC.**

RESEARCH AND DEVELOPMENT ON NEW PROCESSES
OF PRODUCING DUCTILE MOLYBDENUM

15 February 1963

Prepared under Navy, Bureau of Naval Weapons

Contract No. NOrd-15915

Progress Report Covering Period
1 August 1962 - 31 January 1963

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Detroit, Michigan

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ABSTRACT

Eleven arc-cast molybdenum heats have been prepared in pursuance of the general objective of obtaining molybdenum with a low transition temperature. Deoxidation with carbon, titanium, and thorium has been investigated. One carbon-deoxidized, unalloyed molybdenum heat has been converted to bar stock, and the impact transition temperature has been determined. Small additions of chromium, nickel, and aluminum have been made to arc-cast molybdenum for the purpose of studying the solid-solution softening phenomenon.

Two button melts produced by the Bureau of Mines installation at Albany, Oregon, have been examined. On the basis of hardness measurements and chemical analyses, the purity of the molybdenum buttons was not significantly different from that of commercially-available vacuum-arc-cast molybdenum.

INTRODUCTION

Two phases of the subject contract have been pursued during the current report period. The objective of the first of these phases is the improvement of the transition temperature of wrought molybdenum. It is planned to achieve the improvement in transition temperature through the use of (1) higher purity molybdenum powder as the arc-melting stock and (2) additions of deoxidizers and/or neutralizers to the charge to decrease further and/or modify the size and distribution of deleterious interstitial elements. The objective of the second phase covered in this report is the evaluation of high-purity molybdenum prepared at other facilities.

Two important modifications in the production and handling of powder have been introduced to improve the purity of the molybdenum powder melting stock. The molybdenum powder which is destined to become the arc-melting stock is reduced in the conventional manner. Prior to arc-melting, the powder is subjected to a re-treatment operation at temperatures equivalent to or slightly above that utilized for the final stage of conventional reduction, but in hydrogen which has been purified through a palladium diffuser. The ultrapure hydrogen should reduce the oxygen, nitrogen, and carbon contents of the molybdenum powder, thus minimizing the amount of deoxidation and/or neutralization required during arc-melting. The second modification in the preparation of molybdenum powder feed stock is concerned with the handling of the powder after re-treatment. The re-treatment furnace has been so constructed that the muffle tubes lead directly into a hydrogen-filled handling chamber. Thus, the re-treated molybdenum powder is cooled to room temperature in the hydrogen atmosphere. The powder is blended in the handling chamber with the desired additions, the blended charge is placed in sealed containers, and the sealed containers are removed from the handling chamber and transferred to the arc-casting equipment. By this procedure, the molybdenum powder, after re-treatment in ultrapure hydrogen, is never exposed to air until it becomes an ingot.

With the availability of the low-oxygen, low-carbon, low-nitrogen molybdenum powder, the following experiments will be performed:

A. It has been observed* that the presence of small quantities (0.04-0.16%) of nickel, iron, cobalt, silicon, aluminum, and chromium decreases the room temperature hardness of vacuum-arc-cast molybdenum when the ingots are produced from commercial grades of molybdenum powder. The lowest hardness recorded for molybdenum containing one of the above-mentioned additions is 143 DPH, as compared to a hardness of 170-180 DPH for vacuum-arc-cast molybdenum deoxidized with carbon.

The "solid-solution softening" of the molybdenum matrix by the presence of small amounts of nickel, iron, cobalt, silicon, aluminum, and chromium is attributed to a decrease in the solid solubility of the interstitials in the base metal. Two factors support this postulate:

1. All of the above alloying elements decrease the lattice parameter of molybdenum, thus decreasing the interstitial holes, and decreasing the solid solubility of the interstitials.

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* 1955 Summary Report for "Arc-Cast Molybdenum-Base Alloys," by M. Semchyshen and R. Q. Barr, pp 63-64

2. For comparable amounts of carbon, oxygen, and nitrogen present
    in the castings, the microstructure of the castings containing
    small additions of nickel, iron, cobalt, silicon, aluminum, and
    chromium contains greater amounts of grain boundary precipitate.
    The increased amount of precipitate cannot be attributed to
    formation of an intermetallic phase, as the substitutional solu-
    bility of the metallic elements is appreciably in excess of the
    amounts present. The increased amount of grain boundary precip-
    itate must be attributed to the decreased solid solubility of
    the interstitial in the matrix, resulting in the formation of
    molybdenum interstitial compounds, e.g., oxides, carbides, and
    nitrides.

It is important to ascertain whether solid-solution softening can be
achieved by the addition of elements such as nickel, iron, cobalt, silicon,
aluminum, and chromium when the molybdenum powder used for the melting
stock contains appreciably less interstitial impurities. Even if lower
hardness values are not attained, the use of high-purity molybdenum powder
might result in ingots with little or no precipitate at the grain bound-
aries. The absence of precipitate should result in the desired higher
ductility and lower transition temperature.

B. From thermodynamic considerations, the most effective deoxidizer for molyb-
    denum is carbon. The reaction, $\underline{C} + \underline{O} \rightleftharpoons CO$ (gas), if carried out to equi-
    librium at low partial pressures of $\overline{CO}$, such as exist during vacuum-melting
    at total pressures of one micron Hg, would result in amounts of oxygen and
    carbon remaining in solution in the molten molybdenum in the order of
    5×10^{-7} and 10^{-3} moles, respectively, or approximately 0.1 and 100 ppm,
    respectively. With the availability of exceedingly pure molybdenum powder,
    the effectiveness of carbon deoxidation during vacuum melting should be ex-
    plored. Addition of other deoxidizers and/or neutralizers such as boron,
    titanium, thorium, yttrium, and zirconium will be made to the high-purity
    molybdenum powder charge prior to arc-melting. The effectiveness of these
    elements will be assessed as to their ability to produce cast molybdenum
    exhibiting lower transition temperatures.

C. It has been demonstrated that Mo + 35% Re alloy possesses low transition
    temperature and good ductility at room temperature and below. It is pro-
    posed to ascertain in this investigation whether these desirable attributes
    can be obtained with significantly lower rhenium contents when rhenium is
    present in the ingots produced from high-purity molybdenum powder.

The second of the two phases pursued during the current report period in-
volved the evaluation of specimens of pure molybdenum produced by other labora-
tories with respect to chemical purity, hardness, and microstructure. Two
molybdenum buttons produced by the Bureau of Mines at Albany, Oregon, were sub-
jected to such an evaluation.

PART I

DEOXIDATION AND NEUTRALIZATION STUDIES

As stated in the Introduction, previous studies at this laboratory have shown that interstitial elements present in molybdenum may be removed by suitable deoxidizing agents during vacuum-arc-melting, or may be caused to change their amount and distribution in the ingot by the presence of certain substitutional alloying elements. It was also pointed out that high-purity molybdenum powder has become available as a result of final reduction of the powder with palladium-purified hydrogen. Furthermore, it is now possible to blend the desired charge with the high-purity molybdenum powder and transfer the entire charge from the high-purity hydrogen atmosphere to the melting chamber without exposure to air. This phase of the investigation will attempt to combine the principles and the improved techniques described above to produce molybdenum exhibiting lower transition temperatures. Evaluation of the transition temperature will be made on bar stock processed from the ingots.

Preparation of Ingots

To date, eleven ingots have been prepared for this investigation. A single lot of commercially-available, high-purity molybdenum powder was earmarked for this investigation. The molybdenum powder required for a particular heat was re-treated in the palladium-diffused hydrogen atmosphere just prior to the melting operation, thus mitigating the uncertainty of powder purity as a result of storage. The re-treated powder was blended with the desired second element additions, and the charge was transferred to the melting chamber, all operations being conducted in a hydrogen atmosphere. The charge was melted in the press-sinter-melt equipment developed at the Climax Molybdenum Company laboratory. The eleven ingots produced to date are listed in Table 1. All of the ingots except No. 4162, to which aluminum was added, were vacuum-arc-cast. Heat 4162 was melted in an ambient atmosphere of argon maintained at a pressure slightly above atmospheric.

The heats in Table 1 can be divided into three classes: The first class includes heats for which carbon was the sole deoxidizing agent, Heats 4097, 4106, 4121, 4123, and 4124. In the second class, no carbon addition was made, and the deoxidizing elements were aluminum, titanium, or thorium (Heats 4125, 4149, 4162, and 4163). In the third class of heats, in addition to carbon for deoxidation, chromium or nickel were added to produce the aforementioned solid-solution softening effect.

The purpose of preparing several unalloyed, carbon-deoxidized molybdenum heats was to assess the role of residual carbon content on the transition temperature. The carbon contents of the ingots produced cover the range from 0.002 to 0.006%. The 4-in.-diameter casting of carbon-deoxidized unalloyed molybdenum, Heat 4106, permitted the utilization of an available 3-1/4-in.-diameter extrusion container for primary working.

TABLE 1

Arc-Cast Ingots

| Heat No. | Composition, %* | | | | Ingot Size | | | As-Cast, DPH |
| | Addition | | Analysis | | Dia., in. | Length, in. | Wt., lb | |
	Carbon	Other	Carbon	Other				
4097	0.013	-	0.004	-	2-1/2	8	14.0	175
4106	0.010	-	0.004	-	4	15-1/2	67.7	176
4121	0.011	-	0.003	-	2-1/2	9	15.5	168
4123	0.014	-	0.006	-	2-1/2	8-1/2	14.9	169
4124	0.010	-	0.002	-	2-1/2	9	15.4	164
4125	0.003	0.11 Ti	N.A.	N.A.	2-1/2	6	10.0	169
4149	0.003	0.013 Th	N.A.	N.A.	2-1/2	9	14.5	170
4163	0.003	0.05 Th	N.A.	0.036 Th	2-1/2	9	15.0	180
4147	0.018	0.65 Cr	0.010	0.22 Cr	2-1/2	9	14.9	165
4148	0.018	0.15 Ni	0.014	0.090 Ni	2-1/2	8	13.7	164
4162	0.003	0.20 Al	N.A.	0.15 Al	2-1/2	6-1/2	11.2	145

* Balance molybdenum
N.A. = Not available

The as-cast hardness values of the carbon-deoxidized, unalloyed molybdenum ingots were only slightly lower than those obtained for ingots containing in excess of 0.006% carbon. These hardness values reflect the fact that even 0.002% carbon is sufficient to exceed the solid solubility in molybdenum. At this carbon level, the matrix is saturated with respect to carbon, as evidenced by the metallographic detection of an excess carbide phase.

Preliminary experiments in the area of solid-solution softening involved small additions of chromium, nickel, and aluminum to Heats 4147, 4148, and 4162, respectively. Owing to the high vapor pressure of chromium and nickel at the temperatures attained during the arc-melting of molybdenum, the quantities of these elements added were appreciably in excess of that desired in the ingot. The aim compositions were 0.11% Cr in Heat 4147, and 0.05% Ni in Heat 4148. Some experience was available from earlier heats as to the losses in chromium and nickel that could be expected during arc-melting. The earlier experiences were, however, based on charges that had not been pretreated in purified hydrogen. The conditions under which Heats 4147 and 4148 were vacuum-arc-cast resulted in smaller chromium and nickel losses through volatilization than anticipated; hence the alloy contents of these ingots were substantially higher than the aim values. As a result, the alloy contents were well above those calculated to yield optimum solid-solution softening. This observation is borne out by the fact that hardness values of 165 and 164 DPH were obtained for Heats 4147 and 4148, respectively. A second attempt will be made to prepare these compositions, in which the charge will be adjusted in light of the experience gained on Heats 4147 and 4148.

The aluminum addition to Heat 4162 resulted in a significant softening effect.

Metallographic Examination

In order to evaluate the degree of deoxidation, particularly with respect to carbon-deoxidized unalloyed molybdenum, it has been ascertained that metallographic examination can be more sensitive than chemical or vacuum fusion analyses. This is especially true of ingots containing low carbon, oxygen, nitrogen, and hydrogen contents, where the limit of detection by the analytical techniques is in the same order of magnitude as the amounts of these elements present in the ingot. The present series of ingots is representative of such a situation, and therefore, fractography is a particularly useful technique for the determination of the effectiveness of deoxidation by revealing the amount and morphology of the excess carbide and/or oxide phase.

A detailed description of the fractographic technique has been presented in the literature.* Essentially, this technique consists of fracturing a sample of the relatively coarse-grained, as-cast metal, and examining exposed intergranular facets under the high-power optical microscope. Since the carbide (Mo_2C) and oxide (MoO_2) phases exhibit extremely low solubility in the molybdenum matrix, they are rejected to the grain boundaries during solidification and cooling. Thus, when the grain boundary is viewed head-on, as it were, the observer is afforded an excellent opportunity to characterize the grain boundary constituents that are present and thus to assess the degree of deoxidation that has been achieved.

In practice, a numerical scale from 1 to 10 has been established to provide reproducibility in the rating of molybdenum fractures from the standpoint of completeness of deoxidation. On this scale, the number "1" denotes the highest degree of deoxidation (essentially oxygen-free), while the number "10" denotes a total lack of deoxidation wherein each grain is enveloped with the MoO_2 phase. Fractographs typifying several positions on the rating scale are shown in Figure 1. The fractograph at the upper left is characterized by the familiar, feathery Mo_2C phase, and by the total absence of registrations between the carbide inclusions. Material exhibiting this type of fracture would be adjudged to be extremely well-deoxidized and to be very low in residual oxygen content. As the fracture rating number increases, indications of an increasing oxygen content are manifested in the appearance of speckling in the grain boundary regions not containing the carbide phase. At still higher oxygen contents, the oxide particles become more discrete platelets, ultimately enveloping each grain.

Photomicrographs representing two of the carbon-deoxidized heats listed in Table 1 are reproduced in Figures 2 and 3 (Heat 4123, Mo + 0.006% C, and Heat 4124, Mo + 0.002% C, respectively).

The dark-appearing registrations in the low magnification photomicrographs in Figures 2 and 3 are the result of selective attack of micropores and small matrix carbide inclusions by the polishing electrolyte.

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* *The Metal Molybdenum*, American Society for Metals, 1958, Chapter 17, p 394

On the basis of fracture appearances, good deoxidation was achieved in both materials. Appropriate fracture ratings, based on the numerical scale discussed above, would be No. 2 for Heat 4123 and No. 3 for Heat 4124.

Past experience has shown that ingots having fracture ratings as high as No. 7 can be worked successfully by extrusion. Since the utilization of the pretreated charge technique for Heat 4124 has resulted in a well-deoxidized ingot (No. 3 fracture rating) at a residual carbon content of 0.002%, it is suggested that even smaller carbon additions to the melting charge should be investigated. The lower carbon addition to the charge should result in a lower carbon content in the ingot, perhaps below the solid solubility limit of carbon in molybdenum. Such a low carbon content should indeed be reflected in lower transition temperatures for molybdenum.

Three vacuum-arc-cast ingots have been prepared to evaluate titanium and thorium as deoxidizing agents for hydrogen-re-treated molybdenum powder. Chemical analyses have not been completed on these materials at this writing. Representative photomicrographs are shown in Figures 4 through 6.

The titanium-bearing heat, No. 4125, contained a small amount of precipitate along grain boundaries, probably a mixture of TiO and MoO_2. On the other hand, the volume of grain boundary precipitate present in Heat 4125 was substantially less than that of the carbide phase present in the carbon-deoxidized heats discussed earlier.

The heat with an 0.008% thorium aim, Figure 5, contained sheet oxide. Obviously, an insufficient amount of thorium was present in the charge for Heat 4149 to effect adequate reduction of the oxide present in the charge. An increase in the thorium charged from 0.013% (Heat 4149) to 0.05% (Heat 4163) effected a marked improvement in the state of deoxidation, as evidenced by Figure 6. Some oxide inclusions are present in the latter material; the degree of deoxidation appears, however, to be sufficient to warrant attempted primary working of the ingot.

Photomicrographs representative of the aluminum-deoxidized ingot are presented in Figure 7. The ingot must have an exceedingly low carbon content, as no carbide phase could be detected even upon metallographic examination at X2000. A small amount of second-phase constituent is detectable in the fractograph, as well as in the conventionally-polished specimen photomicrograph, both taken at X2000. These particles are tentatively identified as Al_2O_3 phase.

Working of Castings and Transition Temperature Determinations

As stated earlier, standard extrusion tooling was available at the laboratory to extrude billets machined from 4-in.-diameter castings. It was possible, therefore, to extrude Heat 4106 without delay. One extrusion blank was machined from this ingot; the balance of the ingot was retained in the as-cast condition. Details relating the conversion of one blank from Heat 4106 to an extruded billet, and subsequently to rolled bar stock, are presented in Table 2.

TABLE 2

Conversion of Heat 4106 (Mo + 0.004% C)

Blank Diameter	3.128"
Blank Weight	16.10 lb
Extrusion Temperature	1800 F
Extrusion Ratio	4:1
Extruded Billet Diameter	1.63"
Cropped Billet Weight	13.72 lb
Extrusion Recovery	85.2%
As-Extruded Hardness	243 DPH
Rolling Temperature	1600 F
Rolled Bar Size	1/2" Square
Cropped Bar Weight	9.90 lb
Total Recovery	61.5%

The machined blank was extruded under conditions similar to those that have been reported in recent literature.*

Six unnotched Charpy impact specimens were machined from the rolled bar from Heat 4106. The specimens were machine-shaped to within 0.004 in. of final size, then hand-polished through 1/0 abrasive paper to final size (0.394 in. by 0.394 in. by 2.165 in.). The specimens were cooled to the desired test temperature, transferred rapidly to the testing machine, and impacted with a maximum available energy of 30 ft-lb and a striking velocity of 11.2 fps. Impact energy data are given in Table 3.

TABLE 3

Impact Test Results for Rolled Bar Stock
from Heat 4106, Mo + 0.004% C

Test Temperature, F	Absorbed Energy, ft-lb
-125	13
-100	16
-75	14
-50	24
-25	30+
0	30+

Future work calls for the extrusion of the 2-1/2-in.-diameter heats listed in Table 1, and for the measurement of brittle-to-ductile transition temperatures on the basis of the unnotched Charpy impact test.

* Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys, ASD Technical Report 61-193, June 1961

PART II

EVALUATION OF HIGH-PURITY MOLYBDENUM
PRODUCED AT OTHER FACILITIES

In connection with the objective of evaluating high-purity molybdenum pro-
duced at other facilities, two buttons produced by the Bureau of Mines instal-
lation in Albany, Oregon, were examined.

The following information on the molybdenum buttons was supplied by the
Bureau of Mines or ascertained by this laboratory:

	Button No. 1	Button No. 2
Bureau of Mines Designation	SA-23,463	SA-23,465
Starting Material	Unknown	MoO_3
Starting Material Purified by	Ion Exchange	Unknown
Means of Reduction	Hydrogen	Bomb Reduction
Means of Consolidation	—— Presumably Arc-Melting ——	
Weight	35.5 g	55.1 g
Dimensions	1" dia x 1/4" thick	1-1/4" dia x 1/4" thick
Appearance of Surface	Lustrous	Dull

A photograph of the buttons is shown in Figure 8.

The surfaces of both buttons were examined under the microscope in the
as-received condition. Button No. 1 appeared clean, with thermally-etched
grain boundaries outlining a coarse, equiaxed grain structure. Button No. 2
exhibited a porous, dendritic structure near the center of the top surface and
carbide feathers over the entire surface.

Three Vickers hardness impressions were made on the top surface of each
button in the as-received condition. Hardness numbers obtained from the im-
pressions were as follows:

Button No.	DPH (10 kg)			
	1	2	3	Average
1	175	167	180	174
2	163	167	183	171

Flats 3/8 in. in diameter were then manually ground on the top of the
buttons, using wet silicon carbide abrasive papers. The flats were electro-
polished for four minutes. Hardness numbers taken from the electropolished
surface are given below:

Button No.	DPH (10 kg)							
	1	2	3	4	5	6	7	Average
1	193	179	177	180	181	180	193	183.3
2	187	176	178	186	175	183	-	180.8

The buttons were then sectioned with a 1/32-in.-thicк abrasive wheel (de Sanno A-120-FR-107) mounted on a surface-grinding machine. The cutting was done under flowing water with a 0.0005 in. depth of cut per pass. One-half of each button was mounted in Acralite Fastmount, without heat or pressure. The specimens were hand ground on wet silicon carbide papers and then electropolished for four minutes. Hardness impressions randomly located on the cross sections gave the following hardness numbers:

Button No.	DPH (10 kg)										Average
	1	2	3	4	5	6	7	8	9	10	
1	188	188	186	186	186	186	185	189	188	-	186.9
2	176	178	176	175	178	178	178	175	171	172	175.8

The mounted specimens were repolished for examination at 2000 diameters. Button No. 1 contained oxides at the grain boundaries, and Button No. 2 had carbides both within the grains and at grain boundaries. Figure 9 illustrates the microstructures.

Drillings from the unmounted halves were analyzed for carbon by a combustion-conductometric method. The results, which confirmed the microstructural observations, were as follows:

<div align="center">

Button No. 1   0.003 Wt-% Carbon

Button No. 2   0.057 Wt-% Carbon

</div>

The evaluation of Button No. 2 was not carried further because its high carbon content removed it from the "high purity" category.

Button No. 1 was analyzed for oxygen by an inert-fusion-conductometric method, and an inert-fusion-chromatographic method was employed to determine the oxygen, nitrogen, and hydrogen contents. The results are given below.

Element	Wt-%	
	Conductometric	Chromatographic
Oxygen	0.009	Approx. 0.007
Nitrogen	-	Approx. 0.001
Hydrogen	-	Nil

Chips machined from the cross section of Button No. 1 were analyzed spectrographically by the National Spectrographic Laboratories, Inc., Cleveland, Ohio. The results are presented in Table 4, where they are compared with typical values for arc-cast molybdenum. The values for arc-cast molybdenum are averages for 132 heats made at the Climax production facility with molybdenum powder prepared by hydrogen reduction of ammonium paramolybdate. It is apparent from Table 4 that the total metallic impurity content of Button No. 1 is somewhat greater than that of vacuum-arc-cast unalloyed molybdenum.

TABLE 4

Spectrographic Analysis of Button No. 1
Compared with Average Analysis for 132
Heats of Climax Arc-Cast Molybdenum

| Element | Concentration, ppm, by wt. | |
	Button No. 1	Average of 132 Arc-Cast Heats
Al	1	5.0
Ca	35	3.8
Co	< 5*	5.2
Cu	8	1.6
Cr	< 1	1.1
Fe	30	7.4
Mg	2	3.9
Mn	< 1	1.8
Pb	<10	10.5
Si	45	14.4
Ni	< 1	3.6
Ti	< 1	7.0
V	<10	-
Sn	<10	<10.0
Zr	4	2.7

* < = element was present but in less
     than the indicated concentration

It is clear from the hardness, microstructure, and chemical composition evaluations that the submitted samples of molybdenum do not satisfy present-day standards of high purity. In the absence of detailed information on the starting materials, purification procedures, and melting conditions, it is not possible to suggest reasons as to why greater purity was not achieved.
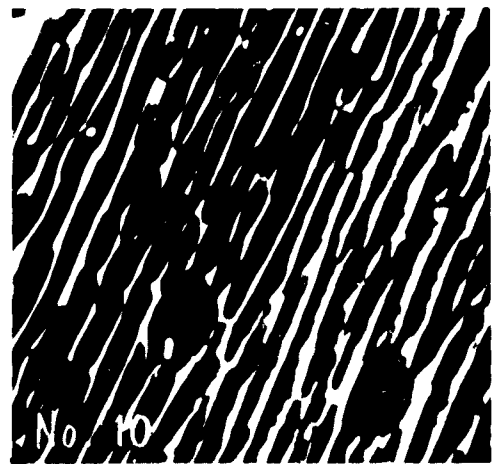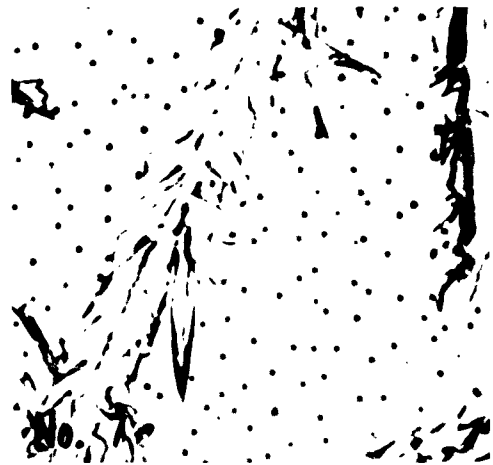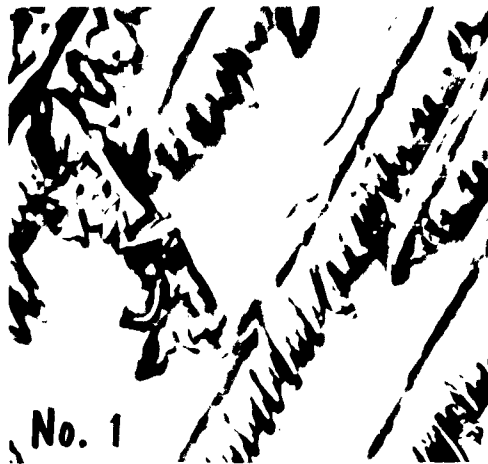
FIGURE 1 - Fracture Rating Scale for Carbon-Deoxidized
Arc-Cast Molybdenum. All Fractographs X2000.

(N1637)   Electropolished,   X100   (N1636)   Electropolished,   X2000
          Etched in NaOH+K₃Fe(CN)₆   Etched in NaOH+K₃Fe(CN)₆
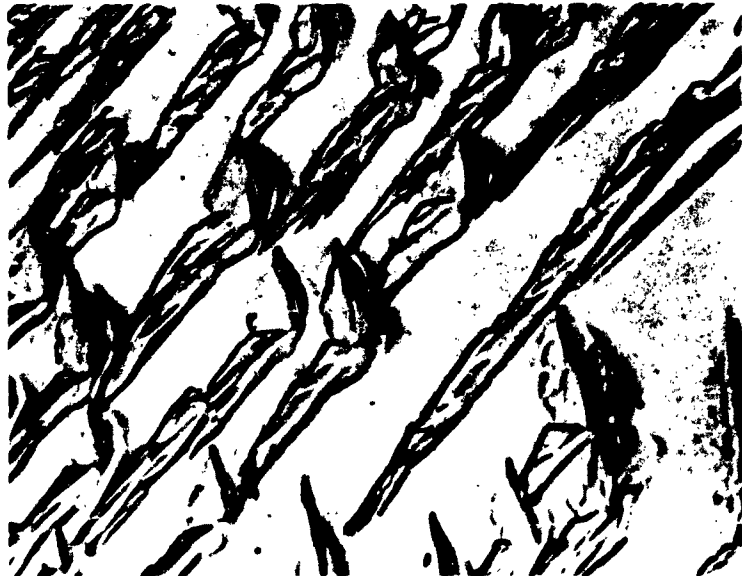
(N1635)   Fracture   X2000

FIGURE 2 - Microstructure of Heat 4123, Mo + 0.006% C -
As-Cast
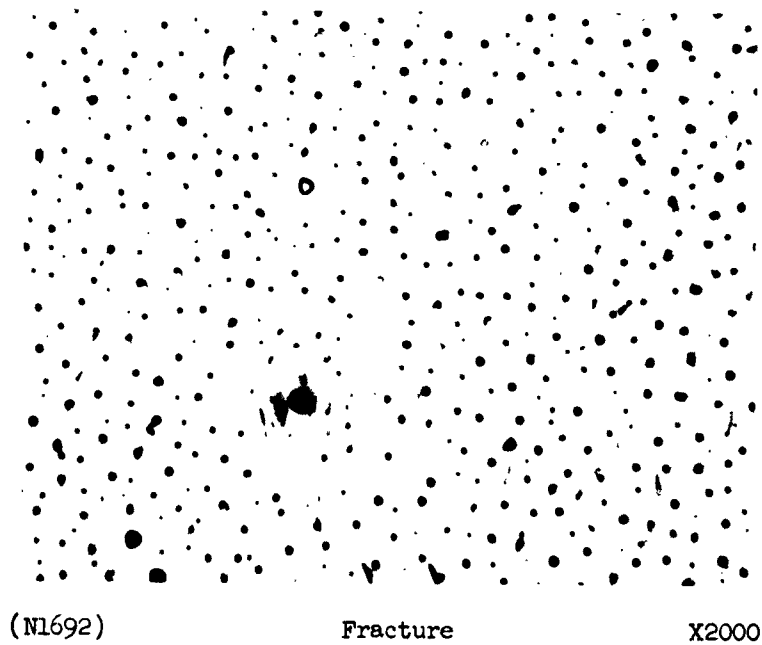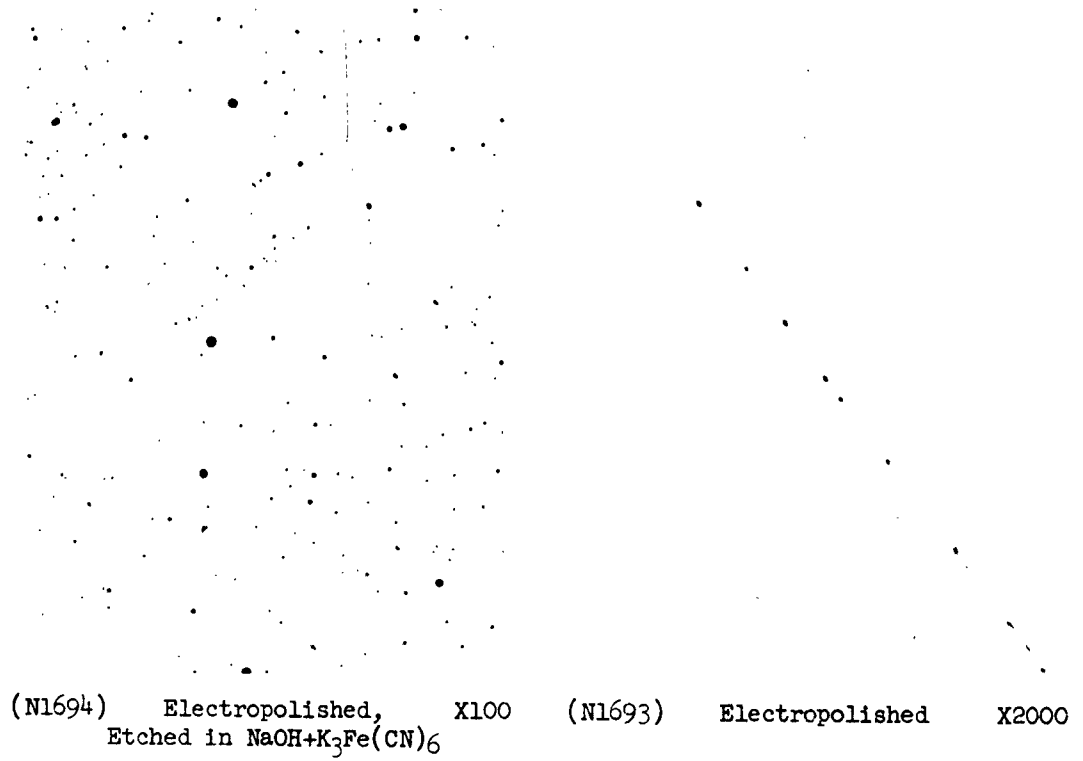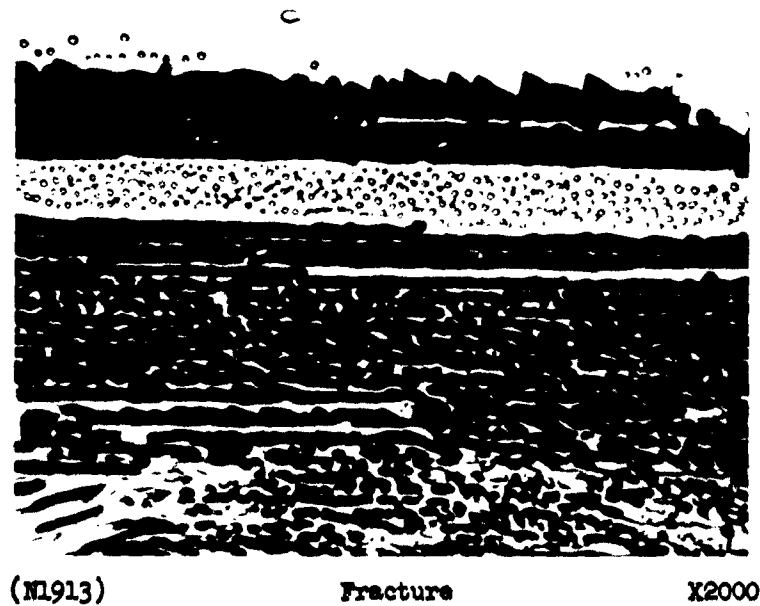
(N1647)   Electropolished,   X100
Etched in NaOH+K$_3$Fe(CN)$_6$

(N1648)   Electropolished,   X2000
Etched in NaOH+K$_3$Fe(CN)$_6$

(N1646)   Fracture   X2000
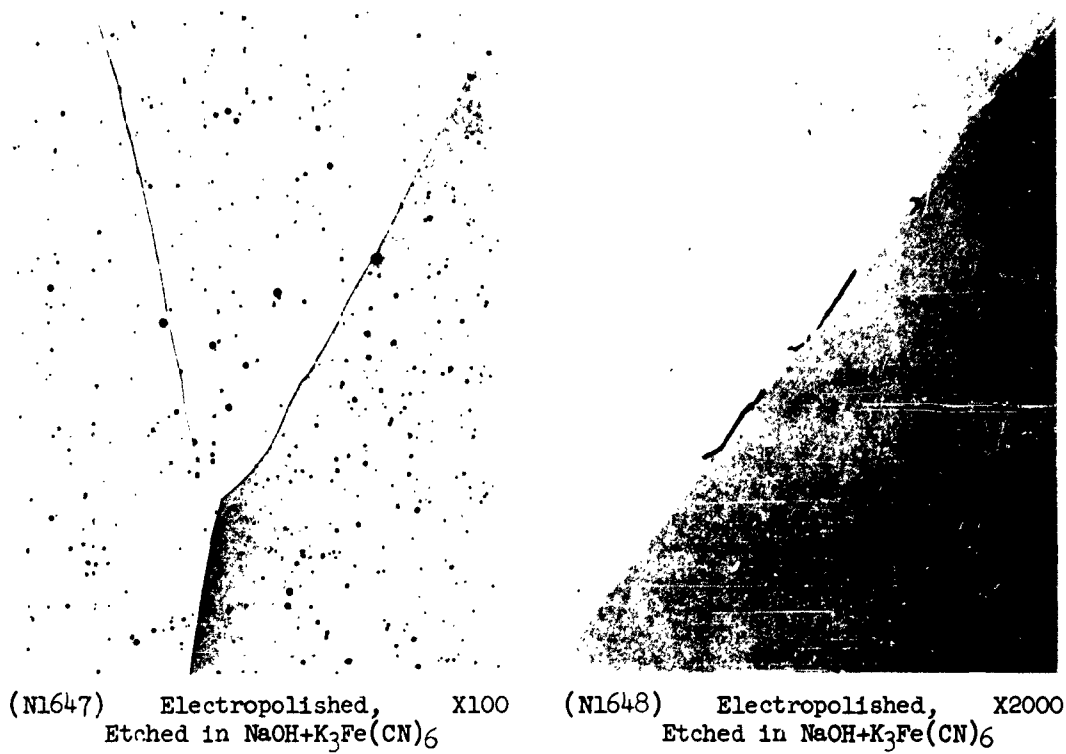
FIGURE 3 - Microstructure of Heat 4124, Mo + 0.002% C -
As-Cast

(N1694)   Electropolished,   X100   (N1693)   Electropolished   X2000
Etched in NaOH+K$_3$Fe(CN)$_6$

(N1692)   Fracture   X2000

FIGURE 4 - Microstructure of Heat 4125, Mo + 0.005% Ti (aim) -
As-Cast

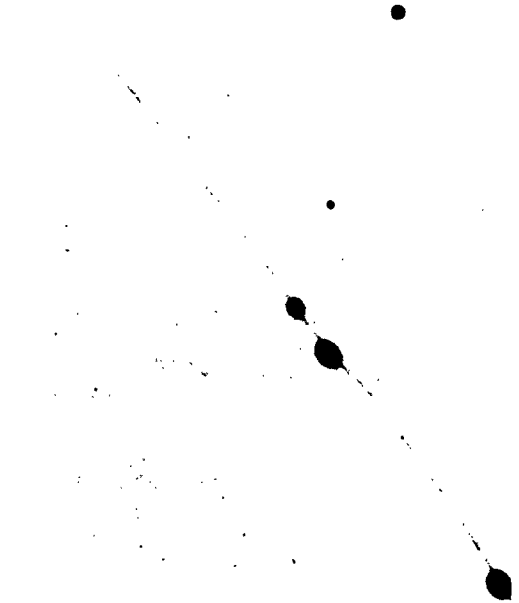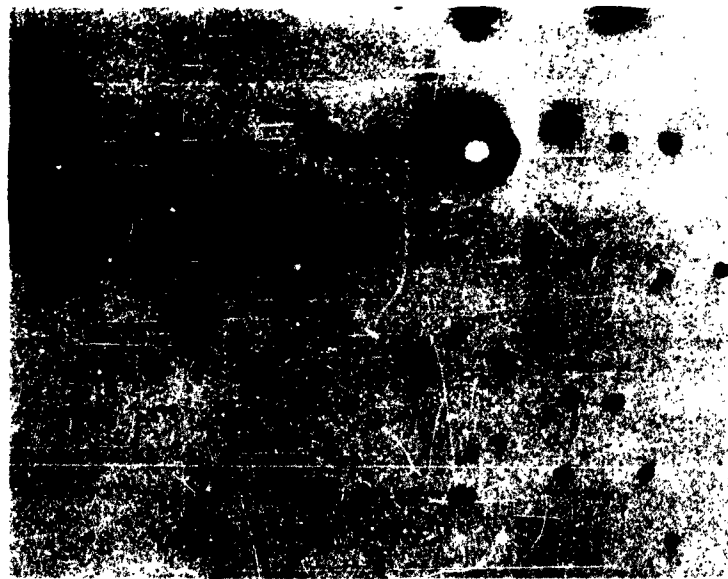(N1915) Electropolished,   X100   (N1914)   Electropolished   X2000
Etched in NaOH+K$_3$Fe(CN)$_6$

(N1913)   Fracture   X2000
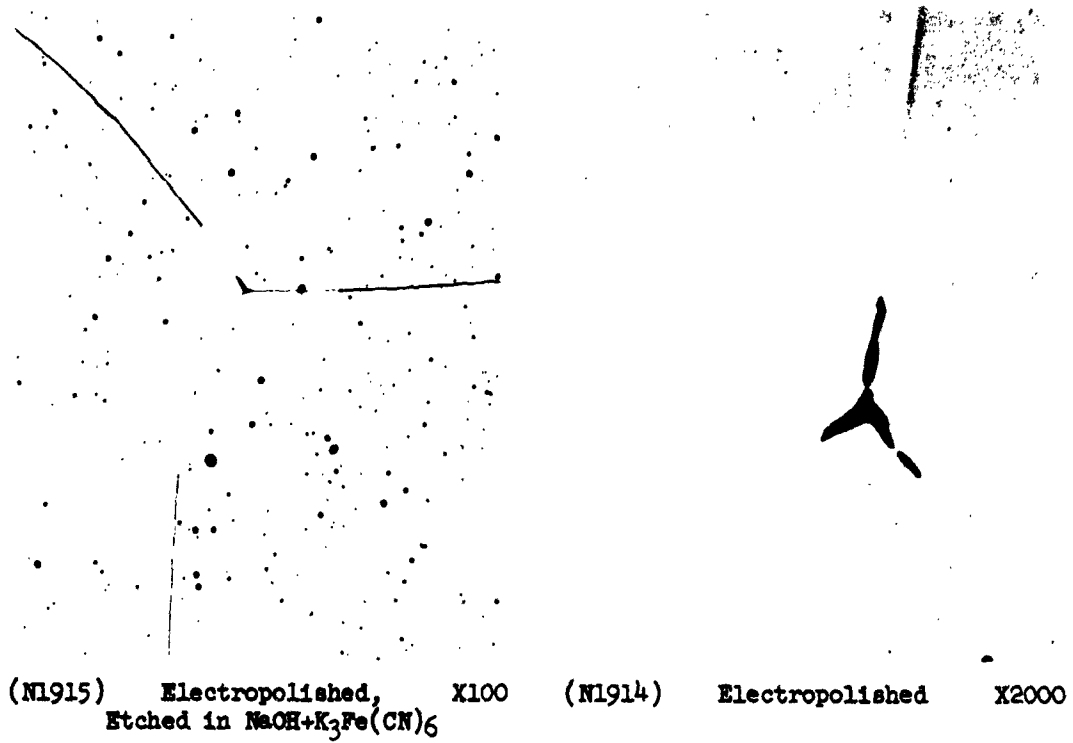
FIGURE 5 - Microstructure of Heat 4149, Mo + 0.008% Th (aim) -
As-Cast

(N1992)   Electropolished,   X100   (N1991)   Electropolished   X2000
        Etched in NaOH+K$_3$Fe(CN)$_6$
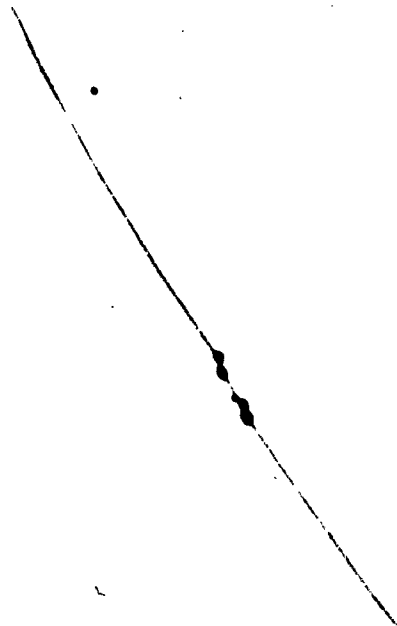

(N1990)   Fracture   X2000

FIGURE 6 - Microstructure of Heat 4163, Mo + 0.036% Th -
                        As-Cast

(N1989)   Electropolished,   X100
Etched in NaOH+K$_3$Fe(CN)$_6$

(N1988)   Electropolished,   X2000
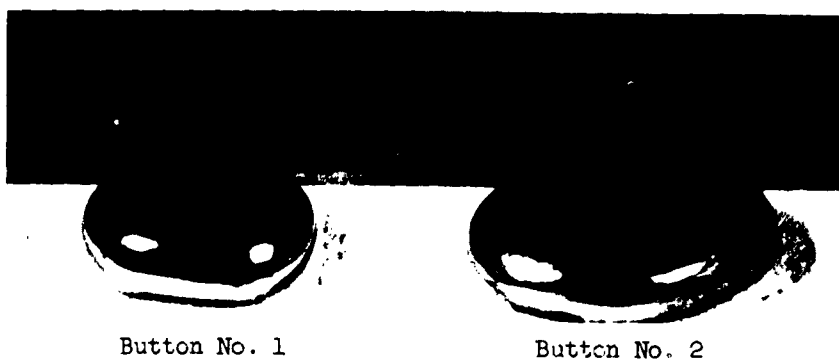Etched in NaOH+K$_3$Fe(CN)$_6$

(N1987)   Fracture   X2000

FIGURE 7 - Microstructure of Heat 4162, Mo +
0.15% Al + <0.001% C (aim) -
As-Cast

Button No. 1   Button No. 2

Scale in Inches

FIGURE 8 - Photograph of Molybdenum Buttons
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(N1807)   Electropolished   X2000

A. Button No. 1

(N1808)   Electropolished   X2000

B. Button No. 2

FIGURE 9 - Microstructures of Unalloyed Molybdenum Buttons