

AFML-TR-69-117  
PART II

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**PHASE EQUILIBRIA INVESTIGATIONS OF  
BINARY, TERNARY, AND HIGHER  
ORDER SYSTEMS**

**PART II**

**Effect of Rhenium and Aluminum Additions on the  
Metal-Rich Equilibria in the Titanium-Molybdenum-Carbon  
and Titanium-Niobium-Carbon Systems**

*C. E. BRUKL*

*Aerojet-General Corporation*

TECHNICAL REPORT AFML-TR-69-117, PART II

AUGUST 1969

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## FOREWORD

The work described in this technical report was carried out at the Materials Research Laboratory, Aerojet-General Corporation, Sacramento, California. The principal investigator for this project is Dr. E. Rudy, under USAF Contract AF 33(615)-67-C-1513. This contract was initiated in April 1967 under the direction of Capt. P. J. Marchiando.

The author wishes to thank Dr. E. Rudy for his advice and help during the course of this investigation; he further wishes to thank R. Taylor, J. Pomodoro, R. Cobb, and O. Catrino for their valuable help in various aspects of the experimental work.

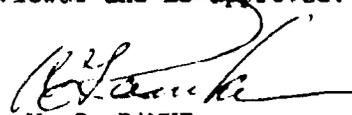
Finally, the author wishes to acknowledge the following persons for their help in the preparation of this manuscript; Mr. R. Cristoni and Mrs. Donna Breuer for the preparation of the drawings and the final typing.

The manuscript of this report was released by the author in May 1969 for publication as a Technical Report.

The other report issued under USAF Contract F33(615)-67-C-1513 was

Part I: The Phase Diagrams of the Ti-Nb-C, Ti-Ta-C, and Ti-Mo-C System

This technical report has been reviewed and is approved.



W. G. RAMKE

Chief, Ceramics and Graphite Branch  
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## ABSTRACT

The solid state phase equilibria of the metal-rich regions of the Titanium-Molybdenum-Carbon and Titanium-Niobium-Carbon systems with up to 12 At.% Rhenium and 10 At.% Aluminum additions, respectively, have been determined on hot pressed, heat treated, and in part arc melted alloys.

The phase equilibria in the metal-rich regions, with these additions, is practically unchanged over that of the ternary Titanium-Molybdenum-Carbon and Titanium-Niobium-Carbon systems; the existence of the large two-phased areas, monocarbide + metal phases, remains.

Distribution of this abstract is unlimited.

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## I. INTRODUCTION AND SUMMARY

### A. INTRODUCTION

Titanium carbide based alloys form the backbone of a large portion of carbide cutting tools today; in recent times, attempts have been made to improve the cutting behavior and strength properties of carbide cutting tools by using binder phases other than the conventional iron-cobalt-nickel alloys. Refractory metal alloys may be used as binder phases, but since the fabrication of such carbide-refractory metal combinations must depend on high temperature techniques, the high temperature phase equilibria of said proposed combinations must be investigated and ascertained to guarantee the integrity of possible cutting tool alloys.

It is known that in the metal-rich portions of the Ti-Mo-C and Ti-Nb-C ternary systems<sup>(1)</sup> there are large two-phased areas consisting of monocarbide and metal phases in thermodynamic equilibrium. The purpose of this investigation is to ascertain whether or not rhenium additions to the metal-rich portion Ti-Mo-C system and aluminum additions to the Ti-Nb-C system disturb the basic two-phased equilibria, metal + monocarbide, since rhenium and aluminum additions may be beneficial to the overall cutting behavior and physical properties of proposed carbide cutting tool alloys.

### B. SUMMARY

#### 1. The Ti-Mo-C-Re System

The basic phase equilibria of the metal-rich portion of the Ti-Mo-C system with up to 12 At.% Rhenium substituted for molybdenum is unchanged as determined from solid state samples at 1800°C. Figure 1 shows the Ti-[Mo, (Mo<sub>0.80</sub> Re<sub>0.20</sub>)]-C metal-rich phase equilibria.

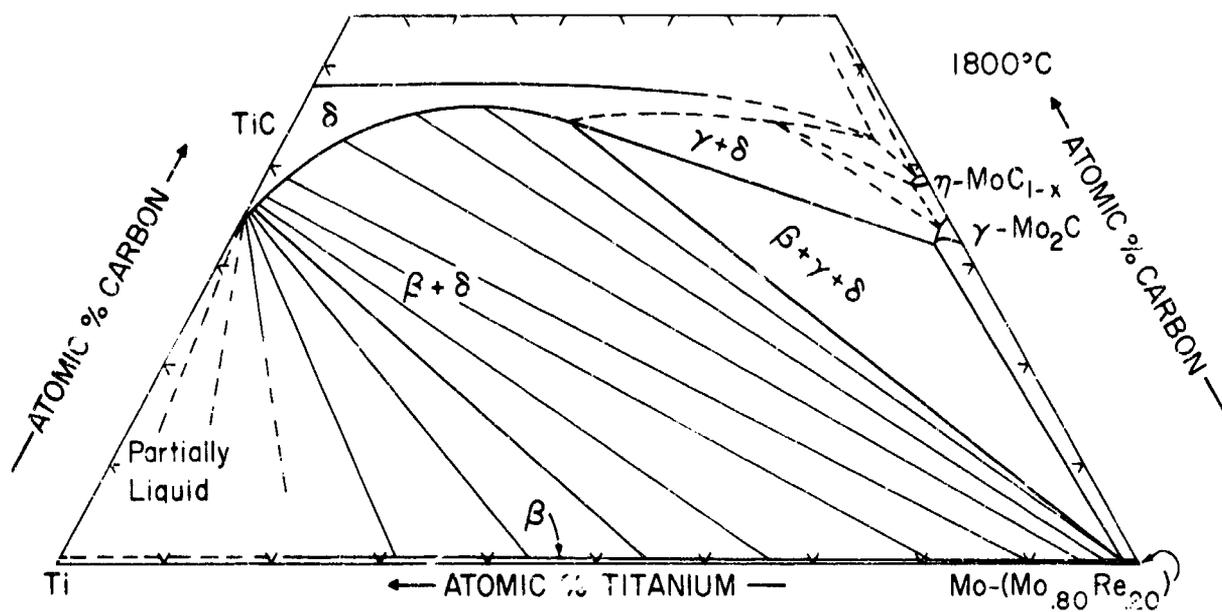


Figure 1. Ti-Mo-Re-C: Metal-Rich Phase Equilibria of the Ti [Mo, (Mo<sub>0.80</sub> Re<sub>0.20</sub>)]-C System at 1800°C

2. The Ti-Nb-C-Al System

The phase equilibria of the metal-rich portion of Ti-Nb-C-Al system with contents of up to 10 At.% aluminum is unchanged over that of the base Ti-Nb-C ternary system at 1400°C. Several of the alloys had to be arc melted to attain equilibrium. Figure 2 shows the phase equilibria of the metal-rich portion of the [Ti, (Ti<sub>0.875</sub> Al<sub>0.125</sub>)] - [Nb, (Nb<sub>0.875</sub> Al<sub>0.125</sub>)]-C system.

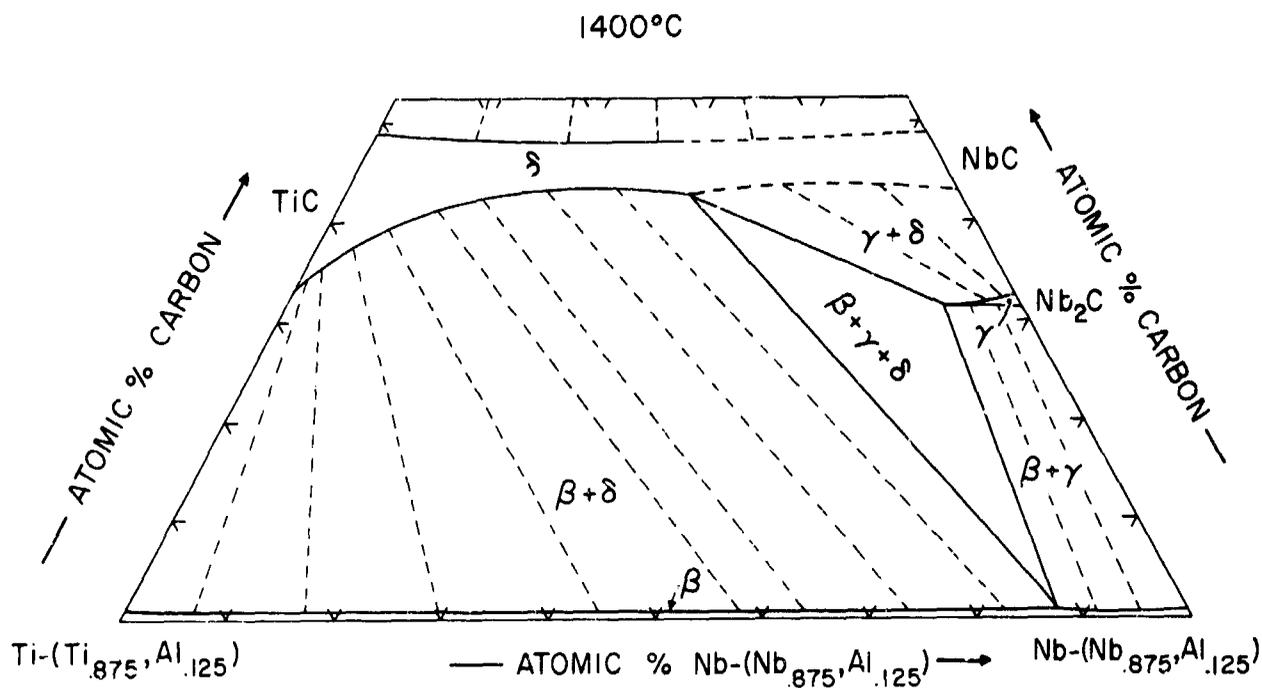


Figure 2. Ti-Nb-Al-C: Metal-Rich Phase Equilibria of the  $[\text{Ti}, (\text{Ti}_{.875} \text{Al}_{.125})] - [\text{Nb}, (\text{Nb}_{.875} \text{Al}_{.125})] - \text{C}$  System at 1400°C

## II. LITERATURE REVIEW

### A. THE TITANIUM-MOLYBDENUM-CARBON SYSTEM

This ternary system has recently been investigated in its entirety by E. Rudy as a part of this report series<sup>(1)</sup>. Figure 3 shows an isothermal section of this ternary system at 1750°C.

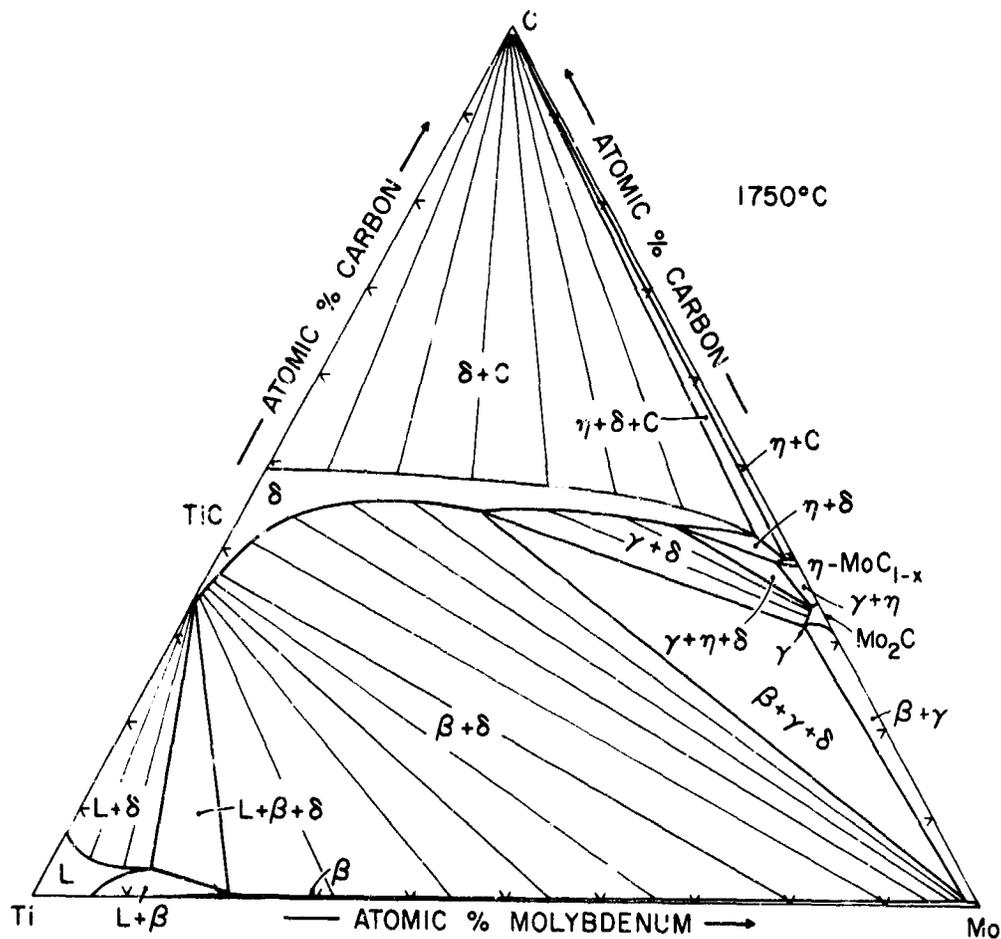


Figure 3. Ti-Mo-C: Isothermal Section at 1750°C<sup>(1)</sup>

The area of interest, for the purpose of this study, is the metal-rich region. The salient feature of this area is a large two phased metal + monocarbide field which extends from the titanium-richest compositions to quite high molybdenum concentrations; on the molybdenum-rich side this two phased area is bonded by a three-phased metal + monocarbide + molybdenum subcarbide field.

Towards higher temperatures, melting is incipient at the titanium-carbon binary side and proceeds along a eutectic trough located in the metal-rich portion of the ternary field across to the molybdenum-carbon binary side.

The tie lines in the metal + monocarbide region indicate that titanium-rich monocarbide solid solutions are in equilibrium with niobium-rich metal alloys.

#### B. THE TITANIUM-NIOBIUM-CARBON SYSTEM

The phase equilibria of this system has also recently been investigated in detail from the solid state up through melting; this work was done by E. Rudy and is presented as part of a separate report<sup>(1)</sup> issued under this contract series.

The monocarbides form a continuous series of solid solutions as does niobium-metal with the high temperature  $\beta$ -form of titanium. The titanium exchange in  $\text{Nb}_2\text{C}$  is not very large. The main characteristics of this ternary system is a large two-phased metal + monocarbide region which extends from the titanium-carbon binary side to about 80 At.% niobium exchange. The phase equilibria at  $1500^\circ\text{C}$  is shown below in Figure 4.

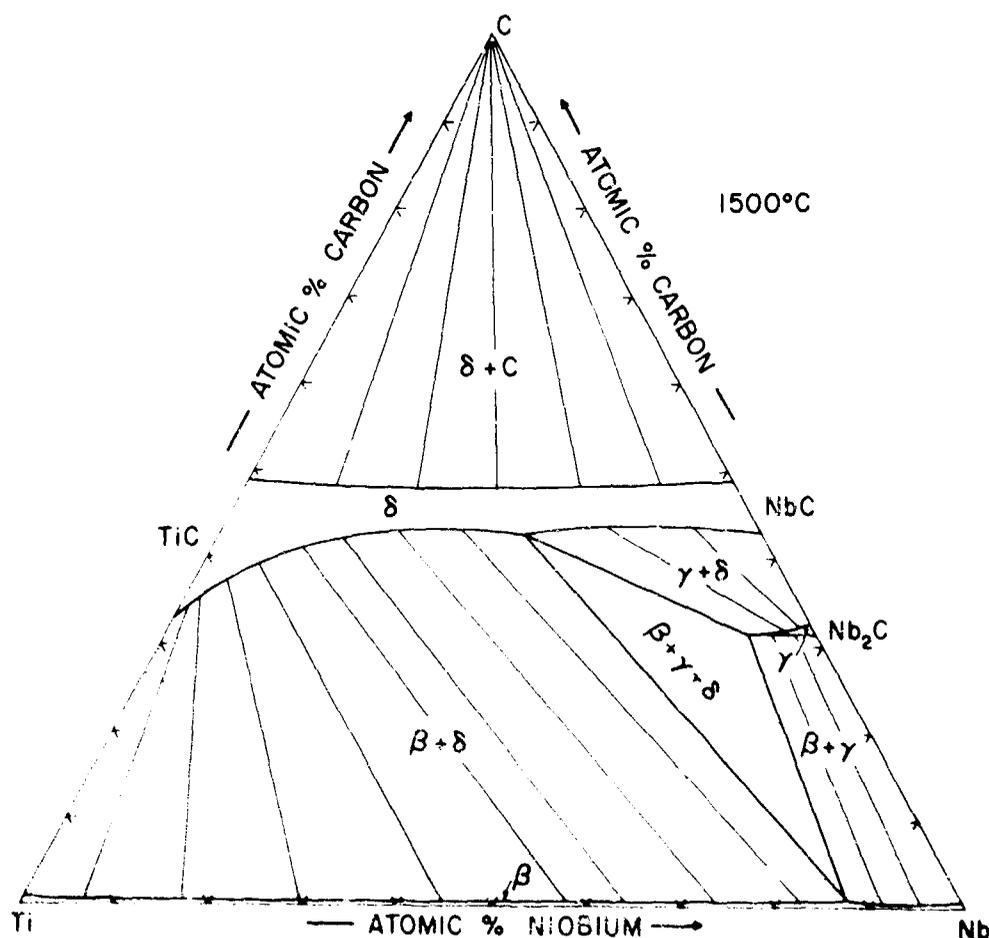


Figure 4. Ti-Nb-C: Isothermal Section at  $1500^\circ\text{C}$ <sup>(1)</sup>

### III. EXPERIMENTAL PROCEDURES

#### A. STARTING MATERIALS

In these investigations, the ternary and quaternary alloys were made using the elemental powders, pre-prepared subcarbide powders, and commercial titanium carbide. The metal powders and compounds had the following analyses:

##### 1. Titanium

The titanium used was supplied by Var-Lac-Oid Chemical Company, New York. According to the vendor's analysis, 95% of the titanium metal powder was smaller than 74 micrometers, and the major impurities listed were (in ppm): Carbon-1300, Hydrogen-1500, Nitrogen-10, (Iron, Cobalt, Nickel, Copper, Zinc)-500, Chlorine-1200, and Oxygen-1000. A Debye-Scherrer powder diagram of this material showed only the hexagonal  $\alpha$ -form of titanium which had lattice parameters of  $a = 2.950$  and  $c = 4.685 \text{ \AA}$ .

##### 2. Niobium

Niobium metal powder with a particle size of less than 74 micrometers was purchased from the Fansteel Metallurgical Corp., Muskogee, Oklahoma. The major impurities cited in the vendor's analysis were (in ppm): Tantalum-492, Tungsten-120, Zirconium-200, Titanium-100, Iron-50, Molybdenum-100, Carbon-84, Oxygen-1125, Nitrogen-24, and Hydrogen-29. An "in-house" analysis for oxygen at the Aerojet Chemical and Plastics Testing Laboratory yielded a value of 1360 ppm. A lattice parameter of  $3.300 \text{ \AA}$  was measured for this niobium metal powder.

##### 3. Molybdenum

The molybdenum metal powder used was supplied by the Wah Chang Corporation, Glen Cove, New York. The analysis accompanying the powder had the

following major impurities (in ppm): Aluminum-15, Cobalt-10, Chromium-30, Copper-10, Iron-100, Nickel-20, Oxygen-900, Silicon-80, and Tungsten-100. The lattice parameter of this molybdenum powder was 3.147 Å.

4. Aluminum

The aluminum powder, which had an average particle size of 16 micrometers, was obtained from the Metals Disintegrating Corporation, Elizabeth, New Jersey. The vendor's analysis stated (in ppm): Iron-1500, Volatile Matter-600, balance-free aluminum. A Debye-Scherrer powder x-ray showed only the face centered cubic structure of aluminum, and a lattice parameter of 4.050 Å was measured for this material.

5. Rhenium

The high purity rhenium powder was purchased from Cleveland Refractory Metals, Solon, Ohio. The material was sized smaller than 74 micrometers, and the vendor's analysis cited (in ppm): Al-2, Be- < 2, Cr-3, Cu-15, Fe-10, Mg-2, Mn-4, Mo-25, and other trace elements - < 22. The lattice parameter of this hexagonally crystallizing metal was  $a = 2.76$ , and  $c = 4.459$  Å.

6. Graphite

The graphite powder used was supplied by the National Carbon Company and had the following typical impurities (in ppm): S-110, Si-45, Ca-44, Fe-40, Al-8, Ti-4, Mg-2, V -trace, and ash-800 max. Ninety-nine percent of this graphite had a particle size smaller than 44 micrometers. Highly overexposed X-ray films of the graphite powder showed no traces of any impurities.

7. Titanium Carbide

The Wah Chang Corporation, Albany, Oregon, was the source of the titanium carbide powder. This powder had a particle size of smaller than 88 micrometers; the carbon content was 19.7 Wt.% (49.4 At.%), and an in plant carbon analysis

with a Leco Combustion Carbon Analyzer yielded a value of 49.2 At.% carbon; the lattice parameter of this commercial titanium carbide was 4.330 Å.

#### 8. Niobium Subcarbide

The Nb<sub>2</sub>C alloy was made by direct combination of the elements in the following manner:

The weighed in metal powder and graphite were well mixed in a ball mill jar. After the addition of an ether-camphor solution as a binder, the powder was pressed into small bricks and loaded into a graphite can in a carbon pot furnace; after the furnace was purged several times with helium, the bricks were heated to about 150°C under vacuum to remove the camphor. The starting material was then allowed to react at about 1300°C under helium; after the mild exothermic reaction the samples were sintered at 1850°C for 3 hours. The sintered bricks were broken down, ball milled, and sieved to a particle size of less than 60 micrometers. The powder was then analyzed for its carbon content by direct carbon analysis and by inspection of its Debye-Scherrer powder photographs. The carbon content was 33.3 At.% and the X-ray film showed only the pattern of the hexagonal, L'-3 type subcarbide structure.

### B. ALLOY PREPARATION AND HEAT TREATMENTS

#### 1. The Titanium-Molybdenum-Carbon-Rhenium System

Starting with the powdered materials TiC, Ti, Mo, Re and Graphite, sample series at 25 atomic % carbon were made by hot pressing in graphite dies at about 1600°C. The compacted alloys were surface cleaned after hot pressing and heat treated at 1800°C for 30 hours under vacuum. Several samples were arc melted for metallographic examination in a tungsten arc button melting furnace. Alloys, starting from the base ternary Ti-Mo-C compositions

shown in Figure 5 (Refer to Section IV), were made with rhenium additions in a manner such that 5, 10, 15 and 20% of the molybdenum content (Atomic % basis) of each base ternary sample was substituted for by rhenium; in this way a maximum rhenium content of 12 At.% was obtained in the most molybdenum-rich sample.

## 2. The Titanium-Niobium-Carbon-Aluminum System

The starting materials for these investigations were powders of TiC, Ti, Nb, Nb<sub>2</sub>C, and Al. Alloys, starting from the base ternary Ti-Nb-C compositions were made with 5 and 10 At.% Al additions, substituted in such a manner that the ratio Ti/Nb was constant and equal to the same ratio as in the respective base ternary sample. The well mixed starting powders were placed in graphite dies for hot pressing; to avoid squeezing out the low melting aluminum before it had a chance to react with the other components, minimum pressure was used and the temperature was held to about 600°C for about 5 minutes. After this initial time and temperature, the temperature was increased to about 1200°C and the pressure to normal hot pressing pressures. The pressed compacts, which were quite dense and showed no signs of melting loss, were cleaned, placed in a tantalum container and heat treated first at 800°C for 12 hours and then at 1400°C for 30 hours under helium. Several samples were subsequently arc melted in a tungsten electrode button arc furnace; these arc melted samples were then re-heat treated at 1400°C for 35 hours.

### C. X-RAY ANALYSIS

Copper K<sub>α</sub>, and in many cases Chromium K<sub>α</sub>, Debye-Scherrer powder X-ray photographs were made of all alloys after the heat treatments; powder photographs were also made of the arc melted alloys. In the case of the titanium-richer samples, a cover film was used to eliminate the film blackening caused by copper and chromium radiation induced titanium self-fluorescence.

In the Ti-Mo-C-Re system, only the three known crystal structures from the base Ti-Mo-C ternary system, the monocarbide, subcarbide, and metal phases, were observed. In the Ti-Nb-C-Al system, however, in addition to the analogous crystal structures mentioned above, other phases were observed in some heat treated samples; these crystal structures were subsequently identified as belonging to two phases in the Nb-Al binary system,  $Nb_3Al$  (A-15) and  $Nb_2Al$  ( $\sigma$ -phase).

Almost all of the subcarbide, monocarbide, and metal phase patterns were measured to obtain lattice parameters; the measurements of the film strips were made using a Siemens Kirem coincidence scale with a micrometer (.01mm scale divisions) attachment.

#### D. METALLOGRAPHY

Metallographic examinations were performed on several rhenium-containing arc melted alloys of the Ti-Mo-Re-C system. Arc melted portions of the samples were mounted in an electrically conductive mixture of diallyl-phthalate-lucite copper base mounting material. The samples were roughly ground on varying grit sizes of silicon carbide paper; the final polishing was performed on a microcloth using a suspension of 0.05 micrometer alumina in Murakami's solution. The etching procedure in all cases consisted of an electro-etch using oxalic acid followed by a dip etch in an acid solution consisting of 60%  $H_2O$ , 20%  $HNO_3$ , 10%  $HCl$ , and 10%  $HF$ . This etching technique was sufficient enough to give excellent phase contrast even in the finely dispersed carbide-metal eutectics.

Photomicrographs were taken of representative portions of the samples using a Zeiss Ultraphot II microscope.

#### IV. RESULTS

##### A. THE TITANIUM-MOLYBDENUM-CARBON-SYSTEM WITH RHENIUM ADDITIONS

##### 1. Solid State Investigations at 1800°C

Since rhenium behaves, in some cases, chemically and physically quite similarly to molybdenum, it was expected that the phase equilibria of the metal-rich region of the Ti-Mo-C system would not change greatly with small rhenium substitutions for molybdenum. The sample series prepared contained 5, 10, 15 and 20% exchange (At.% basis) of rhenium for molybdenum in the base ternary Ti-Mo-C alloys whose compositional locations are shown in Figure 5.

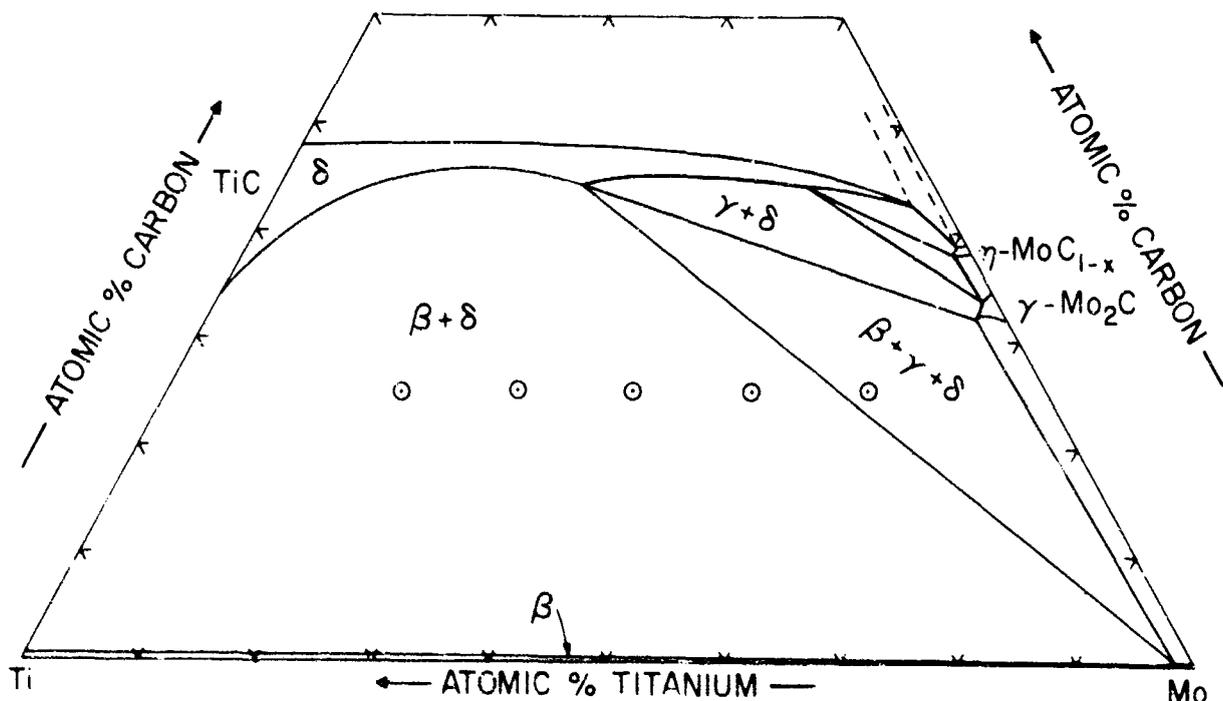


Figure 5. Ti-Mo-C: Sample Locations of Base Ternary Compositions for Rhenium Additions

In all cases, even up to a maximum rhenium content of 12 At.% overall, lattice parameter measurements indicated that there was practically no change in the phase equilibria over that presented by the base Ti-Mo-C ternary system. The phase equilibria of the metal-rich region of rhenium containing alloys is therefore drawn quite similar to that of the base Ti-Mo-C ternary system. (Figure 6). Table I shows the comparison of the lattice parameter data for the various percentage rhenium substitutions.

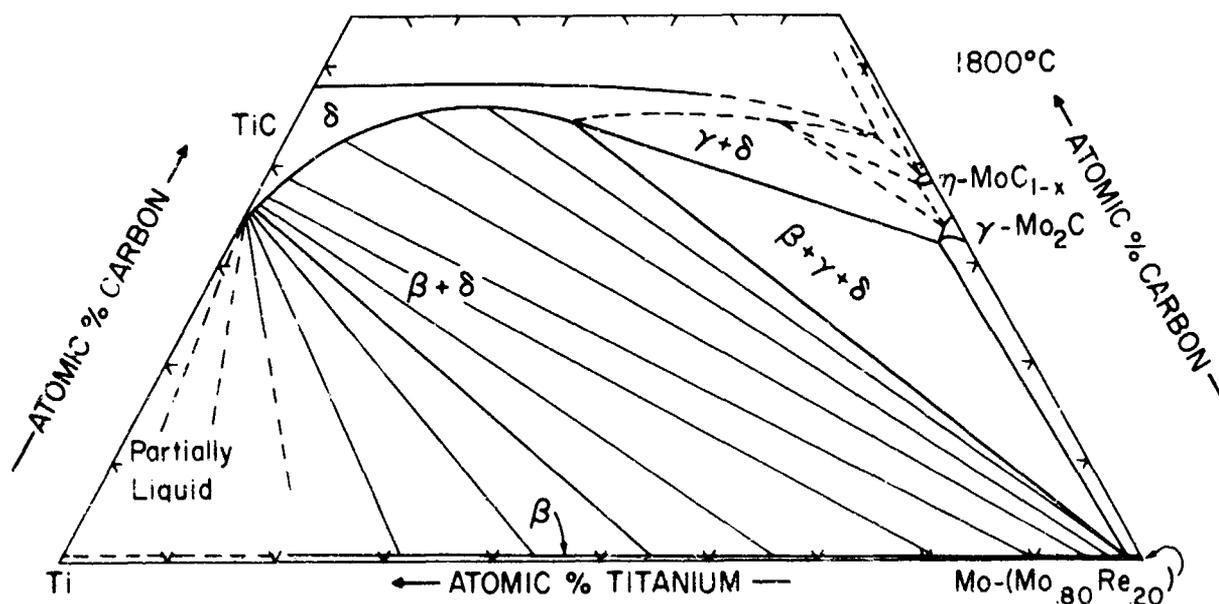


Figure 6. Ti-Mo-C-Re: Phase Equilibria of the Metal-Rich Region of the Ti-[Mo, (Mo .80 Re .20)]-C System at 1800°C.

Randomly picked rhenium containing samples from the two-phased metal + mono-carbide region were arc melted to ascertain if the high temperature phase equilibria changed at slightly subsolidus temperatures over that observed at 1800°C. The specimens were studied metallographically and also by Debye-Scherrer powder X-ray photographs; these X-ray film strips showed only the

Table I. Comparison of Lattice Parameters in Rhenium and Non-Rhenium Containing Alloys in the Ti-Mo-C System.

% Exchange (At.% Basis) Re/Mo+Re	Phase	Base Sample Composition (At.%) Ti-Mo-C				
		55-20-25	45-30-25	35-40-25	25-50-25	15-60-25
		Lattice Parameter, Å				
0	Monocarbide	4.30 <sub>9</sub>	4.31 <sub>0</sub>	4.30 <sub>5</sub>	4.30 <sub>0</sub>	4.28 <sub>4</sub>
	Metal	3.16 <sub>6</sub>	3.15 <sub>1</sub>	3.14 <sub>5</sub>	3.14 <sub>5</sub>	3.14 <sub>1</sub>
	Subcarbide	-	-	-	-	-
5	Monocarbide	4.31 <sub>1</sub>	4.31 <sub>0</sub>	4.30 <sub>9</sub>	4.30 <sub>2</sub>	4.27 <sub>0</sub>
	Metal	3.16 <sub>8</sub>	3.14 <sub>4</sub>	3.14 <sub>0</sub>	3.14 <sub>3</sub>	3.13 <sub>0</sub>
	Subcarbide	-	-	-	-	(2.99 <sub>3</sub> ) (4.73 <sub>3</sub> )
10	Monocarbide	4.31 <sub>3</sub>	4.31 <sub>3</sub>	4.31 <sub>3</sub>	4.29 <sub>4</sub>	4.28 <sub>5</sub>
	Metal	3.16 <sub>2</sub>	3.14 <sub>3</sub>	3.13 <sub>8</sub>	3.13 <sub>4</sub>	3.12 <sub>9</sub>
	Subcarbide	-	-	-	-	(3.00 <sub>0</sub> ) (4.74 <sub>6</sub> )
15	Monocarbide	4.30 <sub>9</sub>	4.31 <sub>9</sub>	4.31 <sub>4</sub>	4.30 <sub>0</sub>	4.27 <sub>9</sub>
	Metal	3.15 <sub>7</sub>	3.14 <sub>4</sub>	3.13 <sub>6</sub>	3.13 <sub>4</sub>	3.12 <sub>6</sub>
	Subcarbide	-	-	-	-	(2.99 <sub>5</sub> ) (4.73 <sub>6</sub> )
20	Monocarbide	4.31 <sub>3</sub>	4.31 <sub>4</sub>	4.31 <sub>3</sub>	4.30 <sub>5</sub>	4.27 <sub>6</sub>
	Metal	3.16 <sub>1</sub>	3.13 <sub>7</sub>	3.13 <sub>3</sub>	3.13 <sub>1</sub>	3.12 <sub>7</sub>
	Subcarbide	-	-	-	-	(2.99 <sub>2</sub> ) (4.73 <sub>2</sub> )

metal and monocarbide phases. Metallographically, as shown in Figures 7 through 10, only primary monocarbide in a monocarbide + metal eutectic matrix was observed; this behavior is entirely analogous to the findings in the base Ti-Mo-C ternary system which has a eutectic trough running from the titanium-rich binary side to the molybdenum-rich binary side in the metal-rich region of the ternary system. Therefore, the conclusion, as far as the basic phase equilibria is concerned, is that no change in the metal-rich region of the Ti-Mo-C system from intermediate temperatures up to melting with up to 20% Rhenium exchange (At.% basis) for molybdenum.

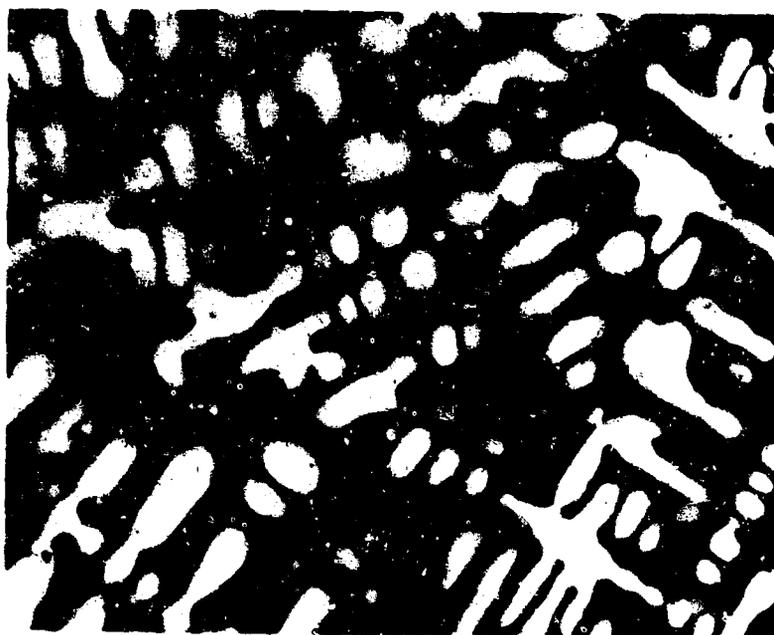


Figure 7. Ti-Mo-Re-C: Photomicrograph of a 25-45-5-25 Arc Melted Alloy Showing Primary Monocarbide in a Monocarbide + Metal Eutectic-Like Matrix

X625

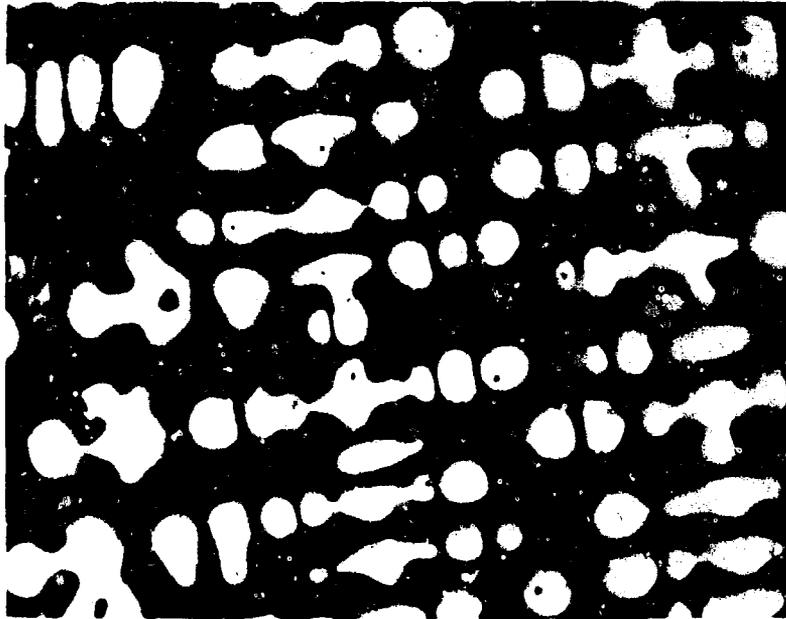


Figure 8. Ti-Mo-Re-C: Photomicrograph of an 35-34-6-25 Arc Melted Alloy Showing Primary Monocarbide in a Monocarbide + Metal Eutectic-Like Matrix

X1000



Figure 9. Ti-Mo-Re-C: Photomicrograph of an 35-32-8-25 Arc Melted Alloy Showing Primary Monocarbide in a Monocarbide + Metal Eutectic-Like Matrix

X1000

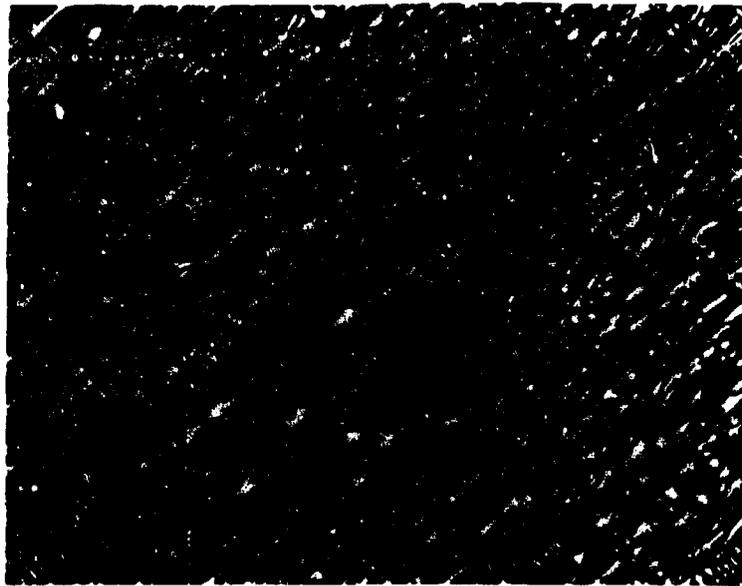


Figure 10. Ti-Mo-Re-C: Photomicrograph of an 25-40-10-25 Arc Melted Alloy Showing Primary Monocarbide Dendrites in a Monocarbide + Metal Eutectic-Like Matrix (Carbide in Eutectic Not Resolved at this Magnification). X200

B. THE TITANIUM-NIOBIUM-CARBON SYSTEM WITH ALUMINUM ADDITIONS

These investigations are confined to the study of the effect of up to 10 At.% substitution of aluminum for niobium + titanium ( $Ti/Nb = \text{const}$ ) on the metal-rich phase equilibria of the Ti-Nb-C ternary system. Figure 11 shows the compositional location of the samples in the base Ti-Nb-C ternary system to which 5 and 10 At.% aluminum was substituted for the total metal (Ti+Nb) content.

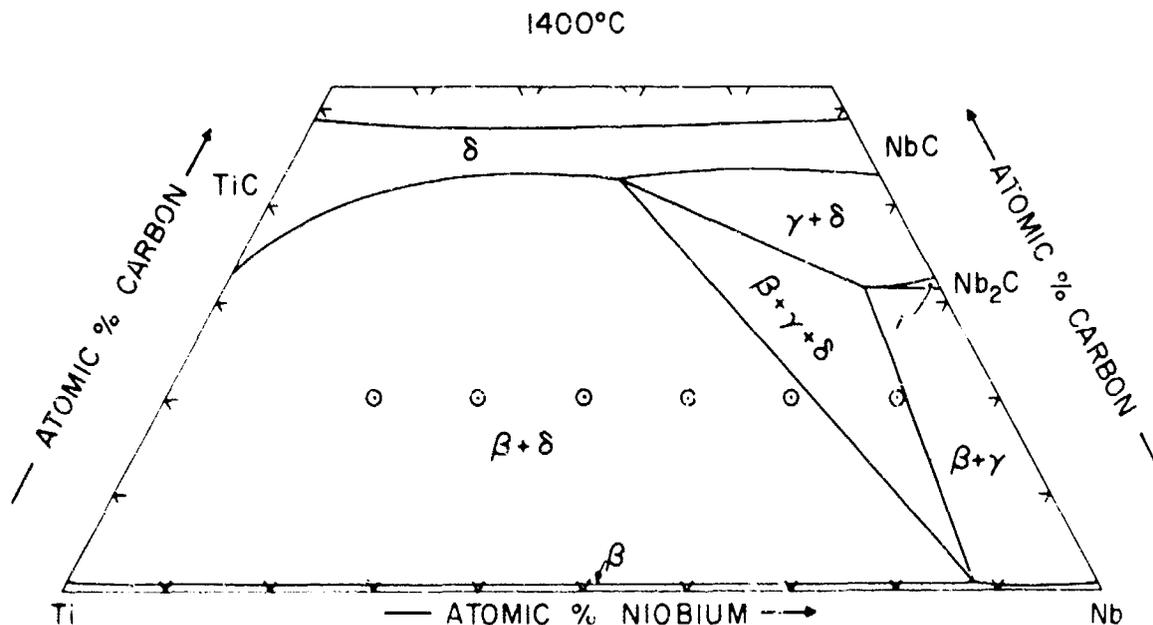


Figure 11. Ti-Nb-C: Base Ternary System Showing Compositional Location of Samples to Which 5 and 10 At.% Aluminum Additions were Made ( $Ti/Nb = \text{const.}$ )

In both series, one with 5% and the other with 10% Al substitution, it was found from the Debye-Scherrer powder photographs of the alloys heat treated at 1400°C that with increasing niobium content, increasing amounts, even though in varying proportions, of crystal structures not belonging to the base Ti-Nb-C ternary system, along with the expected structures of the monocarbide, metal and subcarbide phases were observed. It was subsequently ascertained that these structures belonged to the Nb<sub>3</sub>Al (A-15 type) and Nb<sub>2</sub>Al (σ-type) phases. The general diffused appearance of the X-ray films indicated that, even after heat treatment for 30 hours at 1400°C, the samples were not in equilibrium. Several of these samples were arc melted and re-heat treated for 35 hours at 1400°C. X-rays of these arc melted samples showed only monocarbide and metal phases, and in the more niobium-rich alloys, in addition, the Nb<sub>2</sub>C-based subcarbide solid solution. The results were identical when these arc melted samples had received the additional heat treatment at 1400°C. It is quite evident, then, that of the starting materials, TiC, Nb<sub>2</sub>C, Nb, and Al, in the hot pressed samples, the low melting aluminum reacted preferentially with the niobium to form the rather stable niobium aluminides, Nb<sub>3</sub>Al and Nb<sub>2</sub>Al. Neither the heat treating time nor the temperature (1400°C) was sufficient to permit the establishment of equilibrium. After arc melting and subsequent re-heat treatment, the aluminides vanished as the correct equilibria consisting of monocarbide, metal, and subcarbide were attained. The lattice parameters of the monocarbide, metal, and subcarbide phases for the series of alloys with 5 and 10 At.% Al substitution were measured from both single heat treated and arc melted heat treated alloys and are recorded in Table II.

Table II. Comparison of Lattice Parameters in Aluminum and Non-Aluminum Containing Alloys in the Ti-Nb-C System

At.% Al Substitution for (Ti + Nb) (At.% Basis) Ti/Nb = const.	Phase	Base Ternary Composition Ti-Nb-C (At.%)						
		60-20-20	50-30-20	40-40-20	30-50-20	20-60-20	10-70-20	
		L A T T I C E P A R A M E T E R, Å						
0	Monocarbide	4.31 <sub>6</sub>	4.33 <sub>0</sub>	4.34 <sub>8</sub>	4.35 <sub>4</sub>	4.37 <sub>2</sub>	--	
	Metal	3.25 <sub>6</sub>	3.28 <sub>4</sub>	-	3.29 <sub>0</sub>	3.28 <sub>7</sub>	--	
	Subcarbide	-	-	-	-	-	$\begin{pmatrix} 3.10_8 \\ 4.94_9 \end{pmatrix}$	
5	Monocarbide	4.32 <sub>0</sub>	4.32 <sub>4</sub>	4.33 <sub>5</sub>	4.34 <sub>9</sub>	4.36 <sub>8</sub>	--	
	Metal	3.27 <sub>1</sub>	3.27 <sub>3</sub>	3.26 <sub>9</sub>	3.28 <sub>7</sub>	-	-	
	Subcarbide	-	-	-	-	-	-	
10	Monocarbide	4.31 <sub>9</sub>	4.22 <sub>6</sub>	-	4.34 <sub>1</sub>	-	-	
	Metal	-	3.27 <sub>9</sub>	-	3.27 <sub>7</sub>	-	-	
	Subcarbide	-	-	-	-	-	$\begin{pmatrix} 3.11_4 \\ 4.97_0 \end{pmatrix}$	

Without a more extensive qualitative evaluation of not only the limits of the lower phase boundary of the (Ti,Nb,Al)C monocarbide solid solution, concurrent with the measurement of many lattice parameters of the necessary samples to obtain an enumeration of the said lower monocarbide boundary (beyond the scope of these investigations); it is not possible to present precise tie lines in the two-phased metal + monocarbide region. It can be said, however, that the phase equilibria and tie line distribution in this region of the quaternary system is quite similar to that of the parent Ti-Nb-C system. Figure 12 shows the metal-rich phase equilibria of the Ti-Nb-C system with up to 10 Atomic % Aluminum substitutions; the tie lines are indicated with uncertainty.

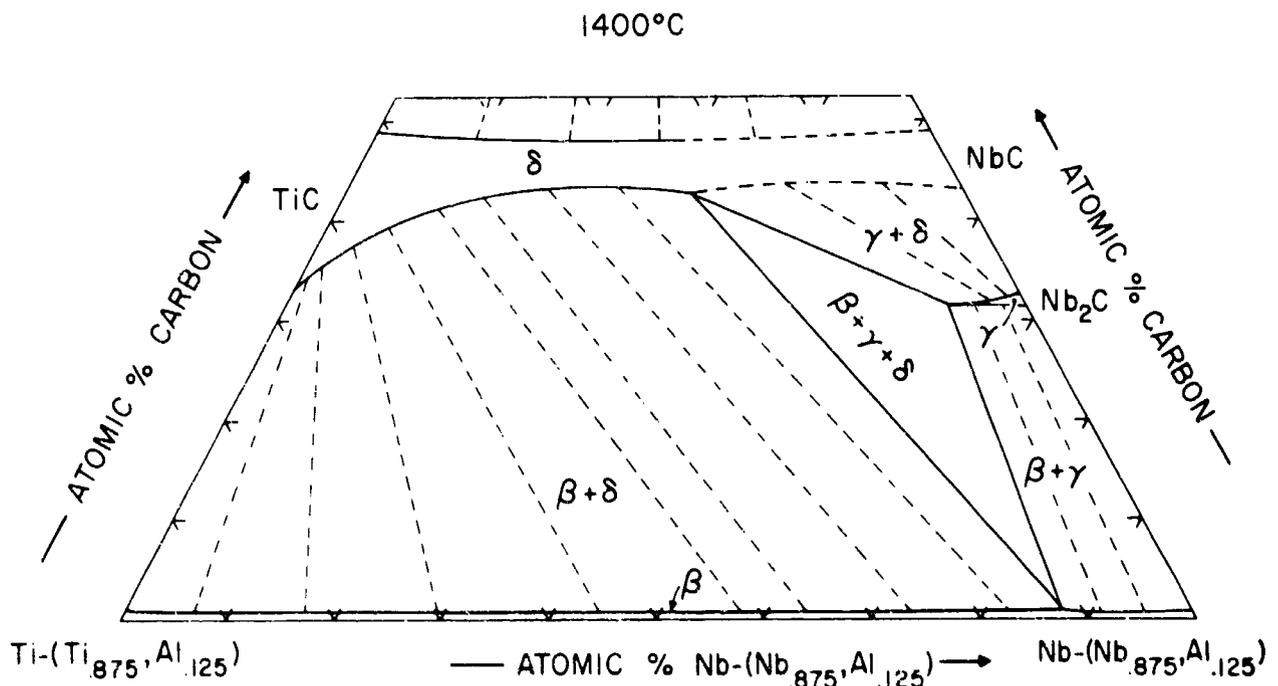


Figure 12. Ti-Nb-C-Al: Metal-Rich Phase Equilibria of the  $[Ti(Ti_{.875}, Al_{.125})] - [Nb-(Nb_{.875}, Al_{.125})] - C$  System at 1400°C.

## V. CONCLUSIONS AND DISCUSSION

### A. THE TITANIUM-MOLYBDENUM-CARBON-RHENIUM SYSTEM

These investigations have shown that rhenium may be added to the metal-rich portion of the Ti-Mo-C ternary system in quantities up to at least 12 atomic % without affecting the basic metal-rich phase equilibria exhibited by this ternary system. At higher rhenium concentrations, the phase equilibria will probably show a significant change due to the formation of titanium-rhenium and molybdenum-rhenium intermetallic phases.

If the mechanical and physical properties of these quaternary alloys containing small amounts of rhenium are deemed promising for cutting tool applications, the thermodynamic behavior of such alloys with these small amounts of rhenium permit the maintaining of the desired monocarbide + metal alloy two-phased equilibrium. Furthermore, since rhenium behaves very similarly to molybdenum in many instances, it is safe to say that in analogy to the tie line distribution in the base Ti-Mo-C ternary system; the added rhenium will enrich itself in the metal (Mo-rich) alloy proportionately more than in the coexisting monocarbide. This is, of course, more desirable if the mechanical properties of the metal alloy binder phase could possibly be improved by rhenium additions to increase the overall cutting performance of such tools.

### B. THE TITANIUM-NIOBIUM-CARBON-ALUMINUM SYSTEM

The results of these studies have indicated that there is no basic change in the phase equilibria in the metal-rich portion of this quaternary system over that of the base Ti-Nb-C ternary system under aluminum substitution of up to 10 atomic percent. There is, however, considerable

doubt as to whether such alloys from the two-phased region monocarbide + metal can conveniently be prepared (brought into a thermodynamic equilibrium state) by sintering alone if they contain aluminum additions. These investigations have shown that unless the alloys are melted for homogenization, rather stable, unwanted niobium aluminides are present.

If aluminum additions are indeed desired to improve the characteristics of possible Ti-Nb-C based cutting tool alloys, steps will have to be taken, probably melting or the preparation of suitable master alloys containing aluminum, to assure the attainment of homogeneous monocarbide + metal alloys.

#### REFERENCES

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13 ABSTRACT <p>The solid state phase equilibria of the metal-rich regions of the Titanium-Molybdenum-Carbon and Titanium-Niobium-Carbon systems with up to 12 At.% Rhenium and 10 At.% Aluminum additions, respectively, have been determined on hot pressed, heat treated, and in part air melted alloys.</p> <p>The phase equilibria in the metal-rich regions, with these additions, is practically unchanged over that of the ternary Titanium-Molybdenum-Carbon and Titanium-Niobium-Carbon systems; the existence of the large two-phased areas, monocarbide + metal phases, remains.</p>		

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	ROLE	WT	ROLE	WT	ROLE	WT
Phase Equilibria Cutting Tools Titanium-Molybdenum-Carbon-Rhenium Titanium-Niobium-Carbon-Aluminum						

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