PHYSICAL PROPERTIES AND MICROSTRUCTURES OF A SELECTED
PORTION OF THE TITANIUM-VANADIUM-SILICON ALLOY SYSTEM

A THESIS

SUBMITTED TO THE FACULTY OF THE UNIVERSITY OF NEVADA IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

BY

PETER FREDERICK YOUNG

RENO, NEVADA

APRIL 30, 1956
Approved by:

[Signature]

Director of Thesis

Approved by:

[Signature]

Major Professor

Approved by:

[Signature]

Chairman of Graduate Committee
The author wishes to express his grateful appreciation for the valuable assistance rendered in this study by the United States Bureau of Mines, Rare and Precious Metals Experiment Station, Reno, Nevada. He is particularly indebted to Professor John S. Winston and Mr. William H. Lens whose guidance and generous help carried this thesis to its completion, and to Mrs. Edna Voigt who rendered assistance with some of the metallographic work and proof read this manuscript.
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I

ABSTRACT

A portion of the titanium-vanadium-silicon system was chosen to be studied after a literature survey of this system had been conducted. Various procedures and methods of alloy preparation were studied and, in a few cases, were perfected. Alloys containing equal parts of titanium and vanadium and up to 7% silicon were considered. The study, however, concentrated on alloys containing under 1% silicon when it was found that only these alloys were readily formed into useful shapes. Physical properties and microstructures of these alloys are discussed and some recommendations for future investigation are made.
The purpose of this thesis was to perform a preliminary evaluation of vanadium metal with possible useful applications in mind. Because this is a relatively new metal with some possibilities for commercial application, it was thought it would make an interesting metal to start on as a basis for research. Metallurgical references on vanadium are decidedly few in number, although this seems reasonable since ductile vanadium has been available commercially only since about 1951. With the development of the calcium reduction process for vanadium pentoxide, vanadium metal can be produced which is low enough in interstitials and metallic impurities to permit severe deformation both hot and cold.

It was next decided that an alloy would be studied rather than pure vanadium because of the only fair physical properties and rather high cost of the pure metal (\$75 per pound in the as-reduced state). The number of possible alloying additions was then narrowed down because only a handful of metals give ductile alloys when added to vanadium in amounts of over 10% (1), although numerous elements theoretically have appreciable solubility in vanadium according to the Hume-Rothery rules of alloying (2). These rules state that agreement of atomic diameters of the proposed elements to be alloyed within 15% indicates the possibility of limited solid solubility and agreement within about 7% usually
indicates extensive solid solubility. Al, Ti, Cr, Mo, and Fe fall under the 7% limit while Si, Ta, W, and Zr fall between 7% and 15%. However only Ti, Zr, and small amounts of Si can be added and still have ductility retained in the resultant alloy (3). Titanium was chosen as the second large alloying addition since it can be added to vanadium in amounts of over 50% without appreciably affecting the ductility of the resultant alloy and because it tends to increase the tensile strength of vanadium. (Further tests later showed that the aforesaid increase actually was quite substantial.)

When it was discovered that the combination of titanium and vanadium made definite improvements over the physical properties of either metal used individually, it was decided to add silicon in small amounts as a third alloying addition to see if even better physical properties could be obtained. A basic alloy of 50% vanadium and from 43% to 50% titanium was chosen to make these silicon additions to because this composition seemed to combine optimum tensile strength and ductility. (see fig. 3 and ref. 4) Many problems were encountered in melting, forming, and testing these alloys which are, of course, to be expected in the investigation of new metals and procedures. Fairly reproducible results and some positive answers were obtained from the experimental data.
DESCRIPTION OF EQUIPMENT

Button melting furnace

The button melting furnace used to melt the high temperature alloys is essentially a water cooled arc melting furnace with an inert atmosphere surrounding the melting area. Unfortunately, due to patent restrictions, a picture of this furnace cannot be shown here. The furnace was designed and built at the United States Bureau of Mines Experiment Station, Boulder City, Nevada. The electrode is a water cooled copper tube with a 1/16" tungsten electrode fastened to the end. The electrode is movable and current up to 400 amperes is supplied by a General Electric D.C. arc welding unit. Two glass windows are fixed in the furnace. One provides illumination and the other is used for observation of the interior during the melting operation. Water jackets are affixed to the furnace for cooling purposes. A charge box is located on the left of the melting chamber to facilitate charging and emptying the furnace. Evacuation of the charge box is accomplished by a small Welch vacuum pump. Access is made to the furnace interior during operation by means of a rubber glove located behind a sliding door at the right of the furnace. Helium can be introduced into the furnace either through the charge box or directly into the melting chamber. The flow of helium is controlled either by flow meters on the tank or by bubblers located...
on the exhaust sides of the two chambers. The actual melting is done on a water cooled copper plate positioned on the floor of the melting chamber. Because copper has such a high rate of heat conduction, the plate does not melt even when subjected to temperatures over 2500 degrees centigrade. Very little difficulty is experienced with metals alloying directly with the copper plate. Buttons varying in size from five grams to 100 grams have been melted successfully and small ingots up to 300 grams or more can be made by melting a number of smaller buttons together at a high amperage.

**Tube furnace**

The tube furnace is used for most of the heat treating operations. A non-reactive medium is provided by passing helium gas through the tube while the treatment is in progress. The tube diameter is one and a half inches, which is large enough for most specimens to be accepted. The samples to be treated are put into a "boat" made of cold rolled titanium sheet. The boat is then inserted in the tube and the atmosphere of helium and the heat are turned on. Temperatures as high as 1600 degrees centigrade can be reached. If desired, quenching can be accomplished by withdrawing the boat and quickly immersing it in water or oil before the alloys can react with the normal atmosphere.
In some cases it was desirable to anneal material under vacuum conditions and for this purpose a HARESCO vacuum furnace was employed. This furnace allowed temperatures up to 2000 degrees centigrade and pressures down to $10^{-5}$ millimeters of mercury to be reached. Unlike the tube furnace, a helium atmosphere is not used. The main advantage of this furnace lies in the fact that it can be used to pull embrittleing hydrogen out of the molten buttons while they are being annealed. Temperatures above 700 degrees centigrade were read by means of an optical pyrometer.
IV

GENERAL EXPERIMENTAL PROCEDURES

Preparation of compacts

The materials to be alloyed were weighed out to 0.05 gram. The weighed materials were then poured into a die and pressed into round flat compacts about one quarter to one half inch in thickness and two and one quarter inches in diameter. (see plate no. 1) In making the compacts, care had to be taken to see that the distribution of the metals was as uniform as possible and that none of the finer material sifted out of the compact in handling. This became a bit of a problem occasionally as the material varied in size from -3 mesh to plus 40 mesh. Depending upon the size of the die used, (the compression machine has an upper limit of 120,000 pounds), the pressure of compaction was 68,000 psi for the one and one quarter inch die and 30,200 psi for the two and one quarter inch die. The usual weight of compacts varied from twenty to seventy grams because smaller or larger ones were difficult to melt. No special purging of the die or material with helium was performed before compression.

Melting procedures

The general plan of the button furnace has been previously
Plate No. 1  - Alloy compact ready for melting.
Approximately natural size.
described. The compacts to be melted were put into the charge box. The box was then evacuated for thirty minutes whereupon helium was allowed to flow into the chamber until slightly more than one atmosphere pressure was reached. The charge box was again evacuated for the same amount of time and helium was again allowed to flow into the chamber. This cycle was repeated for the third time after which the inner door to the furnace was opened and the compacts were placed on the melting plate. Although a slight flow of helium is maintained twenty four hours a day, the furnace still must be purged of all nitrogen and oxygen before every melting run. For this purpose 3 or 4 seventy gram compacts of titanium sponge were melted before the main run in order to scavenge these undesirable gases out of the furnace. As titanium absorbs nitrogen and oxygen quite readily when molten, removal of the gases was accomplished quite successfully. After the preliminary scavenging, the alloys to be melted were put into the furnace. Every separate melt consisted of four compacts, one "blank" of titanium of known hardness, and one scavenger button to strike the arc on. The blank was included to determine whether the melt picked up any embrittling gases during the operation, while the scavenger was included because the buttons tend to pick up tungsten from the electrode if the arc is struck on them. Helium at slightly above atmospheric pressure was passed continuously through the furnace during melting at a flow rate of approximately 10 cubic feet per hour.
Plate No. 2 - Alloy button after removal from melting furnace. Approximately natural size.
When melting the first side of the button the arc current was usually about 180 amperes. The button was then turned over and melted on the other side at the same amperage. After the first two meltings the current was raised to 250 to 350 amperes depending upon the size of the buttons. This was necessary in order to produce a stirring action, thereby melting the button all the way through thus creating a homogeneous alloy. Buttons were usually melted twice on each side for a total of four times, being turned over between each melting. It was found that more meltings than this substantially increased the hardness of the final alloys and fewer meltings did not give a homogeneous alloy.

**Surface preparation and hardness testing**

After the buttons were removed from the furnace they were set up on a lathe and the two opposite faces were machined off until they were parallel and free from imperfections. A tungsten carbide bit had to be used for this as ordinary carbon steel was not hard enough to satisfactorily machine vanadium alloys. These two faces were used for conducting Brinell and Rockwell hardness tests. It was found that the type of surface on which the hardness tests were performed affected the hardness number to some extent. A smoothly sanded surface gave a slightly lower reading in some cases than a smoothly machined surface. This was probably due to the absence of grooves and the work hardening caused by the machining. The sanding was done under a coolant and there-
Plate No. 3 - Alloy button after hardness testing. Note test indentations. Approximately natural size.
fore, no work hardening of the sample occurred with this method. Any work hardened metal left by the initial machining was removed in the subsequent sanding operation.

The Brinell test used a 1500 kilogram load on a ten millimeter ball for thirty seconds. The Rockwell test used the "A" and "B" Rockwell scales when applicable. Generally the Brinell test was used rather than the Rockwell to offset possible erroneous readings due to large and non-uniform grains in many of the alloys.

Rolling

Cold reduction of the buttons was accomplished on a small set of wire rolls. Hot rolling was tried but certain obstacles such as the problem of oxygen and nitrogen pickup rendered this practice rather impractical at the present time. Hot rolling would be possible and probably superior to cold rolling if facilities were available for sheathing the alloys in some protective material before heating and rolling. This material would protect the alloy during working and after the hot rolling was finished the sheath would be stripped off the alloy.

Annealing

Annealing was accomplished in either the aforementioned tube furnace or the NARESCO vacuum furnace. (see page 5).
Annealing times for the ternary alloys were about two hours at 900 to 1000 degrees centigrade unless otherwise stated.

**Tensile testing**

Tensile testing was accomplished on a Baldwin Universal Testing Machine. Buttons were rolled into sheets which were then sheared into five eights inch strips. These strips were machined into tensile specimens on a Tensile-Kut machine. Gauge marks were then inscribed and the specimen was inserted in the machine. A microformer for measuring and recording the stress strain curve was attached and the specimen was pulled. A ram travel of about 700 pounds per minute was usually used, and a drum type recorder recorded the stress strain curve. After the specimen broke, the breaking strength, percentage elongation, and percentage reduction in area were recorded. Any imperfections which may have caused premature breakage were noted also.
Vanadium - Electro Metallurgical Co., Niagara Falls, New York

Analysis - (125 BHN)  
C = 0.043 %  
H = 0.0017 %  
N = 0.050 %  
O = 0.064 %

Titanium - United States Bureau of Mines Experiment Station, Boulder City, Nevada

Analysis - (68 BHN)  
C = 0.008 %  
H = 0.006 %  
N = 0.001 %  
O = 0.024 %  
Cl = 0.01 %  
Mg = 0.05 %

Analysis - (92 BHN)  
C = 0.012 %  
H = 0.019 %  
N = 0.001 %  
O = 0.046 %  
Cl = 0.06 %  
Mg = 0.05 %

Analysis - (120 BHN)  
C = 0.016 %  
H = 0.0028 %  
N = 0.005 %  
O = 0.112 %  
Cl = 0.10 %  
Mg = 0.09 %

Silicon - United States Bureau of Mines Station, Rolla, Missouri

Analysis - (Brittle)  
Si = 99.9+ %
Titanium - vanadium system

A fair amount of information is available on this system.

(5) The constitution of the whole system was investigated independently by two groups of investigators with fair agreement between them. The solidus curve was determined by the incipient melting method and the composition of the minimum is located at approximately 30\% vanadium and 1620 degrees centigrade. The melting point of vanadium is 1900 ± 25 degrees centigrade and that of titanium is about 1720 degrees centigrade. The boundaries of the alpha and alpha plus beta fields are outlined on the phase diagram. (See diag. no. 1)

Titanium - silicon system

The phase diagram of this system (See diag. no. 2) is fairly well established (6). The solid solubility of silicon in beta titanium is about 3.0\% (extrapolated) at the critical temperature of 1330 degrees centigrade, between 1.68 and 1.95 \% at 1100 degrees centigrade, approximately 0.9 \% at 860 degrees centigrade, and about 0.3 \% at 600 degrees centigrade. Note the three compounds Ti$_2$Si$_3$, TiSi, and TiSi$_2$ in this system. The melting point of silicon is about 1410 degrees centigrade.
Diagram No. 1

VANADIUM - TITANIUM
PHASE DIAGRAM

DEGREES CENTIGRADE

1900°C

1620°C

L

L + β

β

% VANADIUM
Vanadium - silicon system

Diagram number three shows the probable form of the vanadium-silicon phase diagram. Not too much work has been done on this system but recent work (7) indicates the following:

1. The solubility limit of silicon in vanadium appears to be just less than 5% and an annealed 2.5% silicon alloy showed a rejected phase indicating a reduced solubility boundary at room temperature.

2. The limited vanadium solid solution enters into a eutectic reaction with an intermetallic phase \( V_3Si \) (7.5% silicon) at about 1840 degrees centigrade.

3. A peritectic reaction occurs at 15% silicon and approximately 2060 degrees centigrade forming \( V_3Si \) and an unknown phase. It has been suggested that the other compound be \( V_2Si \) but some investigators have expressed doubt on this point, believing that a \( VSi \) phase would be more likely.

4. Other recent work indicates a \( VSi_2 \) plus Si eutectic at 1145 degrees centigrade and 95% silicon. The intermetallic phase \( VSi_2 \) has a maximum melting point of 1654 degrees centigrade.

The above bits of information will evidently have to serve for the present as a rough indication of this system.
VANADIUM - SILICON
PHASE DIAGRAM

Diagram No. 3

VSi + L
1840°C

V3Si + V
1900°C

VSi + L
2060°C

L

VSi

V3Si

V

VSi2

Si

VSi2 + Si

VSi2

1145°C

1100

1000

1200

1400

1450

1600

1654°C

1500°C

1800

1850

1900

1950

2000

2050

2100

2150

2200

2250

2300

% VANADIUM

DEGREES CENTIGRADE

0

10

20

30

40

50

60

70

80

90

100
VII
PRELIMINARY INVESTIGATIONS

Alloy analysis

No positive control was kept on the compositions of the various alloys either in relation to the major components or to the minor impurities because no facilities were available at the Bureau for these types of analysis. Nominal compositions therefore, are used exclusively in this investigation. There is no reason to believe that the compositions varied more than \( \pm 0.1\% \) from the ideal values in the minor constituent silicon and not more than \( \pm 1.0\% \) in the major constituents vanadium and titanium. The metals were weighed out to 0.05 grams and their total weight was recorded. The alloy was weighed again after compaction and again after melting. If there was any loss above 0.5 gram in either of these steps, the alloy was discarded and a new one was prepared.

Hardness was used as a control on the impurities, especially nitrogen, oxygen, and hydrogen which the alloys might pick up during melting and subsequent heat treating. A pickup of very minute quantity of these impurities will usually cause a large increase in hardness and, of course, a correspondingly more brittle alloy. (8) Because of the great affinity these metals have for impurities such as these, this hardness control was a good way to check on the purity of the furnace atmosphere. It has been found
that only if the sum of nitrogen and oxygen are below 0.12 to 
0.16 % can vanadium be satisfactorily cold worked. (9) When such 
minor amounts of impurities have a large effect on a metal, it 
becomes very difficult to obtain usable metal and make satis-
factory alloys out of it.

**Formability of alloys**

The relationship of hardness, workability, and composition of the alloys was considered carefully at the beginning of this investigation. As will be seen later, the alloys of over 1.0 % silicon proved to be very difficult to form, and in many cases were so brittle as to be unusable, so these were discarded and the investigation then concerned itself mainly with the under 1.0 % silicon composition range. There was no difficulty in cold working pure vanadium or pure titanium. It is possible to reduce them 90 to 95 % by cold rolling without intermittent annealing. The 50% titanium-50% vanadium alloy was a little more difficult to reduce than either of the pure metals, but large reduction was accomplished without undue amounts of edge cracking. As mentioned above, the addition of silicon radically changed the picture. The alloys of over 1.0% silicon cracked after one or two passes through the rolls with a total of less than 5% reduction. If the alloys contained under 1.0% silicon
they reduced 50% without annealing. Various heat treatments, before rolling, to decrease grain size which might thereby give greater workability were tried with little success. The eutectic which silicon forms with titanium and vanadium probably caused the alloys to be brittle. The severe edge cracking which was encountered in these alloys can be seen in plate no. 4.

Quality of titanium used in alloys

Another problem to be considered was which grade of titanium to use in making these alloys. Two facets of the question were the availability of the raw material and the physical properties (including ease of working) of the resultant alloys. The latter point ruled out the 150 BHN titanium on the grounds that the resultant alloys were difficult to work and gave physical properties which were not representative of high purity metals. This same point ruled out the 120 BHN titanium, although there was a possibility that it could be used. The 90 BHN and 68 BHN titanium gave satisfactory physical properties but since little or no difference in ductility was noted between the 68 BHN and 90 BHN titanium and since the 90 BHN material had slightly higher tensile strength and was more readily available it was decided to use the 90 BHN titanium exclusively except for a few tests with the other grades which merely generally defined their properties.
Plate No. 4 - 50% vanadium, 49% titanium and 1% silicon alloy showing severe edge cracking after about 50% reduction. Approximately natural size.
VIII

METALLOGRAPHIC RESULTS

Specimen preparation

The problems encountered in the metallographic preparation of vanadium and its alloys were too numerous to be discussed in this paper. Suffice to say that so far as the author knows, no satisfactory method of preparation which will give reproducible results has been perfected up to this time. Problems concerning pitting, scratching, and metal flow were very evident. Some progress is being made with electro polishing, but no reliable procedure has been found as yet.

The etchant used in these experiments was standardized at 20% HF, 20% HNO₃, and 60% glycerin. Good results were obtained with this etch and no attempts were made to investigate further.

All the photomicrographs represent specimens which were annealed at 950, ± 25 degrees centigrade for two hours under a helium atmosphere. Generally speaking, the photographs show the solid solution of vanadium and beta titanium with small amounts of alpha titanium needles and varying amounts of the vanadium-titanium-silicon eutectic. Descriptions of specific microstructures which are particularly interesting will follow.

Plate No. 5 (50% vanadium-50% titanium) The field consists of the solid solution vanadium and beta titanium. Notice the needles of alpha titanium in the grains and along
the grain boundaries. Normally the field would contain no alpha titanium, but the minor amounts of nitrogen and oxygen in the vanadium tend to act as alpha stabilizers and the alpha phase appears. (10) Some alpha titanium can also be noticed in plates 6 and 7.

Plates No. 6 and 7 (50% vanadium-49.5% and 49% titanium-0.5% and 1.0% silicon) Notice first appearance of the silicon-titanium-vanadium eutectic as very fine particles.

Plate No. 8 (2.0% silicon) The silicon eutectic can be plainly seen now as the quantity of silicon increases.

Plate No's. 9, 10, 11, and 12 (3.0 to 6.0% silicon) Shows increasing amounts of vanadium-titanium-silicon eutectic.

Plate No's 13 and 14 (7.0% silicon) These plates show approximately the titanium-vanadium-silicon eutectic point. This eutectic point occurs somewhere between 7.0 and 8.0% silicon.
Plate No. 5 - 50% vanadium, 50% titanium alloy. Standard etch. 200X magnification.

Plate No. 6 - 50% vanadium - 49.5% titanium - 0.5% silicon alloy. Standard etch. 200X magnification.
Plate No. 7 - 50 % vanadium - 49 % titanium - 
1 % silicon alloy. Standard etch. 
200 X magnification.

Plate No. 8 - 50 % vanadium - 48 % titanium - 
2 % silicon alloy. Standard etch. 
200 X magnification.
Plate No. 9 - 50% vanadium - 47% titanium - 3% silicon alloy. Standard etch.
200X magnification.

Plate No. 10 - 50% vanadium - 46% titanium - 4% silicon alloy. Standard etch.
200X magnification.
Plate No. 11 - 50% vanadium - 45% titanium - 5% silicon alloy. Standard etch. 200 X magnification.

Plate No. 12 - 50% vanadium - 44% titanium - 6% silicon alloy. Standard etch. 200 X magnification.
Plate No. 13 - 50% vanadium - 43% titanium -
7% silicon alloy. Standard etch.
200 X magnification.

Plate No. 14 - 50% vanadium - 43% titanium -
7% silicon alloy. Standard etch.
600 X magnification.
PHYSICAL TESTING RESULTS

Hardness

The hardness values of the alloys and pure metals are shown in Figures 5, 6, and 7. The as cast vanadium averaged about 183 BHN while the titanium was 68 or 90 BHN, depending upon the purity. Figure 5 indicates hardness for the vanadium titanium system up to 50% titanium. Note the dips in the hardness curve at 10% titanium and 40% titanium. An attempt has been made to explain this (11), but no definite investigation of the matter has been taken. Figure 6 shows the 50% vanadium 50% titanium system with 0 to 7.0% silicon. Note the steady increase from 210 BHN to 355 BHN. Figure 7 shows a magnification of the 0 to 1% silicon range. Two minima occur at 0.2 and 0.6% silicon which are unexplained. Notice also that in most cases where alloys were annealed the hardness of the annealed alloy was, in some cases, somewhat less than the as cast form. Note particularly the decrease from 315 BHN to 250 BHN in the 3% silicon alloy. In review, we can say that silicon causes a noticeable increase in hardness up to 1% and a considerable increase in hardness from 1% to 7%. As we saw on page 21 and 22, only the alloys under 1% were ductile enough to form into tensile specimens, however heat treatment might render some of the other alloys workable.
Refer to Figure 1-4 for the results of the physical testing program. The data obtained with 50% reductions of the alloys made with 90 BHN titanium is used in this comparison. As can be seen, vanadium has the lowest ultimate strength which is about 86,000 psi; titanium is next with about 96,000 psi; titanium-vanadium follows with about 138,000 psi; and the 0.2% silicon alloy is the highest with about 156,000 psi. Note that the percentage elongation is about the same for the pure vanadium and the pure titanium. In the vanadium-titanium alloy and the vanadium-titanium-silicon alloys the elongation drops about 50%. As a brief explanation, elongation indicates the ductility of a metal, to a certain extent, under tension. All elongations are taken over a two inch gauge length. These results seem to compare somewhat generally with the findings of other investigators, (12, 13), although the tensile strength particularly seems to be lighter than other investigators have found.

Apart from the relationship of tensile strength to alloy composition as seen above, there seems to be a correlation between hardness and tensile strength. Note especially in the 0 to 1% silicon range that when there is an increase in tensile strength there seems to be a corresponding decrease in hardness. The same effect is observed with pure titanium and pure vanadium where the vanadium is harder than the titanium but has a lower tensile strength.
Figure 1 - Tensile Properties of Pure Titanium Metal
Figure 2 – Tensile Properties of Pure Vanadium Metal
Figure 4 - Tensile Properties of the Titanium-Varadium-Silicon Alloys

- **Δ**: 68 BHN
- **O**: 90 BHN

Percentage silicon in alloy (approximately 50% reduction)
Figure 5 - Brinell Hardness Versus Composition For The Titanium Vanadium System

- 68 BHN
- 90 BHN
Figure 6 - Brinell Hardness Versus Composition For The Vanadium

Titanium - Silicon System (0 to 7% Silicon)

- O - 90 BHN - As Cast
- □ - 90 BHN - Annealed
Figure 7 - Channel Hardness Versus Composition for the Vanadium
Titanium - Silicon System (0 to 1.0% Silicon)
RESULTS AND CONCLUSIONS

It was found that the addition of titanium and silicon to vanadium increased the ultimate tensile strength of the metal about 70,000 psi, however the ductility of these high strength alloys was much lower than that of pure vanadium. The optimum alloy of titanium and vanadium seemed to be the 50-50 alloy. The range of silicon alloys having any ductility at all was narrowed down to the 0 to 1% silicon range. In this range, the 0.2% silicon alloy was the best alloy in regard to physical properties. The hardest alloy encountered was the 7% silicon alloy at 354 BHN and the softest was 68 BHN for pure titanium. The 0.2% silicon alloy had the highest tensile strength at 156,000 psi, while pure vanadium had the lowest tensile strength at 86,000 psi. The most ductile was the 68 BHN titanium at 11% elongation, and the most brittle was the 7% silicon alloy.

If the cost of vanadium could be reduced and the fabricating techniques perfected, commercial applications of this metal might be considered. Otherwise, as it appears from this study, the most useful alloy (0.2% silicon) does not surpass many commercially used titanium alloys and has the added deterrents of high cost and difficult fabrication. Applications utilizing the high corrosion resistance and the low creep of vanadium at high temperatures might be commercially feasible (14).
Areas for further study might include the unexplained reverse trends and abnormalities in the vanadium-titanium and vanadium-titanium-silicon systems. The high temperature creep and corrosion properties, if known, would help to complete the picture on this interesting and promising new metal.
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BIBLIOGRAPHY


The foregoing bibliography represents only a portion of the available literature on vanadium. Only those references which were actually used in this thesis or those which the author suggests might be used for some further reading were included in this bibliography.
REFERENCES


3 Rostoker, op cit. p 4.

4 Ibid. pp 13,14,18,19.


6 Ibid. pp 103-105.


12 Ibid. pp 4,5,13,18,19.

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