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# Effect of Temperature and Notch Geometry on the Tensile Behavior of a Titanium Alloy

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A comprehensive study was made of the effects of notch geometry on the mechanical behavior of a duplex-annealed titanium-8 aluminum-1 molybdenum-1 vanadium alloy within the temperature range 75 to 1200 °F (297 to 921 °K). Yield strength, tensile strength, and true stress at fracture increased with increase in notch depth and decrease in notch angle and temperature. The maximum strength (tensile and yield) properties were obtained for the cylindrical specimens having a root radius of 0.01-inch. Generally, the increase in tensile properties was accompanied by a decrease in reduction of area values. The microstructures and the initiation and propagation of fracture of the specimens were affected by the notch geometry and test temperature.

Key Words: Notch geometry, tensile behavior, elevated temperature, titanium alloys, fracture, stress concentration, notch strength.

## 1. Introduction

Although many papers have been published describing the influence of notch geometry on the mechanical behavior of metals, only limited data are available from which consistent interpretations can be made when unnotched and notched cylindrical specimens having circular cross section are used. Brown and coworkers [1] [1] have recently made an extensive literature survey of high temperature properties of notched specimens. Geil and Carwile [2, 3] and Geil [4] have made comprehensive studies on the behavior of titanium alloys and the mechanisms of deformation of stainless steel at low temperatures. The present study was undertaken as a part of a general program designed to evaluate fundamental factors affecting flow, fracture, and ductility of metals at elevated temperatures.

## 2. Material, Specimens, and Test Procedures

The experimental program included short-time tensile tests at 75 to 1200 °F (297 to 921 °K) on unnotched and notched cylindrical specimens of a duplex-annealed Ti-8 Al-1 Mo-1 V alloy.

The test specimens were prepared from bars obtained from a single heat of the titanium alloy. The bars were supplied by the manufacturer in the form of 1-in. rounds in the hot-rolled and annealed condition. The chemical composition of the alloy is given in table 1.

[1] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1. *Chemical composition (percentage by weight) of the alloy used* [a]

| | |
|---|---|
| Titanium | 90.4 |
| Aluminum | 7.7 |
| Molybdenum | 1.0 |
| Vanadium | 0.7 |
| Iron | .08 |
| Carbon | .01 |
| Hydrogen | .0094 |
| Oxygen | .0628 |
| Nitrogen | .0022 |

[a] Analysis made at the National Bureau of Standards.

The bars were cut into lengths, each about 6.5-in. and annealed at 1750 °F (1226 °K) for 1 hr and air-cooled. This was followed by a stabilizing anneal for 8 hr at 1050 °F (838 °K). The specimens were then air-cooled. This process, called duplex annealing, is recommended by the manufacturer for obtaining a good combination of properties at high temperatures.

Each unnotched specimen had a 2-in. gage length and a gage diameter of 0.357 in. The reduced section was finished by grinding and polishing in the axial direction.

Each of the notched specimens had a circumferential **V**-notch of a predetermined notch angle and a root radius at the midpoint of the specimen. The root diameters were held constant at 0.357 in. while the diameters of the reduced sections were varied to produce notch depths of 10, 30, 50, 70, or 85 percent.[2] The different combinations of notch angles, notch depths, and root radii used in this investigation are shown in table 2.

[2] Notch depth $=\frac{D^2-d^2}{D^2}\times 100\%$
where $D$ = reduced diameter
$d$ = diameter at root of notch.

TABLE 2. *Notched specimens*

| Notch angle | Notch depth | Root radius | Elastic stress concentration factor | Figure numbers where data are plotted | | | |
|---|---|---|---|---|---|---|---|
| | | | | Yield strength | Tensile strength | Notch strength / Tensile strength | Reduction of area |
| *Degrees* | *Percent* | *Inch* | | | | | |
| 0 | 50 | 0.01 | 3.9 | 4A | 5A | 7D | 8A |
| 30 | 50 | .01 | 3.9 | 4A | 5A | ............................ | 8A |
| 60 | 50 | .01 | 3.9 | 4A, 4B, 4C | 5A, 5B, 5C | 7B, 7C | 8A, 8B, 8C, 9A |
| 90 | 50 | .01 | 3.7 | 4A | 5A | 7D | 8A |
| 150 | 50 | .01 | 2.2 | 4A | 5A | 7D | 8A |
| 60 | 10 | .01 | 2.6 | 4B | 5B | 7B | 8B, 9A |
| 60 | 30 | .01 | 3.5 | 4B | 5B | 7B | 8B, 9A |
| 60 | 70 | .01 | 4.2 | 4B | 5B | 7B | 8B, 9A |
| 60 | 85 | .01 | 4.2 | 4B | 5B | 7B | 8B, 9A |
| 60 | 10 | .10 | 1.4 | 6A | 6B | 7A | 9B |
| 60 | 30 | .10 | 1.6 | 6A | 6B | 7A | 9B |
| 60 | 50 | .10 | 1.6 | 4C, 6A | 5C, 6B | 7A, 7C | 8C, 9B |
| 60 | 70 | .10 | 1.6 | 6A | 6B | 7A | 9B |
| 60 | 85 | .10 | 1.7 | 6A | 6B | 7A | 9B |
| 60 | 50 | .003 | 6.7 | 4C | 5C | 7C | 8C |
| 60 | 50 | .50 | 1.1 | 4C | 5C | 7C | 8C |

Notch geometries were selected to produce stress concentration factors [3] [5] varying from 1.1 (60° notch angle, 0.5-in. root radius, 50 percent notch depth) to 6.7 (60° notch angle, 0.003-in. root radius, 50 percent notch depth) as shown in table 2. Photographs of an unnotched specimen and several notched specimens are shown in figure 1. Representative microstructures of the material after duplex annealing are shown in figure 2. The microstructure indicates the existence of equiaxed alpha with stringers of Widmanstatten structure composed of alpha and beta. The presence of alpha (predominantly) and beta (small amounts) was confirmed by x-ray analysis of the samples.

[3] Stress concentration factor is equal to the ratio of the maximum normal stress to the nominal normal stress. It is directly proportional to notch depth and inversely proportional to notch angle and root radius.

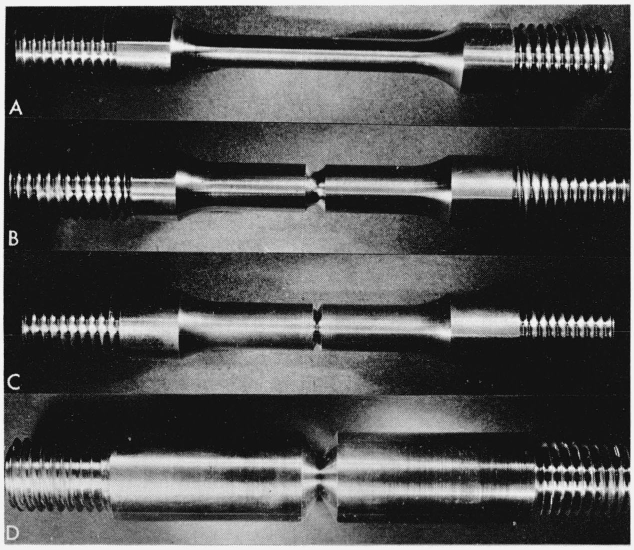


FIGURE 1. *Photographs, showing appearance of specimens before testing.* $\times 1/2$

| | Notch angle | Notch depth | Root radius |
|---|---|---|---|
| | *Degrees* | *Percent* | *Inch* |
| A | Unnotched | .............. | .............. |
| B | 60 | 50 | 0.1 |
| C | 60 | 50 | .01 |
| D | 60 | 85 | .01 |

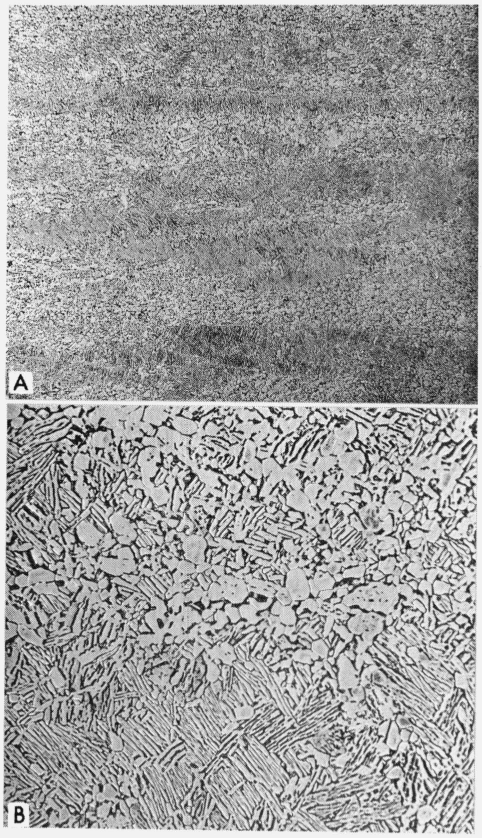


FIGURE 2. *Microstructure of the Ti-8 Al-1 Mo-1 V alloy after duplex-annealing.*

Longitudinal sections. Etched in a solution containing 3 ml HF, 6 ml $HNO_3$, and 100 ml $H_2O$. A, $\times 55$. B, $\times 275$.

Each tensile specimen was heated in air in a tube furnace to the desired temperature (above 75 °F), held for 1 hr, and tested at temperature. The movement of the crosshead of a hydraulic machine was controlled to produce the same rate of strain for all the specimens tested to fracture. This rate was about 1 percent per minute.

## 3. Results and Discussion

Some of the tensile properties of both the notched and unnotched specimens are shown in figures 3 to 12. The data are average values obtained from tests on different specimens tested under the same conditions. Yield strength values for the unnotched specimens were calculated by the 0.2 percent offset method. Yield strength values for the notched specimens were based on the stress at the first observable occurrence of plastic deformation. These values were further confirmed by load-time observations made throughout the tests. True stress at fracture values were calculated by dividing the load at fracture by the cross-sectional area of the specimens after fracture.

A small yield point drop was observed for all unnotched specimens tested at 75 and 300 °F (297 and 422 °K). The difference in stress between the upper and lower yield points was approximately 300 psi. At 600 and 800 °F (588 and 699 °K), no discontinuous flow was evident. At 1000 and 1200 °F (811 and 921 °K) wavy stress-strain curves of the type generally associated with extensive recovery or recrystallization were observed after the attainment of maximum load conditions.

The influence of temperature on tensile strength, yield strength and elongation of the unnotched specimens is shown in figure 3. The slope of the strength-temperature curve increases with increase in temperature up to 700 °F (644 °K). Thereafter this slope decreases as the temperature is increased. Apparently, the mechanisms associated with deformation of the alloy change near 700 °F as indicated by the rapid increase in the slope of the elongation-temperature curve. The possibility of changes in active slip systems in commercially pure titanium has also been mentioned [6] as a probable cause of this phenomenon.

The effect of notch geometry on yield and tensile strength of specimens tested at different temperatures is shown in figures 4 and 5. The shapes of the yield strength curves (fig. 4) are similar to those of the corresponding tensile strength curves (fig. 5). Although little or no plastic deformation is associated with the yield strength values, plastic deformation with its accompanying strain hardening effects plays an important part in the determination of the tensile strength of the alloy.

The increase of elastic stress concentration factor is a cause for the increase in both the yield and tensile strength. However, increase in notch depth (figures 4B and 5B) is a more effective strengthener than decrease in notch angles or root radius. For example, decreasing the notch angle from 150 to 0° had practically no effect on the strength values between 600

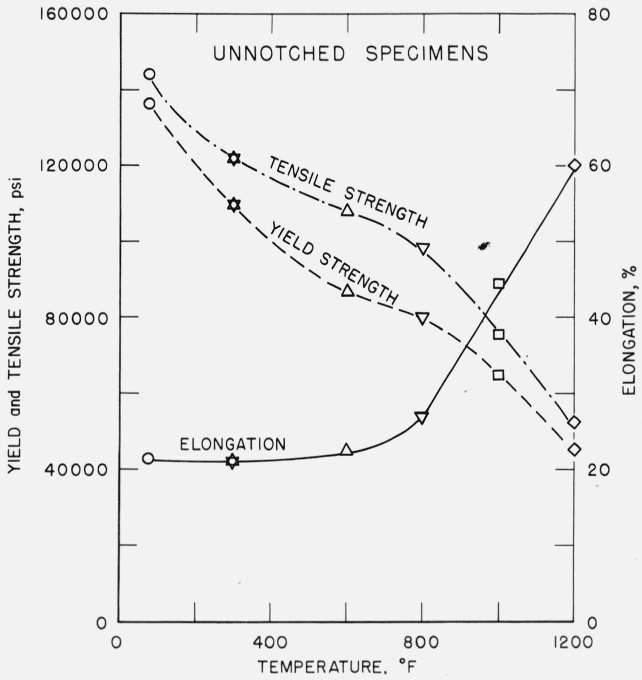


FIGURE 3. *Effect of temperature on tensile strength, yield strength and elongation of unnotched specimens.*

Each symbol (circle, triangle, etc.) designates the same test temperature in all figures except figure 10.

and 1200 °F (figs. 4A and 5A). Curves describing the effect of root radius on strength values (figs. 4C and 5C) indicate that an intermediate value of root radius exists for which the strength is a maximum. This relationship is more pronounced as the temperature is decreased. Although strength values generally increased with increase in notch depth, the sigmoidal shape of the strength-notch depth curves (figs. 4B and 5B) indicate the existence of a notch depth for which the rate of change of strength with notch depth is a maximum.

Another series of tests were run on specimens having a different root radius from those described in figures 4B and 5B to ascertain whether the conclusions drawn from one group of specimens were generally applicable when only one variable in the notch geometry was changed. The results shown in figure 6 were obtained on notched specimens having elastic stress concentration factors varying from 1.4 (10 percent notch depth) to 1.7 (85 percent notch depth) whereas data shown in figures 4B and 5B are for specimens having elastic stress concentration factors from 2.7 (10 percent notch depth) to 4.2 (85 percent notch depth).

Tensile and yield strength values for specimens having an 0.10-in. root radius (fig. 6A and B) were consistently lower than corresponding values for the specimens having an 0.01-in. root radius (figs. 4B and 5B). A general trend of increase in strength with increase in notch depth was observed for both notch geometries; however, the shapes of the curves at 600 and 800 °F were markedly affected by the increase in root radius from 0.01 to 0.10-in. That is, the specimens, having the 0.1-in. root radius, show a continuous

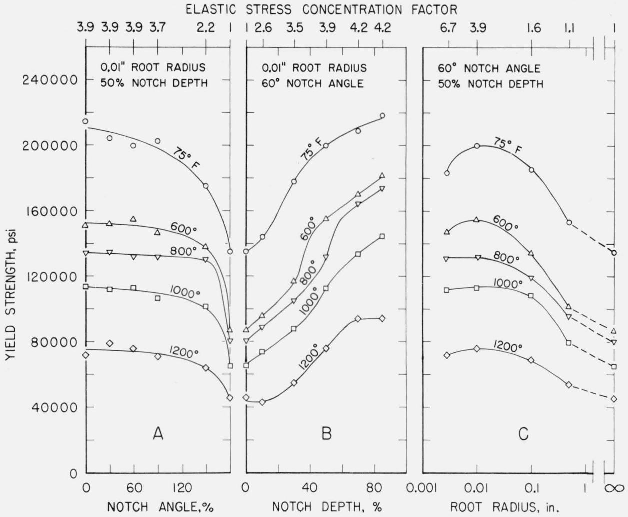


FIGURE 4. *Effect of notch angle, notch depth, and root radius on the yield strength of specimens tested at different temperatures.*

Data at 180-deg notch angle, zero percent notch depth, and infinite root radius indicate values for unnotched specimens.

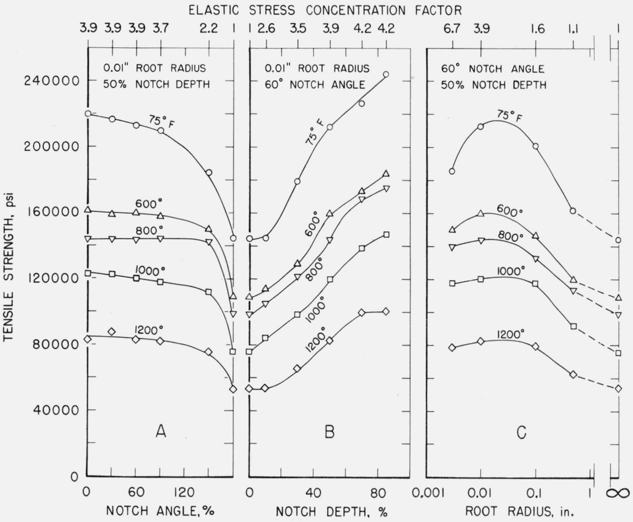


FIGURE 5. *Effect of notch angle, notch depth, and root radius on the tensile strength of specimens tested at different temperatures.*

Data at 180-deg notch angle, zero percent notch depth and infinite root radius indicate values for unnotched specimens.

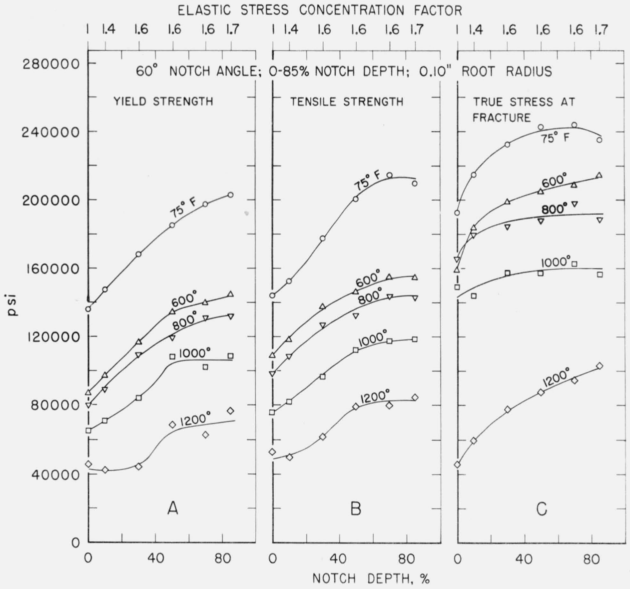


FIGURE 6. *Effect of notch depth on yield strength, tensile strength, and true stress at fracture of specimens having a 60-deg notch angle and 0.10-in. root radius.*

Data at zero percent notch depth indicate values for unnotched specimens.

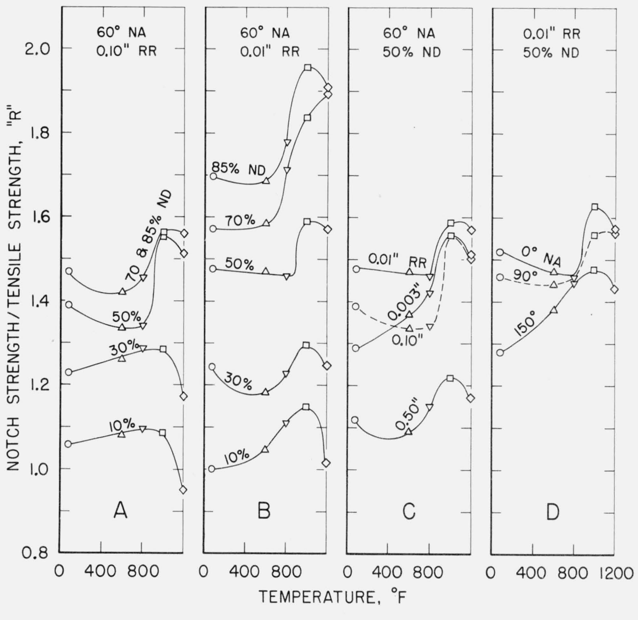


FIGURE 7. *Effect of temperature on the notch strength-tensile strength ratio (R) of specimens having various notch geometries.*

increase in strength, at a decreasing rate, with increase in notch depth at these temperatures (fig. 6A and B); whereas, the corresponding curves for the specimens having an 0.01-in. radius have a sigmoidal shape (figs. 4B and 5B).

True stress at fracture increased with increase in notch depth and with decrease in test temperature as shown in figure 6C. These data give further evidence that, even at high temperatures and large strains, work hardening and fracture strength are dependent on the initial stress concentration factor.

One means of assessing the notch sensitivity of a metal is by calculating the ratio (R) of the tensile strength of the notched specimen to the tensile strength of the unnotched specimen at the same temperature. The effect of temperature on these ratios is shown in figure 7. For most of the specimens, the value appeared to be the highest at 1000 °F. Furthermore, it was more dependent on notch depth (ND) than on notch angle (NA) or root radius (RR). For an equal range of notch depths the spread in values is greater as the root radius is decreased (fig. 7A and B). However, there is a limiting value of root radius between 0.003 and 0.1-in. at which the "R" values begin to decrease with decrease in root radius (fig. 7C).

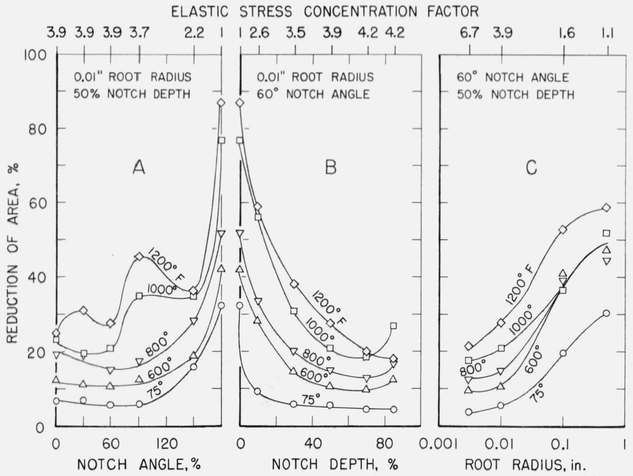


FIGURE 8. *Effect of notch angle, notch depth, and root radius on the reduction of area values of specimens tested at different temperatures.*

Data at 180-deg notch angle and zero percent notch depth indicate values for unnotched specimens.

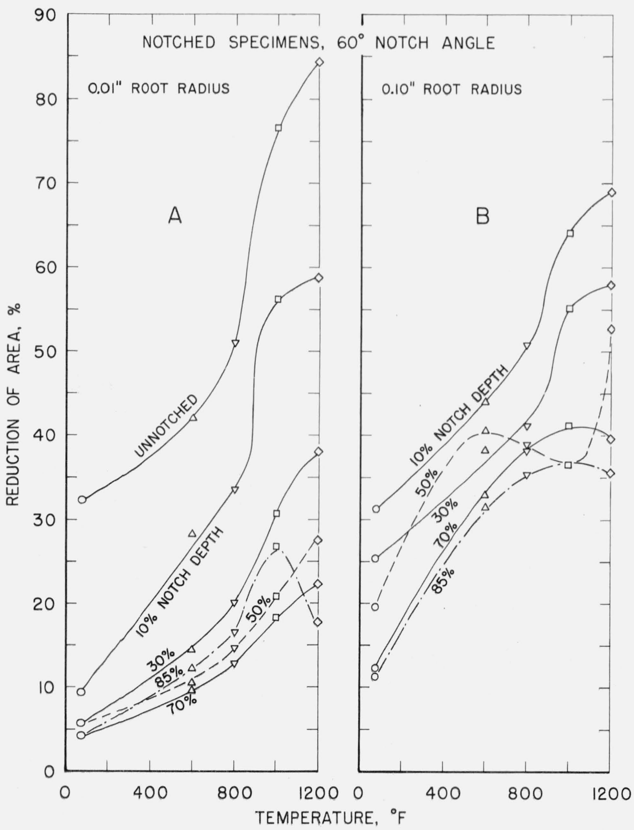


FIGURE 9. *Relation of temperature to reduction of area values for notched specimens having various notch depths.*

A — 0.01-in. root radius; B — 0.10-in. root radius.

Reduction of area values for unnotched specimens are included for comparison purposes.

The "R" values for 30 and 60° notch angles are not included in figure 7D as they lie between those for the zero and 90° notch angles. This is rather expected as, within limits, the angles have little effect on the stress concentration factors for specimens with the same notch depth, root radius, and diameter. For example, the stress concentration factor for the 90° angle specimen is 3.7 and for the 0° angle it is 3.9.

The effects of notch geometry and temperature on reduction of area values are shown in figures 8 and 9. In general, reduction of area values increased with increase in notch angle (fig. 8A) and root radius (fig. 8C) and with decrease in notch depth from 70 percent to zero (fig. 8B). The anomalies occurring at 1000 and 1200 °F (fig. 8A) are attributed to changes in recovery characteristics as the notch angles are changed. The cause of the inconsistent values for the specimens having an 85 percent notch depth is not known.

Reduction of area values increased with increase in temperature for most of the specimens having the same notch geometries as shown in figure 9. As indicated in figure 9A the presence of any notch causes some amount of embrittlement. However, increasing the root radius reduces the amount of embrittlement for all the conditions used (fig. 9B). Although duplicate tests have confirmed the test data for the 85 percent (fig. 9A) and the 50 percent notch depth specimens (fig. 9B) the reasons for the anomalies occurring at the different temperatures have not been discovered.

The relationship between true strain and true stress at fracture is shown in figure 10. True strain values in this figure are defined as $\log_e (A_0/A)$, where $A_0$ is the minimum cross-sectional area at the root of the notch before testing and $A$ is the minimum area after fracture. The minima in figure 10A and the maxima in figure 10B indicate the existence of intermediate true strain values for which work-hardening is, respectively, least or most effective. This strain dependence is influenced by both temperature and stress system.

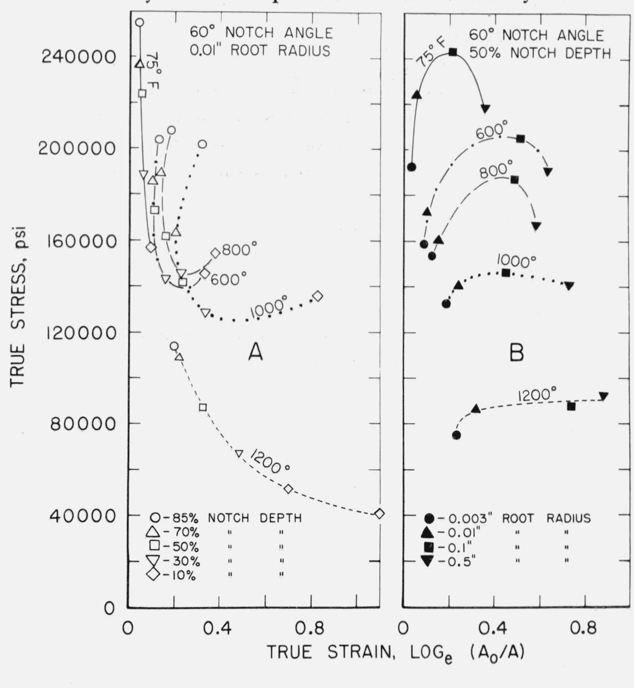


FIGURE 10. *True stress-true strain (at fracture) relations for notched specimens having (A) different notch depths and (B) different root radii.*

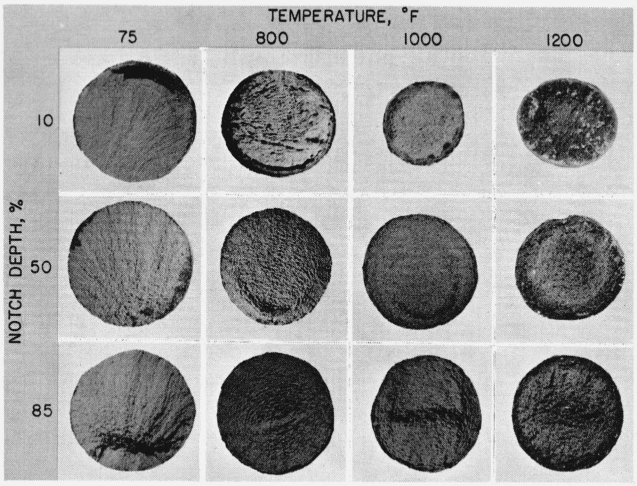


FIGURE 11. *Effect of temperature and notch depth on initiation and propagation of fracture.*
Cross sections at fracture of specimens having 60-deg. notch angle, 0.01-in. root radius. Unetched, × 2.

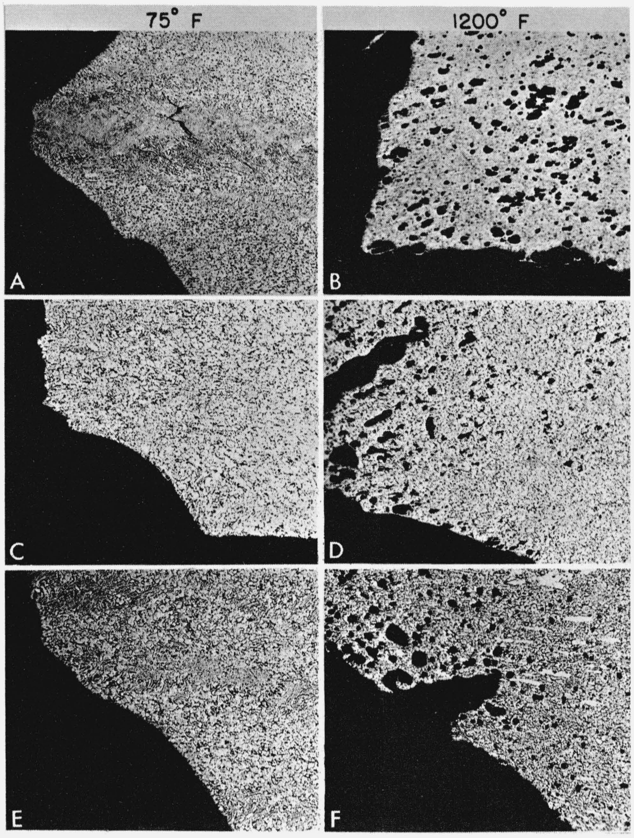


FIGURE 12. *Effect of notch depth on microstructures near root of the notch of Ti-8 Al-1 Mo-1 V specimens after fracture.*
A, B – unnotched; C, D – 60° notch angle, 10 percent notch depth, 0.01 in. root radius; E, F – 60° notch angle, 85 percent notch depth, 0.01-in. root radius. Longitudinal sections. Etched in a solution containing 3 ml HF, 6 ml $HNO_3$, and 100 ml $H_2O$. ×55.

## 4. Metallography

Geil and Carwile [3] have indicated that the position of initiation of fracture for titanium specimens was more dependent on notch geometry than on temperature within the temperature range −320 to 212 °F (77 to 373 °K). Fracture surfaces of some Ti-8 Al-1 Mo-1 V alloy specimens in the present investigation are shown in figure 11. Fracture at 75 °F was initiated at or near the root of the notch. As the temperature was increased, the point of initiation progressed towards the axis. At 1200 °F, fracture was initiated at the axis for all the specimens tested. Embrittlement effects associated with triaxiality were more predominant in the 85 percent notch depth specimens than in those with shallower notches. Furthermore, the more fully developed triaxiality conditions existed at lower temperatures for the specimens with the deeper notches. These observations indicate that, at high temperatures, the position of initiation of fracture and its mode of propagation are more dependent on test temperature than on the notch geometry.

Soltis [7] has observed that, during creep of Ti-8 Al-1 Mo-1 V alloy, voids were initiated at alpha grain boundaries in the vicinity of beta particles. In addition, Widmanstatten structure offered high resistance to deformation in smooth creep specimens of this duplex-annealed alloy. The effect of notch geometry on microstructures of specimens used in the present investigation is shown in figures 12, 13 and 14. Very few cracks were observed at the root radius of the notch (fig. 12A, C, and E) or at the axis (fig. 13A, C, and E) of the specimens tested to fracture at 75 °F. However, a number of holes and secondary cracks were observed near the surface (fig. 12B, D, and F) and near the center (fig. 13B, D, and F) of the specimens fractured at 1200 °F. The number and the size of the holes appeared to decrease as the notch depth was increased.

Several examples of the regions in which cracks or holes were formed are shown in figure 14. An isolated crack traversing an area of Widmanstatten structure is illustrated in figure 14A for an unnotched specimen fractured at 75 °F, whereas at 1200 °F the cracking was confined principally to the alpha grain boundaries (fig. 14B). A crack at the grain boundary of alpha grains that were formed from a metastable beta region in a 10 percent notch depth specimen is shown in figure 14C. Several cracks were observed in the region between alpha platelets and equiaxed alpha grains after fracture at 1200 °F (fig. 14D). Rounded holes rather than well defined cracks occurred in the regions of equiaxed alpha grain boundaries of the specimens having an 85 percent notch depth. Generally, these were observed near the regions having Widmanstatten structure (fig. 14E) in specimens tested at 75 °F while they were initiated near the vicinity of beta particles for specimens tested at 1200 °F (fig. 14F). It is apparent that both stress system and temperature had an effect on crack nucleation and growth in this alloy.

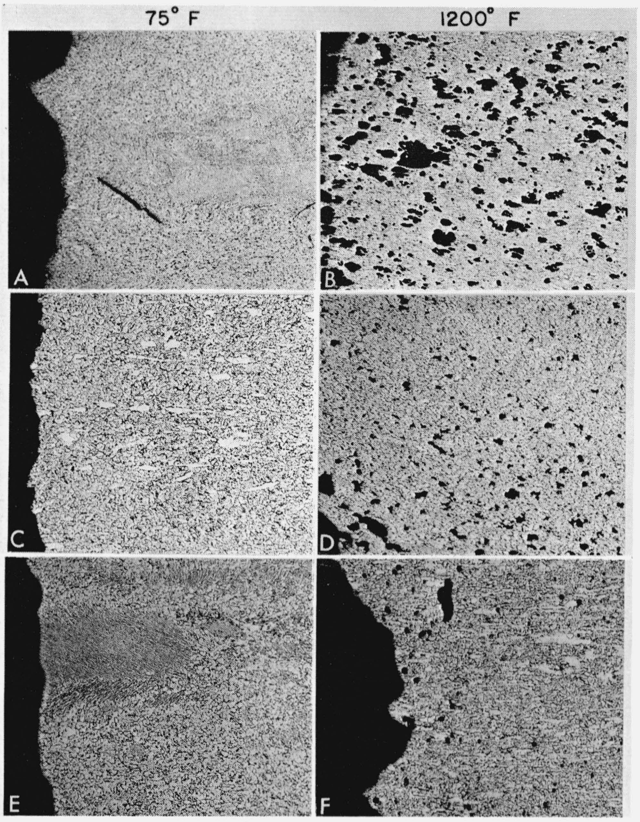


FIGURE 13. *Effect of notch depth on microstructures near axis of Ti-8 Al-1 Mo-1 V specimens after fracture.*

A, B–unnotched; C, D–60° notch angle, 10 percent notch depth, 0.01-in. root radius; E, F–60° notch angle, 85 percent notch depth, 0.01-in. root radius. Longitudinal sections Etched in a solution containing 3 ml HF, 6 ml $HNO_3$, and 100 ml $H_2O$. ×55.

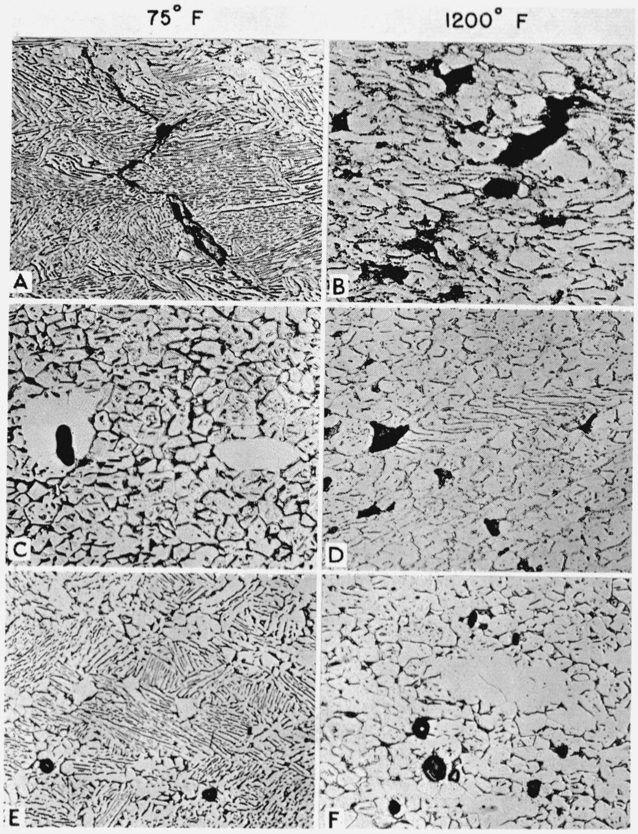


FIGURE 14. *Effect of notch depth on microstructures and crack formations in Ti-8 Al-1 Mo-1 V specimens.*

A, B–unnotched; C. E–60° notch angle, 10 percent notch depth, 0.01-in. root radius; E, F–60° notch angle, 85 percent notch depth, 0.01-in. root radius. Longitudinal sections. Etched in a solution containing 3 ml HF, 6 ml $HNO_3$ and 100 ml $H_2O$. ×275.

## 5. Summary

A. Short-time tensile tests were made to ascertain the effect of notch geometry and variation of temperature between 75 and 1200 °F on the mechanical behavior of a duplex-annealed Ti-8 Al-1 Mo-1 V alloy.

B. Yield and tensile strength decreased and elongation and reduction of area values usually increased with increase in temperature. Strength values generally increased and ductility decreased with decrease in notch angle and root radius and with increase in notch depth. Isolated exceptions to these general trends were observed at 1000 and 1200 °F, at 85 percent notch depth and at 0.003-in. root radius.

C. The notch strength-tensile strength ratio was the greatest at 1000 °F and was more dependent on notch depth than on root radius or notch angle.

D. Strength increased and ductility decreased with increase in elastic stress concentration factor and triaxiality. The manner in which these indicies changed was dependent on the test temperature and the parameters used in the evaluation of the data.

E. The point of initiation of fracture and its subsequent propagation were influenced by both temperature and notch geometry.

F. Only a few cracks or holes were observed for specimens tested at 75 °F; however, a large number were evident in specimens tested at 1200 °F. The number, size, shape, location, and distribution of the cracks were affected by notch geometry and temperature.

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