Determination of Optimum Diffusion Welding Temperatures for Ti-6A1-4V

Using a two-step welding cycle, initally a temperature of about 1750° F provides maximum surface creep while, in the subsequent period, the temperature is raised to promote diffusion

BY H. G. KELLERER AND L. H. MILACEK

ABSTRACT. It was the purpose of the present study to determine the creep ductility of Ti-6Al-4V at potential diffusion welding temperatures.

Standard tensile, tensile creep, and compression creep tests were conducted in the 1600 to 1900° F temperature range. Test atmospheres varied from air atmosphere to inert gas and vacuum.

The results of these tests indicate that the creep rate increases with increasing temperature from 1600 to 1750° F and decreases from 1750 to 1900° F. Metallography shows that the grain size increases drastically with increasing temperature, due to the decrease in the amount of primary alpha. It is believed that the creep rate decreases with increasing grain size because of reduced grain boundary sliding.

A two step diffusion welding cycle is proposed where initially a temperature around 1750° F provides maximum surface creep and in the subsequent period the temperature is raised to promote diffusion.

Introduction

Diffusion welding of both similar and dissimilar metals has received increasing attention in recent years. The process is generally considered to consist of three steps where:

1. Surface roughness on the faying surfaces is eliminated by creep.
2. Diffusion takes place across the surfaces now in contact.
3. Grain growth occurs across the interface.

The first step, the surface creep, is the most critical one because it determines the effective contact area between the two parts to be joined. High temperatures are usually chosen for diffusion welding under the assumption that the creep rate increases with temperature. This has been shown to be true for pure titanium at temperatures up to 1600° F,[1] but no data appear to be available for Ti-6Al-4V. It was the purpose of the present study to determine the creep ductility of Ti-6Al-4V at temperatures close to the beta transus.

Two series of tests were conducted. The first series was intended to produce approximate base line data. To simplify these tests, they were run in argon and air atmospheres where surface contamination occurred but never exceeded 7 to 8% of the total specimen cross section. These tests included:

1. Standard tensile tests at 1600 to 1900° F where elongation was measured on a standard 2 inch gage length.
2. Tensile creep tests at 1600 to 1900° F where strain was continuously recorded as a function of time.

The second series of tests was designed to be more fully representative of the compression creep occurring during diffusion welding. Compressive creep tests were conducted with dead weight loading on 2 by 1 in. diameter specimens in a 10^{-5} Torr vacuum. Total deformation was measured after a nominal 4 hr exposure to temperature and this value therefore included the creep which occurred during heating and cooling.

Results

Tensile Tests

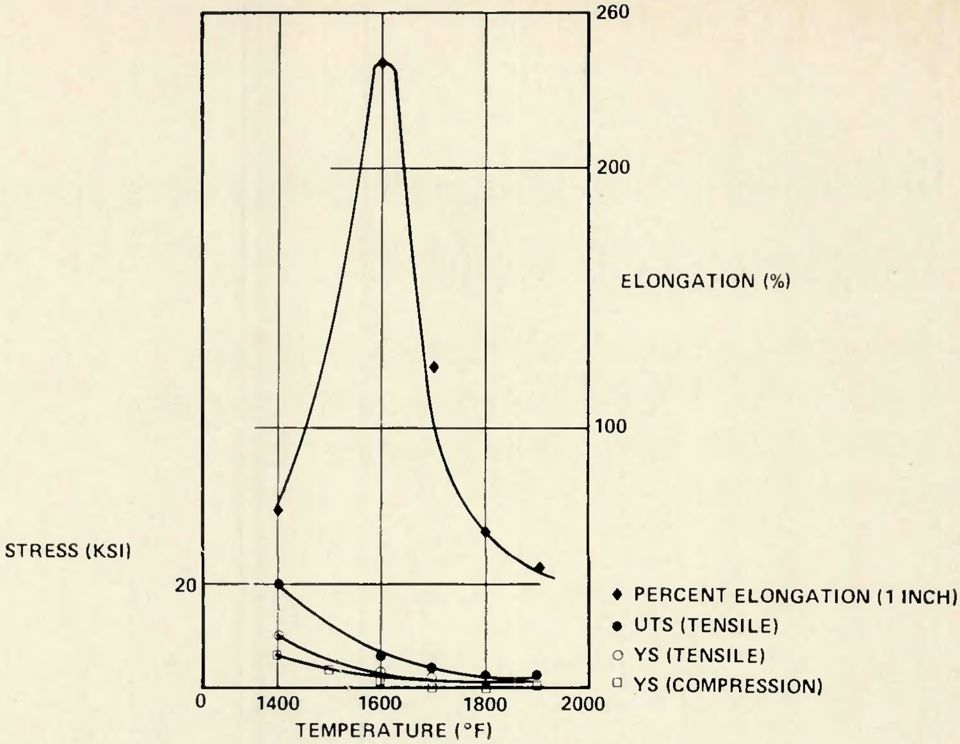
The results of the tensile tests shown in Fig. 1 display a continuous increase in total elongation in the temperature range from 1000 to 1600° F. However, above 1600° F, the ductility drops markedly and extremely low values are obtained at temperatures above the beta transus. The differences in tensile elongation are due to large differences in the necking behavior. At 1600° F necking extends over the full length of the specimen. At higher temperatures necking is very localized. Although oxidation increases with increasing temperature, it is assumed that the drop in ductility is not due to oxygen contamination.

Metallographic cross sections were prepared from the broken tensile specimens and examined in the unetched, as-polished condition. In agreement with literature data,[2,3] it was found that the tensile specimens exhibit a large number of internal strain induced cavities. The number of internal voids increases with temperature from 800 to 1400° F with a maximum number of voids occurring at approximately 1400° F. Although the number of voids increases, the average void size does not increase significantly unless link-up between voids occurs. A single cavity almost never grows to dimensions exceeding that of a grain. This cavity to grain size relation corresponds to findings in commercially pure titanium tensile specimens which exhibited a somewhat larger grain size and therefore larger voids.

At temperatures above 1200° F cavitation becomes optically visible in all areas of the tensile specimen where the local reduction in areas exceeds 5%. As the etching required to delineate grain boundaries destroys the void boundaries, the relationship between phase distribution and void location is difficult to determine. However, the available evidence indicates that the voids are generated at short

H. KELLERER is with Messerschmitt-Bölkow-Blohn Co., Munich, Germany, and L. H. Milacek is with The Boeing Company, Seattle, Wash.

Fig. 1—Tensile properties and compression strength of Ti-6Al-4V at elevated temperature



alpha–alpha grain boundaries connected to beta grains. The deformation causing the opening of the voids appears to occur mainly in alpha grains. These findings are in partial agreement with those of Margolin, et al.[4]

Examination of Fig. 2 shows that at temperatures above 1400° F, the temperature at which maximum void formation occurs, cavitation tends to decrease. No voids were seen above 1800° F. This is thought to be due to the decreasing amount of alpha phase with increasing temperature with a corresponding decrease in the number of alpha-alpha interfaces at which void formation is thought to occur.

From this metallographic investigation it is concluded that internal cavitation plays an important role in the high temperature tensile deformation of Ti-6Al-4V. Therefore, the elongation data obtained from tensile tests may not be fully representative of the creep deformation occurring during diffusion welding, which involves considerably lower deformation.

Creep Tests

Several representative high temperature tensile creep curves are plotted in Fig. 3. Despite the fact that the data are not fully reliable because of oxygen contamination it is felt that they are indicative of Ti-6Al-4V deformation behavior at potential diffusion welding temperatures. They permit two conclusions to be drawn:

1. The high temperature, high stress creep behavior of Ti-6Al-4V can be interpreted in terms of the classical Andrade creep equation:

$$\epsilon = \epsilon_o + \beta t_o^m$$

where ϵ is the creep strain, t_o is time and ϵ_o β and m are constants.

2. The ductility decrease above 1700° F observed in the tensile test has a parallel in tensile creep where the 1600° F test temperature yields the highest creep rate and creep rate decreases markedly above the beta transus. Passage from the two phase

Fig. 2—Strain induced cavitation produced by tensile deformation at high temperature. A (left)—1400° F; B (center)—1550° F; C (right)—1800° F. X100 (reduced 38% on reproduction)

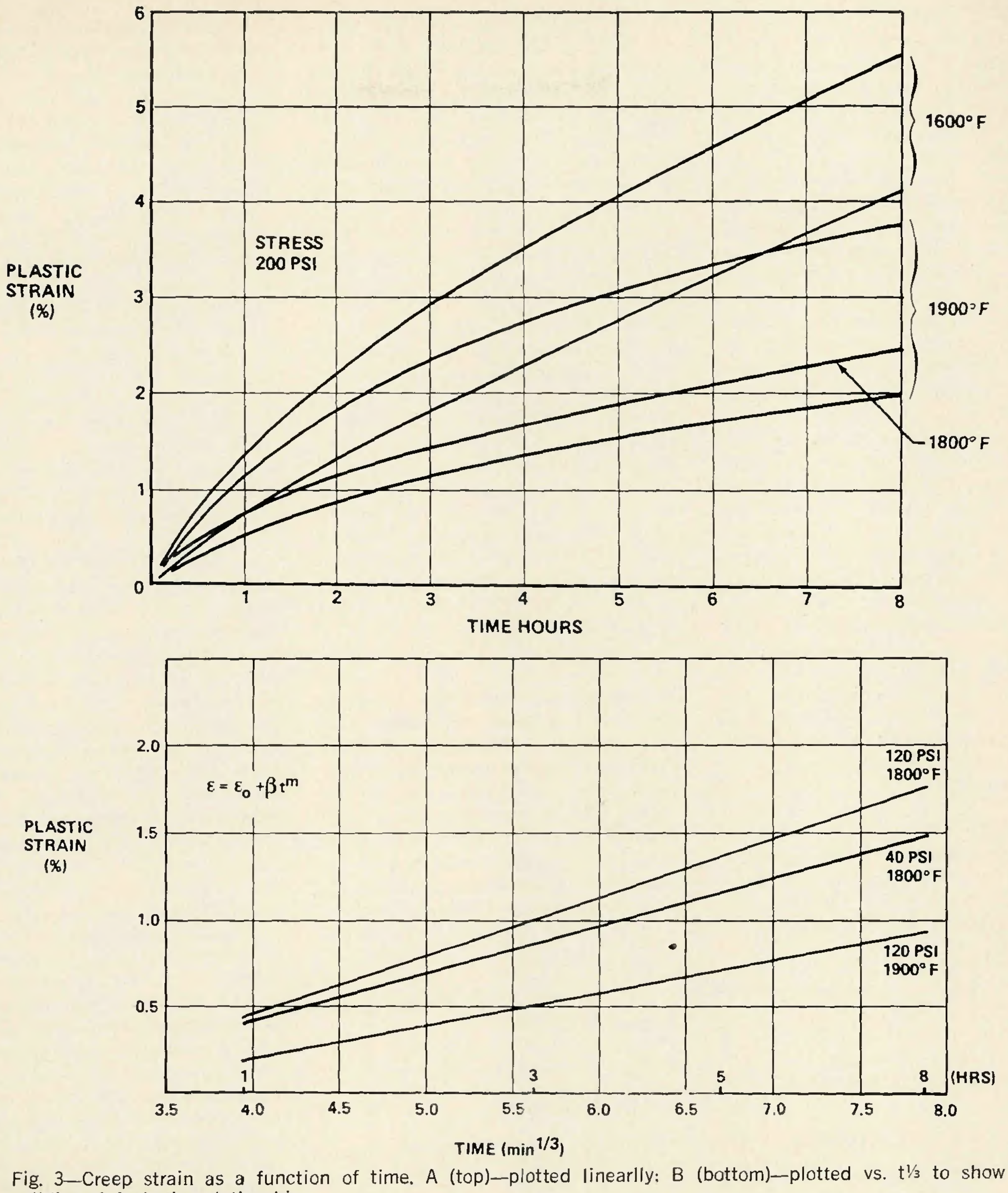


Fig. 3—Creep strain as a function of time. A (top)—plotted linearlly; B (bottom)—plotted vs. $t^{1/3}$ to show validity of Andrade relationship

alpha–beta field (1800° F) into the all beta area (1900° F) reduces not only the primary creep elongation but has also an influence on the secondary creep rate.

It is concluded that both tensile and creep ductility do not continuously increase with increasing temperature and there is obviously a peak temperature yielding a maximum creep rate. This optimum temperature was determined by compression creep testing under simulated diffusion welding conditions.

The results obtained with three different load levels are plotted in Fig. 4 as creep rate vs. $1/T$. It can be readily seen that a pronounced maximum is again obtained, but is shifted, however, into the 1725—1750° F temperature range. It is assumed that this shift can be explained by:

1. A somewhat different deformation mechanism in tension and compression, expecially concerning internal cavitation.

2. The relative low deformation values of only 2% vs. up to 250% in the tensile tests.

3. The fact that the compression values are somewhat distorted because of additional deformations occurring during heating and cooling.

The low compressive stresses investigated in this study are typical for many diffusion welding operations. On the basis of the limited results available it appears that in the stress range up to 60 psi and at temperatures between 1600 and 1800° F the creep rate is directly and linearly related to the imposed stress.

In the plot of creep rate vs. $1/T$, different loads produce approximately parallel curves, indicating the same basic deformation mechanism occurring at the three load levels. However, because of the peak at 1750° F, the creep behavior in the temperature range investigated cannot be explained by assuming a single process. It is likely that two different mechanisms are operative above 1750° F.

To obtain information on the deformation mechanism, representative metallographic cross sections were prepared from the center of the compressive creep specimens. Typical examples are shown in Fig. 5. In the temperature range up to 1750° F, the grain size increases slowly with increasing temperature. At higher temperatures, the grain size increases drastically with an average grain size of 0.55 mm obtained above the beta transus.

Figure 6 contains a plot of grain size temperature and indicates the relative amounts of equilibrium beta vs. temperature.[5] From a comparison of the two plots, it can be concluded that the fast grain growth of beta grains above 1750° F can be associated with the disappearance of alpha grains which retard growth at the lower temperatures. It is evident that the break in the creep rate vs. temperature curve occurs in the same temperature range as the break in the creep rate vs. temperature and tensile elongation vs. temperature curves. Therefore, it is assumed that the low creep rates at temperatures approaching the β transus are due to the coarse grain structure associated with the fast grain growth occurring at these temperatures.

Discussion

Although insufficient data are available in the literature on the high temperature creep of Ti-6Al-4V, it can be assumed that two mechanisms are rate controlling; these are grain boundary sliding and diffusion creep.

Below 1850° F, the structure consists of alpha–beta which have different lattices (hcp and bcc) and different specific volumes (V_α = 0.96 V_β).[6] Therefore, the incoherent phase boundaries can be considered as good vacancy sources which will increase the creep rate. Above a peak temperature in the $\alpha - \beta$ field where a maximum amount $\alpha - \beta$ phase boundaries exist, the number of vacancy sources will decrease. It is not known to what extent this decrease in $\alpha - \beta$ grain boundary area is compensated for by the increase in temperature with increased self diffusion coefficients. The two top curves of Fig. 5 permit an approximate calculation of the apparent activation rate for creep in the low-temperature range. The value obtained, 40 kcal/-mol, is in reasonable agreement with the activation energies for diffusion of Ti and V in Ti-10% V alloys (35 and 41 kcal/mol, respectively[7]).

It is assumed that the drop in ductility above 1750° F is due to the increased grain size which is one to two orders of magnitude higher than at temperatures below the ductility maximum. It has been shown for both pure metals and alloys[8] that at elevated temperatures the creep rate tends to decrease with increasing grain size. This is generally attributed to a decrease in grain boundary sliding because of the reduced amount of grain boundary area. Although grain boundary creep does not usually account for the total observed creep deformation, its contribution to the overall creep rate can be very high. In addition, in many alloys it is found that the ratio of grain boundary sliding to total creep deformation stays constant over a large range of temperatures. This would indicate that a decrease in grain boundary sliding with increasing grain size would reduce the total creep rate proportionally.

When the above findings are compared to those in the literature there is an apparent contradiction; Conrad[9] has shown that for grain sizes up to 30μ the room temperature tensile elongation increases with increasing grain size, but it is known that after exposure above the β tranus, commercially pure titanium and Ti-6Al-4V display large grain size and low ductility.

All the experimental findings in this study can be reconciled with the literature data by assuming that during room temperature deformation, large grains will deform not only by slip but also by twinning. This tends to reduce ductility in hcp crystals.[10] Therefore, the results of Conrad, which were obtained on relatively small grained materials, cannot be extrapolated to large grain size materials. Also, the exposure to temperatures above the β transus changes the grain morphology and the new grain boundary configuration is probably associated with a change in deformation mechanism.

Further confirmation for these conclusions are the creep results of Bollenrath[11] for small grain size materials which suggest that the transition temperature below which increasing grain size increase ductility and above which it decreases ductility can be placed at about 400° C.

Analysis of on Arrhenius type equation applied to the compression creep results permits an approximate evaluation of the order of magnitude of the grain size effect. In the temperature range under consideration (1500–1900° F), the grain size appears to affect only the preexponential term, so that we may write:

$$\dot{\epsilon} = \frac{1}{d^n} \cdot A \cdot \epsilon \times p \left(- \frac{Q}{RT} \right)$$

$\dot{\epsilon}$ = creep rate

d = grain size

Q = activation energy

A plot of ϵ. $D^{0.25}$ vs. $1/T$ yields approximately a straight line. Therefore, it appears that the activation energy for creep has little dependence on grain size. The constant n, which is a measure of the influence of grain

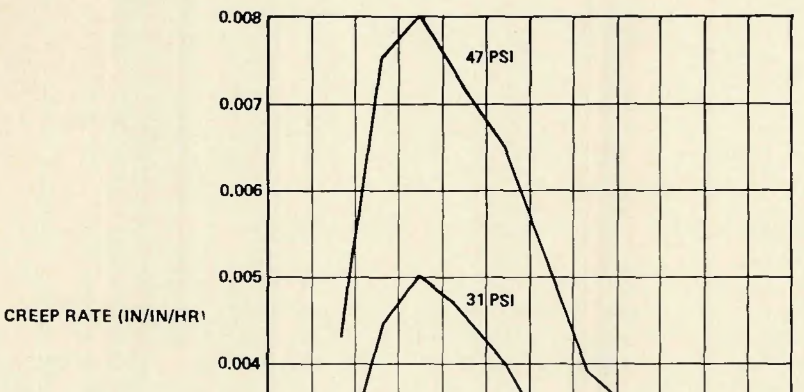


Fig. 4—Influence of temperature on the creep rate in compression at three different load levels

size upon the creep rate, is roughly 0.25 and considerably lower than the value of 2–3 for cases where creep deformation is controlled strictly by diffusion.[12] However, because of the very large grains obtained close to the beta transus the grain size is the determining factor for the overall creep deformation.

Conclusion

For practical diffusion welding applications, the required intimate contact between faying surfaces is most readily achieved with a high creep rate. It may be concluded from the results presented here that the most efficient temperatures for achieving the maximum creep rate in Ti-6Al-4V is in the range of 1725 to 1775° F. An increase in temperature will require longer periods of time at temperature to achieve the desired deformation.

This approach has not taken into consideration the diffusion processes which occur after intimate contact of the faying surfaces has been achieved. The literature data on self diffusion in Ti-10% V alloys[7] show that decreasing the temperature from 1830 to 1740° F decreases the diffusion coefficient of Ti by 40% and that of V by 45%. Therefore, if diffusion welding of Ti-6Al-4V is to be accomplished within the 1725 to 1775° F temperature range, this decrease in the diffusion coefficient will have to be compensated for by longer times at temperature.

In the initial stage of the diffusion welding process, the creep deformation of the surface and not the diffusion coefficient will be the rate controlling mechanism. Therefore, choice of the diffusion welding parameters for this stage should be based on the creep rate, while later stages which depend upon movement of atoms should be based upon diffusion rates. It has been found in steel[13] that, once a good surface contact is established, grain growth may be of advantage, because grains may grow across the joint-line and thereby produce a metallurgically perfect bond.

Therefore, it appears that a two step process could be used with advantage where in the initial period a temperature around 1750° F provides maximum surface creep, and in the subsequent period the temperature is raised to increase the diffusion rate and promote grain growth across the joint.

Acknowledgement

The authors wish to thank Mr. Sven Axter and D. Montgomery for helpful discussions.

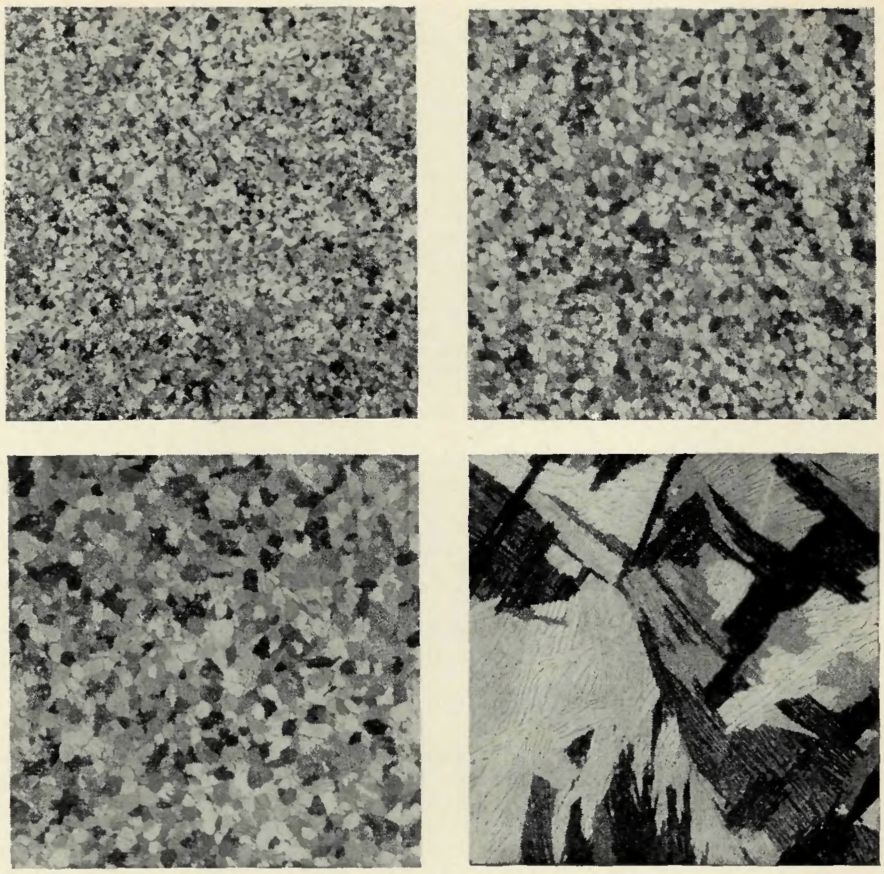
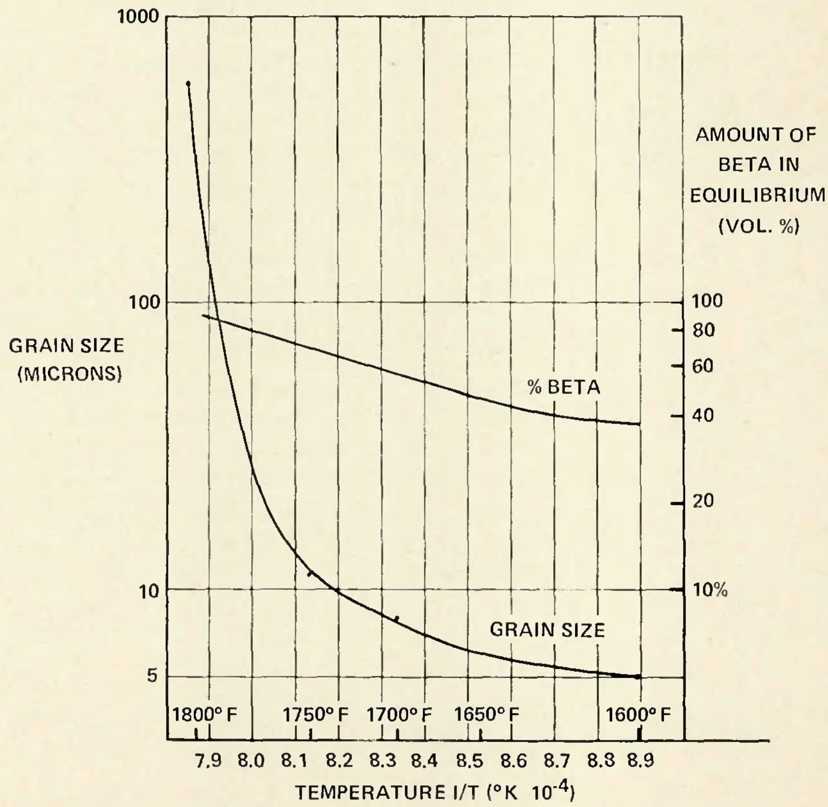


Fig. 5—Influence of test temperature on grain size. A (top left)—1600° F; B (top right)—1500° F; C (bottom left)—1750° F; D bottom right)—1800° F. X200 (reduced 38% on reproduction)



Fip. 6—Grain size and equilibrium content of beta phase as a function of temperature

References

1. King W. H., and Owcarski, W. A., "Diffusion Welding of Commercially Pure Titanium," WELDING JOURNAL, 46 (7), Research Suppl., 289-s to 298-s (1967).

2. Wood, R. A., Williams, D. N., Ogden, H. R., and Jaffee, R. I., "Porosity in Formed Titanium," *Trans AIME*, 215 (1959), 308-315.

3. Kellerer, H., and Montgomery, D. M., "Quenching of Ti-6Al-4V to Aging Temperatures," Westec Conference, Los Angeles 1969, (ASM paper W9-18.3).

4. Margolin, H., Farrar, P. A., and Greenfield, M. A., "Thermo Mechanical Strengthening of High Strength Aluminum Alloys," Intern. Conference on Titanium, London 1968.

5. Olsen, R. H., "Electron Microprobe Analysis of the Alpha and Beta Phases of 6Al-4V and 4Al-3Mo-1V Titanium," 1st National Conference Electron Probe Microanalysis, University of Maryland, 1966.

6. English, J. J., and Powell, G. W., "Thermal Dilation Behavior of Titanium Alloys," *Trans AIME* 236 (1966), 1467-1473.

7. Murdock, J. F., and McHargue, C. J. "Self-Diffusion in Body-Centered Cubic Titanium-Vanadium Alloys," *Acta Met.* 16 (1968), 493-500.

8. Bell, R. L., and Langdon, T. G., "Grain Boundary Sliding," Conference on Interfaces, Melbourne, 1969.

9. Jones, R. L., and Conrad, H., "The Effect of Grain Size on the Strength of Alpha Titanium," *Trans AIME*, 245 (1969), 779-789.

10. Partridge, P. G., "The Crystallography and Deformation Modes of HCP Crystals, Metals and Materials," *Metallurgical Review*, 118 (1969), 169-194.

11. Bollenrath, F., Domick, G., and Feldmann, H., "Creep Behavior of some $\alpha + \beta$ Titanium Alloys," *Metall*, 22 (1969), 25-32.

12. Coble, R. L., "A Model for Boundary Diffusion Controlled Creep in Polycrystalline Materials," *J. Appl. Phys.*, 34 (1963), 1679-1682.

13. Kasatkin, B. S., and Korab, G. N., "Determining the Welding Condition Parameters for the Diffusion Welding of Steel," *Avt. Svarka* (English), (1969) 10-13.

WRC Bulletin No. 146 Nov. 1969

"Structural Stability Design Provisions—A Comparison of the Provisions of the CRC Guide and the Specifications of AASHO, AISC and AREA"

By B. T. Yen, J. S. Huang, P. J. Patterson and J. Brozzetti

The purpose of this report is to examine the stability provisions of the specifications of the American Association of State Highway Officials (AASHO), the American Institute of Steel Construction (AISC), and the American Railway Engineering Association (AREA) and to compare them with pertinent recommendations of the Column Research Council (CRC) "Guide to Design Criteria for Metal Compression Members."

The major specifications selected are those dealing with buildings and bridges, structures which have been of particular interest to the Council in the past. The findings of the Column Research Council are summarized in its "Guide to Design Criteria for Metal Compression Members." It is used as a reference and as the basis of many design provisions.

This comparison has been prepared under the authorization of the CRC Executive Committee as an aid in its own deliberations, as a useful reference document for its research workers, and as a means of pinpointing topics for which additional documentation might be needed. Also the report should be a help in future deliberations of the various specification-writing bodies.

As new editions of the three specifications and of the Guide become available, it is planned to issue revisions of this comparison.

The arrangement of the material in this Bulletin is according to the sequence of the "Guide." Topics such as arches, hybrid girders and box girders, which are not covered in the present edition of the Guide but are treated in the specifications, are listed at the end of the comparison. A table of contents, arranged in tabular form, precedes the detailed tabulaion of provisions.

A comparative nomenclature (symbols) is included in the Appendix. The sequence follows that used in the CRC Guide, but the symbols used in the individual specifications are retained in the appropriate lisings.

The price of WRC Bulletin 146 is $2.00 per copy. Orders should be sent to The Welding Research Council, 345 E. 47th Street, New York, N.Y. 10017.