ELEVATED TEMPERATURE FORMABILITY OF Ti-6Al-4V

by

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ABSTRACT

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Submitted to the Department of Metallurgy on May 21, 1970 in partial fulfillment of the requirements for the degrees of Bachelor of Science and Master of Science.

A study was made of the effects of temperature and strain rate on the bending formability of the titanium alloy Ti-6Al-4V at temperatures between 600°C and 970°C and strain rates from 10^{-3} sec^{-1} to 10^{-1} sec^{-1}. Formability testing was performed by conducting three-point bending with a sharp punch and matching die. A strong temperature dependence of the bending load was found to persist to temperatures approaching the beta transus. The strain rate dependence of the bending load was also found to be quite large over the range of strain rates investigated, but less than the temperature dependence.

The results presented permit selection of suitable combinations of temperature and strain rate for producing sharp bends with zero elastic springback.

Thesis Supervisor: Walter A. Backofen
Title: Professor of Metallurgy

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INTRODUCTION

A recent investigation of superplasticity in some titanium alloys showed that at strain rates below about 10^{-2} sec^{-1} the flow strength decreased markedly as the temperature was increased through the α(hcp) plus β(bcc) region[1]. Since the relatively high strength of titanium alloys leads to excessive amounts of elastic springback in conventional sheet metal forming operations -- as much as 15 to 25 degrees at room temperature for the alloy Ti-6Al-4V[2] -- it was natural to wonder if proper selection of temperature and forming speed could lower the flow strength sufficiently to reduce springback to an acceptable level. Since no such information was found in the literature, it was decided to undertake a systematic study of the effects of temperature and strain rate on the bending formability of the titanium alloy Ti-6Al-4V.

Conventional practice in sheet metal forming of Ti-6Al-4V includes hot forming at temperatures of 1100°F[3] to 1350°F[2] and hot sizing or "creep" forming of pre-formed parts at 1200°F to 1450°F[2,4]. Sheet forming operations are not performed at higher temperatures since partial solutionization occurs as the α plus β region is entered.

Hot sizing is a time and temperature dependent deformation process which brings the part to final shape by pressing between matched dies for a period of from a few minutes to several hours[4], depending upon the complexity of the shape change involved.

It is difficult to determine the strain rates involved in these processes, since the necessary information concerning the die geometry and other details of the proceudre are seldom reported. Rough estimates of the average strain rates may be made, however, by letting $\dot{\varepsilon} \approx \varepsilon/t$, where ε is the maximum strain required to produce the part and t is the time required for the forming operation.

For the case of bending, the critical value of strain may be taken as the maximum tensile fiber strain at the outer surface of the bend. If the neutral axis of the bend coincides with the central axis of the specimen, this strain is given by[5]:

$$\varepsilon = T/(2R + T) \tag{1}$$

and therefore the average strain rate is given by:

$$\dot{\varepsilon} = \frac{T/(2R + T)}{t} \tag{2}$$

where R is the inner bend radius, T the metal thickness and t is the forming time. For the typical case of a bend with $R = 4T$, which can be formed successfully above 400°F[2], $\varepsilon = 0.11$. An approximate lower bound for the strain rate in conventional bending processes can be calculated by assuming this value for the strain and taking the forming time to be 0.5 second, as recommended in a bending formability testing program designed to simulate conventional practice[6]. The resulting value of the strain rate is 2.2×10^{-1} sec^{-1}.

Recent work has shown that slower forming speeds may be used if heat loss to the die is minimized by heating the die to the forming temperature[7,8]. The combination of forming at slower speeds and holding the part under load for several minutes after forming eliminates the need for a separate hot sizing operation[7].

Bends with a 2.25T radius have been successfully formed at 1200°F by this method in Ti-6Al-4V of 0.025 inch and 0.070 inch thickness by bending at punch speeds up to 12 inches per minute and subsequently holding the part under load for several minutes[7]. The maximum tensile strain in this case, given by Equation 1, is 0.18. Since only the punch velocity is reported in Reference 7, the forming time, t, must be replaced by x/v in Equation 2, to yield the relation:

$$\dot{\varepsilon} \approx \frac{T/(2R + T)}{x/v} \tag{3}$$

where x is the distance the punch must travel to complete the bend and v is the punch velocity. The punch stroke, x, may be estimated by assuming the use of a standard press brake-type 90 degree V-notched die, in which the recommended bending span (or die opening), S, is given by[9]:

$$2R + 2T \leq S \leq 3R + 2T \tag{4}$$

The punch stroke required to seat the part against the flanks of the die is determined from geometry to be:

$$x = S/2 + T - \sqrt{2}\,T - \sqrt{2}\,R + R \quad \text{or:} \tag{5a}$$

$$x = S/2 + (1 - \sqrt{2})(R + T) \tag{5b}$$

For R = 2.25T, this reduces to $x \approx 2T \rightarrow 3T$ for the range of S in Equation 4.

The maximum strain rate employed in the work reported in Reference 7 can then be estimated by taking the minimum value of x, namely x = 2T (which equals 0.050 inch for the 0.025 inch thick sheet) and the maximum punch velocity (12 inches per minute). The result is 7.2×10^{-1} sec^{-1}.

A report from another source[10] concerning the same project gave 4 minutes as a typical forming time, which indicates a strain rate of 7.5×10^{-4} sec^{-1}. Therefore the range of strain rates studied in that work was apparently about 7×10^{-4} sec^{-1} to 7×10^{-1} sec^{-1}.

A continuous roll-forming process operating at 1450°F and feed rates up to 40 feet per minute has produced bends with 1.3T radii[11,12]. The forming rolls have 1T radii, but 0.3T radial springback occurred[11]. Therefore the maximum strain in the outer fiber is 0.28.

A crude estimate of the minimum strain rate for this process can be made by taking the maximum forming time to be the time required for the part to travel through the several rolling stations. This distance must be of the order of 20 feet, although such information can only be guessed from the photographs of the apparatus contained in References 11 and 12. Therefore the maximum forming time is roughly of the order of 10^{-2} sec^{-1}, or about two orders of magnitude higher than those of Reference 7.

Similarly, the strain rates associated with hot sizing at 1200°F to 1450°F can be estimated for the typical case of

$R = 2T$, which represents a maximum tensile strain of 0.2, by taking the forming time to be from 2 minutes to 6 hours, in agreement with conventional practice[4]. The range of strain rates is then seen to be approximately 5×10^{-5} sec^{-1} to 2×10^{-3} sec^{-1}.

Four important points are apparent from this brief survey of sheet metal forming of Ti-6Al-4V:

1. Hot forming at strain rates of the order of 10^{-1} sec^{-1} results in sufficient ductility to permit 2T bends to be made above 1300°F, but elastic springback is excessive. Therefore either over-forming or hot sizing is required.
2. Decreasing the strain rate by about an order of magnitude permits bending to 1.3T at 1450°F, but springback is still excessive.
3. Hot sizing at 1200°F to 1450°F involves such low strain rates that forming times are excessively long. Therefore parts must be pre-formed to larger radii and then hot sized to final shape.
4. Forming at intermediate rates of 10^{-3} sec^{-1} to 10^{-1} sec^{-1} and subsequently holding the part under load for several minutes permits forming bends with radii as small as 2.25T at temperatures of 1200°F to 1450°F. Springback is eliminated by this process.

Most formability studies on titanium alloys have been conducted by selecting a temperature and forming speed and then determining the minimum bend radius possible under those conditions. No systematic study has been found which addresses itself to the problem of determining the combinations of stress, strain rate and temperature required to accomplish a specified bend. It is the purpose of this work to do just that for the limiting case of a sharp bend.

EXPERIMENTAL

MATERIALS AND APPARATUS

Formability of the titanium alloy of nominal composition (in wt pct) 6Al-4V was studied by conducting three-point bending tests with a matching punch and die. The material was received as annealed, 3/16 inch thick sheet and was the same as that studied by Lee and Backofen[1].

All specimens were taken from the plane of the sheet and the rolling direction was placed perpendicular to the bend line so the tensile fiber strain was directed along the rolling direction. Testing was performed on specimens in the mill-annealed condition. Specimen edges were machined to prevent crack initiation there, but no further surface preparation was made.

The punch and die assembly was constructed of Incoloy 802 and consisted of a 90 degree V-notched die with a die opening, or span, of 0.75 inch and a matching 90 degree punch. 1/16 inch radii were cut on the edges of the die opening to reduce sticking and facilitate entry into the die cavity. Although some initial testing was done with a 1T punch tip radius, the bulk of the study was performed with a sharp punch in order to provide the most severe bending formability test.

Limitations in the size of the die restricted the specimen width to 1 inch, so the specimen thickness was reduced to 0.125 inch by machining equal amounts of metal from both surfaces. This design satisfied the criterion for achieving plane strain[5,6]. An attempt to verify the attainment of plane strain by using a photographic grid was unsuccessful, since the oxide layer formed on the specimen made it impossible to take measurements from the grid. The macroscopic transverse strain along the bend line was measured, however, and found to be about 4 per cent along the outer surface and 3 per cent along the inner surface in all cases.

TESTING

Bending tests were conducted at temperatures of 600°C to 970°C and punch speeds of 0.05, 0.50 and 5.0 inches per minute. The punch and die assembly was heated in an air furnace mounted on a screw-driven testing machine. 10 to 15 minutes were required to return to the forming temperature after raising the furnace to insert the specimen in the die. Since the complete forming cycle required 20 to 45 minutes, the specimen was subject to oxygen contamination for one half to one hour.

Ti-6Al-4V is an alpha plus beta alloy and oxygen is an alpha stabilizer, so the extent of oxygen contamination can be determined by measuring the depth of the layer of alpha grains -- the alpha case -- on the surface of the specimen. This was found to be less than 0.003 inches at 1775°F, the maximum temperature employed in this work. It is standard procedure to remove 0.005 inch from both surfaces of titanium parts heated to between 1600°F and 1750°F for one half to two hours.

A suspension of finely powdered Corning 8871 glass in isopropyl alcohol was used as a lubricant and for protection against oxygen contamination in initial testing. Since the glass tended to cause the specimen to stick to both the punch and the die, its use was discontinued for the major portion of the testing program. No significant change in the load required for bending was detected upon elimination of the glass, presumably because the glass layer had been pushed away from underneath the punch tip and also from the lines of contact with the die opening edges upon application of the load.

Bending was accomplished in a manner similar to that of Reference 7, namely a continuous process combining hot forming and hot sizing. It was found by interrupted testing that the process of bending to a sharp inner radius occurs in three distinct steps, which can be seen in the representative chart record presented in Figure 1:

1. The part is bent to an inner radius of 0.75T to 1.1T by advancing the punch at constant speed to the point at which the load begins to increase rapidly as the part makes contact with the flanks of the die cavity. These values of the radii were found to be independent of temperature and punch speed, within the accuracy of measurement. Using Equation 1, the maximum tensile strain at this point is determined to be between 0.32 and 0.40. Since

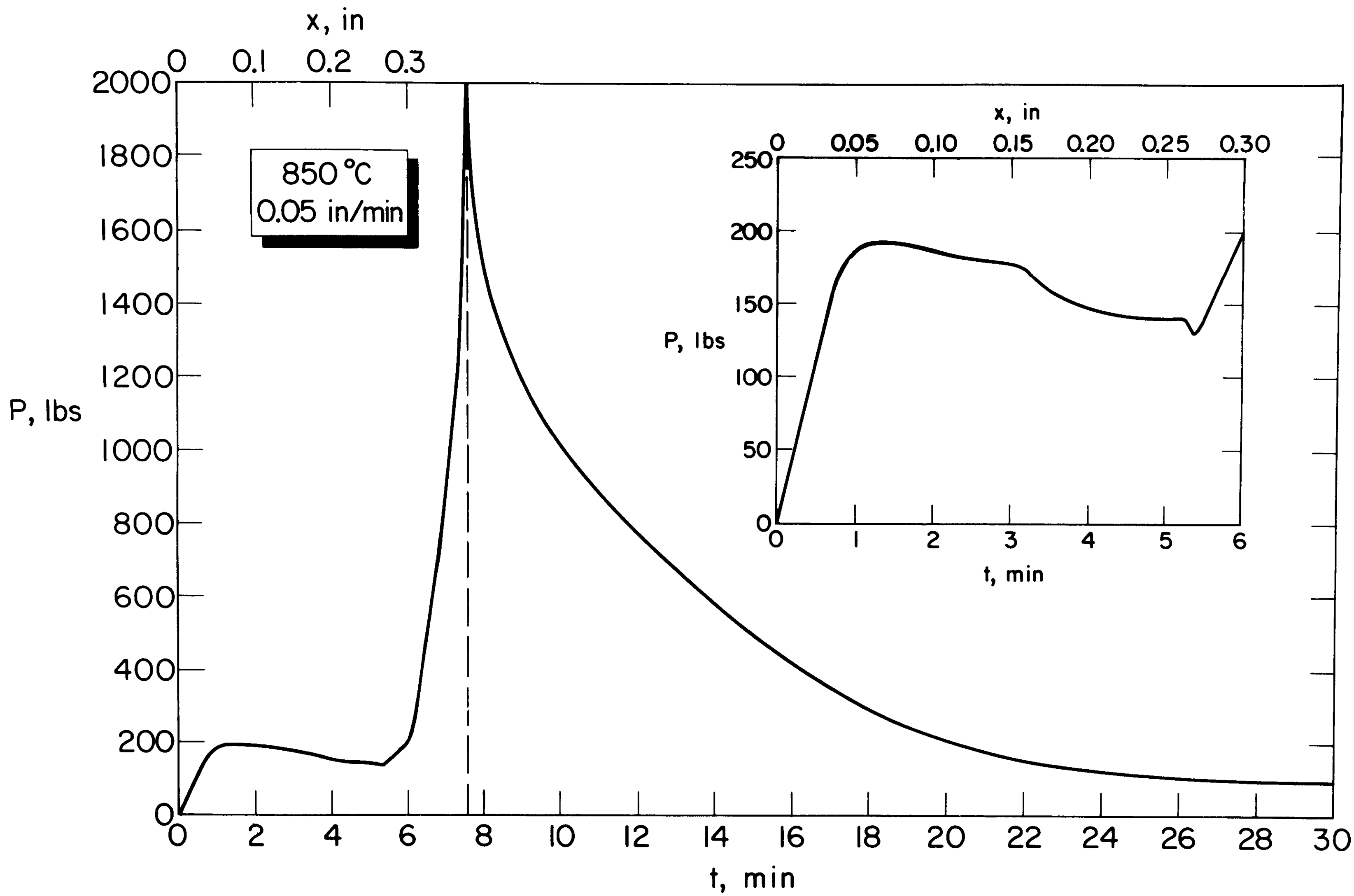

Figure 1. Chart record from a representative bending test. The dotted line indicates the end of the loading cycle.

the time required for this cycle is seen from Figure 1 to be between 5.5 and 7.5 minutes (for $v = 0.05$ inches per minute), the strain rate, ε/t, is between 8.2×10^{-4} sec^{-1} and 1.2×10^{-3} sec^{-1}. Therefore, for purposes of comparison with the data of Reference 1, the strain rates associated with the initial bending cycle are taken as 10^{-3}, 10^{-2}, and 10^{-1} sec^{-1} for punch speeds of 0.05, 0.50 and 5.0 inches per minute, respectively.

The average load required for this step of the forming cycle was measured and reported as the bending load. A variation of ± 20 pounds was typical. Most of this variation in the load can be accounted for by thermal expansion and contraction of the punch resulting from the observed temperature fluctuation of ± 2.5°F. The compliance of the punch and die assembly, C_m, was determined to be 2.25×10^{-5} in/lbs. The relation between the compliance and the thermal coefficient of expansion, α, which is 10.0×10^{-6} in/in/°F for Incoloy 802[13], is given by:

$$\Delta P = \frac{\Delta L}{C_m} = \frac{\alpha L \Delta T}{C_m} \tag{6}$$

where ΔP is the load variation, ΔL the length change (of the punch), ΔT the temperature variation and L is the length of the punch. L is approximately 15 inches, so $\Delta P = \pm\ 16.5$ lbs.

2. Further motion of the crosshead from this position results primarily in elastic strain in the punch, although some coining of the part must also occur. The insert in Figure 1, which is an enlarged view of Step 1, indicates a drop in load between Step 1 and Step 2. This apparently represents some type of transient behavior of the type commonly observed in deformation processing.
3. After reaching the load at which the elastic loading line extrapolates back to produce the required amount of punch travel (0.323 inch for 0.125 inch thick sheet), the crosshead is stopped and the load allowed to decay with time. This critical load is denoted P_{max} and was determined, at least in part, by trial and error. P_{max} must be reached or exceeded in Step 2, or there will not be sufficient elastic strain stored in the punch to produce the final shape change from a radius of approximately 1T to a sharp bend.

This final hot sizing process was terminated when the load had decayed away to a constant value, indicating that the part had fully conformed to the shape of the punch.

RESULTS

The load per unit width, P, required for the initial bending to a radius of approximately 1T (Step 1) at punch speeds of 0.05, 0.50 and 5.0 inches per minute or $\dot{\varepsilon}$ = 10^{-3}, 10^{-2}, and 10^{-1} sec^{-1}, respectively, is shown as a function of forming temperature in Figure 2. The lines shown are fitted to the data by the method of least squares. The bending moment (per unit width), $M \equiv \ell P/2$, where ℓ is the length of the lever arm and P is the bending load, is also indicated in Figure 2. Since ℓ equals one half of the die opening, or ℓ = 0.375 inch, M = 0.1875 P = 3P/16.

Bending loads were predicted from the data of Reference 1 by assuming the bending load to be the load corresponding to the limiting value of the bending moment, M_L, in a fully plastic beam. This load is given by[14]:

$$P = \frac{bh^2}{S} \sigma \tag{7}$$

where b is the width of the beam, h the height, S the span and σ is the flow stress. Since b = 1 inch, h = 0.125 inch and S = 0.75 inch, Equation 7 becomes:

$$P = \frac{\sigma}{48} \tag{8}$$

The solid symbols in Figure 2 were calculated from Equation 8 with the flow stress at the appropriate temperature and strain rate taken from Reference 1. Considering the difficulty inherent in accurately determining the strain and therefore the strain rate for the case of bending, the

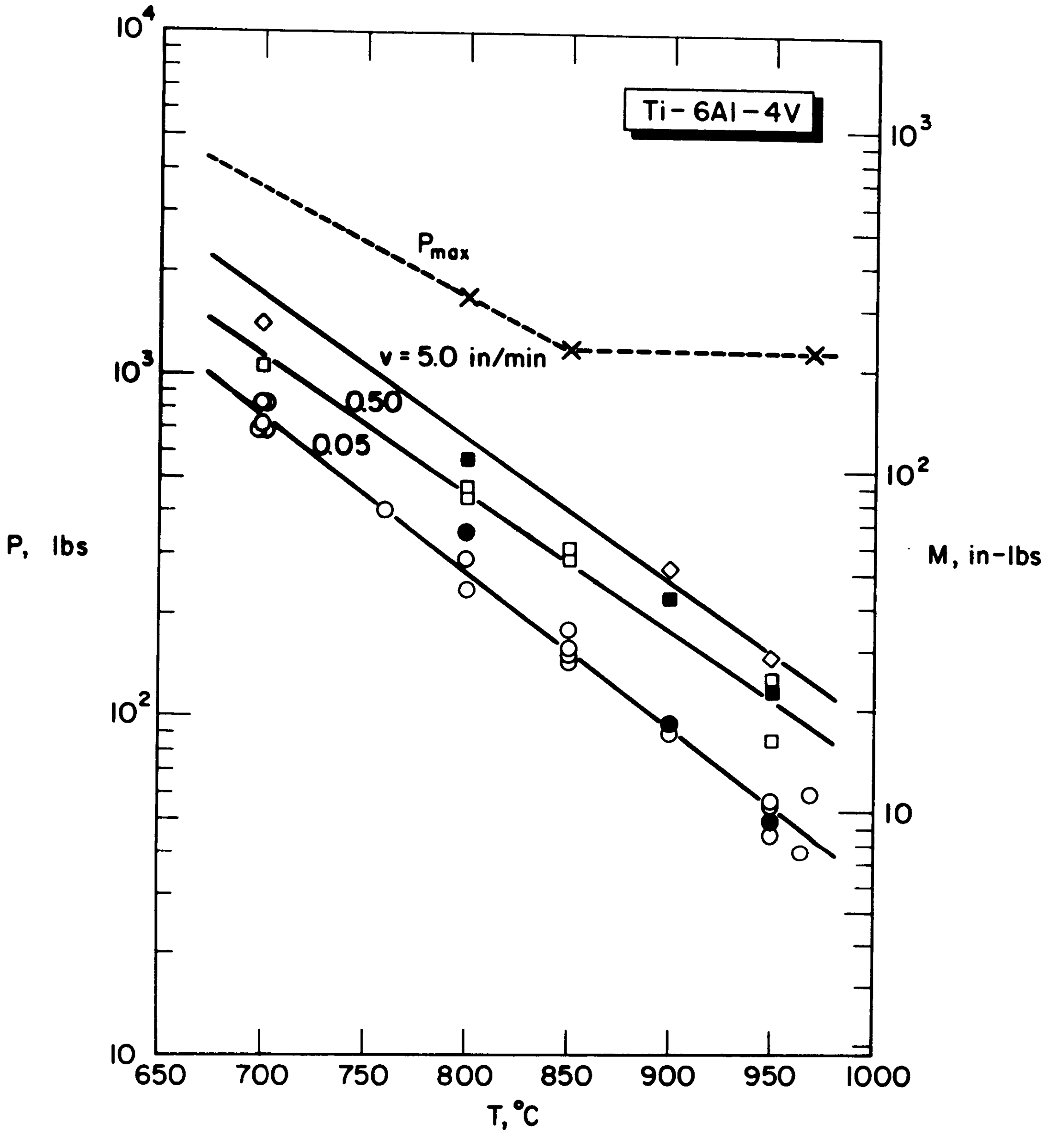

Figure 2. Variation of the bending load and maximum load with temperature. Solid symbols are values calculated from the data of Reference 1.

observed agreement with measured values of the bending load is quite good.

P_{max}, the load required for successful completion of the hot sizing step (Step 3) is also plotted in Figure 2. It is necessary to reach or exceed P_{max} in Step 2 to produce a sharp, 90 degree bend.

The time required for completion of the final relaxation or hot sizing process was determined by measuring the time required for the load to decay to a constant value and was found to be approximately 30 minutes for temperatures up to 850°C and about 15 minutes for temperatures up to 970°C. Since the radius to which the part is bent at the beginning of the relaxation cycle is independent of the punch speed used in Step 1, the strain accomplished during the final step is also not a function of the punch speed. Therefore the relaxation time is a function of temperature only. The relaxation time was, in all cases, sufficient to completely eliminate elastic springback.

The strain rate dependence of the bending load is more dramatically illustrated by plotting the load, P, against the punch speed, v, at constant temperature, as in Figure 3.

Values of the strain rate sensitivity factor, $m \equiv \partial \log \sigma / \partial \log \dot{\varepsilon}$, were calculated for changes in punch speed from 0.05 to 0.50 inches per minute and from 0.50

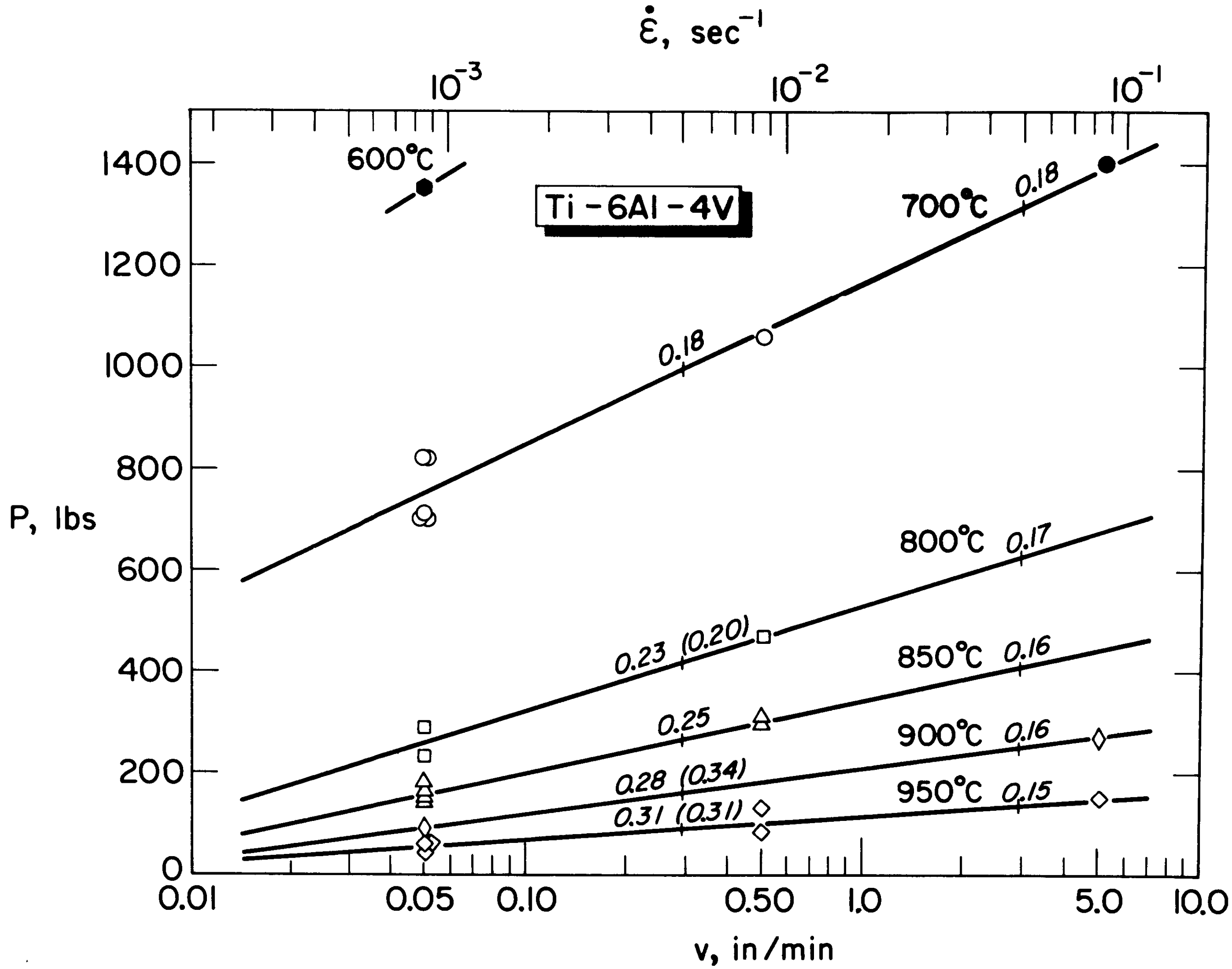

Figure 3. Variation of the bending load with punch speed. Values of m are indicated in italics. Numbers in parentheses are the corresponding m values from Reference 1. Solid symbols indicate parts which failed by cracking.

to 5.0 inches per minute. Since the value of m determined by changing from $\dot{\varepsilon}_1$ to $\dot{\varepsilon}_2$ is to be associated with the mean strain rate $(\dot{\varepsilon}_2 + \dot{\varepsilon}_2)/2$, the values reported here are relevant at punch speeds of 2.75×10^{-2} and 2.75×10^{-1} inches per minute. These correspond to strain rates of approximately 5×10^{-3} sec^{-1} and 5×10^{-2} sec^{-1} respectively. The measured values of m are indicated along the appropriate line in Figure 3. Numbers in parentheses are the corresponding values of m from Reference 2. It should be observed that the m values reported here were measured by changing v (or $\dot{\varepsilon}$) by a factor of 10, while in the more extensive work of Lee and Backofen[1] the strain rate was changed by only a factor of 2 or 2.5.

The solid symbols in Figure 3 indicate parts which failed by cracking along the tensile surface of the bend.

DISCUSSION

The results of this study indicate clearly that both temperature and strain rate strongly influence the load required for sheet metal forming operations in Ti-6Al-4V. The effect of temperature is strongest, with a bending load reduction of more than half resulting from a temperature increase of 100°C. The temperature dependence continues to be strong up to 970°C, which is about 20°C below the beta transus.

It is seen from the data presented in Figures 2 and 3 that strain rates as high as 10^{-2} sec^{-1}, and perhaps even 10^{-1} sec^{-1} at temperatures above 850°C, permit bending to a sharp radius in a single, continuous step. Forming times are longer than those employed in conventional forming processes, but elastic springback is eliminated and there is no limit to the bend radius which can be produced.

Since the temperature range investigated in this work is essentially that for annealing and solution heat treating, and since forming times are of the order of 20 to 40 minutes, the possibility of combining the forming operation with heat treating exists. Some duplex-annealing is already performed on Ti-8Al-1Mo-1V by forming mill-annealed material at 1450°F and allowing the part to air cool[3]. Simultaneous forming and aging of solution heat treated Ti-6Al-4V has also been investigated and found to be feasible[7]. Complex parts could, perhaps, be formed at

850°C or above, then water quenched, cleaned and aged.

The demonstrated ability to predict from tensile flow stress data the loads required for more complex forming operations, such as bending, is a significant result.

CONCLUSIONS

1. Sharp bends (R = 0) can be made, with zero elastic springback, at a temperature of 700°C (1292°F) and a strain rate of 10^{-2} sec^{-1} in Ti-6Al-4V.
2. There is a strong temperature dependence of the bending load throughout the range of strain rates investigated -- 10^{-3} sec^{-1} to 10^{-1} sec^{-1}.
3. A substantial decrease in the load occurs between 700°C (1292°F) and 800°C (1472°F) at all strain rates investigated.
4. The strain rate dependence of the forming load is significant, but less so than the temperature dependence.
5. A continuous forming cycle consisting of hot forming at strain rates between 10^{-3} sec^{-1} and 10^{-2} sec^{-1} followed by hot sizing or relaxation forming results in complete elimination of elastic springback.
6. Simultaneous forming and solution heat treating processes appear to be feasible. These would render the use of such high forming temperatures considerably more economical.

APPENDIX

A Technique for Fabrication of Fiber-Reinforced Ti-6Al-4V-Matrix Composites

Composites of boron filaments in a matrix of the alloy Ti-6Al-4V have been prepared by diffusion bonding 4-mil boron filament mats between 6-mil foils of Ti-6Al-4V[16]. Consolidation was accomplished at 1550°F (843°C) to 1650°F (899°C) by the application of a pressure of 3,600 psi for a period of several hours in an evacuated chamber (10^{-4} to 10^{-5} torr). Filament contents up to 26 per cent have been achieved by Reference 16.

From a deformation processing viewpoint, the process of consolidation is essentially a problem of extruding the matrix metal into the channel formed by two adjacent filaments. In this sense, what is required is a reduction by extrusion from D + s to s, where D is the filament diameter and s is the spacing between filaments. If the filaments are assumed to be arranged in a square array, the volume fraction of fibers is given by:

$$f \equiv V_f/V = \pi(D/2)^2\ell/(D + s)^2\ell = \pi D^2/4(D + s)^2 \qquad (9)$$

Therefore as the volume fraction of fibers is increased, the extrusion strain, given by:

$$\varepsilon_e = \ln \{(D + s)/s\} \qquad (10)$$

is increased and consequently a higher forming pressure is required. The extrusion pressure, p_e, is given by:

$$p_e = 2\sigma \ln \{(D + s)/s\} \qquad (11)$$

where σ is the flow stress, and 50 per cent efficiency has been assumed.

Since the boron filaments may be damaged by excessive pressure, it would be desirable to reduce the flow stress, σ, so that, for a large reduction, the pressure will be sufficiently small.

The marked decrease in the flow stress as the temperature is increased toward the beta transus suggests that forming at low strain rates in the alpha plus beta region should permit large reductions without damaging the filaments. Therefore larger volume fractions of fibers should be attainable.

To test the feasibility of this technique, several tests were performed at 950°C with sandwiches consisting of five 0.125 inch diameter tungsten carbide rods between two 3/16 inch thick coupons of Ti-6Al-4V. These specimens were compressed at a crosshead speed of 0.02 inches per minute. Since the sandwich was initially 0.50 inch thick, the initial strain rate, $\dot{\varepsilon} = v/l$, was 6.7×10^{-4} sec^{-1}. Five tungsten carbide rods were used, with $s = 0$, so the specimen width was 5/8 inch, initially. Problems of thermal expansion made it difficult to prevent the rods from separating during the forming process.

Figure 4 is a photomicrograph taken from such a specimen. The cavity which contained the center rod is pictured. Measurements taken from Figure 4 indicate that s is slightly less than 0.010 inch, so the strain, given by Equation 10, is 2.50, and the volume fraction of fibers is 67 per cent.

The specimen was loaded to a pressure of 8,110 psi and then the load was allowed to relax for a period of 36 minutes. After that time, the load had not yet assumed a constant value. Therefore, it is likely that further extrustion would have occurred if the test had not been prematurely terminated.

Reference 1 gives the flow stress at 950°C and $\dot{\varepsilon}$ = 6.7 x 10^{-4} sec^{-1} as about 2,000 psi. Inserting this value and the measured value of the reduction, 2.50, into Equation 11 yields an expected extrusion pressure of 10,400 psi.

The alpha case produced by oxygen contamination is clearly visible in the figure. Actual composite fabrication would obviously have to be conducted in a vacuum, but the feasibility of the technique is apparent.

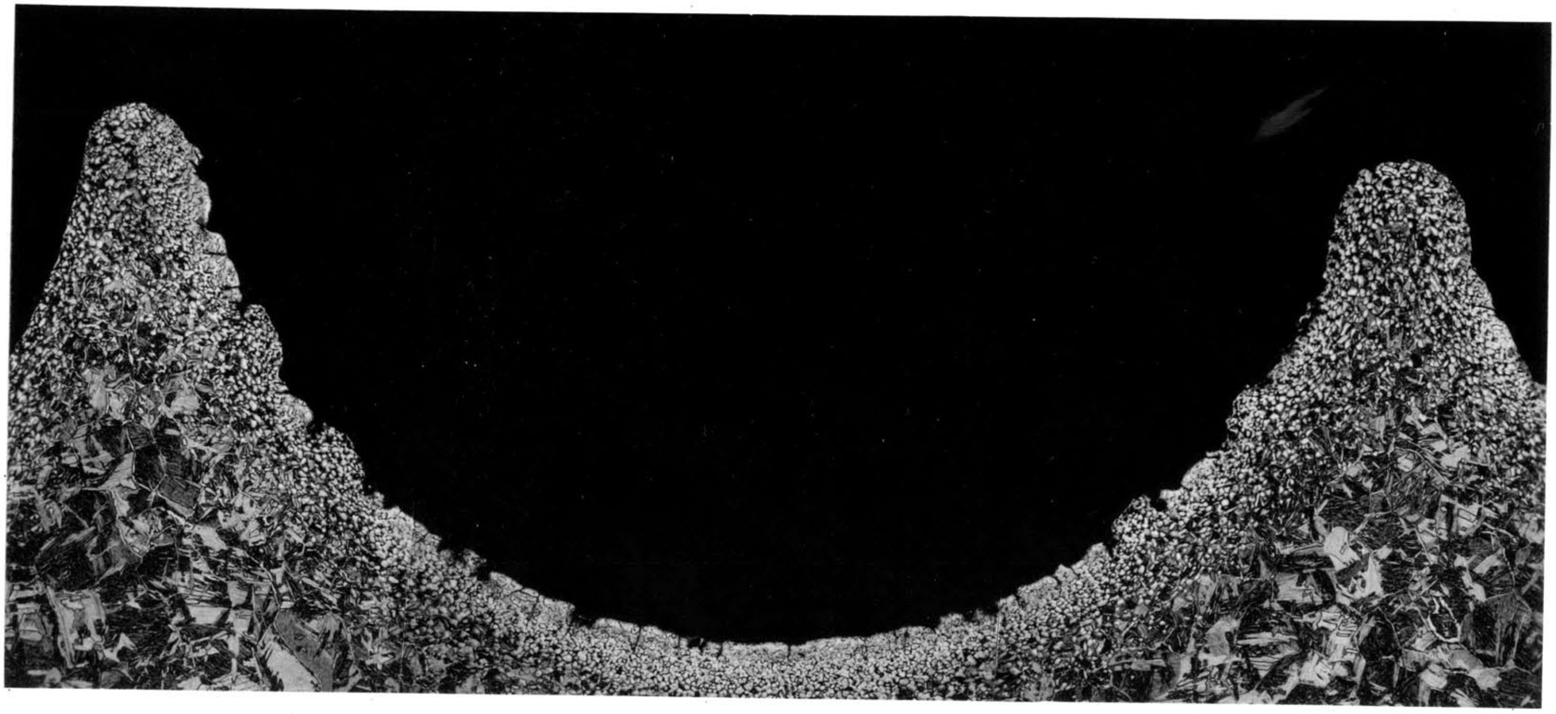

Figure 4. Photomicrograph of composite specimen. Tested at 950°C, $\dot{\varepsilon} = 6.7 \times 10^{-4}$ sec^{-1}. The alpha case produced by oxygen contamination is clearly visible. 50x

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