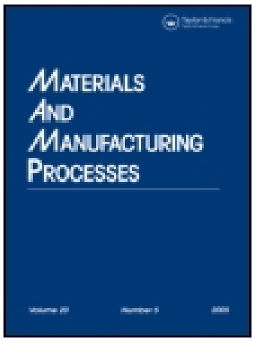

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Compression Testing of Ti-6Al-4V in the Temperature Range of 303–873 K

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Compression testing of Ti-6Al-4V alloy has been carried out at temperatures between 303 K to 873 K. To prevent embrittlement due to atmospheric oxygen and nitrogen, the samples were given a glass coating, which also acts as a lubricant simultaneously. Dynamic Strain Aging was observed to occur in the temperature range of 600 K to 800 K. Below 600 K stresses were high. Warm working has to be done above 800 K but below 1163 K ($0.6\,T_m$ where $T_m = 1940$ K) which is the recrystallization temperature. Based on these conclusions, warm extrusion has been successfully carried out in the Materials Forming Laboratory of I.I.T., Madras, Chennai, India.

Keywords Compression; Dynamic strain aging; Flow properties; Temperature; Ti-6Al-4V; Warm working; Work hardening.

1. Introduction

Ti-6Al-4V an $(\alpha + \beta)$ titanium alloy is one of the major outlets for titanium about half of the total titanium produced being in this form [1]. The microstructure can be fully utilized and controlled to have different proportions of individual phases so that a wide range of values of properties such as strength and toughness can be achieved. The alloy possesses adequate strength-to-weight ratio to be considered as an important aerospace material [2]. Extrusion is an important metal working process in which all the stresses are compressive [3] and in consequence the amount of deformation that can be given is high. Warm working [4] is gaining prominence since one can realize the advantages and minimize the disadvantages of both cold and hot working. Compression tests are essential to characterize the flow properties of the alloy at the different temperatures used in warm working [5]. Hence the present study has been carried out on the behavior of Ti-6Al-4V alloy in the various temperatures between R. T. (303 K) and 873 K, by means of axysymmetric compression test.

2. Experimental

Ti-6Al-4V rods of 40 mm diameter and 250 mm length were reduced to 28 mm diameter by hot forging in a Double Action Pneumatic Hammer at 1223 K after applying a glass coating to prevent oxygen and nitrogen penetration into the alloy. Annealing has been carried out at 773 K for 2 hrs after giving a glass coating to the forgings. From these forgings of 28 mm diameter rods, compression test samples (axysymmetric) of height 37.5 mm and diameter 25 mm $[h_o/d_o = 1.5]$ were machined. These samples were given a MoS_2 coating and heated in an in situ furnace. Temperatures used were 373, 473, 573, 673, 773, and 873 K. They were upset in a 100 T hydraulic press. Room temperature compression testing was also carried out. The schematic set up is shown in Fig. 1.

3. Results

Force stroke diagrams were recorded and from these, true stress–true strain diagrams were generated as shown in Fig. 2. Log–Log plots of stress and strain were plotted in Fig. 3, as well as stress against adiabatic temperature in Fig. 4.

The strength coefficients, strain hardening exponents, and work hardening rates were determined at various temperatures and plotted in Figs. 5, 6, and 7, respectively. Lowering the test temperature can be seen to raise the strength of alloy and the work hardening behavior as might be expected. The material shows a double 'n' behavior as seen in Fig. 3. The plot of stress against temperature at different strains shows a hump between 600–800 K as seen in Fig. 4. Strength coefficient decreases first as temperature increases up to 373 K and then increases as temperature goes to 573 K and again decreases from 573–873 K as shown in Fig. 5. Corresponding behavior of strain hardening exponent is shown in Fig. 6. It decreases up to 373 K, increases up to 773 K, and then decreases up to 873 K. The work hardening rate $(\Delta\sigma/\Delta\varepsilon)$ plotted against adiabatic temperature shows a peak between 600–800 K. The upset samples broke vertically into two pieces at 573, 673, and 773 K as shown in Fig. 8. This happened during testing in the hydraulic press. To estimate the mean flow stress and the adiabatic temperature rise in the deformation zone, two nomograms have been plotted as shown in Figs. 9 and 10. The temperature rise in the present case of operating stresses, strains, and temperatures have been given in Table 1 and the yield stresses are given in Table 2

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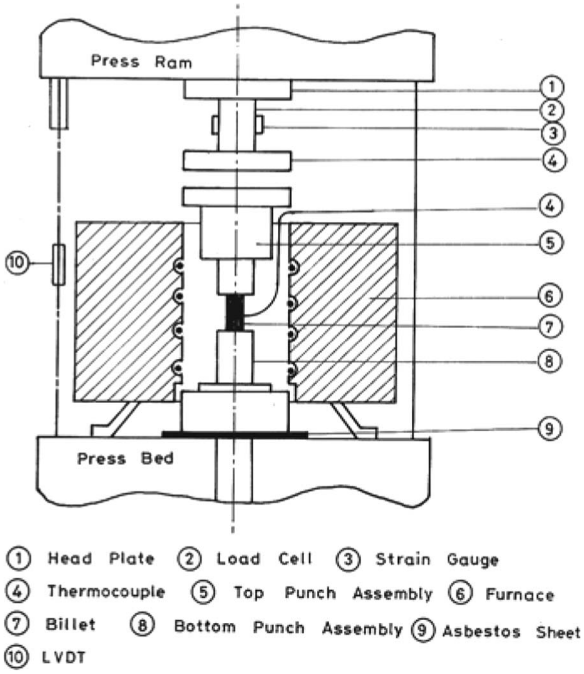

FIGURE 1.—Schematic setup for in situ compression test.

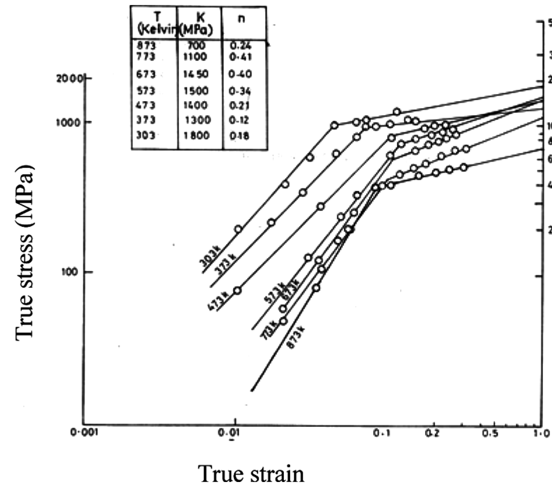

FIGURE 3.—Log–log plot of true stress and true strain.

for different temperatures. As the temperature of working increases, adiabatic temperature rise decreases at a constant strain. As strain increases, this temperature rise increases at a constant working temperature.

4. DISCUSSION

Dynamic strain aging occurs in the temperature range of 573–773 K as indicated by the hump in Fig. 4, the rise in K and n in Figs. 5 and 6, the peak in Fig. 7, and the breakage of samples in Fig. 8 [6, 7] at very low strains which were less than the maximum strain of 0.35 at 773 K, 0.32 at 673 K, and 0.26 at 573 K. Hydraulic press is a soft machine in which working media is oil. Because of dampening, the serrations caused by dynamic strain aging are not faithfully reproduced and recorded. Such a result has

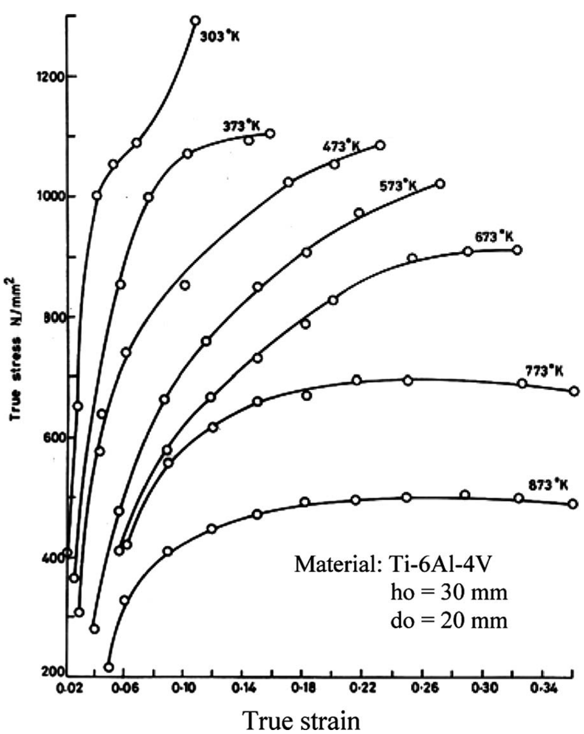

FIGURE 2.—Plot of true stress against true strain at different temperatures.

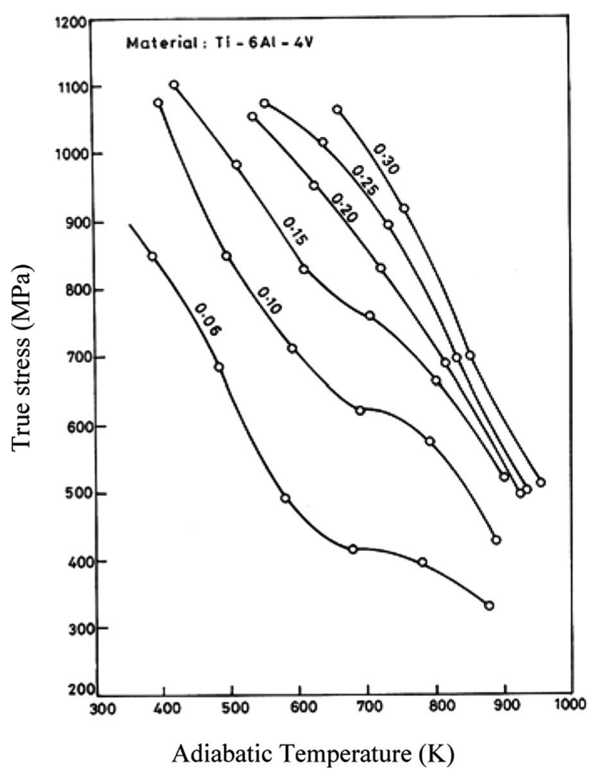

FIGURE 4.—Plot of true stress against adiabatic temperature at different strains.

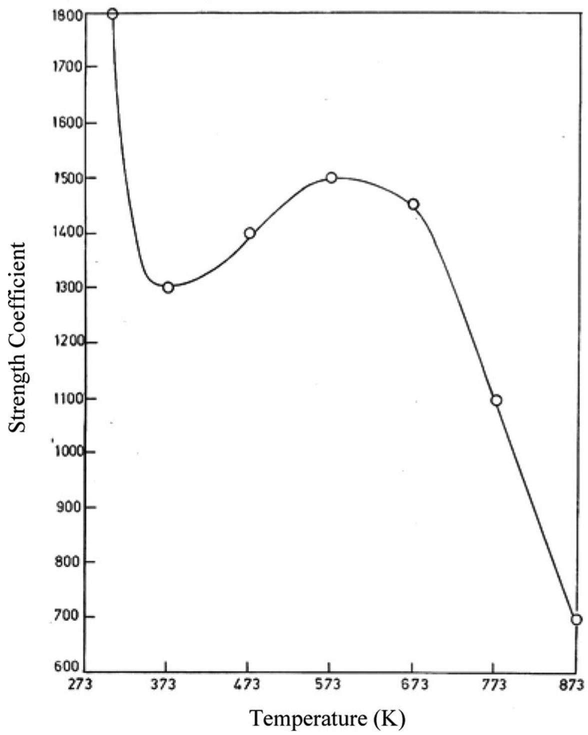

FIGURE 5.—Plot of strength coefficient against temperature.

been reported in an earlier work also [7]. Dynamic strain aging is a rule rather than an exception during deformation of metals [8]. It is caused by interstitial elements such as carbon in iron and oxygen in titanium. In the present case, during hot forging and annealing, some oxygen might have penetrated the glass coating. Also during high temperature extrusion, the MoS_2 lubricant would not have been an effective barrier for penetration of oxygen. Dynamic strain aging increases the flow stress and decreases the ductility. The work hardening rate becomes abnormally high in the temperature range of DSA [8]. DSA is totally undesirable during mechanical processing. Therefore, this temperature range should be avoided while working Ti-6Al-4V [9]. Below the recrystallization temperature [it is 1163 K (0.6 T_m when T_m is melting point in Kelvin) for Ti-6Al-4V as T_m is 1950 K] and above room temperature warm working is to be done to maximize the advantages of both hot and cold working and minimize the disadvantages. But above 873 K, there will be severe oxidation of Ti-6Al-4V. Moreover application of lubricant above this temperature also makes the processing tricky [10]. At very low temperatures, the stresses will be high and ductility low [11]. At room

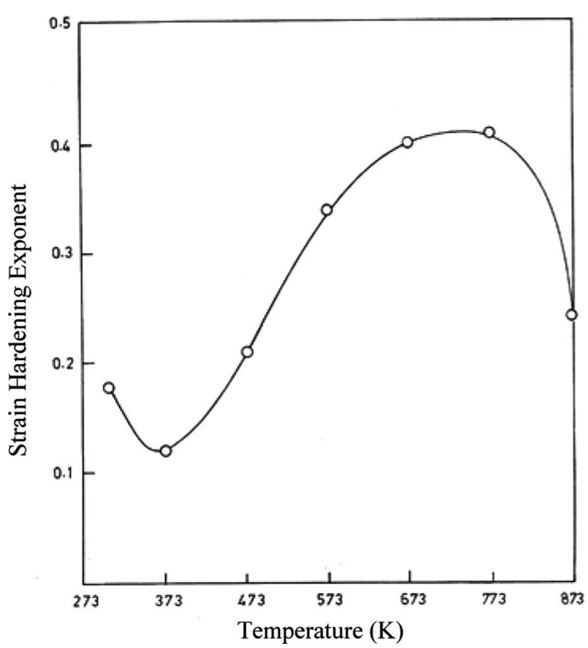

FIGURE 6.—Plot of strain hardening exponent against temperature.

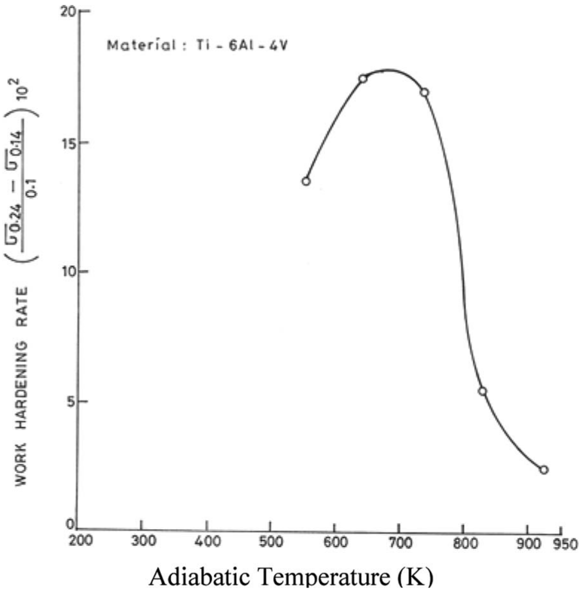

FIGURE 7.—Plot of work hardening rate against adiabatic temperature.

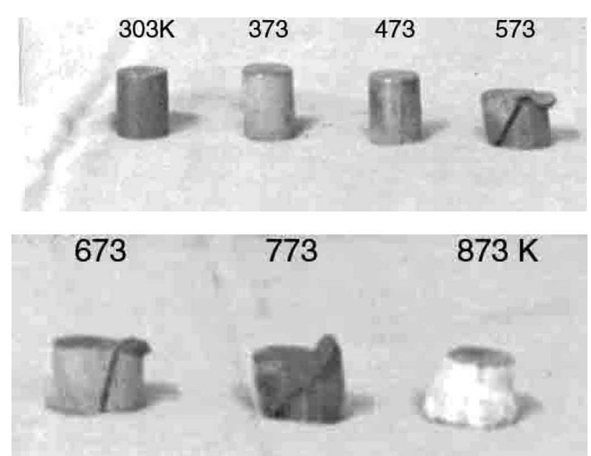

FIGURE 8.—Sample subjected to axysymmetric compression testing.

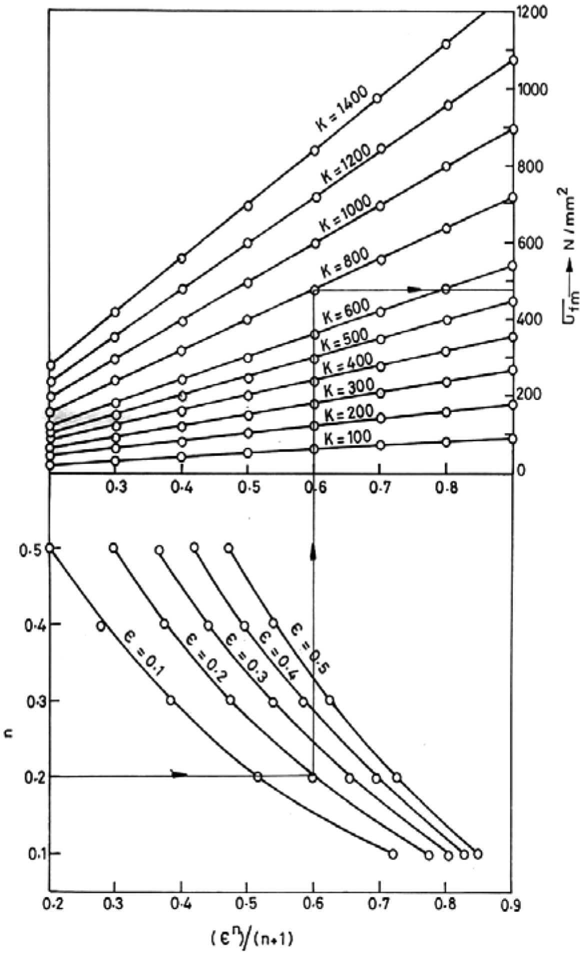

FIGURE 9.—Nomogram for estimating mean flow stress.

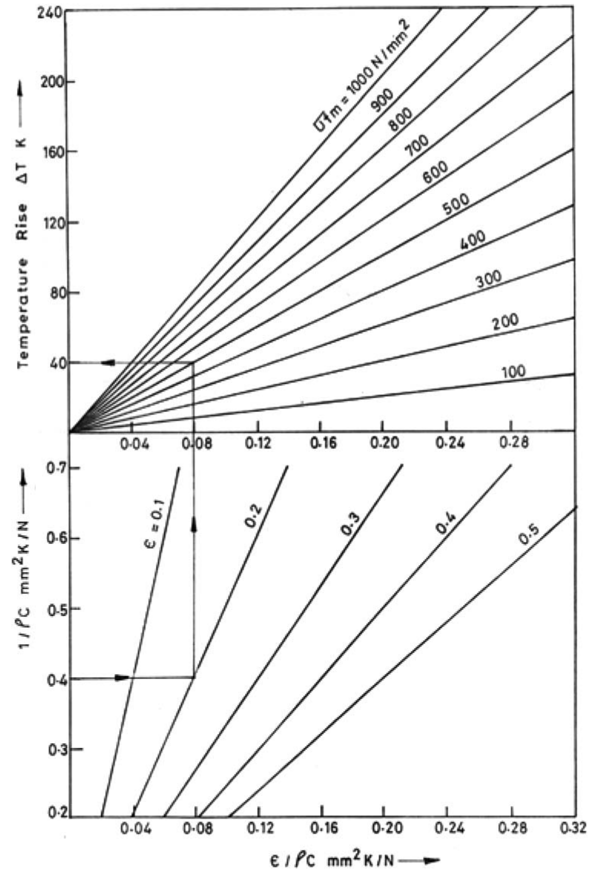

FIGURE 10.—Nomogram for estimating adiabatic temperature rise.

temperature the plasticity is very limited, as indicated by a high level of stress (1300 MPa) required for a small deformation strain of 0.10. The adiabatic temperature rise is higher at lower temperature and lesser at higher temperature at a given strain, as seen in Table 1. This can also be taken advantage of if processing is done at medium temperatures in the warm working temperature range.

5. CONCLUSION

It is to be concluded that Ti-6Al-4V alloy can be mechanically processed economically and with ease in the range 773–873 K. It can be done with a glass coating on the alloy to act as an effective lubricant and at the same time act as a barrier preventing oxygen, hydrogen, and nitrogen penetration from atmosphere, thereby eliminating embrittlement. This will ensure lesser forces adequate plasticity, nonbreakdown of lubricant, and minimization of embrittlement.

TABLE 1.—Adiabatic temperature T_A (in Kelvin).

ε T_w	303 K	373 K	473 K	573 K	673 K	773 K	873 K
0.06	325	389	486	583	682	781	880
0.10	343	403	498	594	691	789	887
0.15	367	423	515	609	705	801	898
0.20	395	445	534	626	720	815	911
0.25	423	468	555	643	737	830	925
0.30	453	492	587	664	761	82	932

APPENDIX

A.1. Mean Flow Stress

$$\sigma = K\varepsilon^n$$

$$\int_{\varepsilon_0}^{\varepsilon_f} \sigma \, d\varepsilon = \int_{\varepsilon_0}^{\varepsilon_f} K\varepsilon^n \, d\varepsilon,$$

when $\varepsilon_o = 0$

$$\sigma_{fm}\varepsilon_f = \left(K\varepsilon^{n+1}\right)/(n+1)\Big|_0^{\varepsilon_f}$$

$$\sigma_{fm} = (K\varepsilon_f^n)/(n+1)$$

K = strength coefficient

n = strain hardening exponent

σ_{fm} = mean flow stress

TABLE 2.—Yield stress at different temepratures.

T (Kelvin)	303	373	473	573	673	773	873
Sy (MPa)	925	830	575	480	425	350	205

A.2. Adiabatic Temperature Rise

$$\Delta T_{Ad} = \beta \sigma_{fm} \varepsilon / \rho C$$

$$\beta = 0.95$$

$$\sigma_{fm} = \text{mean flow stress}$$

$$\varepsilon = \text{strain}$$

$$\rho = \text{density}$$

$$C = \text{specific heat}$$

$$\Delta T_{Ad} = T_A - T_W$$

$$\Delta T_{Ad} \uparrow T_W \downarrow \text{ at a constant } \varepsilon$$

$$\Delta T_{Ad} \uparrow \varepsilon \uparrow \text{ at a constant } T_W$$

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