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# Correlation of data on the hot deformation of Ti - 6Al - 4V

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Published data on the hot deformation of Ti–6Al–4V alloy were correlated by the Zener–Hollomon relation. Within the temperature range of 700 to 1000° C, for which the alloy is two phase, two mechanisms are operable. The one associated with lower temperature–strain-rate combinations has an activation energy of about 85 000 cal $\text{mol}^{-1}$, which is considerably greater than any reported experimental activation energy for self diffusion in titanium. Thus, mechanisms other than dislocation climb must be considered. An apparent activation energy of 172 000 cal $\text{mol}^{-1}$ was found for higher temperature–strain-rate combinations and is felt to be related to the occurrence of dynamic recrystallization.

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## 1. Introduction

A fairly large amount of data on the effect of strain-rate on the working stress required for the alloy Ti–6Al–4V have been published. These data, covering the approximate temperature range from 700 to 1000° C, were obtained using several types of deformation including tensile [1–3], compression [4, 5], torsion [6], and extrusion [7]. To persons contemplating the hot deformation of this alloy, these data would be of greater usefulness once they were combined into simple relationships. It was thus the purpose of this work to test the possibility of correlating these data with an equation relating effective stress to strain-rate and temperature.

## 2. Procedure

The relation chosen for possible correlation of the deformation data was due to Zener and Hollomon [8] and given by

$$\bar{\sigma} = f\,|\{(\dot{\bar{\epsilon}}\,\mathrm{e}^{\Delta H/RT})\}|\,\epsilon \qquad (1)$$

where $\bar{\sigma}$ is an effective stress related by some function, $f$, to an effective strain-rate, $\dot{\bar{\epsilon}}$, and to the exponential of the activation energy, $\Delta H$, of the deformation process divided by the product of the universal gas constant, $R$, and the absolute temperature, $T$.

As suggested by this relation, $\bar{\sigma}$ is taken at constant total strain, $\epsilon$. The use of invariant functions of stress and strain such as the effective (significant) stress and effective (significant) strain permits comparison between plastic stress–strain values for any state of stress (type of deformation). The effective stress and effective strain (and from it effective strain-rate) are defined by relationships given in texts containing plasticity theory, e.g. [9]. These relations reduce to very simple equations for tensile, compression, and torsion testing. Relations for effective stress and strain rate in extrusion are given in [10].

By using data for constant $\bar{\sigma}$, assuming that the function in Equation 1 is the natural logarithm and performing partial differentiation with respect to $1/T$, one obtains

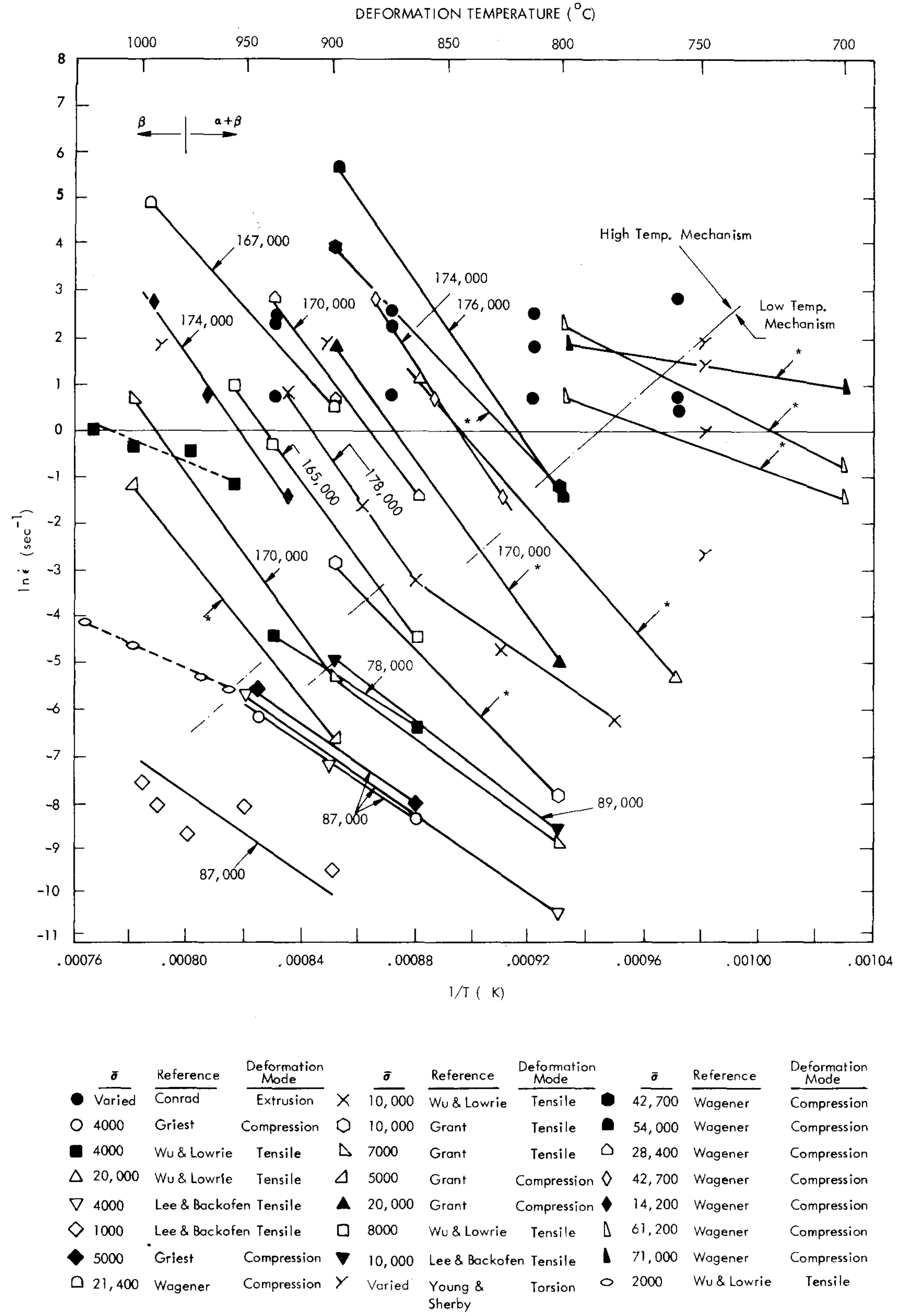
$$\frac{\partial\bar{\sigma}}{\partial(1/T)} = \frac{\partial \ln \dot{\bar{\epsilon}}}{\partial(1/T)} + \frac{\Delta H}{R} \;. \qquad (2)$$

Since $\bar{\sigma}$ is constant, Equation 2 reduces to

$$\frac{\partial \ln \dot{\bar{\epsilon}}}{\partial(1/T)} = \frac{-\Delta H}{R} \;. \qquad (3)$$

Equation 3 states that the negative of the slope of $\ln \dot{\bar{\epsilon}}$ plotted against $1/T$ is the quantity $\Delta H/R$. A number of these plots, from which activation energies were determined, are given in Fig. 1.

Several points concerning this figure must be mentioned. The data from [6] and [7] were not adequate for determining activation energy values. Thus to render these data useful for establishing the desired correlation, it was necessary to assign activation energies to them that were the average



| | $\bar{\sigma}$ | Reference | Deformation Mode | | $\bar{\sigma}$ | Reference | Deformation Mode | | $\bar{\sigma}$ | Reference | Deformation Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ● | Varied | Conrad | Extrusion | × | 10,000 | Wu & Lowrie | Tensile | ⬢ | 42,700 | Wagener | Compression |
| ○ | 4000 | Griest | Compression | ⬡ | 10,000 | Grant | Tensile | ◼ | 54,000 | Wagener | Compression |
| ■ | 4000 | Wu & Lowrie | Tensile | ◺ | 7000 | Grant | Tensile | ⌂ | 28,400 | Wagener | Compression |
| △ | 20,000 | Wu & Lowrie | Tensile | ◁ | 5000 | Grant | Compression | ◇ | 42,700 | Wagener | Compression |
| ▽ | 4000 | Lee & Backofen | Tensile | ▲ | 20,000 | Grant | Compression | ♦ | 14,200 | Wagener | Compression |
| ◇ | 1000 | Lee & Backofen | Tensile | □ | 8000 | Wu & Lowrie | Tensile | ◺ | 61,200 | Wagener | Compression |
| ◆ | 5000 | Griest | Compression | ▼ | 10,000 | Lee & Backofen | Tensile | ◢ | 71,000 | Wagener | Compression |
| ⌂ | 21,400 | Wagener | Compression | Y | Varied | Young & Sherby | Torsion | ⬭ | 2000 | Wu & Lowrie | Tensile |

* High temperature point on curve belongs to "High Temperature" mechanism while low temperature point belongs to "Low Temperature" mechanism.

*Figure 1* Log strain-rate as a function of reciprocal of temperature for Ti–6Al–4V alloy.

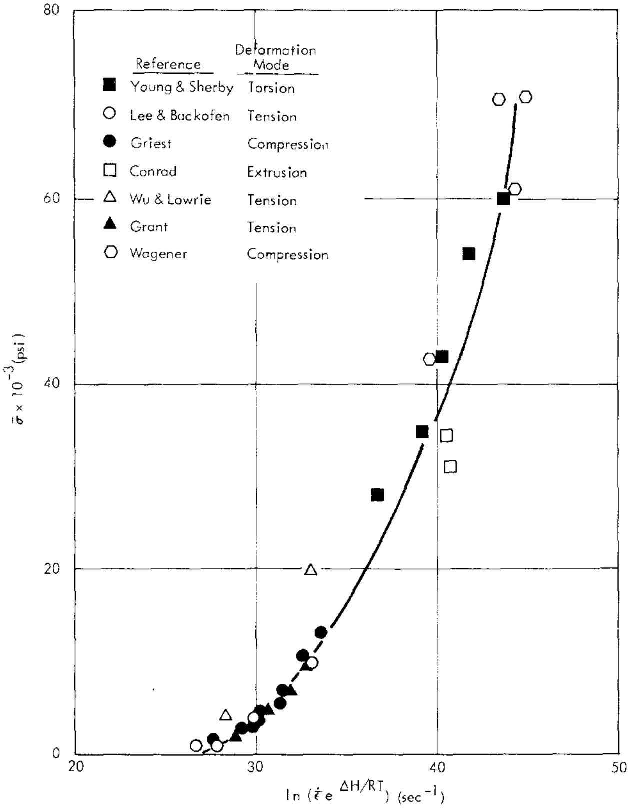


*Figure 2* Zener–Hollomon correlation for Ti–6Al–4V alloy deformed by a low temperature mechanism. $10^3$ psi ≡ 6.89 N mm$^{-2}$.

of the values determined from the remaining data.

It is also important to note that the data of this figure fall into three distinguishable regions. The highest temperature data evidently are to be associated with the single phase, $\beta$. The remaining data apply to the two-phase $\alpha + \beta$ structure and are further subdivided into two regions denoted as "high temperature mechanism" and "low temperature mechanism". The data corresponding to the two phase material are the ones of interest. The absence of an activation energy value for several curves is the result of that particular set of data being comprised of one value within each of the two subregions (mechanisms).

Data for each sub-region of Fig. 1 were separately correlated to determine the applicability of Equation 1.

## 3. Results

Data for the low temperature mechanism are given in Fig. 2. The correlation appears to be fairly good. The overall average activation energy for this mechanism is 85 000 cal mol$^{-1}$.

The correlation for the high temperature mechanism (Fig. 3) is not easily established. However, by eliminating the data of [7] (the points on the curve corresponding to extrusion), the observed spread could be reduced appreciably. Such an action is possibly justified since, as that author states, the relation used to calculate the contribution of redundant work to the extrusion pressure is likely to be inappropriate for the deformation conditions used in his study.

The overall average activation for the high temperature mechanism is 170 000 cal mol$^{-1}$.

## 4. Discussion

For the temperature range studied (approximately 700 to 1000° C), the activation energy for the low-temperature mechanism of 85 000 cal mol$^{-1}$ is not unduly high. Conrad [7] reports an activation energy of 70 000 cal mol$^{-1}$ for the temperature range of 760 to 940° C.

The anomalous behaviour of titanium has led to a fairly wide range of experimental activation energies for self diffusion in both the $\alpha$ [11] and $\beta$

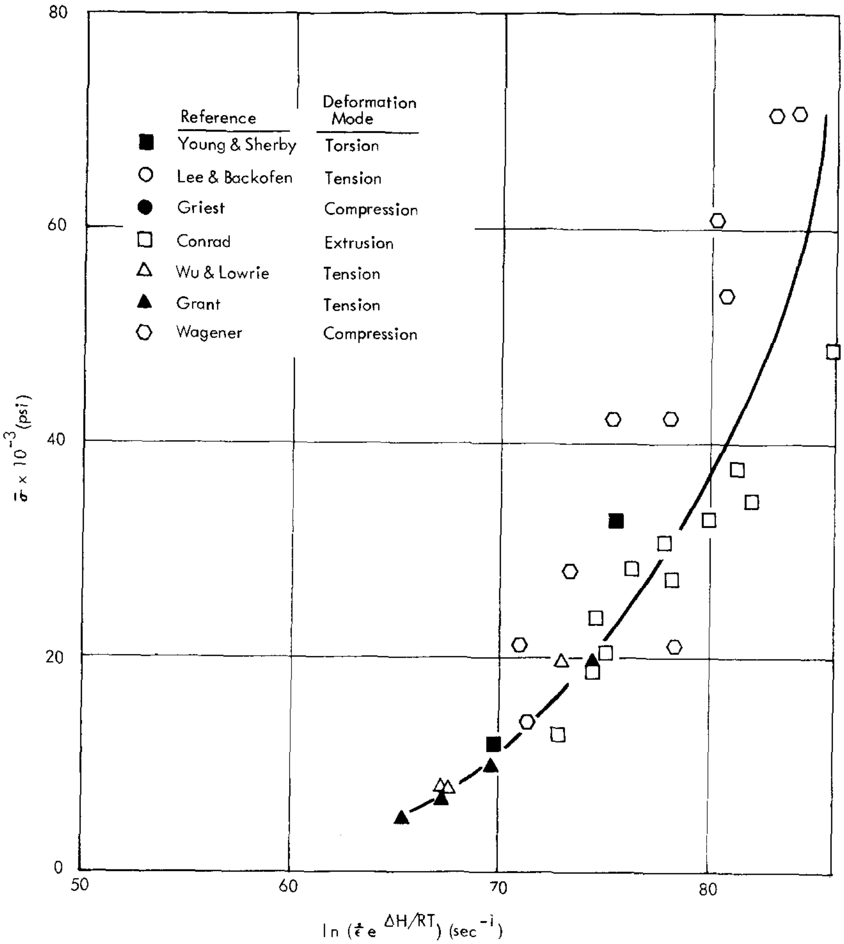


*Figure 3* Zener–Hollomon correlation for Ti–6Al–4V alloy deformed by a high temperature mechanism.

[11–13] phases. However, even the largest of these values are less than either of the above values for the low temperature mechanism. This would seem to rule out deformation rate control by dislocation climb. Other mechanisms, unrelated to self-diffusion, must be examined before the low temperature activation energy for Ti–6Al–4V deformation can be identified.

In the present study, an activation energy of 172 000 cal mol$^{-1}$ was determined for the high-temperature mechanism. This large increase over the value obtained at lower temperature–lower strain-rate combinations is not unique. Lee and Backofen [2], in their study of deformation in Ti–5Al–2.5Sn, found behaviour which is very similar to that noted in Fig. 1 in that plots to determine activation energy displayed rather abrupt changes to very steep slope as temperature and strain-rate were increased. This slope corresponded to an activation energy of several hundred kcal mol$^{-1}$.

It is quite possible that the large difference in activation energies for the low and high temperature deformation of two phase Ti–6Al–4V is due to dynamic recrystallization. However, only an experimental effort could establish this conclusion with certainty and simultaneously rule out a change in rate-controlling mechanism which is not dependent on a simultaneous change in structure. None of the papers on which the present study is based established any mechanistic explanation for the change in activation energy. However, work on other metals, as described below, conclusively demonstrate that very large increases in activation energy can occur as a consequence of recrystallization.

Using the data of Richardson *et al.* [14] for creep strain of nickel as a function of time, the change in slope ($\dot{\bar{\epsilon}}$) associated with recrystallization was calculated. Since $\Delta H$ is given by $R[\Delta \ln \dot{\bar{\epsilon}} / \Delta(1/T)]$ this slope change should be proportional to the change in activation energy which occurs with the onset of recrystallization. From these data the activation energy for nickel deformation should be expected to increase by 280% once recrystallization is underway.

By similar calculations, increases in activation energies of deformation with the occurrence of recrystallization of 162% and 128% were determined for aluminium [15] and lead [16], respectively.

In two separate studies on creep of aluminium [17, 18], the activation energy was found to increase with recovery (or recrystallization); in one instance from 30 000 to 54 000 (an increase of 180%) and in the other instance from about 35 000 to 64 000 cal mol$^{-1}$ (also an increase of 180%).

If recrystallization during hot deformation accounts for the abrupt change in activation energy for Ti–6Al–4V deformation, the dependence of $\Delta H$ on both temperature and $\dot{\bar{\epsilon}}$ (Fig. 1) rather than merely on temperature is explained since it is well known that recrystallization depends upon both the amount of work as a function of time (since it is competing with recovery processes) and the temperature.

## 5. Conclusions

Data on the hot deformation of Ti–6Al–4V alloy can be correlated on the basis of the Zener–Hollomon relation.

For temperatures corresponding to the two phase $\alpha + \beta$ structure, two separate deformation controlling mechanisms were noted and were found to have activation energies of 85 000 and 172 000 cal mol$^{-1}$, respectively.

The latter activation energy, associated with larger effective stresses and greater strain-rates, is believed to represent the process of dynamic recrystallization. No mechanism has as yet been identified with the former activation energy.

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