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A STUDY OF THE ELECTROPLASTIC EFFECT IN METALS.(U)
JUL 79 H CONRAD , K OKAZAKI

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A STUDY OF THE ELECTROPLASTIC EFFECT IN METALS

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Final Report
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A STUDY OF THE ELECTROPLASTIC EFFECT IN METALS

Hans Conrad and Kenji Okazaki

Summary

The effects of high density, direct current pulses ($10^3 - 10^4$ A/mm² for periods of 55-120 μ s) on the flow stress determined in an Instron tensile testing machine were studied in a number of polycrystalline metals representing various crystal structures (Pb, Sn, Fe and Ti), with most attention being focused on Ti. The current pulses produced a decrease in the flow stress $\Delta\sigma_p$ in all four metals. The work on Ti indicated that $\Delta\sigma_p$ contains a contribution in addition to heating and pinch effects. This contribution (the electroplastic effect) increased significantly with current density, interstitial content and temperature (77-300K), to a lesser degree with strain, but no change was detected for a 25 fold increase in strain rate. Computer calculations of the dynamic stress changes associated with the approximately sinusoidal current-time pulses employed here yielded a contribution due to the electron-dislocation interaction (for a current density of 5000 A/mm² at 300K) which was 32% of $\Delta\sigma_p$. A model is proposed for the electroplastic effect which is based on theoretical considerations that the current flow exerts a force on the dislocations which adds to the applied force pushing a dislocation against obstacles.

Complementary studies were performed on: (a) the decremental unloading method for determining the internal stress in metals, (b) the effects of temperature, grain size and interstitial content on the flow stress of Ti and (c) plastic instability in Ti sheet.

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A STUDY OF THE ELECTROPLASTIC EFFECT IN METALS

1. Introduction

It is now generally accepted that the change in flow stress and other mechanical phenomena which occur when a metal undergoes the transition from the normal to the superconducting state is associated with the interaction of electrons with dislocations (1-4). Additional evidence for an interaction between electrons and dislocations is provided by the change in the flow stress of Cu and Al which results when a magnetic field is suddenly applied during the plastic deformation of these metals at 4.2K (5,6). Since 1969 Russian scientists (7-12) have proposed that a significant interaction between electrons and dislocations also occurs for the application of high, direct-current density pulses ($\sim 10^3 \text{ A/mm}^2$) for short periods of time ($\sim 100 \mu\text{s}$) during the plastic deformation of metals. They termed the effect an "electroplastic effect". They further claimed that the electroplastic (ep) effect had practical value in metal working operations. For example, Klimov et al (13) reported that W and W-alloy wire could be satisfactorily cold-rolled into microribbons 20-30 μm thick by applying the ep effect rather than heating the metals to high temperatures under a vacuum as was required otherwise. Metallographic examination of the electroplastically cold rolled specimens revealed a noticeable grain size reduction and a well defined texture. Besides the improvements in the rolling of W-alloys, Spitsyn et al (14) reported that the drawing of stainless steel tubes was significantly improved by the application of high current pulses during the drawing operation. Thus, the ep effect is of both scientific interest and practical value.

2. Russian Work

For the most part, the work by Russian scientists on the ep effect in metals has been by Troitskii and coworkers (7-12). They applied direct current pulses of the order of 10^3 A/mm^2 for a duration of $\sim 10^{-4} \text{ s}$ and at intervals of 2-10s to single and polycrystalline specimens of Zn, Cd, Sn, Pb and In during uniaxial tensile deformation at a constant strain rate and noted stress drops in the stress-strain curves, which were associated with each current pulse and represented a decrease (up to 40%) in the flow stress. An example of their results is given in Fig. 1. They obtained stress drops of similar magnitude during

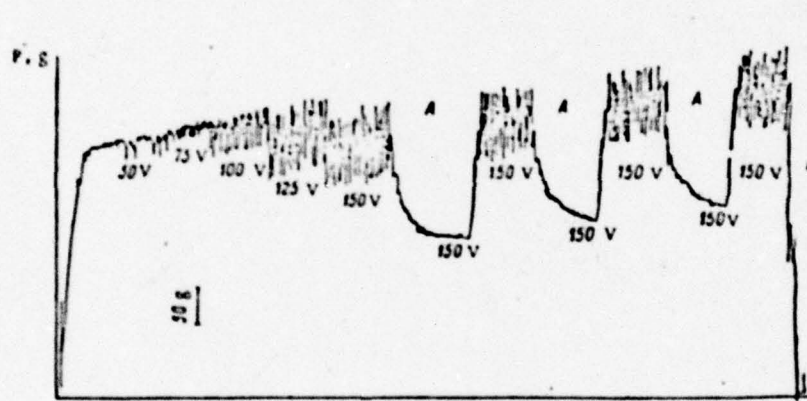


Fig. 1. Stress drops in the stress-strain curve of a Zn single crystal produced by the application of direct current pulses of the voltages indicated during deformation at 78K. Regions A correspond to periods of stress relaxation. After Troitskii and Rozno (8).

compression tests. Further, the application of a magnetic field of 2000 Oe during the compression tests did not produce a noticeable effect on the size of the serrations, within the scatter of their data.

Troitskii and coworkers (7-12) reported that the amount of the flow stress

drop increased with voltage and current density of the stress pulse and with decrease in temperature from 300 to 78K. It increased with strain rate at low rates, but decreased at high rates. The stress drop also increased with impurity content and varied with the orientation of single crystals with respect to the tensile axis. Furthermore, the stress drop increased when electrons provided by an electron beam from an accelerator were injected into the specimen along the slip plane while it was being deformed. When the current polarity was changed, there occurred a slight difference in the stress drop, the effect of polarity being higher for alloyed Zn-Cd crystals than in pure Zn crystals. Of further interest is that the effect of the current pulses was significantly less in the elastic region of the stress strain curve, or following stress relaxation, compared to the changes in the flow stress which occurred in the plastic region; anomalously large drops occurred near the yield stress. Moreover, it was found that the current pulses improved the ductility of zinc single crystals at low temperatures. Based on their results, Troitskii and coworkers concluded that the electroplastic effect was closely associated with the multiplication, motion and interaction of dislocations.

A number of critical tests were conducted by Troitskii and coworkers to establish that the drops in the flow stress were primarily due to the interaction of electrons with mobile dislocations rather than to a magnetic pinch effect or to any heating effects from the electric current. That the pinch effect made only a minor contribution was established by employing dual specimens in series, whereby loading was applied to one specimen (A) while the other (B) was not subjected to a load. Current was passed through both specimens to induce elastic vibrations. They found the pinch effect in the load-free specimen to be small compared to the ep effect in the deforming specimen. Some of the results which

indicated that heating effects made only a minor contribution to the observed stress drops were the following:

- (1). The maximum temperature rise noted with the thermocouples attached to the surface and embedded in the center of single crystal Zn and Zn-0.2% Cd alloy specimens was approximately 1°C for tests in liquid nitrogen. This value was in accord with that calculated for the energy input during a current pulse. The accuracy of the temperature measurement was 0.005°C .
- (2). The difference in readings of thermocouples attached to the surface and embedded in the interior of the specimens did not exceed 0.3°C ; the interior temperature was higher, indicating the absence of a skin effect.
- (3). The difference in the heating of a Zn-0.2% Cd alloy single crystal compared to a pure Zn crystal did not exceed 0.3°C , whereas the magnitude of the stress drops was at least twice as large.
- (4). The threshold current for the ep effect in the Zn-0.2% Cd alloy (500-600A) was not much different from that of pure Zn (400-500A), although the resistance of the alloy was significantly higher.
- (5). Heating of Zn crystal specimens by pulsed ac current for periods of 20-30s to yield the same temperature rise ($1-2^{\circ}\text{C}$ at 77K) as the direct current pulses of $\sim 10^3$ amps for $\sim 100\mu\text{s}$ did not produce load drops. There only occurred a slight decrease in the strain hardening coefficient.
- (6). The size of the stress drop for specimens tested in liquid nitrogen was larger than for those cooled by air, the cooling efficiency of the liquid nitrogen far exceeding that of the air.
- (7). Stress drops were observed in compression as well as in tension, indicating that thermal expansion due to heating was not a major factor.
- (8). The observed polarity effect indicates that the ep effect is electronic in nature rather than due to heating.

To explain the electroplastic effect in metals Troitskii (11) proposed that the electrons exerted a force f_e (electron wind) on the dislocations

according to the theory of Kravchenko (15)

$$f_e = \frac{b}{4} \left(\frac{\bar{v}_e}{v_d} - 1 \right) \frac{v_d}{v} \frac{\partial n_0}{\partial \mu} \Delta^2 \quad (1)$$

where b is the dislocation Burgers vector, v_d the dislocation velocity, $\bar{v}_e$ the electron drift velocity, v the electron velocity on the Fermi surface, n_0 the electron density in the undeformed metal, μ the chemical potential and Δ a constant of the deformation potential related to the lattice strain associated with a dislocation. Thus, the force is positive (producing an acceleration of the dislocations) if the electron drift velocity is greater than the dislocation velocity and negative (producing a deceleration) if it is less. It can be shown that the electron drift velocity is given by

$$\bar{v}_e = VC/tenA = I_d/en \quad (2)$$

where V is the voltage, C the capacitance of the capacitors employed to yield the current pulses, t the pulse duration time, e the electron charge, n the density of conduction electrons, A the specimen cross-sectional area and I_d the current density.

Troitskii (11) proposed two possible effects of the electron wind:

- (1) An acceleration of dislocations.
- (2) A change in the dynamics of the vibrating dislocation segments held up at obstacles so as to produce a decrease in the time required for the detachment of dislocations from the obstacles.

Troitskii considered his experimental results to be in better accord with the latter mechanism than the former.

Employing a somewhat less sophisticated approach, Klimov et al (13) derived the following equation for the force on a dislocation due to the action of conduction electrons

$$f_e = (1/3)n m^* v_F b (\bar{v}_e - v_d) \quad (3)$$

where n is the density of conduction electrons, m^* the effective electronic mass, $v_F = (2E_F/m^*)$ the value of the electron velocity determined by the Fermi energy E_F , b the Burgers vector, $\bar{v}_e$ the electron drift velocity and v_d the dislocation velocity. Again, when $\bar{v}_e < v_d$, the electric current dampens the dislocation motion, but when $\bar{v}_e > v_d$ it accelerates its motion. Further, in the case $\bar{v}_e > v_d$, a pinned dislocation will experience a force helping it to overcome the pinning obstacle.

3. University of Kentucky Work

(a) General:

Major emphasis of the work at the University of Kentucky has been to establish whether the electroplastic effect is general for metals and, if so, what are the effects of such variables as test temperature, strain rate and presence of solutes. Special attention was given to eliminating or correcting for any heating effects which might be associated with the current pulses. Studies were made on polycrystalline wires (0.12 - 1.3 mm dia.) of Pb, Sn, Ti and Fe representing common crystal structures, with most work being performed on Ti. The specimens were subjected to direct current pulses up to 12,000 A/mm² peak current density and of ~100μs duration during tensile straining at a rate of ~10⁻⁴s⁻¹, by discharging a condenser bank with an ion switch. The time between pulses was sufficiently large (>30s) to avoid any temperature rise of the specimen following a current pulse and to allow the flow stress to return to the original stress-strain curve. Tests were conducted at room temperature with forced air cooling and by immersing the specimen and test fixture in liquid nitrogen. The test procedure and results are given in detail in Refs. 16-20; only a summary of the results will be given here.

An example of the decrease in stress which occurred during the plastic deformation of a Ti specimen subjected to current pulses of increasing current density is shown in Fig. 2. Similar behavior was noted for the other metals

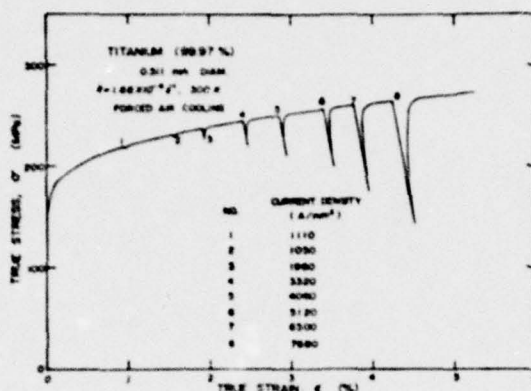


Fig. 2. Effect of direct current pulses on the true stress-strain curve of polycrystalline Ti. From Okazaki, Kagawa and Conrad (17).

considered, the magnitude of the stress drop $\Delta\sigma$ increasing in the order: Sn, Pb, Ti and Fe; see Fig. 3.

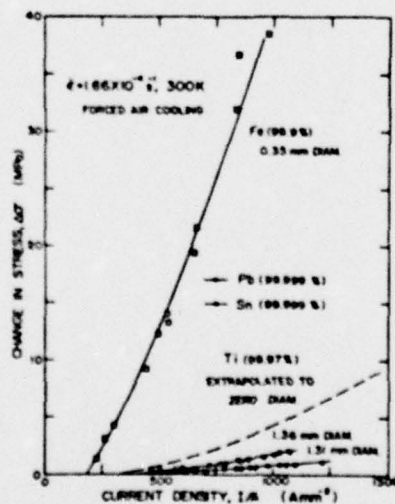


Fig. 3. Decrease in flow stress associated with a current pulse versus current density for several metals. From Okazaki, Kagawa and Conrad (17).

Three specific stress-drops due to current pulses were identified in the extended work on Ti, depending on the region of the stress-strain curve where

the current pulse was applied (see Fig. 4): (a) during the initial elastic region, $\Delta\sigma_H$, (b) during the subsequent plastic region, $\Delta\sigma_p$ and (c) at a stress level near the long-range internal stress determined by decremental unloading, $\Delta\sigma_R$.

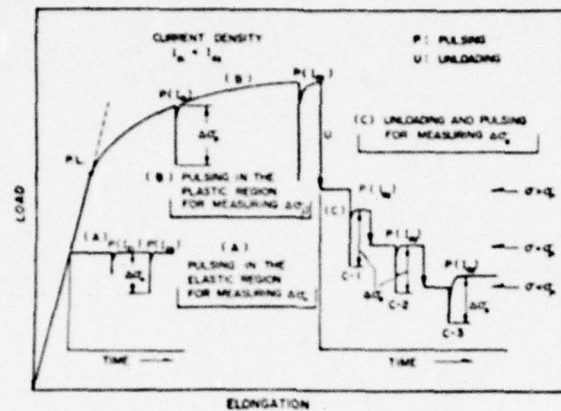


Fig. 4. Schematic of experiments to determine $\Delta\sigma_H$, $\Delta\sigma_p$ and $\Delta\sigma_R$ associated with current pulses. From Okazaki, Kagawa and Conrad (18).

In each case the stress returned to the level which existed prior to the application of the current pulse, indicating that no permanent change in the structure had occurred during the pulse. All three types of stress drop increased with current density I_d (Fig. 5); for a constant I_d , $\Delta\sigma_p > \Delta\sigma_R > \Delta\sigma_H$. $\Delta\sigma_p$ and $\Delta\sigma_R$ increased slightly with strain and all three stress drops increased with interstitial solute content. All three stress drops were independent of strain rate within the range $0.67 \times 10^{-4} - 1.67 \times 10^{-3} \text{ s}^{-1}$.

(b) Skin, Pinch and Thermal Effects

Skin, pinch and thermal effects can contribute to the decrease in flow stress associated with a current pulse and therefore were considered in evaluating the ep effect. Calculations of these effects in high purity Ti tested at 77K are given in Ref. 20, a copy of which is attached. It is shown that the skin depth associated with the current pulse is about 6 times larger than the specimen radius employed in most of our tests and hence the

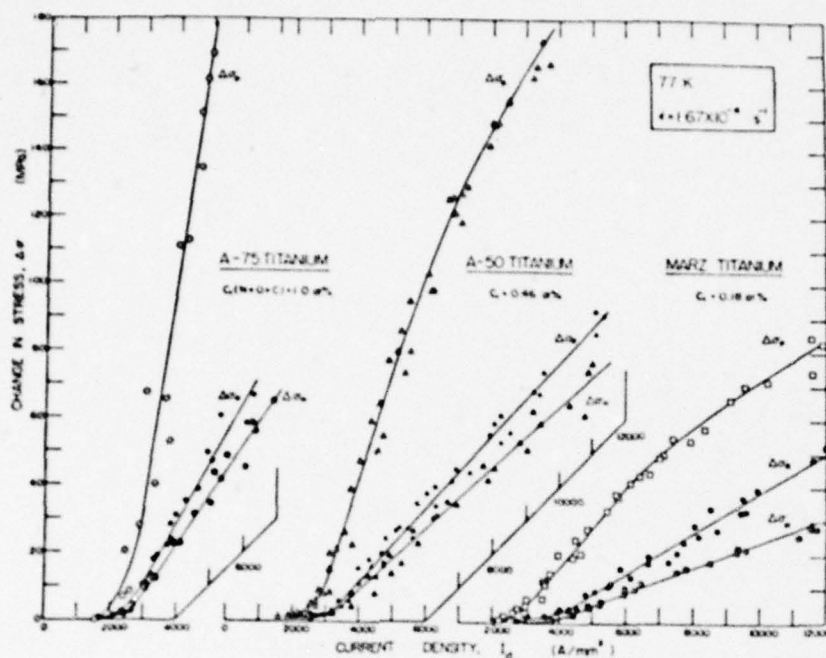


Fig. 5. Effect of current density on the stress drops during the deformation of polycrystalline Ti with various interstitial contents at 77K: (a) $\Delta\sigma_H$ is for the initial elastic region; (b) $\Delta\sigma_R$ is at a stress level near the internal stress determined by decremental unloading; and (c) $\Delta\sigma_P$ is during plastic flow. From Okazaki, Kagawa and Conrad (19).

current flow can be considered to be uniform throughout the specimen cross-section. The pinch effect produces a contributing stress of the order of $0.3 \text{ MPA at } 5000 \text{ A/mm}^2$ which, as will be seen below, is only a small fraction of the effect presumed to be due to the interaction of electrons with dislocations.

Assuming that all of the Joule heating supplied by a current pulse stays in the specimen, the temperature rise was calculated to be 8 - 225K in the range of 2000 to 10,000 A/mm² current density at 77K and 22-270K in the range of 2000 to 7000K at 300K. However, the actual temperature rise in the specimen will be less, since the specimen was surrounded with liquid nitrogen at 77K and forced-air cooled at 300K, which extract heat from the specimen surface. It was shown (18) that the heating effects associated with the ep effect in metals can be identified by performing tests on specimens of various radii r and extrapolating the stress changes resulting from the application of the current pulses to $r^2 = 0$, which represents a condition of infinite cooling rate (21). Plots of $\Delta\sigma_H$, $\Delta\sigma_R$ and $\Delta\sigma_p$ versus r^2 are presented in Fig. 6 for specimens tested with forced air cooling. $\Delta\sigma_H$ values are only given for the two larger specimen diameters because relaxation of the tensile fixtures occurred at the low stresses required for the smallest specimen size. However, the straight lines joining the two data points for $\Delta\sigma_H$ can be considered to pass through the origin, supporting the idea that the temperature rise of the specimen can be calculated from the $\Delta\sigma_H$ measurements. Extrapolations of $\Delta\sigma_R$ and $\Delta\sigma_p$ to $r^2 = 0$ yield intercepts, indicating that these stress-drop parameters contain effects other than those due to heating. A plot of these intercepts ($\Delta\sigma_R^\circ$ and $\Delta\sigma_p^\circ$) versus current density I_d is presented in Fig. 7. It is seen that $\Delta\sigma_R^\circ$ and $\Delta\sigma_p^\circ$ increase in a nearly linear fashion with I_d starting from about 1800 A/mm².

The results of Fig. 6 suggest that heating effects may be removed from $\Delta\sigma_p$ and $\Delta\sigma_R$ by subtracting $\Delta\sigma_H$. The effect of temperature on $(\Delta\sigma_p - \Delta\sigma_H) \equiv \Delta\sigma_p^\circ$ as a function of I_d is given in Fig. 8a. It is here seen that $(\Delta\sigma_p - \Delta\sigma_H)$ increases with increase in temperature. Fig. 8b shows that the effect of temperature on $(\Delta\sigma_p - \Delta\sigma_R)$ is significantly less than on $(\Delta\sigma_p - \Delta\sigma_H)$. The effect of interstitial content (C + N + O) on $(\Delta\sigma_p - \Delta\sigma_H)$ in Ti is shown in Fig. 9, where it is seen that $(\Delta\sigma_p - \Delta\sigma_H)$ is proportional to the interstitial content.

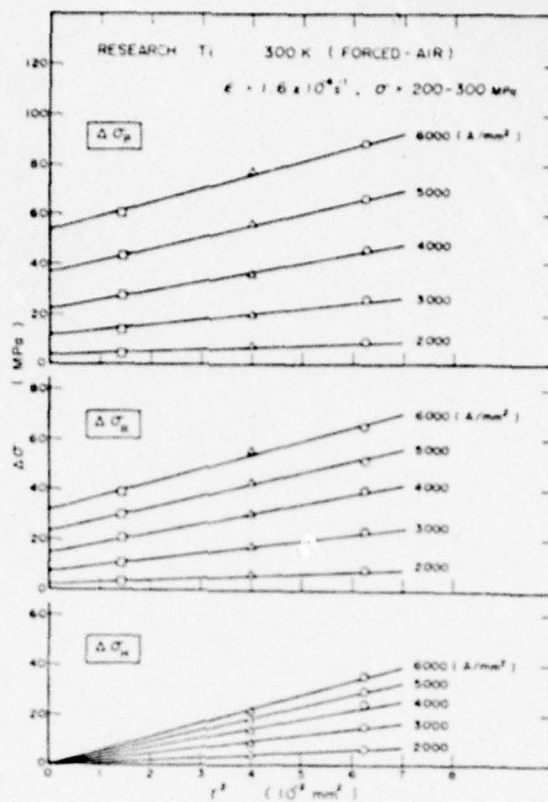


Fig. 6. Effect of specimen radius on $\Delta \sigma_H$, $\Delta \sigma_R$ and $\Delta \sigma_p$ for Ti at 300K.

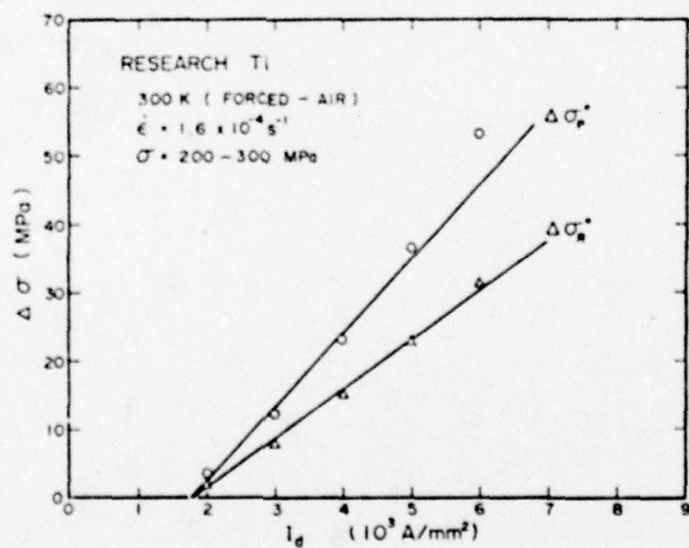


Fig. 7. Effect of current density on $\Delta \sigma_p^0$ and $\Delta \sigma_R^0$ for Ti at 300K.

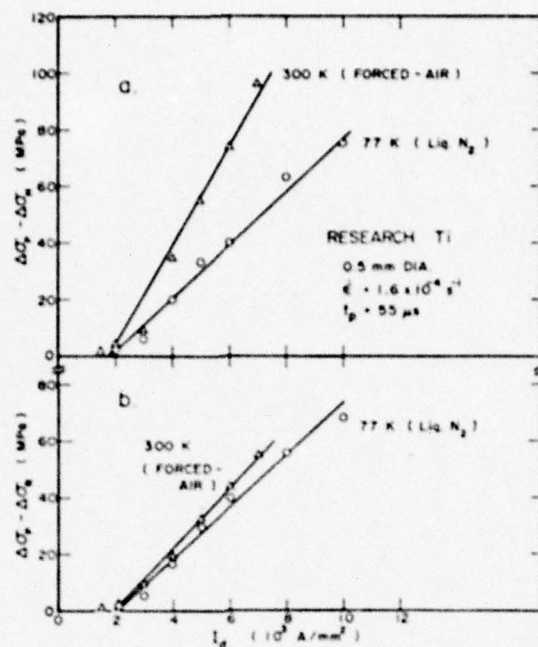


Fig. 8. Effect of temperature on: (a) $(\Delta\sigma_p - \Delta\sigma_H)$ and (b) $(\Delta\sigma_p - \Delta\sigma_R)$ as a function of current density.

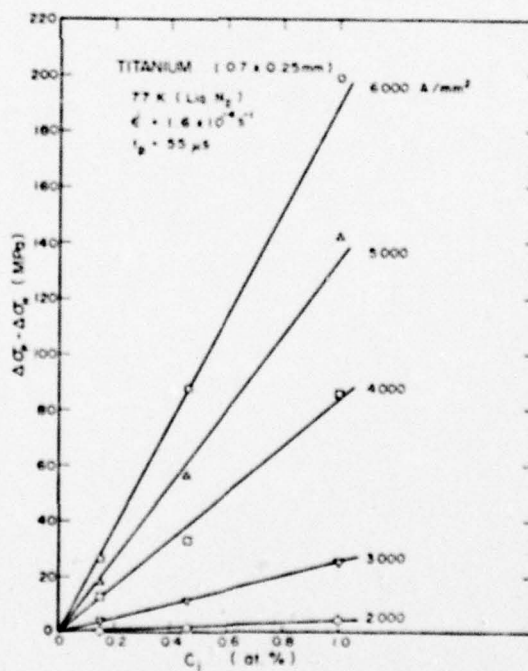


Fig. 9. Effect of interstitial content ($C + N + O$) on $(\Delta\sigma_p - \Delta\sigma_H)$ at 77K as a function of current density.

The actual temperature rise ΔT which occurred during the ep effect in Ti was calculated from: (a) the stress drop $\Delta\sigma_H$ due to thermal expansion which results when a current pulse is applied in the initial elastic region of the stress-strain curve and (b) the current-time profile obtained with an oscilloscope. To calculate the temperature rise from $\Delta\sigma_H$ the following equation was employed, which gives the elongation Δl of the specimen due to the temperature increase

$$\Delta l_{\Delta T} = \Delta\sigma_H l / E_e \quad (4)$$

where l is the length of the specimen and E_e the effective modulus of the test system. The temperature rise producing this elongation is then

$$\Delta T = \Delta l_{\Delta T} / \alpha l = \Delta\sigma_H / \alpha E_e \quad (5)$$

where α is the linear coefficient of expansion. The temperature increases at 77 and 300K calculated using Eq. 5 ranged from 2 - 270K, being 0.4 to 0.7 the maximum possible due to Joule heating (20).

The decrease in flow stress associated with a temperature rise is generally taken as

$$\Delta\sigma_{\Delta T} = \sigma_T - \sigma(T + \Delta T) \quad (6)$$

where σ_T and $\sigma(T + \Delta T)$ are the flow stresses at T and $(T + \Delta T)$ taken from the $\sigma - T$ curve for the material at a constant strain rate (22). However, considering the applied stress alone and the time available in the present experiments for thermal activation to occur, computer calculations of the dynamic stress changes indicated that $\Delta\sigma_T$ was negligible and therefore did not contribute to the ep effect as expected from Eq. 6. Rather, it was found that the experimental results could only be explained if an additional stress $\Delta\sigma_{ep}$ (presumed to be due to electron-dislocation interaction) was added to the thermal component of the flow stress σ^* . An example of the computer calculation with the addition of $\Delta\sigma_{ep}$

to σ^* is presented in Fig. 10. Also shown here as a function of time are the current I , the temperature rise ΔT (based on a reasonable heat transfer coefficient), the applied stress change $\Delta\sigma_a$, the elastic strain change $\Delta\epsilon_e$, the strain due to thermal expansion $\Delta\epsilon_H$ and the plastic strain change $\Delta\epsilon_p$. Details regarding the calculation of these various parameters are found in the paper (20) attached to this report.

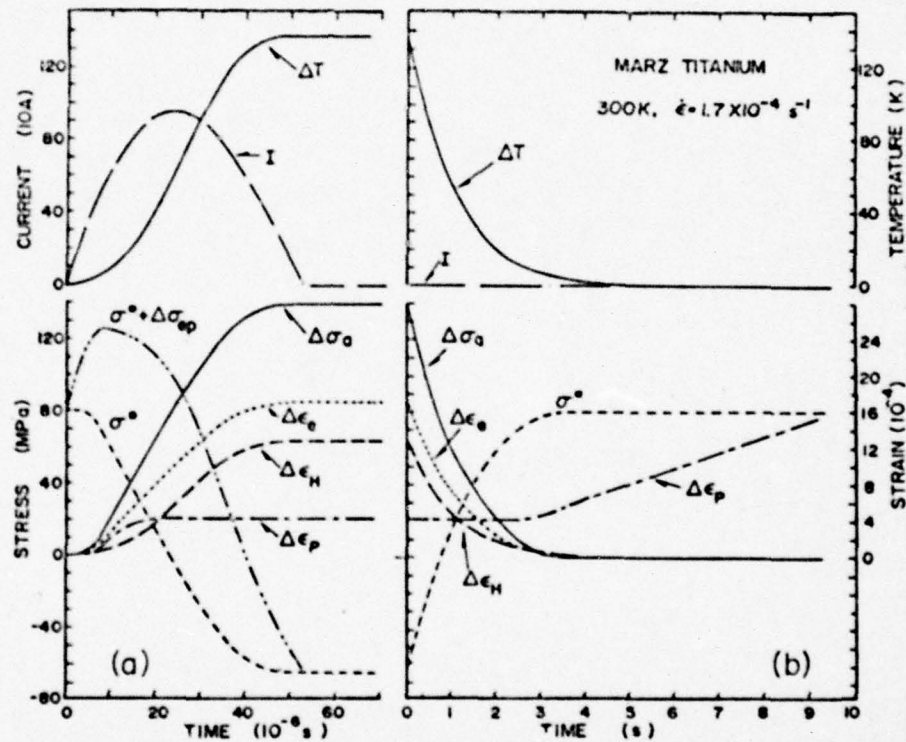


Fig. 10. Computer simulation of ΔT , σ^* , $(\sigma^* + \Delta\sigma_{ep})$, $\Delta\epsilon_e$, $\Delta\epsilon_H$ and $\Delta\epsilon_p$ at 300K for the current pulse I shown assuming a contribution $\Delta\sigma_{ep} = 0.019 I_d$ to σ^* (20).

The response time of the recorder pen used to measure the stress drops associated with the current pulses was $\sim 0.3 \text{ s}$. Therefore, the measured values of

$\Delta\sigma_H$, $\Delta\sigma_p$ and $\Delta\sigma_R$ correspond to this time following the application of a current pulse. The calculated values of ΔT ($\Delta\sigma_H$) and $\Delta\sigma_p$ at 0.3s were found to be in reasonable accord with the experimentally measured values, giving some confidence to the validity of the computer calculations. The computer simulation studies indicated that $\Delta\sigma_{ep}$ amounted to 32% of $\Delta\sigma_p$.

(c) Summary of Experimental Results on the Electroplastic Effect

Tests by Russian scientists and those at the University of Kentucky have demonstrated that a marked decrease in the flow stress of metals occurs upon application of a high, direct-current density pulse ($10^3 - 10^4$ A/mm²) for a short period of time ($\sim 100\mu s$). Critical tests by both groups have established that a significant fraction of the total stress drop $\Delta\sigma_p$ is due to causes other than a temperature rise (as normally considered or measured) or to skin or pinch effects. It is concluded that the remaining component is due to an electron-dislocation interaction. A comparison of the experimental results obtained by the Russians and by the present authors on the ep effect is presented in Table 1.

TABLE 1. Comparison of experimental results on the electroplastic effect.

Test Variable	Russian	U.K.
Effect of current density, I_d	$\Delta\sigma_p$ for Zn single crystals increases in a linear fashion with I_d with a threshold of ~ 500 A/mm ²	$\Delta\sigma_p^o$ for polycrystalline Ti increases in an approximately linear fashion with I_d with a threshold of ~ 2000 A/mm ² .
Effect of temperature, T	$\Delta\sigma_p$ for Zn increases significantly with decrease in T.	$\Delta\sigma_p^o$ for Ti increases with T.
Effect of strain rate, $\dot{\epsilon}$	$\Delta\sigma_p$ for Zn increases with $\dot{\epsilon}$ at low rates, but decreases with $\dot{\epsilon}$ at high rates	$\Delta\sigma_p^o$ for Ti is relatively independent of $\dot{\epsilon}$ in the range 0.67×10^{-4} to 16.7×10^{-4} s ⁻¹ .
Effect of solute content, C	Significant increase in $\Delta\sigma_p$ occurs for addition of 0.2% Cd to Zn.	$\Delta\sigma_p^o$ is proportional to interstitial content in Ti.

Separate direct evidence for an electron-dislocation interaction during current flow through a deforming specimen is provided in the paper by Troitskii (9), who showed that the stress drops associated with current pulses in deforming Zn, Pb and Sn single crystals were augmented by the injection of electrons along the slip plane using an electron accelerator. Further evidence for an electron-dislocation interaction during current flow through a deforming specimen is the observation that the creep rate of metals heated by an electric current passing through the specimen is higher than when the specimen is heated by radiation and conduction (23).

(d) Theoretical Considerations

Theoretical considerations by Kravchenko (15) and Klimov et al (13) indicate that the electrons associated with current flow exert a force f_e on a dislocation, which is proportional to the difference between the mean electron drift velocity and the dislocation velocity, the former being proportional to the current density (see Eqs. 1-3 above). One possible effect of such a force would be to add to the applied force pushing dislocations against the obstacles opposing their motion. Assuming this to be the major effect, an expression for the decrease in flow stress $\Delta\sigma_{ep}$ associated with a current pulse will now be derived.

Let us assume that the force f_e on a dislocation due to the current pulse adds to that due to the applied stress f_a , so that the total force f_t is

$$f_t = f_a + f_e \quad (7)$$

Further, let us make the reasonable assumption that f_t is constant for a constant rate of deformation. We then obtain upon application of a current pulse

$$-df_a = df_e = f_e \quad (8)$$

Now, dislocation theory gives for deformation without a current pulse

$$f_a = f \quad (9)$$

where f is the back-force exerted on the dislocation by the pinning obstacle.

Theoretical considerations and available experimental data give (22)

$$\tau = \alpha f^n C^m \quad (10)$$

where τ is the resolved shear stress, α a constant which includes the dislocation line tension, C the concentration of the pinning points and n and m are constants. n generally takes values between 1.0 and 3/2 and m between 1/2 and 4/3⁺.

Taking the derivative of Eq. 10 gives for a constant C

$$d\tau = \alpha C^m n f^{n-1} df \quad (11)$$

$$= \alpha_1 C^{\frac{m}{n}} \tau^{\frac{n-1}{n}} df \quad (11a)$$

Substituting Eq. 8 into Eq. 11a and taking $\Delta\tau_{ep} = d\tau$ yields

$$-\Delta\tau_{ep} = \alpha_1 C^{\frac{m}{n}} \tau^{\frac{n-1}{n}} f_e \quad (12)$$

for the change in stress associated with a current pulse.

Eqs. 1 to 3 above give

$$f_e = A(\bar{v}_e - v_d) = A_1 I_d - A v_d \quad (13)$$

where A and A_1 are constants. Substituting Eq. 13 into Eq. 12 yields

$$-\Delta\tau_{ep} = (\alpha_2 C^{\frac{m}{n}} \tau^{\frac{n-1}{n}} I_d) - B v_d \quad (14)$$

where α_2 and B are constants.

A direct comparison of the available experimental results on the ep effect with the predictions of Eq. 14 is difficult, because the response time of the stress-time recorder is so much larger than the pulse time and because, according

⁺ m for interstitials in Ti is -2/3. (22).

to the computer calculations, $\Delta\sigma_{ep}$ varies with time. However, if we assume that the experimental value of the stress drop $\Delta\sigma_p$ is a single-valued function of $\Delta\sigma_{ep}$, some qualitative comparisons may perhaps be made. In regard to the effect of current density, Eq. 14 requires that $\Delta\tau_{ep}$ increase linearly with I_d beyond a threshold value. This is observed experimentally (see Figs. 7-9)[†]. Assuming that $v_d = \bar{v}_e$ at the threshold I_d of $\sim 2000 \text{ A/mm}^2$, one obtains $v_d = 11 \text{ cm/s}$, which is considerably above the value of 10^{-3} cm/s deduced for the average dislocation velocity in Ti from etch pit or flow stress measurements (24), and below that for the propagation of shear waves (25).

The effect of temperature on $\Delta\sigma_{ep}$ is expected to be mainly through its effect on the flow stress τ (which generally increases with decrease in temperature) and on n and m , the former tending to increase and the latter to decrease with increase in temperature (22). Therefore, depending on the values of n and m , a decrease in temperature can lead to either an increase or decrease in $\Delta\tau_{ep}$. The fact that $\Delta\sigma_p^\circ$ in the present experiments increased with temperature would suggest that the product $C \tau^{\frac{m}{n}} \tau^{\frac{n-1}{n}}$ increases with temperature.

The effect of strain rate on $\Delta\tau_{ep}$ can be through its effects on both τ and v_d . Since the threshold current suggests that the appropriate dislocation velocity v_d is orders of magnitude higher than the average velocity $\bar{v}_d$ determined from etch-pit and flow stress measurement, it is unlikely that the 25-fold change in strain rate considered in the present investigation will have a significant effect on v_d and in turn on $\Delta\tau_{ep}$. Thus, the fact that $\Delta\sigma_p^\circ$ was found to be independent of the strain rate in the present investigation is consistent with the value of the threshold current, or possible effects of strain rate on m and n .

In considering the concentration dependence of $\Delta\tau_{ep}$, it is desirable to substitute Eq. 10 for τ into Eq. 12. This gives

[†] $\Delta\sigma_p = M\Delta\tau_p$ where the constant M represents the Taylor orientation factor (~ 2.0 for polycrystalline Ti(22)).

$$-\Delta\tau_{ep} = \alpha_e C^m f_e \quad (15)$$

The proportionality between $\Delta\sigma_p^0$ and C in Fig. 9 suggest that $m=1$. There are insufficient data to clearly separate $m=1$ obtained here from $m=2/3$ obtained from the effect of interstitial content on the flow stress (22).

Thus, the experimental results obtained in the present investigation are in some qualitative accord with the model proposed here and described by Eq. 14. Similarly, the results obtained by Troitskii and coworkers (7-11) are in qualitative accord with this model. To recapitulate, this model assumes that the current flow exerts a force on a dislocation which is proportional to the difference between the mean electron drift velocity and the dislocation velocity and adds to the applied force pushing the dislocations against obstacles. However, additional studies are needed before we can fully accept this model. In addition to the effect considered above, electron-dislocation interactions resulting from a current pulse may produce one or more of the following:

(a) accelerate the motion of dislocations between obstacles and (b) increase the frequency of vibration of dislocations. A good starting point for evaluating these effects is a consideration of the models which have been proposed to explain the decrease in stress which results in the normal-to-superconducting transition (1-4).

(e) Mechanical Property Studies Bearing on the Electroplastic Effect

From the above discussion it is evident that to fully evaluate the electroplastic effect in metals a detailed knowledge of the following two mechanical property phenomena is required:

- (1). The effects of strain rate and temperature on the flow stress as a function of grain size and impurity (or alloy) content.
- (2). The internal stress determined by the decremental unloading technique, i.e. by the so-called stress dip method.

Therefore, these two phenomena were considered in some detail for Ti in the present investigation, the effort consisting mainly of correlating and interpreting results obtained in previous work by the authors.

A summary of the effects of grain size on the yield stress of titanium as a function of interstitial content (mainly oxygen) and temperature are presented in Figs. 11-13. It is seen in Fig. 11 that the effect of grain size on the yield stress follows the Hall-Petch relation

$$\sigma = \sigma_i + K_y d^{-1/2} \quad (16)$$

α -Ti (~ 0.2 at % O_{eq})
 $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$

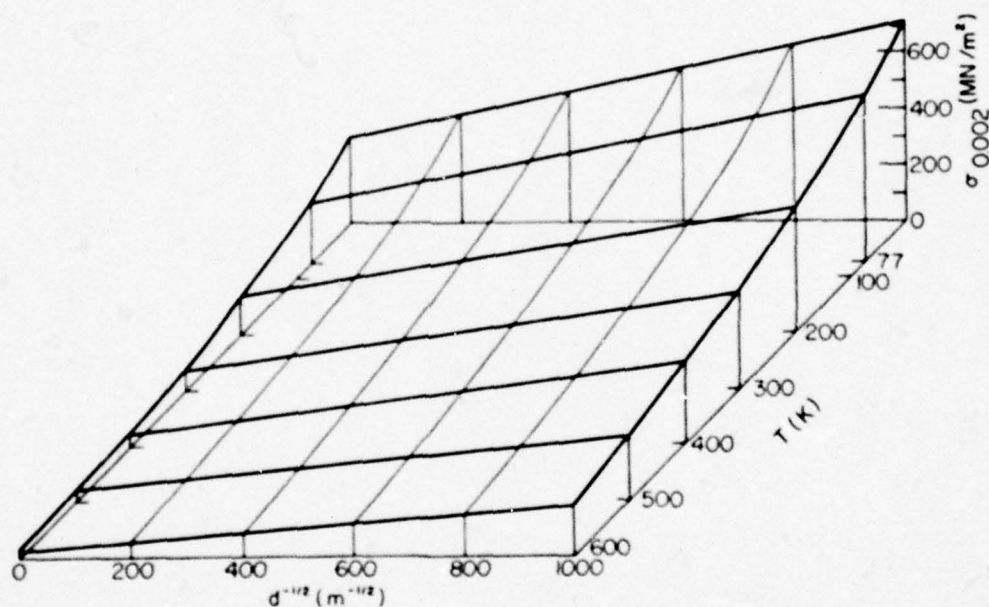


Fig. 11. Hall-Petch plot of the effect of grain size on the yield stress of high purity Ti (~ 0.2 at % O_{eq}) as a function of temperature.

in which σ_i increases with increase in interstitial content and with decrease in temperature (Fig. 12). K_y is relatively independent of interstitial content,

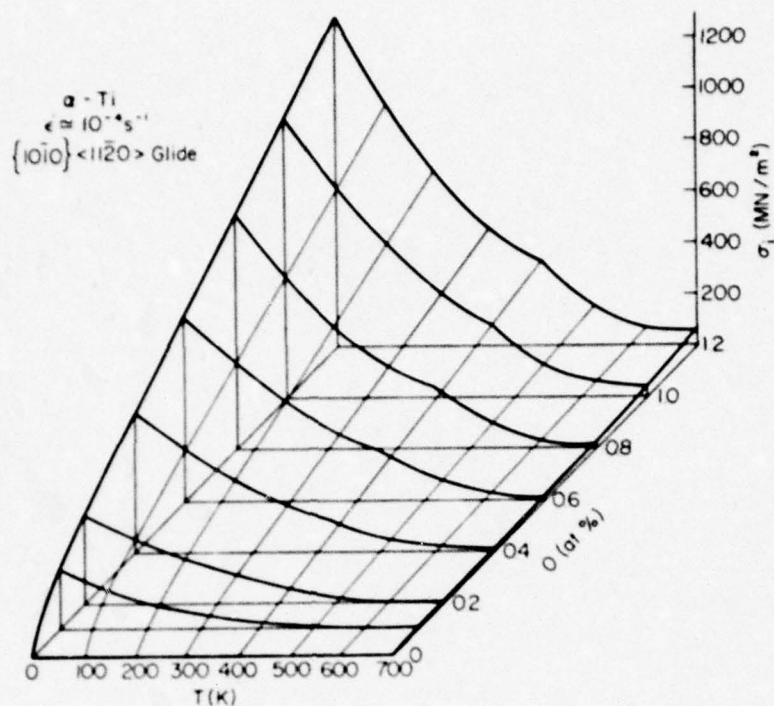


Fig. 12. Effect of temperature on the Hall-Petch parameter σ_i for the yield stress of Ti as a function of oxygen content.

but decreases with temperature more markedly than Young's modulus, which is indicated by the difference between K_y and K_u in Fig. 13. The data of Figs. 11-13, along with other data in the literature (26, 27), were employed to describe the deformation kinetics used in the computer calculations of Fig. 10 and in Ref. 20.

It is generally accepted that the flow stress of metals can be considered to consist of a thermal component σ^* associated with short-range, low energy obstacles to dislocation motion and an athermal component σ_μ associated with long-range, high energy obstacles such as the long-range internal stress field, so that

$$\sigma = \sigma^* + \sigma_\mu \quad (17)$$

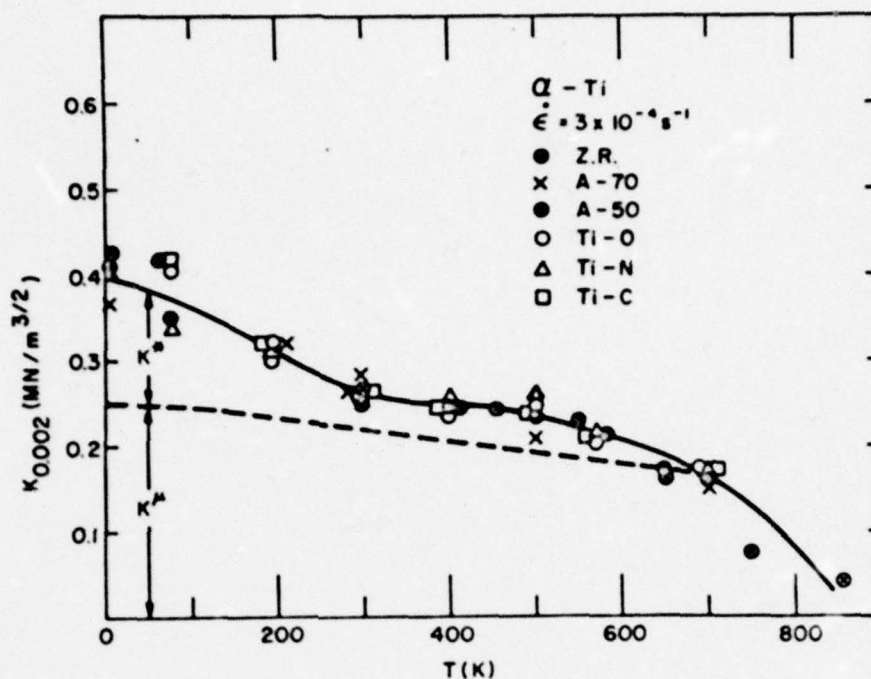


Fig. 13. Effect of temperature on the Hall-Petch parameter K_y for the yield stress of Ti as a function of interstitial content.

A method frequently used to determine σ_μ is the decremental unloading technique (28,29). It was found in the present study that a current pulse produced a decrease in the internal stress σ_{Int} determined by decremental unloading in the usual manner. This decrease was termed $\Delta\sigma_R$ (see Figs. 3 and 4). To better define the nature of the internal stress determined by decremental unloading, a study was made of this technique (30). Typical results obtained for A-50Ti (0.5 at.% O_{eq}) are presented in Fig. 14. These show that the value of σ_{Int} determined by the decremental unloading method depends on the time allowed between load decrements, σ_{Int} decreasing with increasing time t . Only as

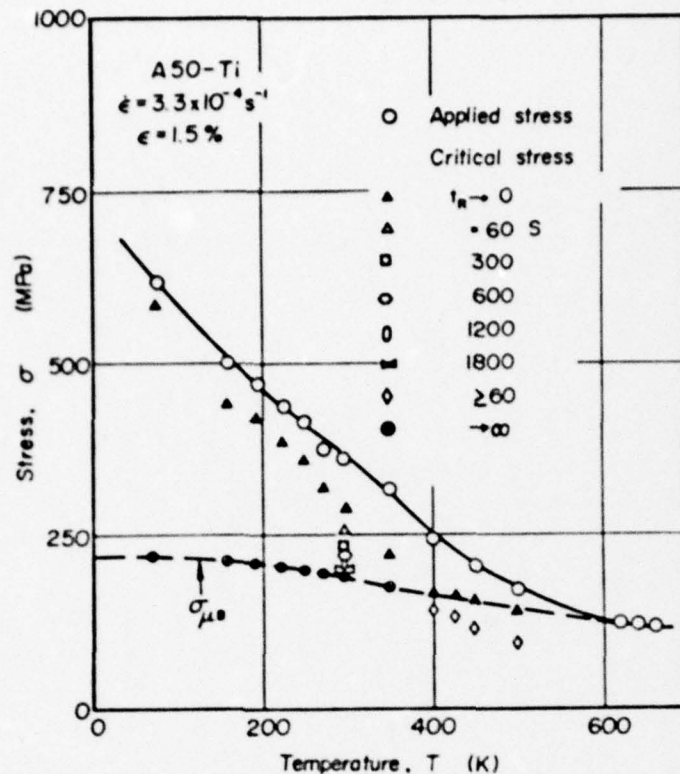


Fig. 14. Effect of temperature on the internal stress (critical stress) in A-50Ti ($\sim 0.5 \text{ at.}\% \text{ O}_{eq}$) as a function of time between load decrements for the decremental unloading method (30).

$t \rightarrow \infty$ was σ_{Int} approximately equal to σ_{μ} determined by the back-extrapolation method. Therefore, it is expected that some thermally activated dislocation motion occurs at the stress level σ_{Int} determined by the decremental unloading method. This then must be taken into account when interpreting the effect of a current pulse on σ_{Int} .

Since work by the Russians indicated that the ep effect had technological application in metal working operations, it was decided to look into this as part of the present investigation, time permitting. Stretch forming was chosen for initial investigation, because failure in this operation is by plastic instability or necking and the uniaxial tension test on sheet is considered to represent a point on the forming limit diagram (FLD). Since little was known

regarding plastic instability in uniaxial tension of Ti sheet, a limited study was first made of the instability in sheet specimens without current pulses to provide background information which could be used for comparison with results to be obtained later with the application of current pulses. In these tests attention was focused on the onset of instability and the effects of the material parameters $n (= d \ln \sigma / d \ln \epsilon)$ and $m (= \partial \ln \sigma / \partial \ln \dot{\epsilon})$ on the strain at which the onset occurs at test temperatures of 300-700K. Gridded specimens were employed to establish the initiation of instability and follow its development to fracture. The details of the experimental procedure and the results obtained on A-75Ti ($\sim 1.0 \text{ at. \% } O_{eq}$) sheet specimens are presented in Refs. 31 and 32. A summary of the results will now be given.

Typical strain distributions along the length of the gridded sheet specimens after various amounts of deformation are presented in Fig. 15. Starting from the

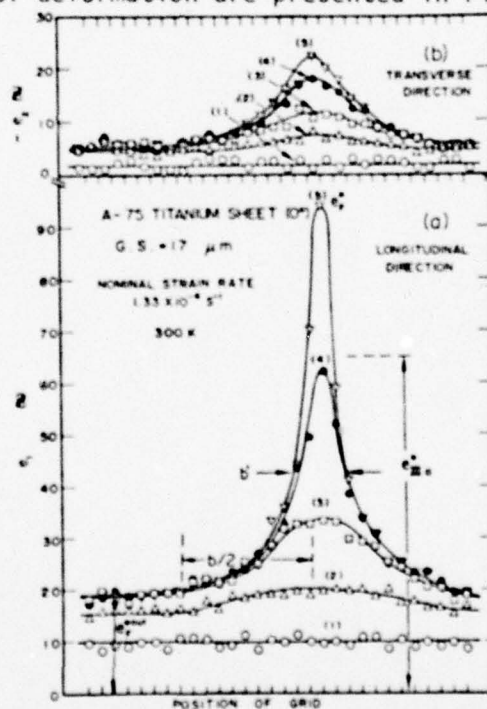


Fig. 15. Engineering strain distribution along the length of an A-75Ti ($1.0 \text{ at. \% } O_{eq}$) sheet specimen strained at 300K and a strain rate of $1.33 \times 10^{-4} \text{ s}^{-1}$: (a) longitudinal strain e_1 and (b) width strain e_2 (31).

bottom of the figure, diffuse necking is first observed at the (2) set of measurements, flow restriction to the neck first occurs at (4) and local necking between (4) and (5). Fig. 16 gives log-log plots of the strain rate versus

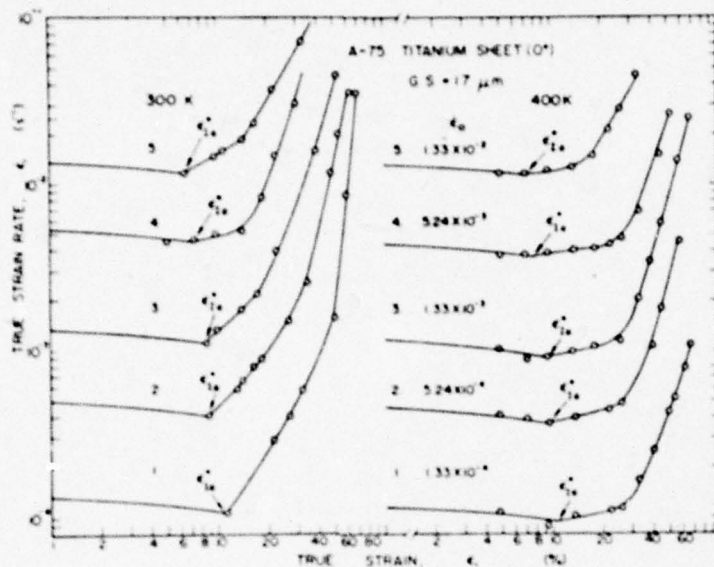


Fig. 16. Log-log plots of $\dot{\epsilon}_I$ versus ϵ_I of the element which eventually fractured for the tests at 300 and 400K (31).

strain of the element which eventually failed, the data in this graph having been derived from results such as those of Fig. 15. A change in the curve from a decreasing strain rate with strain (due to the fact that the tests were conducted at a constant crosshead speed rather than a constant strain rate) to an increasing rate to failure occurs at the instability strain ϵ_{II}^* , which is smaller than the strain at maximum load ϵ_u . Three plastic instability strains were thus identified: (a) ϵ_I^* the initiation of strain concentration leading to a diffuse neck, (b) ϵ_{II}^* the restriction of strain to the diffuse neck region and (c) ϵ_{III}^* the initiation of local necking. The effects of material parameters on the critical strains for each of these instability conditions were given reasonably well by the following expressions:

$$\epsilon_I^* = n_I + \delta \ln A_0 / \delta \ln \epsilon \quad (18)$$

$$\epsilon_{II}^* = \epsilon_I^* + 3.3 m_u^{2/3} \quad (19)$$

$$\epsilon_{III}^* = 2 \{ n_u + m_u (\alpha_{III} + \epsilon_u) \} \quad (20)$$

where A_0 is the initial cross-sectional area and $\alpha = d \ln \epsilon / d \ln \epsilon$ of the element which eventually failed. The subscripts indicate the strain at which the material parameters were determined. The expressions for ϵ_I^* and ϵ_{III}^* were derived, whereas that for ϵ_{II}^* is purely empirical. n , m and α were found to vary with strain, strain rate and temperature. The effect of temperature on the various material parameters and instability strains for tests at the strain rates of 1.33×10^{-4} and $5.24 \times 10^{-3} \text{ s}^{-1}$ are presented in Fig. 17.

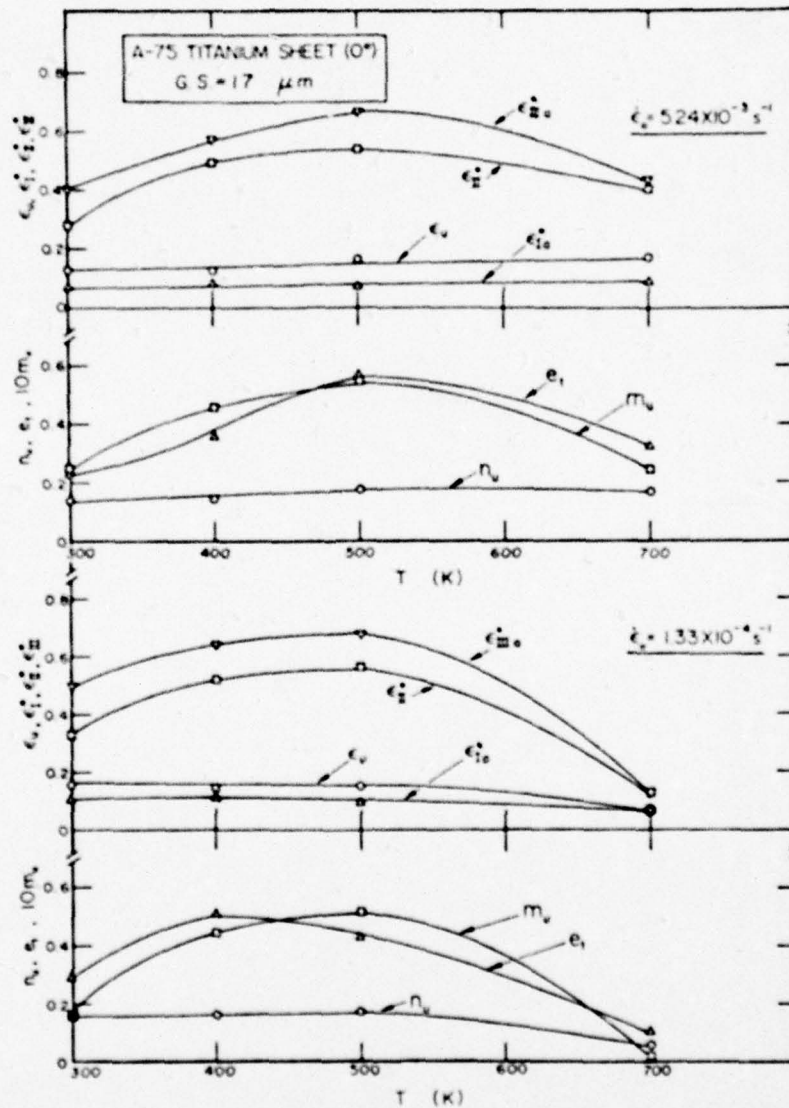


Fig. 17. Effect of temperature on the various material parameters and instability strains for the tests at the strain rates of 1.33×10^{-4} and $5.24 \times 10^{-3} \text{ s}^{-1}$ (31).

Appendix

I. Personnel Participating in the Project

A. Faculty

1. Dr. Hans Conrad, Principal Investigator.
2. Dr. Kenji Okazaki, Visiting Professor from Kyushu Institute of Technology, Japan.

B. Students

1. M. Kagawa, Graduate Student, University of Kentucky, (Planned to receive PhD in Dec. 1979).
2. L. Filler, Undergraduate Student, University of Kentucky (Received B.S. degree, May 1979).
3. L. Carey, Undergraduate Student, Kentucky State University (Planned to receive B. Mfg. Tech., May, 1980).

II. Scientific Papers

A. Published

1. K. Okazaki, M. Kagawa and H. Conrad, "A Study of the Electroplastic Effect in Metals," Scripta Met. 12 1063 (1978).
2. K. Okazaki, M. Kagawa and H. Conrad, "Additional Results on the Electroplastic Effect in Metals", Scripta Met. 13 (1979).
3. K. Okazaki, M. Kagawa and H. Conrad, "Effects of Strain Rate, Temperature and Interstitial Content on the Electroplastic Effect in Titanium", Scripta Met. 13 473 (1979).
4. K. Okazaki, Y. Aono, T. Kaneyuki and H. Conrad, "Measurement of the Internal Stress in Metals by the Decremental Unloading Technique", Mat. Sci. Eng. 33 253 (1978).
5. H. Conrad, K. Okazaki, C. Yin, "Effect of Material Parameters on the Limiting Strain in Cup Tests on Sheet Metals," Proc. 6th. North Amer. Metalworking Res. Conf. (NAMRC VI) (1978) p. 264.
6. K. Okazaki, M. Kagawa and H. Conrad, "Plastic Instability in A-75 Titanium Sheet Deformed in Uniaxial Tension at 300-700K," Acta. Met. 27 301 (1979).

B. Submitted for Publication

1. K. Okazaki, M. Kagawa and H. Conrad, "The Electroplastic Effect in Titanium", Submitted for presentation and publication at the 4th Int. Conf. on Titanium, Kyoto, Japan, May 19-22, 1980.

2. K. Okazaki, M. Kagawa and H. Conrad, "Evaluation of the Skin, Pinch and Thermal Effects Associated with the Electroplastic Effect in Titanium", submitted to Scripta Met.

C. Presented at Technical Meetings or Seminars

1. K. Okazaki, M. Kagawa and H. Conrad, "Plastic Instability in A-75 Titanium Sheet Deformed in Uniaxial Tension at 300-700K", presented at AIME Spring 1978 meeting, Denver, Colo. Feb. 1978.
2. H. Conrad, K. Okazaki and C. Yin, "Effect of Material Parameters on the Limiting Strain in Cup Tests on Sheet Metals", presented at 6th. North American Metalworking Res. Conf. (NAMRC VI), Gainesville, Fla. May 1978.
3. K. Okazaki, "A Study of the Electroplastic Effect in Metals", seminar at Wayne State University, Detroit, June, 1979.
4. K. Okazaki, M. Kagawa and H. Conrad, "A Study of the Electroplastic Effect in Ti", to be presented Fall 1979 AIME meeting, Milwaukee, Wis., Oct. 1979.

III. Visits to DOD Facilities

1. H. Conrad to AFOSR, Bolling A.F. Base, Washington, D.C., for discussions with Col. J. P. Morgan, Nov. 7, 1978.
2. H. Conrad to ONR, Arlington, Va. for discussions with Dr. A. Diness, May 11, 1979.

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EVALUATION OF THE CONTRIBUTIONS OF SKIN, PINCH AND HEATING EFFECTS TO THE ELECTROPLASTIC EFFECT IN TITANIUM

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ABSTRACT

Introduction

The effects of high density, direct current pulses on the plastic deformation of metals at 77-300K have been presented by Russian scientists (1-11) for Pb, Sn, Cd and In and by the present authors (12-14) for Pb, Ti, Fe and Sn. It was proposed that the stress changes which resulted from the current pulsing were mainly due to the interaction of electrons with moving dislocations, i.e. an electroplastic (ep) effect. However, there still remains the argument that this ep effect may be due to trivial heating of the specimen (15, 16).

In a previous paper (13), the present authors showed that the heating effects associated with the ep effect in metals can be identified by performing tests on specimens of various radii r and extrapolating the stress changes resulting from the application of the current pulses to $r^2 = 0$, which represents a condition of infinite cooling rate (17). In the present paper we determine the temperature rise ΔT which occurs during the ep effect in Ti from: (a) the stress drop $\Delta\sigma_H$ due to thermal expansion which results when a current pulse is applied in the initial elastic region of the stress-strain curve and (b) the current-time profile of the pulse obtained with an oscilloscope. Further, since skin and pinch effects could contribute to the stress drop, the contributions from these two phenomena are also calculated. It is found that these latter contributions are quite small compared to the total stress changes which result from the current pulses. Having removed the contributions due to the skin, pinch and heating effects it is found that there still remains a significant fraction of the total stress change which results from the application of a current pulse during plastic deformation.

Experimental

The polycrystalline Ti (99.97%) wire employed in this study was purchased from the Research Organic/Inorganic Corp. and annealed at 1073K for 3.6 ks in a vacuum of $\sim 10^{-6}$ Torr. The mechanical test procedure is similar to that described previously (13), except that in the present tests the entire fixture of grips and specimen was immersed in a liquid nitrogen bath, in addition to conducting tests at 300K using forced-air cooling. The stress drops due to the current pulses which are here considered are the same as those in the previous paper (13), namely: (a) $\Delta\sigma_H$, which occurs in the initial elastic region of the stress-strain curve, (b) $\Delta\sigma_p$, which occurs in the plastic flow region and (c) $\Delta\sigma_R$, which occurs near the long-range internal stress level determined by decremental unloading. The stress-strain behavior and the stress drops were recorded on the Instron test machine load-time, strip-chart recorder, whose full-scale pen response time is ~ 1 s. Zero suppression was employed in the present tests so that the response time for the stress drops is estimated to be ~ 0.3 s. Typical shapes of the current pulses for the tests at 77K are presented in Fig. 1.

Results and Discussion

When a current pulse of 10^3 - 10^4 A/mm² density is applied to a specimen for the short period of 5.5×10^{-5} s, side-effects other than an electron-dislocation interaction are expected to occur. They are: (a) the skin effect, (b) the pinch effect and (c) the reduction of the flow stress due to the temperature rise. The magnitudes of these effects will now be considered.

1. Skin Effect

Localization or concentration of current near a specimen surface (the skin effect) is expected when a high frequency current is applied to a specimen. To establish whether or not a skin effect occurred in our experiments, the skin depth δ was calculated using

$$\delta = [\pi f \mu (1/\rho)]^{-1/2} \quad (1)$$

where f is the frequency of the pulse, μ the permeability and ρ the resistivity of the specimen. Typical values for the parameters in eq. (1) at 300K are: $f = 9$ kHz, $\mu = 4\pi \times 10^{-7}$ H/m (18) and $\rho = 8.2 \times 10^{-6}$ Ω cm (measured for the present specimens). Substituting these values into eq. (1) gives $\delta = 1.52$ mm, which is about 6 times the radius of the largest size specimen (0.5 mm dia.) employed in the present investigation. It is therefore concluded that the current is distributed uniformly throughout the specimen cross-section for our test conditions.

2. Pinch Effect

Upon the application of a high current pulse, a pinch effect may occur, whereby the pressure created by the intrinsic magnetic field produces radial compressive stresses. This pinch effect causes a decrease in the axial stress of a specimen undergoing tensile deformation at a constant plastic strain rate. To calculate this effect let us consider the equivalent electrical circuit of our apparatus, which is shown in Fig. 2. The basic equation for a discharge circuit is

$$L \frac{dI}{dt} + RI + \frac{1}{C} \int I dt = V_0 \quad (2)$$

where V_0 is the voltage to which the capacitor is charged, R the resistance of the specimen and I the current. Assuming that L (combined inductance of the specimen and circuit), C (capacitance) and V_0 are independent of time, we obtain upon differentiating eq. (2)

$$L \frac{d^2 I}{dt^2} + R \frac{dI}{dt} + I \frac{dR}{dt} + \frac{I}{C} = 0. \quad (3)$$

The solution of eq. (3) for $I = 0$, $V = V_0$ and $R = \text{constant}$ at $t = 0$ is

$$I = K e^{-\beta t} \sin \omega t \quad (4)$$

where $K = V_0/L$, $\beta = R/2L$ and $\omega^2 = (1/LC) - \beta^2$.

In the previous section it was established that the current is distributed axisymmetrically in the wire specimen. The magnitude B of the magnetic field is then

$$\oint \vec{B} d\vec{a} = \mu \times \text{current linked} \quad (5)$$

where B is the magnetic flux density and a the distance from the axis of the wire. Within the cylindrical wire this gives

$$2\pi a B = \mu a^2 I_d \quad (6)$$

where I_d is the current density. The $\vec{I}_d \wedge \vec{B}$ force acts radially inwards and is irrotational. The radial pressure gradient is

$$\partial P / \partial a = (-1/2) \mu a I_d^2 \quad (7)$$

and hence

$$P = (-1/4) \mu a^2 I_d^2 + \text{const.} \quad (8)$$

Applying the boundary condition of $P = 0$ at $a = r$, one has

$$P = (1/4) \mu I_d^2 (r^2 - a^2) \quad (9)$$

where r is the radius of the wire.

Let us now calculate the maximum pressure at the center of the wire ($a = 0$) in our experiments. The data used for this calculation are: $\mu = 4\pi \times 10^{-7}$ H/m (18) and current density $I_d = 5000$ A/mm². These yield a pinch pressure of $P(a = 0) = 0.49$ MPa at 5000 A/mm². The decrease in axial stress due to this pinch pressure will be

$$\Delta \sigma_{\text{pinch}} = 2\nu P \quad (10)$$

where ν is Poissons ratio. Taking $\nu = 0.34$ (19) gives $\Delta \sigma_{\text{pinch}} = 0.33$ MPa at 5000 A/mm².

This is only 0.4% of the total change in flow stress ($\Delta\sigma_p = 87.5 \text{ MPa}$ at 5000 A/mm^2), 0.6% of $\Delta\sigma_R (= 55.0 \text{ MPa})$ and 1.0% of $\Delta\sigma_H (= 32.5 \text{ MPa})$ respectively at 300K. It is therefore concluded that the pinch effect associated with the current pulsing is small and only a secondary factor in the electroplastic effect in Ti.

3. Heating Effects

When a current passes through a specimen whose resistance is finite but not zero, Joule heat is generated. The total energy ΔQ due to current flow is given by

$$\Delta Q = I^2 \rho (l_0/A_0) t = I^2 R t \quad (11)$$

where l_0 and A_0 are the length and cross-sectional area of the specimen. The maximum possible change in the specimen temperature ΔT_m is then

$$\Delta T_m = \Delta Q / C_p \quad (12)$$

where C_p is the heat capacity of the metal.

Let us calculate ΔT_m for the present experimental conditions. Typical test conditions at 77K were: (a) $l_0 = 50.30 \text{ mm}$, (b) $A_0 = 0.196 \text{ mm}^2$, (c) $R = 0.021 \Omega$, (d) $t_e = t/2 = 2.75 \times 10^{-5} \text{ s}$ and (e) $C_p = 5.07 \times 10^{-2} \text{ cal/deg/g}$ (20, 21). The calculated values of ΔT_m for tests at 77K and at 300K are summarized in Tables 1 and 2 respectively, where the maximum possible temperature rise is 8 - 225K in the range of 2000 to 10,000 A/mm^2 current density at 77K and 22 - 270K in the range of 2000 to 7000 A/mm^2 at 300K. However, the actual temperature rise in the specimen will be less than these values, since the specimen is surrounded with liquid nitrogen (77K) or forced-air cooled (300K), which extract heat from the specimen surface.

Since it was shown above that the skin and pinch effects are small, the actual temperature rise of the specimen can be calculated from the change in stress $\Delta\sigma_H$ which results from the application of a current pulse in the initial elastic region of the stress-strain curve, by employing the effective modulus of the system and the coefficient of expansion of Ti. The elongation of the specimen due to the temperature rise is given by

$$\Delta l_{\Delta T} = \Delta\sigma_H l / E_e \quad (13)$$

where l is the length of the specimen and E_e the effective modulus of the test system. The temperature rise producing this increase is then

$$\Delta T = \Delta l_{\Delta T} / \alpha l = \Delta\sigma_H / \alpha E_e \quad (14)$$

where α is the linear coefficient of expansion, which is approximated for Ti by $\alpha_T = 5 \times 10^{-7} \text{ T}^{1/2}$ in the range of 73 to 300K and $\alpha_T = 2 \times 10^{-5} \text{ T}^{1/4}$ above 300K (21). The temperature increases at 77 and 300K calculated from measured values of $\Delta\sigma_H$ using eq. (14) are listed in Tables 1 and 2. It is seen that these temperature rises are 0.4 to 0.7 the maximum possible due to Joule heating. Also included in Tables 1 and 2 are the values of $\Delta\sigma_p$ and $\Delta\sigma_R$ for the same test conditions as $\Delta\sigma_H$.

The decrease in flow stress associated with a temperature rise is generally taken to be

$$\Delta\sigma_{\Delta T} = \sigma_T - \sigma(T + \Delta T) \quad (15)$$

where σ_T and $\sigma(T + \Delta T)$ are the flow stresses at T and $(T + \Delta T)$ taken from the $\sigma - T$ curve for the material at a constant strain rate (22). The values of $\Delta\sigma_{\Delta T}$ so calculated are listed in Tables 1 and 2; they are on the order of 21 to 88% of $\Delta\sigma_p$. It should however be noted that this estimate of $\Delta\sigma_{\Delta T}$ is based on the assumption that the temperature rise ΔT can reduce the flow stress from σ_T to $\sigma(T + \Delta T)$ via thermally activated processes in a time equal to t_e^* that of the response time of the recorder ($\sim 0.3 \text{ s}$), i.e. the extra effective stress $\Delta\sigma^* [= \sigma_T - \sigma(T + \Delta T)]$ at $(T + \Delta T)$ can produce enough plastic strain during this time period to cause the stress change observed in the experiment. However, it will now be shown that the plastic strain produced by $\Delta\sigma^*$ via thermal activation is vanishingly small and that in turn $\Delta\sigma_{\Delta T}$ is negligible.

[†]The I-t curves shown in Fig. 1. are here approximated by a triangle and the effective time t_e is taken as one-half of the total pulse time t .

The influence on the electroplastic results of the actual temperature rise based on the current-time profile and heat transfer from the specimen surface will now be considered. The total strain rate $\dot{\epsilon}_{\text{total}}$ is given by

$$\dot{\epsilon}_{\text{total}} = \dot{S}/l = \dot{\epsilon}_p + \dot{\epsilon}_e + \dot{\epsilon}_H \quad (16)$$

where $\dot{S}$ is the crosshead speed of the test machine, l the specimen gauge length, $\dot{\epsilon}_p$ the plastic strain rate, $\dot{\epsilon}_e$ the elastic strain rate and $\dot{\epsilon}_H$ the strain rate due to the thermal expansion. Within a sufficiently small time period from t to $(t + \Delta t)$, eq. (16) becomes

$$-\Delta\epsilon_e = \Delta\sigma_a/E_e = \Delta\epsilon_p + \Delta\epsilon_H - (\dot{S}/l)\Delta t \quad (17)$$

where $\Delta\sigma_a$ is the applied stress change and E_e the effective modulus of the system. The strain due to the thermal expansion is given by

$$\Delta\epsilon_H = \alpha(T)[(T - T_0)] \quad (18)$$

where $\alpha(T)$ is the linear thermal expansion coefficient at T and T_0 is the original temperature prior to pulsing. $\Delta T (=T - T_0)$ as a function of time during a current pulse can be calculated from

$$\Delta T(t) = \Sigma \Delta Q'(t)/C_p M \quad (19)$$

where M is the mass of the specimen and $\Delta Q'(t)$ is the net heat retained in the specimen at time t . $\Delta Q'(t)$ is taken to be

$$\Delta Q'(t) = \{I^2(t)R(T) - HA(T - T_0)\}\Delta t \quad (20)$$

where $I(t)$ is the current at time t , $R(T)$ the resistance of the material at temperature T , Δt the time interval, H the heat conduction rate at the material surface and A the surface area of the specimen.

Assuming that $\Delta\epsilon_p$ is due to thermally activated plastic deformation processes we can write

$$\Delta\epsilon_p = \dot{\epsilon}_p \Delta t \quad (21)$$

For T_i we have the choice of describing $\dot{\epsilon}_p$ by either (23, 24)

$$\dot{\epsilon}_p(1) = \beta(\sigma^*(T))m^*(T) \quad (22)$$

where β is a constant, $\sigma^*(T)$ the effective stress (applied stress σ minus long-range internal stress σ_μ) and $m^*(T)$ its velocity exponent, or

$$\dot{\epsilon}_p(2) = \dot{\epsilon}_0 \exp(-\Delta G(\sigma^*)/kT) \quad (23)$$

where $\dot{\epsilon}_0$ is a constant and ΔG the Gibbs free activation energy, which is given by

$$\Delta G = \Delta G_0 \{1 - (\sigma^*(T)/\sigma_0^*)^2\} \quad (24)$$

where ΔG_0 is the total energy at $\sigma^*(T) = 0$. During a current pulse the effective stress $\sigma^*(T)$ is then given by

$$\sigma^*(T) = \sigma_0 - \sigma_\mu(T) - \Delta\sigma_a \quad (25)$$

where σ_0 is the flow stress immediately prior to the application of the pulse and $\sigma_\mu(T)$ the long-range internal stress.

The change in flow stress $\Delta\sigma_a$ due to a current pulse can be calculated using eqs. (17) to (25) once values have been assigned to the various parameters in these equations. This calculation was made employing a computer for forced air-cooling of the specimen at 300K and $I_d = 4977 \text{ A/mm}^2$. The values used for the various parameters were:

Present Test Conditions

$\sigma^*(T = 300K) = 80.9 \text{ MPa}$
 $\sigma_\mu(T = 300K) = 65.0 \text{ MPa}$
 $\sigma_0^* = 294 \text{ MPa}$
 $E_e = 8.91 \times 10^4 \text{ MPa}$
 $T_0 = 300K$
 $\epsilon = 1.7 \times 10^{-4} \text{ s}^{-1}$
 $I_d = 4977 \text{ A/mm}^2$

Parameters

$\sigma^*(T) = 6.43 (515 - T)^{1/2} \text{ MPa (ref. 23)}$
 $\sigma_\mu(T) = 65.0 + 4.5 \times 10^{-2} (T - 300) \text{ MPa (ref. 23)}$
 $\Delta G_0 = 1.6 \text{ eV (ref. 24)}$
 $m^*(T) = 1.94 \times 10^4 / T^{1.29} \text{ (ref. 23)}$
 $C_p(T) = 0.51 + 4.22 \times 10^{-4} (T - 275) \text{ Jg}^{-1}\text{K}^{-1} \text{ (ref. 20)}$
 $\alpha(T) = 2.04 \times 10^{-5} T^{1/4} \text{ (ref. 21)}$
 $R(T) = [42 + 0.178(T - 300)] \times 2.54 \times 10^{-3} \Omega \text{ (ref. 19)}$
 $H = 2.9 \times 10^{-4} \text{ Js}^{-1}\text{K}^{-1}\text{mm}^{-2} \text{ (ref. 25)}$
 $T \text{ in K}$

Typical results obtained using eq. (23) for the plastic strain rate are shown in Fig. 3, where the left side (Fig. 3a) is drawn on a microsecond scale, whereas the right side (Fig. 3b) on a second scale. To be noted in Fig. 3a is that the temperature rise ΔT increases with time, reaches a maximum of 137K at $t = 47 \times 10^{-6}$ s and remains at this value for a short period even after the current pulse is gone. However, as seen in Fig. 3b, at longer times ΔT decreases with time and returns to the original temperature in about 4 s, which is approximately the time noted with thermocouples attached to the specimen. Also, Fig. 3b shows that ΔT attains the value of 76K calculated above from $\Delta\sigma_H$ (Table 2) after about 0.6 s, which is in reasonable accord with the recorder pen response time associated with the measurement of $\Delta\sigma_H$, especially considering possible errors resulting from the choice of the value for the heat transfer coefficient and the expression for the deformation kinetics.

Figure 3a shows that the maximum of $\Delta\sigma_a$ occurs at $t = 47 \times 10^{-6}$ s; the maximum plastic strain $\Delta\sigma_p$ produced by thermal activation at this time is of the order of 10^{-8} . This implies that the expected stress change $\Delta\sigma_{\Delta T}$ from thermal activation processes is only of the order of 10^{-4} MPa and therefore the total stress change $\Delta\sigma_a$ is almost entirely due to the thermal expansion, which reduces the effective stress σ^* to a negative value. In other words, the thermal expansion brings the stress level down so quickly and so low that insufficient effective stress is available to produce a significant amount of plastic strain. However, once the temperature begins to decrease (Fig. 3b), σ^* increases to produce the plastic strain (strain rate) which is required by the crosshead motion. It reaches its original value after about 1.4 s, when the plastic strain rate imposed by the crosshead motion first approaches that prior to the current pulse. The results of Fig. 3 thus indicate that by assuming no contribution of the current to σ^* , thermally activated deformation cannot provide significant plastic strain within the time period (0.3 s) of the measured stress drop $\Delta\sigma_p$, and therefore the calculation of $\Delta\sigma_{\Delta T}$ using eq. (15) is not applicable to our experiments.

The results of Fig. 3 therefore indicate that the heating produced by a current pulse causes a thermal expansion of the specimen but does not lead to any significant plastic flow. However, two experimental results lead to the conclusion that "significant" plastic flow does in fact occur during the time involved in the stress drop measurement (i.e. in 0.3 s): (a) that $\Delta\sigma_p > \Delta\sigma_R > \Delta\sigma_H$ and (b) a permanent drop in stress results following a current pulse applied during a stress relaxation test (13). To account for the required plastic strain and to simulate the stress change $\Delta\sigma_p$ observed in the experiments, an electron-dislocation interaction is now assumed to occur and is taken to be of the form

$$\Delta\sigma_{ep} = \gamma I_d \quad (26)$$

where I_d is the current density and γ a constant. This proportionality between $\Delta\sigma_{ep}$ and I_d is presently assumed because theory (26, 27) and the previous results on the ep effect in titanium (12-14) suggest a linear relationship between $\Delta\sigma_{ep}$ and the current density. $\Delta\sigma_{ep}$ is added to $\sigma^*(T)$ giving

$$\sigma^*(T)_{\text{total}} = \sigma^*(T) + \Delta\sigma_{ep} \quad (27)$$

and inserted in eq. (24) to yield

$$\Delta G = \Delta G_0 \left[1 - \left(\frac{\sigma^*(T) + \Delta\sigma_{ep}}{\sigma_0^*} \right)^2 \right] \quad (28)$$

A computation is then made under the same conditions as those of Fig. 3. The results are shown in Fig. 4, where $\gamma = 0.019$ has been used to produce the plastic strain of 4.2×10^{-4} , which is equivalent to $\Delta\sigma_{ep} = 34.5$ MPa. It is seen in Fig. 4 that $\sigma^*(T)$ is now reduced rather more quickly and steeply than in Fig. 3 and that $[\sigma^*(T) + \Delta\sigma_{ep}]$ exhibits a peak of 126 MPa at 8×10^{-6} s, giving a maximum plastic strain rate of $4.8 \times 10^5 \text{ s}^{-1}$. With this contribution of $\Delta\sigma_{ep}$ to σ^* a significant amount of plastic strain (four orders of magnitude larger compared to the case without $\Delta\sigma_{ep}$ shown in Fig. 3) is now produced before 20×10^{-6} s. It should also be noted that the temperature rise does not now entirely determine the production of the plastic strain during the microsecond time scale. Again, once the pulse is gone, the temperature begins to decrease (Fig. 4b) and $\Delta\sigma_p$ starts to increase again after about 2.7 s, at which time the effective stress σ^* becomes equal to that for plastic flow at the strain rate imposed by the crosshead motion. Worthy of note is that $\Delta\sigma_{ep}$ at the maximum of $(\sigma^* + \Delta\sigma_{ep})$ is $-0.8 \sigma_0^*$; further, $\Delta\sigma_a$ at 0.3 s in Fig. 4 is 32 MPa larger than in Fig. 3 for the same time.

Reasonable agreement exists between ΔT and $\Delta\sigma_a$ at 0.3 s in Fig. 4b (where comparisons can be made with experimental values) and the experimentally derived values of ΔT and $\Delta\sigma_p$

we come to the conclusion that the current pulse provides an extra stress $\Delta\sigma_{ep}$ in addition to any heating effects. Taking the measured value of $\Delta\sigma_p$ equal to $\Delta\sigma_a$ at 0.3 s in Fig. 4, the ep contribution derived from Figs. 3 and 4 comes to 32% of $\Delta\sigma_p$.

Summary and Conclusions

1. Skin and pinch effects make only small contributions to the electroplastic effect in polycrystalline Ti.
2. The temperature rise due to a current pulse has been determined from the change in stress which results when a current pulse is applied in the initial elastic region of the stress-strain curve. This rise is in reasonable accord with that calculated from the current-time profile using a reasonable heat transfer coefficient.
3. Computer simulation of the dynamic stress changes during current pulsing indicates that the current produces an effect in addition to that due to the heating.

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TABLE 1. Various stress components and temperature rises for the electroplastic effect in Ti at 77K[†]

I_d (A/mm ²)	$\Delta\sigma_H$ (MPa)	$\Delta\sigma_p$ (MPa)	$\Delta\sigma_R$ (MPa)	ΔQ (J)	ΔT_m (K)	ΔT (K)	$\Delta\sigma \Delta T$ (MPa)
2000	0.8	2.5	1.0	0.074	8.2	2.2	2.2
3000	1.5	7.0	2.0	0.167	18.6	4.0	4.0
4000	10.0	27.5	11.1	0.318	35.5	24.6	20.0
5000	16.4	50.0	20.5	0.498	55.6	38.0	30.0
6000	21.5	68.0	28.0	0.721	80.3	47.8	38.0
8000	35.5	99.0	43.0	1.273	141.9	72.2	51.0
10,000	51.0	126.0	58.0	2.016	224.9	96.3	69.0

[†] Notes:

- (1) Temperature dependence of the flow stress (Ref. 22)
- (2) Specimen-machine stiffness: $E_e = 9.3 \times 10^4$ MPa (for flow)
 $E_e = 8.05 \times 10^4$ MPa (for $\Delta\sigma_H$)
- (3) Linear expansion coefficient: $\alpha = 5 \times 10^{-7} T^{1/2} \text{ deg}^{-1}$ in the range of 77-300K (Ref. 21)
- (4) Heat capacity: $C_p = 0.2177 \text{ J.g}^{-1} \text{ deg}^{-1}$ at 77K (Ref. 20)

TABLE 2. Various stress components and temperature rises for the electroplastic effect in Ti at 300K[†]

I_d (A/mm ²)	$\Delta\sigma_H$ (MPa)	$\Delta\sigma_p$ (MPa)	$\Delta\sigma_R$ (MPa)	ΔQ (J)	ΔT_m (K)	ΔT (K)	$\Delta\sigma \Delta T$ (MPa)
2000	5.0	9.5	7.0	0.545	22.0	12.2	5.0
3000	13.0	22.0	23.0	1.196	48.2	31.3	12.5
4000	23.5	58.0	38.5	2.146	86.2	55.6	16.0
5000	32.5	87.5	55.0	3.382	136.3	75.9	20.0
6000	41.0	115.0	71.0	4.834	194.8	94.5	26.0
7000	43.5	140.0	85.0	6.700	270.0	99.9	30.0

[†] Notes:

- (1) Temperature dependence of the flow stress (Ref. 22)
- (2) Specimen-machine stiffness: $E_e = 8.9 \times 10^4$ MPa (for flow)
 $E_e = 4.77 \times 10^4$ MPa (for $\Delta\sigma_H$)
- (3) Linear expansion coefficient $\alpha = 2.04 \times 10^{-6} T^{1/4} \text{ deg}^{-1}$ in the range of 500-600K (Ref. 21)
- (4) Heat capacity: $C_p = 0.5122 \text{ J deg}^{-1} \text{ g}^{-1}$ at 300K (Ref. 20)

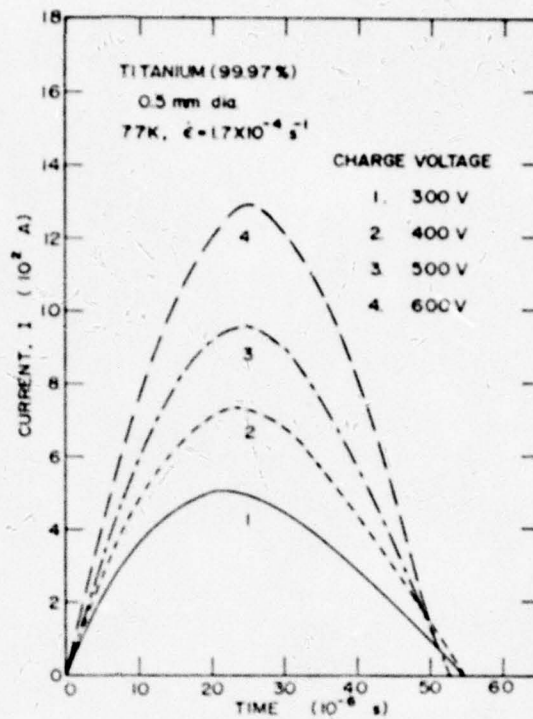


Fig. 1. Typical current-time profiles of current pulses at 77K.

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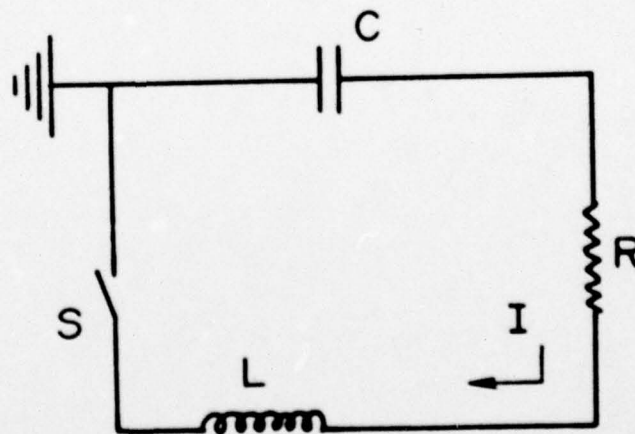


Fig. 2. Schematic of the equivalent electric circuit for the electroplastic effect studies

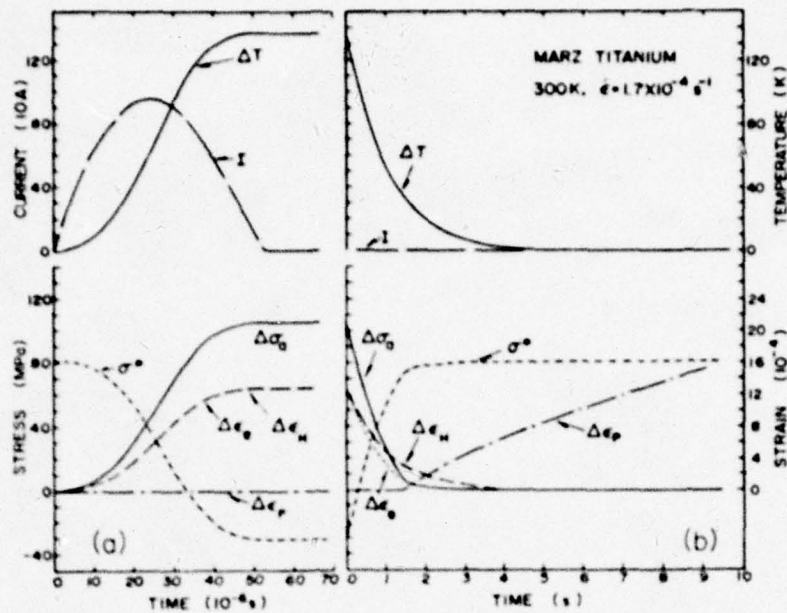


Fig. 3. Computer simulation of ΔT , σ^* , $\Delta\sigma_a$, $\Delta\sigma_e$, $\Delta\sigma_H$ and $\Delta\sigma_p$ at 300K for the current pulse I shown, assuming no effect of current on σ^* .

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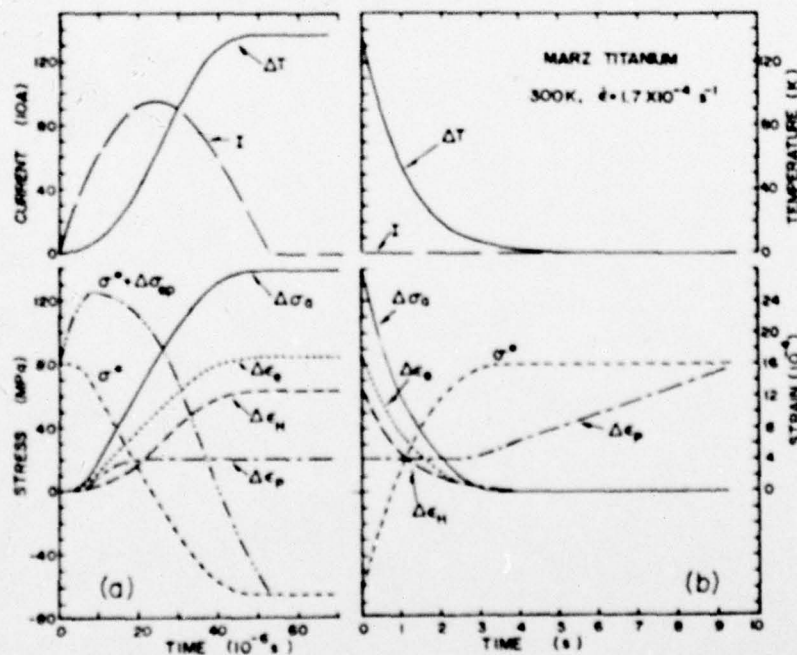


Fig. 4. Computer simulation of ΔT , σ^* , $(\sigma^* + \Delta\sigma_{ep})$, $\Delta\sigma_a$, $\Delta\sigma_e$, $\Delta\sigma_H$ and $\Delta\sigma_p$ at 300K for the current pulse I shown, assuming a contribution $\Delta\sigma_{ep} = 0.009 I_d$ to σ^* .

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <i>Micro Sec</i> The effects of high density, direct current pulses (10^3-10^4 A/cm²) for periods of 55-120 μs on the flow stress determined in an Instron tensile testing machine were studied in a number of polycrystalline metals representing various crystal structures (Pb, Sn, Fe and Ti), with most attention being focused on Ti. The current pulses produced a decrease in the flow stress $\Delta\sigma_p$ in all four metals. The work on Ti indicated that $\Delta\sigma_p$ contains a contribution in addition to heating and pinch effects. This contribution (the electroplastic effect) increased significantly with current density, interstitial content and temperature (77-300K), to a lesser degree with												

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$\Delta\sigma_p$

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strain, but no change was detected for a 25 fold increase in strain rate. Computer calculations of the dynamic stress changes associated with the approximately sinusoidal current-time pulses employed here yielded a contribution due to the electron-dislocation interaction (for a current density of 5000 A/mm² at 300K) which was 32% of $\Delta\sigma_p$. A model is proposed for the electroplastic effect which is based on theoretical considerations that the current flow exerts a force on the dislocations which adds to the applied force pushing a dislocation against obstacles. Complementary studies were performed on: (a) the decremental unloading method for determining the internal stress in metals, (b) the effects of temperature, grain size and interstitial content on the flow stress of Ti and (c) plastic instability in Ti sheet.

5g mm

$\Delta\sigma(\text{O sub p})$

* strain

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