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TITLE **INFLUENCE OF STRAIN RATE ON THE SUBSTRUCTURE EVOLUTION AND YIELD BEHAVIOR OF TI-6Al-4V**

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IFLUENCE OF STRAIN RATE ON THE SUBSTRUCTURE EVOLUTION AND YIELD BEHAVIOR OF Ti-6Al-4V

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INTRODUCTION

'stematic dynamic testing experiments, in which microstructural and mechanical 'operty effects are characterized quantitatively, constitute an important tool › investigate the effect of strain rate on mechanical behavior and deformation ›chanisms. While extensive experimental data is available for FCC and BCC ›tals, the strain rate response of HCP metals, particularly alloys, remains ›orly investigated. Studies to date/1-4/ of the mechanical response of .tanium and titanium alloys to increasing strain rate suggest a marked strain ›te sensitivity, although few studies encompassed strain rates > 10^2 s^{-1}. The ›fluence of a large variation in strain rate on substructure development has ›t received wide-spread attention, particularly for alloys, except that in HCP ›tals it has been observed that deformation twinning becomes more prevalent .th increasing strain rate/5/.

›e purpose of the current study was to investigate the influence of strain ›te on the substructure evolution and mechanical response of Ti-6Al-4V ›ereafter Ti-6-4). The results of the mechanical properties are analyzed in ›cordance with the procedure proposed by Kocks and Mecking/6/ and it is shown ›w this simple model can be extended to the multi-mechanism strengthening in .-6-4. The approach of our modeling work is to characterize the deformation .netics as a function of strain rate, temperature, and strain through the use ! the flow stress at 0K (the mechanical threshold stress) which represents the ›ress required to force a dislocation past the average obstacle without the ›sistance of thermal activation energy. Substructural characterization on ›-received and on samples prestrained as a function of strain and strain rate ›ovides the link required to verify that the assumptions made in the analysis ! the mechanical property data are valid. Substructure analysis of the Ti-6-4 › a function of strain rate shows the deformation mechanism changes from ›lely planar slip during slow stain rate deformation to a mixture of planar .ip and (11$\bar{2}$1) deformation twinning at high strain rates.

EXPERIMENTAL

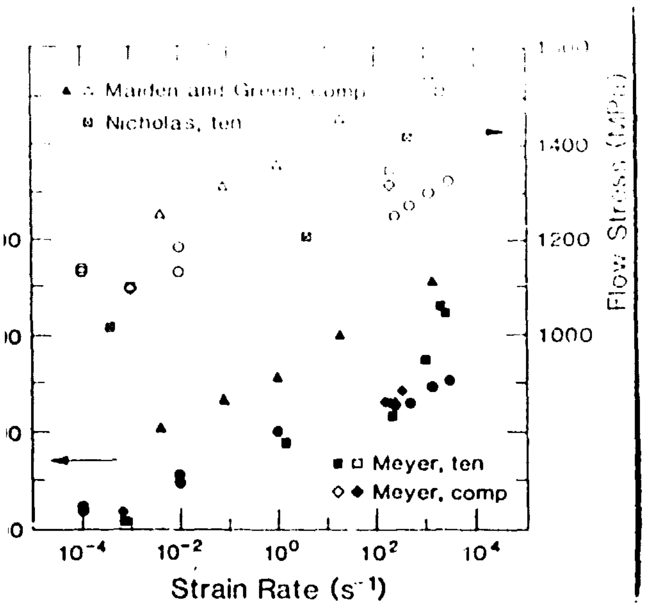
›is investigation was performed on Ti-6-4, predominantly in the as-received ›t-worked and partially recrystallized condition(termed the AR condition), ›pplied in the form of 13.8 mm thick plate with composition in (wt. %) : 6.4 ., 4.0 V, 0.12 Fe, 0.065 C, 0.001 N, 0.18 O, and bal. Ti. The starting .crostructure was an equiaxed alpha grain structure, with the alpha grain size ›minally 5 microns with beta at the grain boundary triple points. Selected 'ea diffraction (SAD) analysis of transmission electron microscope (TEM) ›ages of the as-received Ti-6-4 material showed diffraction maxima at 1/2 .010] positions. These maxima are indications of either SRO or very small .pha-2 precipitates, both of which can form during slow cooling, and are both ›own to promote planar slip. The texture of the as-received Ti-6-4 plate, in ›e plane of the plate, was measured to be a transverse texture with the maxima nted at approximately 25 degrees from the rolling plane normal and oriented 5, 135, 225, and 315 degrees in the (0002) pole figure relative to the rent rolling direction of the as-received plate. This texture suggests the -4 plate may have been cross-rolled rather than solely unidirectional ed which would typically yield only two transverse maxima at 0 and 180 ees in line with the rolling direction/7/. To compare the influence of the ation of microstructure on the strain rate sensitivity of Ti-6-4 some riments were also conducted on Ti-6-4 material following a solution tment at 1000 ^{0}C for 1 hour followed by a water quench(termed the ST iton) and a ST condition that was additionally given an aging treatment at C for 8 hours to enhance SRO or alpha-2 contributions(termed the AG ition).

les for compression testing were cut from the Ti-6-4 plate stock material the sample compression axis normal an apparent rolling direction of the e in the plane of the plate. The compression yield behavior of Ti-6-4 was ured as a function of strain rate over the strain rate range of 0.001 to s^{-1}. The temperature and strain rate dependence of the yield and flow ss is examined through determination of the mechanical threshold stress g experimental techniques discussed indepth elsewhere/8,9/. In brief, les are prestrained to a prescribed strain, strain rate, and temperature, owed by a reload operation at a strain rate of 0.001 s^{-1} to probe the rate ndency of dislocation interactions with short-range obstacles. Prestraining train rates of 0.001 and 2500 s^{-1} were done utilizing a standard w-driven mechanical testing machine and in a split Hopkinson bar, ectively.

les for TEM were sectioned from deformed Ti-6-4 specimens, in the AR ition, at strain rates of 0.001 and 5000 s^{-1} strained to a true strain of to allow deformation mechanism comparison with the mechanical behavior lts. TEM foils were prepared in a solution of 84% methanol, 10% butanol, 6% perchloric acid at -40 ^{0}C with 10 volts using a Struer's Electropolisher. foils were examined using a JEOL 2000EX operating at 200 kV equipped with a le-tilt stage.

ESULTS & DISCUSSION

strain-rate dependence of the yield and flow stress of Ti-6-4 at a true in of 0.04 is shown in Figure 1. Included with this data are measurements everal previous investigators on Ti-6-4 tested in tension/2,3/ and in ression/2-4/ to strain rates as high as 3000 s^{-1}. In general, the current lts and those included for comparison show a high strain rate sensitivity oth the yield and flow stresses. The differences in flow stress levels een the various studies are thought to be due to differences in the ting microstructural conditions of the Ti-6-4 studied. The variation of the ad yield stress in the AR condition with the reload test temperature and in rate is plotted in Figure 2 using normalized coordinates. The data in e 2 shows that the reload yield stress decreases with increasing test erature for all the prestraining conditions studied. Experiments on the ST AG conditions showed similar temperature behavior.



re 1: Strain rate dependence he yield and flow stress at 04 in Ti-6-4 and comparison previous results/6-8/.

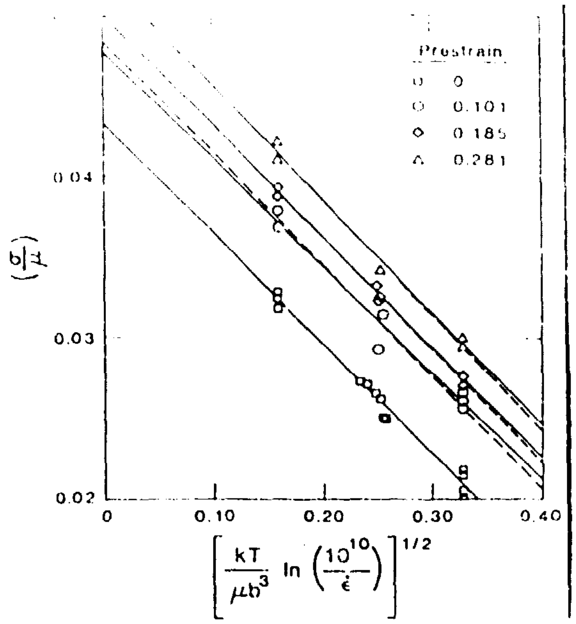


Figure 2: Variation of the reload yield stress with reload temperature and strain rate. Solid line shows fit to Eq. [1].

solid lines through the data in Figure 2 show fits according to a thermal vation law of the form/10/:

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + s(\dot{\varepsilon}, T)\,\frac{\hat{\sigma}}{\mu} \qquad [1]$$

e

$$s = \left[1 - \left(\frac{kT}{g_0 \mu b^3} \ln \frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right)^{1/q}\right]^{1/p}. \qquad [2]$$

ast squares fit of the data to Eqs. [1] and [2] gives the mechanical shold stress and normalized activation free energy. The mechanical shold stress (given by the intercept at T=0) is found to increase with easing strain for a constant strain rate. Interestingly, the mechanical ss for prestrains at a strain rate of 2500 s^{-1} to a strain of 10% is the as that for a prestrain of 0.001 s^{-1} to the same strain. This is in rast to the behavior in FCC metals where the mechanical threshold stress es with the strain rate of the prestrain.

ysis of the data for the ST and AG heat-treatment conditions similarly ed that the mechanical threshold stress increases with increasing strain. ddition the ST condition resulted in a lower threshold stress most probably to a slightly larger alpha grain size and more recrystalized structure e the AG condition yielded a higher threshold stress probably due to a -range contribution from either SRO or alpha-2 precipitates. The modeling ictions of Eq. [1] also provided a good fit to the reload response of the

ST and AG conditions.

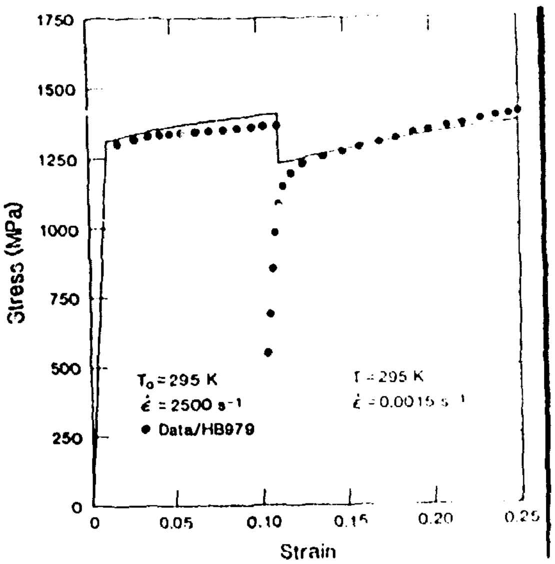
To assess a possible means to separate the various strengthening mechanisms that influence the mechanical response of Ti-6-4, the presence of interstitials and solutes on the yield behavior of pure Ti is estimated utilizing the low strain rate yield data for Ti-Al alloys of Paton et. al./11/. For these alloys, Eq. [1] is rewritten in terms of a linear summation of the contributions of interstitial, solute, and dislocation/dislocation interactions.

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + \sum A_i \frac{\hat{\sigma}_i}{\mu} \qquad [3]$$

$$A_i = \left[1 - \left(\frac{kT}{g_{0i} \mu b^3} \ln \frac{\dot{\varepsilon}_{0i}}{\dot{\varepsilon}} \right)^{1/q_i} \right]^{1/p_i} . \qquad [4]$$

The variation of the dislocation/dislocation interaction portion of the threshold stress ($\hat{\sigma}_D$) with strain for quasi-static prestrains is modeled with the fit of the Voce Law/8/ equation to threshold stress data as a function of strain to obtain the structure evolution component, i.e., the influence of strain hardening. Combining these formulations we obtain a form of the Kocks/Mecking model which includes the influences of linear summation of the strengthening mechanisms in Ti-6-4. The applied stress for a specific temperature and strain rate can then be calculated using Eq. [3].* * Indepth presentation of this model and predictions will found in a paper submitted to Metallurgical Transactions. An example of the prediction of the model is shown in Figure 3 which shows a prestrain at a strain rate of 2500 s^{-1} to a strain of 10% followed by unloading and reloading at a low strain rate of 0.015 s^{-1}. The measured flow stress is seen to be reasonably accurately predicted by our model although the measured dynamic flow stresses are slightly less than predicted. We believe that the lower dynamic yield stress may be related to the onset of deformation twinning at high rates.

The substructure evolution of Ti-6-4 in the AR condition was found to depend on both the applied strain rate and the temperature of deformation. The equiaxed alpha exhibited the most evident changes in substructure with deformation history which is consistent with the fact that the alpha grains dominate the mechanical behavior of Ti-6-4 due to the high volume fraction of alpha in this alloy. The beta grains displayed no apparent change in substructure or morphology independent of deformation history. The substructure of Ti-6-4 deformed to a true strain of 0.10 at a strain rate of 0.001 s^{-1} was characterized by planar slip concentrated in bands on basal, prism, and



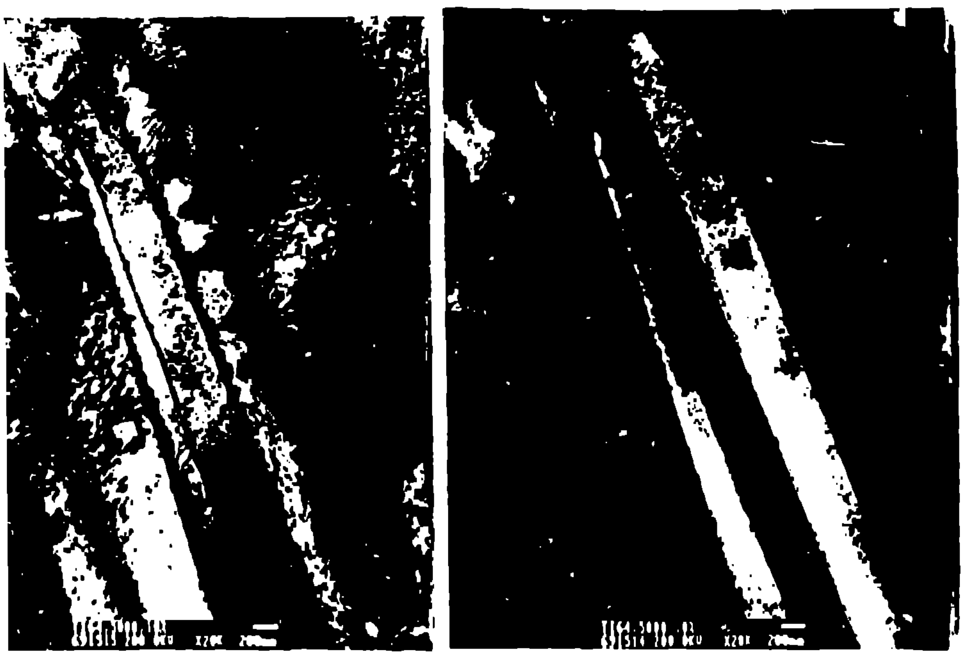
gure 3: Model prediction and
mparison with experimental
sults for a prestrain at 2500 $^{-1}$
to E=0.10 reloaded at 0.001 s^{-1}.

Figure 4: TEM micrograph of Ti-6-4 deformed at 295K at 0.001 s^{-1} to E=0.101 showing planar slip bands.

ramidal planes(Figure 4). These planar dislocation arrays are similar to
ose known to dominate deformation behavior in Ti-Al alloys containing greater
an 4 wt.% Al and demonstrate that cross-slip is difficult in Ti-Al alloys at
w temperature and high Al content/11/. The presence in the current Ti-6-4
loy, in the AR condition, of SRO or fine alpha-2 precipitates further favors
ncentration of dislocation activity into narrow slip bands/11/.

mples strained an equivalent amount but at a strain rate of 5000 s^{-1}
splayed planar slip in the alpha grains, similar to those seen in the
asi-static samples, with the addition of numerous deformation twins. Twins
re observed to have formed preferentially in grains whose mean size was
rger than the average. The twins were thin and lenticular in morphology with
D analysis revealing that the twins were (1121) type "tension" twins, i.e.
ey allow for an expansion along the c-axis. Figure 5 shows TEM bright field /
rk field micrographs and associated SAD pattern of (1121) twins in a [1010]
pha zone axis. Grains exhibiting deformation twins were seen to display a
duced amount of planar slip bands which is consistent with the shear strain
commodation accompanying twins in titanium/11/. The observation of only a
ngle twinning type (1121), while not statistically conclusive, is based on
D anaysis of atleast 10 grains in atleast 4 TEM foils sectioned from
fferent portions of the deformed samples. This TEM examination further showed
at similar diffraction conditions existed in numerous grains at a given
iting condition suggesting that the sample texture was of importance to the
inning mode. The substructure evolution of Ti-6-4 was also investigated as a
nction of testing temperature at low strain rate. Increasing the temperature
deformation to 200 °C at a strain rate of 0.001 s^{-1} was seen to alter the
slocation morphology from solely that of planar slip bands to that of less
arse planar slip interspersed with random dislocation tangles. Deformation

ıs were not observed in any samples deformed at 200^{0}C. To investigate if the ırrence of twinning at high strain rates in Ti-6-4 could be correlated with increased flow stress at these rates, a sample of the AR Ti-6-4 was ›rmed



ıre 5: TEM micrograph of Ti-6-4 ›rmed at 5000 s^{-1} to E=0.10 showing ıar slip and twins in a) brightfield b) darkfield.

Figure 6: TEM micrograph of twins in Ti-6-4 deformed at 77K.

7K to a true strain of 8% at a strain rate of 0.001 s^{-1}. TEM examination of sample showed that the substructure was similar to that of the room ›erature 5000 s^{-1} specimen being characterized by numerous deformation twins some grains displaying planar slip bands. The twins in the 77K sample were found to be (1121) type twins as seen in the bright field / SAD ographs in Figure 6.

substructure evolution of Ti-6-4 is observed to depend on the strain rate temperature of deformation as well as the starting texture. The incidence (1121) deformation twins with increasing strain rate and decreasing erature correlates with the known dependency of twin mode on texture and starting texture in the Ti-6-4 plate in this study. Studies on the tensile rmation of polycrystalline Zr by Reed-Hill/5/ showed that while (1121) type s occur infrequently at room temperature and slow strain rates(0.016 s^{-1}), easing the strain rate to 16 s^{-1} greatly increased the number of observed 1) twins. In addition to higher strain rate deformation, high rate rmation in Zr at 77K was observed to further favor (1121) twinning. During rmation at 77K twins in Zr were also observed to occur on planes with the est orientation factor, irrespective of the mode of twinning, implying that the critical resolved shear stresses for all the twinning modes apparently eached the same value. Applied stress orientation studies on Zr/10/ further ed that (1121) twinning is favored in the orientation range where the

:ss axis makes an angle between 20 and 60 degrees with the basal pole where ıcidently the orientation factors for prism slip and {1012} twinning are . In the present study the starting transverse texture of the Ti-6-4 :ting plate orients the sample compression axis approximately 65^{0} off the ıl pole. The observation of {1121} type twinning is therefore consistent ı the previous work on Zr due to texture considerations and the influence of ıin rate and temperature on deformation twinning. The increased incidence of ›rmation twins at high strain rates and low temperature, which are both ›ciated with high flow stresses, suggest that twin nucleation is strongly :ss dependent. Converserly, increasingly random slip with increasing ›erature at low strain rates has been linked to the convergence of the ›lved shear stresses for prism, pyramidal, and basal slip in Ti-Al alloys at ıer temperatures/9/. The tendency towards random dislocation arrangements jests that with increasing temperature the stress for dislocation motion on ious slip planes becomes comparable, permitting more cross slip which ılts in more random arrangements of dislocations.

:ONCLUSIONS

:d upon a study of the influence of strain rate on the substructure .ution and mechanical response of Ti-6-4 the following conslusions can be ɪn: 1) The deformation substructure of Ti-6-4 is observed to depend on both ›erature and strain rate. Deformation at quasi-static strain rates at 293K :haracterized by planar slip bands in the alpha grains while the deformation :tructure at high strain rates (e.g., 5000 s^{-1}) and at quasi-static rates at consists of numerous deformation twins, {1121} type believed to be related :he starting texture and strain rate effects. 2) The constitutive equations :d on the Kocks/Mecking model have been successfully applied to predict the ›rmation response of Ti-6-4 to loading path changes involving a relatively :ow regime in strain rate and temperature. Changes in slip character or in ›rmation mechanism (e.g., deformation twinning) have been observed to :elate with changes in the expected flow behavior, although these results beyond the current modeling procedures outlined in this paper.

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