Processing-Microstructure Relationships for Ti-6Al-2Sn-4Zr-2Mo-0.1Si

S. L. SEMIATIN, J. F. THOMAS, Jr., and P. DADRAS

The detailed relationships between thermal-mechanical processing parameters and resulting microstructures for Ti-6Al-2Sn-4Zr-2Mo-0.1Si (Ti-6242) have been established through compression testing and heat treatment. Beginning with either an equiaxed alpha or Widmanstätten alpha preform microstructure, isothermal compression tests were run at strain rates typical of isothermal forging (10^{-3} to 10^{-1} s^{-1}) and conventional forging (1 to 100 s^{-1}). Metallographic investigation of these test specimens in as-deformed and heat treated conditions was used to characterize deformation-induced microstructures and transformations. For the equiaxed alpha microstructure, it was shown that deformation, as well as post-deformation heat treatment, were more effective in promoting microstructures close to the expected equilibrium ones than heat treatment alone, a finding similar to that for other alloy systems. For the metastable Widmanstätten alpha microstructure, the deformation and heat treatment parameters that promote the development of an equilibrium, equiaxed alpha microstructure have been determined. For this microstructure, two separate temperature-strain rate regimes have been identified, and the resulting microstructures correlated with the measured flow stress behavior. For the low temperature regime, deformation is highly nonuniform, and the microstructural features are shown to be similar to those in pearlitic steels and other lamellar alloys. In the higher temperature regime, on the other hand, deformation is much more uniform. The results presented can be applied to select hot forging parameters for the control of final microstructure and properties in Ti-6242 and similar α/β titanium alloys.

I. INTRODUCTION

RECENT advances in the development of a scientific basis for deformation processing have provided a new perspective on the traditional study of microstructure-property relationships by metallurgists. It is now realized that hot deformation parameters, as well as post-deformation heat treatments, can be selected to control final microstructure and properties in addition to producing a shape and conforming to workability limits. Hence, increased understanding of processing-microstructure-property relations is now being sought to improve performance specifications of high technology components.

The metallurgical systems which have the most sensitive response to variations in processing in terms of microstructure and properties are the multiphase alloys. Of these systems, steels are surely the best documented with regard to the effects of thermomechanical processing.[1,2] Another important alloy class, with an equally varied range of microstructures, is the two phase α/β titanium alloy class which includes important commercial alloys such as Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo. For these alloys, microstructure-property relations are well understood,[3,4] but only limited data on the effect of varying processing conditions on microstructure and hence properties are available.[5] Because of this shortcoming, commercial metalworking and heat treatment schedules of titanium alloys are often based on extensive plant trials and developed through experience.

The research reported here was part of a larger program whose purpose was to develop a science-based methodology for the hot forging process which would allow control of microstructure and properties in a finished product.[6,7,8] Part of this program involved characterization of the flow behavior of the alloy Ti-6Al-2Sn-4Zr-2Mo-0.1Si (Ti-6242) under hot forging conditions. The results of this phase of the research have been described elsewhere.[9,10] In this paper, the results of a subsequent investigation of deformation-induced microstructures of Ti-6242 are reported. These studies have established the effects of preform, or starting, microstructure, hot forging parameters, and heat treatment parameters on microstructural evolution and final microstructure.

For an α/β titanium alloy such as Ti-6242, two preform microstructures are most common. A microstructure of equiaxed alpha phase in a matrix of transformed beta phase is provided by hot working and subsequent heat treatment below the beta transus temperature [990 °C (1815 °F) for Ti-6242]. This microstructure is termed $\alpha + \beta$ and is known to possess good high temperature fatigue properties. Heat treatment above the beta transus results, upon cooling, in a Widmanstätten alpha or basketweave microstructure. This will be termed the transformed β or, simply, β microstructure and is known to have good high temperature creep properties.

In the work reported here the effect of hot forging and subsequent heat treatment on each of these preform microstructures will be described and interpreted in terms of similar phenomena for other alloy systems. An interesting feature of this work involves the relative stability of the two microstructures. From a morphological standpoint, the $\alpha + \beta$ microstructure is essentially stable whereas the β microstructure, produced during nonequilibrium cooling, is metastable at subtransus temperatures. Hence, during hot working below the transus, a β preform microstructure evolves toward the $\alpha + \beta$ microstructure, and the nature

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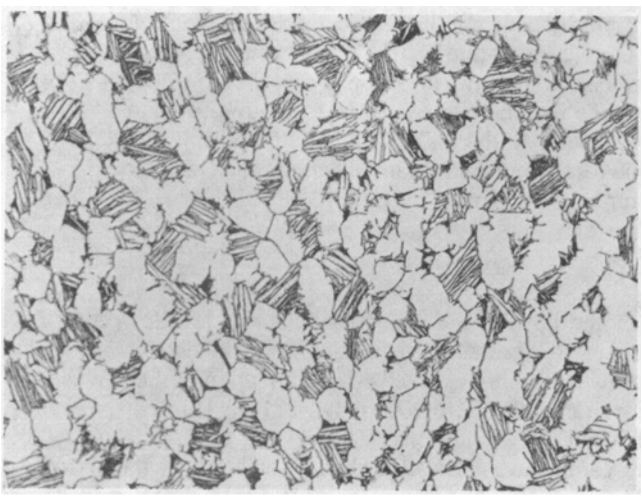
and extent of this transformation depend upon temperature and strain. This allows the possibility of controlling the final microstructure and property distribution in a Ti-6242 forging by control of preform geometry and hot-forging parameters. The results reported here are currently being applied to investigate this possibility for design of a Ti-6242 turbine engine compressor disk for which a gradient in properties, from the bore to the rim, is desirable.[6,7,8]

II. EXPERIMENTAL PROCEDURES

A. *Material*

The Ti-6242 alloy used in this investigation was obtained from RMI Company in the form of 203 mm (8 inch) diameter billets and had a composition of 6.1 pct Al, 2.1 pct Sn, 3.9 pct Zr, 2.1 pct Mo, and 0.084 pct Si, balance titanium. Wyman-Gordon Company produced the starting microstructures by finish forging the material to 121 mm (4.75 inch) diameter bar. This was done at either 954 °C (1750 °F) followed by annealing at 968 °C (1775 °F) (two hours + air cool) or at 1038 °C (1900 °F) followed by annealing at 1024 °C (1875 °F) (two hours + air cool). The former forge-heat treatment cycle produced an $\alpha + \beta$ preform microstructure with α-grain size $\approx$10 μm as shown in Figure 1(a). The latter cycle was above the beta transus temperature and produced a β preform microstructure of prior beta grain size $\approx$400 μm.[5,11] This is shown in Figure 1(b).



(*a*)

50μm

(*b*)

Fig. 1—Microstructures of (*a*) $\alpha + \beta$ preform material and (*b*) β preform material.

B. *Procedures*

The microstructures of Ti-6242 were determined (1) after heat treatment alone, (2) after isothermal hot deformation in uniaxial compression, and (3) after hot deformation and post-deformation heat treatment.

The isothermal hot deformation by uniaxial compression was performed at a variety of strain rates and temperatures. Low strain rate tests (10^{-3} to 10^{-1} s^{-1}) were conducted in an Instron machine modified to allow constant true strain rate.[10] Higher strain rate tests were run either in a mechanical press[9] (1 to 10 s^{-1}) or a cam plastometer[8] (10^{-1} to 10^{2} s^{-1}). In a mechanical press, the strain rate is nearly constant for approximately the first 60 pct of the deformation.[9] The constant true strain rate tests performed on a cam plastometer were conducted at the Los Alamos National Laboratory.[8,12] Test temperatures ranged from 899 to 1038 °C (1650 to 1900 °F) with only $\alpha + \beta$ microstructure specimens being tested above the beta-transus temperature where both starting microstructures transform to single phase beta. In all tests, specimens were heated to temperature in 5 to 15 minutes and soaked at temperature 5 to 15 minutes prior to testing.* Most specimens were compressed to 50 pct reduction in height ($\varepsilon \approx 0.7$) although total strain was varied ($\varepsilon = 0.2$ to 1.0) for a limited number of tests on β microstructure specimens to investigate the effect of strain on the evolution of this microstructure. All specimens were air-cooled immediately after deformation. Further details of the test procedure are contained in References 7 and 8.

Specimens for post-deformation heat treatment were obtained by sectioning compression test specimens parallel to the compression axis. These sections, as well as sections from undeformed bars, were wrapped in tantalum foil, encapsulated in quartz tubes, which were evacuated and backfilled with 0.5 atmosphere of argon gas, and heated in tube furnaces with temperature controlled to ±3 °C (±5 °F). The capsules were water-quenched after the specified annealing times. Temperatures of 899 to 1010 °C (1650 to 1850 °F), which are typical for solution treatment of Ti-6242 after forging, were selected for the present study. Sectioned specimens, either as-compressed or heat-treated, were prepared for metallographic investigation using standard procedures. Chemical etchants consisted of a mixture of HNO_3

*Metallography on specimens heated subtransus for two hours revealed no changes in microstructure (relative to those soaked only 15 minutes) for either $\alpha + \beta$ or β specimens, suggesting that an equilibrium or near-equilibrium microstructure was obtained at the shorter heating times used for most of the present study.

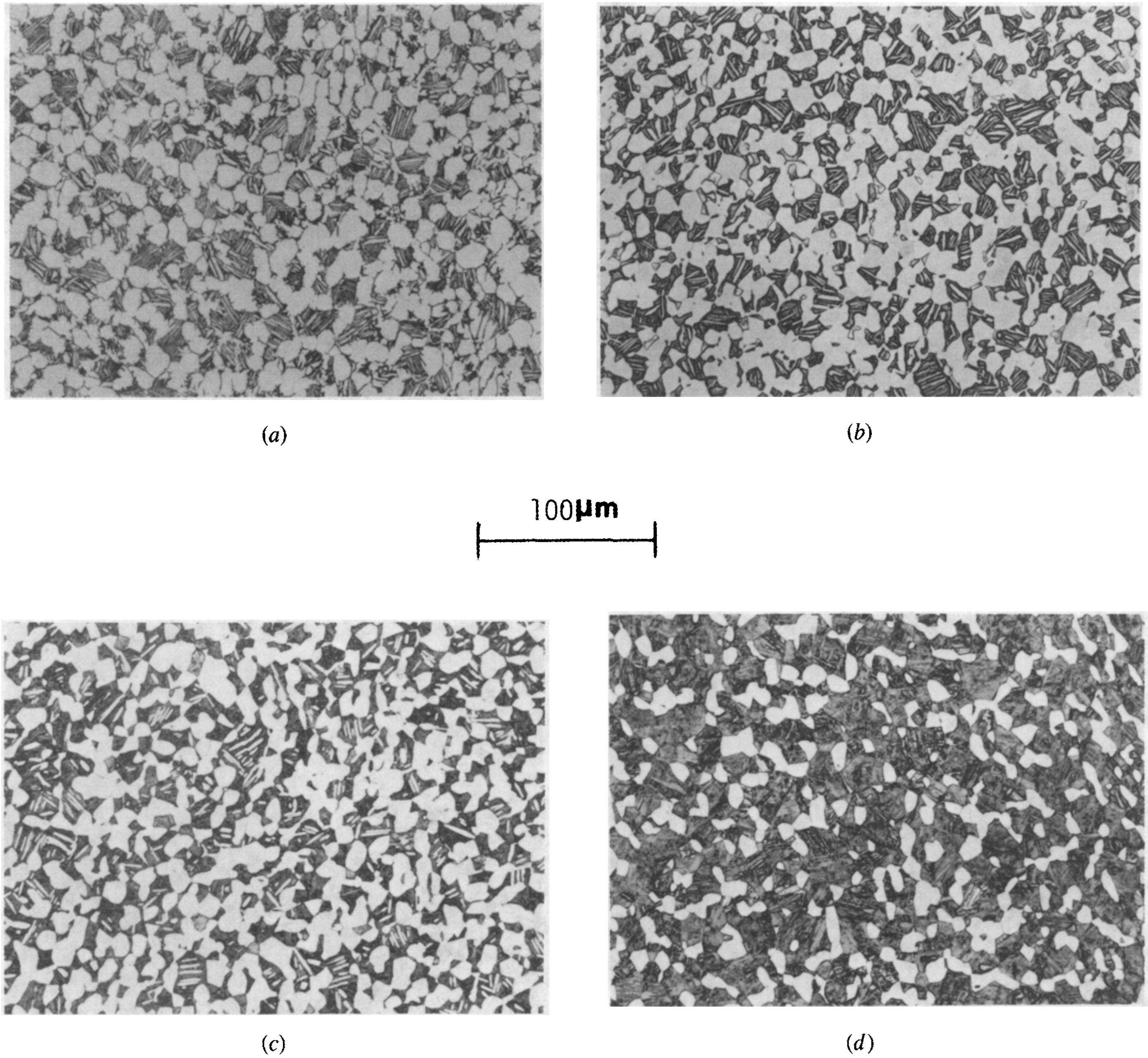


Fig. 2—Microstructures in $\alpha + \beta$ preform microstructure material (*a*) as-received and after heat treatment for 2 h (+AC) at (*b*) 899 °C (1650 °F), (*c*) 954 °C (1750 °F), and (*d*) 982 °C (1800 °F).

and HF in H_2O, primarily 3.5 vol pct HNO_3, 1.5 vol pct HF, balance H_2O.

III. RESULTS AND DISCUSSION

A. $\alpha + \beta$ *Microstructure*

Microstructures after Heat Treatment Alone. Metallographic results demonstrated that preheat temperature, hot deformation, and post-deformation heat treatment temperature all influence the microstructure developed in $\alpha + \beta$ microstructure material. Heat treatment of the as-received $\alpha + \beta$ microstructure at increasing temperatures from 899 °C (1650 °F) to 982 °C (1800 °F) tends to decrease the percent of globular alpha phase and modify the morphology of the transformed beta matrix. The as-received microstructure is compared to those produced by heat treatment for two hours at 899 °C, 954 °C, and 982 °C (1650 °F, 1750 °F, and 1800 °F) in Figure 2. The decrease in amount of globular alpha is most noticeable at 982 °C (1800 °F), and this is supported by quantitative measurements of percent globular alpha presented in Table I. This rapid decrease in percent globular alpha for heat treatment temperature near the beta transus is expected from phase equilibrium considerations.

The change in morphology of the transformed β matrix of the specimen heat treated at 982 °C (1800 °F) is due to reversion to single phase beta and retransformation during cooling. Transmission electron microscopy showed that the resulting matrix is at least partially martensitic, which is consistent with the more rapid cooling rate which results for

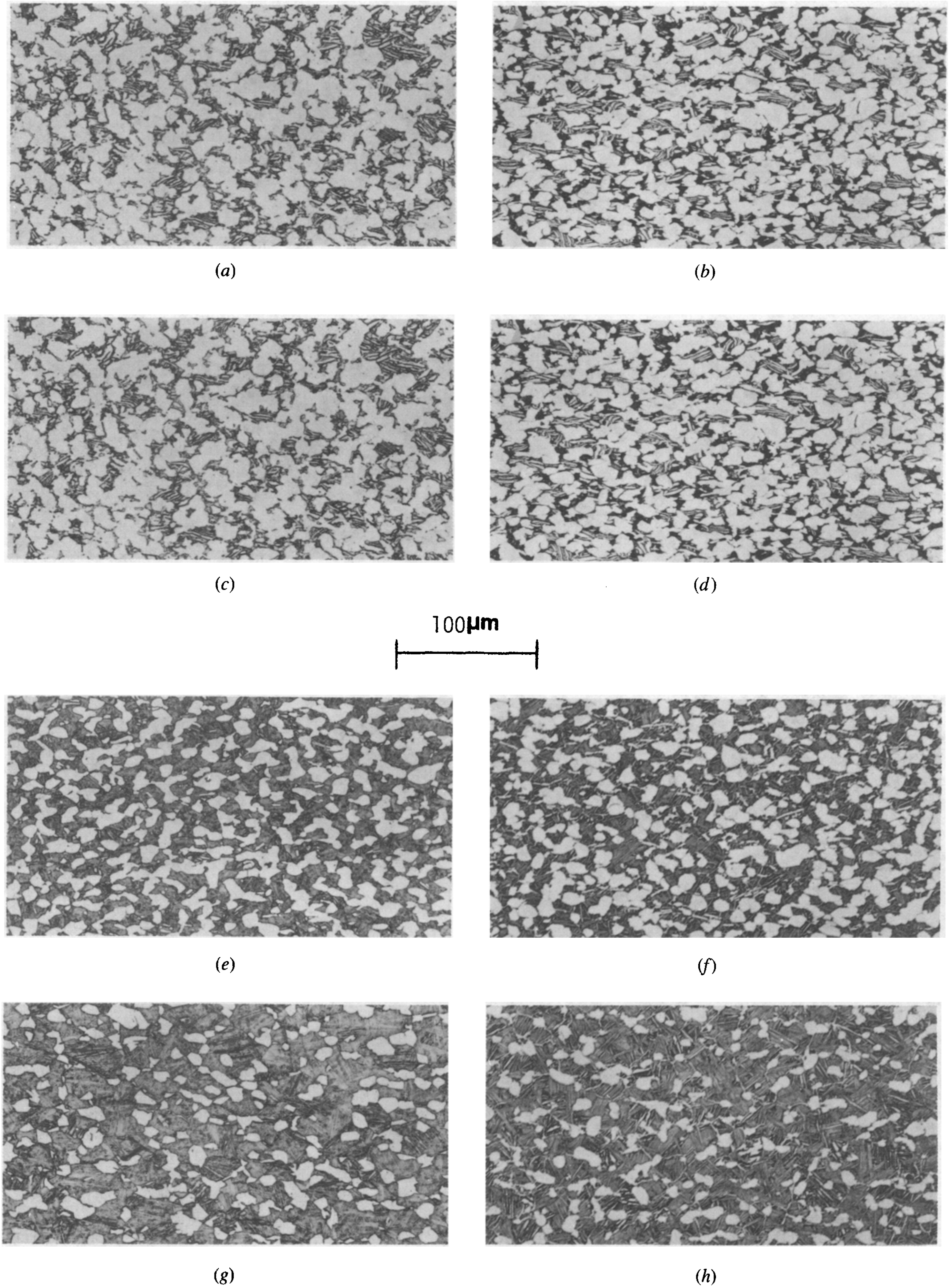


Fig. 3—Microstructures in as-deformed $\alpha + \beta$ microstructure specimens compressed (to $\varepsilon = 0.7$) at strain rates of (*a, c, e, g*) 10^{-3} s^{-1} or (*b, d, f, h*) 10 s^{-1} at temperatures of (*a, b*) 899 °C (1650 °F), (*c, d*) 927 °C (1700 °F), (*e, f*) 954 °C (1750 °F), and (*g, h*) 982 °C (1800 °F).

Table I. Percent Globular Alpha in $\alpha + \beta$ Microstructure Specimens*

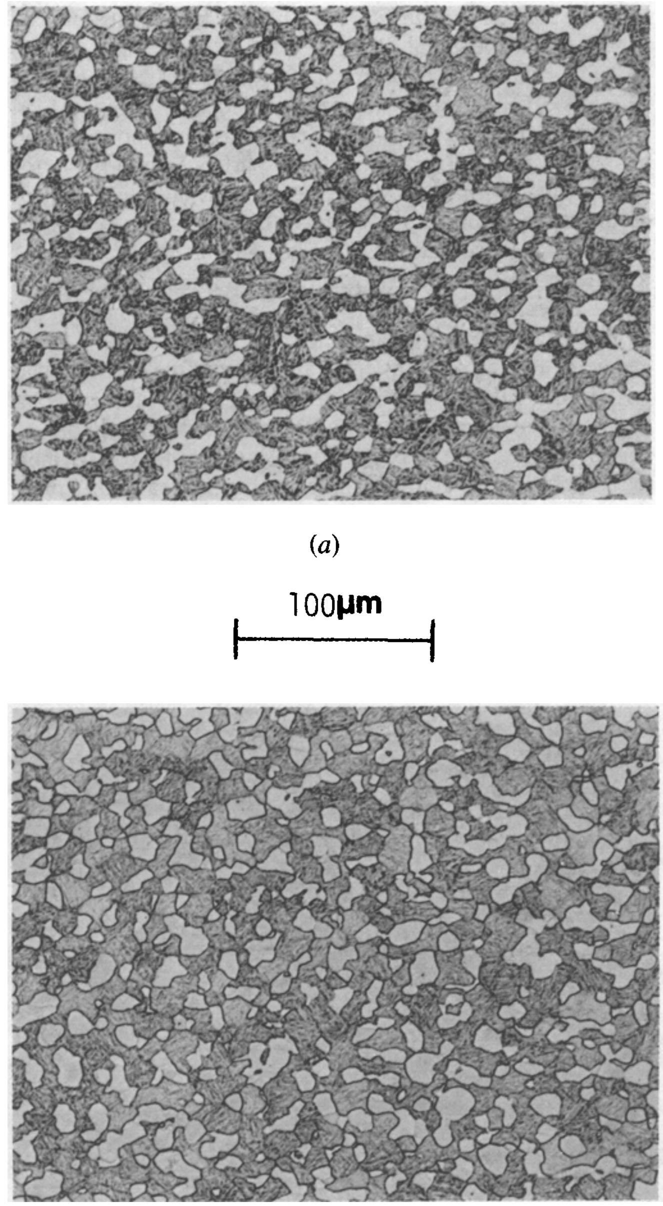
Heat Treatment or Deformation Temperature, C (F)	Percent Alpha Phase after Two-Hour Heat Treatment	Percent Alpha Phase after Deformation at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$	Percent Alpha Phase after Deformation at $\dot{\varepsilon} = 10\ s^{-1}$
899 (1650)	55	69	61
927 (1700)	54	55	64
954 (1750)	53	44	40
982 (1800)	28	28	26

*Percent globular alpha in as-received material — 60 pct.

the small heat treatment coupon (*vs* air cooling the larger as-received billet) and a relatively high M_s temperature of approximately 800 °C (1472 °F).[13] For the specimens heat treated at lower temperatures, the transformed β matrix appears similar to that of the as-received material. This could be due to failure of the beta phase to transform martensitically since its Mo content increases with decreasing heat treatment temperature, leading to a lower M_s temperature.[13] Alternatively, at the lowest temperatures, the Widmanstätten α structure may fail to revert to single phase beta during heat treatment prior to cooling. This is discussed further by Gegel, *et al.*, in Reference 7.

Microstructures after Hot Deformation. The microstructures developed in $\alpha + \beta$ microstructure material by hot deformation were found to be very dependent on deformation temperature, though somewhat less dependent on deformation strain rate. A comparison of microstructures developed by compression at 10^{-3} and 10 s^{-1} at several temperatures is shown in Figure 3. With the combined, simultaneous effects of high temperature and deformation (to $\varepsilon \approx 0.7$), the variations in percent globular alpha with temperature, listed in Table I, are more marked than in the microstructures developed by heat treatment alone. For example, when the microstructures of a specimen heat treated at 899 °C (1650 °F) and compressed at 899 °C (1650 °F) are compared [Figure 2(b) *vs* Figures 3(a) and 3(b); also Table I], one notes a significantly larger amount of globular alpha in the compressed specimen, an amount which is probably closer to the equilibrium percentage. Also, by and large, a continuous decrease in percent alpha phase with increasing deformation temperature is evident.

It is suggested that these changes in phase fractions may result from diffusion of vacancies, leading to interphase boundary migration.[14] Boundary migration, in concert with boundary sliding, could also account for the observations[9,10] that the flow stress of the $\alpha + \beta$ material is nearly independent of strain and the alpha grains retain their equiaxed shape after deformations to $\varepsilon \approx 0.7$. On the other hand, the observed lack of strain hardening would not be consistent with a more classical dynamic recrystallization mechanism for the phase changes which occur during deformation.[15] In any case, the important observation of the more rapid kinetics of these changes during hot compression (~10 minutes for $\varepsilon = 0.7$ at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$ in compression) relative to those involved in static heat treatment (in which limited changes are noted even after two hours at temperature) are in basic agreement with the well-known influence of hot-working in enhancing phase transformation rates.[15] In addition to the common examples of recovery and recrystallization, the work of Weiss and Jonas,[16] who have reported a rapid increase in precipitation kinetics in microalloyed steels when the reaction occurs during hot deformation, provides an interesting analogy in another two-phase system.



(*a*)

(*b*)

Fig. 4 — Microstructures formed in $\alpha + \beta$ preform microstructure material after a heat treatment of 954 °C (1750 °F)/2 h which follows compression (to $\varepsilon = 0.7$) at a strain rate of 10 s^{-1} at a temperature of (*a*) 899 °C (1650 °F) or (*b*) 954 °C (1750 °F).

Microstructures after Hot Deformation and Post-Deformation Heat Treatment. Metallographic results show that residual subtransus hot work in the $\alpha + \beta$ preform microstructure is also effective in increasing the phase transformation kinetics during post deformation, subtransus heat treatment. This is demonstrated, for example, by the nearly identical microstructures obtained from heat treatment at 954 °C (1750 °F) for two hours after deformation at either

899 °C (1650 °F) or 954 °C (1750 °F). This is illustrated in Figure 4 for specimens deformed at 10 s^{-1}. These microstructures can also be compared to those of as-deformed [Figures 3(b) and 3(f)] and heat treated only [Figure 2(c)] specimens to realize the full effect of residual hot work on phase transformations. Similar comparisons were made for specimens deformed at lower strain rates, and the effect of deformation strain rate appears to be negligible in this regard. These observations are also similar to the effect of residual hot work on static precipitation kinetics in a microalloyed steel, which are an order of magnitude faster in the worked state than in an annealed state.[16]

The $\alpha + \beta$ preform microstructure specimens which had been either deformed or heat treated at temperatures above the beta transus temperature transformed completely to single phase beta. Upon cooling, the beta phase then retransformed to a Widmanstätten or basketweave structure. In these cases, the final microstructure is determined solely by the deformation temperature or heat treatment temperature and time, which determine the prior beta grain size, and the rate of cooling from above the transus.

B. *β Microstructure*

Microstructures after Heat Treatment Alone. Somewhat similar to results for the $\alpha + \beta$ microstructure, subtransus heat treatment of the transformed β microstructure led to no significant morphological changes relative to the as-received Widmanstätten microstructure. There were some changes in phase distributions (*i.e.*, increases in beta phase with increasing temperature), particularly for heat treatment temperatures nearest the transus.

Dilatation studies by Gegel, *et al.*,[7] have shown that transformation of the as-received Widmanstätten microstructure to single phase beta begins at approximately

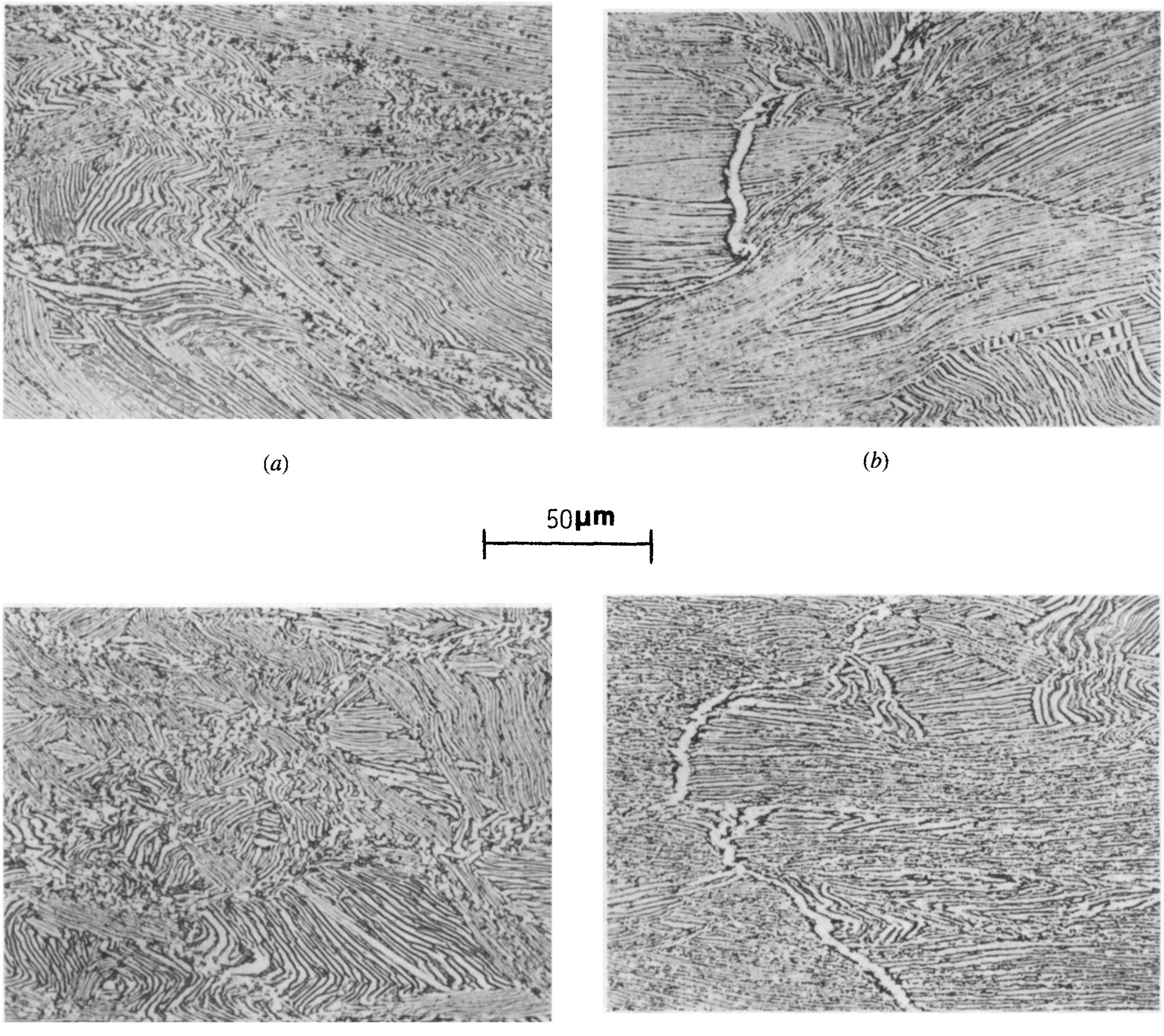


Fig. 5—Microstructures in as-deformed β microstructure specimens compressed (to $\varepsilon = 0.7$) at strain rates of (*a, c*) 10^{-2} s^{-1} or (*b, d*) 10 s^{-1} at temperatures of (*a, b*) 899 °C (1650 °F) and (*c, d*) 927 °C (1700 °F).

916 °C (1680 °F) for Ti-6242 specimens heated at a rate of 4 °C (7 °F) per minute. For heat treatment between this temperature and the transus, the microstructure approaches equilibrium volume fractions of alpha and beta phases while retaining the original plate morphology of the alpha phase.[17] However, these changes can be masked by reverse transformations during cooling, and the final microstructure may appear very similar to the starting microstructure.

For heat treatment at the lowest temperature considered here, 899 °C (1650 °F), which is below the minimum transformation temperature determined by dilatation studies,[7] no microstructural changes were observed, reflecting, in this case, no microstructural changes during heating. For heat treatment at 954 °C (1750 °F) transformations during heat treatment are expected resulting in changes in volume fractions of the two phases but not morphological changes; unfortunately, such changes are affected by phase transformations during cooling. Observations of the β microstructure after hot deformation, to be discussed next, give an insight into these effects, however.

Microstructures after Hot Deformation. Although somewhat resistant to change during heat treatment alone, the β microstructure undergoes large morphological changes during hot deformation. These changes depend strongly on deformation temperature and total strain and to a lesser degree on strain rate.

At temperatures of 899 °C (1650 °F) and 927 °C (1700 °F), the microstructure exhibits very nonuniform deformation at both low and high strain rates, but more noticeably at the higher strain rates. This is illustrated for specimens deformed to $\varepsilon \approx 0.7$ in Figure 5. This nonuniform deformation is manifested by two distinct features: (1) the occurrence of regions of intense localized shear which results in sharp curvature of the α- and β-platelets in

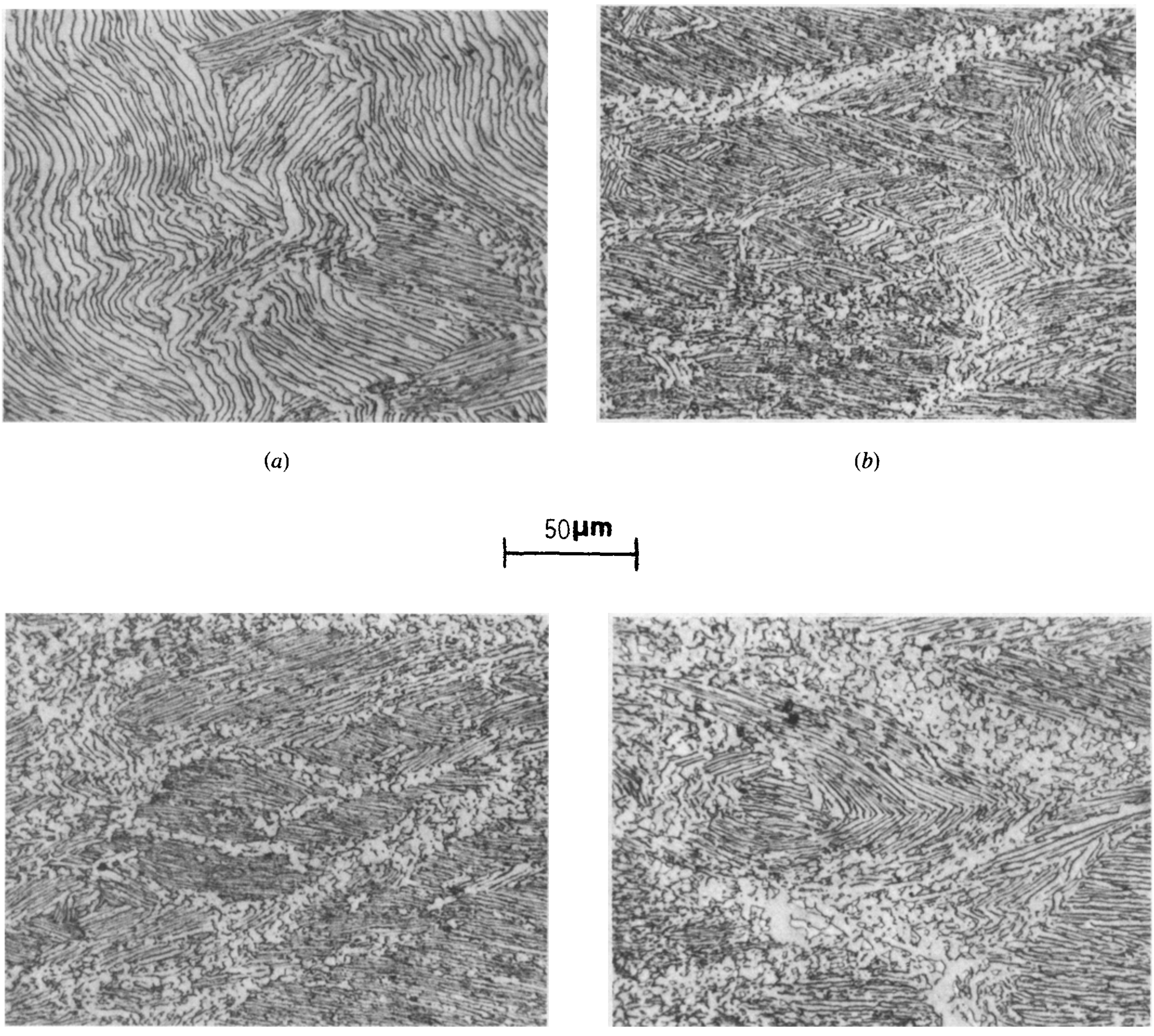


Fig. 6—Microstructures in as-deformed β microstructure specimens compressed at a strain rate of 2×10^{-3} s^{-1} at 899 °C (1650 °F) to reductions which correspond to true axial strains of (*a*) 0.3, (*b*) 0.4, (*c*) 0.7, and (*d*) 1.0.

the Widmanstätten microstructure and the grain boundary alpha and (2) a breakup and spheroidization of the alpha and beta platelets in the Widmanstätten structure. Other studies have shown that those modes of deformation are connected with large degrees of flow softening observed in the compressive flow curves of this microstructure at these temperatures.[7,9,10,18]

Metallographic results on β microstructure specimens deformed to various strain levels at a temperature of 899 °C (1650 °F) and a strain rate of $2 \times 10^{-3}\ s^{-1}$ provide further insight into the development of the deformation inhomogeneities and are illustrated in Figure 6. At the lowest strains, $\varepsilon = 0.2$ to 0.3, the first observable effect of deformation is the occurrence of the regions of localized shear. The number of these regions increases with strain, although they never occupy more than a small fraction of the specimen volume. It may be that only Widmanstätten colonies of certain orientations with respect to the local stress are subject to sharp curvature by localized shear. The observation of these curved platelets after hot deformation strongly supports the previous conclusion regarding the thermal stability of the Widmanstätten microstructure below and near the minimum transformation temperature determined by dilatation.[7] It is unlikely that such nonuniform microstructures would be preserved after deformation and cooling unless the Widmanstätten structure was stable during preheating prior to deformation. Severely curved and kinked platelets have also been observed in other lamellar alloys such as pearlitic steels[19] and eutectic Cd-Zn.[20]

The second type of inhomogeneity, the breakup and spheroidization of the Widmanstätten colonies, first appear at a total strain of approximately $\varepsilon \approx 0.4$ in narrow regions near the colony boundaries [Figure 6(b)]. Since the β microstructure is stable at this temperature prior to deformation, the breakup of the platelets must be occurring during straining. Thus, this behavior is similar to the observation by Sherby and co-workers[21,22] of rapid spheroidization of pearlitic steels during deformation in contrast to a much lower rate during static heat treatment. At higher strains, $\varepsilon = 0.7$ and $\varepsilon = 1.0$ [Figures 6(c) and 6(d)], the volume fraction of the spheroidized regions increases as these regions become thicker and occur more frequently. There is a parallel increase in the volume of highly sheared regions particularly near the edges of the spheroidized bands. This suggests that it is the highly sheared platelets that are subsequently broken up and initiate the spheroidization-like transformation. Similar behavior was observed for the Cd-Zn lamellar eutectic and attributed to localized intense slip.[20]

However, even at the highest strain level investigated, $\varepsilon = 1.0$, the microstructure still contains an appreciable fraction of Widmanstätten colonies which appear essentially undeformed. In fact, a recent study by Rauch, *et al.*,[23] involving torsion tests on Ti-6242 at a temperature of 913 °C (1675 °F) and strain rate of $10^{-2}\ s^{-1}$, demonstrated that quite large strains, of the order of $\varepsilon = 5$, are required to complete the breakup and spheroidization of the Widmanstätten structure. This is important in that it is the spheroidized regions which transform to the equilibrium $\alpha + \beta$ microstructure during post-deformation heat treatment as will be discussed below.

The microstructures developed in β specimens compressed to $\varepsilon \approx 0.7$ at higher temperatures, 941 °C (1725 °F) to 982 °C (1800 °F), show much less nonuniform deformation, as illustrated in Figure 7. Although there appears to

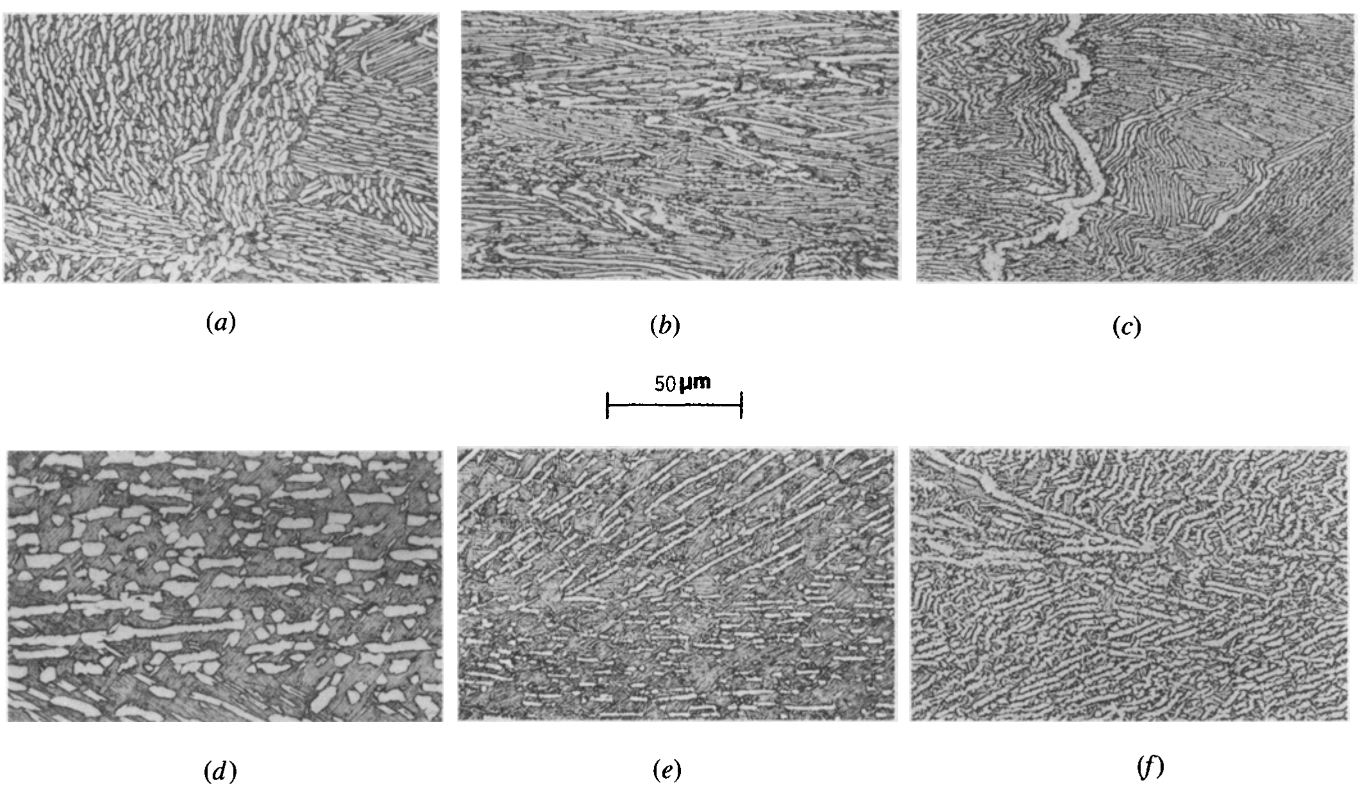


Fig. 7—Microstructures in as-deformed β microstructure specimens compressed (to $\varepsilon = 0.7$) at strain rates of (*a, d*) $10^{-3}\ s^{-1}$, (*b, e*) $10^{-1}\ s^{-1}$, or (*c, f*) $10\ s^{-1}$ at temperatures of (*a, b, c*) 954 °C (1750 °F) and (*d, e, f*) 982 °C (1800 °F).

be a variety of alpha morphologies in these microstructures, the general trend is toward thicker alpha plates and an overall coarsening of the structure, similar to that developed by heat treatment alone in this temperature range. This suggests that the disappearance of deformation inhomogeneities is partly related to the microstructure developed during preheating prior to deformation and partly to some thermally-assisted process which occurs most readily at these temperatures.

It should be noted that the temperature range for the more uniform deformed microstructures occurs above the minimum temperature for reversion of alpha determined by dilatometry.[7] In addition, it has been shown that the flow behavior of the transformed β microstructure exhibits a dual mode, or bilinear, dependence of the logarithm of flow stress on inverse temperature.[10] The transition from one mode to the other occurs at approximately 930 °C (1706 °F) for deformation at a strain rate of approximately 10^{-2} s^{-1}, a characteristic temperature in close agreement with the dilatometry results. Thus, it appears possible to define low and high temperature regimes for hot working of β microstructure Ti-6242 separated by a transition temperature which is expected to be a function of strain rate.

Table II. Deformation Parameters Required for Uniform Microstructure at ε = 0.7

Strain Rate (s^{-1})	Observed Minimum Temperature (C)	$Z = \dot{\varepsilon} \exp (Q/RT)$ (s^{-1})	Calculated Transition Temperature (C)[10]
10^{-3}	941	1.33×10^{23}	924
10^{-1}	968	3.47×10^{24}	934
10	982	1.81×10^{26}	970

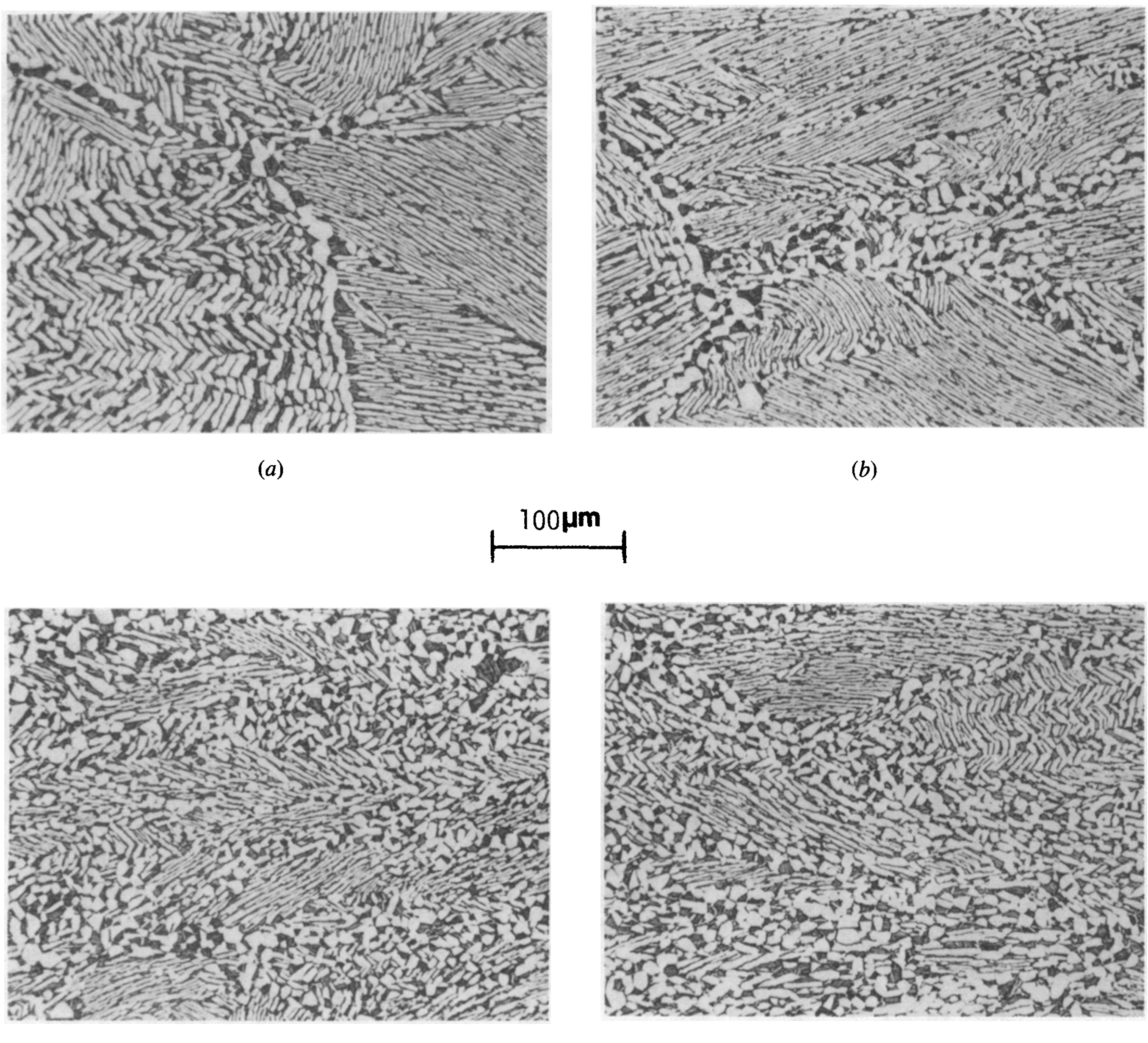


Fig. 8—Microstructures of β preform material heat treated at 954 °C (1750 °F) for 4 h following compression at 899 °C (1650 °F) at a strain rate of 2×10^{-3} s^{-1} to true axial strains of (*a*) 0.3, (*b*) 0.4, (*c*) 0.7, (*d*) 1.0.

In order to quantify such a relationship, a large number of deformed microstructures was examined, and the minimum temperature at which no nonuniform features appeared for a specific strain rate was determined. These are listed in Table II for three different strain rates. It may be expected that these temperature-strain rate combinations could be correlated using a temperature-corrected strain rate factor, $Z = \dot{\varepsilon} \exp (Q/RT)$, commonly used to explain high temperature deformation.[15,21,22] Here $\dot{\varepsilon}$ is the strain rate, Q is an apparent activation energy, and R and T are the gas constant and absolute temperature, respectively. Using an average activation energy $Q = 612$ kJ/mole, determined previously for Ti-6242,[24] Z-parameters ranging from $\sim 10^{23}$ to $\sim 10^{26}$ were calculated for the listed temperature-strain rate combinations. The Z-parameters calculated from a single activation energy do not correlate with the microstructural observations implying that there is no single thermally-activated process controlling the phenomenon. This is not unexpected since, over this temperature range, both phase fractions and chemical compositions of the phases are changing, unlike the case for single phase materials or even some eutectic or eutectoid materials such as pearlitic steels. It might be noted that a relatively small change in activation energy, say, a decrease from 612 to 535 kJ/mole as the temperature increases from 941 °C (1725 °F) to 982 °C (1800 °F), would provide for a constant Z-factor correlation of the critical strain-rate temperature combinations listed in Table II.*

*A careful examination of the flow stress data suggests that Q might indeed decrease with increasing temperature by the amount suggested above. This trend is opposite to that normally observed for single phase materials (for which Q normally increases with temperature), a fact which might perhaps be due to the changes of phase compositions and percentages with temperature for the particular two-phase alloy under investigation.

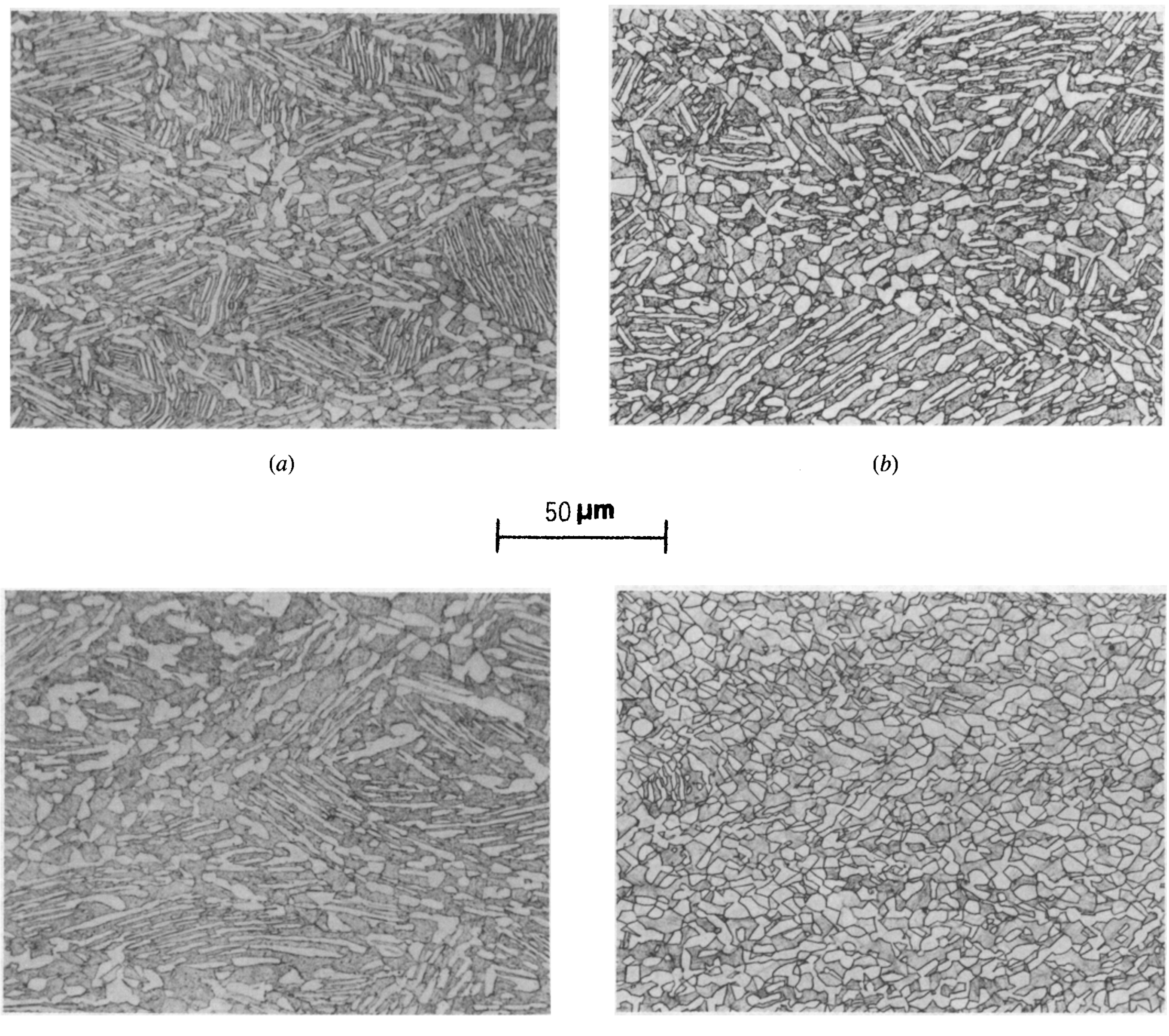


Fig. 9—Microstructures developed in β preform material heat treated at 954 °C (1750 °F) for 2 h following deformation (to $\varepsilon = 0.7$) at strain rates of (a, c) 10^{-2} s^{-1} or (b, d) 10 s^{-1} at temperatures of (a, b) 899 °C (1650 °F) or (c, d) 954 °C (1750 °F).

However, a different correlation can be attempted by using a set of empirical flow laws developed recently for Ti-6242 by Dadras and Thomas.[10] These have successfully modeled the dual mode temperature dependence of the flow stress mentioned above. The transition temperatures from one mode to the other have been calculated based on the set of empirical equations presented in Reference 10 and these are also listed *vs* strain rate in Table II. The correlation with the temperatures based on microstructural observation is seen to be good. Essentially, this simply means that the temperature dependent flow behavior correlates well with the observed deformation-induced microstructures, and a transition temperature between low and high temperature hot-working regimes can be calculated as a function of strain rate. This result can be used in the selection of forging temperatures to obtain uniform microstructures.

Microstructures after Hot Deformation and Post-Deformation Heat Treatment. The effect of post-deformation heat treatment on microstructure for transformed β microstructure specimens depends primarily on the temperature-strain rate regime of the hot deformation. This phenomenon differs from the static heat treatment response of the $\alpha + \beta$ microstructure which is relatively insensitive to prior deformation temperature and strain rate. Although some static recrystallization of the deformed β microstructures is observed at low heat treatment temperatures [$T \approx 913$ °C (1675 °F)], the effects of prior hot work are most clearly seen at heat treatment temperatures near and above 954 °C (1750 °F).

For β microstructure specimens deformed at 899 °C (1650 °F) and 2×10^{-3} s^{-1} to various strains, microstructures developed by heat treatment at 954 °C (1750 °F) for four hours are shown in Figure 8. Since this deformation is in the low temperature regime, the deformed microstructures are characterized by regions of highly localized deformation (Figure 6). After heat treatment, it is seen that it is the highly deformed regions which apparently recrystallize while the remainder of the specimen shows little response other than a general coarsening of the Widmanstätten structure. At the lowest strain illustrated, $\varepsilon = 0.3$, for which the localized deformation takes the form of kinked or bent Widmanstätten plates, the breakup of these plates into short, straight segments is seen in Figure 8(a). For the higher strains, where the spheroidized regions develop, it is seen in Figures 8(b) to 8(d) that these regions recrystallize to form bands of equiaxed alpha in a matrix of transformed beta. Thus, deformation in the low temperature regime followed by heat treatment near 954 °C (1750 °F) results in transformation from the β to the equilibrium $\alpha + \beta$ microstructure. The extent of this transformation is controlled by strain. It is only partially complete for $\varepsilon = 1$ [Figure 8(d)] with full transformation expected to require strains near $\varepsilon \approx 5$.[23]

After heat treatment which follows deformation in the high temperature regime, the only observable effect is some additional static recrystallization resulting in more equiaxed alpha. A comparison of microstructures developed by heat treatment at 954 °C (1750 °F) for two hours following deformation to $\varepsilon = 0.7$ is shown in Figure 9. For Figures 9(a), 9(b), and 9(d), the deformations are all in the low temperature regime [even 9(d) because the strain rate equals 10 s^{-1}] and the microstructures are dominated by inhomogeneous deformation and subsequent localized static recrystallization. For the microstructure shown in Figure 9(c), the more uniform deformation characteristics of the high temperature regime resulted in less observable changes during the post-deformation heat treatment.

IV. SUMMARY AND CONCLUSIONS

The effects of heat treatment alone, hot deformation, and the combination of hot deformation and subsequent heat treatment on the microstructure developed in $\alpha + \beta$ and transformed β preform microstructure specimens of Ti-6Al-2Sn-4Zr-2Mo-0.1Si have been documented. The following conclusions have been drawn.

1. Heat treatment of the $\alpha + \beta$ microstructure material below the transus temperature leads to minimal changes in the percent globular alpha and transformed beta matrix morphology except at temperatures very near [$T = 982$ °C (1800 °F)] the transus. Subtransus deformation or deformation plus heat treatment lead to a significantly greater variation in the amount of primary, globular alpha. This finding emphasizes the improvement in transformation kinetics brought about by hot deformation or residual hot work.
2. Subtransus heat treatment of transformed β microstructure material also leads to minimal microstructural changes. Because deformed microstructures exhibit kinked platelets, it must be concluded that the general platelet morphology after heat treatment (and prior to deformation) remains relatively unchanged.
3. For subtransus deformation of the β microstructure, two distinct temperature-strain rate regimes have been identified. For deformation at a strain rate of 10^{-2} s^{-1}, the transition between these is at $T \approx 930$ °C (1706 °F) increasing to $T \approx 970$ °C (1780 °F) at a strain rate of 10 s^{-1}. For the low temperature regime, deformation is highly nonuniform resulting in regions of intense localized shear and bands in which the Widmanstätten colonies break up and spheroidize. During post-deformation heat treatment near 954 °C (1750 °F) these regions statically recrystallize to form the equilibrium $\alpha + \beta$ microstructure. Strains greater than $\varepsilon \approx 1$, probably near $\varepsilon \approx 5$, are required for complete transformation to obtain a uniform microstructure. For deformation in the high temperature regime, the nonuniform deformation features are not observed although a variety of coarsened alpha morphologies are produced. Post-deformation heat treatment increases the amount of equiaxed alpha. The definition of the low and high temperature regimes along with the approximate influence of total strain allows the design of forging processes in order to predict the distribution of final microstructure and properties in a finished part.

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