J Mater Sci (2010) 45:6046–6051
DOI 10.1007/s10853-010-4689-8

Kinetics of flow stress in ultra-pure tantalum single crystals in stress/temperature regime III

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Received: 15 February 2010 / Accepted: 1 June 2010 / Published online: 15 June 2010

Abstract The temperature dependence of the critical resolved shear stress (CRSS), τ, of ultra-pure tantalum single crystals (RRR $\geq$ 14000) observed below 250 K for a range of shear-strain rates $\dot{\gamma} = 2 \times 10^{-5} - 6 \times 10^{-3}\ s^{-1}$ was analyzed within the framework of a kink-pair nucleation model of flow stress. The CRSS/strain-rate data follow the model formulation $\tau^{1/2} = C + D \ln\dot{\gamma}$, where C and D are positive constants, for each deformation temperature T in the range 78–250 K. Evaluation of the various slip-parameters of flow stress points to (211)[$\bar{1}$11] slip system responsible for the yielding of ultra-pure tantalum single crystals in the so-called stress/temperature regime III ($T < 250$ K). The value of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius-type equation for the shear-strain rate $\dot{\gamma}$ is found to be of the order of $10^5\ s^{-1}$, which is substantially lower than that ($\dot{\gamma}_o \sim 10^7\ s^{-1}$) determined in the stress/temperature regime II (250–400 K) and contradicts the assumption invariably made in most of the theoretical models of flow stress that $\dot{\gamma}_o$ is a constant over a wide temperature range.

Introduction

The kinetics of plastic deformation in body-centered cubic (bcc) metals are quite different from those of face-centered cubic (fcc) and hexagonal close-packed (hcp) metals. For instance, slip in bcc crystals can occur on any slip planes of <111> zones, and is not restricted to definite, low-index, crystallographic planes, typical of close-packed metals. At rather low temperatures below $T_o = 0.1$–$0.2\ T_{melt}$, where diffusional processes are dormant in the crystal, the critical resolved shear stress (CRSS) of high-purity refractory bcc metals strongly depends on the temperature and on the strain-rate at which deformation is carried out. The CRSS–T curve below T_o is divided into two regimes, each with a different gradient or slope. However, the sensitivity of the CRSS to the temperature and to the strain-rate is far less at temperatures $T > T_o$. Thus Diehl et al. [1] divided the CRSS–T curve for a given strain rate into three temperature or stress regimes: I for high temperatures or low stresses, II for intermediate temperatures or intermediate stresses, and III for low temperatures or high stresses.

According to Seegar [2], the glide mechanism of the refractory bcc metals is the same in regimes I and II but different from that operative in regime III. He attributed the change in the glide mechanism to a first-order phase transition in the (a_o/2) <111> screw-dislocation cores from a rather high-temperature configuration that can glide only on one definite {211} plane (regimes I and II) to a low-temperature configuration that allows glide of a given (a_o/2) <111> screw-dislocation on any of its three {110} planes (regime III).

On the other hand, Brunner and Diehl [3] used stress-relaxation measurements technique for investigations on the flow stress of high-purity α-Fe single crystals between 30 and 380 K. They observed characteristic differences of vital importance for the three temperature/stress regimes. Contrary to Seeger [2], they found unexpected uniformity in the stress dependence of the activation enthalpy in regimes II and III, which excludes a first-order phase transition in the (a_o/2) <111> screw-dislocation cores from the high-temperature {211} configuration to the low-temperature {110} configuration at the transition from regime II to regime III. The distinction between these two regimes

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was attributed by Brunner and Diehl [3] to the difference in the value of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius-type equation shear-strain rate $\dot{\gamma}$. They found $\dot{\gamma}_o$ to be constant in regime III ($T < 130$ K), which later on decreases gradually with an increase in the temperature depicting a weak temperature dependence of $\dot{\gamma}_o$ within regime II ($T = 130$–250 K) of the CRSS–T curve for high-purity in α-Fe single crystals.

It is well known that the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius strain-rate equation, which is often taken as the starting point for thermodynamical treatments of plastic deformation of crystalline materials, is a material constant, which depends on the density of glide dislocations, the magnitude of the Burgers vector, the average distance the dislocations travel after successful activation event, and the attempt frequency of the dislocation, which is reciprocal of the waiting time needed for the dislocation [4, 5]. It is invariably assumed in most of the models of flow stress [4–17] that the pre-exponential factor $\dot{\gamma}_o$ is to a good approximation constant or insensitive to T over a wide temperature range. Recently, Butt et al. [18] derived an analytical expression for the strain-rate dependence of the CRSS, τ, of crystals with high intrinsic lattice friction, which helps to evaluate the pre-exponential factor $\dot{\gamma}_o$ rather directly with out making use of any adjustable parameters. Using this formulation, they investigated the kinetics of deformation in ultra-pure Ta single crystals deformed by Werner [19] for a range of shear-strain rates $\dot{\gamma} = 2 \times 10^{-5} - 6 \times 10^{-3}\ s^{-1}$, and found that the slip system responsible for yielding in regime II (250–400 K) was $(211)[\bar{1}11]$. Butt et al. [18] also determined the value of the pre-exponential factor $\dot{\gamma}_o$ from the observed strain-rate dependence of the yield stress in regime II, and found it to be of the order of $10^7\ s^{-1}$, independent of the deformation temperature T in the range 250–400 K.

Keeping in view the observation of Brunner and Diehl [3] on the role of the pre-exponential factor $\dot{\gamma}_o$ rather than the change of glide mechanism in separating regimes II and III of the CRSS–T curve of high-purity α-Fe single crystals referred to above, it was considered instructive to extend the investigations of Butt et al. [18] pertaining to regime II of ultra-pure Ta single crystals to regime III. Thus, the first objective of the present work was to evaluate the pre-exponential factor $\dot{\gamma}_o$ from the wealth of data on the yield stress of ultra-pure Ta single crystals deformed by Werner [19] for a range of shear-strain rates $\dot{\gamma} = 2 \times 10^{-5} - 6 \times 10^{-3}\ s^{-1}$ in regime III ($T < 250$ K) in order to compare it with that determined by Butt et al. [18] for regime II ($\dot{\gamma}_o = 8.5 \times 10^7\ s^{-1}$, $T = 250{-}400$ K), and to assess the commonly assumed temperature independence of $\dot{\gamma}_o$ over a wide temperature range. The second objective was to determine the slip system of yielding at rather low temperatures in regime III ($T < 250$ K) so as to explore any change in the glide mechanism at the transition from regime II to regime III.

The model

Referring to Feltham–Butt model of flow stress in crystals with high intrinsic lattice friction [7] the unit activation process of yielding comprises stress-assisted, thermally-activated, nucleation of a kink-pair in $(a_o/2)$ <111> screw-dislocation segment trapped in a Peierls valley, leading to its forward movement over the Peierls hill to the next Peierls valley, after attainment of the saddle-point configuration. At temperatures below 0.1–0.2 T_{melt}, where diffusional processes are dormant in the crystal, the activation energy (free enthalpy), $W(\tau)$, for the formation of a kink-pair of critical maximum height, nb, for saddle-point configuration is given by [7]:

$$W = 2W_o - 2\alpha_o \tau^{1/2} \tag{1}$$

with the yield criterion

$$W = mkT, \quad m = \ln(\dot{\gamma}_o/\dot{\gamma}) = 25 \pm 2.3 \tag{2}$$

Here $W_o = n(UGb^3)^{1/2}$, $\alpha_o = (1/2)(nb)^{3/2}(Gb^3)^{1/2}$, G is the shear modulus, U is the Peierls energy per interatomic spacing along the screw-dislocation, $2W_o$ is the kink-pair formation energy W_{kp} at $\tau = 0$, k is the Boltzmann constant, $\dot{\gamma}$ is the shear rate of the crystal with typical values in the range 10^{-3} to $10^{-5}\ s^{-1}$, and the pre-exponential factor $\dot{\gamma}_o$ is of the order of $10^7\ s^{-1}$. The critical maximum height, nb, of the kink-pair for saddle-point configuration, where n is a numerical constant and b is the length of the Burgers vector, nb can be at the most equal to the distance a between two consecutive Peierls valleys, as the formation of the kinks having a height larger than the inter-valley distance a is hardly probable. Thus for two consecutive Peierls valleys along $[\bar{1}11]$ direction in bcc crystals, one finds that when $nb = a$, the value of $n = (a/b)$ will be 0.9428, 1.6329, and 2.4945 for (110), (211), and (321) slip planes, respectively.

In terms of the deformation temperature T, one can re-write Eq. 1 in conjunction with Eq. 2 as under:

$$\tau^{1/2} = A - BT \tag{3}$$

where

$$A = (W_o/\alpha_o) = \tau_o^{1/2},\ B = (mk/2\alpha_o), \text{ and } \tau_o = \left(4U/nb^3\right).$$

Equation 3 shows that for a given strain rate (i.e., if m is constant), $\tau^{1/2}$ of crystals with high intrinsic lattice friction decreases linearly with the increase in temperature T. The value of A is in fact the intercept made on the stress axis at $T \to 0$ K on extrapolation of the $\tau^{1/2}$–T straight line fitted

to the data, and helps to determine τ_o, i.e., the CRSS at $T \rightarrow 0$ K. Similarly B, the magnitude of the slope of the $\tau^{1/2}$–T line, helps to evaluate the parameter α_o, and this together with A then yields the value of W_o, i.e., the formation energy of a solitary kink. Moreover, the intercept made by the $\tau^{1/2}$–T line on the temperature axis for $\tau = 0$ provides the so-called knee temperature $T_k = (A/B) = (2W_o/mk)$, which also facilitates the determination of W_o or the kink-pair formation energy $W_{kp}(=2W_o)$.

As far as the dependence of the CRSS τ on the shear rate $\dot{\gamma}$ at a constant temperature T is concerned, Butt et al. [18], on re-writing Eq. 3 in conjunction with Eq. 2, derived an analytical expression:

$$\tau^{1/2} = \tau_o^{1/2} - (kT/2\alpha_o)\ln(\dot{\gamma}_o/\dot{\gamma}) \quad (4)$$

or

$$\tau^{1/2} = C + D\ln\dot{\gamma} \quad (5)$$

where C and D are positive constants such that

$$C = \tau_o^{1/2} - D\ln\dot{\gamma}_o \quad (6)$$

and

$$D = (kT/2\alpha_o) \quad (7)$$

Equation 5 shows that $\tau^{1/2}$ increases linearly with the increase in $\ln\dot{\gamma}$ such that the slope $[d\tau^{1/2}/d(\ln\dot{\gamma})]$ of the $\tau^{1/2}$–$\ln\dot{\gamma}$ line fitted to the data at a given temperature T is equal to D. Since D is directly proportional to T (Eq. 7), the slope $[d\tau^{1/2}/d(\ln\dot{\gamma})] = D$ (Eq. 5) decreases linearly as T is lowered such that $D = 0$ at $T \rightarrow 0$ K. So, the value of the constant $C(= \tau_o^{1/2} - D\ln\dot{\gamma}_o)$ should decrease linearly with the rise in temperature T at which deformation is carried out. This has been confirmed [18] by experiment in the case of ultra-pure Ta single crystals deformed by Werner [19] at various temperatures in the so-called regime II (250–400 K) of CRSS-T curve.

Data analysis

We shall now examine the validity of Eqs. 5–7 in regime III ($T < 250$ K) of the CRSS–T curve of ultra-pure Ta single crystals. The symbols in Fig. 1 depict in semi-logarithmic coordinates the values of the square root of the CRSS as a function of five different shear-strain rates at which ultra-pure Ta single crystals (RRR $\geq$ 14000) were deformed by Werner [19] at various temperatures in the so-called regime III. The least-squares fit to the data for a given temperature is encompassed by Eq. 5 with the values of constants C and D, along with linear correlation coefficient r, given in Table 1.

The observed temperature dependence of the value of the slope, $D = [d\tau^{1/2}/d(\ln\dot{\gamma})]$, of the $\tau^{1/2} - \ln\dot{\gamma}$ line has been illustrated in Fig. 2. The straight line drawn through the data, taken from Table 1, and denoted by symbols in Fig. 2, can be seen to pass through the origin, i.e., $D = 0$. The slope, dD/dT, of the D–T line is found to be equal to 1.09×10^{-3} MPa$^{1/2}$ K^{-1}. On noting from Eq. 7 that $(dD/dT) = (k/2\alpha_o)$, one can readily find that $\alpha_o = 3.95 \times 10^{-2}$ eV MPa$^{-1/2}$.

Reference to Fig. 3 shows the values of constant C, taken from Table 1, denoted by symbols, as a function of temperature T. The least-squares fit to the data are encompassed by the mathematical expression:

$$C = 15.85 - 1.30 \times 10^{-2}T \quad (8)$$

with linear correlation coefficient $r = -0.979$. The value of the slope, dC/dT, of the C–T line comes out to be 1.30×10^{-2} MPa$^{1/2}$ K^{-1}. This in conjunction with Eqs. 6

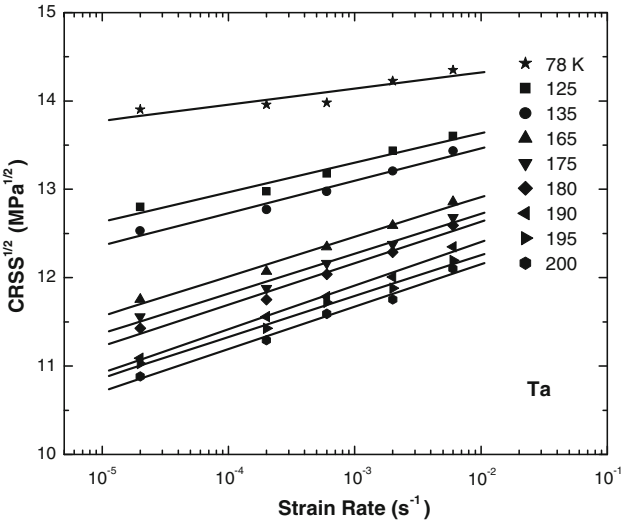

Fig. 1 Relation between CRSS$^{1/2}$ and strain rate $\dot{\gamma}$ for ultra-pure Ta single crystals in semi-logarithmic coordinates. Data points are taken from Werner [19]. The deformation temperature T, from top to bottom curves, are 78, 125. 135, 165, 175, 180, 190, 195, and 200 K, respectively

Table 1 Numerical values of the positive constants C and D in $\tau^{1/2} = C + D\ln\dot{\gamma}$ obtained by a least-squares fit to the $\tau^{1/2}/\ln\dot{\gamma}$ for ultra-pure Ta single crystals in regime III

T (K)	C (MPa$^{1/2}$)	D (MPa$^{1/2}$)	r
78	14.68	0.079	+0.901
125	14.31	0.146	+0.979
135	14.20	0.159	+0.988
165	13.81	0.195	+0.992
175	13.63	0.196	+0.992
180	13.58	0.204	+0.991
190	13.39	0.215	+0.996
195	13.19	0.201	+0.995
200	13.11	0.209	+0.994

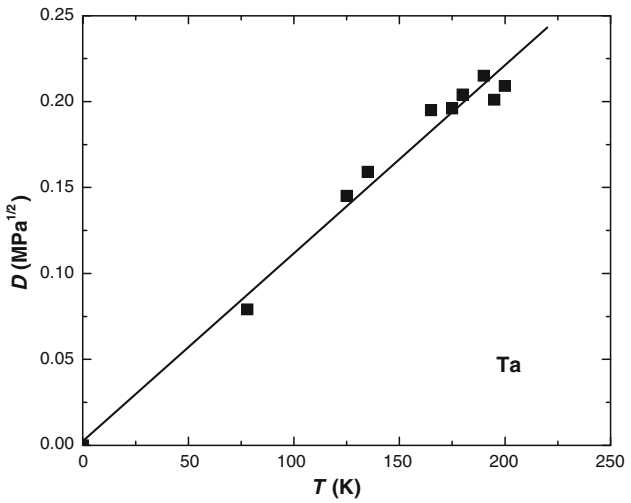

Fig. 2 Relation between the Feltham–Butt model parameter $D = \mathrm{d}\tau^{1/2}/\mathrm{d}(\ln\dot{\gamma})$, evaluated from Fig. 1, and the deformation temperature T for ultra-pure Ta single crystals

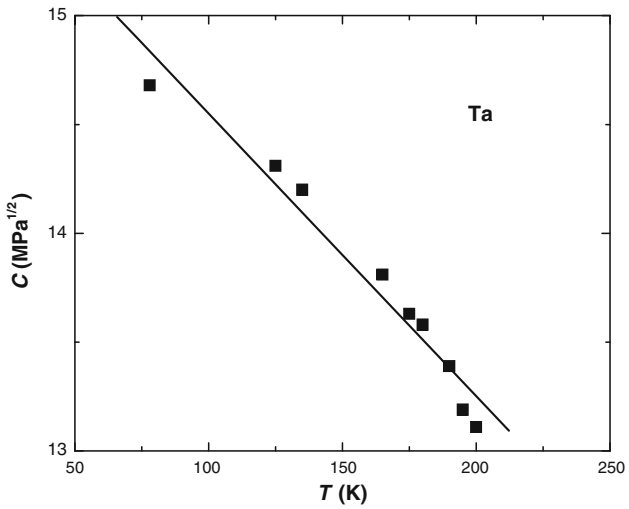

Fig. 3 Relation between the Feltham–Butt model parameter C and the deformation temperature T for ultra-pure Ta single crystals

and 7, i.e., $(\mathrm{d}C/\mathrm{d}T) = (k\ln\dot{\gamma}_o/2\alpha_o)$, together with $\alpha_o = 3.95 \times 10^{-2}$ eV MPa$^{-1/2}$ leads to $\ln\dot{\gamma}_o = 11.92$, and hence $\dot{\gamma}_o = 1.5 \times 10^5\ \mathrm{s}^{-1}$, which is by two orders of magnitude lower than that ($\dot{\gamma}_o = 8.5 \times 10^7\ \mathrm{s}^{-1}$) determined in the so-called stress/temperature regime II (250–400 K). This means that the value of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius strain-rate equation is not constant over a wide temperature range. This is in contrast with the common assumption invariably made in the models of flow stress that $\dot{\gamma}_o$ is insensitive to the deformation temperature T. The present investigations, however, reveal that $\dot{\gamma}_o$ is independent of T only within limited deformation temperature ranges. The marked difference in the measured values of $\dot{\gamma}_o$ in regimes III ($1.5 \times 10^5\ \mathrm{s}^{-1}$) and II ($8.5 \times 10^7\ \mathrm{s}^{-1}$) can probably be attributed to rather low density of mobile dislocations in regime III ($T < 250$ K) as compared with that in regime II (250–400 K).

On substituting the average values of $C = 13.77$ MPa$^{1/2}$ and $D = 0.178$ MPa$^{1/2}$, together with $\ln\dot{\gamma}_o = 11.29$ in Eq. 6, one gets $\tau_o^{1/2} = 15.89$ MPa$^{1/2}$, and therefore $\tau_o = 253$ MPa. Similarly, on using $\alpha_o = 3.95 \times 10^{-2}$ eV MPa$^{-1/2}$ and $\tau_o^{1/2} = 15.89$ MPa$^{1/2}$ in $W_o = \alpha_o\tau_o^{1/2}$, one can readily find that the formation energy of a solitary kink $W_o = 0.628$ eV, and the kink-pair formation energy $W_{kp} = 2W_o = 1.255$ eV.

To identify the slip system responsible for the flow stress in ultra-pure Ta single crystals in the so-called regime III, we shall now evaluate the parameter n related to the critical maximum height, nb, of the kink-pair for saddle-point configuration, the Peierls energy per interatomic spacing along the screw-dislocation U, the initial length L_o of the screw-dislocation segment taking part in the unit activation process of yielding at $T \to 0$ K under the action of applied shear stress τ_o, and the activation volume, v_o, associated with τ_o. This can be achieved on using the model expressions [7]:

$$n^3 = \left(W_o/Gb^3\right)^2 \cdot (4G/\tau_o) \tag{9}$$

$$U = (W_o/n)^2\left(1/Gb^3\right) \tag{10}$$

$$L_o = b\,(4Gn/\tau_o)^{1/2} \tag{11}$$

$$v_o = (1/4)nL_ob^2 \tag{12}$$

Thus on putting $G = 6.5 \times 10^4$ MPa, $b = 0.2860$ nm and, therefore, $Gb^3 = 9.5$ eV along with $W_o = 0.628$ eV and $\tau_o = 253$ MPa in Eq. 9, the value of the parameter n related to the critical maximum height, nb, of the kink-pair for saddle-point configuration is found to be 1.65. This means that $nb = 1.65b$, which is quite close to the Peierls valley separation $a_{(211)} = 1.6329b$ in the slip plane (211). Substituting $n = 1.65$ together with the values of W_o and Gb^3 in Eq. 10, one obtains the Peierls energy per interatomic spacing along the screw-dislocation $U = 15.3$ meV. Similarly, Eqs. 11 and 12 help to determine, respectively, the value of the screw-dislocation length $L_o = 41.2b$ and that of the activation volume $v_o = 17.0\mathrm{b}^3$ involved in the unit activation process of yielding at $T \to 0$ K. Both are in good agreement with those specific to Peierls mechanism, i.e., $L_o = 20$–$50b$ [20] and $v_o = 1$–$100b^3$ [4, 21].

It is evident from the above analysis that in order to determine the absolute value of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius strain-rate equation, i.e., Eq. 2, and to identify the slip system associated with the plastic flow in a given crystal, one must have CRSS–$\dot{\gamma}$ data for a range of temperatures, at which deformation is carried out. On the other hand, if the CRSS–$\dot{\gamma}$ data is available only for a single deformation temperature, then will it be possible to identify the slip system responsible for the flow stress in a given

Table 2 Numerical values of the activation parameters of low-temperature slip in ultra-pure Ta single crystals via strain-rate dependence of the CRSS at a given temperature using Feltham–Butt model (2007) yield criterion $m = \ln(\dot{\gamma}_o/\gamma) = 25$

T (K)	$\tau_o^{1/2}$ (MPa$^{1/2}$)	α_o (eV MPa$^{-1/2}$)	τ_o (MPa)	W_o (eV)	W_{kp} (eV)	n	U (meV)	L_o (b)	v_o (b^3)
78	16.06	4.25×10^{-2}	258	0.683	1.366	1.74	16.3	41.8	18.2
125	16.83	3.70×10^{-2}	284	0.623	1.246	1.57	16.0	37.0	14.8
135	16.96	3.65×10^{-2}	288	0.619	1.238	1.56	16.7	37.1	14.4
165	17.20	3.64×10^{-2}	296	0.623	1.246	1.55	17.0	36.6	14.2
175	17.03	3.80×10^{-2}	290	0.654	1.308	1.61	17.3	37.7	15.2
180	17.12	3.79×10^{-2}	293	0.650	1.300	1.60	17.3	37.4	14.9
190	17.12	3.80×10^{-2}	293	0.653	1.306	1.57	18.0	37.0	14.8
195	16.68	4.17×10^{-2}	278	0.696	1.392	1.70	17.6	39.5	16.8
200	16.75	4.12×10^{-2}	280	0.691	1.382	1.70	17.4	39.7	16.9
Average	16.86	3.88×10^{-2}	284	0.655	1.310	1.62	17.1	38.2	15.6

crystal with out the knowledge of the absolute value of the pre-exponential factor $\dot{\gamma}_o$? Answer to this can be found by proceeding as under.

Consider the CRSS–$\dot{\gamma}$ data for ultra-pure Ta single crystal obtained data at a given deformation temperature $T = 78$ K (Fig. 1) in regime III. The value of $D = [d\tau^{1/2}/d(\ln\dot{\gamma})]$ is found to be 7.9×10^{-2} MPa$^{1/2}$ (Table 1), which on its substitution in Eq. 7 provides $\alpha_o = 4.25 \times 10^{-2}$ eV MPa$^{-1/2}$. This together with Feltham–Butt model [7] yield criterion $m = \ln(\dot{\gamma}_o/\dot{\gamma}) = 25$, $\tau^{1/2} = 14.08$ MPa$^{1/2}$, i.e., the average of the five measured values of the square root of the CRSS in the strain-rate range 2×10^{-5} s^{-1} to 6×10^{-3} s^{-1} (Fig. 1), and $D = 7.9 \times 10^{-2}$ MPa$^{1/2}$ leads to $\tau_o^{1/2} = 16.06$ MPa$^{1/2}$ on making use of Eq. 4. Since $W_o = \alpha_o\tau_o^{1/2}$, one can readily find $W_o = 0.683$ eV and $W_{kp} = 1.366$ eV. The above data enables one to evaluate various microscopic parameters of slip, i.e., n, U, L_o, and v_o, with the help of Eqs. 9–12. The values obtained in this manner for $T = 78$ K are given in Table 2. Similarly, analysis of the $\tau^{1/2} - \dot{\gamma}$ data pertaining to other deformation temperatures in the range 78–200 K (Fig. 1) provides the values of various microscopic and macroscopic parameters of Feltham–Butt model [7], which are also listed in Table 2.

Reference to Table 2 shows that the values of $\tau_o^{1/2}$, α_o, τ_o, W_o, W_{kp}, n, U, L_o, and v_o, obtained for each deformation temperature in regime III ($T < 250$ K) are in good agreement with the corresponding ones determined earlier while taking into account collectively the entire CRSS–$\dot{\gamma}$ data for all the deformation temperature in regime III. The value of n (Table 2) obtained for each temperature, being close to inter-valley separation $(a_{(211)}/b) = 1.6329$, again points to $(211)[\bar{1}11]$ slip system which determines the CRSS of ultra-pure Ta single crystals in regime III. The remarkable agreement in the identification of slip system $(211)[\bar{1}11]$ responsible for flow stress of ultra-pure Ta single crystal in regime III using the entire CRSS–$\dot{\gamma}$ data for a range of deformation temperatures collectively leading to $\dot{\gamma}_o \approx 10^5$ s^{-1} or that for individual deformation temperatures assuming $\dot{\gamma}_o \approx 10^7$s^{-1} can be attributed to the mathematical structure of Eq. 2, which is such that the variation of the pre-exponential factor $\dot{\gamma}_o$ by even two orders of magnitude does not affect the function W in a substantial way.

Conclusions

Data analysis of the so-called stress/temperature regime III ($T < 250$ K) in the CRSS–T curve of ultra-pure Ta single crystals leads us to the following conclusions:

1. The CRSS/strain-rate data follow the Feltham–Butt model formulation $\tau^{1/2} = C + D\ln\dot{\gamma}$, where C and D are positive constants, for each deformation temperature $T < 250$ K.
2. The value of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius-type equation for the shear-strain rate $\dot{\gamma}$ is found to be 1.5×10^5 s^{-1}, which is by two orders of magnitude lower than that ($\dot{\gamma}_o = 8.5 \times 10^7$ s^{-1}) determined in regime II (250–400 K). This contradicts the common assumption invariably made in most of the models of flow stress that $\dot{\gamma}_o$ is insensitive to T over a wide temperature range. However, $\dot{\gamma}_o$ can be said to be independent of T only within limited deformation temperature ranges.
3. Evaluation of the various slip-parameters of flow stress points to $(211)[\bar{1}11]$ slip system, which is responsible for the yielding of ultra-pure Ta single crystals in regime III, like that in regime II.
4. A common slip system $(211)[\bar{1}11]$ for regimes III and II in the CRSS–T curve of ultra-pure Ta single crystals shows that the distinctions in the two regimes can be attributed to the difference in the values of the pre-exponential factor $\dot{\gamma}_o$ in the Arrhenius strain-rate equation. Most probably, the density of mobile

dislocation is low in regime III ($T < 250$ K) as compared with that in regime II (250–400 K).

5. Identification of $(211)[\bar{1}11]$ slip system in regime III using either the entire CRSS–$\dot{\gamma}$ data for a range of deformation temperatures collectively, which leads to $\dot{\gamma}_o \approx 10^5 s^{-1}$, or that for an individual deformation temperature assuming $\dot{\gamma}_o \approx 10^7 s^{-1}$, is due to the mathematical structure of the Arrhenius strain-rate equation, which is such that the variation of the pre-exponential factor $\dot{\gamma}_o$ does effect the activation energy $W = kT\ln(\dot{\gamma}_o/\dot{\gamma})$ in a substantial way.

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