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Healing the cracks in crystalline solids under uniaxial compression normal to the plane of crack deposition

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The results of experimental and theoretical investigations on the process of healing the artificially created disc-like cracks in uniaxially compressed samples of galvanic purified (99.999%) polycrystalline copper at room (T_{room}) and high (T=873 K) temperatures are described. It has been shown that at $T=T_{room}$ under loading, cracks emitting dislocation loops reduce their radius to some stationary value depending on loading; dislocation mechanism of healing takes place. The obtained calculated dependence of the crack radius on loading has been experimentally supported.

It has been shown that at high temperature, the formed after loading dislocation assemblage becomes quasi-stationary due to diffusion dissolving the dislocation loops and generating the new ones – that is dislocation-diffusion mechanism of healing. The calculated relations describing the process have been obtained and experimentally tested. The assumption has been made on possible dissolution of dislocation loops at the expense of absorption of interstitial atoms migrating over lattice by crowdion mechanism.

Keywords: crack, dislocation loop, stationary and quasi-stationary state, interstitial atom, crowdion, dislocation and dislocation-diffusion mechanism.

Изложены результаты экспериментального и теоретического исследований процесса залечивания дискообразных искусственно созданных трещин в одноосно сжимаемых образцах гальванически очищенной (99,999 %) поликристаллической меди при комнатной (T_{room}) и высокой (T=873 К) температурах. Показано, что при $T=T_{room}$ при нагружении образца трещины, испуская дислокационные петли, уменьшают свой радиус до некоторого стационарного значения, зависящего от нагрузки – дислокационный механизм залечивания. Полученная расчетная зависимость радиуса трещины от нагрузки экспериментально подтверждена.

Показано, что при высокой температуре образующееся после нагружения дислокационное скопление вследствие диффузионного растворения дислокационных петель и рождения новых становится квазистационарным – дислокационно-диффузионный механизм залечивания. Получены расчетные соотношения, описывающие указанный процесс, которые проверены экспериментально. Высказано предположение о возможном растворении дислокационных петель за счет поглощения межузельных атомов, мигрирующих в решетке краудионным механизмом.

Ключевые слова: трещина, дислокационная петля, стационарное и квазистационарное состояния, межузельный атом, краудион, дислокационный и дислокационно-диффузионный механизмы.

Викладені результати експериментального і теоретичного досліджень процесу заліковування дископодібних штучно створених тріщин в зразках гальванічно очищеної (99,999 %) полікристалічної міді, що одноосно стискаються, при кімнатній (T_{room}) і високій (T=873 К) температурах. Показано, що при $T=T_{room}$ при навантаженні зразка тріщини, випускаючи дислокаційні петлі, зменшують свій радіус до деякого стаціонарного значення, залежного від навантаження, – дислокаційний механізм заліковування. Отримана розрахункова залежність радіусу тріщини від навантаження експериментально підтверджена.

Показано, що при високій температурі дислокаційне скупчення, що утворюється після навантаження, унаслідок дифузійного розчинення дислокаційних петель і народження нових стає квазістаціонарним – дислокаційно-дифузійний механізм заліковування. Отримані розрахункові співвідношення, що описують вказаний процес, які перевірені експериментально. Висловлено припущення про можливе розчинення дислокаційних петель за рахунок поглинання міжвузельних атомів, мігруючих в решітці краудіонним механізмом.

Ключові слова: тріщина, дислокаційна петля, стаціонарний і квазістаціонарний стани, міжвузельний атом, краудіон, дислокаційний і дислокаційно-дифузійний механізми.

Introduction

Behavior of cracks in single crystals determines in many aspects their carrier ability and durability of work under loading. Studying the possibilities of healing remains a problem actual at all times. It is known that in plastic materials the cracks are able to self-healing (if mouths of cracks are sharp enough), and the plastic zone occurs around the crack [1-3]. This phenomenon is analogous to the effects of plasticity under powders sintering and self-compaction. Under uniaxial loading, like under full compression, crack healing by the dislocation-diffusion mechanism may be expected.

In the present work, we give the results of studying the mechanisms and kinetics of crack healing under uniaxial loading at low (room) and high (T=873 K) temperatures.

Materials and methods of the experiment

As the sample material, pure (99.999 %) and well annealed polycrystalline copper was used as both widely used material and suitable model object.

Each sample with cracks consisted of two plates with sizes (20×20×5) mm. One of the surfaces (20×20) mm of each plate was properly treated as to its flatness and mirror smoothness. In one of the plates, flat-bottom hollows with diameter to 1.5 mm and depth ($10^{-4} \div 10^{-3}$) cm were made using a special attachment. The plates were joined by pairs (with and without hollows) and then were subjected to diffusion welding at $T=1073$ K in vacuum ($10^{-5} \div 10^{-4}$) mm Hg during 30 min under loading below Peierls threshold, afterwards were annealed in vacuum 10^{-4} mm Hg without loading at $T=1073$ Kfor structure normalization. The initial sizes of cracks in the samples obtained were the following: radius $a_0=(2\div5)\cdot10^{-2}$ cm and thickness $(3\div5)\cdot10^{-4}$ cm. Experiments were carried out at room (T_{room}) and high (T=873 K) temperatures. Crack sizes were measured using an optical microscope.

Results and Discussion

Under applied loading, the stress state occurs in the neighborhood of the crack mouth, while on the surface of the mouth – dislocation loops of vacancy type are generated forming a dislocation assemblage with opposite stress deactivating the source on the mouth surface, so the healing process comes to stop. The crack radius attains some stable value *a* corresponding to a given value of applied stress σ; the both are related as:

$$1-\left(\frac{a}{a_0}\right)^2 = B\sigma^3, \qquad (1)$$

where $B=\frac{2\pi(1-\nu)c^{1/2}}{a_0^{1/2}G\sigma_p^2}$, ν is Poisson coefficient, a_0 is initial radius of the crack, *c* is thickness (or height) of the crack, *G* is shear modulus, σ_p is critical stress of shear (Peierls barrier).

Such state will be stable, if the assemblage formed near the mouth is stable. This is possible at low (room) temperature. Obtained experimental data represented in coordinates $1-(a/a_0)^2$ versus σ^3 are really linearized (Fig. 1), and σ_p value following from the plot slope is quite reasonable: $\sigma_p/G\approx0{,}5\cdot10^{-5}$.

In the extreme case of high temperature [2], vacancy type prismatic dislocation loops quickly formed a dislocation assemblage and reduced the crack radius from a_0 to a_0', are dissolved by diffusion; the opposite stress of the dislocation assemblage decreases that gives a possibility to generating new loops and further healing. At any temperature, generation of dislocation loops begins immediately after loading application, and the dislocation assemblage occurs quickly with corresponding reducing the crack radius to a'_0. At low temperature a'_0 is some stable value corresponding to a given loading level.

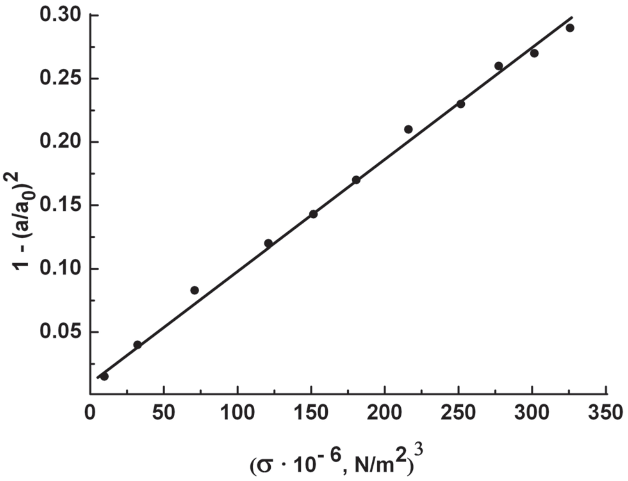

Fig.1. Dependence $1-(a/a_0)^2$ on σ^3.

At high temperature, a'_0 radius corresponds to loops coming out from the crack mouth for forming a quasi-stationary assemblage. This is initial state for further crack healing due to diffusion dissolution of the assemblage loops and replacement these by new loops (Fig. 2).

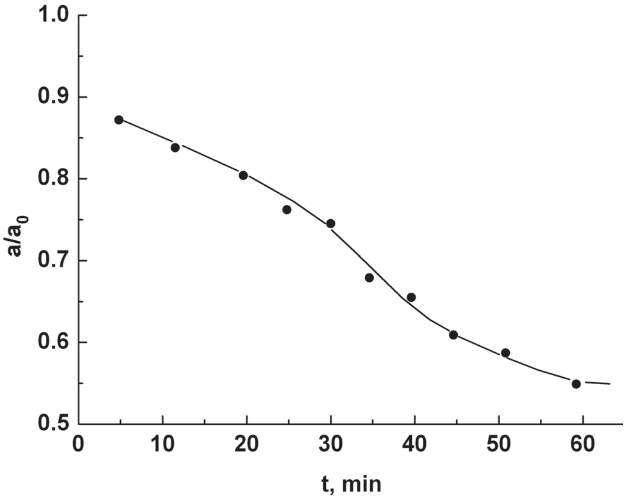

Fig.2. Dependence of stabilized relative crack size (a/a_0) on loading exposure time *t* under external compressive loading $\sigma\approx5\cdot10^6$ N/m^2.

Such mechanism of healing is called as dislocation-diffusion one.

Kinetic equation describing the dependence *a(t)* can be obtained, if to equate the flux of "emptiness" brought out from the crack volume dV_{cr}/dt to the "emptiness" flux from dissolved dislocation assemblage surrounding the mouth, and to take into consideration the equality of the dislocation assemblage opposite stress σ_{tur} and the stress caused by external loading σ; as a result we obtain a differential equation [3] from which it follows:

$$1-\left(\frac{a}{a'_0}\right)^2=\left(\alpha\gamma+\alpha\beta D_V\Delta C_i\right)\frac{\left(t-t_0\right)}{\sigma_p^2}, \qquad (2)$$

where $\alpha=\frac{2}{\left(a'_0\right)^2}\frac{\pi a_0^{3/2}\sigma^3}{c^{3/2}}$, $\beta=\frac{4\pi\left(1-\nu\right)R_l}{Gb\ln\left(8R_l/b\right)}$,

$\gamma=\frac{D\omega}{kT}$, t, t_0 are, respectively, the current time and the time for formation of a quasi-stationary dislocation assemblage at the vertex of the crack (here t_0 = 5 min); a_0, a, a_0' are, respectively, initial (before loading) and current radii of the crack, and radius to time t_0 ($a_0 = 4.5\cdot10^{-4}$ m, $a_0' = 0.88\ a_0$); $c = 4\cdot10^{-6}$ m is crack thickness; $\nu = 0.3$ is Poisson coefficient; $b \approx 3\cdot10^{-10}$ m is Burgers vector; $\omega = 1.18\cdot10^{-29}$ m^3 is atomic volume; $k = 1.38\cdot10^{-23}$ J/K is Boltzmann constant ; T is experimental temperature (T = 873 K); R_l is radius of an emitting dislocation prismatic loop (taken as $R_l \approx c/2 = 2\cdot10^{-6}$ m); $G = 4.15\cdot10^{10}$ N/m^2 is shear modulus in copper; $\sigma \approx 5\cdot10^6$ N/m^2 is stress from external loading; D is self-diffusion coefficient of atoms in copper (at T = 873 K, $D = 3.1\cdot10^{-17}$ m^2/s); $D = D_V C^0_V$; D_V is vacancy diffusion coefficient; C^0_V is equilibrium concentration of vacancies at given temperature T; $\Delta C_i = C_i - C^0_i$ is supersaturation of the lattice by interstitial atoms; C_i, C^0_i are, respectively, real and equilibrium concentrations of interstitials at temperature T; σ_p is Peierls threshold.

The first term in parentheses corresponds to contribution into crack healing of loops diffusion dissolution by vacancy mechanism, and the second – to contribution of loop diffusion dissolution into crack healing due to absorption of interstitial atoms. The first term is the known value. In the second one – ΔC_i is unknown. If $\Delta C_i=0$ is assumed, then after plotting dependence (a/a'_0) versus $(t-t_0)$ in coordinates $1-(a/a'_0)^2$ versus $(t-t_0)$ from the plot slope we obtain $\sigma_p / \text{G} \approx 0,34$. This value, in principle, is reasonable for given experimental conditions therefore we cannot estimate the contribution of interstitials.

On the other hand, it is known that under conditions like local plastic deformation, there take place intersections of dislocation screw parts generating interstitials and vacancies [4]. Concentrations of both components are almost equal. But, because of high mobility of interstitials [4] the quantity of generated interstitial atoms is larger therefore these are in excessive concentration.

The second circumstance is related with the fact that external applied stress lowers energy barrier for generation of an interstitial by the value σbla, and concentration of interstitials can be determined from the relation [4]:

$$C_i = Be^{-\frac{U_{fi}-\sigma bla}{kT}} . \qquad (3)$$

According to [4], $\text{B}\approx 1$, l is length of a dislocation assemblage. If to assume the terms in parentheses of (2) be equal, it follows: $\Delta C_i \approx C_i \approx 6{,}2\cdot10^{-13}$. From (3) it follows that at $\sigma \approx 5\cdot10^6$ N/m^2, it should be $l \approx \frac{U_{fi}+kT\ln C_i}{\sigma ba} \approx (4{,}6 \div 4{,}8)\cdot10^{-7}$ m. This l value is in accordance with data from [4], therefore the assumption on the possible participation of interstitial transfer is reasonable. The most probable mechanism of interstitial atom migration may be “relay-race” motion in a close-packed ray in the form of crowdion configuration [5, 6].

Conclusions

It has been shown in the work that at low temperature there takes place dislocation mechanism of healing; its result is determined by the level of loading applied.

At high temperature, due to diffusion dissolution of dislocation loops and generation of new ones, the healing process becomes permanent and is described by the kinetic equation (dislocation-diffusion mechanism of healing). It follows from experiments that dissolution of dislocation prismatic loops may be caused not only by action of the vacancy diffusion mechanism, but also by absorption of interstitial atoms which occur in excess concentration in plasticity processes within crack mouth and migrate over the lattice in the form of crowdion configurations.

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