MASTER

Diffusional Creep of Multicomponent Systems

Progress Report

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Abstracts

The accomplishments this year are as follows:

1. A paper on penetration creep was presented at the spring meeting of TMS-AIME and it was well received. Two organizations approached us for details with the intention to use our technique in their tests.
2. The size of the plastic zone ahead of the penetrating rod was observed and measured for the first time. This was done in a transparent amorphous polymer which became birefringent under non-hydrostatic stresses. The first fringe corresponded to approximately the yield stress of the material and hence delineated the plastic zone. It was found that the zone size was about 3-5 times the size of the rod and increased with applied load.
3. A manuscript entitled "Simultaneous Processes in the Creep of Uranium Dioxide" was submitted to J. Nuclear Materials. ~~A copy is attached in this report.~~
4. Hydrogen embrittlement was studied from the viewpoint of the interaction of hydrogen with the stress field of particles. Some details are summarized in this report.
5. The interaction between dislocation loops was studied to include shear components of the Burgers vector. It turned out that this additional component could stabilize both the cuboidal arrangement and the stair-step configuration of square dislocation loops. These results were used to explain certain precipitation morphologies.
6. The main effort of this project was to produce penetration creep data on multicomponent alloy systems. However, the progress was slower than expected because of limitations of our supporting equipment. During this

period, we built two low temperature furnaces, a room temperature controller, a vacuum zone refining apparatus, an environment chamber, a high temperature inert atmosphere setup, and several improvements on the penetration creep arrangements.

7. The only creep results we obtained so far were the temperature and stress dependences of penetration velocity on a beta-tin single crystal, and the stress dependences of lead and succinonitrile polycrystals. They agree with published results in the literature by conventional methods.

Hydrogen Embrittlement

As part of a related study on the interaction of mobile solutes with internal stress fields in a solid, the interaction of hydrogen with a crack and with dispersed particles was studied and reported as part of an invited panel presentation at a recent international conference.

In the presentation, the basic thermodynamics was reviewed and then the interaction of hydrogen with mode I, mode II, and mixed mode cracks was described as shown in Figs. 1-3 here. Briefly, depending on the mode, the flow of hydrogen may be toward the crack tip or away from the crack tip. The cracked surfaces provide a discontinuity in the flow pattern of hydrogen caused by the crack stress fields.

However, unless the material is very brittle, any ductility will produce a plastic zone ahead of the crack tip. The interaction of hydrogen with the crack tip stresses is thus not as important as that with the plastic zone. Another way of looking at the problem is that a material with any ductility does not obey the original Griffith criterion. Any effect on the surface energy caused by the diffusion of hydrogen toward the crack tip, which is the essence of decohesion theory, cannot have any magnitude of importance unless the material is extremely brittle. Therefore it is more important and fruitful to look at the interaction of hydrogen within the plastic zone.

Moutier cycles were used to deal with general chemical equilibria in a stress field. The concept of strain volumes was introduced which relates to the effect of stress on the equilibrium constant. The problem of the reorientation of hydride particles in a stress field was discussed as an

example.

The interaction of hydrogen with precipitate particles was considered more important than that with dislocations in the plastic zone. The reason was given as follows: Dispersed systems are more susceptible to hydrogen embrittlement than homogeneous systems. In the dispersed system, crack nucleation and propagation take place by the coalescence of voids produced at the particles due to plastic flow. Thus a possible cause of hydrogen embrittlement is the interaction of hydrogen with particles in the plastic zone. This interaction can be in the form of enhanced nucleation or growth of voids around these particles.

The interaction of hydrogen with small particles whose stress fields can be approximated by dislocation loops was discussed as shown in Figs. 4-5 here. It was noted that the redistribution of hydrogen could cause segregation of hydrogen toward certain parts of the particles. This effect was illustrated more clearly in the case of large particles as shown in Figs. 6-7 here. For prismatic particles, hydrogen tends to segregate at all the edges and for shear particles, it tends to segregate at certain edges and part of the interface. Such localized segregation could be a cause for void nucleation and subsequent growth.

Void nucleation at a particle can be modelled by the use of a wedge disclination quadrupole as shown in Fig. 8. In a two dimensional approximation, the particle has a dimension x along the plastic shear flow direction and a dimension $2L$ perpendicular to it. After plastic flow a misfit strain ϵ between the particle and the matrix is produced which is usually much larger than the elastic misfit before plastic flow. Before void nucleation, the misfit strain energy is the same as that of a wedge disclination quadrupole

which is shown in Fig. 8. When this strain energy exceeds the surface energy associated with the two voids, the latter may be nucleated. Thus there is a critical plastic strain for void nucleation. This plastic strain is a lower limit of the ductility of the material without hydrogen.

At the presence of hydrogen, several processes may take place to reduce the ductility of the material. One of them is the interaction of hydrogen with the misfit stress field of the particle before void nucleation. This process brings hydrogen into the vicinity of the particle, either by diffusion or by dislocation transport. Then a second process can take place which is the interaction of hydrogen with the particle-matrix interface to enhance decohesion and to facilitate void nucleation. After void nucleation, the misfit stress field disappears and the hydrogen becomes supersaturated. Now a third process can take place in which the supersaturated hydrogen can become molecular hydrogen and pressurize the voids to enhance their propagation. It is seen that all these processes could cause a reduction in ductility of the material.

A schematic representation of this embrittling effect is shown in Fig. 9. The misfit strain energy of the particle is plotted versus strain. Without hydrogen, voids will be nucleated when the strain energy exceeds the surface energy as shown. This strain is a lower limit of the ductility of the material. With hydrogen, extra chemical energy is stored around the particle in addition to strain energy. This chemical energy can be released at the time of void nucleation either in the form of reduced surface energy or in the form of pressure in the voids. This chemical energy is represented by the dotted line marked H potential. It goes through a maximum because of the fact that the total amount of hydrogen is constant and at increasing strain

(more slip bands or dislocations) the amount per particle decreases. The combined effects of both the chemical energy of hydrogen and the misfit strain energy of the particle is to reduce the ductility as shown. The effect may be small or large depending on the circumstances and the level of $2\gamma_L$ as illustrated.

Precipitation Morphology and Interaction between Dislocation Loops

In another related study, the interaction between dislocation loops was examined and used to understand certain precipitation morphologies. Tanner and Laughlin¹ studied the microstructures concomitant with quenching, aging and reversion of a Cu-Be alloy of 1.3 wt.% Be and discovered that, about the Guinier-Preston Zone (G.P.Z.) solvus, the tetragonal metastable phase γ'' nucleate within the quenched-in tweed matrix both homogeneously and heterogeneously. When the alloy iced-brine quenched from 800°C, aged 208 hours at 270°C, dislocation strain fields were the initial nucleation sites. When these were saturated, subsequent nucleation was quasi-homogeneous, displaying a rather unusual "Sympathetic" behavior. That is, coherent $\{100\}\gamma''$ plates^s appeared randomly throughout the matrix in groups of 6 in the form of cuboidal configuration. These in turn became new sites for heterogeneous nucleation.

Meanwhile Phillip and Tanner² found that, when Cu-Be system of 0.8wt.% Be iced-brine quenched from 800°C and aged at 100°C for 97.5 hours or at 198°C for one hour, a rather high density of $\{100\}$ G.P.Z. plates in regular stair-step arrays were revealed.

An attempt was made to rationalize these "multiple homogeneous nucleation" in terms of complex mutual coherency strain field interactions. These coherency strain fields can be approximated by those of square dislocation loops.

Based on the point force method, the stress field at a point (x,y,z) due to a rectangular interstitial dislocation loop with four corners located at (x_1',y_1',z') , (x_1',y_2',z') , (x_2',y_2',z') , (x_2',y_1',z') and Burger's vector b_z' is

$$\sigma_{xx} = \left(\frac{-2\nu(y-y')}{R(R-x+x')} + \frac{\partial}{\partial z'} \frac{(x-x')(z-z')}{R(R-y+y')} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (1)$$

$$\sigma_{yy} = \left(\frac{-2\nu(x-x')}{R(R-y+y')} + \frac{\partial}{\partial z'} \frac{(y-y')(z-z')}{R(R-x+x')} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (2)$$

$$\sigma_{zz} = \left(-1 - (z-z') \frac{\partial}{\partial z'} \right) \left[\frac{(x-x')}{R(R-y+y')} + \frac{(y-y')}{R(R-x+x')} \right] \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (3)$$

$$\sigma_{xy} = \left(\frac{(1-2\nu)}{R} - \frac{(z-z')^2}{R^3} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (4)$$

$$\sigma_{yz} = \left((z-z') \frac{\partial}{\partial z'} \frac{(z-z')}{R(R-x+x')} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (5)$$

$$\sigma_{zx} = \left((z-z') \frac{\partial}{\partial z'} \frac{(z-z')}{R(R-y+y')} \right) \begin{vmatrix} x_2' & x_2' \\ x_1' & y_1' \end{vmatrix} \quad (6)$$

where $R^2 = (x-x')^2 + (y-y')^2 + (z-z')^2$ and the unit of the stress is $\mu b_z' / 4\pi(1-\nu)$.

Similarly the stress field produced by a pure shear rectangular dislocation loop with Burger's vector b_x' is

$$\sigma_{xx} = \frac{-(z-z')}{R(R-y+y')} \left(1 + \frac{(x-x')^2}{R^2} + \frac{(x-x')^2}{R(R-y+y')} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (7)$$

$$\sigma_{yy} = \left(-\frac{2\nu(z-z')}{R(R-y+y')} + \frac{(y-y')(z-z')}{R^3} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (8)$$

$$\sigma_{zz} = \frac{(z-z')}{R(R-y+y')} \left(1 - \frac{(z-z')^2}{R^2} - \frac{(z-z')^2}{R(R-y+y')} \right) \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (9)$$

$$\sigma_{xy} = \left[-\frac{(1-\nu)(z-z')}{R(R-x+x')} + \frac{(x-x')(z-z')}{R^3} \right] \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (10)$$

$$\sigma_{yz} = \left[-\frac{\nu}{R} + \frac{(z-z')^2}{R^3} \right] \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (11)$$

$$\sigma_{zx} = \frac{(1-\nu)(y-y')}{R(R-x+x')} + \frac{(x-x')}{R(R-y+y')} \left(1 - \frac{(z-z')^2}{R} \right) - \frac{(z-z')^2}{R(R-y+y')} \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (12)$$

all with unit $\mu b_x'/4\pi(1-\nu)$.

From these equations the interaction energies between two square dislocation loops and the formation energies of cuboidal and stair-step configurations are summarized as follows:

1. The interaction energies between two loops whose relative configurations are shown in Fig. 10 are:

$$W_1 = -\frac{\mu b_x' b_x}{4\pi(1-\nu)} \left[(1-\nu)(x-x') \ln(R-x+x') + (y-y') \ln(R-y+y') \right. \\ \left. + (2-\nu)R + \frac{(z-z')^2 R}{(x-x')^2 + (z-z')^2} \right] \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (13)$$

$$W_2 = \frac{\mu b_x' b_y}{4\pi(1-\nu)} \left[\nu(y-y') \ln(R+x-x') + \nu(x-x') \ln(R+y-y') \right. \\ \left. - (1+\nu)(z-z') \tan^{-1} \frac{(x-x')(y-y')}{(z-z')R} \right] \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \begin{vmatrix} x_2' & y_2' \\ x_1' & y_1' \end{vmatrix} \quad (14)$$

$$W_3 = \frac{\mu b'_x b_z}{4\pi(1-\nu)} \left(\frac{(x-x')(z-z')}{R-y+y'} - (z-z') \ln(R+x-x') \right) \left| \begin{matrix} x'_2 & y'_2 & x_2 & y_2 \\ x'_1 & y'_1 & x_1 & y_1 \end{matrix} \right| \quad (15)$$

$$W_4 = \frac{\mu b'_x b_x}{4\pi(1-\nu)} \left(R + (y-y') \ln(R-y+y') - \frac{(x-x')^2}{R-y+y'} \right) \left| \begin{matrix} x'_2 & y'_2 & y_2 & z_2 \\ x'_1 & y'_1 & y_1 & z_1 \end{matrix} \right| \quad (16)$$

$$W_5 = \frac{\mu b'_x b_y}{4\pi(1-\nu)} \left(-(1-\nu)(y-y') \ln(R+x-x') - (2-\nu)(x-x') \ln(R+y-y') \right. \\ \left. + (1-\nu)(z-z') \tan^{-1} \frac{(x-x')(y-y')}{(z-z')R} \right) \left| \begin{matrix} x'_2 & y'_2 & y_2 & z_2 \\ x'_1 & y'_1 & y_1 & z_1 \end{matrix} \right| \quad (17)$$

$$W_6 = \frac{\mu b'_x b_z}{4\pi(1-\nu)} \left((1-\nu)(z-z') \ln(R+x-x') + (1-\nu)(x-x') \ln(R+z-z') \right. \\ \left. - \frac{(x-x')(z-z')}{R-y+y'} - (1-\nu)(y-y') \tan^{-1} \frac{(x-x')(z-z')}{(y-y')R} \right) \left| \begin{matrix} x'_2 & y'_2 & y_2 & z_2 \\ x'_1 & y'_1 & y_1 & z_1 \end{matrix} \right| \quad (18)$$

$$W_7 = \frac{\mu b'_x b_x}{4\pi(1-\nu)} \left((2-\nu)R + (1-\nu)(x-x') \ln(R+x-x') \right) \left| \begin{matrix} x'_2 & y'_2 & x_2 & z_2 \\ x'_1 & y'_1 & x_1 & z_1 \end{matrix} \right| \quad (19)$$

$$W_8 = \frac{\mu b'_x b_y}{4\pi(1-\nu)} \left(-2\nu(x-x') \ln(R+y-y') + (1-2\nu)(y-y') \ln(R+x-x') \right. \\ \left. + 2\nu(z-z') \tan^{-1} \frac{(x-x')(y-y')}{(z-z')R} \right) \left| \begin{matrix} x'_2 & y'_2 & x_2 & z_2 \\ x'_1 & y'_1 & x_1 & z_1 \end{matrix} \right| \quad (20)$$

$$W_9 = \frac{\mu b'_x b_z}{4\pi(1-\nu)} \left(\nu(z-z') \ln(R+x-x') - (1-\nu)(x-x') \ln(R+z-z') \right. \\ \left. + (1+\nu)(y-y') \tan^{-1} \frac{(x-x')(z-z')}{(y-y')R} \right) \left| \begin{matrix} x'_2 & y'_2 & x_2 & z_2 \\ x'_1 & y'_1 & x_1 & z_1 \end{matrix} \right| \quad (21)$$

$$W_{10} = \frac{\mu b_z^2 b_z}{4\pi(1-\nu)} \left[(y-y') \ln(R-y+y') + (x-x') \ln(R-x+x') \right. \\ \left. + \frac{(x-x')^2}{R-y+y'} + \frac{(y-y')^2}{R-x+x'} \right] \Bigg|_{x_1'}^{x_2'} \Bigg|_{y_1'}^{y_2'} \Bigg|_{x_1}^{x_2} \Bigg|_{y_1}^{y_2} \quad (22)$$

$$W_{11} = \frac{\mu b_z^2 b_x}{4\pi(1-\nu)} \left[2\nu(z-z') \ln(R-x+x') + 2\nu(x-x') \ln(R-z+z') \right. \\ \left. + \frac{(x-x')(z-z')}{R-y+y'} + 2\nu(y-y') \tan^{-1} \frac{(x-x')(z-z')}{(y-y')R} \right] \Bigg|_{x_1'}^{x_2'} \Bigg|_{y_1'}^{y_2'} \Bigg|_{y_1}^{y_2} \Bigg|_{z_1}^{z_2} \quad (23)$$

where μ is shear modulus, ν is Poisson's ratio and $R^2 = (x-x')^2 + (y-y')^2 + (z-z')^2$.

2. The formation energy of a cuboidal configuration of square dislocation loops is:

$$\begin{aligned}
 W_{\text{cub}} = & (2.72477 + \ln \frac{r_0}{a}) [(b_{1x} - b_{3x})(b_{5x} - b_{6x}) + (b_{3y} - b_{1y})(b_{2y} - b_{4y}) \\
 & + (b_{2z} - b_{4z})(b_{5z} - b_{6z})] - 1.67498 [(b_{1x} + b_{3x})(b_{2z} + b_{4z}) \\
 & + (b_{2y} + b_{4y})(b_{5x} + b_{6x}) + (b_{5z} + b_{6z})(b_{1y} + b_{3y})] + 1.4811 [(b_{1z} + \\
 & b_{3z})(b_{2x} + b_{4x}) + (b_{2x} + b_{4x})(b_{5y} + b_{6y}) + (b_{5y} + b_{6y})(b_{1z} + b_{3z})] \\
 & + 0.160858 (b_{1x}b_{3x} + b_{1y}b_{3y} + b_{2y}b_{4y} + b_{2z}b_{4z} + b_{5z}b_{6z} + b_{5x}b_{6x}) \\
 & + 3.0545 (b_{1z}b_{3z} + b_{2x}b_{4x} + b_{5y}b_{6y})
 \end{aligned} \tag{24}$$

where r_0 is the core radius and a is the side of the cube.

3. The formation energy of a stair-step configuration of square dislocation loops is:

$$\begin{aligned}
 W_{\text{str}} = & (3.0048 + \ln \frac{r_0}{a}) [b_{2y}(b_{1y}+b_{3y})+b_{2z}(b_{1z}+b_{3z})+b_{4y}(b_{3y}+b_{5y}) \\
 & +b_{4z}(b_{3z}+b_{5z})+b_{5y}b_{6y}+b_{5z}b_{6z}] + (2.72477 + 0.7 \ln \frac{r_0}{a})(b_{1x}b_{2x} \\
 & +b_{2x}b_{3x}+b_{3x}b_{4x}+b_{4x}b_{5x}+b_{5x}b_{6x}) - 1.67498(b_{1y}b_{2z}+b_{2z}b_{3y}+b_{3y}b_{4z} \\
 & +b_{4z}b_{5y}+b_{5y}b_{6z}) + 1.4811(b_{1z}b_{2y}+b_{2y}b_{3z}+b_{3z}b_{4y}+b_{4y}b_{5z}+b_{5z}b_{6y}) \\
 & + 0.142006(b_{1x}b_{3x}+b_{3x}b_{5x}+b_{2x}b_{4x}+b_{4x}b_{6x}) - 0.761677[b_{3y}(b_{1z}+b_{5z}) \\
 & +b_{3z}(b_{1y}+b_{5y})+b_{4y}(b_{2z}+b_{6z})+b_{4z}(b_{2y}+b_{6y})] - 0.463614[b_{3y}(b_{1y}+b_{5y}) \\
 & +b_{4z}(b_{2z}+b_{6z})] + 0.407653[b_{3z}(b_{1z}+b_{5z})+b_{4y}(b_{2y}+b_{6y})] \\
 & + 0.019473(b_{1x}b_{4x}+b_{2x}b_{5x}+b_{3x}b_{6x}) - 0.213511(b_{1y}b_{4y}+b_{1z}b_{4z}+b_{2y}b_{5y} \\
 & +b_{2z}b_{5z}+b_{4y}b_{6y}+b_{4z}b_{6z}) + 0.205781(b_{1z}b_{4y}+b_{2y}b_{5z}+b_{3z}b_{6y}) \\
 & - 0.215423(b_{1y}b_{4z}+b_{2z}b_{5y}+b_{3y}b_{6z}) + 0.03274(b_{1x}b_{5x}+b_{2x}b_{6x}) \\
 & - 0.0957(b_{1y}b_{5y}+b_{2z}b_{6z}) - 0.104486(b_{1y}b_{5z}+b_{1z}b_{5y}+b_{2y}b_{6z}+b_{2x}b_{6y}) \\
 & + 0.00782(b_{1z}b_{5z}+b_{2y}b_{6y}) + 0.007855b_{1x}b_{6x} - 0.04903(b_{1y}b_{6y}+b_{1z}b_{6z}) \\
 & + 0.049732b_{1z}b_{6y} - 0.05193b_{1y}b_{6z}
 \end{aligned} \tag{25}$$

where r_0 is the core radius and a is the side of the square dislocation loop.

Based on the equations for the formation energies of the cuboidal and stair-step configurations of square dislocation loops, we came to the following conclusions:

(1) For pure prismatic dislocation loops the formation energies of both cuboidal and stair-step configurations are positive, indicating that precipitates without any shear displacement of the crystal lattice atomic planes cannot form these two configurations.

(2) For square dislocation loops with pure shear Burger's vector b_s , the formation energy of the most stable cuboidal configurations with the relative shear directions shown in Fig. 11 is

$$W_c = (3.149 + 2.1 \ln \frac{r_0}{a}) b_s^2 \frac{\mu}{4\pi(1-\nu)} \quad (26)$$

where r_0 is the core radius and a is the edge length of the square dislocation loops. For stair-step configuration with a/r_0 less than 1435, the most negative formation energy is

$$W_{s1} = -11.119 b_s^2 \frac{\mu}{4\pi(1-\nu)} \quad (27)$$

with relative shear directions shown in Fig. 12. For a/r_0 ratio larger than 1436, the most stable formation energy is

$$W_{s2} = (14.323 + 3.5 \ln \frac{r_0}{a}) b_s^2 \frac{\mu}{4\pi(1-\nu)} \quad (28)$$

with the relative shear directions shown in Fig. 13. From equations (26), (27), and (28) we can conclude that if the precipitates formed are of pure shear type, and with an edge length a such that $a/r_0 \leq 892$ or $a/r_0 \geq 2927$, they will form the stair-step configuration. On the other hand, if the edge length is such that $893 \leq a/r_0 \leq 2926$ then they will form the cuboidal configuration (Fig. 14).

(3) For square dislocation loops with both prismatic and shear components, the stable morphology of the precipitates with $d = b_s/b_p$ less than 3 and

$100 \leq a/r_0 \leq 10000$ is stair steps with formation energy (consists six square dislocation loops)

$$W_s = (-11.119d^2 + 22.158d + 9.719 + 10d \ln \frac{r_0}{a}) \frac{\mu b_p^2}{4\pi(1-\nu)} \quad (29)$$

Equipment Building

While we were about ready to collect data in a wide range of temperatures and stresses, we ran into some limitations of our previous equipment. Since Materials Science is new at the University of Rochester, we are not as fully equipped as places like Cornell. Our students have to build most of the equipment themselves. While it is a good education and training for our students, it does delay the production of valuable creep data. Some of the new equipment building is described as follows:

1. Low Temperature Creep Equipment:

The major equipment for the low temperature penetration creep has been rebuilt to accomodate high stress tests. As shown in Figs. 15 and 16, the thin rod held by the chuck was attached to the lower end of the shaft which was guided by bushings for vertical motion. The stress was applied by putting weights on the top of the platform at the upper end of the shaft. A linear displacement transducer was attached to the platform to record the penetration rate.

Two furnaces were built for the penetration creep to be performed at temperatures up to 500°C. They are shown in Fig. 17. The one shown in Fig. 3b with windows on the side was designed to observe the plastic zone ahead of the tip of the rod in transparent materials by means of polarized light. A RFL Model 871 temperature controller was used with a variac to control the temperature of the furnace. The entire setup is shown in Fig. 18.

Since the output of the displacement transducer is very sensitive to the variation in room temperature, an on-off type temperature controller was built to fire a room heater. Figure 19 shows the controller and the heater.

A vacuum zone refining apparatus was constructed for the purpose of preparing pure materials. It is shown in Figs. 20 and 21. It can also be used for vacuum annealing.

2. High Temperature Creep Equipment:

Since the room temperature may fluctuate a few degrees during the test and the circulation of air in the building may affect the output of the LVDT, a big rectangular box was built to stabilize the air inside. Everything on the table is inside this big box: the steel framework, the furnace, the loading system, and the LVDT.

The front panel of the box was made of 3/16" thick plexiglas. Because the maximum temperature the plexiglas can stand is about 100°C, and the maximum operating temperature of the LVDT is about 120°C, it is necessary to dissipate some heat that might build up inside the box. Hence, the other sides of the box were made of 1/16" thick Al-alloy. The frame of the box is constructed with equal angles, the front panel was reinforced with stainless steel strip before it was fastened to the frame. A layer of insulation tape was placed in between the frame and the sides of the box to cut down as much leakage as possible.

Two holes were made on the front panel and two gloves were attached to the holes. The LVDT can be manipulated and the weights on the loading pan can be changed through these two gloves.

In order to avoid oxidation of the specimen at high temperatures, the specimen is surrounded by Argon. A two stage regulator capable of a delivery pressure range of 0-30 psig is used to regulate the inert gas. Two miniature needle valves are used to control the flow of gas.

An opening was made at the center of the top circular plate, a

ceramic tube with flange larger than the opening is then inserted into the furnace through the opening, and the upper piece of the ceramic unit is then hung on this ceramic tube. This upper ceramic unit can be moved around, so more data can be extracted from one specimen. On top of this ceramic unit is an Al-alloy disk, it can be fastened to the top circular plate through three sets of bolt and nut and thus lock the top ceramic unit in place. The locking plate also has an opening at the center to pass the inert gas into the ceramic tube which is sealed with silicon oil at the bottom. The air inside the ceramic tube is flushed out and replaced with Argon before bringing up the temperature. The outlet of the box is connected to a bubbler to check the gas flow from the box.

Since the silicon oil is in direct contact with the ceramic tube, and the ceramic tube is partly inside the hot zone of the furnace, a copper tubing with circulating cooling water was used to cool the ceramic tube outside the furnace to keep the temperature of the silicon oil under 150°C.

The LVDT used for this study has been replaced with a more sensitive one, 24 DCDT-100, 1 μ m displacement will produce a signal of about 4.2 mv. Since the LVDT is so sensitive, outside disturbances should be kept to a minimum. A special kind of rubber sheet, isomode rubber, designed to absorb vibration was used. Two layers of this rubber sheet were placed under the big heavy base plate to take care of any small disturbances that might arise from the table by accident, a layer of this rubber sheet was placed under each leg of the table to absorb any vibrations from the floor and the building.

The LVDT unit is enclosed inside the big box. A thermometer was hung adjacent to the LVDT unit to measure the temperature inside the box.

The temperature will reach thermal equilibrium after some time. Once the thermal equilibrium condition is reached, very little temperature effect will result on the LVDT output. The cables connected to the LVDT unit are all coax cables with very low resistance, less than 0.5 ohm. The connections are BNC pomona jacks to avoid any noise that might pick up from the air. The output of the LVDT is connected to a strip chart recorder.

The specimen, 1.25-2.50 cm in diameter and 1.00-1.50 cm long is seated on the top of the lower ceramic unit. It is located in the middle of the furnace within the uniform temperature zone. The temperature of the test specimen is measured by a thermocouple of Type B, inserted into the lower ceramic unit and touched the seat of the specimen. The output of this thermocouple is connected to the strip chart recorder, and is recorded simultaneously with the displacement throughout the test. A two-pen OmniScribe strip chart recorder uses all solid state electronics and has the following features: a full 10" recording chart width, 5 spans of 1, 10, 100 mv, and 1, 10 volts, 11 pushbutton selectable chart speeds, and a digital stepper motor driving rotary web. A ten-turn zero control knob has a range of $\pm 110\%$ of full scale and can be used to set zero point at any position on the chart. A zero check knob can verify position and allow precise measurement of zero signal without disconnecting or shorting input signal. The overall inaccuracy is less than $\pm 0.3\%$ of full scale.

The upper and lower ceramic units are shown in Figs. 22 (inverted) and 23. Figure 24 was taken during a test; the furnace, LVDT, and loading system etc. can be seen in this picture.

Some Preliminary Results

Penetration creep tests have been performed on a beta-Tin single crystal bought from Cornell. Typical penetration creep curves are shown in Fig. 25 where the penetration distance is recorded as a function of time. As expected, the penetration velocity becomes constant after a transient period. The stress and temperature dependence of the steady state penetration velocity was measured and they are plotted in Figs. 26 and 27. Both the stress exponent and the activation energy of penetration creep have values consistent with the reported values in the literature from conventional creep tests.

Penetration creep tests have also been done on lead polycrystals. The stress dependence of the penetration velocity is shown in Fig. 28. The stress exponent has a value also consistent with the value reported in literature by conventional creep tests.

In order to evaluate the stress and temperature dependence of the plastic zone ahead of the tip of the rod, penetration creep test has been done on PMMA and the plastic zone was observed by using polarized light as shown in Figure 29. In Figure 30 the zone size is plotted as a function of load applied.

References

1. L. E. Tanner and D. E. Laughlin, to be published in Proc. 33rd EMSA Meeting, 1975.
2. V. A. Phillips and L. E. Tanner, Acta Met. 21, 441 (1973).

FIG. 1 DILATATION FIELD OF MODE I CRACK

FIG.2 DILATATION FIELD OF MODE II CRACK

FIG. 3 DILATATION FIELD OF MIXED MODE CRACK

FIG.4 DILATATION FIELD OF SMALL PRISMATIC LOOP

UNIT: $b_x (1 - 2\nu) / 500\pi (1 - \nu)$

AREA OF LOOP: a^2

LOOP IN XY PLANE AT ORIGIN

FIG.5 DILATATION FIELD OF SMALL SHEAR LOOP

FIG.6 DILATATION FIELD OF SQUARE PRISMATIC LOOP

FIG. 7 DILATATION FIELD OF SQUARE SHEAR LOOP

FIG. 8 ENERGY OF WEDGE DISCLINATION QUADRUPOLE

FIG.9 VOID FORMATION ENHANCED BY HYDROGEN

FIG. 10

FIG. 11 FOUR MOST STABLE CASES FOR CUBOIDAL CONFIGURATIONS.

FIG. 12 THE RELATIVE SHEAR DIRECTIONS BETWEEN LOOPS FOR STAIR-STEP CONFIGURATION (EQ. 27).

FIG. 13 THE RELATIVE SHEAR DIRECTIONS BETWEEN LOOPS FOR STAIR-STEP CONFIGURATION (EQ. 28).

FIG. 14 THE FORMATION ENERGY VS a/r_0 FOR PURE SHEAR PRECIPITATES IN CUBOIDAL (W_c) AND STAIR-STEP (W_{s1} & W_{s2}) CONFIGURATIONS.

FIG. 15

FIG. 16

(a)

(b)

FIG. 17

FIG. 18

FIG. 19

FIG. 20

FIG. 21

FIG. 22

FIG. 23

FIG. 24

FIG. 25

FIG. 26

FIG. 27

FIG. 28

FIG. 29

FIG. 30