

# The Fracture of Metals with Voids

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## 1 Introduction

It is well known that the fracture phenomenon is studied by the theory of rate processes. We have used Larson-Miller's<sup>(1)</sup> equation to calculate a time of creep rupture. Therefore it is evident that creep rupture is explained by the theory of rate processes. The dimple fracture face of creep rupture or tensile rupture of ductile metals has been thought a result of many void nucleations and these conjunction.<sup>(2)</sup> Void nucleation is advanced from several view points, but it must be considered nonuniform nucleation.<sup>(3)</sup> Fisher<sup>(4)</sup> proposed that fracture of liquid is a phase change from liquid to gas, and he studied fracture time based on uniform nucleation and rate processes. Zhurkov<sup>(5)</sup> had reported for uniaxial tensile test of solid materials that the free energy of activation on tensile rupture is correlated with the heat of sublimation of the material.

A phase change from solid to gas has been hardly discussed at present time,<sup>(6)</sup> because this reaction time is very long and it is difficult to estimate the strain energy. But we thought that it is most reasonable to consider the void nucleation a phase change from solid to gas.

## 2 Phase change

### 2.1 Phase stability

A common equilibrium phase diagram is shown in Fig.1. A saturated vapour pressure of metal is very low, but it is

surely positive, and free energy of activation for a change from solid to gas is very large, therefore a phase change from solid to gas is difficult to occur, and does not discussed.

If a specimen is stated in negative pressure (point B) mainly a spherical negative part of uniaxial tensile stress etc., this solid is clearly unstable. Gas is stable state at point B, so solid at B must be

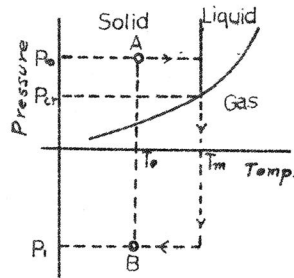


Fig.1 Model of equilibrium phase diagram.

considered under-saturated vapour pressure solid.

2.2 Energy of a phase change

An enthalpy change in equilibrium state from A to B in

Fig.1 is,

$$H = \int_{T_0}^{T_m} C_p^{(s)} dT + \int_{P_0}^{P_{cr}} \left(\frac{\partial h}{\partial P}\right)_T dp + \Delta h(P_{cr}, T_m) + \int_{P_{cr}}^{P_i} \left(\frac{\partial h}{\partial P}\right)_T dp + \int_{T_m}^{T_0} C_p^{(g)} dT$$

Where  $T_m$ ; Melting temperature.  $P_{cr}$ ; Saturated vapour pres..

$C_p$ ; Specific heat of constant pressure.

$\Delta h$ ; Heat of sublimation. Suffix (s), (g); Solid, gas.

As under-saturated vapour pressure solid,

$$\int_{T_0}^{T_m} C_p^{(s)} dT + \int_{T_m}^{T_0} C_p^{(g)} dT = 0$$

so  $H = \Delta h(P_{cr}, T_m) + \int_{P_0}^{P_i} \left(\frac{\partial h}{\partial P}\right)_T dp = \Delta h(P_{cr}, T_m) + \int_{P_0}^{P_i} v(1 - T\alpha) dp$

Where  $v$ ; Atomic volume.  $\alpha$ ; Coefficient of linear expansion.

$$\Delta h(P_{cr}, T_m) \gg \int_{P_0}^{P_i} v(1 - T\alpha) dp$$

$$\therefore H \approx \Delta h(P_{cr}, T_m) \quad \text{--- (1)}$$

2.3 Nucleation with the phase change

Nucleation with the phase change is occurred at point B in

Fig.1. This nucleation must be considered with  $P_i$  and  $P_0$  as

shown in Fig.2.

Where  $P_i$ ; Spherical part of the applied stress.

$P_v$ ; Vapour pressure.

This energy  $W$  is,

$$W = 4\pi r^2 \gamma + PV - P_i V$$

Where  $r$ ; Radius of embryo.

$\gamma$ ; Surface energy.

$V$ ; Volume of embryo.

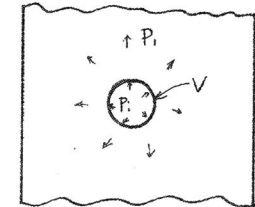


Fig.2 Nucleation

As  $P_i$  is almost zero<sup>(7)</sup>,  $W$  can be calculated to estimate the energy when an applied stress with a spherical negative part make a void with radius  $r$ .  $P_i V$  come to a change of Gibbs free energy with a void or no void. The result of this calculation is<sup>(8)</sup>,

$$W = 4\pi r^2 \gamma - \pi r^3 / 3E(1-\nu)\sigma^2 \quad \text{Where } E \text{; Young's modulus.}$$

$\nu$ ; Poisson's ratio.

$\sigma$ ; Uniaxial tensile stress.

$$W(\text{MAX}) = 256\pi E \gamma^3 / 3(1-\nu)^2 \sigma^4 \quad \text{--- (2)}$$

3 Rate process of the phase change

We get the energy barrier of the phase change at point B from eqn.(1), (2). This rate process may be the Stress-dependent Rate Processes, therefore the free energy of activation is  $H + W(\text{MAX}) - a\sigma$

Where  $a$ ; Activated volume.

This phenomenon is nonuniform nucleation and a stochastic process based on thermal fluctuations, so fracture time is,

$$t_f = Z \nu' \exp\left(-\frac{H + W(\text{MAX}) - a\sigma}{RT}\right) \quad \text{--- (3)}$$

Where  $t_f$ ; Fracture time.  $\nu'$ ; Frequency of lattice vibration.

$R$ ; Universal gas constant.  $T$ ; Absolute temperature.

$Z$ ; Number of activated complex.

#### 4 Experiment

The life-time has been studied in uniaxial tension (constant load) on Aluminium specimens (99.7% pure) after annealing 400°C, 1hr. This result is Fig.3.

These lines are,

0 - lines equations

$$3 - \log 1/t = 17.35 - 9.97 \times 10^3/T$$

$$4 - \log 1/t = 17.53 - 8.49 \times 10^3/T$$

$$5 - \log 1/t = 18.57 - 7.89 \times 10^3/T$$

Where  $\sigma$ ; Nominal stresses (kg/mm)

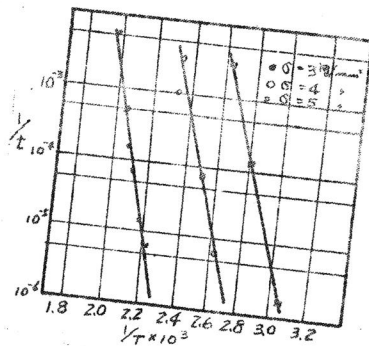


Fig.3 Fracture time vs. absolute temp..

#### 5 Discussion and conclusion

5.1 An intersection of the longitudinal axis in Fig.3 shows  $ZV$  of eqn.3. The mean of the intersections is 18.0, therefore  $\log ZV = 18.0$ . As  $V$  may be thought Debye's frequency, i.e.  $10^{13}$ ,  $Z$  is equal  $10^5$ , namely number of activated complexes is  $10^5$ /mol. The material-constant of Larson-Miller's eqn. is 20 (15-23), and this experimental result is 21.5, therefore this result agreed to Larson-Miller's eqn..

5.2 Fig.4 is plotted  $\sigma$  vs.  $T(\log t + 18.0) \times 10^{-3}$  to obtain the activation energy of this fracture phenomenon. A point in Fig.4 is made from a line of Fig.3.

$H, a$  and  $\gamma$  are determined from Fig.4 and the results are,

$$H = 50.6 \text{ Kcal/mol}, a = 2.18 \times 10^{-21} \text{ cm}^3$$

$$\gamma = 1.36 \times 10^6 \text{ erg/cm}^2$$

$H$  must be coincided with the heat of sublimation by the calculation

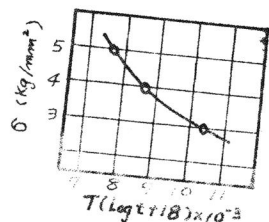


Fig.4 Stress dependence of activation energy.

In 2.2 of this report. The heat of sublimation in polycrystalline Aluminium is induced 53Kcal/mol<sup>(5)</sup>, therefore our result is almost coincided.

5.3 It had been reported that a void radius on the fracture face is a few micrometers<sup>(2)</sup>. We examined the void radius of Aluminium by the Thomson-Freundlich's eqn.<sup>(9)</sup> which shows a relation the void radius and its solubility from the chemical potential. The diagram of his eqn. substituting  $\gamma = 10^6 \text{ erg/cm}^2$  is shown in Fig.5. It is clear that voids radii are stabled at a few micrometers. So it is reasonable that the surface energy added the strain energy when a void is nucleated, must be considered  $10^6 \text{ erg/cm}^2$ .

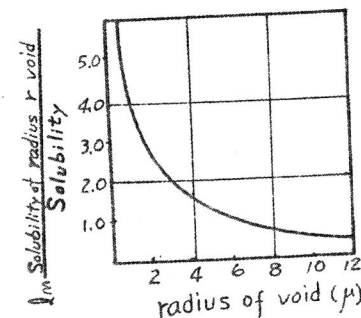


Fig.5 Solubility vs. radius of void.

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