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A Study on Creep-Fatigue Interaction of Polycrystalline Metal at Elevated Temperature (Specially, on the Effect of Hydrostatic Pressure on Crack Behavior).*

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Sheet test specimen of commercial pure copper was used and tests on three types of stress waves were performed under atmospheric and hydrostatic pressures of 1000kg/cm^2 at 270°C . From the present experiments the following were concluded. At the same stress wave, time to rupture of the material under hydrostatic pressure was remarkably longer than that in atmosphere. In this connection, slower crack initiation and propagation rate were observed under hydrostatic pressure as compared to atmospheric pressure. From the calculation of both fatigue damage ϕ_f of the material and creep damage ϕ_c in the tests of fatigue with hold-time, the value of cumulative damage, $\phi_c + \phi_f$, is larger than unity under both hydrostatic and atmospheric pressures. The fatigue damage of the material is predominant under hydrostatic pressure but the creep damage of the material is influential under atmospheric pressure.

1. Introduction

Recently, the necessity for study on creep-fatigue interaction of structural metals has been emphasized in connection with the strength of nuclear component,⁽¹⁾ turbine component⁽²⁾ and others. In a field of study on creep-fatigue interaction, a series of experiments has been carried on using the triangular stress or strain waves with hold-time. It is well known that this hold-time causes drastic reduction of fatigue life of the metals by the creep damage during the hold-time⁽³⁾⁽⁴⁾. But, at present, we cannot say that such a hold-time effect on life of the metals has been completely clarified. For example, the effect of multiaxiality of stress on hold-time effect, the effect of notches, the effect of atmosphere and others are not fully clear. As to the effect of multiaxiality of stress on both creep and creep rupture, a remarkable decrease of strain rate and an increase of time to rupture of polycrystalline metals at both room and elevated⁽⁵⁾⁽⁶⁾ temperatures have been observed under hydrostatic pressure compared to atmospheric pressure. On the other hand, as the effect of hydrostatic pressure on metallic fatigue life seems to be different from the case of creep, it is noteworthy to investigate the creep-fatigue interaction of the metals under hydrostatic pressure. In the

present paper, through the finding of drastic difference between the effect of pressure on metallic creep and that of metallic fatigue at elevated temperature, the creep-fatigue interaction of commercial pure copper at 270°C was studied in three types of tests under both hydrostatic pressure of 1000kg/cm^2 and atmospheric pressure.

2. Test specimen and apparatus

The material tested in this

Table 1 Mechanical properties of test material at room temperature.

Ultimate strength (kg/mm ²)	Yield strength (kg/mm ²)	Elongation (%)
22.9	8.6	65

(a) Test specimen for creep test.

(b) Test specimen for pure fatigue and fatigue test with hold-time.

Fig.1 Shape and dimension of test specimens (Dimension, mm).

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study was commercial pure copper (JIS H3101 Cu P2) and two types of center notched plate test specimens were employed. Mechanical properties of this material at room temperature are shown in Table 1, and the shape and dimension of the test specimens are shown in Fig.1. In the figure, the test specimen of type (a) was used for the static tensile creep test, and that of (b) was used for both the stress controlled zero to tension low-cycle fatigue test and the zero to tension low-cycle fatigue test with hold-time. Both test specimens of (a) and (b) had been annealed at 400°C for one hour in vacuum after machining. All the test specimens had a center notch hole with diameter of 0.5mm for easier confirmation of crack initiation. Average grain diameter of the test specimen after heat treatment was about 30 μ . We define the crack length l as shown in Fig.2.

The test apparatus* was originally designed such that both creep and low-cycle fatigue tests could be performed under atmospheric and external hydrostatic pressures at elevated temperature. The maximum temperature and hydrostatic pressure are

Fig.2 Definition of crack length l .

(a) Micrometer for detecting the displacement of coil spring (a), (b) Thermocouple which is attached to the end of specimen (a), (c) O-ring, (d) Inlet of cooling water, (e) Key, (f) Cooling chamber, (g) electric furnace, (h) Bachup ring, (i) O-ring, (j) Worm wheel, (k) Plate, (l) Dial gauge for measurement of combined displacement of coil spring and elongation of specimen, (m) Pressure tube (Titanium alloy), (n) Core, (o) DTF, (p) Rod by which displacement of coil spring is transmitted to DTF core, (q) Inlet of oil, (r) Pressure vessel, (s) Coil spring for loading, (t) Plunger, (u) Bearing, (v) Worm gear.

Fig.3 Test apparatus.

500°C and 3000kg/cm² respectively. A sketch of the apparatus is shown in Fig.3. It is a feature in this type of test apparatus that the load which is applied to the test specimen under combined hydrostatic pressure can be detected accurately. In this apparatus, the displacement of a coil spring (a) which is connected longitudinally with the test specimen is measured accurately by DTF. The details of the apparatus are omitted here, because they were reported in the previous paper⁽⁸⁾ by one of the authors. Diffusion oil which was likely to cause comparatively a little chemical change at elevated temperature was used as the pressurizing fluid.

Three types of stress waves employed in this study are shown in Fig.4. The type (a) in the figure is tensile static creep test, (b) is zero to tension low-cycle fatigue test (in the following, simply referred to as pure fatigue) and (c) is zero to tension low-cycle fatigue test with hold-time (in the following, simply referred to as fatigue with hold-time). Frequency of the stress wave of (b) is about 1cpm and the stress wave of (c) is composed of cyclic tension during 30min and constant tension during 30min. The three types of tests were performed at a constant temperature of 270°C.

Crack length of the specimen was observed by intermittent tests in atmosphere, and after measuring the crack length the test specimen was reloaded to continue the test. To examine the effect of the intermission on rupture life of the material, the rupture lives in both intermittent test and continuous test were compared. No significant difference was

(a) Static tensile creep test (nominal stress is constant).

(b) Zero to tension low-cycle fatigue test.

(c) Zero to tension low-cycle fatigue test with hold-time during 30min every pure fatigue during 30min.

Fig.4 Load waves.

* The pressure fills the pressure vessel from (q) in Fig.3 and pressurizes the test specimen (v). The pressure fluid is sealed by O-rings (i) and (c).

observed between both lives and it was concluded that the intermission had a little effect.

3. Test results and the discussions

3-1. The influence of superposed hydrostatic pressure on rupture life.

Times to rupture t_r of the material tested under the three types of stress waves are shown in Fig. 5. The data points show the results under both atmospheric and hydrostatic pressures. The ordinate of the figure represents the maximum nominal tensile stress σ_{max} . The figure shows remarkable increase of time to rupture of the material under combined hydrostatic pressure for the three types of tests. As is seen from the figure, the order of rupture life of the material with distinction of type of stress wave is very different under each pressure. Under atmospheric pressure, the creep test shows the shortest time to rupture, and both the pure fatigue test and the fatigue test with hold-time show almost the same rupture time which is longer than that in the creep test. On the other hand, under hydrostatic pressure, the shortest rupture time is observed in the pure fatigue test, the intermediate is observed in the creep test, and the longest is observed in the fatigue test with hold-time. It seems that this phenomenon on the rupture life of the material results from the difference in the effect of pressure on metallic creep

Fig. 5 Experimental relation between maximum nominal stress σ_{max} and time to rupture t_r under both atmospheric and hydrostatic pressures at 270°C.

Fig. 6 Experimental relation between maximum nominal tensile stress σ_{max} and number of cycles to rupture N_f under both atmospheric and hydrostatic pressures at 270°C.

and the low-cycle fatigue at elevated temperature.

Fig. 6 also shows the experimental relation between maximum nominal tensile stress σ_{max} and number of cycles to rupture N_f in both the pure fatigue and the fatigue test with hold-time. Under atmospheric pressure, rupture time under pure fatigue is almost the same as that under fatigue with hold-time, but the number of cycles to rupture under fatigue with hold-time is far smaller than that under pure fatigue. This reduction in the number of cycles to rupture under hold-time is recognized as a common phenomenon at elevated temperature. This is very important problem in design if we are to estimate the life of fatigue with hold-time on the basis of either time to rupture or number of cycles to rupture. The cause of an increase in life under hydrostatic pressure will be discussed in the later section.

3-2. The effect of hydrostatic pressure on creep and fatigue damages.

Fig. 7 shows the experimental relation between the creep damage $\phi_c (= \Delta t/t_r)$ and the fatigue damage $\phi_f (= N/N_f)$ of the material in the fatigue test with hold-time under both pressures. The sum of creep and fatigue damages of the material is apparently greater than unity under both pressures. It was found from the figure that the creep damage is predominant under atmospheric pressure, but the fatigue damage is dominant under hydrostatic pressure. The shift in the amount of damage under combined loading of hydrostatic pressure will be attributable to the fact that the effect of superposed hydrostatic pressure on rupture life is greatly affected by the stress wave form. In fact, the rupture life is increased 22 times under superposed hydrostatic pressure, but the increase ratio is only 4 in the pure fatigue test. Thus the amount of damage to the material accumulated in a unit time is decreased to 1/22 in the creep test but to 1/4 in the pure fatigue test. It seems that a remarkable decrease in

Fig. 7 Shift from predominance of creep damage ϕ_c of the material in atmosphere to that of fatigue damage ϕ_f under hydrostatic pressure in the fatigue test with hold-time.

accumulation rate of creep damage of the material in the hold-time under pressure results in a shift of the amount of damage as shown in Fig.7.

In order to discuss the variation in increase ratio of time to rupture with distinction of the stress waves, an example of tensile strain versus time curves of the material in all the types of tests under $\sigma_{max} = 6.5 \text{ kg/mm}^2$ is shown in Fig.8. In the figure, (a) shows the data in atmosphere and (b) shows the data under hydrostatic pressure. It is obvious that the rupture strain is greatly increased by superposed hydrostatic pressure in all the stress waves. Besides, the effect of superposed hydrostatic pressure on strain rate is different in each stress wave form. The strain rate of the material in both the creep and the fatigue with hold-time is greatly decreased by hydrostatic pressure, but the strain rate of the pure fatigue is hardly affected. Moreover, the decrease of strain rate in the fatigue with hold-time under superposed hydrostatic pressure is larger than that of creep under pressure.

Assuming the material has the characteristic rupture ductility B under both pressures, the relation between steady strain rate $\dot{\epsilon}$ and time to rupture t_r is represented in the following, ⁽¹⁾

$$\dot{\epsilon} t_r = B \quad (1)$$

It is considered that the cause of longer life in the pure fatigue under hydrostatic pressure mainly lies in the increase of rupture ductility. That is, since the strain rate in the

pure fatigue is not decreased by the pressure, the magnitude of B in Eq. (1) is increased by hydrostatic pressure. On the other hand, in both the creep test and the fatigue test with hold-time, rupture ductility B is also increased and moreover steady strain rate $\dot{\epsilon}$ is greatly decreased by the hydrostatic pressure. Therefore, it is considered that both the decrease of strain rate and the increase of rupture strain are influential factor for a larger increase ratio in both cases of creep and fatigue with hold-time compared to the pure fatigue. Fig.9 shows the experimental relation between steady strain rate and rupture time of the material in the three types of tests under both pressures. It is apparent in the figure that the superposition of hydrostatic pressure results in an increase of rupture ductility B of the material. As the slope of the figure is nearly -1 , it is noted that the relation of Eq.(1) holds without distinction of the stress waves.

3-3. The effect of hydrostatic pressure on crack behavior.

Growth of crack of the material with time is shown in Fig.10 on the example of Fig.8. In the present paper, crack initiation time is defined as the time when the extrapolation of crack propagation curves intersects the axis of crack length of 0.5 mm being parallel to the abscissa which is the length of initial notch diameter. The crack propagation rate is also defined as the average rate from crack initiation time to the time when the instability of crack propagation occurs. Under the hydrostatic pressure, both the retardation of crack initiation and the deceleration of crack propagation rate are observed compared to those in atmosphere. These effect of pressure were also observed in the torsional low-

(a) Under atmospheric pressure.

(b) Under hydrostatic pressure.

Fig.8 Tensile strain curves in the three types of tests.

Fig.9 Experimental relation of steady strain rate $\dot{\epsilon}$ to time to rupture t_r or time to crack initiation t_c of the material at 270°C (no dashed mark represents time to rupture t_r and dashed mark represents time to crack initiation t_c).

cycle fatigue test of low carbon steel at room temperature.⁽¹²⁾

Both the retardation of crack initiation and the deceleration of crack propagation rate by the superposed pressure will be discussed in connection with pressure dependency of strain rate and rupture strain near the crack tip. Mechanical factors which control the crack propagation rate are not necessarily understood under the condition of applied stress being over the yield stress of the material, but it seems that the crack propagation rate is closely related to the strain rate and the strain gradient near the crack tip. Assume that the local strain rate $\dot{\epsilon}_{loc}$ and the rupture strain ϵ_{floc} at the crack tip are proportional to the global strain rate $\dot{\epsilon}$ and the rupture strain of the specimen. That is,

$$\left. \begin{array}{l} \dot{\epsilon} \propto \dot{\epsilon}_{loc} \\ \epsilon_f \propto \epsilon_{floc} \end{array} \right\} \quad (2)$$

and It is considered from Eq. (2) that the decrease of crack propagation rate of the material under pressure will be attributable to both the decrease of local strain rate and the increase of local rupture strain at the crack tip. Moreover, it was clarified previously that the hydrostatic pressure has an effect of multiple crack initiation⁽¹²⁾ at the notch root. This will be one of the influential factors to deceleration of the crack propagation rate of the material. In the present study, however, the multiple crack initiation at the notch root was not observed.

Crack propagation rate under

Fig. 10 Crack growth curves in the three types of tests under $\sigma_{max} = 6.5 \text{ kg/mm}^2$ and atmospheric and hydrostatic pressures.

Fig. 11 Integral path of the J-integral.

both pressures will be discussed in reference to the J-integral proposed by Rice. The J-integral⁽¹³⁾ is shown in the two-dimensional deformation field of Fig. 11 as

$$J = \int_{\Gamma} (w dy - T \cdot \frac{\partial u}{\partial x} ds), \quad (3)$$

where w is strain energy density and is written as $w = \int_0^{\epsilon} \sigma_{ij} d\epsilon_{ij}$. In the equation T is the traction vector on the contour surrounding the crack tip defined to the outward normal, $T_i = \sigma_{ij} n_j$, where σ_{ij} is the stress tensor and n_i is the unit outward normal vector on the contour Γ . The line integral is made from the lower crack surface to the upper one in counterclockwise sense as shown in Fig. 11. Now, assume that there are two identical bodies A and B with an exception of distinction of crack length. Denoting the crack lengths of the bodies A and B as l and $l + dl$, respectively, the strain versus stress relation of two bodies is shown schematically in Fig. 12 (a). The hatched part in Fig. 12 (a) represents the decrease of potential energy ΔU of the body and the relation between ΔU and the J-integral is given** by

$$J = -\Delta U / \Delta l \quad (4)$$

Now, consider the application of the J-integral to the crack problem in creep. In the first place, we approximate the hatched part of Fig. 12 (a) by a triangular shape as shown in Fig. 12 (b). Assume that the body with crack length l in creep is in the state of point P of Fig. 12 (b) and also the crack propagates instantaneously over length of dl , then a virtual stress drop $\Delta \sigma$ will occur. But such a virtual stress drop will be compensated at once by the creep stress and the body will elongate by da during the compensation. Therefore, the potential energy ΔU released during the increase of crack length dl is represented by the area of $\Delta \sigma Pq$ in Fig. 12 (b), and is given by

$$\Delta U = \Delta \sigma Pq = \frac{1}{2} \sigma da \quad (5)$$

Employing the conventional sign of energy and substituting Eq. (5) into Eq. (4), the following modified J-integral J'_c by unit thickness of the specimen under creep condition is derived;

$$J'_c = \frac{1}{2} \sigma \frac{da}{dl} \quad (6)$$

Fig. 12 Nominal stress versus elongation curves of two bodies with different crack lengths.

In the cases of pure fatigue and fatigue with hold-time, the modified J-integrals J_f and J_{fc} are calculated in the same manner. As is seen from Eq.(6), the modified J-integral J' is calculated from both the strain-time and the crack length-time curves. The physical meaning of J' is quite different from the usual crack extension force g . It is considered that J' represents the sum of the crack extension force g and the force E_p to extend the plastic strain range of the whole specimen. Therefore, J' will be written as (see, Appendix)

$$J' = g' + E_p \quad (7)$$

Figs.13 (a), (b) and (c) show the experimental relation between the modified J-integral J' calculated in the three types of tests and the rupture time ratio t/t_r . It was found from the figure that the effect of hydrostatic pressure on J' of the material is quite different with distinction of stress waves. In the creep, J_c under atmospheric pressure is greater than that under hydrostatic pressure, but as regards J_f in the fatigue test this relationship is quite contrary. Therefore, it is worthy of note that the effect of hydrostatic pressure on the crack behavior is quite different with distinction of stress waves.

Next, by using the modified J-integral J' , we discuss the change of the crack extension force g' of the material by superposed pressure. In the pure fatigue, it is considered that E_p in Eq.(7) will take almost the same value under both pressures because the strain rate does not decrease by superposed pressure. From the fact that the magnitude of J' of the material tested under hydrostatic pressure is greater than that under atmospheric pressure, it is noted that g' under hydrostatic pressure will be greater than that under atmospheric pressure. This shows good agreement with the tensile tear test result⁽¹⁸⁾ on commercial pure copper that the crack extension force g' of the material under hydrostatic pressure is larger than that under atmospheric pressure. Therefore, it is noted that a remarkable decrease in fatigue crack propagation rate under pressure corresponds to an increase in g' under pressure from a viewpoint of fracture mechanics. In the creep test, on the other hand, it seems that E_p of the material under hydrostatic pressure will be smaller than that under atmospheric pressure from the following two facts. One is that the strain rate of the material is decreased remarkably by superposed pressure. Another is that both imperfection and dislocation densities of commercial pure aluminum (99.75% Al) in the tensile creep test at 200°C are also decreased⁽¹⁹⁾ remarkably by

superposed hydrostatic pressure. The imperfection and dislocation densities were calculated from misorientation obtained by X-ray Laue Method.^{(19)***} It seems that a decrease in J' value under hydrostatic pressure results from a decrease in strain rate or in imperfection and dislocation densities of the materials. Besides, as the creep crack propagation rate of the material under hydrostatic pressure is smaller than that under atmospheric pressure, it is estimated that g' of the material tested under hydrostatic pressure will be

(a) Creep test.

(b) Pure fatigue test.

(c) Fatigue test with hold-time.

Fig.13 Comparison of the modified J-integral J' under atmospheric pressure with that under hydrostatic pressure under the condition of $\sigma_{max} = 6.5 \text{ kg/mm}^2$ at 270°C.

*** In the linear fracture mechanics, the J-integral is equal to the energy release rate g .

greater than that under atmospheric pressure. But the quantitative estimation of g' under hydrostatic pressure is a problem which will be investigated in the future.

4. Conclusions

Three types of tests, i.e., static tensile creep test, zero to tension low-cycle fatigue test and zero to tension low-cycle fatigue test with hold-time were performed on commercial pure copper under both atmospheric pressure and hydrostatic pressure of 1000kg/cm^2 at 270°C . From the test results the following were concluded.

(1) Both time to rupture and number of cycles to rupture of the material are increased in three types of tests under hydrostatic pressure compared to those under atmospheric pressure. The increase ratio of rupture life under hydrostatic pressure to that under atmospheric pressure is the greatest in the creep test, in the fatigue test this ratio is the smallest, and in the fatigue test with hold-time the ratio takes an intermediate value. Consequently, it is suggested that this increase ratio of rupture life becomes smaller as the stress wave frequently changes.

(2) The cause of an increase in rupture life under hydrostatic pressure mainly lies in both the retardation of the crack propagation rate by superposed pressure. Those crack behaviors under hydrostatic pressure mainly result from both the decrease of local strain rate and the increase of local rupture strain at the crack tip.

(3) Total damage, $\phi = \phi_c + \phi_f$, calculated by linear cumulative damage rule for the fatigue with hold-time under both the pressures is clearly greater than unity. Under hydrostatic pressure the fatigue damage ϕ_f of the material is predominant and under atmospheric pressure the creep damage ϕ_c is dominant.

Appendix

It was proved by Rice⁽¹³⁾ that the J-integral takes the same value when it is integrated by two different integral paths, and this is sometimes called the J-integral being path-independent. Besides, the J-integral has the same form as the equation proposed by Eshelby⁽¹⁶⁾ which is given as

$$F_m = \int_{\Sigma} P_{jm} d\Sigma_j \quad (8)$$

In the equation, P_{jm} is called the energy momentum tensor and is shown as $P_{jm} = -\sigma_{ij} \partial u_i / \partial x_m + E \delta_{jm}$ where $E = (1/2) \sigma_{ik} \epsilon_{ik}$ is the elastic energy density and Σ

*** In general, g' is the sum of g and the forces to extend the plastic strain range near the crack tip which is directly related to the crack extension.

is a contour enclosing the singularity. σ_{ij} , u_i and δ_{ij} are also stress tensor, strain tensor, displacement vector and Kronecker's delta, respectively. If Σ embraces several singularities, the integral of Eq.(8) gives the sum of the forces on them. Thus it is noted in this meaning that the J-integral is one application of F_m to the crack problem. Now, consider the dislocation arrays which are piled up to an obstacle under shear stress τ as shown in Fig.14. It was already shown⁽¹⁷⁾ that the J-integral which is integrated along the path Σ_1 embracing any number of free dislocations in the pile-up takes the same value as the integral which is integrated along the path Σ embracing a locked dislocation only. Therefore, we can see that the J-integral takes a definite value J_d when the integral path embraces the leading dislocation at the head of the pile-up. As there are many locked dislocations near the crack tip, the J-integral along the loop embracing the crack tip as shown in Fig.15 is given in the following manner,

$$J_r = J_e + J_d \quad (9)$$

In the equation, J_e is a part contributed from the geometrical singularity of crack tip only and J_d is one from locked dislocations near the crack tip. J_d in the equation will be related to g' and E_p in Eq.(7), but as the integration of J' in Eq.(7) embraces the whole specimen, it seems that J_d is mainly related to E_p . When there is a large plastic zone at the crack tip, many locked dislocations will be present there and the path-independence of the J-integral no longer holds. Therefore, it is worthy of note that the J-integral of the materials with microstructure will

Fig.14 Dislocation pile-up and path of the J-integral.

**** It was clarified by one of the authors⁽¹⁵⁾ that both the imperfection density and the dislocation density of the material are represented by Riemann-Christoffel curvature tensor and torsion tensor which characterize non-Riemann space with a Euclidean connection, respectively. As to the physical meaning of the imperfection density, it is shown that the existence of atom vacancies, interstitial atoms and jogs in crystal leads to the concept of the curvature tensor.

Fig.15 Force on locked dislocations at the crack tip and integral path of the J-integral.

alter with distinction of the integral path. It is also noted that estimation of the embracing region is very important in the calculation for the crack tip of the engineering materials.

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