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Investigation of Low Cycle Fatigue at Elevated Temperatures*

(Factors Which Govern Number of Strain Cycles to Failure)

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In order to clarify how the number of strain cycles to failure is influenced by temperature and frequency of straining in low cycle fatigue, it is necessary to observe the process of the fatigue failure. To obtain the knowledge of the process, crack appearances existing on the failed specimens were compared with each other. Fatigue tests were carried out in a push-pull testing machine on the AISI 321 stainless steel under various temperatures and frequencies of straining conditions.

According to the results, the crack appearance does not depend on the temperature and frequency of straining conditions but on the plastic strain range. If fatigue tests are carried out in the same plastic strain range but at different temperatures and frequencies of straining conditions, similar distributions of crack density from the outer surface to the interior of specimens are always observed in the failed specimens.

Thus, it is concluded that in low cycle fatigue the behaviour of fatigue cracks is governed primarily by the plastic strain range and it is deduced that the rate of fatigue process depends on temperature, strain rate, and plastic strain energy per cycle.

1. Introduction

Some attempts have been made in order to establish the relations between low cycle fatigue at constant temperature and thermal fatigue^{(1) (2)}. But the factors governing low cycle fatigue were not investigated in detail.

Many investigations of low cycle fatigue at elevated temperatures dealt with the relations between number of strain cycles to failure and test conditions. Not only the relations between number of strain cycles to failure and test conditions but also the knowledge of the process of fatigue fracture is necessary in order to clarify the phenomena of low cycle fatigue. The present authors reported about the influence of temperature on thermal fatigue⁽³⁾ and about the behaviour of cracks due to thermal fatigue⁽⁴⁾. But the significance of temperature to the process of thermal fatigue was not clarified.

When low cycle fatigue tests are carried out at

different temperatures T_1 and T_2 ($T_1 < T_2$), for example, the relations between plastic strain range and the number of strain cycles to failure are schematically shown as in Fig. 1. At $T = T_1$, the numbers of strain cycles to failure are N_{f1} and N_{f2} for $\Delta\epsilon_{p1}$ and $\Delta\epsilon_{p2}$ of plastic strain range, respectively. In these cases, it is not clear whether the process of fatigue failure is the same or not. On the other hand, the number of strain cycles to failure is N_{f2} for $\Delta\epsilon_{p1}$ at T_2 . This number of strain cycles to failure is the same as for $\Delta\epsilon_{p2}$ at T_1 . In view of these results, three cases are considered as showing the significance of temperature to the process of low cycle fatigue.

(1) The process of fatigue fracture is the same for the two conditions of $T = T_1$, $\Delta\epsilon_p = \Delta\epsilon_{p2}$

Fig. 1 Illustration of dependence of number of strain cycles to failure on temperature

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and $T=T_2$, $\Delta\epsilon_p=\Delta\epsilon_{p1}$. As the result, the same numbers of strain cycles to failure are obtained (relation between II and IV indicated in Fig. 1).

(2) The process of fatigue fracture is the same for the two conditions of $T=T_1$, $\Delta\epsilon_p=\Delta\epsilon_{p1}$ and $T=T_2$, $\Delta\epsilon_p=\Delta\epsilon_{p1}$. But the rate of fatigue process depends on temperature. As the result, the different numbers of strain cycles to failure are obtained in the same plastic strain range at various temperatures (relation between I and IV).

(3) The process of fatigue fracture and the rate of fatigue process depend on a complicated combination of temperature, plastic strain range, and so on (relation between III and IV).

In some investigations which were published^{(1)~(8) (5)}, the relations between mechanical conditions and temperature were examined under the same number of strain cycles to failure. But there is no necessity of examining under the same number of strain cycles to failure. In order to clarify the process of fatigue fracture, the authors proposed the concept of "crack density" and made an attempt to examine the behaviour of fatigue cracks⁽⁴⁾.

In this paper, the results of fatigue tests carried out under various temperatures and various frequencies of straining are discussed and also the process of fatigue fracture is examined about the distributions of the crack density from the surface to the interior of the failed specimens.

2. Experimental procedure

2.1 Material and profile of specimen

The test material employed is an austenitic stainless steel (AISI 321) and its chemical composition is given in Table 1. The material was pre-heated for one hour at 600°C and heated for another hour at 1150°C and quenched in water. After the heat treatment, specimens were machined and polished with No. 06 emery paper. Figure 2 shows the profile of the specimen.

Results of tensile tests at elevated temperatures for this material are shown in Fig. 3.

2.2 Fatigue testing machine

An outline of a push-pull testing machine em-

ployed is shown in Fig. 4. Revolution of a motor is reduced by reduction gears and the frequency of straining is changed through combination of sprockets.

When fatigue tests were carried out at elevated temperature, the specimen and chucks of testing machine were heated together by an electric furnace. The temperature was controlled within the limits of $\pm 3^\circ\text{C}$ by a Pt-Pt-Rh thermo-couple welded on the surface of the specimen by percussion welding. The furnace has a glazed window so that the movements of marked points can be observed.

2.3 Measurements of strain and stress

Stress is found as the load divided by the area of original cross section. The load is detected by a load cell.

Fig. 3 Results of tensile tests at elevated temperatures

Fig. 4 Fatigue testing machine

Table 1 Chemical composition of the material (%)

C	Si	Mn	P	S	Ni	Cr	Ti
0.04	0.58	1.72	0.027	0.006	10.90	18.01	0.39

Fig. 2 Profile of specimen (in mm)

Figure 5 shows the method of measuring strain range. Movements of the marked points between the maximum tensile strain and the maximum compressive strain are measured with a magnifying glass. This change of the movements is designated by Δx_1 and Δx_2 for the marked points of fixed side and driving side, respectively. Using the notations shown in Fig. 5, each strain range is defined as follow.

Total strain range:

$$\Delta \varepsilon_{e+p} = \frac{l_t - l_c}{l_0} = \frac{\Delta x_2 - \Delta x_1}{l_0} \quad \dots\dots\dots (1)$$

Elastic strain range: $\Delta \varepsilon_e = \Delta \sigma / E \quad \dots\dots\dots (2)$

Plastic strain range: $\Delta \varepsilon_p = \Delta \varepsilon_{e+p} - \Delta \varepsilon_e \quad \dots\dots\dots (3)$

where E indicates the modulus of elasticity under the test temperature.

2.4 Measurement of cracks

State of cracks existing on the failed specimen by fatigue test was indicated with crack density which is defined below. On a cylindrical surface of a unit length of a specimen, ds is taken at the distance s and the number of cracks existing in the strip of the width ds is expressed as n (Fig. 6). The number of n is the number of cracks intersecting the meridian line at the distance s , as $ds \rightarrow 0$.

l_0 : Original gauge length
 l_t : Gauge length at the maximum tensile strain
 l_c : Gauge length at the maximum compressive strain

Fig. 5 Stress-strain hysteresis diagram and measurement of strain range

Fig. 6 Illustration of crack density

The mean value of n at s indicated as $\bar{n}$, i.e. crack density, is expressed as follows:

$$\bar{n} = \frac{1}{2\pi r} \int_0^{2\pi r} n ds \quad \dots\dots\dots (4)$$

where r is the radius of the cylindrical surface.

Not only the value of crack density at the outer surface, but also the value of crack density at the interior of the specimen was measured in order to find the distribution of crack density from the surface to the interior of specimen.

The surface of the specimen was electropolished uniformly in order to observe the interior of the specimen. After polishing, the surface of specimen was electroetched to reveal grain boundaries and cracks. A solution of phosphoric acid and chromium

	R. T.	180°C	320°C	490°C	650°C	760°C
14°C/min	○	□	△	◇	▽	×
4°C/min	●	■	▲	◆	▼	×
1/2°C/min	●	■	▲	◆	▼	×

Fig. 7 Relations between plastic strain range and stress range

trioxide was used for electro-polishing at 100~140°C. Saturated oxalic acid solution was also used for etching. The cracks were magnified 100 times for observation under a microscope. The number of cracks intersecting with the meridian lines was counted on the lines which divide the circumference uniformly into 12 or 24 divisions. The number of cracks was divided by the total length of the measured meridian lines.

In this experiment, a thin layer of the surface of specimen, say 5~10 μ , was removed in order to take off the oxidized surface, and the interior surface at 5~10 μ depth was regarded as the outer surface of the specimen.

2.5 Test conditions

Conditions of temperature and frequency of straining were selected as follows.

Temperature: 23°C, 180°C, 320°C, 490°C, 650°C, and 760°C, and frequency of straining: 14 c/min, 4 c/min, and 1/2 c/min. For each combination of the temperatures and the frequencies of straining, fatigue tests were carried out in 3 to 5 stages of strain range.

3. Experimental results and discussions

3.1 Results of fatigue test

In early stage of fatigue life under each condition, stress range increases slightly with repeated strain cycles. For the major part of the number of strain cycles to failure, stress range remains constant. This constant value is taken as representative of stress range. Tensile component of stress range decreases rapidly at the last several percent of the number of strain cycles to failure; then, the specimen is broken completely. The value of strain

Fig. 8 Relations between stress range and temperature for the same plastic strain range

range corresponding to the representative stress range is taken as representative of strain range.

3.1.1 Relations between plastic strain range and stress range

Stress range, which is necessary to cause plastic strain, increases with the increasing value of plastic strain range under the same conditions of temperature and frequency of straining. Figure 7 shows these relations. Stress range for the same plastic strain range changes with the increase of temperature. Examples of these phenomena are shown in Fig. 8 for 0.5% and 1.0% of the plastic strain range. By raising the temperature for each condition of plastic strain range, the stress range decreases up to about 300°C, then increases, finally decreases again at over 500~600°C. This dependence

Fig. 9 Relations between stress range and number of strain cycles to failure (marks indicate the same conditions as in Fig. 7)

on temperature is similar to the dependence of tensile strength on temperature (Fig. 3), and this phenomenon may be caused by the phenomena of aging and over-aging at the elevated temperature.

3.1.2 Relations between stress range and number of strain cycles to failure

The relations between stress range and number of strain cycles to failure are shown in Fig. 9. Figure 10 shows the dependence of stress range on temperature for the same number of strain cycles to failure. There is a similar dependence on temperature to that in Fig. 8.

3.1.3 Relations between plastic strain range and number of strain cycles to failure

Figure 11 shows the relations between $\Delta\epsilon_p$ and N_f . In order to make these results correspond with Fig. 10, the dependence of $\Delta\epsilon_p$ on temperature for the same number of strain cycles to failure is shown in Fig. 12. The plastic strain range for the same number of strain cycles to failure becomes maximum at about 300°C and decreases rapidly beyond this temperature.

By making a comparison of Fig. 12 with Fig. 10, the number of strain cycles to failure must be governed remarkably by the condition of temperature but also it depends on the conditions of plastic strain range and stress range. The facts that though the stress range has the minimum value at about 300°C, the plastic strain range has the maximum value at about 300°C for the same number of strain cycles to failure signify the dependence of number of strain cycles to failure on the conditions of plastic strain range and stress range. The same thing is understood by comparing Fig. 8 with Fig. 13 which shows the dependence of N_f on the condition of temperature at the same condition of $\Delta\epsilon_p$.

Fig. 10 Relations between stress range and temperature for the same number of strain cycles to failure

The phenomenon that N_f has the maximum value at about 300°C as shown in Fig. 13, must be caused by the decrease of stress range.

3.2 Observation of cracks

Figure 14 shows the results of observation of crack density from the outer surface to the interior of specimen. The distribution of crack density depends primarily on the condition of plastic strain range. Value of crack density at the outer surface decreases with the decrease of plastic strain range on the same condition of temperature. With the increase of depth, crack density decreases rapidly for the

Fig. 11 Relations between plastic strain range and number of strain cycles to failure (marks indicate the same conditions as in Fig. 7)

Fig. 12 Relations between plastic strain range and temperature for the same number of strain cycles to failure

Fig. 13 Relations between number of strain cycles to failure and temperature for the same plastic strain range

Fig. 14 Distributions of crack density from the surface to the interior of failed specimens (4 c/min)

large plastic strain range, while crack density decreases slightly for the small plastic strain range.

Judging from the definition of crack density, it is not clear that the value of crack density corresponds to the number of cracks. But it is recognized by microphotographic observations that in the case of large discrepancy in the value of crack density there is a discrepancy in the number of cracks⁽⁴⁾. Accordingly, the fact that crack density decreases rapidly with the increase of the depth from the outer surface implies that all cracks which initiate at the outer surface do not propagate in the same way but some of them stop propagating near the outer surface.

It may be considered that the behaviour of the deepest crack is more important for the phenomenon of fracture than those of many small cracks which exist near the outer surface. There are two possible ways of crack development. One is the independent propagation of separate cracks, and the other is the connection of one crack with another. As the difficulty of the connection of one crack with another depends on the value of crack density at the outer surface, the behaviour of many small cracks which exist near the outer surface is also important for the phenomena of fracture.

For the same condition of temperature, the plastic strain and stress range may be important to determine the number of strain cycles to failure as the factor governing the rate of fatigue process. However, the condition of plastic strain range governs the crack density near the outer

surface which influences the crack leading to a complete fracture in the specimen. Accordingly the condition of plastic strain range is also important for determining N_f , as it governs the process of fatigue fracture.

The dependence of crack density at the outer surface of the failed specimen on the condition of temperature and frequency of straining is discussed below.

Relations between the value of crack density at the outer surface and N_f are shown in Fig. 15 with the parameters of temperature and frequency of straining. In these figures it is shown that in case

Fig. 15 Relations between number of strain cycles to failure and crack density at the outer surface (marks indicate the same conditions as in Fig. 7)

of the same N_f , the value of crack density at the outer surface of the failed specimen depends considerably on the condition of temperature and frequency of straining. Accordingly, in spite of the same number of strain cycles to failure, the behaviour of fatigue cracks varies with the test conditions. Therefore, the results that the same number of strain cycles to failure is obtained at the conditions of $T=T_1$, $\Delta\epsilon_p=\Delta\epsilon_{p2}$ and $T=T_2$, $\Delta\epsilon_p=\Delta\epsilon_{p1}$ in Fig. 1, include the influence of different behaviours of fatigue cracks.

In order to clarify on what the behaviour of fatigue cracks depends, the relations between the crack density at the outer surface and the conditions of temperature for the same number of strain cycles to failure are taken from Fig. 15 and are

Fig. 16 Relations between crack density at the outer surface and temperature for the same number of strain cycles to failure

Fig. 17 Relation between crack density at the outer surface and plastic strain range (marks indicate the same conditions as in Fig. 7)

shown in Fig. 16. The value of crack density for the same number of strain cycles to failure becomes maximum at about 300°C and decreases rapidly beyond this temperature. The influence of condition of frequency of straining appears above 200~300°C, and the condition of smaller frequency of straining corresponds to the condition of higher temperature. This relation is quite the same as the relation between the plastic strain range and the temperature for the same number of strain cycles to failure shown in Fig. 12. Accordingly it is considered that the value of crack density at the outer surface of the failed specimen depends on the condition of plastic strain range. Figure 17 shows the relation between the crack density and the plastic strain range. There is no difference due to the conditions of temperature and frequency of straining. When fatigue tests are carried out in the same plastic strain range at different conditions of temperature and frequency of straining, the same value of crack density at the outer surface of failed specimen is obtained in spite of different numbers of strain cycles to failure. The crack density at the outer surface

Fig. 18 Relation between crack density at 0.2 mm depth from the outer surface and plastic strain range (marks indicate the same conditions as in Fig. 7)

Fig. 19 Relations between plastic strain energy per cycles and temperature for the same plastic strain range

depends largely on the condition of the plastic strain range, and it increases with the increase of the plastic strain range except above about 2% of plastic strain range.

The value of crack density at the outer surface is dealt with in above discussions. In order to compare the distributions of crack density from the outer surface to the interior of the specimens with each other, the crack density at 0.2 mm depth from the outer surface is compared in Fig. 18. In this figure the same value of crack density is also obtained under the same condition of plastic strain range.

From these observations, it is concluded that the behaviour of fatigue cracks depends on the condition of plastic strain range.

4. Factors which govern the number of strain cycles to failure

In the previous section, it has been found that N_f in low cycle fatigue depends on plastic strain and stress range. The significance of plastic strain range and stress range on N_f will be discussed in the following. As shown in Fig. 5, the stress range is the sum of the absolute value of the maximum tensile stress and the maximum compressive stress which are related to the tensile flow stress and the compressive flow stress. Therefore, the stress range does not influence N_f as the instantaneous tensile or compressive stress but as the stress which causes the plastic strain.

The plastic strain energy per cycle is mentioned as the quantity which is related to the plastic strain range and the stress which causes the plastic strain. The plastic strain energy per cycle is indicated by the area of stress and strain hysteresis diagram. As the hysteresis diagram can not be obtained exactly in this experiment, it is approximated by the product of the plastic strain range and the stress range as shown by dotted line in Fig. 5.

In the previous section it has also been found that the behaviour of fatigue cracks, which is governed by the condition of plastic strain range, influences N_f . Therefore, in the discussion about the dependence of N_f on the condition of temperature and frequency of straining, it is necessary to consider the influence of the behaviour of fatigue cracks on N_f . The dependence of the relation between the plastic strain energy per cycle and N_f on the condition of temperature and frequency of straining will be discussed for the same conditions of the plastic strain range in order to maintain the influence of the behaviour of fatigue cracks on N_f constant.

As shown in Fig. 13, N_f becomes maximum at about 300°C. On the other hand the plastic strain energy per cycle decreases with the increase of tem-

perature up to about 300°C, then increases, and decreases again with the increase of temperature beyond 500~600°C (Fig. 19).

Accordingly, for the same condition of the plastic strain range the number of strain cycles to failure becomes small under the conditions of large plastic strain energy per cycle, high temperature, and small frequency of straining. From these results it is concluded that the rate of fatigue process is governed by the conditions of the plastic strain energy per cycle, temperature, and frequency of straining.

Fig. 20 Relations between plastic strain range and UN_f (marks indicate the same conditions as in Fig. 7)

The factor governing the rate of fatigue process could be designated as U^* . It is assumed that U^* is indicated by

$$U^* = C(T, \tau)U \quad (5)$$

where T is temperature in °K, U is plastic strain energy per cycle and τ is a factor which is related to the frequency of straining; and also that the number of strain cycles to the same state of cracks existing on the specimen is proportional to reciprocal number of U^* . Proof of these assumptions will be discussed in a following paper. In the present paper, the dependence of N_f on T and τ is discussed under these assumptions.

Fig. 21 Relations between UN_f and temperature for the same plastic strain range

Fig. 22 Dependence of $C(T, \tau)$ on temperature for 0.5% plastic strain range

As the state of cracks at the failed specimen is the same for the same condition of the plastic strain range, the relation between U^* and N_f can be written as follows:

$$U^*N_f = f(\Delta\epsilon_p), \quad C(T, \tau)UN_f = f(\Delta\epsilon_p) \dots\dots(6)$$

The relations between UN_f and $\Delta\epsilon_p$ are shown in Fig. 20 in order to clarify the dependence of $C(T, \tau)$ on T and τ , and the dependence of $f(\Delta\epsilon_p)$ on $\Delta\epsilon_p$. Figure 21 shows the relations between UN_f and temperature for the same condition of $\Delta\epsilon_p$. In this figure UN_f has a nearly equal value up to 200~300°C and UN_f decreases rapidly with the increase of temperature above 200~300°C. There is no dependence of UN_f on frequency of straining up to 200~300°C but above this temperature UN_f for smaller frequency of straining is smaller than UN_f for larger frequency of straining.

As it is difficult to discuss the absolute value of $C(T, \tau)$, the relative value of $C(T, \tau)$ to the value at room temperature is discussed in this paper. In Eq. (6), $C(T, \tau)UN_f$ which is constant for the value at room temperature is obtained from the dependence of UN_f on T for the same condition of $\Delta\epsilon_p$ shown in Fig. 21. The relation between $C(T, \tau)$ and T shown in Fig. 22 is formulated to be

$$C(T, \tau) = ae^{-\frac{c_1}{T}} + b \dots\dots\dots(7)$$

where c_1 , a and b are selected to give close agreement to each diagram obtained from the experiment. These values are shown in Table 2 for 0.5% of plastic strain range. The values of c_1 are nearly equal with each other and are independent of the condition of frequency of straining. On the other hand a depends on the condition of frequency of

Table 2 c_1 , a , and b for 0.5% of plastic strain range
 $C(T, \tau) = ae^{-(c_1/T)} + b$

c/min	c_1	a	b
1/2	7.6×10^3	4.9×10^4	0.91
4	8.0×10^3	3.6×10^4	0.87
14	7.4×10^3	1.4×10^4	0.85

Table 3 a and b for $c_1 = 7600$
 $C(T, \tau) = ae^{-(7600/T)} + b$

c/min	$\Delta\epsilon_p = 0.5\%$		$\Delta\epsilon_p = 1.0\%$	
	a	b	a	b
1/2	4.9×10^4	0.91	3.6×10^4	0.85
4	2.4×10^4	0.85	1.9×10^4	0.96
14	1.8×10^4	0.85	1.1×10^4	0.97

Table 4 a for $c_1 = 7600$ and $b = 1.00$ and τ
 $C(T, \tau) = ae^{-(7600/T)} + 1.00$

c/min	$\Delta\epsilon_p = 0.5\%$		$\Delta\epsilon_p = 1.0\%$	
	a	τ	a	τ
1/2	5.4×10^4	7350	4.3×10^4	3680
4	2.8×10^4	930	2.0×10^4	470
14	2.1×10^4	310	1.2×10^4	160

straining. Regarding c_1 as constant, the choice of $c_1 = 7600$ gives close agreement to all diagrams from the experiment. The values of a and b for $c_1 = 7600$ are shown in Table 3. Equations shown in Fig. 22 are represented with these values.

As the value of $C(T, \tau)$ is based on the value at room temperature, b becomes 1.00, because at room temperature the first term is negligibly small for the second term in Eq. (7). The value of a is shown Table 4 for $c_1 = 7600$ and $b = 1.00$. The value of b does not depend on the condition of frequency of straining and $C(T, \tau)$ is influenced by b only at room temperature. These results are not contradictory to the experimental results that there is no dependence of UN_f on the condition of frequency of straining at room temperature.

In order to clarify the dependence of a on frequency of straining, time per one strain cycle designated by t can be taken as the factor τ which is related to the frequency of straining. t must be constant for the same condition of frequency of straining. Figure 23 shows the relations between t and a . There is a difference between two conditions of $\Delta\epsilon_p$. a increases with the increase of t and with the decrease of $\Delta\epsilon_p$. Therefore, the factor τ must be related to the strain rate. The reciprocal number of the mean strain rate could be taken as τ , i.e.

$$\tau = \frac{1}{\dot{\epsilon}} = \frac{t}{2\Delta\epsilon_{e+p}} \text{ where } t \text{ is time per strain cycle in sec and } \Delta\epsilon_{e+p} \text{ is the total strain range.}$$

As the relations between UN_f and T are indicated for the same condition of $\Delta\epsilon_p$ in Fig. 22, τ is not always the same under each condition of temperature for the same frequency of straining. The difference between them is so small that τ can be regarded as constant for the same condition of $\Delta\epsilon_p$. But τ depends on $\Delta\epsilon_p$ considerably. Therefore, for the same frequency of straining, the value of τ corresponding to 0.5% and 1.0% of plastic strain range respectively must be taken. These values are shown in Table 4. Figure 24 shows the relation between a and τ , and this relation is formulated to be

$$a = 2.1 \times 10^3 \tau^{0.37} \dots\dots\dots(8)$$

Accordingly, the strain rate is the most suitable for

Fig. 23 Relations between a and t

the factor which is related to the frequency of straining. Consequently U^* can be represented as follow :

$$U^* = \{2.1 \times 10^3 \tau^{0.37} e^{-(7600/T)} + 1.00\} U \dots \dots (9)$$

Figure 25 shows the relation between $\Delta \epsilon_p$ and $U^* N_f$ using the representation of Eq. (9). There is no difference due to the conditions of temperature and frequency of straining. This relation is formulated to be

$$U^* N_f = \frac{4.19 \times 10^3}{(\Delta \epsilon_p)^{0.45}} \dots \dots \dots (10)$$

In Eq. (10) the number of strain cycle to failure decreases with the increase of $\Delta \epsilon_p$ for the same value of U^* . As one of the interpretations of this result, it can be stated that the connections of one crack with another easily cause in larger plastic strain range and a crack leading to a complete fracture in the specimen can develop under a smaller number of strain cycles.

In above discussions the factor governing the rate of fatigue process U^* is introduced and is represented as Eq. (9). It is suggested by this equation that in the low cycle fatigue at various temperatures there are two mechanisms of developing cracks. One depends remarkably on temperature and strain rate, and the other has no relation with them. Fatigue fracture at temperature between 23°C and 200~300°C is governed by the former mechanism and at above 200~300°C, fatigue fracture is governed by the latter. However, in order to clarify these mechanisms in detail it is necessary to discuss about the shape of cracks or the micro-

structure of metals.

AISI 321 is the only material employed in this experiment. Therefore, it is interesting to see whether or not the conclusions which are obtained here are applicable to other materials. As experimental results of fatigue tests for many materials have been reported by many investigators, these results must be examined again. However, it is difficult to discuss this, because the stress ranges of other data are not indicated in those reports except in a few^{(6) (7)}. The authors also wish to clarify the relations between different materials by conducting fatigue tests of many other materials.

5. Conclusions

In order to clarify the dependence of the number of strain cycles to failure on the conditions of temperature and frequency of straining, fatigue tests were carried out on AISI 321 stainless steel and the state of cracks existing in the failed specimens was observed under microscope. The following conclusions were obtained.

(1) The stress range for the same condition of plastic strain range depends on temperature. Aging and over-aging is considered as one of the reasons of this result.

(2) The relations between number of strain cycles to failure and the plastic strain range are influenced by the relation between the plastic strain range and the stress range. The plastic strain energy is an important factor which governs the number of strain cycles to failure.

(3) Under the same plastic strain range, identical state of cracks are obtained on a failed specimen in spite of the different conditions of temperature and frequency of straining.

(4) In large plastic strain range, it is easier for the cracks to develop leading to a complete fracture in the specimen by connecting one crack with another than in small plastic strain range.

(5) In order to clarify the dependence of N_f on temperature and frequency of straining, it is necessary to examine maintaining the influence of behaviour of fatigue cracks on N_f constant.

(6) The factor U^* which governs the rate of fatigue process depends on plastic strain energy per cycle U , temperature T , and strain rate $1/\tau$, as indicated below ;

$$U^* = \{2.1 \times 10^3 \tau^{0.37} e^{-(7600/T)} + 1.00\} U$$

The relation between U^* and N_f is

$$U^* N_f = 4.19 \times 10^3 / (\Delta \epsilon_p)^{0.45}$$

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Fig. 24 Relation between a and τ

Fig. 25 Relation between plastic strain range and $U N_f$ (marks indicate the same conditions as in Fig. 7)

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