BASIC CHARACTERISTICS OF SURFACE MICROCRACKS IN TYPE 304 STAINLESS STEEL AT 538℃

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This paper deals with the basic characteristics of surface micro-cracks on unnotched smooth specimens of Type 304 stainless steel under creep and creep-fatigue condition with holding time of 1 and 10 minutes respectively at 538℃ in air. The behaviors of the microcracks have been analysed via surface replica method and photomicrographs techniques. Quantitative information, such as initiation period, growth and coalescence behavior, statistical distributions of crack length, density of cracks, distribution patterns and crack growth properties, was obtained. Knowledge of these parameters is critical for the application of fracture mechanics to the life assessment and the damage evaluation of structures at elevated temperature.

Key Words: Major Crack, Creep-Fatigue, Weibull Distribution, Surface Replica Method, Surface Microcrack, Grain Boundary, Time Ratio, Holding Time.

1. INTRODUCTION

Crack initiation and growth measurements of microcracks and short cracks on unnotched smooth specimens represent an important part of fatigue studies. There have been many recent studies understand the mechanism of microcracking processes associated with the cracks, creep-fatigue life assessment, inspection of cracks or defects, and the integrity of structures. This comes from the need for safety and reliability, which is supported by recent developments in non-destructive inspection(NDI) techniques and fracture mechanics. Some of the more common techniques for observing, monitoring and measuring the crack growth behaviour are described in references(Kitagawa, et al., 1979 ; Suh and Kim, 1984). The basic characteristics of microcracks in the fracture process of unnotched smooth specimens, which is governed by the initiation, growth, and coalescence of many distributed microcracks, have been reported(Kitagawa, et al., 1979 ; Kitagawa, et al., 1983). It could be recognized that in almost all fatigue microcracks, most of the lifetime is spent in the initiation and slow growth stages, yet these have received less attention, until recently, compared to macrocrack growth at higher growth rates.

Owing to recent developments in fracture mechanics, much data has been obtained on the growth of a through crack which started from a large initial flaw. However very little data is available on surface microcracks or short cracks in the early stages of fatigue life. The initiation or growth behaviour of these cracks can occupy a significant fraction of the fatigue life of unflawed materials. The basic characteristics of micro-cracks in an unnotched smooth specimen are thus studied here.

The main objectives of this study are to determine : (1) the location and distribution patterns of microcracks which initiate randomly together with the paths of their growth, (2) the initiation and growth behavior of the main crack which leads to final fracture of the specimen, (3) the variation in density of microcrack per unit area with respect to the time ratio, (4) the statistical distribution of microcrack length, (5) the increase of average crack length with the time ratio, (6) the variation of longitudinal strain and lateral strain, and (7) the crack growth properties of microcracks and comparison of these data with those from room temperature and 538℃ pit specimen fatigue tests (Suh and Kim, 1984 ; Yuuki, et al., 1982).

2. EXPERIMENTAL PROCEDURES

In an effort to answer these objectives, it is necessary to conduct an experiment to provide adequate data for subsequent analysis. Axial tensile creep and creep-fatigue tests(trapezoidal waveform) with holding times of 1 and 10 minutes, respectively, of Type 304 stainless steel with microcracks initiated on an unnotched smooth surface at 538℃ in air were chosen for this study. The material was solution-

Table 1 Mechanical properties

Temperature ℃	Yield point 0.2% offset MPa	Tensile strength MPa	Elongation %	Reduction of area %
Room temperature	358	698	65.2	79.0
538	196	537	40.1	65.9

KS No. 14A tensile specimen, loading speed : 3mm/min

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treated, and its tensile mechanical properties were shown in Table 1.

Successive observations and measurements were made on the unnotched smooth surface in the central portion of the plate specimen(width of 14 mm and thickness of 3 mm) throughout the tests at regular intervals until final fracture. Before testing, specimens were polished to a mirror finish and etched to identify grain boundaries ; the etchant used was a solution of nitric and hydrochloric acids. Before replication, specimens were cooled slowly to room temperature. It was confirmed that these interruptions did not affect the creep-fatigue life of specimens.

Qualitative and quantitative determinations of the initiation and growth behavior of microcracks and cavities with respect to the grain boundaries, with an accuracy of 1 μm, were needed for this study. Hence two dimensional recordings with good resolution were required in order to backtrack from the final fracture to the initial crack, or crack pattern. For these purposes, a combined surface replica method and a photomicrograph technique were developed and applied. Many thousands of photomicrographs and replicas were taken in this research.

3. DISTRIBUTION PATTERNS AND LENGTH OF SURFACE MICROCRACKS

An example of microcrack distribution is shown in Fig. 1. Numerous microcracks were observed on the smooth surface of specimens subjected to static loading and cyclic stresses. The images in Fig. 1 were produced by tracing the cracks on the photomicrographs. This technique was used to verify crack size and growth behavior. Fatigue microcrack initiation is generally defined as the formation of a visible crack through microscopic observation. It is difficult to discriminate between a microcrack and a cavity during the early stages of the high temperature creep and creep-fatigue processes. A conventional engineering definition is used to discriminate between the two. That is, when any crack or crack-like mark grows through a grain boundary, or separation of grain boundaries becomes clear, then a crack is said to have initiated. The average grain size of the material used in this study is about 10 μm. The surface crack length at the initiation stages in this study was from 0.006 to 0.012 mm. Figure shows that the major crack(which led the specimen to fracture) and other cracks are likely to have initiated during very early stages of testing.

Many of these distributed microcracks were initiated by grain boundary damage, which is regarded as the primary process of cavity nucleation and growth, and triple-point cracking. Since grain boundaries are regions of high defect concentration due to the mismatch of the contiguous crystal lattices, they provide a rapid diffusion path for oxide attacking and cracking. Furthermore, the grain boundaries can act as a site of stress concentration, resulting in high local stress and plastic anisotropy. Once grain boundary sliding occurs by plastic deformation at elevated temperature, it stimulates the nucleation of grain boundary voids and the local diffusion that contribute to their growth. Grain boundary damage has been more generally studied in creep under static loading, but recently this topic has been reviewed for the elevated temperature fatigue and creep-fatigue cases(James, 1972 ; Suh et al., 1985).

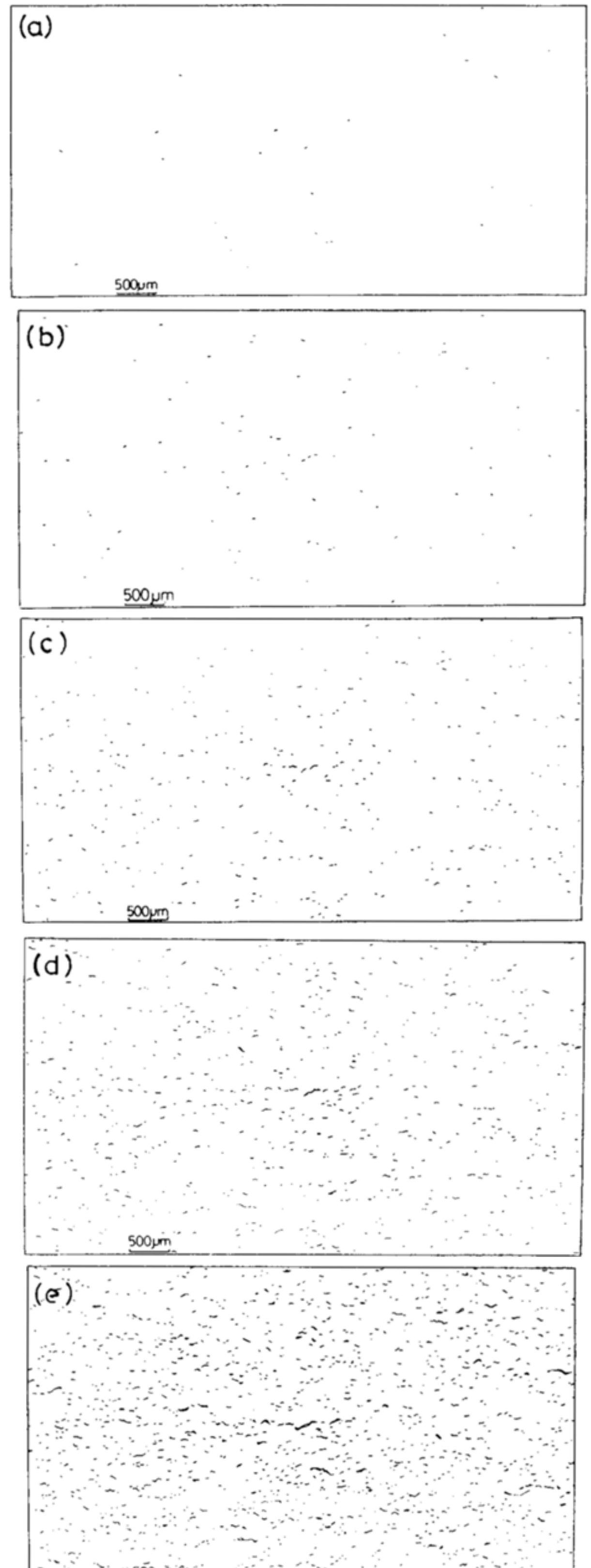

Fig. 1 A typical example of initiation, growth and coalescence of fatigue microcracks distributed on the surface of a smooth specimen (σ = 392 MPa, 538°C in air, hold time 10 min.)
(a) $t/t_f = 0.171$ (b) $t/t_f = 0.284$ (c) $t/t_f = 0.512$
(d) $t/t_f = 0.712$ (e) $t/t_f = 0.879$

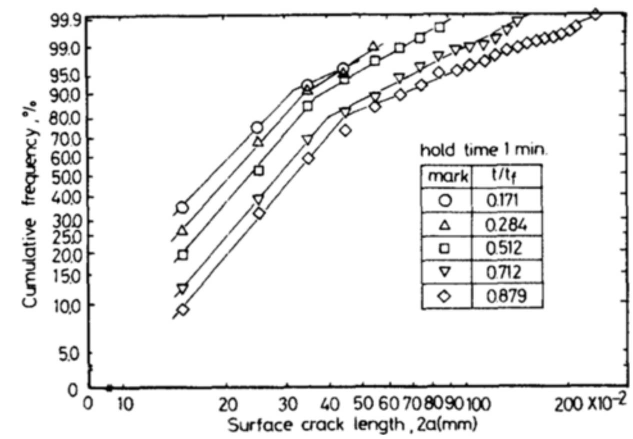

Fig. 2 Weibull distribution of the cumulative probability of fracture at a stress level of 392 MPa.

Photomicrographs show the initiation and growth of microcracks through a field enriched with cavities and voids. The cracks have a two dimensional distribution in their location and size. They are distributed close enough for interaction and coalescence. This tendency is more probable at later stages in a creep-fatigue life as judged from qualitative observations.

The crack paths are irregular ; the growth of microcracks on a smooth surface looks random. However, their general orientation seems to be perpendicular to the axis of the principal tensile stress. The tip-to-tip lines of comparatively larger cracks also are in a direction perpendicular to the tensile stress axis. The distance, perpendicular to the stress axis, of the tip-to-tip distance of a crack was measured as "crack length". After coalescence with other cracks, the coalesced crack was measured as one crack. The number of cracks and the length of each crack in replicas such as in Fig. 1 were counted and measured using a microscope or photomicrograph within $1\mu m$ accuracy. Another significant observation in Fig. 1 is the decrease of horizontal length and the increase of vertical length of the observation area as a function of a time ratio. This comes from material inelastic deformation at high temperature and will be discussed in more detail later.

Figure 2 shows a composite Weibull distribution of the cumulative probability versus microcrack length. These data show that even just before or at the final fracture of a specimen, the surface crack length, $2a$, of most cracks does not exceed 0.2-0.4 mm, and only a few cracks exceed 0.5 mm. This distribution moves to larger crack lengths and lower slopes as the time ratio increases. The intersection of two straight lines occurs at a crack length in the range of 2 to 4 grain sizes. Fractography revealed intergranular surface cracks of about 1 to 3 grain diameters in depth. Similar results were reported in another work (Suh, et al., 1985).

4. INCREASE OF MEAN CRACK LENGTH AND CRACK DENSITY

Figure 3 shows the increase of the mean value of the crack length, "mean crack length", $2a_m$, with time ratio obtained from Fig. 2. The mean crack length increases linearly with time ratio. Just before the final stages of fatigue life, the

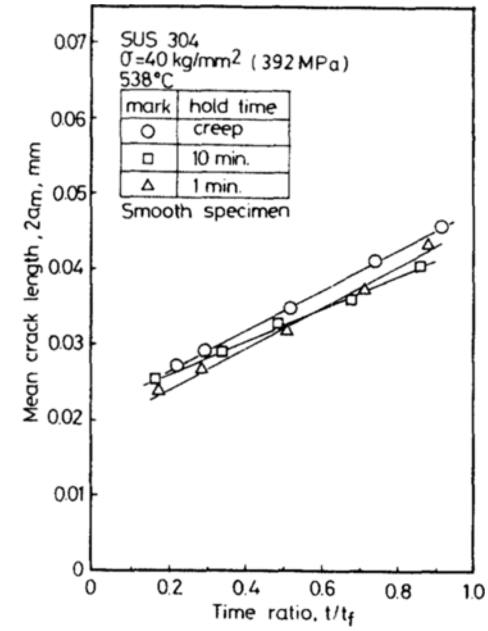

Fig. 3 Relation between the mean crack length and the time ratio

mean crack length is shorter than 0.06mm. This means that the mean crack length probably does not govern fatigue life nor play an important role in determining creep-fatigue life. The similar tendancy was obtained in 1020 low carbon steel at room temperature(Kitagawa and Suh, 1979).

Figure 4 shows the increase of the crack density, δ, with time ratio, defined as the mean value of the number of cracks in 1 mm². In this study, about 20 microcracks were observed in one square millimeter at $t/t_f = 0.6$. This value is remarkably low compared with that of a slow-fast waveform of Type 304 stainless steel at 400 cpm, 538 C, in air. Under the

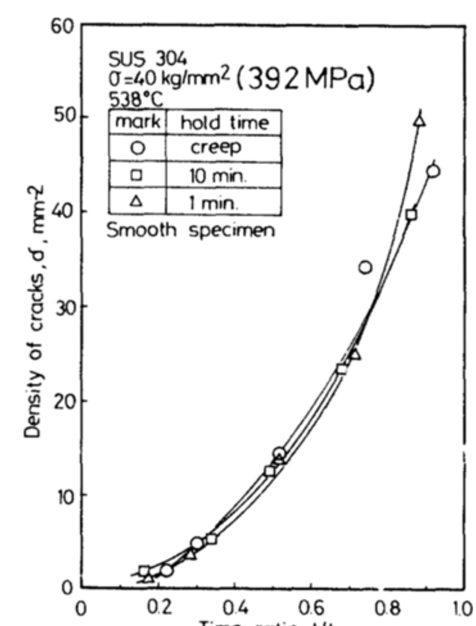

Fig. 4 Crack density as a function of time ratio

slow-fast waveform, about 300 microcracks were observed in one square millimeter at $t/t_f = 0.6$. Sidey and Coffin(1979) studied the effect of waveforms on fatigue life at elevated temperatures and found the slow-fast waveform to be the severest for fatigue of austenitic stainless steels. The density of surface cracks at room temperature (Suh and Kim, 1984) in Type 304 stainless steel is remarkably low compared to that of this study, but the values of δ for the three different testing conditions employed in this study are almost the same. It may be that microcrack density is a significant measure of the remaining life and the damage. Just before final fracture, the number of cracks in one square millimeter may be anywhere between one hundred to several hundred. The number of microcracks counted here does not include cracks which do not clearly separate grain boundary and cavities so that the actual crack density is much higher than this value.

It is suggested from these results that a small crack or cracks can be formed at any moment, and its growth is accelerated by its interaction and coalescence with other randomly but closely distributed microcracks. This tendency depends upon the combination of the crack density(Fig. 4) and the mean crack length(Fig. 3) or the statistical distribution of cracks with respect to their lengths or distribution patterns(Fig. 1). The major crack or the larger microcracks can be attributed to a local intensification of crack initiation and growth, as can be seen in Fig. 1 and plays an important role in smooth specimen fracture.

This observation suggests that measuring the behavior of initiation, growth, and coalescence of the major crack is necessary for understanding and controlling the creep-fatigue life. A basic method of analysis for such processes by means of statistical analyses and fracture mechanics has been developed by one of the authors (Kitagawa, et al., 1983) and has been successfully applied to the fatigue process at room temperature. Similar method can be applied to the creep-fatigue process at elevated temperatures, by use of the quantitative data.

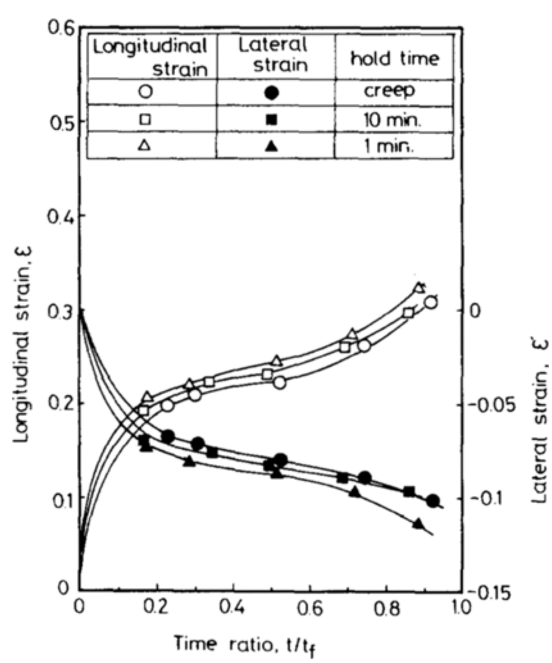

Fig. 5 Variation of longitudinal strain and lateral strain as a function of time ratio

5. VARIATION OF LONGITUDINAL STRAIN AND LATERAL STRAIN

Figure 5 shows the variation of longitudinal strain, ε, and lateral strain, ε', as a function of time ratio at three kinds of tests. These data were obtained from Fig. 1(i.e., elongation and contraction of the observation area in contrast to that before testing). This variation is caused by inelastic deformation throughout the creep-fatigue life. Longitudinal strain increases rapidly before $t/t_f = 0.2$, slowly until $t/t_f = 0.8$, and then increases rapidly again after $t/t_f = 0.8$(i.e., near the fracture of the specimen). Lateral strain behaves as the inverse to longitudinal strain(i.e., rapid contraction before $t/t_f = 0.2$). Similar results were reported in another work(Suh, et al., 1985).

6. RELATIONSHIP OF MAJOR CRACK LENGTH TO TIME RATIO

The central surface area of the specimen was two dimensionally recorded at every 5-10% intervals of creep-fatigue life by a replication method. After final fracture, the major crack was identified on the replicas(or the final photomicrographs) and backtracked to its initiation stages. The behavior of the major crack is very important on the smooth specimen, as previously stated. Increase of the length of the major crack, $2a_{maj}$, against the time ratio for this study is shown in Fig. 6. This figure shows that:

(1) The major crack initiates and grows in the very early stages of specimen life(e.g., 10%-20% of it). Results presented in the recent literature (Suh, et al., 1985; Kitagawa and Suh, 1979; Re Los Rios, et al., 1984) agree very well with this behavior in spite of the differences in test conditions.

(2) The relationships between the major crack length and time ratio are compressed into a relatively narrow band, regardless of the three different test conditions. This behav-

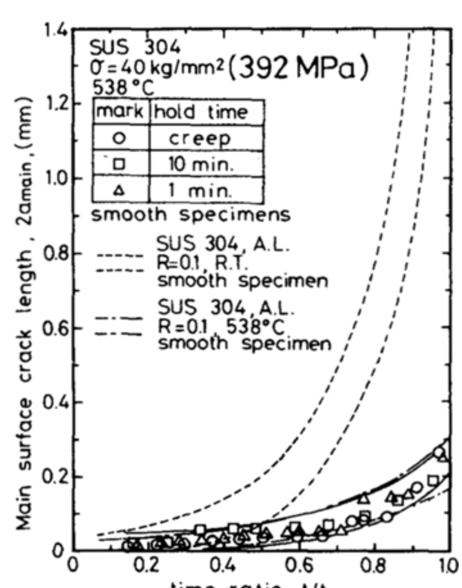

Fig. 6 Increase of major crack length against time ratio

ior is almost the same as the behavior of fatigue microcrack initiated at 400 cpm, 538℃, in air (Suh, et al., 1985).

(3) The final fracture is governed almost exclusively by the behavior of the major crack.

(4) The length of the major crack, $2a_{maj}$, is small throughout almost the whole specimen life. At $t/t_f = 0.5$, it is smaller than 0.1 mm while at $t/t_f = 0.8$ to 0.9, the major crack is smaller than 0.5 mm.

(5) From the result in (d) and the very high crack density after $t/t_f = 0.6$, it is suggested that final fracture occurs by the growth of the major crack and coalescence with other randomly distributed microcracks, not by growth of a single crack.

(6) At room temperature, small cracks initiate and grow as a single crack in Type 304 stainless steel (Suh and Kim, 1984), and the crack density is very low when compared with that at elevated temperature. For this reason, the length of the major crack at room temperature is larger than that at 538℃, as shown by the dotted line in Fig. 6.

7. CRACK GROWTH BEHAVIOUR OF THE MAJOR MICROCRACK

In recent years growing attention has been paid to microcracks, whose length is less than several tenths of a millimeter. It is critical that designers understand the crack growth behavior. They must know whether a microcrack(s) will follow the usual crack growth properties for larger cracks. In Fig. 7(a), the crack growth rate of major crack at three conditions, i.e., creep and creep-fatigue condition with holding time of 1 and 10 minutes respectively at 538℃ is plotted against stress intensity factor, $\sigma\sqrt{\pi a}$. This figure suggests that microcracks in Type 304 stainless steel at 538℃ in air do follow the $\sigma\sqrt{\pi a}$ vs da/dt relation. But the microcrack growth rate shows a slight difference between creep and creep-fatigue.

The fatigue crack growth rate data at room temperature, which coincides with the through-crack data at room temperature, is also plotted in Fig. 7(b). There is some increase in microcrack growth rate at 538℃ compared with that of room temperature even though the crack size is very small as seen in Fig. 6. The fatigue test data of cracks initiated at a small artificial pit(diameter of 0.5 mm and depth of 0.5 mm) and grown as a single crack under slow-fast sawteeth waveform (Suh, et al., 1985) at 538℃ in air is also plotted in Fig. 7(b). These data (Yuuki, et al., 1982) agree with the data for large through-crack. The data for microcrack growth on smooth specimens at 538℃ in air would fall above the extension of the dotted line describing the crack growth in the pit specimen and through crack specimen. It was found that the crack growth rate of the major crack in smooth specimens showed a slight difference among the three test conditions and was higher than the growth rate of creep-fatigue with the holding time of 1 minute.

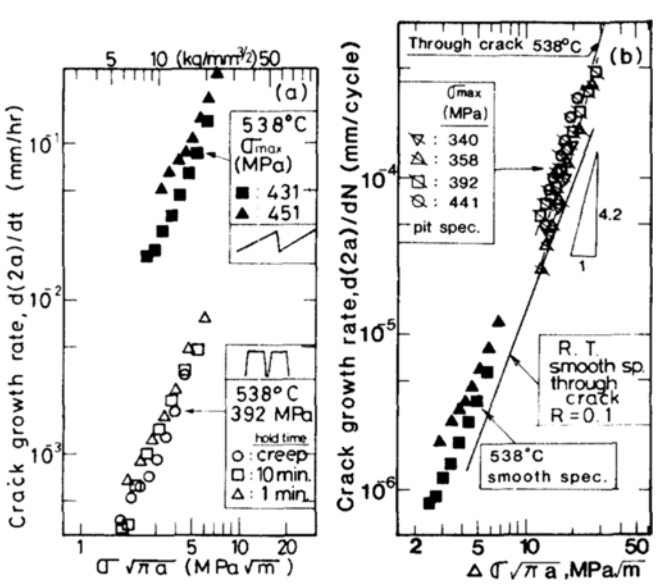

Fig. 7 Dependence of crack growth rate of microcrack upon the stress intensity factor

These facts suggest that the parameters of elastic-plastic fracture mechanics such as the J-integral or the strain intensity factor (Kitagawa, et al., 1979) are necessary to characterize the crack growth of the microcracks at elevated temperature. It is very significant that the microcracks at elevated temperature can grow far below the threshold condition K_{th} for a large crack. Usami et al.,(1984) reported that the value of K_{th} decreases significantly at elevated temperature with decrease of crack size.

8. CONCLUSIONS

The initiation, growth, and coalescence of surface microcracks have been studied in smooth Type 304 stainless steel specimens by means of a surface replica method and by optical photomicrographs. By using these techniques, the basic characteristics of the surface microcracks initiated under creep and creep-fatigue with holding times of 1 and 10 minutes respectively, at 538℃ in air has been obtained. Some of the results are as follows:

(1) Microcracks begin to initiate during the early stages(10 to 20%) of creep and creep-fatigue conditions and continue to grow during the rest of life. New microcracks continue to initiate up until final fracture.

(2) Most cracks do not exceed 0.4 mm in length. Just before the final fracture the major crack(which led the specimen to fracture) length is about 0.5 mm. This suggests the rapid coalescence of closely distributed microcracks just before the final fracture.

(3) The major crack or few larger microcracks can be attributed to a local intensification of crack initiation, growth and coalescence, and play an important role in the unnotched smooth specimen fracture.

(4) The microcrack length distributions shown by composite Weibull curves may be approximated by two straight lines which diverge at a value given by the transient region between stage I and stage II crack growth.

(5) The crack growth rate of a major crack can be plotted against the stress intensity factor.

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