Effects of Test Temperature on Internal Fatigue Crack Generation Associated with Nonmetallic Particles in Austenitic Steels

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Internal crack generation associated with nonmetallic inclusions or precipitates has been investigated on high-cycle fatigue at 4 K, 77 K, and 293 K of 25Mn-5Cr high-manganese austenitic steel and nitrogen-strengthened 25Cr-13Ni austenitic stainless steel. In both steels, the internal crack initiation typically occurred at 4 K or in long-life range over 10^6 cycles at 77 K. Particles such as inclusions and precipitates were responsible for the internal crack-generation behavior, and the origins were identified as mainly Al_2O_3 inclusions in 25Mn-5Cr steel and AlN precipitates in 25Cr-13Ni steel, respectively. We discuss the crack-generation stage I mechanism and the relationship between stress range and size of crack-initiation site. The generation of fatigue cracks associated with the nonmetallic particles in the specimen interior involved a stage I crack. A threshold condition assumption was proposed, that the crack propagation occurred at any stress level when the local stress intensity factor range reached over a constant at or around the initiation crack associated with defects.

I. INTRODUCTION

THE generation of subsurface (internal) fatigue cracks in high-strength alloys is usually associated with the presence of nonmetallic inclusions, as illustrated in the case of fish-eye-type fractures.^[1,2] While the mechanism of the crack generation and its growth originating from a nonmetallic inclusion near the specimen surface has been discussed,^[3,4] it has not been sufficient to understand the internal crack-generation mechanism associated with pre-existing defects, such as inclusions. Table I provides a summary of our results^[5-10] on the fatigue crack-initiation site and subsurface crack origin at cryogenic temperatures. Subsurface crack initiation is dominant at lower temperatures and in the long-life range, while surface crack initiation occurs in high peak stress tests or in short-life tests. For example, the Ti-6Al-4V alloys and 24Cr-15Ni-4Mn-0.3N steel listed in Table I have the highest strength level among the cryogenic structural alloys, and their subsurface crack initiation apparently occurs due to transgranular or intergranular cracking.^[6,9] The dependence of subsurface crack-initiation site size on the peak stress was able to be accounted for by a threshold condition assumption such that microcracks grew until a critical crack size depending on the peak stress.

Furthermore, the possibility that, even in an S-N curve, different crack initiation mechanisms can exist has not been focused. For an A2219 alloy, two types of internal crack initiation origins, of which were precipitate and intergranular cracking, were detected at cryogenic temperatures.^[10] This means that the microcrack originating from a pre-existing defect may not always provide a critical crack size. In order to determine the defect that is finally responsible for fatigue failure, not only the metallurgical origin but also

the geometry of the initial cracks have to be discussed. Hence, the metallurgical and micro-fractographical investigations are necessary to clarify the mechanism of internal crack generation from defects such as nonmetallic particles.

The internal crack initiation in high-cycle fatigue has been detected in 25Mn-5Cr high-manganese austenitic steel and nitrogen-strengthened 25Cr-13Ni austenitic stainless steel at cryogenic temperatures. For the 25Mn-5Cr steel, in which the important role of inclusions on its fatigue crack-growth behavior was already reported elsewhere,^[11] the internal crack initiation associated with nonmetallic inclusions was dominant at cryogenic temperature.^[8] The 25Cr-13Ni steel also contained fine particles.^[12] In the present study, the internal crack generation in each steel has been characterized. Special attention is given to present the important role of nonmetallic particles at initiation sites for the microcracking and its growth.

II. EXPERIMENTAL

A. Materials and Fatigue Test Conditions

Two kinds of austenitic steels in solution-treated condition, 25Mn-5Cr^[13] and nitrogen-strengthened 25Cr-13Ni,^[12] were examined. The chemical compositions of each steel are listed in Table II. The 25Mn-5Cr steel was hot rolled (heating at 1473 K) into 30-mm-thick plate and solution treated at 1323 K. The 25Cr-13Ni steel was also hot rolled into 30-mm-thick plate and solution treated. Figure 1 shows optical microstructures for each steel. The 25Mn-5Cr steel contains inclusions that are aligned along the rolling direction (RD), as shown in Figure 1(a). The existence of Al_2O_3 inclusions was confirmed by an X-ray microprobe analysis. For the 25Cr-13Ni steel, no inclusion is visible in Figure 1(b), but it contained the fine particles with 0.076 pct in volume where the nonmetallic inclusions (such as Al_2O_3 , CaO, and CaS), and the precipitate (such as AlN) were detected. The inclusions and their volume fraction were determined by a computer aided macroanalysis.

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Manuscript submitted April 29, 1997.

Table I. Summary of Crack Initiation Site and Subsurface Crack Origin for the Tested Materials

Materials	Crack Initiation Site (10 ⁴ to 10 ⁷ cycles)			Subsurface Crack Origin	References
	293 K	77 K	4 K		
<u>Titanium alloy (mill annealed)</u>					
Ti-5Al-2.5Sn extra low interstitials	S	S	S > I	transgranular (fine α phase)	5
Ti-6Al-4V forged	S > I	S > I	S > I	transgranular (α phase)	6
Ti-6Al-4V forged + rolled	S > I	S > I	S > I		6
<u>Austenitic steel (solution treated)</u>					
SUS316LN	S	S	S > I	pore	8
SUS316LN + 20 pct cold rolled	S	S > I	I	Cr, Mo-rich zone	8
32Mn-7Cr-0.1N	S	S > I	I	intergranular	9
24Cr-15Ni-4Mn-0.33N	S > I	S > I	S > I	intergranular	9
<u>Aluminum alloy</u>					
A2219-T87	S / I	S / I	S / I	precipitate or intergranular	10

S: Surface crack initiation; I: subsurface (internal) crack initiation; S > I: The initiation site shifts from surface to interior at lower stress; and S / I: Both types of crack initiation are detected.

Table II. Chemical Compositions of Tested Steels in the Present Study

Steels	Concentration (Mass Pct)														
	C	P	Si	S	Mn	Ni	Cr	Mo	Al	Nb	N	Ca	Ti	O	Fe
25Mn-5Cr	0.22	0.024	0.86	0.001	25.60	0.97	4.67	—	0.009	0.043	0.040	—	—	—	bal
25Cr-13Ni	0.015	0.035	1.12	<0.001	0.78	13.52	25.06	0.76	0.065	—	0.368	0.002	<0.01	0.0030	bal

Table III. Tensile Properties and Toughness of the Tested Steels at Cryogenic Temperatures

Steel	Temperature (K)	UTS (MPa)	YS (MPa)	El (Pct)	RA (Pct)	CVN (J)	K_{IC} (J) (MPa $\sqrt{m}$)
25Mn-5Cr	4	1529	958	42.3	44.0	68	255
	77	1239	619	55.7	45.1	77	—
	293	702	364	65.1	62.7	155	—
25Cr-13Ni	4	1886	1381	18.0	45.2	60	118
	77	1542	1024	43.8	59.6	69	—
	293	805	428	51.3	64.7	177	—

*Temp: temperature; UTS: ultimate tensile strength; YS: 0.2 pct proof stress; El: elongation; RA: reduction of area; and CVN: Charpy absorbed energy.

Fig. 1—Optical microstructures of the transverse section in fatigue specimen: (a) 25Mn-5Cr steel and (b) 25Cr-13Ni steel.

Fatigue test conditions were as follows: hourglass-type unnotched specimens with a reduced diameter of 6 mm

were fatigued in liquid helium (4 K), liquid nitrogen (77 K), and air (293 K). The longitudinal direction of the spec-

Fig. 2—S-N data of (a) 25Mn-5Cr and (b) 25Cr-13Ni steels at cryogenic temperatures. Slanting bars in each plot indicate the crack initiation in conjunction with nonmetallic particles.

Fig. 3—SEM micrographs of fatigue fracture surfaces and crack initiation sites for 25Mn-5Cr steel at 4 K: (a) through (c) $\sigma_{\max} = 841$ MPa, $N_f = 2,943,880$ cycles; and (d) through (f) $\sigma_{\max} = 917$ MPa, $N_f = 473,600$ cycles. Photographs (b) and (c) are matching halves at the crack initiation site in photograph (a). Photographs (e) and (f) are also matching halves at the crack initiation site in photograph (d).

Fig. 4—The internal crack initiation site of sample failed at 4 K for the 25Mn-5Cr steel ($\sigma_{\max} = 994$ MPa, $N_f = 97,100$ cycles). SEM micrographs (a) and (b) are matching halves of fracture surfaces. Photograph (c) shows the A-B section shown in photograph (a). Illustration (d) describes the debonding and cracking at the internal crack initiation site in the longitudinal section.

imens was perpendicular to the RD for each steel. The specimen surface was ground and polished. Using the cryogenic servo-hydraulic fatigue testing machine,^[14] load-control tests were done with a sinusoidal waveform and a minimum-to-maximum stress ratio R of 0.01. Testing frequency was 4 Hz at 4 K, 10 Hz at 77 K, and 20 Hz at 293 K.^[8,15]

B. Microscopy and Characterization

The fatigue crack-initiation sites were examined by scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS), laser microscopy (LM), electron probe microanalyzer (EPMA) and scanning Auger multi-probe (SAM), (PHI model 650). The SEM was operated with 20 keV accelerating voltage, and secondary electron images were obtained. The LM, EPMA, and SAM analyses were done in the vicinity of an internal crack-initiation site of 25Cr-13Ni steel, as shown in Figures 5(b) and (c). The LM analysis achieved a three-dimensional characterization

of the crack-initiation site, *e.g.*, a birds-eye view and its cross sections. The EPMA was operated with 10 keV. The accelerating voltage of the electron probe beam in the SAM was 3 keV, and that of Ar ion sputtering was 3 keV. To calibrate the results on the internal crack-initiation site, EPMA and SAM analyses were also done for the aluminum, AlN, and Al_2O_3 samples. In addition, transmission electron microscopy (TEM) observations were also done to characterize the dislocation structures after fatigue testing.

In this study, we introduced the parameters mentioned later to determine the geometry of the internal crack-initiation site. At first, the internal crack-initiation site was defined as the whole of the inclined area that does not place on the main fatigue crack-propagating plane, as in the previous study.^[6] The distance from the internal crack-initiation site to the nearest specimen surface d was evaluated from SEM photographs. The size of the crack-initiation site associated nonmetallic particles was also quantified by a crack-length parameter. The crack size f_s was defined as the

Fig. 4 Continued—The internal crack initiation site of sample failed at 4 K for the 25Mn-5Cr steel ($\sigma_{\max} = 994$ MPa, $N_f = 97,100$ cycles). SEM micrographs (a) and (b) are matching halves of fracture surfaces. Photograph (c) shows the A-B section shown in photograph (a). Illustration (d) describes the debonding and cracking at the internal crack initiation site in the longitudinal section.

minor axis of an orthographic projection of the crack-initiation site on the main crack-propagating plane, as in the previous study.^[6] In the present study, we apply the parameter f_s to the surface crack-initiation site associated with nonmetallic inclusion and to the internal crack-initiation site.

III. RESULTS

A. Initiation and Early Growth of Fatigue Crack Originating from Nonmetallic Particle

Figure 2 shows the S-N data for 25Mn-5Cr^[8] and nitrogen-strengthened 25Cr-13Ni^[15] steels, which distinguishes

Horizontal angle : 45 degree
Elevation : 30 degree

Fig. 5—The internal crack initiation site of a sample failed at 4 K for 25Cr-13Ni steel ($\sigma_{\max} = 1509$ MPa, $N_f = 88,600$ cycles). Photographs (b) and (c) are matching halves of fracture surfaces. Three-dimensional indication (d) resulting from laser microscopy corresponds to the crack initiation site in photograph (b). The areas marked 1 and 2 represent the SAM analyses region.

each crack-initiation site, whether on the specimen surface (open plots) or on the specimen interior (solid plots). The internal crack initiation is dominant at 4 K or in longer life range over 10^6 cycles in both steels. The slanting bars in Figure 2 exhibit the fatigue crack initiation due to the non-metallic inclusion or precipitate, as mentioned below.

1. 25Mn-5Cr high-manganese austenitic steel

The fatigue crack initiation occurred from the nonmetallic inclusion in all samples, regardless of whether at specimen surface or interior. The internal crack initiation was typically detected at 4 K, as shown in Figure 2(a). Figure 3 shows the fatigue fracture surfaces and crack-initiation sites at 4 K. The fatigue crack is radially propagating from an inclusion in each case, and the ripple mark appears in Figure 3(d). The radius of the stage II region was increased when decreasing the peak cyclic stress. The inclusion related with surface crack initiation was smaller than that associated with internal crack initiation.

The EDS analyses were done for the particular inclusions at which the fatigue crack was initiated. In the inclusions, aluminum was highly enriched, and Mn and S were partly detected. Most of the inclusions were identified as Al_2O_3 .

Figure 4 shows a typical example of the internal crack-initiation site. Micrographs (a) and (b) are matching halves of the fracture surface. The cracking of inclusion or the interfacial separation (debonding) between inclusion and surrounding matrix has occurred at the internal crack-initi-

tiation site. The sample shown in Figure 4(a) was sliced vertically at the line A-B. Figure 4(c) shows the plane section A-B of the right side shown in micrograph (a), but the inclusion had already fallen off during sample preparation. The internal crack-initiation site is inclined about 45 deg to the principal stress axis in Figure 4(c) and reveals the transition from the stage I crack to the stage II crack where the crack propagating plane is macroscopically normal to the principal stress axis. In addition, these photographs clearly indicate that the nonmetallic inclusion has only partial contact with the matrix, and that the inclusions link up to form a secondary crack in the plane section C, as illustrated in Figure 4(d). These micrographs revealed the poor adhesion between the nonmetallic inclusion and the matrix. Similar observations were also made in other samples.

2. Nitrogen-strengthened 25Cr-13Ni austenitic stainless steel

The internal crack initiation was typically detected at 4 K or in long-life range above 10^6 cycles in Figure 2(b). Figure 5 represents the internal fatigue crack-initiation site in the 25Cr-13Ni steel failed at 4 K. The internal crack initiation at 4 K and 77 K seemed to originate from a brittle cracking of a facet-like form with oval or larger aspect ratio shape, as shown in Figures 5(b) and (c). According to the LM analyses in Figure 5(d), the internal crack-initiation site was macroscopically flat and inclined about 45 deg to the principal stress axis.

Fig. 6—EPMA analyses for the internal crack initiation site shown in Fig. 5(b): (a) secondary image of the analyses region; X-ray (K_{α}) mapping for each element such as (b) O, (c) Al, and (d) N, and (e) Al K_{β} peak energy in a X-ray profile at an Al enriched point.

Figure 6 represents an EPMA analysis result for the internal crack-initiation site shown in Figure 5(b). Aluminum and nitrogen are detected at the initiation site, and no oxygen was detected. Figure 6(e) shows that Al- K_{β} peak energy in the X-ray profile is fitted to that of the AlN standard sample—but of neither the metallic aluminum nor the Al_2O_3 sample. The sample shown in Figure 5(c) was further analyzed with SAM. Figure 7(a) indicates the change of derivative peak height as a function of Ar ion sputtering time

for C, O, Al, and Fe at the marked area 1 in Figure 5(c). At 120 seconds, 720 seconds, 1.98 ks, and 2.82 ks, the scan-differentiated spectra in both areas 1 and 2 were obtained. After 250 seconds sputtering, carbon and oxygen (which were absorbed into the specimen surface) disappeared. At area 1, Al was detected until sputtering time of about 2.4 ks. The number of counts for Fe was remarkably increased with a sputtering time above 1.8 ks. Figure 7(b) represents the spectrum after 720 seconds sputtering. Both

Fig. 7—SAM analyses results at the marked area 1 shown in Fig. 5(c): (a) change of derivative peak height as a function of Ar ion sputtering time with a smoothing treatment, (b) wide scan differentiated spectrum 2, and (c) change of Auger peak shape in low energy field during Ar ion sputtering. Arrows in (a) correspond to the points taking each Auger spectrum shown in (c).

peaks of Al and N are revealed. The energy of each peak in Figures (b) and (c) is fitted to that of AlN, but not of metallic Al or Al_2O_3 . Figure 7(c) shows the change of Auger peak shape in a low energy field below 100 eV. It

Fig. 8—Location of the internal crack initiation site in each fracture surface for 25Mn-5Cr and 25Cr-13Ni steels.

exhibits that the peak-to-peak height of Al decreases with sputtering time. On the other hand, those of Fe and Cr increase with time.

It is concluded that the defect at the internal crack-initiation site is an AlN precipitate. According to sputtering-rate examination for a stainless steel, the thickness of the AlN can be estimated at about 200 nm. The AlN preferably precipitates along prior austenite boundaries.^[16] In the present 25Cr-13Ni steel, it has not been determined whether the AlN precipitated at the boundary or not. The internal crack-initiation site of a sample fractured at 293 K, however, exhibited an intergranular form. There was no evidence of the relation with AlN cracking. The surface crack initiation was not related with any pre-existing defects.

B. Location and Size of the Crack Initiation Site Associated with Nonmetallic Particles

Figure 8 shows the location of the internal crack-initiation sites on the fracture surface. The data plots seem to be scattered over the specimen diameter, although the number of data is not enough. There is no tendency for a favourable depth of the location, as in the case of the Ti-6Al-4V alloys.^[17] The location of the sites must be dependent on the location of a fatal defect in each specimen.

Figure 9 shows the dependence of the crack-initiation site size f_s on peak cyclic stress for 25Mn-5Cr and 25Cr-13Ni steels. In the present data of 25Mn-5Cr steel, the range of size is between 10 and 40 μm for surface defect and between 40 and 100 μm for internal defect. The size of the crack-initiation site associated with inclusions f_s seems to increase with the decrease of the peak cyclic stress. For the 25Cr-13Ni steel, on the other hand, the f_s of the internal crack-initiation-related AlN is equal to about 10 μm re-

Fig. 9—Size of the internal crack initiation sites and of the surface crack initiation sites associated with an inclusion. Assuming the ΔK_{th} value of each steel is equal to 2.5 MPa $\sqrt{m}$ resulting from Fig. 13, solid lines show the calculated threshold crack initiation site size at specimen surface, $d_{c,s}$, and in specimen interior, $d_{c,i}$.

Fig. 10—SEM photographs of debonded inclusions in the longitudinal section, which is from the same plane as in Fig. 4(c): (a) debonded inclusion at which apparent matrix deformation has occurred; and (b) debonded inclusion at which microcracks have linked up to form a tightly closed fatigue crack, which joins the debond seam at D. Arrows indicate microcrackings.

Regardless of stress level and test temperature. However, the internal crack initiation in the much lower peak cyclic stress range at 293 K provided a much larger site with intergranular form instead of the AlN cracking.

IV. DISCUSSION

A. Fatigue Crack Generation Associated with Nonmetallic Particles in the Specimen Interior

The adhesion between the matrix and the nonmetallic inclusion, Al_2O_3 , in the present 25Mn-5Cr steel was weak, as mentioned previously. Although it is not clear that either

the cracking of inclusions or the debonding between those and the matrix took place prior to the fatigue test. Such weak adhesion between the matrix and the inclusion produces a local stress raiser. The fatigue crack originates at the periphery of the inclusion regardless of its location in specimen, *i.e.*, specimen surface or interior. The SEI micrographs in Figure 10 represent the debonded small inclusions in the specimen interior after fatigue cycling. In particular, the growing microcrack does not seem to be related to slip band intrusion/extrusion, but rather to the linkup of microcrackings that might be produced by heterogeneous slip deformation. Figure 10(b) shows that microcracks formed at the point defects have linked up to form a tightly closed fatigue crack and to join at D. It is considered that microcracks formed as the debonded seams around the inclusions in the specimen interior would link together and lead to fatigue crack initiation in the matrix. It means that the proposed model to describe the fatigue crack initiation based on debonding of surface inclusions by Lankford and Kusenberger,^[4] could be applicable to explain the fatigue crack generation due to nonmetallic inclusions in the specimen interior.

On the other hand, the AlN cracking in 25Cr-13Ni steel would provide a sharp crack with enough size to propagate at a given stress level like microstructural cracking.^[6,9] Then the AlN cracking could make the stage I crack itself to start stage II crack propagation. In the present study, there was no evidence of the stage I crack growth from AlN cracking into a matrix to form a larger site.

In both steels, the internal crack initiation associated with defects was dominant at lower temperature and in the sub-surface crack initiation due to microstructural cracking.^[6,9] In the present study, deformation structures of the fatigued samples were also examined. Figure 11 represents the dislocation pileups for 25Cr-13Ni steel that were sharply localized and caused stress concentration in the vicinity of a grain boundary (GB) in Figure 11(a). For both steels, (111) co-planar slip prevailed in the lower stress range where the internal crack initiation occurred. The (111) stacking faults in 25Cr-13Ni steel (Figure 11(c)), and ϵ -martensite and deformation twinning in 25Mn-5Cr steel (Figure 12) were not a major factor in cyclic deformation. Furthermore, the plastic deformation in those steels was highly inhomogeneous. On the other hand, the hard particles, such as Al_2O_3 and AlN in the specimen interior, are a kind of obstacle for the dislocation motion in the matrix and can hardly be deformed. Slip deformation in the matrix could occur in the vicinity of such particles. Therefore, the particles do not yield under cyclic deformation, produce stress concentration around themselves, and finally are cracked or debonded with the matrix to relax the stress concentration. Thus, it is considered that the generation of fatigue cracks associated with the nonmetallic particles in the specimen interior involve a highly localized deformation in the vicinity of the particles.

B. Dependence of Pre-existing Defect Size on Stress Range

Lankford and Kusenberger^[4] have reported that the fatigue life in 4340 steel was more closely related to the diameter of inclusions than to whether the nucleating particle was located at the surface or subsurface, and they suggested

Fig. 11—Dislocation structure of a cyclically deformed 25Cr-13Ni sample at 4 K: (a) stress amplitude, $\sigma_a = 485$ MPa, after 2×10^6 cycles; (b) the magnified image of pileups in (a) with a different two-beam condition; and (c) stress amplitude, $\sigma_a = 745$ MPa, after 88,600 cycles. Beam directions are near $[011]$.

that the mechanism of near subsurface crack initiation should be qualitatively similar to that of surface nucleation. Kitagawa *et al.*^[18] and Murakami^[19] proposed that the fatigue limit of the material containing pre-existing defects was determined from the relationship between the defect size and threshold stress range. These ideas are based on the assumption that a small defect, such as an inclusion, is equivalent to a microcrack (stage I crack) and that the microcrack growth is retained under the fatigue limit. In the range of $2a$ (crack length) $> d_c$ (threshold defect size), ΔK_{th} value determines the fatigue limit threshold stress range. For $2a < d_c$, on the other hand, the threshold stress range is almost equal to the fatigue limit of the material without defects. However, it should be noted that Kitagawa and Murakami took the defect size as a crack size. Generally the microcrack itself does not always provided a critical main crack size. The microcrack needs to grow until it finally forms the initiation site of a critical size and the stage I crack generation resulting from microstructural crackings.^[6,9] It is also necessary to take into account the three-dimensional shape of the defect (stage I crack) and of the radius of curvature at the tip. Hence, it may not be true that the defect size is equal to the nucleus of the main crack or the threshold defect size. Especially in the range of $2a <$

Fig. 12—Deformation structure of a fatigued sample for 25Mn-5Cr steel after 12,390 cycles at 4 K ($\sigma_a = 666$ MPa). Selected area diffraction pattern $[0\bar{1}1]_z$, zone normal showing the ϵ reflections (arrows) and $\{111\}$ twinning reflections.

d_c , it is considered that the size gap between the postulated nucleus of the main crack and the defect is greater. In the

Fig. 13—Relationship between maximum cycle stress range, $\Delta\sigma_{\max}$, and maximum stress intensity factor, $\Delta K_{I\max}$, for 25Mn-5Cr and 25Cr-13Ni steels.

present study, we adopted the f_s defined previously as a crack size parameter. In addition, the deformation mode at the crack tip was simplified into the mode II in stage I and the mode I in stage II.

Then, an approximate equation to give the maximum stress intensity range, $\Delta K_{I\max}$, at the crack tip is roughly represented as follows:

$$\Delta K_{I\max} = 0.65 \Delta\sigma_{\max} \sqrt{\pi f_s} \quad : \text{surface defect} \quad [1]$$

$$\Delta K_{I\max} = 0.5 \Delta\sigma_{\max} \sqrt{\pi f_s} \quad : \text{internal defect} \quad [2]$$

where $\Delta\sigma_{\max}$ is maximum cyclic stress range, and the coefficient in each equation was adopted in the reference.^[19] On the basis of the previous assumptions, Figure 13 rearranges the data in Figure 9 and shows the relationship between $\Delta\sigma_{\max}$ and $\Delta K_{I\max}$. The value of $\Delta K_{I\max}$ for 25Mn-5Cr steel is in a range between 2.5 and 8.5 MPa√m. On the other hand, the value of $\Delta K_{I\max}$ for 25Cr-13Ni steel is in a narrower range between 2.5 and 5 MPa√m. The bigger $\Delta K_{I\max}$ data are considered to exhibit the excess of the crack-initiation site size from a threshold value. Supposing $\Delta K_{th} = 2.5$ MPa√m in each steel, the threshold defect size $d_{c,s}$ (specimen surface) and/or $d_{c,i}$ (specimen interior) are calculated by Eqs. [1] and [2], as shown in Figure 9. It means that a main crack can start to propagate when the f_s is greater than $d_{c,s}$ in the specimen surface or $d_{c,i}$ in the specimen interior. Because the f_s values and related AlN cracking were around 10 μm regardless of stress level for the 25Cr-13Ni steel, it can hardly satisfy the ΔK_{th} condition around $\Delta\sigma_{\max} = 500$ MPa. In the case of the internal crack initiation in such a lower peak cyclic stress range, therefore, the intergranular cracking is considered to form the site over a critical size earlier than the AlN cracking. According to the previous discussions, there might be a critical con-

dition, $\Delta K_{th} = \text{constant}$, at any stress level where the crack generation associated with defects occurs along with the subsurface crack initiation resulting from microstructural cracking.^[6,9,17] It is suggested that the refinement of the defect size in the present steels is effective to increase their fatigue strength.

V. CONCLUSIONS

An investigation has been made on the internal fatigue crack generation associated with nonmetallic particles, such as inclusions or precipitates in high-strength steel, at cryogenic temperatures. The principal results are as follows:

1. The internal crack initiation was dominant at a 4 K or longer life range over 10^6 cycles in 25Mn-5Cr and 25Cr-13Ni steels;
2. The origin of internal crack initiation was Al_2O_3 inclusion in 25Mn-5Cr steel and AlN precipitate in 25Cr-13Ni steel, respectively;
3. The generation of fatigue cracks associated with the nonmetallic particles in the specimen interior involved a stage I crack. This suggests that the nature of the internal crack generation process is almost the same with the subsurface crack generation resulting from microcracking in the matrix;
4. The dependence of the internal crack-initiation site size on the peak stress suggests a threshold condition assumption, that the crack propagation occurs at any stress level when the local stress intensity factor range reaches over a constant at or around the initiation crack associated with defects.

ACKNOWLEDGMENTS

We thank Mr. T. Yuri and Dr. T. Ogata for their help in providing the fatigue data. Thanks are also extended to Dr. M. Imai and Mr. K. Honma for the technical help on SAM and EPMA analyses, respectively.

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