Fatigue Crack Propagation Behavior of Multilayered Low Carbon Steel-stainless Steel Composite Plates*

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Observation and analysis were made on the effect of thermally induced residual stress on propagation and opening behavior of fatigue cracks in multilayered composite plates which were composed of low carbon steel and ferritic or austenitic stainless steel. It was observed that the crack propagation behavior in the composite plates was quite different from that in the monolithic plates, when the crack growth rates were plotted against K_{max} . But, when those were plotted against ΔK_{eff} , the data points of the composite plates came close to those of the monolithic plates, although there were some scatters. This suggested that the residual stress had a large influence on the crack opening behavior in the composite plates. Therefore, by calculating the actual stress intensity factor K_{max} for the composite plates based on an initial distribution of residual stresses, their crack opening behavior was estimated by using K_{max} and the crack opening behavior of monolithic plates. The estimated trends showed a fairly good agreement with those of the observed results.

Key Words: Fatigue, Metal Composite, Fatigue Crack Propagation, Crack Opening, Effective Stress Intensity, Residual Stress

1. Introduction

There have been a number of reports on the fatigue failures of the metal composites including the propagation behavior of fatigue crack in two layered metal composite plates⁽¹⁾⁻⁽³⁾. The authors also have investigated the propagation behavior of fatigue crack in two layered composite plates composed of a low carbon steel and a stainless steel which have the same elastic moduli but have different thermal expansion coefficients and mechanical properties^{(4),(5)}. The experimental results were discussed from a viewpoint of the effects of the residual stress introduced into each constituent during the heat treatment due to the difference in the linear expansion coefficients and the difference in the mechanical properties of constituents on the propagation behavior of fatigue crack in the composite plates.

From these studies, it was concluded that the crack growth rates in the composite plates were rather controlled by the effective stress intensity factor range (ΔK_{eff}). Especially, when the crack starts to propagate in the field of compressive initial residual stress and it

is within the same stress field, the crack opening behavior in the composite plate can be estimated by considering the elastic redistribution of residual stresses and the crack opening behavior of the monolithic plates of constituent materials⁽⁴⁾. And the variations of equi-strain areas at the crack tip before and after crossing the interface of the composite plates can be qualitatively understood by considering both the initial residual stress in the constituent materials and the difference in their yield strength⁽⁵⁾.

The two layered composite plates used in those studies have the simplest structure as composite plates. And, there have been few reports on the propagation behavior of fatigue cracks in multilayered composite plates because of difficulty of fabrication. In the present study, the propagation and opening behavior of fatigue crack was experimentally examined on the multilayered composite plates which consisted of the same materials as in the authors' previous study⁽⁴⁾.

2. Test Specimens and Experimental Procedures

Specimens used in fatigue tests were two series of five or six layered composite plates; one consisting of an Al-killed steel (labeled SA) and a ferritic stainless steel (labeled SUSF) and the other consisting of a rimmed steel (labeled SR) and an austenitic stainless steel (labeled SUSA). The chemical compositions of the constituent materials are listed in Table 1, and the mechanical

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properties and the linear expansion coefficient are listed in Table 2.

The composite plate specimens were fabricated by the same diffusion bonding method as in the authors' previous study (4). The shapes and dimensions of the composite plate specimens are shown in Fig. 1. Fig. 1(a) shows the SA-SUSF series composite plates; one consisting of SA in the first, third and fifth layers

and SUSF in the second, fourth and six-th layers, and the other consisting of SUSF in the first, third and fifth layers and SA in the second and fourth layers. The first type is termed FSI type and the second one SFI type. Fig. 1(b) shows the SR-SUSA series composite plates; one consisting of SR in the first, third and fifth layers and SUSA in the second and fourth layers, and the other consisting of the same layers in the reversed order. The first type is termed FSI type and the second one SFI type. Due to a slight change in fabrication process and a modification of the chucking device, there are some differences of the shape and dimensions between the SA-SUSF and SR-SUSA series composite plate specimens. Especially, in the case of the SA-SUSF series specimens, in order to prevent a fracture of the specimen at pin holes the thickness of test portion was reduced and a thin plate was mounted as shown by chain line in Fig. 1(a). All specimens were machined to the above shapes, after which an indicated slit was introduced on one side. Then they were annealed at 860°C in vacuum.

An electro-hydraulic-servo type testing machine (15kN) was used at a frequency of about 30Hz, and specimens were tested under pulsating tension varying from zero to maximum (stress ratio $R=0$). Crack length was measured by an optical microscope with the aid of a stroboscopic light source, and crack opening stress was measured by the unloading elastic compliance method using the strain gauges mounted on the specimen surface ahead of the crack. Their output was memorized in the digital memory scope and the crack opening stress was evaluated from the compliance curve plotted out on an X-Y recorder. This measurement was only made with the SR-SUSA series composite plates shown in Fig. 1(b).

Fig. 1 Shapes and dimensions of specimen.

Table 1 Chemical compositions of materials.

Type of composite	Material	Chemical composition %										
		C	Si	Mn	P	S	Cu	Sol. Al	Ni	Cr	Mo	Co
FSI SFI	Al-killed steel (SA)	0.097	0.009	0.47	0.011	0.017	-	0.028	-	-	-	-
	SUS405 (SUSF)	0.05	0.63	0.57	0.025	0.007	0.04	-	0.14	12.4	0.03	0.027
FSII SFII	Rimmed steel (SR)	0.07	0.04	0.32	0.013	0.011	0.01	0.003	0.02	0.02	-	-
	SUS316 (SUSA)	0.06	0.56	1.46	0.024	0.005	0.26	-	13.0	16.3	2.17	-

Table 2 Mechanical properties and linear expansion coefficients of materials.

Material	Heat treatment	Upper yield point σ_{yo} MPa	Lower yield point σ_{su} MPa	Tensile strength σ_B MPa	Vickers hardness H_V (Load 500g)	Linear expansion coefficient 2) α
Al-killed steel (SA)	860°C 1hr, F.C.	228	225	360	77	14.3×10^{-6}
SUS405 (SUSF)		310 ¹⁾		520	175	11.5
Rimmed steel (SR)		235	223	322	97	14.3
SUS316 (SUSA)		279 ¹⁾		588	190	18.4

1) 0.2% proof stress. 2) From reference (6).

The initial residual stress σ_{r0} in the composite plate was measured by using a Shimadzu X-ray instrument for the specimen of the same shape as shown in Fig. 1, by swinging the X-ray in the irradiation area of $2.0 \times 1.0 \text{ mm}^2$. The details of the X-ray stress measurement are the same as given in the authors' previous study⁽⁴⁾.

3. Experimental Results

3.1 Propagation behavior of fatigue crack

Relations between the fatigue crack growth rate da/dN and the maximum stress intensity factor K_{max} are presented in Figs. 2 and 3, respectively for SA-SUSF and SR-SUSA series composite plates. The value of K_{max} was calculated in the same way as for the monolithic plate because the elastic moduli of the constituents were the same. The solid straight lines represent the crack growth rate curves for the monolithic plates obtained in the authors' previous study⁽⁴⁾ for the same material. The vertical chain lines give the positions of the interfaces of the composite plates as the value of K_{max} . It is seen that, when the crack propagates in FSI type composite plate (Fig. 2(a)), the crack growth rate da/dN in the first SA layer decreases sharply near the first interface, and, after crossing this interface, it increases rapidly in the second SUSF layer and reaches much higher level than that of the monolithic SUSF plate. Immediately after crossing the

second interface, the growth rate increases slightly in the third SA layer above that of the monolithic SA plate. Then it decreases sharply near the third interface nearly in the same way as it approaches the first interface. Thus the behavior of crack growth rate in the third layer is approximately similar to that in the first layer, and this is also true with the subsequent layers.

When the crack propagates in SFI type composite plate (Fig. 2(b)), the crack growth rate increases rapidly in the first SUSF layer over that of the monolithic SUSF plate as the crack approaches the first interface, and, after crossing the first interface, it decreases sharply in SA of the second SA layer as the crack approaches the second interface. After crossing the second interface, the crack growth rate in the third SUSF layer is considerably low in comparison with that in the monolithic SUSF plate in its first stage and it increases rapidly as the crack approaches the third interface as in the case of the first layer. Thus, the behaviors of the crack growth rates in the third, fourth and fifth layers are approximately similar to those in the first and second layers. But the amount of decrease of the growth rate near the fourth interface is less than that at the second interface where the value of K is at low level. After crossing the fourth interface, the growth rate has almost the same value as that of the monolithic SUSF plate.

When the crack propagates in FSI

(a) FSI type. (b) SFI type.

Fig. 2 Relations between crack growth rate and maximum stress intensity factor for SA-SUSF series composite plates.

(a) FSI type. (b) SFI type.

Fig. 3 Relations between crack growth rate and maximum stress intensity factor for SR-SUSA series composite plates.

type composite plate (Fig. 3(a)), its growth rate in the first layer SR decreases until it reaches the first interface in the case when the maximum applied stress is below $\sigma_{max}=79\text{MPa}$. When the maximum applied stress is above $\sigma_{max}=79\text{MPa}$, the crack growth rate increases with the maximum stress intensity factor. But, the growth rate is considerably low in comparison with that in the monolithic SR plate and decreases sharply as the crack approaches the first interface. At this interface all cracks momentarily cease to grow in the period of $4 \times 10^4 \sim 3.6 \times 10^5$ cycles excepting the case of the highest maximum applied stress $\sigma_{max}=85\text{MPa}$. After crossing the first interface, the crack growth rate increases rapidly in the second SUSA layer, and at the second interface it reaches a higher level than that in the monolithic SUSA plate. After crossing the second interface, the growth rate in the third SR layer has almost the same value as that of the monolithic SR plate in its first stage, but, as the crack approaches the third interface, the growth rate decreases sharply as in the case of the first layer. In this respect the behavior of the crack growth rate in the third, fourth and fifth layers are again similar to those in the first and second layers. However, the crack does not cease to grow at the third interface.

When the crack propagates in SFI type composite plate (Fig. 3(b)), its growth rate in the first SUSA layer is considerably high comparing to that in the monolithic SUSA plate. After crossing the first interface, its early behavior in the second SR layer is almost the same as that in the first layer, and it decreases sharply as the crack approaches the second interface, and momentarily it ceases to grow in the period of $2 \times 10^4 \sim 4 \times 10^4$ cycles at the second interface. After crossing the second interface, the crack growth rate in the third SUSA layer is lower than that in the monolithic SUSA plate but rapidly increases until it takes a fairly high value in comparison with that in the monolithic SUSA plate near the third interface. In this way, the behaviors of the crack growth rate in the third, fourth and fifth layers are approximately similar to those in the first and second layers, although the crack does not cease to grow at the fourth interface as it dose at the second interface.

As mentioned above, the propagation behavior of fatigue crack in the multilayered composite plates is quite different from that in the monolithic plates. But, there are common features between the behavior in one layer of a multilayered plate and that in the corresponding layer of a two layered plate ⁽⁴⁾.

3.2 Crack opening behavior and evaluation of the crack growth rate by ΔK_{eff}

Fig. 4 shows the relations between

the crack opening ratio $U=(K_{max}-K_{op})/(K_{max}-K_{min})$ obtained by experiments and the maximum stress intensity factor K_{max} for the SR-SUSA series composite plates. Curves in the respective figures represent the experimental results for the monolithic plates obtained in the authors' previous study ⁽⁴⁾, and the vertical chain lines give the positions of the interfaces of the composite plates in terms of the value of K_{max} . When a crack propagates in FSI type composite plate, the crack opening ratio in the first SR layer keeps fairly low values comparing to that in the monolithic SR plate and in the first SR layer, but, after crossing the first interface, it increases rapidly in SUSA over that of the second interface. In the third, fourth and fifth layers U is approximately constant and has almost the same value as that in each monolithic plate. When the crack propagates in SFI type composite plate, the crack opening ratio is higher in the first SUSA plate than that in the monolithic SUSA plate. After crossing the first interface, it decreases sharply in SR of the second layer as the crack approaches the second

Fig.4 Relations between crack opening ratio and maximum stress intensity factor for SR-SUSA series composite plates.

Fig. 5 Relations between crack growth rate and effective stress intensity factor range for SR-SUSA series composite plates.

interface. After crossing the second interface U increases rapidly in SUS4 of the third layer, and reaches almost the same value as that in the monolithic plates in the fourth and fifth layers.

It is noted that compressive and tensile residual stresses initially existing respectively in SR and SUS4 of the SR-SUS4 series composite plates which are introduced during the heat treatment as mentioned before (Table 2), and the crack opening behavior can be qualitatively understood by considering these residual stresses. But discussion on this point will be made later.

Fig. 5 shows the relations between the crack growth rate $\dot{a}/dN$ and the effective stress intensity factor range $\Delta K_{eff}(= U \cdot \Delta K)$. The solid lines represent the common scatter range of the data on the monolithic plates of the constituent materials obtained in the authors' previous study⁽⁴⁾. By comparing Fig. 5(a) and (b) with the corresponding figures in Fig. 3(a) and (b) it is seen that the data points replotted against ΔK_{eff} tend to come closer to those of the monolithic plates, though there are still some dispersions.

Therefore, it can be said that ΔK_{eff} is a better controlling parameter than K_{max} in the multilayered composite plates as in the two layered composite plates.

4. Discussion

As was described in the previous chapter, the crack growth rates in the composite plates are controlled by ΔK_{eff} to a certain extent. This fact indicates that the crack opening behavior plays an important role in the propagation of fatigue crack in the composite plates, and the residual stress has a large influence on the crack opening behavior. A quantitative evaluation was made of the initial residual stress in the composite plates, and the actual stress intensity

factor at the crack tip in the composite plate was evaluated taking the initial residual stress into account. Based on this actual stress intensity factor and by combining the crack opening behavior of the monolithic plates, an attempt is made to explain the crack opening behavior in the multilayered composite plates.

4.1 Evaluation of the initial residual stress in composite plates

Since the constituents have different linear expansion coefficients, a residual stress is introduced into each constituent during the heat treatment. Thus introduced residual stress is termed "initial residual stress σ_{r0} ", and its distribution is quantitatively evaluated by three methods; the X-ray stress measurement, the finite element method, and the theoretical analysis based on elementary theory of elasticity.

Fig. 6(a) shows a typical result of the distribution of initial residual stresses evaluated by the X-ray stress measurement for SFI type composite plate, and Fig. 6(b) shows the result of the elastic analysis using the finite element method. The latter analysis was made on a model plate with the dimensions shown in Fig. 6(b) assuming that the constituents only have different linear expansion coefficients at left and right hand sides of the each interface in the state of plane stress. In Fig. 6(b) $\sigma_{r0}/\alpha TE$ is the ratio of the initial residual stress σ_{r0} to αTE , and x/C_5 is the ratio of the crack length x measured from the fourth interface to the width of the Plate 5. α , T and E are difference in the linear expansion coefficients, the effective temperature head and the elastic modulus. By comparing Fig. 6(a) with Fig. 6(b), the distribution of initial residual stresses σ_{r0} can be approximated by a straight line for each constituent, if the stress concentration due to saw cut is ignored. The straight lines in Fig. 6(a) and (b)

Fig. 6 Distribution of residual stress in composite plate.

indicate a theoretical distribution of σ_{p0} derived by the analysis based on the elementary theory of elasticity as in the authors' previous study (4).

Now, let x and y axes and the other symbols be chosen as shown in Fig. 6(c), and consider a plate of width $-(C_1+C_2+C_3+C_4) \leq x \leq C_5$ ignoring the saw cut and let the difference of the linear expansion coefficients between Plate 1, 3, 5 and Plate 2, 4 be $\alpha = \alpha_I - \alpha_{II}$ (>0), then, we obtain an approximate solution by finding stresses which eliminate the resultant force and resultant bending moment at $y = \pm z$ (7). Thus, the stresses σ_y in Plates 1, 3, 5 and Plates 2, 4 which are denoted by σ_{pI} and σ_{pII} are given by the following formulas.

Plate 1, 3, 5:

$$\frac{\sigma_I}{aTE} = \frac{6\{\lambda_2(\lambda_1 - \lambda_3 - 1) + \lambda_4(\lambda_1 + \lambda_3 - 1)\}}{(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + 1)^3} \left(\eta + \frac{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 - 1}{2} \right) + \frac{\lambda_2 + \lambda_4}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + 1} \quad \dots\dots\dots(1)$$

Plate 2, 4:

$$\frac{\sigma_{II}}{aTE} = \frac{6\{\lambda_2(\lambda_1 - \lambda_3 - 1) + \lambda_4(\lambda_1 + \lambda_3 - 1)\}}{(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + 1)^3} \left(\eta + \frac{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 - 1}{2} \right) - \frac{\lambda_1 + \lambda_3 + 1}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + 1}$$

where $\eta = x/C_5$, $\lambda_1 = C_1/C_5$, $\lambda_2 = C_2/C_5$, $\lambda_3 = C_3/C_5$, $\lambda_4 = C_4/C_5$, and $\alpha = \alpha_I - \alpha_{II}$.

The straight line distributions of the residual stresses in Fig. 6(a) and (b) were calculated by Eq.(1) for the indicated dimensions of the plate in the figure. The difference in the linear expansion coefficients, the effective temperature head and the elastic modulus were assumed as $\alpha = 4.1 \times 10^{-6}$, $T = 180^\circ\text{C}$ and $E = 206\text{GPa}$, respectively. Since the value of the effective temperature head was unknown, it was adjusted such as to coincide with the results of the X-ray stress measurement. The calculation agrees well with the results of the X-ray stress measurement and the analysis of the finite element method. Therefore, the following discussion is made by using thus calculated initial residual stress. If $\alpha_I < \alpha_{II}$ (<0), merely the positive and negative signs of residual stress are reversed.

4.2 Analysis of crack opening behavior

Since the actual stress intensity factor K' at the crack tip in the field of residual stress can be calculated by superposing the solutions of stress intensity factor under the applied load and the residual stress, if the distribution of initial residual stresses is found (8), (9), K' at the crack tip in the composite plate is evaluated taking the initial residual stress into account, and the crack opening behavior in the composite plate is estimated by considering K' and the crack opening behavior of the monolithic plates. A discussion is also made on the relation between the crack growth rate and K'_{max} .

When the composite plate having initial residual stress is under pulsating tension varying from zero to maximum as shown in Fig. 7(a), the stress intensity factor at the crack tip in the stress field can be calculated by superposing the solutions of two cases shown in figure (a) and (b). In figure (b) the solution can be obtained by using the following approximate formula of B. Gross and W. F. Brown (10) for single edge crack under uniform distributed load.

$$\left. \begin{aligned} K &= \sigma \sqrt{\pi a} F(\xi); \quad a/W = \xi \\ F(\xi) &\approx 1.12 - 0.231\xi + 10.55\xi^2 \\ &\quad - 21.72\xi^3 + 30.39\xi^4 \end{aligned} \right\} \quad \dots\dots\dots(2)$$

where σ , a and $W (= (C_1 + C_2 + C_3 + C_4 + C_5))$ are the applied stress, the crack length, and the width of plate.

The solution shown in figure (c) is equal to the superposition of that in the case a the crack does not exist but a residual stress is applied at the crack surface over that in the case when a stress distribution the same as the residual stress $\sigma_p(x)$ with reversed sign is applied at the crack surface. Since the former has no singularity, the solution shown in figure (c) is equivalent to that of the latter case and given by the following formula (9).

$$K_r = \frac{2\sqrt{\pi a}}{\pi} \int_{c_1 - c_2}^c \frac{\sigma_p(x)}{\sqrt{a^2 - x^2}} dx \quad \dots\dots\dots(3)$$

where $\sigma_p(x)$ is the distribution of residual stresses by Eq. (1) given in the previous section. Since the saw cut is ignored, the interval of integral is $(C_1 - C_2) \leq x \leq a$.

Since Eq. (3) is a solution for an infinite plate, it is exact only in the case when the plate is wide enough comparing with the crack length and a correction is needed in the case when the crack is comparatively long. Since an exact solution in this case was not

Fig. 7 Actual stress intensity factor at crack tip in composite plates.

obtained, the correction of K_p was made by using the correcting term of Eq. (2).

Fig. 8 shows the variations of the actual stress intensity factor with the propagation of a crack in the field of residual stress under pulsating tension varying from zero to maximum. $K_{\max}^{\text{act}}/K_{\max}$ is the ratio of the maximum actual stress intensity factor $K_{\max}^{\text{act}}$ to the maximum stress intensity factor $K_{\max}$, and γ_n is the ratio of the crack length existing in each plate ($a - \sum_{k=1}^n C_k$) to the width of each plate C_n ($n=1, \dots, 5$). For convenience the variations of $K_{\max}$ in each plate are shown in the same figure. When the crack is in the field of compressive residual stress (figure (a) and figure (b)), the actual stress intensity factor $K_{\max}^{\text{act}}$ becomes small in comparison with the maximum stress intensity factor $K_{\max}$. Therefore, the minimum value of the actual stress intensity factor is negative. Now, if it is assumed that a crack closes under negative actual stress intensity factor, the crack must completely open under the actual stress intensity factor ranging from zero to $K_{\max}^{\text{act}}$, and if this idea is applied to a case of a monolithic plate having no residual stress, the crack opening ratio U must be always unity for the monolithic plate, which contradicts the results of crack opening behavior of the monolithic plates. Therefore, the following assumption is made.

Fig. 8 Variations of actual stress intensity factor with crack propagation.

Fig. 9 Relations between crack opening rate and stress intensity factor range for monolithic plates.

(1) The value of U for the composite plate having initial residual stress is equivalent to that for the monolithic plate under pulsating tension whose stress intensity factor is equal to the positive part of the actual stress intensity factor K' obtained for the composite plate by the previous procedure.

On the other hand, when the crack is in the field of the tensile residual stress, the maximum actual stress intensity factor becomes large in comparison with the maximum stress intensity factor as the crack approaches the interface, and the value of the minimum actual stress intensity factor becomes positive. Hence the stress ratio R becomes larger than zero.

The above assumption is also used in this case and the U -value for the respective composite plates is calculated by the following procedure: By putting the range of the actual stress intensity factor K' in $K' \geq 0$ equal to ΔK , the corresponding value of U was found from the U versus ΔK relation of the corresponding monolithic plate as shown in Fig. 8.

For this purpose, however, it is necessary to obtain the relation between U and ΔK for the monolithic plate for a stress ratio R larger than zero, and such relations are shown in Fig. 9 for the monolithic SR and SUSa plates, in which the curves are drawn to pass the middle one of the experimental points for each stress ratio.

The variations of U thus calculated for the respective composite plates are shown by the curves in Fig. 10. The experimental points are replotted from the relations between U and $K_{\max}$ for the SR-SUSa series composite plates shown in Fig. 4, in which γ_n is the ratio of the crack length in each plate ($a - \sum_{k=1}^n C_k$) to each plate width of each plate C_n . Comparison of these curves with the experimental results shows a fairly good agreement between them when the crack propagates in SR having a compressive residual stress, especially in the first layer as shown in figure (a), excepting in the neighborhood of the interface, though there are some dispersions.

Fig. 10 Analysis of crack opening behavior in composite plates.

When the crack propagates in the SUS4 having a tensile residual stress, the trend of U shows a qualitatively good agreement with the trends of the experimental results, though the magnitude of the calculated U is higher than that of the experimental result.

Consequently it is confirmed that the crack opening behavior of the composite plate having initial residual stresses can be estimated by the above analysis at least as a first approximation.

Based on the above results, Fig. 11 shows the relation between the crack growth rate and the maximum actual stress intensity factor indicated in Fig. 8 for the SR-SUS4 series composite plate. By comparing Fig. 3 with Fig. 11, it is seen that the experimental points tend to come closer to those of the monolithic plates in the latter presentation, though not completely. The reason for the discrepancy is in the variation of crack opening ratio caused by the variation of stress at each stage of the crack propagation.

5. Conclusions

The propagation and opening behavior of fatigue cracks under pulsating tension was experimentally examined with multilayered composite plates consisting of a low carbon steel and stainless steels which have the same elastic moduli but have different thermal expansion coefficients and mechanical properties. Conclusions are summarized as follows:

(1) The crack propagation behavior in the multilayered composite plates is quite different from that in the monolithic plates, when the crack growth rate is plotted against K_{max} . Hence K_{max} is not a good parameter for controlling the crack propagation in these composite plates.

(2) There are common features between the crack propagation behaviors in the

corresponding layers of the multilayered and two layered composite plates. When the crack propagates in the low carbon steel, the crack growth rate decreases in comparison with the monolithic plate when the crack is near the interface of the SA-SUSF series composite plates and similarly when the crack approaches the interface of the SR-SUS4 series composite plate. But, it increases in comparison with the monolithic plates as the crack approaches the interface in the composite plates.

(3) The crack growth rates in the composite plates are approximately controlled by ΔK_{eff} .

(4) The distribution of initial residual stresses σ_{r0} , which are introduced in the cooling process of heat treatment, can be approximated by a straight line distribution calculated by Eq. (1) in each constituent, if the effective temperature head T is known.

(5) When the crack propagates in a compressive residual stress field, the crack opening behavior in the composite plates can be estimated by considering an actual stress intensity factor obtained from the initial residual stress and the crack opening behavior of the monolithic plate. When the crack propagates in a tensile residual stress field, the estimated trend of U agrees only qualitatively with the experimental results.

(6) The maximum actual stress intensity factor K_{max} obtained by initial residual stress is not satisfactory to explain the crack propagation behavior in the composite plates. The reason is in a large variation of the crack opening ratio caused by the variation of stress ratio at each stage of the crack propagation.

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Fig. 11 Relations between crack growth rate and maximum actual stress intensity factor.