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[Discussion]

Influence of Residual Welding Stress on Fatigue Crack Growth Rate (By Chitoshi Miki, Fumio Nishino, Yasuaki Hirabayashi, and Koei Takena)

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▶*Discussion* ——— *By Kentaro Yamada*

The writer appreciates the effort to provide the valuable data on fatigue crack growth rates under welding residual stresses through excellent techniques to introduce various residual stress patterns. However, the authors' approach and conclusion are based on the measurement of "redistribution of residual stresses by strain gages" and may yield to lack of generality. The writer wishes to bring out theoretical means to compute the stress intensity factor of a crack in welding residual stresses, and add some comments on the authors' interpretation to the data on the fatigue crack growth rates.

The stress intensity factor of a crack in the residual stresses can be computed by using concept of superposition, as shown schematically in **Fig. 13**[23),24)]. If the crack is closed by surface forces applied to the crack surfaces, as shown in (a), it is equivalent to the state without crack, and the stress intensity factor is zero. The stresses applied to the crack surface are of the same magnitude of the residual stresses, but in the opposite direction. In order to satisfy the equilibrium condition, the same forces are applied to the crack surface to open it, as shown in (b). Therefore, the stress intensity factor of the crack shown in (c) can be computed by applying the residual stress to the crack surface. This computation is possible and opens the wide possibility to deal with various welding residual stresses, if their distribution is known[24)].

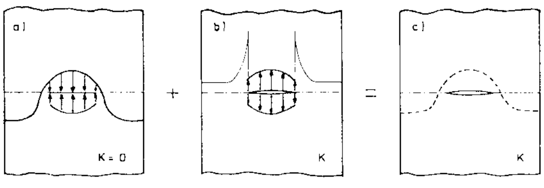

Fig. 13 Schematic illustration of computation procedure of stress intensity factor due to residual stresses by superposition.

The stress intensity factors due to the residual stresses and the applied stresses are computed for specimens reported in Ref. 9. The fatigue crack growth rates were measured on a tensile plate of 105 mm wide of high tensile steel of 80 kg/mm^2 (780 MPa) class. The maximum tensile residual stress at the center is assumed as 60 kg/mm^2 (590 MPa), and it is self-balanced with compressive residual stresses. The applied stress range is 8.5 kg/mm^2 (83 MPa). In order to see the effect of the stress ratio R, three cases, $R=0$ (zero-tention), $R=-1$ (tention-compression) and $R=-\infty$ (zero-compression), are computed, as shown in **Fig. 14**. The stress intensity factor due to the initial residual stress, K_R, is positive until the crack reaches to about 40 mm or 76 percent of the plate width. This is well beyond the point where the residual stress change its sign. When K_R is positive, strains at the leading edge of the crack is always positive and show some indication of singularity. The strains measured by the authors, and shown in **Fig. 5, 6** and 7, clearly show this behavior. It is, therefore, more appropriate that these strains are to be defined as the strain distribution near the leading edge of the crack subjected to the residual stresses at the crack surfaces, as shown in **Fig. 13** (b).

The authors state that it is difficult to define the stress intensity factor ratio, R^* $(=K_{min}/K_{max})$ due to the redistribution of the residual stresses and the singularity of the leading edge of the crack. When the linear elastic fracture mechanics is applied to the fatigue crack growth models, there always exists the small scale yielding at the leading edge of the crack. The Equations 2 and 3 are not the exception. If the authors use these two equations to include the effect of R or R^*, the effort should be made to obtain them for the specimens to be tested in the same manner as shown in **Fig. 14**. The writer normally considers that the stress intensity

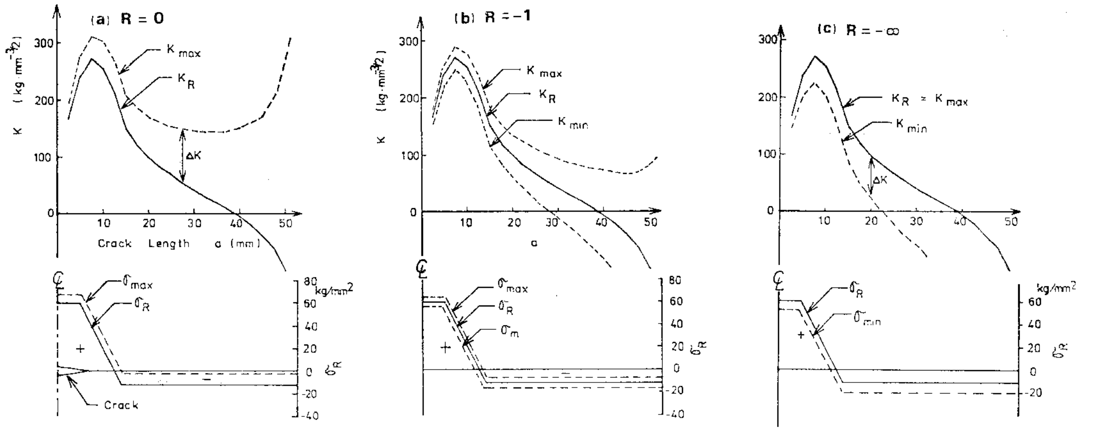

Fig. 14 Model analyses of stress intensity factors due to welding residual stresses and due to applied stresses.

factor above zero is effective in fatigue crack growth.[25] Unless the part of the stress intensity factor become below zero, as shown in **Fig. 14** (b) and (c), the fatigue crack growth rate are insignificantly affected by the stress intensity factor ratio, R^*. As shown in **Fig. 14**, the value of R^* changes as the crack grows. However, difference in crack growth rate may be insignificant when the value of R^* is possitive. Unfortunately, the authors obtain the data on the specimens with tensile residual stresses of different magnitude. If the stress intensity factor ratio really affect the crack growth rate, as is expressed in Equations 2 and 3, there should be some difference in fatigue crack growth behavior. The authors' conclusion may be derived from the small number of data especially around the threshold stress intensity factor range, ΔK_{th}.

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▶*Closure* ——————*By Chitoshi Mii, Fumio Nishino, Yasuaki Hirabayashi and Koei Takena*

The writers would like to thank Yamada for his interest in the paper and for his comment.

The discusser states that this paper "may yield to lack of generality" since it is based on the measurement of "redistribution of residual stresses by strain gages," and in contrast theoretically obtains stress intensity factors in residual stress fields. However, the writers have doubts concerning the analysis of stress intensity factor which forms the basis of the discusser's arguments, and will therefore comment here centering on this point.

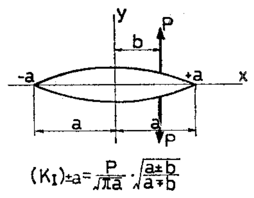

Fig. 15 K_I for a crack subject to a force on the crack surface.

The method of **Fig. 13** is well-known, and principle-wise is correct. However, it is thought that the discusser, in applying this method, has used the solution for the stress intensity factor of **Fig. 15**. That solution is for a crack in an infinite plate, and therefore, cannot correctly take into consideration the redistribution of residual stresses when cracks in a finite plate propagate and the multiaxiality of residual stresses. Also, when the plate is of finite width, it is not appropriate to use this method and make corrections by the so-called secant or tangent formulae.[23] Accordingly, it cannot be said that **Fig. 14** gives the exact stress intensity factor. As one proof of this, K_R in **Fig. 14** are negative values where the crack are long. As **Figs. 5**, **6** and **7**, and many other researchers point out, residual stresses are redistributed with crack propagation, and tensile residual stresses remain at all times at the tips of cracks which have begun to propagate from tensile residual stress fields as with this specimen. Consequently, K_R will always be a positive value, and as ligament length approaches zero, K_R also should become zero. Furthermore, as regards **Figs. 5**, **6** and **7**, the discusser has interpreted them differently. The result shown here is of relieved stresses in a case where a slit has been formed, a strain gage has been mounted, and after taking balance that part has been cut out, and is the residual stress itself remained in this cross section in a condition of slit formed.

In the paper, stress intensity factor range (ΔK) was calculated by the equation (4). It appears that the discusser thinks ΔK values calculated by Eq. (4) and the method of **Fig. 13** are different, but the values of ΔK are the same with both. This is because stress intensity factor is a concept based on linear elasticity theory and superposition can be done. In fact, ΔK in **Fig. 14** and ΔK calculated by Eq. (4) are the same values, and as a matter of course, ΔK remains the same even R is changed. Accordingly, the distribution of residual stress is completely unrelated to the value of ΔK.

That it was stated in the paper for it to be difficult to accurately determine stress intensity factor ratio R^* was because as previously said it is not easy to determine the correct values of K_{max} and K_{min}, and moreover, not much results can be obtained even if detailed analyses are made, and that it is unthinkable for there to be a great difference with the stress ratio considering redistribution of residual stresses disclosed through actual measurements.

The authors also think it important for the effect of residual stress on propagation rate of fatigue cracks to be theoretically examined. And if this were to be completely clarified it would be possible to estimate the life of structural member having any welding stress distribution from only $da/dN-\Delta K$ of the base metal. However, it would be convenient to use the $da/dN-\Delta K$ relationship of a specimen with residual stress as shown in this paper, and it is believed there would be no objection to this for practical purposes.