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Numerical Study of Enhancement of Fatigue Crack Propagation Life by Grain Refinement

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ABSTRACT.

The possibility of grain size refinement treatment using high energy concentrated heating methods for the enhancement of fatigue life are investigated by applying numerical simulation of fatigue crack propagation. The strip yield model in order to represent fatigue crack opening / closing behaviour and improved effective stress intensity factor range (ΔK_{RPG}) are implemented into the numerical simulation model.
The effect of grain refinement for the enhancement of fatigue crack propagation is confirmed in this study.

KEY WORDS: Fatigue; Enhancement of fatigue life; grain size refinement; Numerical simulation for fatigue crack opening / closing; Fatigue crack propagation; RPG load; ΔK_{RPG}

INTRODUCTION

Many fatigue life prolongation techniques has already been proposed in order to keep the structural integrity of large welded built-up structures. One of authors (Nagata et al., 2004) proposed the prolongation method by applying the grain size refinement treatment using high energy concentrated heating methods, e.g. laser or high-frequency induction heating. By performing high energy concentrated heating around stress concentration regions, which correspond to the fatigue crack initiation sites in welded built-up structures, the grain size decrease by this treatment and yield strength in these regions are increasing. As a result of this effect, the appearance of plastic hysteresis by the cyclic loading around stress concentration regions decreases and these effects enable to achieve the significant life prolongation. However, above mentioned method was only confirmed by referring S-N curves of T-shaped non-load carrying fillet welded specimens. Quantitative retardation effect for fatigue crack propagation by applying proposed method has not been investigated yet.

In this study, numerical case studies of fatigue crack prolongation by grain refinement are performed in order to investigate the retardation effect for fatigue crack propagation. Numerical simulation code based on the strip yield model to represent fatigue crack opening / closing behaviour and improved effective stress intensity factor range are applied to perform the simulations.

OUTLINE OF NUMERICAL SIMULATION

Toyosada et al. (2004) proposed an improved effective stress intensity factor range by replacing the crack opening load according to Elber (1971) with the RPG (Re-tensile Plastic zone Generating) load at which stress at the crack tip reaches the value of the material yield stress. The novel crack driving force parameter based on the RPG load level is termed ΔK_{RPG}. Unlike the traditional effective stress intensity factor range based on the crack opening level, the ΔK_{RPG} parameter can account for the threshold behaviour. Consequently, the crack growth rate versus ΔK_{RPG} data can be described using the Paris equation within the full range of crack growth, including the threshold region.

Besides, the numerical simulation of fatigue crack propagation based on the strip yield model, which enables to describe the fatigue crack opening /closing behaviour and the effect of fatigue crack wake generated over crack surfaces for the crack propagation. The ΔK_{RPG} parameter is applied in order to describe the fatigue crack propagation law in this simulation. This simulation procedure is implemented into the numerical simulation code FLARP. FLARP has been shown to give accurate crack growth predictions under various constant and variable amplitude loading conditions and in the residual stress field. However, current FLARP can only consider the crack growth problem in uniform yield strength field. Then, the simulation code is developed in order to apply the crack growth problem in yield stress distributed zone.
In this study, improved simulation code based on FLARP is applied.

CONDITION OF NUMERICAL EXPERIMENT

CCT (Centre Cracked Tensile) specimen is supposed as a specimen. The grain size refinement treatment using high-energy concentrated heating methods is supposed in order to raise the yield strength of material in some region of a specimen. Figs. 1 and 2 show the geometrical conditions of specimen and heating locations.

Two types of heating conditions are supposed in order to investigate the retardation effect of the fatigue crack propagation; see Fig. 2 and Table 1. The Breadth of yield strength rising zone is changed in case 01 series. The centre of location of yield strength rising zone is fixed in this series. On the other hand, the centre position of yield strength rising zone is changed and breadth of the zone is fixed in case 02 series.

All of the numerical investigations, constant stress amplitude is applied to specimens as an external loading.

Although residual stress generated by line heating affects to fatigue life, residual stress effects are ignored in the following simulations. Therefore, the condition which corresponds to PWHT treatment for annealing is set up in this study. Fatigue crack growth histories of the line heated specimens without PWHT show complicated behaviour because of the contribution of residual stress distributions.

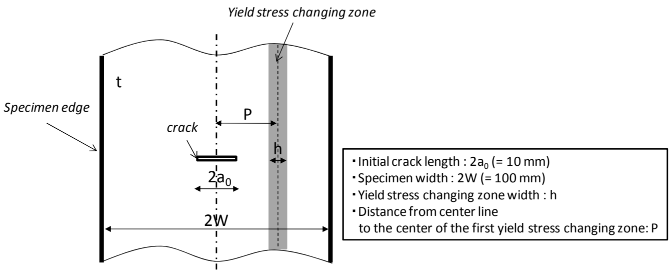

Fig. 1 Geometrical conditions of specimen and heating zone

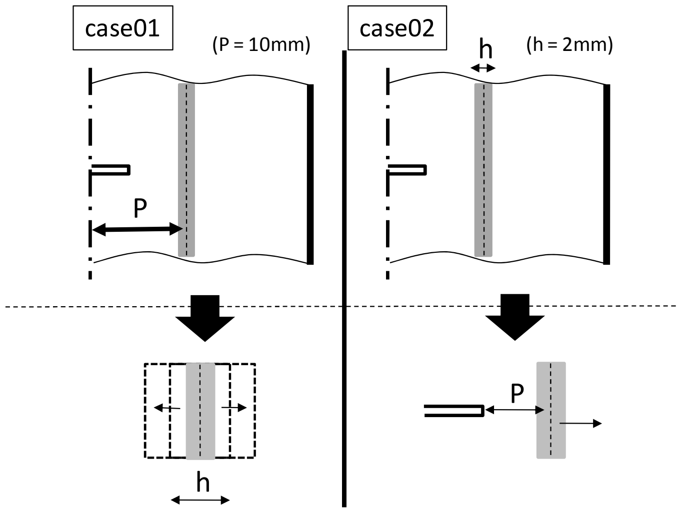

Fig. 2 Location of heating zone

Table 1 Conditions of the numerical simulation

	h/W	P/W
Case 01-a	0.02	0.1
Case 01-b	0.04	
Case 01-c	0.08	
Case 02-a	0.04	0.02
Case 02-b		0.10
Case 02-c		0.20
Case 02-d		0.30

It is well known that yield strength is a function of the grain size. Applying the grain size refinement treatment using high energy concentrated heating methods enables to produce up to about one tenth reduction in the grain size of standard steels. Many grain size refinement technologies are developing now and it is expected that more fine refinement methods will be proposed in the near future.
Considering above mentioned situations, the yield strength of refinement zone is twice of normal (i.e. no refinement treatment) zone is supposed in this study.

CONDITION OF NUMERICAL EXPERIMENT

Effect of Yield stress Rising Zone Breadth

Three conditions of yield stress rising breadth shown in Table 1 are supposed.
Histories of the maximum, minimum and RPG loads and fatigue crack growth curve in case 01 are shown in Figs. 3-1 to 5-2. Numerical simulation results in the case that fatigue crack propagates in uniform yield stress field are also shown in these figures as a reference condition.

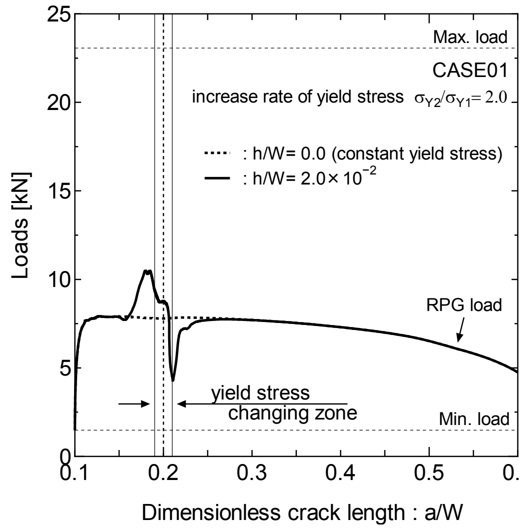

Fig. 3-1 Loading histories (case 01-a)

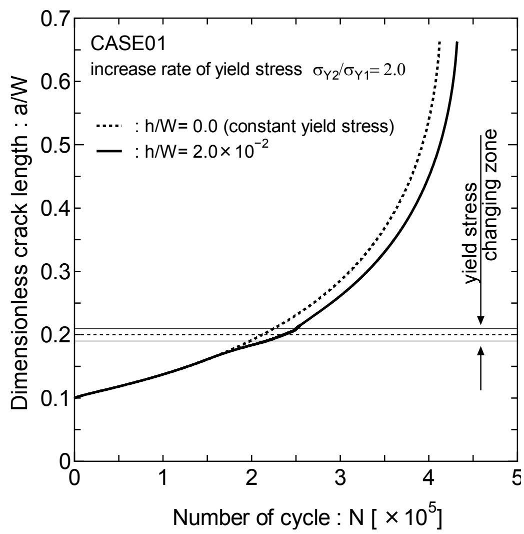

Fig. 3-2 Fatigue crack growth curves (case 01-a)

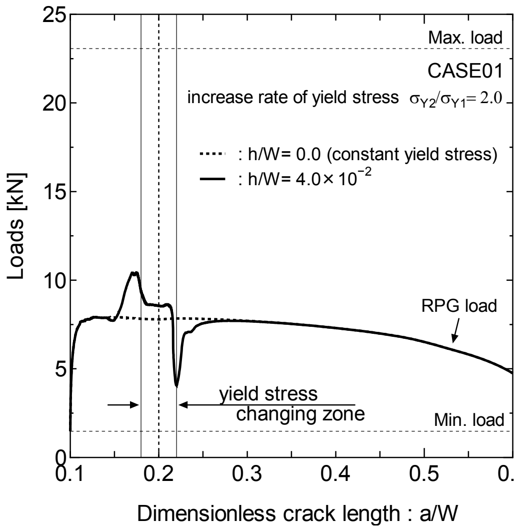

Fig. 4-1 Loading histories (case 01-b)

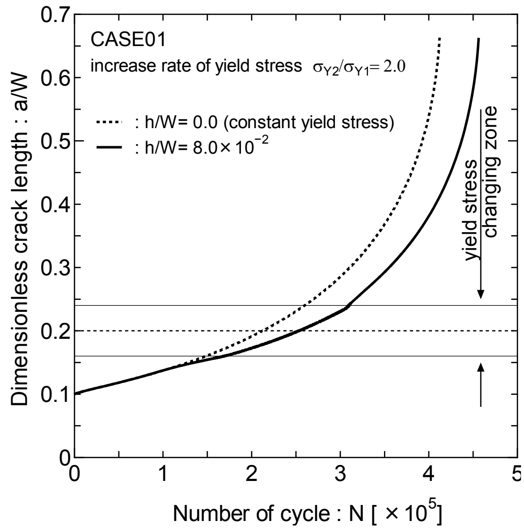

Fig. 5-2 Fatigue crack growth curves (case 01-c)

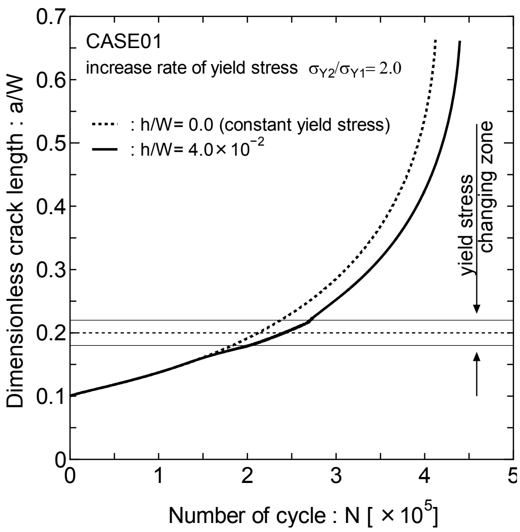

Fig. 4-2 Fatigue crack growth curves (case 01-b)

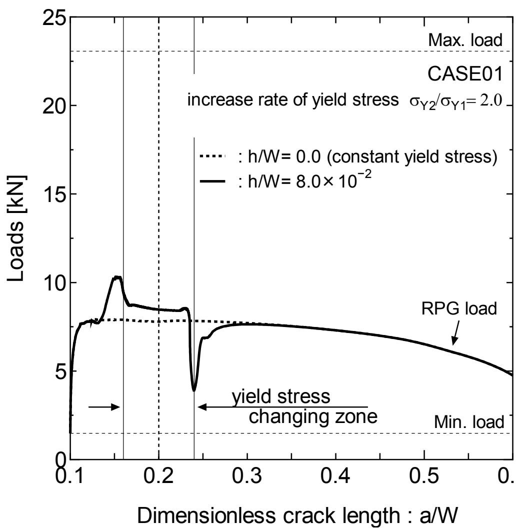

Fig. 5-1 Loading histories (case 01-c)

Focusing on the histories of RPG load around the yield stress changing zone, the retardation effect for fatigue crack propagation can be explained. When a fictitious crack tip, i.e. the plastic zone tip, approaches to the yield stress rising zone, the degree of plastic deformation around a plastic zone tip is reduced. Then, RPG load increasing at the start of yield strength rising zone, because the definition of RPG load is that the tensile plastic zone starts to develop ahead of a crack tip. Just after plastic zone tip passes the zone, the plastic deformation around a crack tip can generate easily. Then, RPG load decreases drastically and recover to normal condition according to the crack propagation. Similar phenomena were found in the other experiments and detailed consideration is introduced in the reference (Toyosada et al., 2004).

Because the effective stress intensity factor range (ΔK_{RPG}) applied in this research is a function of loading range from RPG load to the maximum load, fatigue crack driving force decrease when plastic zone tip reaches the yield strength rising zone. Fatigue crack grows curves shown in Figs. 3-2, 4-2 and 5-2 reflect the RPG loads behaviour shown in Figs. 3-1, 4-1 and 5-1.

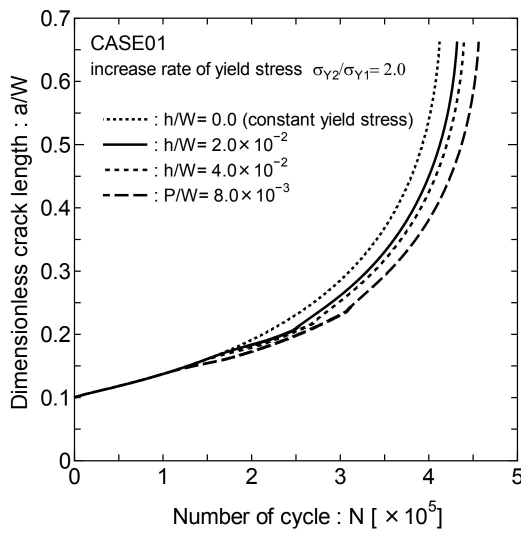

Fig. 6 Comparison of the fatigue crack growth curves (case 01)

Fig. 6 shows the comparison of the curves of fatigue crack growth in case 01. It is confirmed that fatigue life can be improved by the grain size refinement but the ratio of fatigue life enhancement is not in direct proportion to the zone breadth.

From these figures, yield stress rising zone has a role of the retardation of fatigue crack propagation.

Effect of Yield strength Rising Zone Position

Four conditions of yield strength rising position shown in Table 1 are supposed.
Histories of the maximum, minimum and RPG loads and fatigue crack growth curve in case 02 are shown in Figs. 7-1 to 9-2. Numerical simulation results in the case that fatigue crack propagates in uniform yield strength field are also shown in these figures as a reference condition. Calculation results in the case 02-b has already been shown in Figs. 4-1 and 4-2. Fig. 10 shows the comparison of the curves of fatigue crack growth in case 02.

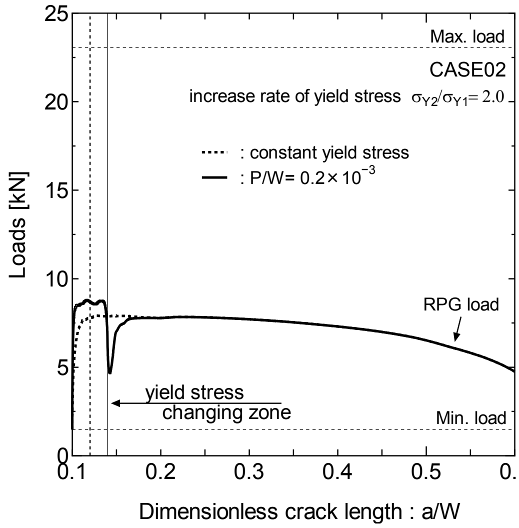

Fig. 7-1 Loading histories (case 02-a)

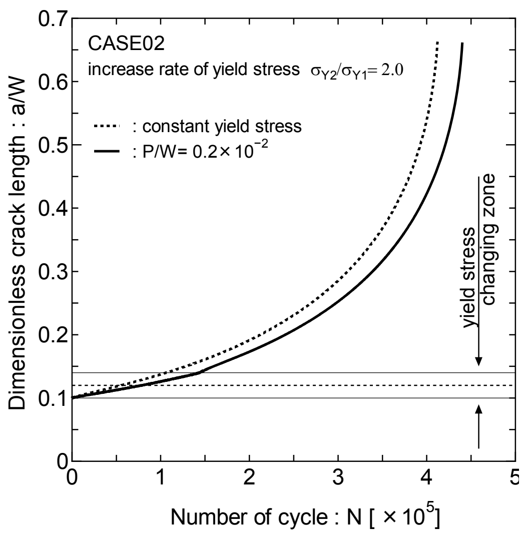

Fig. 7-2 Fatigue crack growth curves (case 01-b)

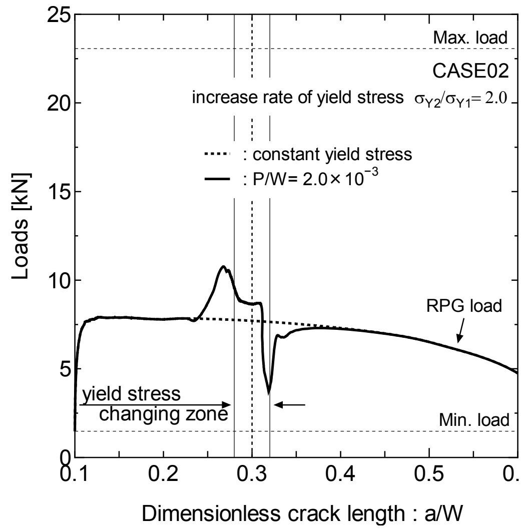

Fig. 8-1 Loading histories (case 02-c)

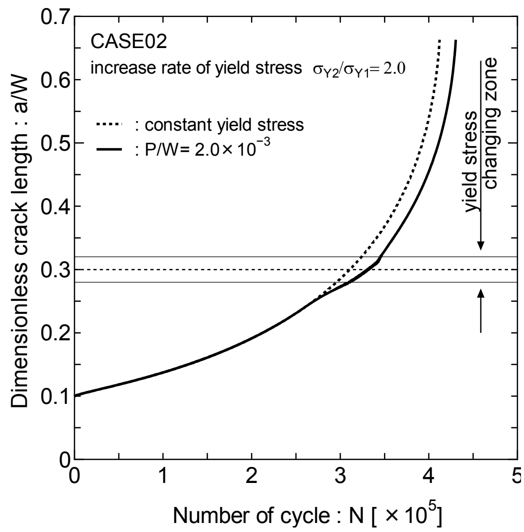

Fig. 8-2 Fatigue crack growth curves (case 01-c)

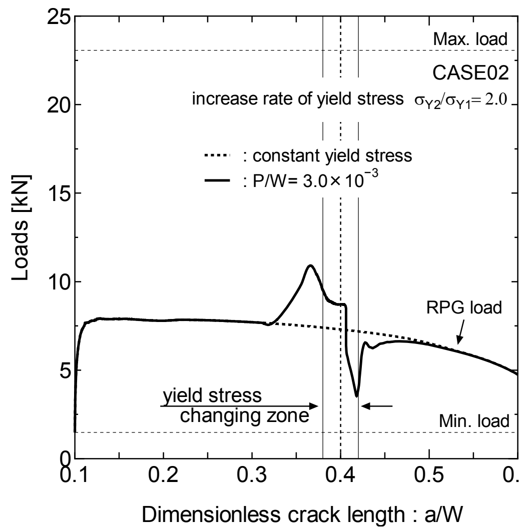

Fig. 9-1 Loading histories (case 02-d)

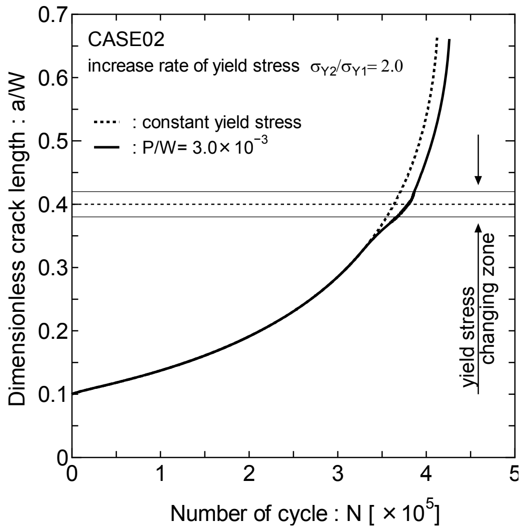

Fig. 9-2 Fatigue crack growth curves (case 01-d)

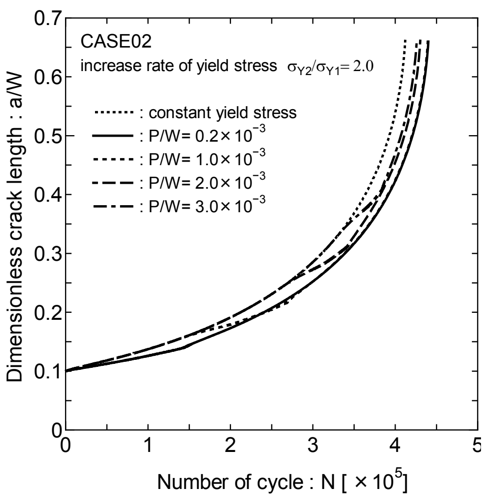

Fig. 10 Comparison of the fatigue crack growth curves (case 02)

The tendency of RPG load histories and the behaviour of crack growth are similar to Figs. 3-1 to 5-2.

The position of yield strength rising zone have a significant effect of the enhancement of fatigue life; see Fig. 10. From calculation results shown in Fig. 10, reducing fatigue crack propagation rate at early stage of fatigue crack found in structures enables to prolong the greater integrity of fatigue life.

CONCLUDING REMARKS

The possibility of grain size refinement treatment for the prolongation of fatigue life is investigated by applying numerical simulation of fatigue crack propagation.

From the simulation results, it is confirmed that the grain size refinement treatment has a possibility of the enhancement procedure of the fatigue crack propagation life and quantitative investigation enables to perform by applying the developed numerical simulation code based on FLARP.

The future plan in this study is as follows.

1. Comparing the experimental results with ones by numerical simulations shown this paper and confirming the validity of this proposed treatment.
2. Investigation of the validity of this method to three dimensional geometrical problems, i.e. out of plane gusset welded joints.

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