産業技術研究(江原大學校 産業技術研究所 論文集) 第 8 輯 (1988)
Research Report, The Institute of Industrial Technology, Kangweon Nat'l Univ., Korea, Vol. 8, 1988.

피로 미소크랙의 정류현상과 허용결함 크기와의 관계

金 敏 健 *

Fatigue Short Cracks — Critical Aspect of Non-Propagation and Tolerant Microflaw

Min Gun Kim*

국 문 요 약

탄소강 평활재 및 미소결함재를 사용하여, 미소 정류크랙의 크랙 개폐구거동의 상세한 관찰과 초기결함을 상정한 미소 원공과의 상호 한계크기의 비교 검토를 통하여, 다음과 같은 결론을 얻었다.
평활재의 정류크랙은, 피로과정중에 압축잔류응력이 크랙선단의 개구를 억제하는 것에 의하여 정류하게 되고, 그 크기는 평활재의 피로한도를 저하시키지 않은 미소 원공의 한계크기와 거의 일치하여, 두 경우가 역학적으로 거의 등가함을 시사해 주고 있다.

It has been reported by the authors that the level of endurance limit of unnotched specimen can be determined by the critical stress for the onset of growth of the non-propagating crack (NPC) in a stage II growth having relatively large length of 200-300μm rather than the length of single size order.[1][2]

Questions are :

i) Why such a crack in a stage II growth does stop propagation during the constant stress amplitude?

ii) What is the mechanism responsible for the existence of NPC?

iii) Does the NPC size coincide with the size of tolerant microflaw?

Critical Experiments I

Material employed was pearlitic

* Assist. Prof., Mechanical Eng., Kangweon National Univ.

steel of 0.85%C and was annealed at 1200℃ for 2 hours to have decarburized ferrite domain in a surface microstructure providing a preferential site for crack nucleation.

A number of precracked specimens having a wide range of crack lengths were prepared by fatigue at the stress level 10% above the endurance limit and were re-stressed in fatigue at the endurance limit 6wo = 210MPa in order to evaluate the maximum tolerant crack length which can survive after $N = 10^7$ cycles of stresses. The maximum tolerant crack length was obtained as about 340μm as shown in Fig. 1.

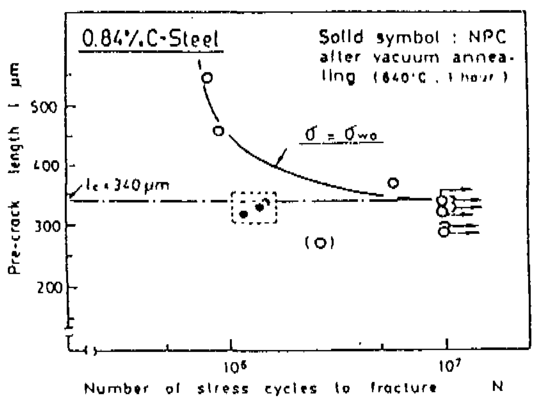


Figure.1. Evaluation of the maximum allowable crack length (i.e., the critical NPC) at the endurance limit employing precracked specimens prepared at 10% above the original endurance limit

It is already mentioned in previous paper concerning medium carbon steel that the maximum tolerant crack length which was obtained from the above procedure coincides with the critical NPC length.

For the purpose of examining the critical NPC behaviour the specimens with such a large NPC were vacuum annealed at 640℃ for elimination of slip markings ahead of the NPC.

After this annealing and electroplishing the specimens were again put into fatigue test at the stress level equal to the original endurance limit. The crack which had been one of the NPCs, began its propagation again at the stress level of endurance limit accompanying a formation of new slip bands at the crack tip and lead to the final fracture of specimen after $N = 10^7$ of stress cylcles. These results were also given in Fig. 1 with solid symbols. It should be noted that the onset of new propagation from the NPC occurs only after the vacuum annealing treatment irrespective of the length NPCs.

On the other hand, the specimen which had a similar length of NPC but no vacuum annealing was electropolished and was put into metallographic observation at the crack tip after a few millions of stress cycles at the endurance limit. It is found that no slip bands appeared at the crack tip and that the crack remained as non-propagating one.

These evidences indicate that the vacuum annealing treatment on the specimen having NPCs turns the NPC into a propagating crack and suggest that this treatment changes the tip of the crack from close to open.

The changes of crack opening displacement of the particular NPC of 340 m was compared before and after vacuum annealing treatment under static stress equivalent to the endurance limit. The crack opening displacement were given in Fig. 2. The curve marked in the

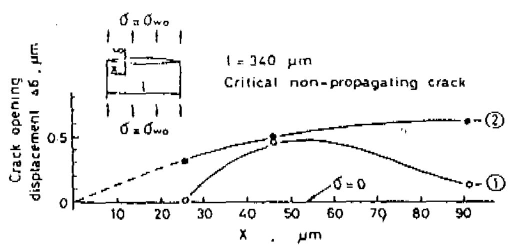


Figure.2. Carck opening displacement in the vicinity of the NPC before (curve marked ①) and after vacuum annealing treatment (curve marked ②)

figure indicates the results before anealing while the curve marked indicates the results after annealing. It is found from this figure that the crack tip of this NPC, which was closed after 10^7 of stress cycles, opens even under the endurance limit when the NPC is vacuum annealed.

In addition, micro-Vickers hardness measurements revealed that there are no appreciable differences in local hardness at the crack tip of fatigued specimens before and after annealing treatment. This implies that the simple effects of strain hardening are negligible for the existence of NPC.

Then, the question raised in the begining part of this paper can be answered in the following manner :

The crack, once propagated under the constant stress amplitude, stops due to the closure at the crack tip which resulted mainly from the local residual compressive stress associated with the localized plasticity introduced during cyclic loading.

Is the plasticity induced closure a sole mechanism responsible for the existence of NPC?

Fig. 3 illustrates the typical feature of propagation curve of crack which finally became NPC. Measurements of crack tip opening displacement were made on the NPC. at the point marked and also on the crack at the onset of

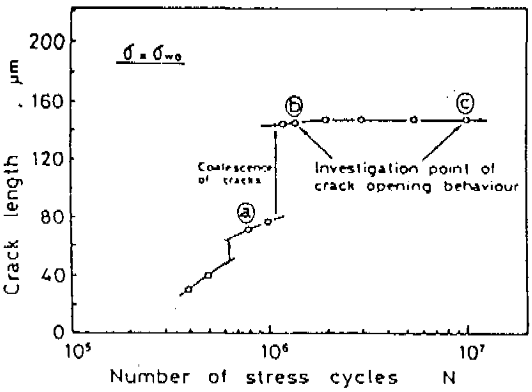


Figure.3. Typical behavior of crack propagation on the surface of smooth specimen under constant stress amplitude

growth into pearlitic structure at the point marked in the figure.

It is found from these measurements that the crack has been alrealy closed at the point but is still open at the point as shown in Fig. 4.

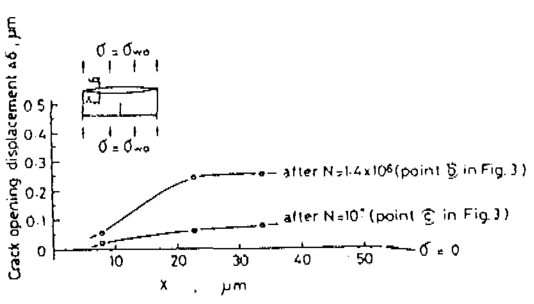


Figure.4. Change in crack opening displacement during fatigue loading

Since the crack length at the point and are $146\mu m$ $(N=1.4\times10^6)$ and $148\mu m(N=10^7)$ respectively, the transition from crack opening to closure must have occurred during the small increment of crack length such as $2\mu m$ with a consumption of more than 10^6 cycles of stress in this experiment. This implies that the crack closure behaviour can be related to the considerablly reduced rate of crack propagation (e. g. $10^{-8} \sim 10^{-9}$ mm/cycle) in the pearlitic structure.

In order to examine whether or not the reduced rate of propagation is related to crack closure, an experimental consideration is made in the following manner.

A loading sequence as shown in Fig. 5 had been quite effective to realize

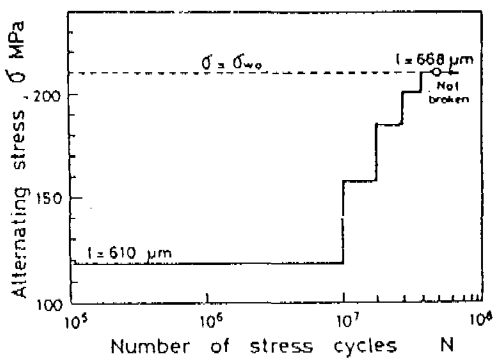


Figure.5. Example of stepwise loading squence on the fatigue pre-cracked specimen

either a reduced rate of crack propagation or no propagation of the crack. This experiment shows that the crack of the length of $610\mu m$ (twice as large as the critical NPC length) became non-propagating one with a small increment of crack length after applying the above loading sequence. It is confirmed that the tip of this crack which had been initially opened became closed after the above particular stepwise loading sequence.

On the other hand, however, even a smaller crack of the length of 357μm could not become NPC under the same condition of loading sequence as the above when the crack tip was prevented from an exposure to ambient air. This may imply that a kind of oxidation at the crack tip during fatigue is associated with the critical condition for the crack opening and/or closure, i. e., the existence of NPC.

Consequently, it may be concluded that not only the plasticity induced closure but also the closure which is related to both the oxidation at the crack tip and the reduced rate of crack propagation, is responsible for the existence of NPC at the endurance limit.

Critical Experiments Ⅱ

In order to discuss the relationship between the critical length of a NPC and the critical size of a of tolerant microflaw, several 0. 84%C steel specimens, with micropits ranging from 100-350μm prepared by Electro-Discharge-Machining (EDM) were fatigue tested at 210MPa, the original endurance limit of unnotched specimen. Results are shown in Fig. 6 by a solid line

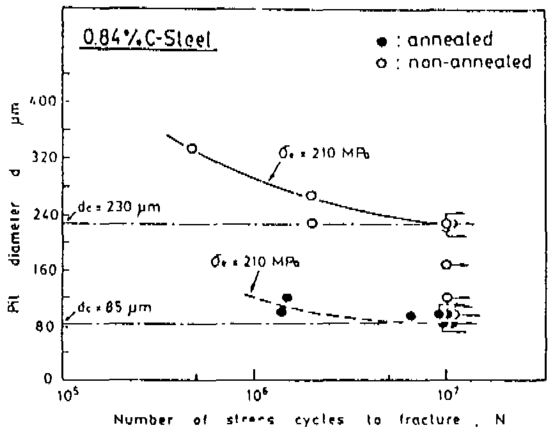
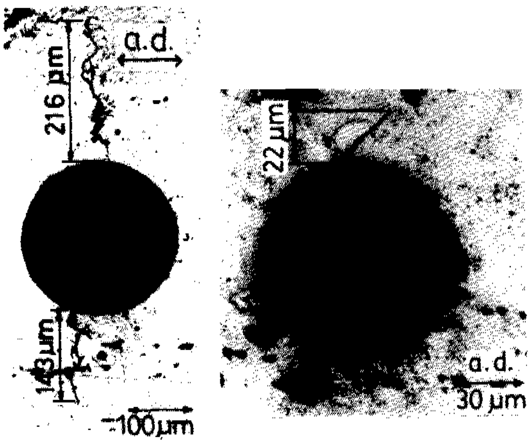


Figure.6. An evaluation of tolerant microflaws at the original endurance limit of $\sigma_e = 210$ MPa

with open symbols. This figure shows that the largest micropit diameter which will not cause a fatigue fracture at the endurance limit is approximately 230μm. This particular size can be regarded as the critical size of a tolerant microflaw which does not affect the original level of the endurance limit of this material.

Furthermore, it is found from

microscopic observations around the pit that NPCs originated from pits and propagated to a length comparable with the pit size; see for example Fig. 7-a.



[A] [B]

Figure.7. a) A NPC which propagated from the edge of a non-annealed EDM pit at 6 = 210MPa and N=10^7 cycles
b) A NPC which propagated from the edge of an annealed EDM pit at 6=210MPa and N=10^7 cycles

It should be noted that if we take "pit diameter+NPC length" as an effective length of a NPC, the critical length of a NPC can be regarded as approximately 580 m which is fairly large compared with the critical length of a NPC on an unnotched specimen which was approximately 340μm (see Fig. 1). A reason for the appearance of such a large NPC can be explained by the possible effects of residual stress associated with localized plasticity at the crack tip during cyclic loading and also from the machining by EDM.

Since an effect of residual stress around the pit can not be negligble even in the case of an EDM pit, the critical size of a pit should be examined under experimental conditions excluding the effect of residual stresses. Therefore newly prepared specimens were all vacuum-annealed after EDM in order to provide specimens with pits free of residual stress. These specimens were fatigue tested at the stress level of the original endurance limit. Results are also shown in Fig. 6. This figure shows the results of fatigue tests on two different types of specimen: the solid lind with open symbols is for specimens having conventional EDM pits while the broken line with solid symbols is for specimens having pits free of residual stress. These results show that the critical size of a tolerant micropit decreases from 230μm to 85 m when the residual stress due to EDM is removed.

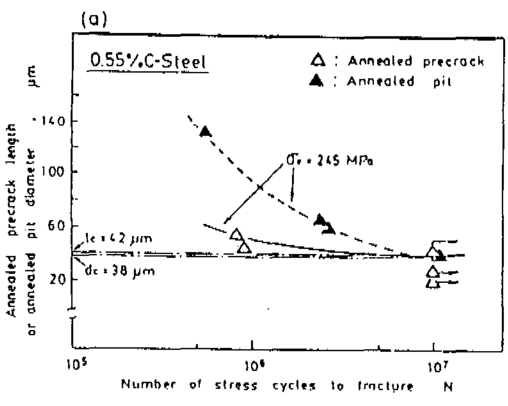
This value of 85μm should be regarded as the tolerant micrflaw size in this material rather than the conventional EDM micropit size of 230μm.

Since a NPC in a plain specimen has resulted from the accumulation of cyclic loading effects, including crack tip closure, and the EDM micropit is free from any fatigue loading history, it is perhaps understandable that the results do not coincide.

As the above critical micropit size of 85μm generates a NPC of 22μm, as shown in Fig. 7-b, the effective crack length amounts to 85+22μm, however, this is much less than the critical NPC length of 340μm.

Further experimental evidence shows that the critical size of a micropit which is free from EDM residual stress, agree well with the critical size from an annealed precracked specimen.

In order to examine the generality of the above coincidence for a wide extent of carbon content, two other kinds of specimen were used for similar fatigue experiments as those for the 0.84% C steel specimens. Results are give in Fig. 8. In the case of the 0.55%C steel,



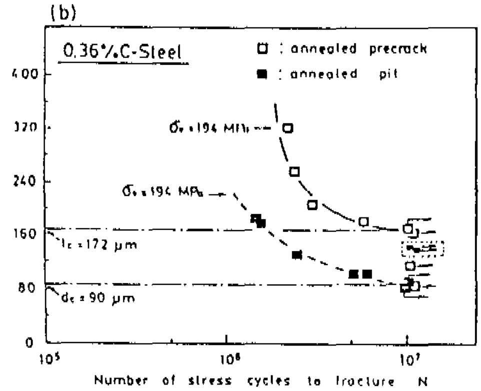


Figure.8. An evaluation of the critical lengths

good agreement is obtained; compare 42 m and 38 m respectively. However, in the case of the 0.36%C steel a relatively poor agreement is recognized between 172μm and 90μm respectively.

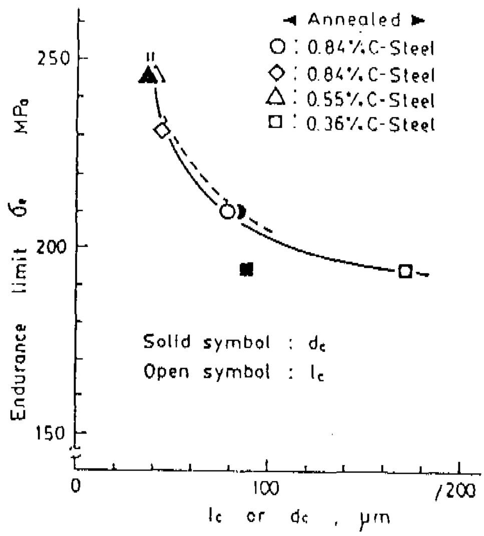


Figure.9. Relationships between the endurance limit and defect sizes (micropits and plain specimen non-propagating cracks) in annealed steels mark: Unpublished work by authors

These results together with that of the 0.84%C specimen are represented in Fig. 9.

The disagreement in 0.36%C steel samples could be associated with the decrease in the volume fraction of pearlite, which acts effectively to suppress the crack the crack propagation around the pit. Since the initiation and propagation of crack is associated with the local volume fraction of pearlite around the pit rather than the averge volume fraction, we may expect good agreement between the two parameters in the 0.36%C steel if the local volume fraction around the pit is pre-arranged by choosing a location of the EDM pit within a pearlite colony.

On the basis of this consideration, two specimens were prepared having annealed pits of 140μm and 144μm diameters. These specimens were then tested at the endurance limit of 194MPa and did not fail after 10^7 stress cycles as expected. The two results are shown surrounded by a broken line in Fig. 8-b.

Thus it is found that the critical micropit size changes from 90 to at least 144μm when the microstructure surrounding the pit is changed from a mixture of pearlite and ferrite to one of pearlite.

It may be concluded that the critical size of a micopit is closely associated with the local state of mixture of pearlite and ferrite arround the pit rather than the average volume fraction of pearlite, i.e., the difference of crack growth resistance between the pearlite and ferrite constituents.

〈 Reference 〉

(1) Kunio, T., Yamada, K., 1979. "Microstructural Aspects of the Threshold Condition for Non-Propagating Fatigue Cracks in Martensitic-Ferritic Structure", ASTM STP 675, pp342~370.

(2) Kunio, T., Yamada, K., M. G. Kim, 1988. "Critical Behavior of Non-propagating Crack in Steel", ASTM STP 924, pp184~193.

(3) Yamada, K, M. G. Kim, Kunio, T., 1986. "Tolerant Microflaw Sizes and Non-propagating Crack Behavior", The Behavior of short Fatigue Cracks, EGP Pub. 1 (Edited by K. J. Miller) Mechanical Engineering Publications, London, pp. 261~274.