Abstract

論 文 の 内 容 の 要 旨

論文題目 Study on Brittle Crack Propagation and Arrest Behavior in Steels from the Perspective of Local Fracture Stress
（局所破壊応力に着目した鋼材における脆性亀裂伝播・停止挙動の研究）

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As the increasing of world trade, the large size container ships play important roles to transport various goods in low cost. Because of the expansion of the usage of the thicker and stronger steel plates for the container ship, so called double integrity against brittle fracture has been considered in the design of the container ship to prevent catastrophic events due to brittle fracture. Although brittle crack arrest is a core concept in the double integrity, the theoretical background to explain brittle crack propagation and arrest behavior in steels has not been established. Therefore, the conventional designs and regulations of brittle crack arrest inevitably have depended on empirical knowledge. This brittle crack arrest concept has been focused on for other steel structures. Accordingly, this dissertation aims to establish the theory to explain the brittle crack behavior because of its importance in both of science and engineering. To achieve this objective, comprehensive studies where both computational mechanics and experimental mechanics were used were carried out to clarify brittle crack propagation and arrest behavior.

This dissertation is composed of 10 chapters.

Chapter 1 describes the social and scientific background about brittle crack propagation and arrest behaviors in steels. In particular, because there has no review articles on brittle crack arrest to cite recent advances, a comprehensive review on recent studies on brittle crack arrest is carried out in Chapter 1. According to this review, it is pointed out that the local fracture stress criterion is the most promising concept to explain brittle crack propagation and arrest behaviors in steel. This

chapter also pointed out that the conventional studies using the local fracture stress criterion depended on some assumptions which were not experimentally or numerically investigated in detail. Accordingly, it is needed to clarify the phenomena which govern brittle crack propagation and arrest behaviors to model the behavior appropriately. In addition, this chapter also mentioned the importance of brittle crack arrest design in the contexts of both of material and structure.

According to the discussion of Chapter 1, the studies in Chapter 2~9 of this dissertation can be categorized to two parts. One is a study aiming to develop a simulation model to theoretically explain brittle crack propagation and arrest behavior based on the local fracture stress criterion. The other is the fundamental studies of crack arrest design. The former contents are explained from Chapter 2 to 7. In addition, because the governing factors are roughly divided to the local tensile stress in the vicinity of the crack tip and 3D effect due to the unbroken shear lip. Chapter 2, 3, and 4 are related to the local tensile stress, and Chapter 5 and 6 explain the 3D effect. Chapter 7 mentions the proposed simulation model based on the findings obtained in Chapter 2 to Chapter 6. Based on the findings from Chapter 2 to Chapter 7, Chapter 8 and 9 explains the crack arrest design of material and structure for engineering application of brittle crack arrest concept.

Chapter 2 mentions the verification of the local tensile stress evaluation in the nodal force release technique in the finite element analyses. This is the fundamental investigation to consider the local fracture stress criterion in finite element method, which is the most common numerical method in fracture mechanics. A series of analyses in this chapter showed that terrible vibration causes serious errors in the local stress evaluation. This vibration deteriorated the local stress evaluation especially in the application phase analyses. To improve the accuracy of the evaluation, Rayleigh damping was introduced to the nodal force release technique to suppress the vibrations. It greatly improved the accuracy both in the generation and application phase analyses.

Chapter 3 carries out the evaluation of the local fracture stress of two ferrite-pearlite steels. Because the 3D effect of brittle crack propagation prevents the accurate evaluation of the local fracture stress, the side grooved specimen is designed based on preliminary finite element analyses. A series of the crack propagation experiments were carried out to measure the crack velocities. The obtained crack velocities in addition to the experimental conditions and constitutive laws were used as input to the finite element analyses to simulate the experiments. The analysis results showed the local fracture stresses are almost constant regardless of the crack velocity, temperature, and stress intensity factor. This result strongly supports the validity of the local fracture stress criterion.

Based on the result of Chapter 3, the local tensile stresses in the vicinity of the rapidly propagating crack tip are analyzed in elastic-viscoplastic solids like steels by using parametric analyses of finite element method in Chapter 4. Steady and unsteady state crack propagation are considered to determine what governs the local tensile stress in the vicinity of the crack tip. A series of analyses showed that temperature, crack velocity, applied stress, and crack length are the governing factors. The influence of crack acceleration is small enough to be ignored in the elastic-viscoplastic solids. These findings are informative to appropriately model the local stress in the vicinity of the propagating crack tip.

Chapter 5 investigates brittle crack propagation and arrest behaviors under extremely high stress intensity factor conditions because the inconsistency between the crack arrest event in the usual width specimen and wider width specimen has been an unsolved problem for these 40 years. The experimental conditions are decided based on the prediction of the conventional model based on the local fracture stress criterion. Although the conventional simulation model mentioned that the cracks would be arrested, the crack was not arrested in one experiments and the crack was arrested in the other experiment. To consider this inconsistency between the experimental results and the formulation of the simulation model, the formulation of the shear lip thickness in the simulation model was modified so that the shear lip thickness was decided by the effective stress intensity factor considering the closure effect.

Chapter 6 describes 3D effects, which are the closure stress and shear lip thickness. The closure stress has been modelled so that the closure stress is equal to the yield stress considering the temperature and unrealistic high strain rate under perfectly plastic condition. Thus, to incorporate actual deformation behavior of the unbroken shear lips, 3D finite element analyses were carried out to evaluate the closure stress. In addition, although Chapter 5 modifies the formulation of the shear lip thickness to make the simulation model consist with the experimental results, the shear lip thickness formulation in brittle crack propagation has not been examined in the first place. Therefore, the shear lip thickness obtained in five brittle crack propagation experiments were measured by the 3D non-contact measure tool to formulate the shear lip thickness during brittle crack propagation. As the result, it is clearly shown that shear lip thickness can be expressed by the stress intensity factor and the crack velocity.

According to the results obtained so far, Chapter 7 shows a new simulation model to theoretically explain brittle crack propagation and arrest behavior based on the local fracture stress criterion. The developed simulation model in this chapter was developed by integrating three element models. The first element model was the response surface of the local tensile stress in the vicinity of the propagating crack tip in the solids which had the steel constitutive law. This response surface was made by a series of 2D plain strain finite element analyses based in the results of Chapter 4. The second one was the approximated equation to evaluate the closure stress. The last one was the shear lip thickness evaluation using the stress intensity factor and the crack velocity. The calculation of this simulation was conducted by solving the simultaneous equations whose variables were the crack velocity and the shear lip thickness. The developed simulation model was validated by comparing the simulated results with the experimental results of the temperature gradient crack arrest tests. In addition to the agreement of $K_{\mathrm{ca}} - T$ relationship with the experimental results, the simulated crack arrest lengths agreed well with the experimental results. The identified local fracture stress in the model simulation was almost equal to the experimentally evaluated value.

Chapter 8 explain influences of the grain size, which is the most fundamental feature of the steel microstructure, to cleavage crack propagation resistance. The simplified method to estimate the local fracture stress was applied to three ferrite-pearlite steels with same chemical compositions and different grain sizes. This study shows that the estimated local fracture stresses were larger in the coarser grain steels. This tendency was already mentioned in the numerical model simulation to represent microscopic cleavage crack propagation. This result is explained by that the cleavage crack propagation resistance is characterized by plastic work of tear ridge formation, which is a ductile fracture process of ligaments between cleavage planes.

Chapter 9 focuses on the structural crack arrest design. Although a series of experimental studies showed that the T-joint structure contributed to brittle crack arrest, the reason of it has not been clarified. This chapter shows the experimental results of high speed observation of brittle crack propagation in the transparent PMMA specimen simulating the structural crack arrest design. The observation showed that the crack front shape contributed to the reduction of the stress intensity factor and thus the brittle crack is promoted to be arrested in the structure.

Chapter 10 summarizes a series of studies carried out in this dissertation and also mentions the limitation of this dissertation as implications for future study.

The main contribution of this dissertation is to develop a simulation model to theoretically explain brittle crack propagation and arrest behavior by investigating each phenomenon which constitutes the brittle crack propagation and arrest behavior to formulate each element model. Such comprehensive approach is the first work to clarify the crack behavior. The results of this dissertation is expected to contribute to strengthen the theoretical back ground of brittle crack arrest concept in engineering application in addition to the contribution in scientific fields.