Quantitative Nondestructive Evaluation of Crack Depth and Closure Stress of Small Cracks Using Ultrasonics(超音波による微小き裂の深さと閉口圧の定量的非破壊評価)

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論文内容要旨

Chapter 1　Introduction

No structure can reasonably be expected to last forever. However, undetected defects that grow under the influence of loads can cause failure even within its planned life. Crack is the most dangerous defect in structural components. In integrity assessment of structural components, it is essential to detect the crack sensitively as well as evaluate them quantitatively, in advance. The potential of using ultrasonic methods in evaluating cracks has greatly been recognized and also verified by fundamental experiments. Although many noteworthy investigations aimed at ultrasonic evaluation of cracks have been done, reliable sizing of closed cracks, specifically, the smaller cracks, is still a big hurdle to overcome.

The crack depth, a, and the crack closure, σ_p, or in other words the effective stress intensity affect the crack propagation rate when a structure is subjected to cyclic loading. The aim of the present study is to develop a reliable ultrasonic nondestructive evaluation (NDE) procedure for both the crack depth and the crack closure stress of small fatigue cracks at no load condition. Quantitative ultrasonic evaluation of crack depth together with the closure stress of closed cracks has not been successful in the past because of the facts that (1) smaller crack normally goes out of detection capacity of conventional technique, (2) cracks having tighter closure are transparent to sound beam – this fact also causes poor detection and (3) crack closure has not yet been modeled appropriately. In an attempt to overcome these difficulties, this study ultimately furnished the development of a new technique with enhanced sensitivity of the inspection using an optimum incidence of shear wave against back-wall crack in steel material as well as the development of a suitable computer based evaluation algorithm with appropriate consideration of the crack closure stress. In this thesis the challenging attempt of the quantitative evaluation of closure stress was particularly in a quest to evaluate the crack opening stress intensity factor which may lead to determine the effective stress intensity range in fatigue crack propagation. The method is fully automated and computer controlled, and can be used to determine crack depth, closure stress and crack opening stress intensity factor. The accuracy and reliability of this quantitative nondestructive evaluation (QNDE) method were checked by comparing the evaluated depths of tightly closed smaller fatigue cracks with their actual depths observed on the fractured surfaces.

Chapter 2 The New Evaluation Approach

This chapter describes an experimental investigation on the ultrasonic NDE of small cracks in the size range of 0.25 to 3 mm. The cracks treated are 0.1 mm-wide slits (as open cracks) and closed fatigue cracks in AISI 304 stainless steel specimens. The fatigue crack in each specimen was developed from the tip of a starter notch by cyclically loading the plate in 4-point bending of tension and tension on dynamic testing machine. After developing the crack, the plate was machined and polished to remove the initial notch, thereby leaving a true fatigue crack in the remaining material. In order to take tighter closure into account, samples were extracted in the L-S orientation. A number of specimens having different crack depths were used.

In order to achieve better repeatability as well as fast and precise ultrasonic measurements, automatic linear scanning was performed by a *xyz*-scanner using water immersion technique. The cracks inspected were situated vertically at the middle of the specimen back wall. All the measurements were performed at room temperature. A single flat pulse-echo transducer transmitting a longitudinal wave of nominal frequency 5 MHz was used for both generating and detecting the elastic waves. The distance between the probe and the specimen back wall was kept fixed at 30 mm, ensuring far-field measurements. All the signals received from the crack-corner zone were post-amplified and then sent to a digitizing oscilloscope from where the digitized data were downloaded directly to a personal computer. The transducer was used to scan over the top surface of the specimen and the measurements were performed with 0.5 mm interval of probe positions.

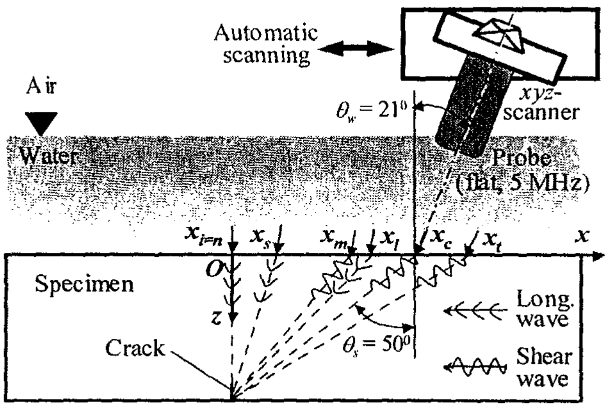

Fig. 2-14 Schematic of ultrasonic testing configuration

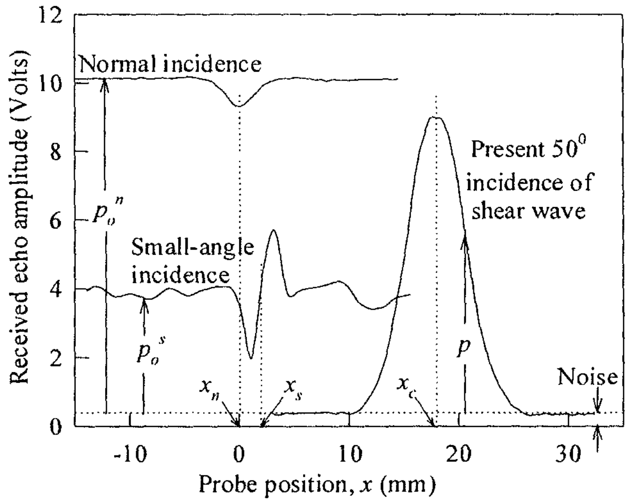

Fig. 2-20 Ultrasonic echo responses obtained by different incidence techniques (slit, a = 3.0 mm)

In order to develop a method for the enhancement of sensitivity of ultrasonic evaluation of small cracks, the capability of usual ultrasonic techniques, i.e., the normal incidence, small-angle incidence and large-angle incidence techniques of longitudinal wave and the large-angle shear wave beam technique, were examined based on the open cracks as shown in Fig. 2-14. Then, the effect of incident beam angle of the longitudinal as well as the shear waves on the crack-surface echo response was investigated. Comparing the nature of echo response curves for different incident angles as shown in Fig. 2-20 the use of shear wave with 50^0 incidence against the crack corner was proposed. The highly sensitive features of the present angle-beam approach compared to the recent techniques were clearly presented. The related basic principles and definitions were briefly explained in an attempt to better understanding the physics of the proposed approach. In the present technique, only the crack echo was visible which also proved its superiority to the recent normal and small-angle incidence techniques where the crack-echo signals were difficult to distinguish from those of uncracked part especially for the smaller closed cracks.

Chapter 3 Analysis of Crack Closure Effect on Ultrasonic Response

The crack-corner echo with the proposed 50^0 incidence of shear wave beam in solid as described in Chapter 2, was used in the rest of the study. Fatigue cracks prepared by tension and tension loading suffer tighter closure under no load condition. This chapter describes a new methodology for analyzing the closure stress of small fatigue cracks. In order to account for the exact effect of crack closure stress on ultrasonic response, the echo amplitude was analyzed based on artificially applying additional closure stress. The variation of echo amplitude with respect to external stress and probe position was found as shown in Fig. 3-6. For estimation of initial closure stress in crack surfaces at no load condition, load versus strain measurements i.e., the compliance measurements for several two-dimensional fatigue crack specimens were taken. The initial closure stress was calculated from the crack opening stress intensity factor, which was determined from the non-linearity of load-strain trace. The net closure stress on crack surfaces due to external loading was considered as the resultant of artificially applied closure stress and the initial closure stress possessed by the crack. The ratio of echo amplitude of a closed crack to that of the same crack under open condition was termed as reflection coefficient and was denoted by γ. A theoretical model of the echo signal received from the closed crack based on this reflection coefficient was proposed in some earlier studies of normal and small-angle incidence techniques where the reflection coefficient was necessarily considered as an assumed function of crack closure stress. Theoretical analysis of closed crack echo signal for large-angle incidence of sound beam was studied here and a simplified expression for closed crack echo amplitude was established for providing the way to deal with γ experimentally. And finally, a relationship between the exact closure stress, σ_p, and the reflection coefficient, γ, was established. The relationship was found to be independent of crack depth. It was also found that a mechanically open crack having occasional asperity-asperity contact of mating fatigue fracture surfaces allowed little transmission of acoustic waves.

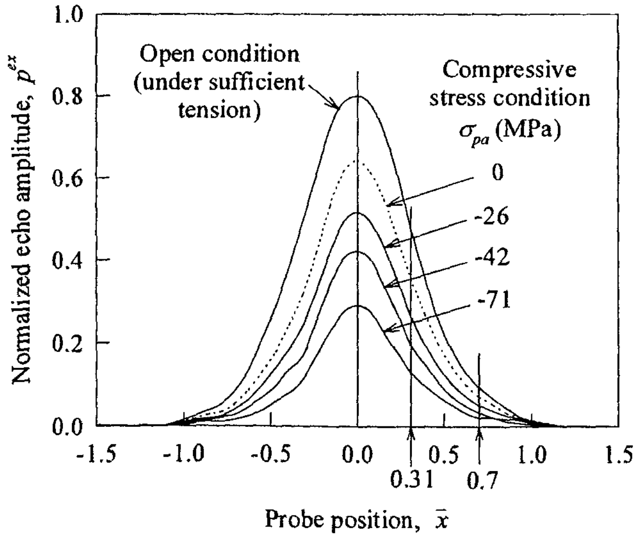

Fig. 3-6 Ultrasonic echo response against fatigue crack (a = 1.82 mm) as a function of external stress σ_{pa}

Chapter 4 Development of the Method for QNDE of Crack Depth and Closure Stress

This chapter is an attempt to give the evaluation technique a quantitative character so that the ultrasonic measurement performed on an unknown crack can be utilized for the quantitative characterization of the same by using an evaluation algorithm. In this regard, surface-connected back-wall cracks of depth ranging from 0.4 to 4.0 mm in steel specimens were considered. First, an empirical relation between the amplitude of the crack echo and the crack depth for open cracks in the above range was determined. Next, the γ-σ_p relation developed in Chapter 3 was extended for wider range of γ and σ_p-values and an empirical relation between them was formulated. Finally, based on these relations an empirical formula for closed crack echo response was developed for estimating the ultrasonic response from the given values of crack depth and crack closure stress. The crack depths and the crack closure stresses of several unknown fatigue cracks based on this empirical formula were determined by inverse analysis of the crack echo response. From the evaluated crack depths and crack closure stresses, the crack opening stress intensity factors, K_{op}, were determined. The accuracy and reliability of this new NDE method were verified by comparing the evaluated crack depth with the actual one obtained by destructive measurement after carrying out ultrasonic testing.

Chapter 5 Simplification of the Evaluation Method

The complete ultrasonic NDE method for cracks in stainless steel material presented in the preceding chapters was based entirely on two calibration equations, namely, the open crack calibration equation and the γ-σ_p relation. As observed, the open crack calibration equation is relatively easier to develop between the two. For any new material specified for testing, the equation can be developed by measuring only the ultrasonic response for a few open crack samples of the material. On the other hand, the preparation of γ-σ_p relation as presented was based essentially on the use of compliance measurements together with the ultrasonic measurements of closed crack samples. Although very few samples of closed cracks are sufficient to develop the relation in the above fashion, an attempt was made in this chapter to prepare the relation in a simpler way, i.e., without the use of compliance measurements.

As described in Chapter 4, a fatigue crack with zero closure stress can be obtained by applying necessary cycles of tension and compression loading on it. The γ-σ_p relation was developed by preparing cracks with zero closure and performing only the ultrasonic measurements under varying compressive load. In order to justify the validity of the relation obtained in this way, it was compared with the γ-σ_p relation obtained from the use of compliance measurements. Good accuracy in the evaluation results and good conformity of the γ-σ_p relations obtained by the two methods established the fact that the NDE method developed in this thesis was independent of the use of the compliance technique. Thus, the method was proved to be a very suitable one for QNDE of cracks, crack closures and crack opening stress intensities.

Chapter 6 Conclusions

The thesis presented a novel ultrasonic technique for the QNDE of crack depths, crack closure stresses and crack opening stress intensity factors of unknown small fatigue cracks. The evaluation was done using inverse analysis of the measured crack-echo response of shear wave with 50^0 incidence upon the specimen back wall based on some predetermined calibration equations. For any material newly tested the calibration equations can be determined performing ultrasonic measurements on few samples of cracks. Quantitative evaluation of crack closure stress or crack opening stress intensity factor has not yet been successful in the past because of the inability to model the exact effect of crack closure in the evaluation procedure, and also the lack of sufficient sensitivity in detection of smaller cracks using the standard ultrasonic techniques. The proposed evaluation method is free from these limitations and enables us to deal with smaller cracks having any degree of closure stress. Experimental investigation showed that the proposed angle-beam technique gives the highest sensitivity in evaluating smaller cracks, especially the smaller closed cracks. The present technique gave the first success in the quantitative determination of the crack closure stress as well as the crack opening stress intensity factor. There is no doubt that the proposed optimum-incidence method would be definitely a powerful tool in the field of ultrasonic NDE of crack and closure stress.

論文審査結果の要旨

機器・構造物の検査に超音波が広く用いられている。危険な欠陥であるき裂の探傷において、き裂の閉じ具合を考慮することなしに、例えばき裂は開いているものと仮定して、受信信号よりき裂の寸法を評価すれば、閉じたき裂の場合に誤った評価を下すことになるため、どのような閉じ具合のき裂をも対象にし得る検査手法の開発が切に待たれていた。

著者は、閉じた微小き裂の高感度超音波検出を踏まえた定量的非破壊評価手法の開発に成功した。本論文は同検出手法とこれに基づく寸法ならびにき裂閉口圧の無負荷状態下での定量的評価についてまとめたもので、全編6章よりなる。

第1章は序論である。

第2章では、被検査材の底面に垂直に存在する微小き裂を対象として、斜角探傷による横波超音波応答の感度を種々の屈折角に対して系統的に比較し、き裂の広い寸法範囲に対して有効で、最も高感度な応答を実現する屈折角を50°と特定している。これは閉じた微小き裂の定量評価の基礎を与える有益な成果である。

第3章では、閉口き裂に対する超音波受信強度とき裂閉口圧の間にき裂寸法によらない関係が存在することを見い出している。ここにき裂閉口圧の評価は、き裂材のコンプライアンスの非線形から線形への挙動変化に基づき実現している。本関係の発見は有用な成果である。

第4章では、閉口き裂に対する超音波受信強度とき裂寸法の間の関係式を導出し、これと第3章の成果を合体させることにより、閉口き裂に対する超音波受信強度をき裂寸法とき裂閉口圧の関数として表現することに成功している。さらにこれを用い、任意のき裂を対象として逆問題を解析することにより、き裂寸法、き裂閉口圧、さらにはき裂開口のための応力拡大係数の値を無負荷状態下で超音波により定量的に評価できることを実証している。これは他に先駆けた成果である。

第5章では、引張－圧縮の繰り返し負荷の後に無負荷状態下にある疲労き裂の閉口圧は零と評価できるという発見に基づき、当該き裂を用いて、き裂材のコンプライアンスの観察を行うことなく、外部からの負荷によるき裂閉口圧と閉口き裂に対する超音波受信強度との関係を求めることにより、第4章で提案の評価法を簡便なものにできることを示している。これは実用にあたり有益な成果である。

第6章は結論である。

以上要するに本論文は、高感度な斜角横波超音波探傷を新たに導入して、閉じた微小き裂の寸法ならびにき裂閉口圧を逆問題解析により定量的に評価することを可能にしたもので、機械知能工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。