Acoustic Emission and Structural Integrity Technology(構造安全性工学とアコースティック・エミッションに関する破壊力学的研究)

著者	MOHAMMAD ASIF　KHAN
号	861
発行年	1981
URL	http://hdl.handle.net/10097/9597

氏　　　名	MOHAMMAD ASIF KHAN（モハマッド・アシフ・カーン）
授与学位	工学博士
学位授与年月日	昭和57年3月25日
学位授与の根拠法規	学位規則第5条第1項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）機械工学専攻
学位論文題目	Acoustic Emission and Structural Integrity Technology（構造安全性工学とアコーステック・エミッションに関する破壊力学的研究）
指導教官	東北大学教授　高橋　秀明
論文審査委員	東北大学教授　高橋　秀明　東北大学教授　萱場　孝雄 東北大学教授　阿部　博之　東北大学教授　川崎　正 東北大学教授　中鉢　憲賢

論文内容要旨

CHAPTER 1 GENERAL INTRODUCTION

Engineering structures subjected to combined static or dynamic loads and environment are vulnerable to the initation and growth nf crack which can lead to structural failures. Many catastrophic failures of metallic structures have occurred over the past decades in the major industrial sector such as chemical, mineral oil production and gas, electricity generation and, perhaps to a lesser extent, the nuclear power. Safeguarding the integrity of such structures has, therefore, prompted the need for a flaw-structure interaction analysis and reliable nondestructive testing.

The aim of the present investigation was to demonstrate that a synergism between acoustic emission (AE) and fracture mechnics methodologies offers attractive capabilities for monitoring structural integrity and characterizing material behavior. The major topics to be treated were organized into eight chapters.

A new AE rating parameter was developed and applied to the prediction of tearing instability during laboratory tests on materials which fail by void coalescence and growth. Furthermore, a relatively simple procedure was proposed to permit an assessment of elastic-plastic fracture toughness and resistance to stable crack growth from a single specimen.

The feasibility of using AE methods for monitoring the initiation and propagation of trans- and intergranular cleavage microcracks for virgin and embrittled materials was investigated. An experimental study was also conducted into the effect of triaxiality on the fracture processes with the AE technique.

A preliminary evaluation of the effects of both neutron irradiation and prestraining on the materials resistance to ductile crack growth was conducted with particular reference to the nuclear reactor surveillance program. Finally, the feasibility of general implementation of AE surveillance along with fracture mechanics methods in structural integrity requirements of the ASME Boiler and Pressure Vessel Code Section XI Appendix A was discussed.

CHAPTER 2 APPLICATION OF ACOUSTIC EMISSION TECHNIQUES TO CRACK DETECTION AND MEASUREMENT IN METALLIC MATERIALS

The aim of the work reported in this chapter was to investigate the possibility of obtaining some reliable information about the onset of crack extention, crack-growth rate, and quantitative crack growth minitoring with the AE technique. Experiments were carried out on different materials (AISI 4340, Cr-Mo-V, SA533B steels, $A\ell$ 2024T351, and Type 304 stainless steel) which exhibited either pop-in cracking, ductile-cleavage transition, or stable ductile tearing.

The experimental results have shown that many failure-related gross material properties which influence the crack propagation resistance of a material produce measurable changes in the AE activity. A clear indication of the onset of a stable crack extension is provided by a significant change in slope of the summation of AE energy versus J curve ($J_{i(AE)}$), irrespective of the specimen size or geometry (Fig. 1).

The AE technique was also applied to continuously monitor the stable crack growth. The experimentally obtained AE data along with the observations of crack growth, toughness and flow properties (Figs. 2 through 4)were used to develop a new AE rating parameter

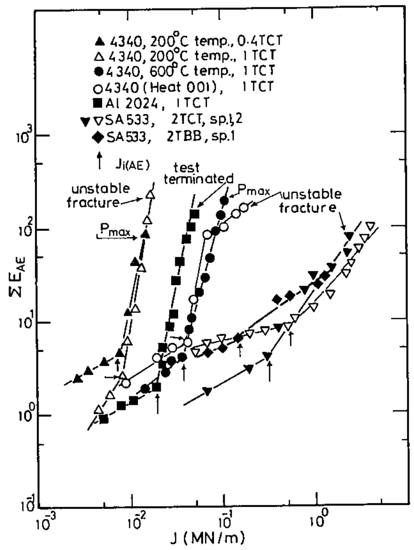

Fig 1 Summation of AE energy plotted as a function of J for various materials.

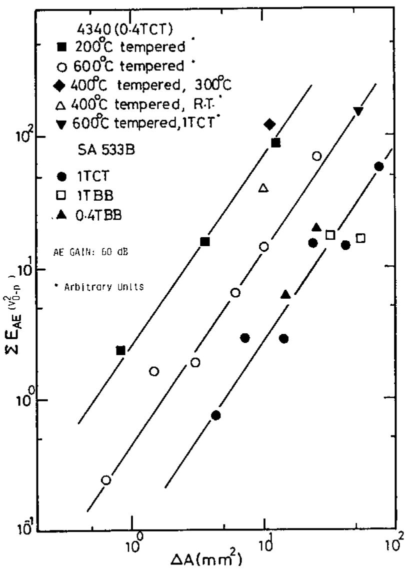

Fig 2 Accumulated AE energy versus cracked area for SA 533B and AISI 4340 steels.

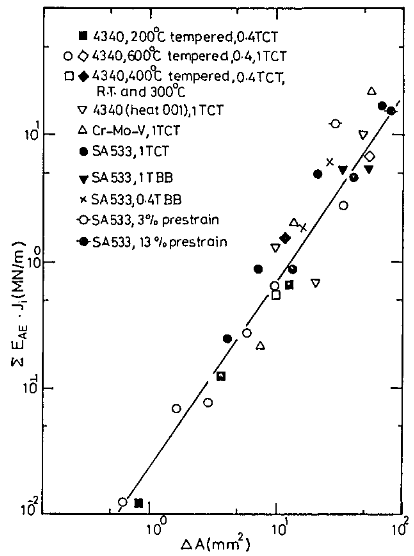

Fig 3 Acoustic key curve ($E_{AE} \cdot J_i$ versus cracked area) for different alloy steels (AE gain :60 dB).

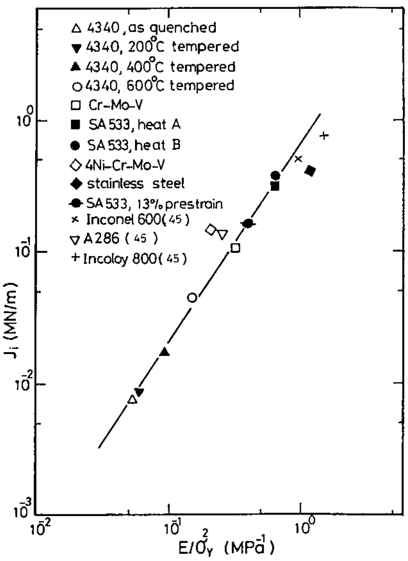

Fig 4 J_i plotted as a function of E/σ_Y^2 for different alloy steels.

$$T_{ac} = \{\Sigma E_{AE}/B\}/\Delta J \quad \cdots\cdots(1)$$

where B is the specimen thickness and ΔJ is the difference of J values corresponding to P_{max} on the load-displacement curve and J_i. This newlv proposed AE rating parameter was correlated to the tearing modulus parameter

$$(T_{mat} = (dJ/da).\frac{E}{\sigma_Y^2}),$$

$$T_{ac} \cdot T_{mat} = k \quad \cdots\cdots(2)$$

to predict tearing instability of elastic-plastic crack growth in structural materials. The proposed correlation between AE rating parameter and materials instability parameter for laboratory test pieces is quite general in its applicability to in-service conditions.

CHAPTER 3 A SIMPLE TEST METHOD FOR THE EVALUATION OF TEARING MODULUS

The acoustic emission rating parameter T_{ac} and tearing instability parameter T_{mat} have been related in Eq. 2. However, limitation here is that the determination of T_{mat} involves costly procedure often using several specimens for a single toughness measurement. The present chapter was intended to develop a simple and inexpensive test procedure for estimating the tearing modulus parameter.

Material characterization studies using the multispecimen J resistance curve procedure have been carried out for plane-strain-like stable crack growth of compact tension and bend-type specimens of a wide variety of ductile materials.

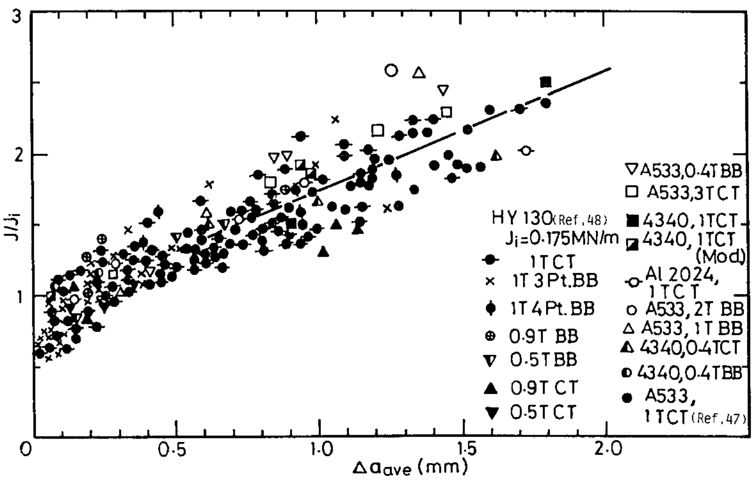

Fig. 5. J/J_i key resistance curve for different geometries and sizes of various metallic materials.

Based on the experimental results, measurement of a critical J value corresponding to a small finite amount of crack growth instead of to an assumend blunting line procedure is proposed. The J resistance curves developed in this investigation along with the data from the literature have been used to demonstrate that these curves can be normalized to a J/J_i key resistance curve (Fig. 5).

A relatively simple and realistic test procedure is proposed to permit an assessment of a critical value of the J integral and the tearing modulus from a single specimen using equations

$$J_i = J / (\beta \Delta a + 1) \quad \cdots\cdots (3)$$

$$T_{mat} = \beta J_i (E / \sigma_Y^2) \quad \cdots\cdots (4)$$

where β ($= 857\,m^{-1}$) is the slope of the J/J_i key resistance curve.

The experimental data have shown that J-controlled crack growth is reasonably unvarying with the size and geometry of the specimen for a comparatively large amount of crack extension, provided the minimum size requirements to ensure a J-based dominance of the crack-tip region are satisfied. The experimental verification of the relationship between AE rating parameter T_{ac} and the tearing modulus parameter T_{mat} (Eq. 2)

$$T_{ac} \quad T_{mat} = k$$

is presented in Fig. 6 where the values of T_{ac} reflect the relative crack growth rates in tearing situations.

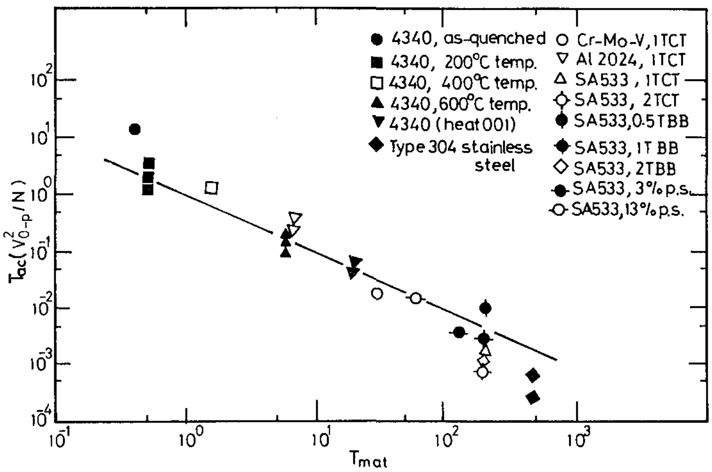

Fig. 6. Acoustic emission rating parameter plotted as a function of tearing modulus (AE gain : 60 dB).

CHAPTER 4 TRIAXIALITY EFFECTS ON DUCTILE FRACTURE AND ACOUSTIC EMISSION CHARACTERISTICS

The ductility of a material under the influence of a particular stress state plays an important role in both the ductile fracture and the brittle fracture processes of an engineering structure. The work described in this chapter has the ofjective of investigating the effect of stress-state on the fracture process using the AE technique. The results for SA533B nuclear pressure vessel steel have shown that the ductility of the specimens decreased markedly with an increase in triaxiality and that the accumulated AE energy increases significatly with the decrease in fracture strain (Fig. 7). The rearystallization-etch technique has also been applied to delineate the intense strain region around the notch, the internal voids and the stable crack growth. The formation and extension behavior of these regions are discussed from a triaxiality view point, with reference to the AE activity.

The source mechanism of AE signals with small or large amplitudes generated during the loading to final fast fracture has been discussed in term of void-nucleation, coalescence and subsequent micro- and macrocrack initiation and propagation from the coalesced voids. It is demonstrated that the AE activity, fracture strain, microfracture mechanism and triaxiality parameter are interrelated. Furthermore, the effects of triaxiality on the AE rating parameter and its implications in the use of the AE technique for continuous in-service structural integrity surveillance are discussed.

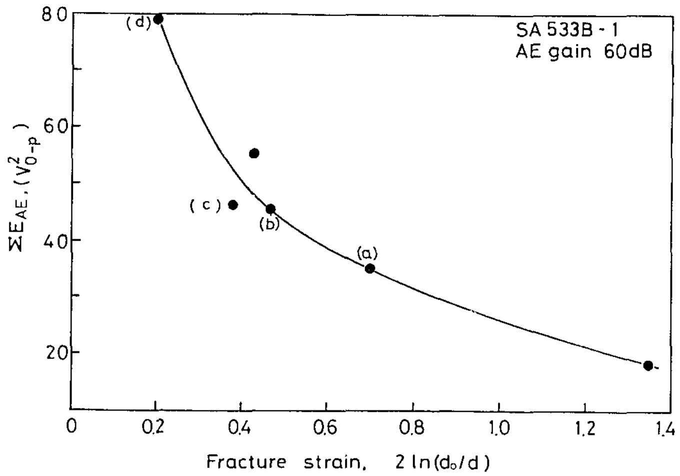

Fig. 7. Accumulated AE energy versus effective plastic strain to fracture for SA533B steel.

CHAPTER 5 AN INVESTIGATION OF ACOUSTIC EMISSION FROM CLEAVAGE MICROCRACKING IN ALLOY STEELS

The brittle fracture is the most crucial since it occurs rapidly with little or no warning. The aim of the investigation described in this chapter was to examine the feasibility of using AE for monitoring the initiation and propagation of cleavage microcracks that lead to unstable fracture. The experimental results indicated that during the onset of rapid unstable crack growth, spontaneous acoustic events with high amplitude are emitted. The scanning electron microscopy studies, carried out for unloaded, fatigue postcraced and fractured specimens, showed a clear correspondence between the number of AE events with large amplitude and the number of cleavage microcracks observed.

The AE data for all the materials examined demonstrated a bilinear nature of the summation of AE energy when displayed versus the stress intensity factor (Fig. 8). It was proposed that the stress intensity factor corresponding to the first trans- or intergranular crack extension should be used as a conservative estimate of fracture toughness for brittle materials.

A model of cleavage crack extension based on the local fracture stress criterion proposed in this chapter, was seen to interpret the emission behavior from the materials tested. The use of AE in the detection of the stress intensity factor corresponding to the brittle crack initiation and final fracture as two seperate points showed the possibility of monitoring the cleavage microcrack growth in real-time, and thus AE rating parameter in the cleavage regime was proposed. The experimental results presented in this chapter have indicated that incorporating AE techniques for the detection of brittle fracture can enhance the failsafe design of the structural component.

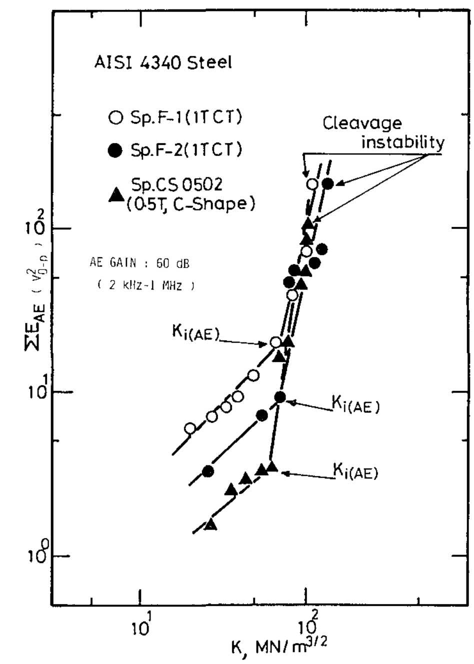

Fig. 8. A typical example of AE activity at the onset of cleavage crack extension. Material: AISI 4340 steel (Heat 106).

CHAPTER 6 EVALUATION OF RADIATION DAMAGE IN REACTOR PRESSURE VESSEL STEEL BY ELASTIC-PRASTIC FRACTURE MECHNICS

The intent of the work reported in this chapter was to explore the effects of irradiation embrittlement through laboratory tests which may help to project conditions required for fast fracture (ductile or cleavage) and thereby aid in developing interpretative procedures. A simple test procedure is given from which the tearing modulus parameter can be estimated for irradiated materials from a single small specimen. The proposed method was applied to investigate the deterioration in the postirradiation fracture toughness of nuclear pressure vessel steel. The elastic-plastic fracture toughness data indicated that neutron irradiation could be detrimental to the materials resistance to stable crack growth represented by tearing modulus T_{mat} (Fig. 9). The analogous effects of strain embrittlement on yield strength and tearing modulus were observed, and the feasibility of using the AE method to the monitoring of stable crack extention in prestrained specimens was demonstrated.

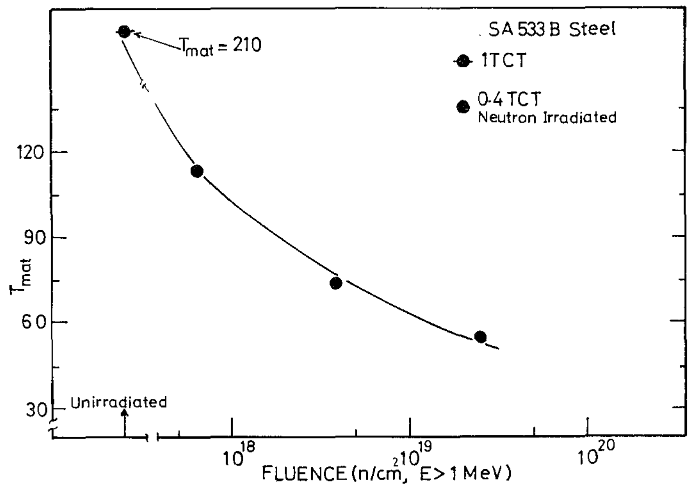

Fig. 9. Effect of neutron irradiation on the tearing instability parameter T_{mat}.

CHAPTER 7 EVALUATION OF STRUCTURAL INTEGRITY OF PRESSURIZED COMPONENTS BY ACOUSTIC EMISSION AND FRACTURE MECHANICS TECHNIQUES

The main bugbear of the AE technique is the extrapolation of laboratory data to the large thickness structures in operation. The interdisciplinary study presented in this chapter was aimed at providing a quantitative relationship between AE and the actual performance of flawed pressure vessels. For this purpose, the AE data base for defining instability in pressurized components such as intermediate pressure vessels was developed. The data obtained during the large-scale flawed vessel tests at different research centers was used to demonstrate the feasibility of the AE rating parameter T_{ac} for treating crack instability problems in intermediate test vessels. Based on the developments in AE and fracture mechanics techniques that result from present investigation, a modified structural integrity plan is outlined in Fig. 10 in a manner acceptable to the practising engineer who is concerned with the design and operation of metallic structures.

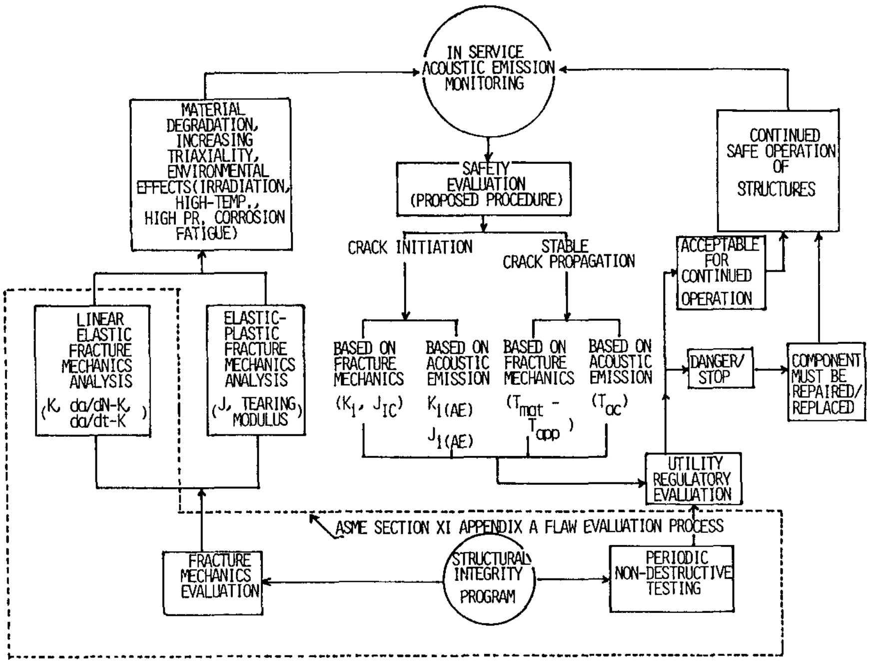

Fig. 10. Structural integrity flow chart based on AE and fracture mechanics techniques.

CHAPTER 8 CONCLUSIONS

The research work presented in this dissertation is an attempt to develop a practical method for the integrity of structures in service where the conjoint action of flaws and service conditions can lead to unstable (ductile or cleavage) fracture. Because of a genuine need for on-line surveillance methods which can identify areas of possible structural degradation, a systematic investigation of acoustic emission and fracture mechanics techniques for monitoring structural integrity has been carried out. The results of this study represent an important step forward in the assessment of structures containing cracks and vulnerable to the concomitant effects of flaw growth, embrittlement, environment and triaxiality.

審　査　結　果　の　要　旨

化学プラントあるいは原子炉圧力容器ばかりでなく各種大型機械・構造物・機器の安全設計ならびに運転保守基準の中に破壊力学の概念が取り入れられ，定期的な非破壊検査ならびに安全評価がなされている。アコーステック・エミッション（ＡＥ）法は，新しい非破壊検査法の一つとして注目されているが，得られたＡＥの測定結果を材料評価をも含めて破壊力学的観点から評価する方法は未だ確立していない。

本研究は第一に金属材料にＡＥ法を用いた普遍的な弾塑性破壊靱性評価法の基礎を確立すること，さらにこれらの材料評価基準をふまえた構造安全性の新しい評価法の提案を目的としており全編８章よりなる。

第１章は序論であり，従来の大型構造物の安全設計ならびに運転保守に採用されている構造安全性評価法の基本的な問題点を列記し，本論文で取り上げるＡＥによる非破壊検査・材料評価法の位置づけを明確にしている。

第２章は種々の金属材料の弾塑性破壊靱性試験におけるＡＥを計測し，破壊力学に基礎をおく新しいき裂評価パラメータとしてＡＥ活性度パラメータ（T_{ac}）を提案し，材料固有の破壊抵抗（テアリングモジュラス，T_{mat}）との関係を誘導している。これはＡＥによる材料評価に極めて重要な関係である。

第３章では現行の複数試験片による弾塑性破壊靱性試験法に代る新しい簡便法を提案し，その普遍性を確めている。この評価法は実用上極めて有効であり，応用性に富んでいる。

第４章では延性破壊ならびにＡＥ放出に及ぼす３軸応力の影響を明らかにし，微視破壊過程とＡＥの相関性を検討している。

第５章では構造物の不安定脆性破壊として重要な鉄鋼材料のへき開破壊とＡＥの関係を明らかにし，最終破壊に到る以前の前兆のＡＥ信号の存在を確認している。

第６章では原子炉圧力容器鋼の中性子照射脆化の評価に関連して第３章で述べた簡易評価法の適用性を確かめ，新しい原子炉監視試験法を検討している。

第７章は上述の試験片について得られたＡＥ評価法の構造物の安全性判定基準として応用するためモデル圧力容器破壊試験において計測されたＡＥについて破壊力学パラメータを用い再評価し，第２，３章で述べた基本的関係が実構造物においても成立していることを確認している。これは圧力容器などの耐圧検査法の発展の上で重要な知見である。

第８章は結論である。

以上，要するに，本論文は非破壊検査法としてのＡＥの新しい評価法だけでなく，これを新しい材料評価法として用いることの有用性を指摘したものであり，機械工学ならびに弾塑性破壊力学の発展に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。