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学 位 論 文 題 目	The Effect of Damage on the Fracture Toughness of C/C composites

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論文内容の要旨

1. Objective

Carbon-carbon (C/C) composite is at present the most mature high temperature material retaining its superior specific strength and specific modulus at temperatures above 2000°C. Despite its superior high temperature behaviour, the C/C composite has some important drawbacks which are their

- high cost,
- susceptibility to oxidation at elevated temperatures, and
- not fully clarified fracture behaviour.

At present, the not fully clarified fracture behaviour prevents the usage of C/C composites in load bearing applications. The aim of this work is to contribute to a deeper understanding of the fracture behaviour in order to promote the usage of C/C composites in a broader variety of applications.

2. Background

The notch insensitive behaviour of C/C s has been explained by Evans et al. [1] by the model so-called "shear band" formation. This concept is simply explained as: Tensile stress concentration leads inevitably to high shear stress at the stress concentration source, e.g. at a crack tip. Due to the C/C's low shear strength, shear damage extends. This shear damage starts at the crack tip and extends normal to the crack parallel to the loading direction as the tensile load increases. The shear damage near completely diffuses the stress concentration at the crack tip leading to notch insensitivity.

According to Evans et al. [1], when the ratio of shear and tensile strength is sufficiently low, the shear band concept is effective for explaining notch insensitive behaviour of brittle matrix composites. C/C composites in general have low ratio of their shear and tensile strength. Thus, Evans et al. have insisted that C/C composites should be categorized into materials exhibiting large shear bands. However, this approach leaves several questions for applying to the tensile fracture of notched C/Cs: The shear bands were not observed at all in notched C/Cs with cross-ply and quasi-isotropic laminations by optical inspection in tensile tests, for example, carried out by Hatta et al. [2], leading to the question of the relevance of this concept.

The present study first shows that the contribution of the shear band formation to the fracture toughness enhancement of laminated C/Cs is not so high as Evans et al. insisted. Then, other source mechanisms of toughness enhancement were explored.

3. Fracture patterns of notched laminated C/Cs

Notched specimens of a uni-directionally reinforced C/C with fibres parallel to the loading direction (UD0) exhibit clear shear bands emanating from notch tips. In contrast, notched C/Cs with fibre orientation normal to the loading direction (UD90) show brittle fracture without shear bands. Thus, in order to examine shear band formation and its contribution to toughening, fracture behaviours of notched and smooth laminated C/C s with a variable ratio between UD0 and UD90 were observed under tensile loads, and notch sensitivity of them was evaluated.

The experimental results showed that the shear bands clearly observed when the ration of the UD0 and UD90 (R) of the C/Cs was larger than 0.6, but did not when $R < 0.6$. Thus, when $R > 0.6$, complete notch-insensitivity was resulted due to the large shear bands. In contrast, when $R < 0.6$, multiple small splits to the loading direction and low degree of notch insensitivity similar to quasi-isotropic (QI), or cross-ply laminates (CP) $(0/90)_n$ were observed.

Although the shear bands for $R > 0.6$ and multiple splits for $R < 0.6$ were parallel cracks extending to the loading direction, both the cracks were different at the following two points;

1) While the shear bands extended through-the-thickness, the splits remain only in the 0° layers. Thus, when $R < 0.6$, remaining 90° layers can transfer a limited amount of the concentrated load to the adjacent 0° ligaments.
2) The sear bands were formed by mode II due to shear stresses, but the splits by mode I due to tensile stresses.

3. Tensile strengths of C/Cs

Tensile tests carried out using double-ends-noched (DEN) specimens with the CP lamination have revealed a surprising result. When the notch length a was small, the fracture stress with respect to the net sectional area, means, the net fracture stress $\sigma_{f,net}$ of the notched specimens, was much higher than the tensile strength obtained using smooth specimens. This means that stress concentration sources lead in some cases to higher tensile strength. A concept like shear band formation, which focuses on the reduction of stress concentration cannot explain a tensile strength higher than that obetained using straight and un-notched specimens.

For deep understanding of the strength enhancement behaviour, tensile tests with CP specimen having several holes were carried out. This configuration was chosen for two reasons. At first, this configuration allowed the observation of the strength-enhancing phenomenon under a wide variety of parameters. Secondly, the hole generates mild stress concentrations. The mild stress concentrations allowed many cycles of a non-linear FEM analysis before termination. Consequently, the process of initiation and propagation of the multiple splits from the stress concentration points could be studied numerically in detail. The conclusion of this comparison was that both the splits and strength enhancing phenomena have a major effect on the high toughness of C/Cs.

In the above study, it was found that the strength enhancing effect at stress concentration sources is caused by damage of the fibre and matrix interface. In this case, the mechanism of rotation and straightification of the carbon fibres in the matrix was identified as source of the fibre-matrix de-bonding. The effect of strength enhancement by fibre-matrix de-bonding was then examined more extensively by application of various damage sources. The shear pre-load, fatigue loads, and slight oxidation were found to yield the tensile strength enhancement effect, and it was verified that the stregth enhancemnet was commonly caused by the interfacial damage between the fiber and matrix.

5. Toughening mechanisms of C/Cs

Through the course of discussion, following conclusions on the toughening mechanisms of C/Cs were obtained;

1) When the mode II toughness propagating parallel to the loading direction is sufficiently lower than mode I toughness normal to the load, shear bands are principal mechanism to yield complete notch insensitivity of C/Cs.
2) In other cases, multiple splits and tensile strength enhancement are identified as source of high toughness of C/Cs.
3) The tensile strength enhancement is caused by interfacial damage between the fiber and matrix.

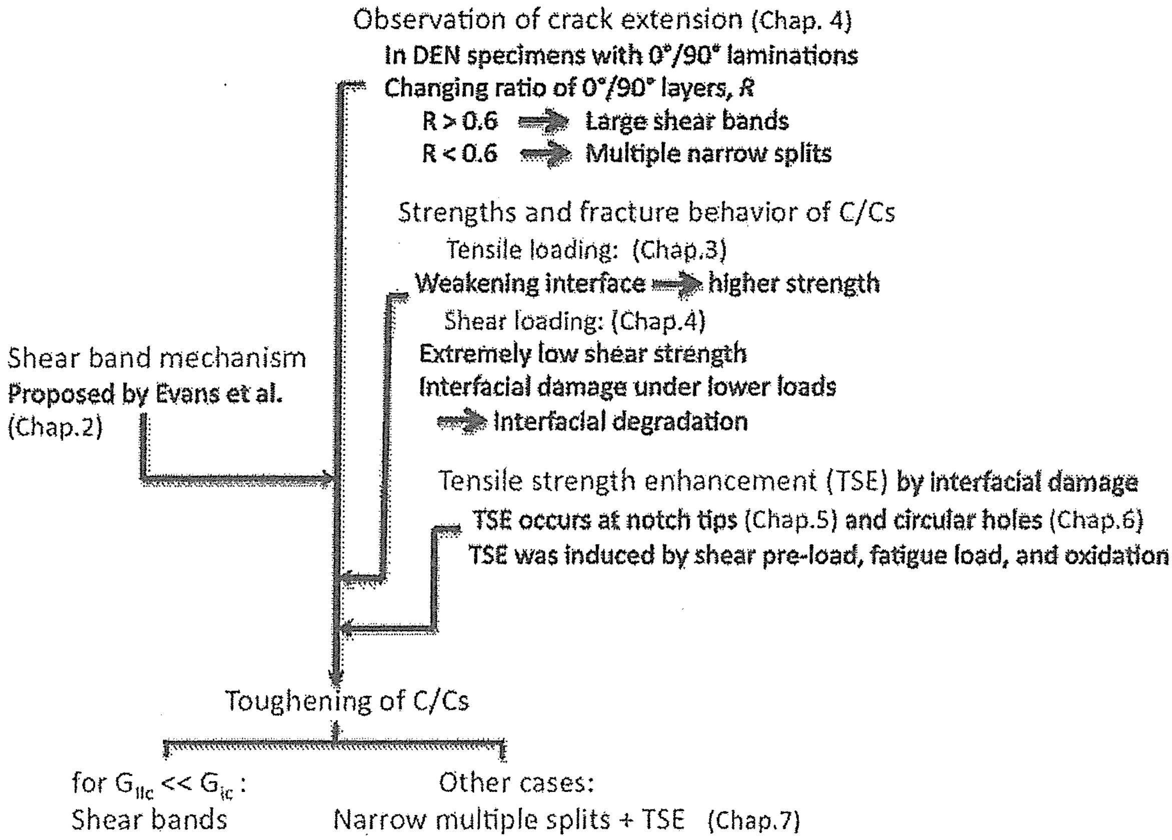
The logical flow and conclusions as well as the constitution of the present thesis are summarized in the Figure 1.

References

[1] A. G. Evans and F. W. Zok, "Review: The Physics and Mechanics of Fibre-Reinforced Brittle Matrix Composites," J. Mater. Sci., 29, 3857-3896, (1994).

[2] Y. Kogo, H. Hatta, H. Kawada and T. Machida, "Effect of Stress Concentration on Tensile Fracture Behavior of Carbon-Carbon Composites", *J. Comp. Mater.*, 32 [13], 1273-1294 (1998).

Figure 1 Toughening mechanism of C/Cs



博士論文の審査結果の要旨

炭素繊維強化炭素基（C/C）複合材料は、ロケットノズルや宇宙往還機エンジン部材などの超高温環境で使用される耐熱材料として適用に向けた検討が進められている。本申請論文では、材料の耐久性を保障するために必要な破壊靭性に着目し、C/C複合材料が高靭性を示すことを示すと共に、その高靭化の機構を解明することを目的とし、広範に亘る実験的検討を実施した。

申請論文は９章により構成されている。第1章と第2章では、関連する脆性マトリックスの耐熱複合材料に関して、開発状況と破壊靭性に対する考え方に関する調査結果をまとめている。特に第２章では、これまでC/C複合材料の高破壊靭性はノッチ端にせん断損傷帯（Shear band）が形成にされるためと定性的に説明されてきたが、この機構では説明できない場合が多いことを説明し、本研究の意義を明らかにしている。

第３章からが研究の具体的内容になり、第３章では、積層パターンをsystematicに変化させた多様な積層C/C複合材料に対して、ノッチからの亀裂進展の挙動を観察し、亀裂進展の挙動が積層パターンにより、1）モードＩ型、2）モードＩ型+モードII型の混合型、及び3）モードII型の三種類のパターンに分類できることを示した。これらの中で、これまでのShear bandによる高靭化機構では、モードII型の場合だけしか説明できないことを示した。第４章では特にモードII型の亀裂進展で重要になるせん断変形時の損傷進展に関して検討を行い、非線形なせん断の応力-歪み曲線で生じる損傷の蓄積過程を明らかにした。特にせん断負荷の初期段階に於ける損傷が繊維/マトリックス界面の剥離であることを見出し、この結果は以下の議論における基本的な知見となった。第５章では、C/C複合材料にせん断荷重を加え、せん断損傷を与えた材料の残留引張強度に関する検討を行い、軽微なせん断損傷すなわち繊維/マトリックス間の界面に軽微な損傷をあたえることにより引張強度が顕著に向上する現象を新たに見出し、この現象がモードＩ型及びモードＩ型+モードIIの混合型においてもC/C複合材料が高破壊靭性を示す主たる要因であることを示唆した。第６章では、繊維/マトリックス界面の剥離によりC/C複合材料の引張強度が向上する機構を実験的に解明し、C/C複合材料の引張破壊機構を初めて明らかにするとともに、新たなモデルを提案した。第７章は本論からやや外れた議論になっているが、実用上は重要な有孔平板に関してもせん断損傷により引張強度が顕著に向上する現象を見出し、C/C複合材料の有孔平板の引張破壊に対する考え方を確立した。第８章では、以上の結果をまとめて、ノッチからの亀裂進展をモデル化する方法を検討し、新たなモデルを提案している。最後の第9章では本論文の結論をまとめている。

以上のように本研究は、C/C 複合材料の引張強度に関して新たな支配要因を見出し、その引張高強度化の機構が C/C 複合材料の高靭化の主たる要因になっていることを初めて明らかにしたもので、C/C 複合材料の力学応答の解明に大きな工学的貢献をするものといえる。この結果は、3 編の論文として当該分野の一流国際誌に発表されており、もう一編の論文投稿も準備されている。以上より、本審査委員会は、本申請論文が博士学位論文としての価値が十分あるものと判断した。