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BSI Standards Publication

Space engineering — Structural materials handbook

Part 6: Fracture and material modelling, case studies and design and integrity control and inspection

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European Foreword

This document (CEN/TR 17603-32-06:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-10-02.

This Technical report (CEN/TR 17603-32-06:2022) originates from ECSS-E-HB-32-20 Part 6A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

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Introduction

The Structural materials handbook is published in 8 Parts.

A glossary of terms, definitions and abbreviated terms for these handbooks is contained in Part 8.

The parts are as follows:

TR 17603-32-01	Part 1	Overview and material properties and applications	Clauses 1 - 9
TR 17603-32-02	Part 2	Design calculation methods and general design aspects	Clauses 10 - 22
TR 17603-32-03	Part 3	Load transfer and design of joints and design of structures	Clauses 23 - 32
TR 17603-32-04	Part 4	Integrity control, verification guidelines and manufacturing	Clauses 33 - 45
TR 17603-32-05	Part 5	New advanced materials, advanced metallic materials, general design aspects and load transfer and design of joints	Clauses 46 - 63
TR 17603-32-06	Part 6	Fracture and material modelling, case studies and design and integrity control and inspection	Clauses 64 - 81
TR 17603-32-07	Part 7	Thermal and environmental integrity, manufacturing aspects, in-orbit and health monitoring, soft materials, hybrid materials and nanotechnoligies	Clauses 82 - 107
TR 17603-32-08	Part 8	Glossary	

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64
Behaviour of advanced composites

64.1 Introduction

The fracture behaviour of metallic and ceramic matrix composites is more complex than that of unreinforced alloys or monolithic ceramics. The fracture characteristics of the more isotropic variants are now well understood and predictive models are widely accepted, e.g. Linear Elastic Fracture Mechanics (LEFM), [See also: ECSS-E-32-01 – Fracture control].

For newer composite materials, attempts have been made to describe and predict their behaviour by extending the models for their more isotropic counterparts. Success has been limited by the anisotropy of the composites, especially for those with continuous fibres. In reality, anisotropic metallic and ceramic composites need to be considered as new classes of materials. Some CMC materials, destined for use in TPS on reusable vehicles, have been investigated for appropriate selection and use of failure criteria, [See: 64.5].

Metal matrix composites are particularly difficult as they show elastic-plastic deformation characteristics, where the degree of plastic deformation is influenced by many factors.

Ceramic composites are elastic in behaviour, although accumulated matrix microcracking gives non-linear deformation characteristics. These composites are desirable because of their high temperature operating capabilities.

This chapter covers three discrete groups of composites:

- Particulate reinforced metals (MMCp).
- Fibre reinforced metals (MMCf).
- Inorganic ceramic matrix composites (ICMCf).

Whisker reinforced metals or ceramics are not explicitly covered because they are primarily of non-European origin and in some European countries whiskers are thought to present health hazards.

The different fracture behaviours of each are described. In particular, the interrelation between residual stresses and thermo-mechanical fatigue effects is highlighted. As materials are pushed towards their physical and chemical limits, the shorter the period that they can sustain the combined effects of thermal cycling, mechanical and thermal stresses and oxidation.

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64.2 Summary of material behaviour

64.2.1 Metal matrix composites

64.2.1.1 Particulate reinforced (MMCp)

This group consists mainly of aluminium matrix composites. The levels of particulate addition are normally in the range of 10 vol.% to 20 vol.% in order to retain the 'metallic characteristics' of ductility, fracture toughness and formability.

Features include:

- 10 vol.% to 20 vol.% particulate reinforcement
- Basically isotropic in macro composition and can be compared with conventional alloys, e.g. LEFM
- Initially elastic materials at low strains, then elastic-plastic to plastic, with limited ductility (4% to 8% maximum).
- Failure determined by particulate-to-matrix adhesion and matrix microstructure plus heat treatment.
- High particulate contents (>20%) show very poor fracture toughness

64.2.1.2 Fibre reinforced (MMCf)

Composites are mainly based on aluminium and titanium, although copper, nickel (superalloy) and magnesium variants have some space applications.

The fracture behaviour of continuous fibre MMCf materials is very different to those of MMCp and conventional alloys. They are highly anisotropic, with very low failure strains. In this respect they are more closely aligned to CFRP materials, but the matrix does display elastic-plastic characteristics as opposed to elastic. High processing temperatures result in high residual stresses within the composite.

Features include:

- 35 vol.% to 50 vol.% fibre reinforcement.
- No direct comparison with the fracture behaviour of conventional alloys can be made.
- Highly anisotropic, low strain to failure materials.
- Fully elastic to very low strains, then complex elastic-plastic behaviour.
- Failure characteristics closer to CFRP than alloys.
- Properties determined by in-situ fibre strength and modest transverse strengths between fibre and matrix.
- Both matrix microstructure and heat treatment are important.
- The presence of reinforcement can change the microstructure of the matrix and alter the matrix yield strength.
- Fibre to matrix adhesion is very important.

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64.2.2 Inorganic ceramic matrix composites

64.2.2.1 Fibre reinforced (ICMCf)

The group of materials includes:

- GMC,
- GCMC,
- CMC, and
- C-C.

These materials do not display the classic brittle, low strain-to-failure and catastrophic fracture behaviour of monolithic ceramics. Instead they rely on multiple crack stoppers at the fibre-matrix interfaces to avoid catastrophic failure. Such materials can function with high levels of microcracking in thermo-structural roles, i.e. where thermal shock resistance and modest strengths are required.

Features include:

- 30 vol.% to 50 vol.% fibre reinforcement.
- No direct comparison with monolithic ceramics can be made.
- Highly anisotropic with modest strength characteristics.
- Possess high temperature, insulative, thermal shock and thermo-cyclic capabilities.
- Benign fracture characteristics exhibited despite low overall strain to failure.
- Fibre to matrix interface is very important as poor bonding is essential and provides a de-coupling mechanism.

[See also: 64.4; 64.5]

64.3 Significant behavioural characteristics

64.3.1 General

In order to understand the behaviour of metal and ceramic composites, the significance of some of their basic characteristics has to be considered.

64.3.2 Modulus mismatch

In most composites, the matrix and reinforcement (particulate or fibre) have different moduli (E). Table 64.3.1 shows some representative examples.

When external load is applied, the stresses sustained by the matrix and reinforcement respectively are determined by the ratio of their moduli and their respective volume fractions.

The stress-strain response of composites is dependent on the combined contributions of the matrix and reinforcement. The 'Law of Mixtures' applies to the initial modulus of the composite provided that all the constituents behave elastically.

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With MMC and CMC materials, true linear elasticity exists only at very low strain levels. As the strain increases, one or more effects can occur:

- Plastic deformation of the matrix (MMC).
- Matrix failure, i.e. microcracking (CMC).
- Accumulation of microcracks with or without matrix-to-reinforcement interface failure (MMC and CMC).
- Particulate fracture and plastic flow of matrix (MMCp).
- Ultimate fibre failure (MMCf and CMC).

With CMC materials, accumulated matrix microcracking can give apparent non-linear and non-elastic behaviour, even though the constituent materials are themselves behaving elastically.

Table 64.3-1 - Modulus mismatch in composites: Examples

Composite						Mismatch ratio † *(Em-Vm/ Ef-Vf)*
Matrix type	*Em* (GPa)	*Vm* (%)	Reinforcement type	*Ef* (GPa)	*Vf* (%)	
Al	72	80	SiC_p	400	20	0.72
Al	72	60	C_f	240	40	0.45
Ti	110	60	SiC_f	390	40	0.42
SiC	400	60	SiC_f	193	40	3.1
Glass	75	60	SiC_f	193	40	0.58

Key † The lower the value, the greater the contribution by the reinforcement in sustaining stresses under elastic conditions.

Also, the lower the value, the greater the compressive stresses retained in the reinforcement on cooling. This, in turn, increases the residual stresses in the matrix when there is a CTE mismatch between reinforcement and matrix.

The SiC-SiC composite is unlike the others in having a matrix with a modulus significantly greater than the reinforcement.

64.3.3 Matrix-to-reinforcement interface

The effective strength of the interface bond between matrix and reinforcement is a critical factor in determining the overall composite fracture behaviour, Ref. [64-1].

Conflicting requirements exist between the need for 'good, strong' and 'poor, weak' bonding.

- Good bonding in theory enables the maximum strength of the reinforcement to be utilised. However, in MMC and CMC materials, good bonding is also synonymous with fibre surface degradation through chemical diffusion mechanisms with the matrix. This causes a loss in fibre strength.
- Poor bonding is essential in CMC materials to promote de-coupling between the fibre and matrix in order to achieve benign fracture behaviour, i.e. acceptable fracture toughness.

A compromise Should be sought to meet the specific features of each composite.

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64.3.4 In-situ fibre strength

All reinforcing fibres have attractive tensile strengths before being incorporated into composites (2000MPa to 7000MPa). In reality, it is extremely difficult to fully utilise this potential in MMC and CMC composites. The actual in-situ strength contribution made by the fibres is influenced by:

- Fibre to matrix adhesion (interface).
- Fibre degradation caused by:
  - composite manufacturing,
  - chemical diffusion, or
  - attack by aggressive environmental exposure, e.g. oxidation.

The fibre's in-situ tensile strength can be reduced to 20% to 70% of theoretical strength. This level can be even lower in poorly constituted composites (poor materials selection) or composites with severe environmental degradation, e.g. thermo-oxidative.

64.3.5 CTE mismatch

The coefficient of thermal expansion (CTE) for matrix and reinforcement are different. For a metallic matrix with a ceramic reinforcement the difference is considerable. The matrix usually has the higher expansion, as shown in Table 64.3.2.

Reinforcement fibres possess higher CTEs in the transverse than in the longitudinal direction.

The significance of the CTE mismatch centres on the residual stresses induced on cooling because the matrix is contracting more than the reinforcement. The matrix experiences retained tensile stresses whilst the reinforcement is under compression. Composites with significant mismatches between their constituents CTE and moduli are particularly susceptible to high residual tensile stresses in the matrix phase.

Table 64.3-2 - CTE mismatch in composites: Examples

Composite				CTE mismatch † *(CTEm-CTEr)*	Process temperature (°C)
Matrix type	*CTEm* (10^{-6}°C^{-1})	Reinforcement type	*CTEr* (10^{-6}°C^{-1})		
Al	23	SiC_p	5	18	650
Al	23	C_f	-1	24	650
Ti	9	SiC_f	3.5	5.5	900
C (PG)	2	C_f	-1	3	1100 - 2000
SiC	5	SiC_f	3.1	2.9	1200
Glass	8	SiC_f	3.1	4.9	800

Key † Ideally the CTE mismatch should be as small as possible.

Aluminium alloys have very high CTE values and combining them with carbon fibres creates a significant CTE mismatch. The residual tensile stresses in the aluminium on cooling are compounded by this and the low E_mV_m/ E_fV_f value, [See: Table 64.3.1].

Where CTE mismatch is smaller, e.g. SiC/SiC and C/C, this compensates for the large temperature range between processing to ambient.

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64.3.6 Thermal history and residual stresses

The thermal history of a composite is important in determining fracture behaviour, Ref. [64-1]. The processing or forming temperature establishes the level of residual stresses when cooled to ambient. Sub-ambient temperatures induce greater residual stresses. Exceeding the processing temperature of ceramic composites reverses the stressing to compression in the matrix and tension in the reinforcement.

With metals, the use of heat treatments can alter the matrix microstructure and alleviate residual stressing. Residual stresses can influence the creep behaviour of MMC materials. Excessive thermal shock, persistent thermal cycling and uneven heating are further mechanisms of relieving internal stresses through the formation of microcracking, matrix yielding and delaminations.

64.3.7 Multiple cracking

64.3.7.1 Fibre reinforced materials

The majority of MMC and CMC materials experience multiple cracking phenomena during progressive fracture in the unnotched condition. Matrix microcracks, ply cracking, voidage and delamination can reach high population densities with the composite still sustaining useful applied loads.

64.3.7.2 Particulate reinforced materials

Only particulate MMC materials show fracture behaviours close to the single crack mechanism of alloys conforming to the LEFM philosophy. Where notched specimens are used to characterise toughness, cracking becomes more localised at the point of maximum stress.

64.3.8 Thermo-mechanical fatigue (TMF)

For MMC and CMC materials, potential uses are applications experiencing both mechanical loading and thermal cycling.

As temperature excursions affect residual stresses within the composite, they can have a compounding effect when coupled with external mechanical loads, Ref. [64-2], [64-3], [64-4]. Material behaviour can be strongly influenced depending on whether thermal stresses and applied stresses are in-phase or out-of-phase with each other, [See: 47.9 for an example of TMF of titanium-matrix composites].

64.4 Basic fracture characteristics

64.4.1 General

An example from each group of composites demonstrates their basic fracture characteristics because they affect tensile stress-strain behaviour. The stress-strain curves are idealised representations and cannot be used for design data.

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64.4.2 Particulate reinforced MMC

Figure 64.4.1 represents the stress-strain behaviour of a particulate reinforced aluminium alloy, with 17 vol. % silicon carbide particles.

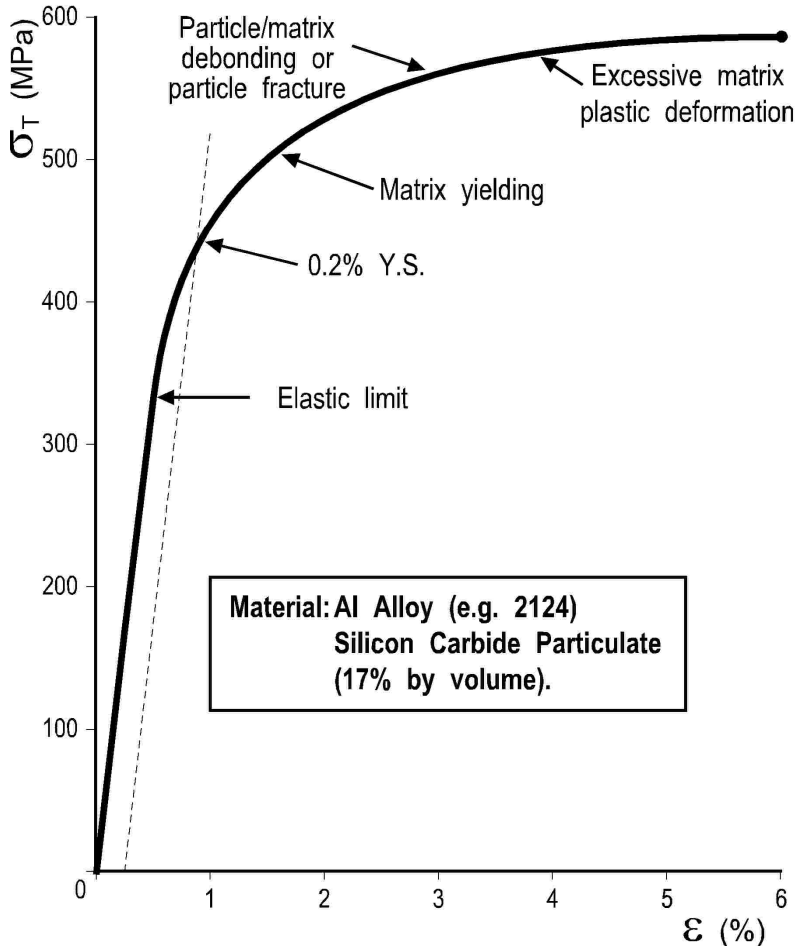


Figure 64.4-1 - Representative stress-strain curve: Particulate reinforced MMC

The material is elastic at very low strain levels with both matrix and particles elastically deforming in unison. Overall linear elasticity is only exhibited to strain levels as low as 0.2% to 0.4%, whereas an unreinforced alloy can be expected to be elastic to approximately 0.5%. Above the elastic limit, permanent deformation and plastic behaviour of some form is shown. The initial deformation process can be difficult to establish. As strain levels exceed 0.5%, a massive accumulation of deformation features makes the picture very confusing. However, important features are:

- The particles themselves have an individual strain to failure less than approximately 0.2%. It is therefore impossible for them to continue straining elastically beyond this level. Consequently they either fracture or debond from the matrix enabling the matrix to continue deforming.
- The matrix retains residual stresses due to CTE mismatch before any external load is applied. The matrix can therefore be expected to start yielding (plastically deforming) at lower overall applied strain, i.e. less than the 0.5% of unreinforced alloys. Matrix behaviour is dominant in MMCp materials.

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This behaviour is important when stating mechanical properties:

- Tensile modulus: quoted as the initial, secant or tangential value.
- Yield strength. For conventional alloys, the 0.2% offset yield value is used against the initial linear elastic portion of the stress-strain curve.

[See: Chapter 65 for further details of MMCp materials]

64.4.3 Fibre reinforced MMC

Figure 64.4.2 uses continuous silicon carbide monofilament reinforced titanium as the example to represent the MMCf group.

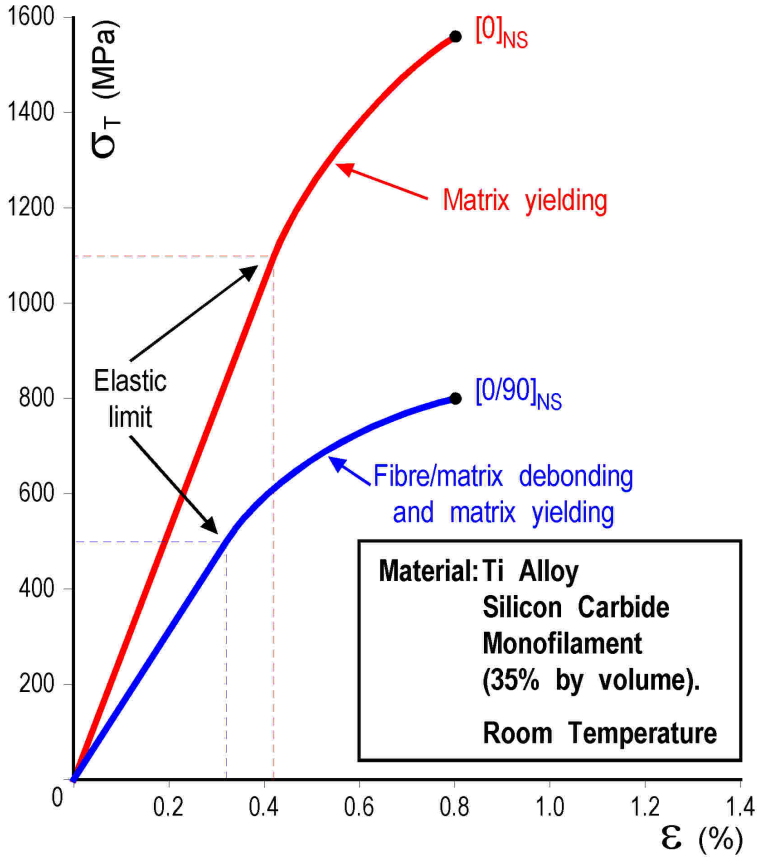


Figure 64.4-2 - Representative stress-strain curves: Monofilament reinforced MMC

The overall composite failure strains are low because they are fibre dominated. Both unidirectional and bi-directional materials exhibit initial linear elastic behaviour. The UD composite shows a gradual reduction in modulus as the overall failure point is approached. This modulus reduction can be explained by the onset of matrix yielding and low level individual fibre failure. The 0°/90° composite shows a reduction in modulus at a much lower strain level. It corresponds to transverse ply failure through debonding of the fibre-matrix interface. This equates to the first-ply failure (FPF) phenomenon seen in CFRP materials where the 90° plies fail first.

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For Ti/SiC materials, the FPF weakness is particularly sensitive to the residual matrix stresses and brittle nature of the fibre-matrix interface.

64.4.4 Fibre reinforced CMC

With ICMCf materials, the generic grouping covers brittle elastic matrices combined with brittle elastic fibres. The stress-strain curve in Figure 64.4.3 depicts a multidirectional SiC-SiC material. The composite modulus is therefore very high. If a glass or carbon matrix were used, an appreciably lower composite moduli results.

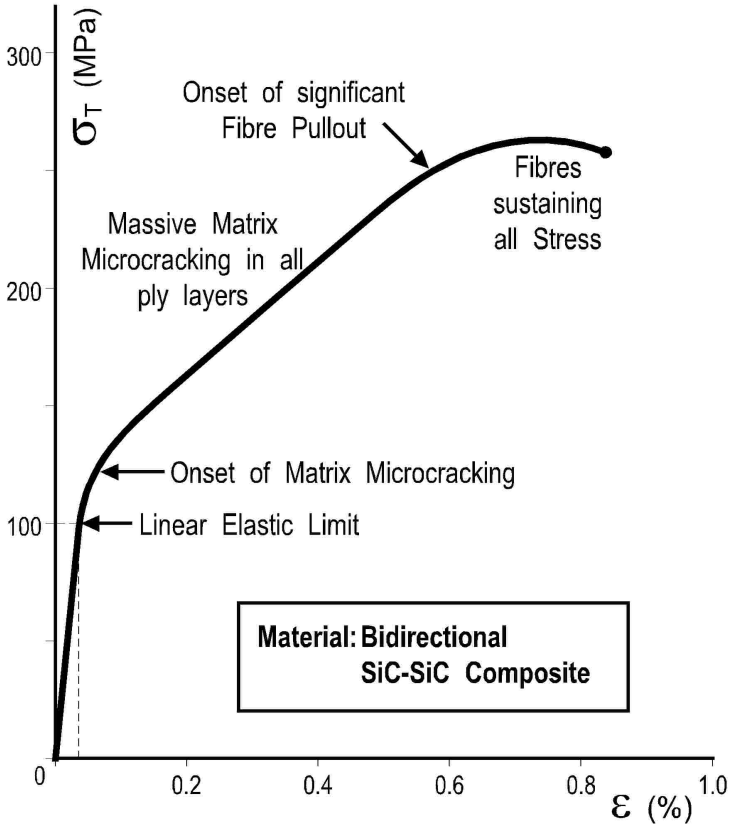


Figure 64.4-3 - Representative stress-strain curves: Bidirectional SiC-SiC composite

This group of composites are always used in with multidirectional (3D or *n*D) reinforcements because transverse tensile strengths are very low.

The composite tensile strength is very much dependent on the in-situ fibre strength and the ability to de-couple fibre and matrix. The truly linear elastic region of these composites is very small. The majority of the stress-strain curve depicts the accumulation of a massive microcracking population with the modulus contribution by the matrix diminishing as ultimate failure is approached.

64.4.5 Defining design values

64.4.5.1 General

With all the metal and ceramic matrix composites, the issue of defining design values for modulus, strength and permissible strain needs close examination.

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A compromise is applied between attainable modulus and strength demands. Stiffness realisation against strength retention is an important issue as significant overall stiffness loss can be experienced at higher stress levels. The loss of stiffness results from some form of permanent deformation or damage in the matrix phase.

64.4.5.2 Failure criteria

Compared with polymer-based composites, confidence in establishing and the use of failure criteria for metal- and ceramic-based composites is lower.

The problem arises because the MMCs and CMCs are not as widely-used in space structures as fibre-reinforced polymer composites. Consequently, the knowledge-base is much reduced and tends to be limited to a small number of organisations. The material applications usually have more hostile conditions than for fibre-reinforced plastics, e.g. hot structures made of CMCs. The materials themselves are complex and their overall characteristics are highly processing-dependent, Ref. [64-5].

Design guidelines have been established for the appropriate use of failure criteria during space structure design as part of an ESTEC-funded study on failure criteria for non-metallic materials, conducted in Germany by HPS and DLR, Ref. [64-7].

The ESTEC study covered FRP, [See: 11.8] and CMC, [See: 64.5].

64.5 Failure criteria for CMC

64.5.1 Introduction

As part of an ESTEC-funded study on failure criteria for non-metallic materials, conducted in Germany by HPS and DLR, design guidelines have been established for the appropriate use of failure criteria during the design phases of space structures, Ref. [64-5], [64-6], [64-7].

64.5.2 Design aspects

64.5.2.1 General

Design guidelines have been established based on structural configuration examples from the TETRA/X-38 nose cap design-development. This used C-C/SiC grades of CMC material developed by DLR, Ref. [64-7].

[See also: 70.24]

64.5.2.2 Materials

The C-C/SiC composite materials investigated are produced by DLR using the LSI (liquid silicon infiltration) process. Grades of material, with different characteristics, are produced by varying the fibre preconditioning and processing parameters. For TPS-type applications, the main grades are designated as XB or XT. A further grade of XT is used for mechanical fasteners (bolts), Ref. [64-7].

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64.5.2.3 Failure loads

Although some specifically-derived failure criteria for CMCs exist, the criteria applied to polymer composites are also used. Of these, either maximum stress or maximum strain tends to be the first choice. Classical criteria based on continium mechanics are not always appropriate for CMCs, Ref. [64-6].

Various failure criteria used for polymer composites were applied to CMC materials. Of these, some performed better than others, e.g. ZTL-hypothesis provides more realistic values than Tsai-Wu. Puck appears inappropriate for CMCs because of the difference in failure modes exhibited by CMCs compared with FRPs, Ref. [64-6]. An example of a comparative failure curve, with high-temperature experimental data is shown in Figure 64.5.1, Ref. [64-6].

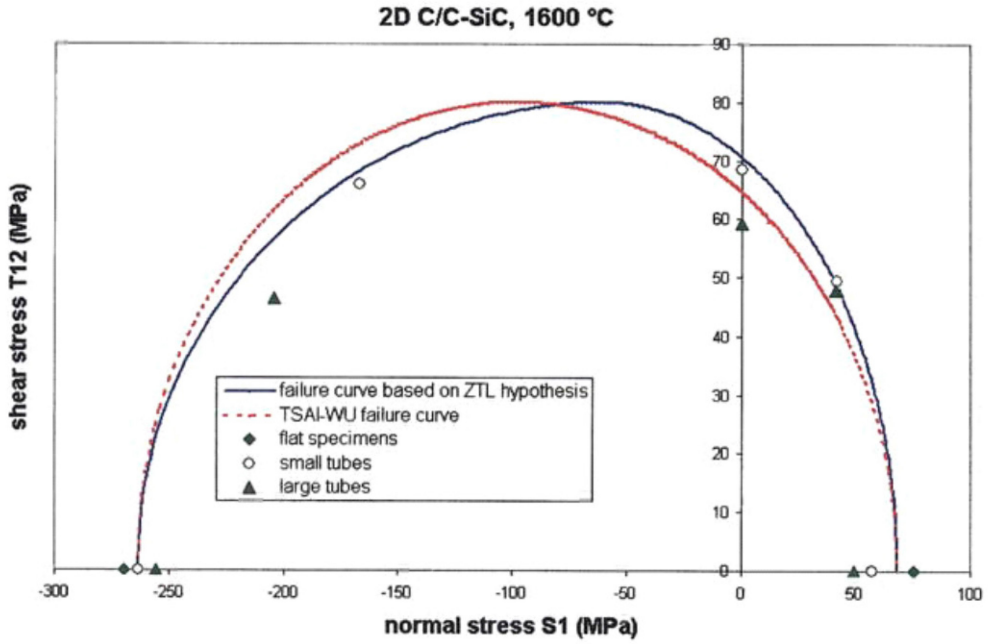


Figure 64.5-1 – Failure criteria: Comparison between predicted failure curves for C-C/SiC composites with experimental data

Since CMC material properties tend to improve with temperature, the use of RT-generated data can provide a conservative estimate of the performance of hot structures, Ref. [64-6].

Based on the evaluation of DLR's materials, a practical approach to estimate the failure loads appears to be the maximum stress criterion, which is similar to that used for monolithic ceramics. The significant difference is that the Weibull modulus is completely different. This means that designers need reliable strength values rather than the statistically-derived probability values used for monolithic ceramics, Ref. [64-6], [64-7].

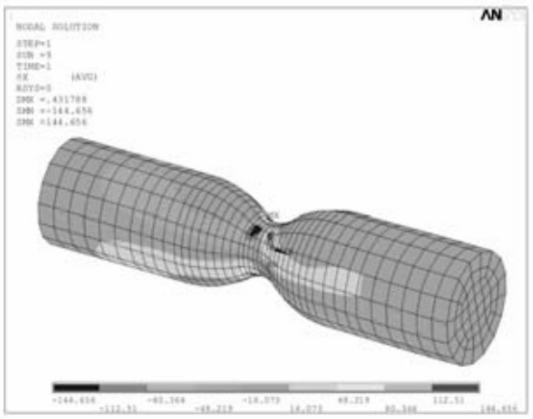
64.5.2.4 Test and analysis

A new test approach was developed and evaluated to confirm the assumption about failure load data, Ref. [64-6], [64-7].

The outcome of this phase of the work was an 'hour-glass' shaped test specimen, as shown in Figure 64.5.2, Ref. [64-6]. The results using this showed reasonable consistency with the maximum stress criterion and enabled combinations of tension and shear load interaction, such as the conditions

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found at load introduction points. Hence, it enables a full set of test data to be generated within the range (+σ1/+τ12), Ref. [64-6], [64-7].



FEM model of 'hour-glass' test specimen



Fractured 'hour-glass' test specimen in high-temperature test rig

Figure 64.5-2 – Failure criteria: 'Hour-glass' test specimen for C-C/SiC composites

64.5.2.5 Load introduction points

To meet the NASA stipulation of avoiding damage to the X-38 CMC shell, joint-related designs were studied in detail. This enabled a series of design guidelines to be established, Ref. [64-7]:

- Permanent joints:
  - castable, which is a combination of an adhesively bonded and potted connection, using a high-temperature ceramic-based compound; an approach used in the CETEX programme.
  - bolted joints, where the component parts of the mechanical fasteners were made of CMC.
- Non-permanent joints, i.e. ceramic rivet-type, which enable inspection, maintenance and repair of the TPS on RLVs.
- Elastic joints, e.g. CMC stand-off concept developed under the FESTIP programme. These connections retain some flexibility in order to cope with thermal mismatch between the CMC TPS and the proposed CFRP or Al-Li alloy cryotank structures.
- Kinematic joints, e.g. X-38 nose cap attachment, which needed to cope with thermal mismatch between the TPS and the aluminium alloy substructure, but which was not feasible using the FESTIP elastic joint (stand-off) configuration.

In the design of elastic and kinematic joints, the aim is to obtain a suitable compromise between the thermal expansion properties of the CMCs and the support structure, usually made from light alloy (flexibility), whilst retaining sufficient mechanical performance (stiffness) under mechanical loading.

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65
Particulate reinforced metals

65.1 Introduction

65.1.1 Materials

65.1.1.1 General

The most common materials are shown in Table 65.1.1.

Table 65.1-1 - Particulate reinforced MMCs

Matrix	Particulate	Sources
Al	SiC	A217 and A817 (BP Composites)
		Duralcan (Alcan)

[See: 46.13 for material properties]

65.1.1.2 Microstructure

The accepted microstructural features which can influence fracture behaviour are:

- In-situ matrix yield strength (for solution heat-treatable alloys with precipitation hardening mechanisms)
- Dispersion strengthening, e.g. ODS with particles sub-micron in size, 0.01μm to 0.1μm.
- Small particulates in the 2μm to 3μm range.
- Large particulates in the range 10μm to 20μm range.

65.1.2 Composites

65.1.2.1 Matrix

Matrix selection can affect the composite behaviour. Composites can be prepared that out-perform the base alloy, providing that some basic guidelines are followed.

The composite modulus, yield strength and UTS reflect that at least 80% by volume of the composite is matrix.

An aluminium matrix is likely to be a 2XXX, 7XXX series, aluminium-lithium, ODS, wrought or cast alloy, [See: Chapter 46]. Heat treatments and mechanical working are also influential.

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The matrix options are equally considerable for copper or magnesium.

[See: Chapter 45 for copper, Chapter 44 for magnesium].

The matrix metal or its alloying elements can react chemically with the particulate, e.g. aluminium reacts with SiC but not with Al_2O_3.

The microstructure and hence properties of an alloy in a selected heat-treated and mechanically worked condition can be disrupted by the presence of particulates acting as nucleating agents, Ref. [65-1].

65.1.3 Particulate reinforcement

65.1.3.1 Types

Types of particulate materials investigated include:

- Alumina (Al_2O_3), Ref.[65-2], [65-3],
- Silicon carbide (SiC), Ref.[65-4] to [65-10],
- Titanium diboride (TiB_2), and
- Boron carbide (B_4C).

SiC is the most widely used particulate reinforcement with aluminium, not least because good bonding can be achieved between matrix and particle by chemical interaction.

65.1.3.2 Size

The size of particulate reinforcement is important, Ref. [65-11]. Very small particles are the most efficient for achieving high strengths. This is reflected in oxide dispersion strengthened alloys, where oxide phases are 0.01µm to 0.1µm but their volumetric percentage is small. The deliberate addition of significant volumetric quantities of discrete particles has the effect of raising both modulus and strength. Again, smaller sizes are preferable given cost and other practical constraints. An evenly distributed dispersion is desirable for reproducible behaviour. Particulate sizes in the range 2µm to 3µm are preferable for high strengths, but expensive powder-metallurgy routes are used. Larger, 15µm+, particles are less efficient, giving lower strength, but are cheaper to incorporate using casting processes.

Some of the factors influencing particle-reinforced composite fracture behaviour are, Ref. [65-5], [65-6], [65-9], [65-10]:

- Aspect ratio,
- Size distribution, and
- Particle shape. Particles can be slightly:
  - elongated,
  - rounded,
  - angular,
  - faceted, and
  - pre-cracked.

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All particles are ceramic, which have high moduli but with low strain to failures of approximately 0.2%.

Particulate MMC materials always have an initial, low-strain tensile modulus which is higher than the base alloy. The strength characteristics, i.e. 0.2% YS, UTS, fracture toughness and ultimate elongation are not always as good because particles have been added.

It is possible to prepare 'good', 'indifferent' or even 'poor' composites from similar constituents. Only composites which are better in performance than their unreinforced counterparts are used where strength requirements prevail, because of the additional cost. If stiffness is the prime requirement, then MMCp materials can be attractive.

65.2 Damage mechanisms

65.2.1 Unnotched specimen

For particulate MMC, the overall fracture behaviour can be closely related to that of the unreinforced base alloy with some additional features. The base alloy undergoes elastic deformation to the elastic limit, after which irreversible plastic deformation accumulates. The plastic deformation is a result of dislocation growth and grain boundary slippage. Ultimately, the combined elastic and plastic deformation gives rise to excessive yielding, necking and failure. This broadly describes the behaviour of an unnotched alloy and is translated to the stress-strain curve in Figure 65.2.1.

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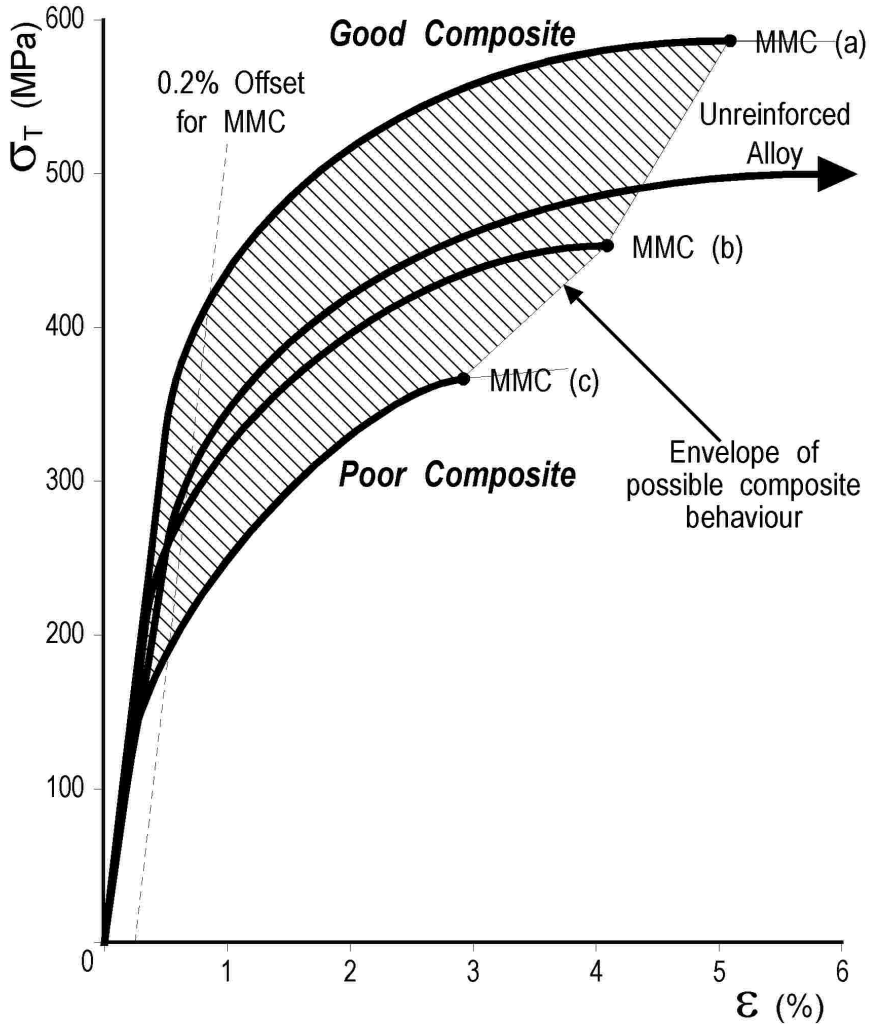


Figure 65.2-1 - Relative stress-strain behaviours of optimised (good) and non-optimised (poor) MMCp composites

65.2.2 Notched specimen

A single crack forms with the plastic deformation occurring ahead of the crack as it propagates until the critical size is reached. Whereupon the energy stored in the loaded specimen is sufficient to cause rapid crack growth and catastrophic failure.

65.2.3 Influence of particles

The inclusion of a large population of particles, whilst of small size, each influences the local 'matrix' volume. Their presence does not affect the gross mode of failure for loaded unnotched or notched material. This is ultimately a single propagating crack. However, the accumulated local events around each particle fashions the overall composite behaviour both before and after the elastic limit, Ref. [65-12].

The particles are there to provide reinforcement, i.e. sustain load that would otherwise be carried by the matrix. However, the strain capacity of the particles is much lower than that of the surrounding matrix. The matrix can deform to 5%, 10% or 20% extension, whilst the particle can only manage approximately 0.2%. A point is therefore reached at a very low strain when the two can no longer strain elastically together and relative movement between the two occurs. The ideal behaviour is for

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the adjacent matrix to remain adhering to the particle, whilst the remainder plastically deforms and ultimately begins to flow until the overall strains are in the 4% to 8% region. Whilst this is occurring, the particle is still performing a function because it is elastically deformed but its ultimate strength and strain to failure have not been reached. Something close to this can be achieved in optimised composites.

Other behaviour can also occur in varying degrees, which lowers the overall composite strength and strain to failure:

- Particles are over-stressed and fracture, Ref. [65-1]. The two parts no longer act in unison and have a gap between them which can grow as a crack in response to plastic deformation around it.
- The particle separates from the matrix through lack of adhesion. Again, an interface forms which can grow into a crack. The particle loses some of its ability to sustain elastic deformation and becomes less efficient as a reinforcing medium. In the worst case, the particle acts as a solid inclusion which is a hindrance rather than a benefit.

65.2.4 Composite performance

A 'performance envelope' exists [See: Figure 65.2.1], which describes that exhibited by a composite in comparison with the unreinforced alloy.

The top portion, designated 'Good', represents an optimised composite whilst the lower portion, occupied by MMC (b) and MMC (c), represent a composite that does not achieve the baseline performance of the unreinforced alloy.

The ‘Good’ position, MMC (a), is achieved by having:

- Good particle dispersion
- Good particle to matrix adhesion
- Optimum particle shape and size distribution
- Matrix microstructure and heat treatment optimised for the presence of particles in the composite.

The composite matrix microstructure or heat-treatment processes used can vary from those of an unreinforced alloy.

65.3 Failure modes and fracture behaviour

65.3.1 Matrix effects

65.3.1.1 General

MMCp composites cannot be viewed simply as an accepted alloy containing solid phases whose addition is aimed at achieving some form of reinforcement.

The presence of the particles alters the accepted microstructure of the isotropic alloy before any external load is applied. In effect, the accumulation of dislocations in the matrix is modified. The basic strengthening mechanisms prevailing in the composite are an accumulation of, Ref. [65-13]:

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- High dislocation densities in the matrix, due to dislocation generation as a result of differences in coefficient of thermal expansion.
- Small subgrain size, as a result of the generation of high dislocation density.
- Residual elastic stresses.
- Differences in texture.
- Dispersion strengthening in the matrix, by the formation of intermetallic particles that otherwise do not form in the unreinforced alloy.
- Classical composite strengthening, through load transfer to the particles.

As such the matrix cannot be viewed as truly isotropic. The macro-yielding of the composite is controlled by the inhomogeneous matrix which is a mixture of high and low dislocation regions. This accounts for the difficulties experienced in modelling MMCp materials beyond their initial, very low strain elasticity.

65.3.1.2 Duplex microstructures

Understanding MMCp behaviour is further complicated by deliberately produced duplex microstructures as a means of improving fracture toughness by:

- Larger particles which, provided they do not exceed an upper critical size, give resistance to unstable crack propagation.
- Finer particles, equivalent to dispersions of less than a lower critical size (no longer classified as particle additions), which provide matrix strengthening and crack initiation toughness.

65.3.2 Failure mode studies

For MMCp materials, differences are recognised between:

- straightforward macro-behaviour of simple tensile tests on unnotched specimens, and
- localised micro-behaviour more prevalent in single crack (notched) propagation studies which are defining fracture toughness.

Most studies attempt to explain composite behaviour by following the slow progression of a single crack and identifying deformation of fracture features in and around the crack tip.

65.3.3 Particulate shape and aspect ratio

No introduced particles are truly spheroid in shape nor elliptical as hypothesised by models, e.g. Eshelby. In reality they are of variable size distribution, usually angular and possess some aspect ratio exceeding unity.

- Aspect ratio >3: Alignment through mechanical working influences the directional properties.
- Aspect ratio >10: Implies that the reinforcement is a whisker or very short discontinuous fibre.

Figure 65.3.1 shows a schematic representation of the features found in MMCp materials.

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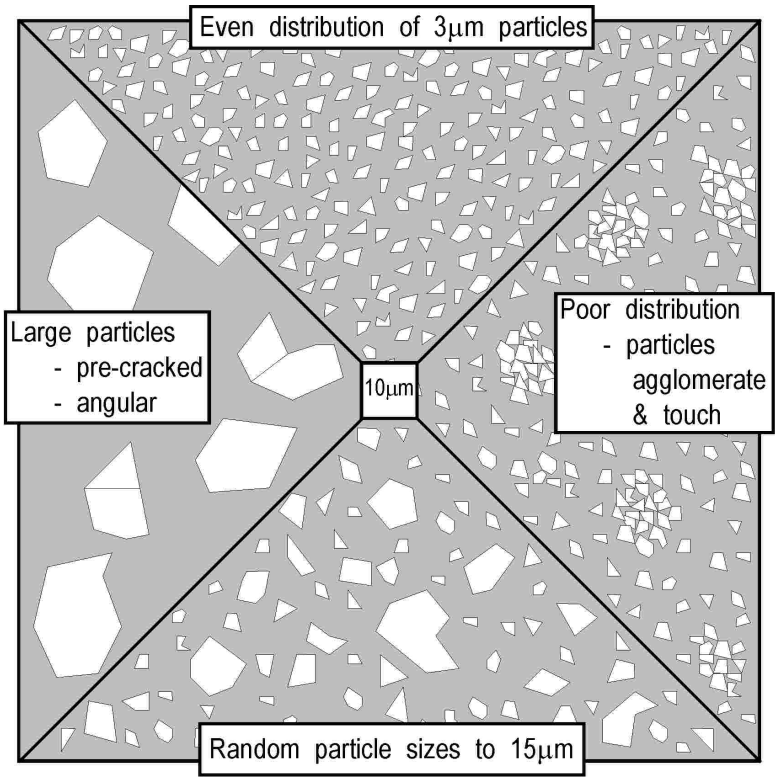


Figure 65.3-1 - Features of particles in MMCp materials

As a single crack propagates, the crack tip can follow a path which is influenced by the features around it, e.g.

- An even particulate distribution is essential for reproducible material behaviour and is an assumption for all models.
- Larger particles (>15μm) do not hinder crack progress in the same way as a population of smaller particles of the same volumetric contribution.
- The angularity of particles influences the presence of stress concentrations in the adjacent matrix. End-effects of sharp tips and whisker or fibre ends influence crack propagation depending on their orientation.

Figure 65.3.2 shows the effect of weak interfaces and cracked particles on crack propagation. The random fracture path is indicative of a good MMCp material where no apparent points of weakness have influenced the propagation of the crack.

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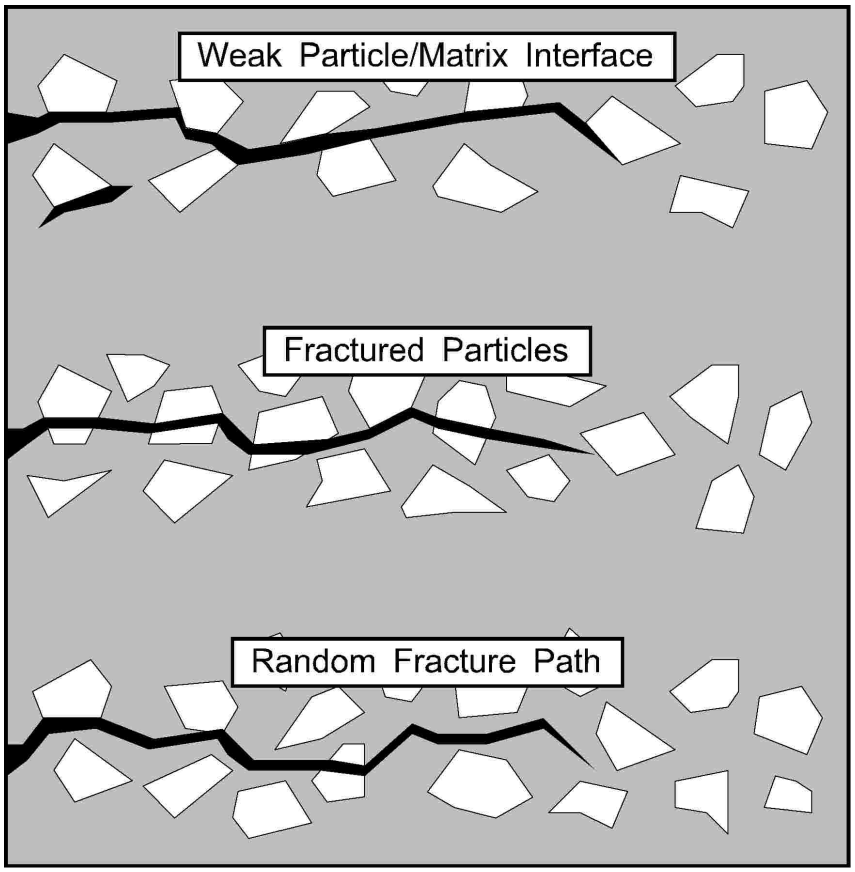


Figure 65.3-2 - Possible crack propagation paths in MMCp materials

65.3.4 Particulate fracture

A particle's fracture behaviour is influenced by:

- Shape, particularly if its surface is recessed.
- The inherent fracture toughness of the particle itself, where the particle can be weakened or cracked during mechanical working of the composite.

[See: Figure 65.3.2 for crack propagation through fractured particles]

65.3.5 Void nucleation and growth

When a single crack propagates, evidence suggests that the crack path is attracted towards particles adjacent to the fracture plane. The ductile fracture of the matrix is characterised by void nucleation and growth (VNG). The spacing between the void nucleating particles is generally considered to be a critical microstructural parameter that, taken together with the tensile properties, controls the toughness of a given composite.

The toughness of Al/SiC composites can be improved when the size of the SiC particles is increased, provided that at least one of the assumptions is met:

- Voids are nucleated by SiC particles.

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- The response of the Al/SiC system to the change in centre-to centre particle spacing remains the same regardless of whether this change is caused by varying the volume fraction or size of particles.

65.3.6 Fracture toughness

65.3.6.1 General

Toughness tests are governed by the principles of LEFM or elastic-plastic fracture mechanics (EPFM).

- LEFM: The plastic zone associated with the developing crack is restricted to a small region at the crack tip.
- EPFM: Gross yielding can occur across the whole of the uncracked portion of the specimen.

The implication being that initial crack growth comes under LEFM whereas EPFM is applicable when the crack has grown appreciably, Ref. [65-14].

65.3.6.2 Common terms

The testing of MMCp materials is complicated by the difficulties in obtaining stable crack growth. It is generally accepted that these composites have lower fracture toughness values than their unreinforced counterparts.

K_{IC}	Plane strain fracture toughness, a measure of a material's resistance to unstable crack extension when the stress state at the crack tip is plane strain and the opening mode (*I*) load is applied. The opening mode corresponds to a load applied perpendicular to the crack plane.
K_Q	A provisional value of K_{IC}, not confirmed until checks made on P_{max}/P_Q, thickness B, and ligament width W-a, are compared with validity criteria in standards.
K_R	Measure of resistance to stable crack growth.
R- curve	Continuous record of toughness, K_R, plotted against stable crack extension.
K_c	Plane stress fracture toughness. The value of K_c, is an instability condition determined by the tangent between the *R*-curve and the applied *K*-curve of the specimen.
G_c	Critical strain energy release rate : for plane stress $G_c = K_c^2/E$.

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