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THERMAL FATIGUE LIMITATIONS OF CONTINUOUS FIBER METAL MATRIX COMPOSITES

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Introduction

The potential structural benefits of unidirectional, continuous-fiber, metal matrix composites (MMCs) are legendary. When compared to their monolithic matrices, MMCs possess superior properties such as higher stiffness and tensile strength, and lower coefficient of thermal expansion in the direction of the reinforcing fibers. As an added bonus, the MMC density will be lower if the fibers are less dense than the matrix material they replace. The potential has been demonstrated unequivocally both analytically and experimentally, especially at ambient temperatures. Successes prompted heavily-funded National efforts within the United States (USAF and NASA) and elsewhere to extend the promise of MMCs into the temperature regime wherein creep, stress relaxation, oxidation, and thermal fatigue damage mechanisms lurk. This is the very regime for which alternative high-temperature materials are becoming mandatory, since further enhancement of state-of-the-art monolithic alloys is rapidly approaching a point of diminishing returns.

Unfortunately, MMCs offer but limited improvement in creep, relaxation, and oxidization resistance, since these resistances are governed largely by the matrix material *per se*, and the matrix is still very much in evidence in the MMC. More seriously, however, MMCs are at a distinct disadvantage over their monolithic matrix counterpart when it comes to resisting damage induced by repeated thermal cycling between ambient temperature and maximum service operating temperatures. As will be shown, thermal cycling is the Achilles' heel of MMCs owing to the large internal thermal stresses and strains that develop in the constituent matrix and fibers because of their significant mismatch in thermal expansion α . The mismatch is an inherent one provided a mismatch in matrix/fiber moduli of elasticity is one of the desired characteristics of an MMC. This is to be expected from the Grüneisen equation (see, for example, ref. 1) that inversely relates α to bulk modulus of elasticity K ,

$$\alpha = (\gamma C_v / 3KV) \quad (1)$$

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where γ is Grüneisen's constant that is related directly to the sum of the two powers in the equations for the attractive- and repulsive-energy versus atomic spacing equations, C_v is the specific heat, and V is the molar volume. Bulk and Young's moduli E are linearly related. Figure 1 depicts Eq. (1) for three major classes of materials; organic, metallic, and ceramic (ref. 2). The more disparate are the values of the modulus between fiber and matrix, the greater the thermal expansion mismatch and hence the greater will be the thermal stresses and strains for a given thermal excursion.

The current analytic research examines the thermal stresses and strains in unit cubes of MMCs induced by exposure of one face to a heat flux, Q , and the opposite face to a fixed temperature heat sink. Faces parallel to the x -direction heat flux were assumed insulated to make the analyses more tractable. A comprehensive range of fiber/matrix MMC architectures and relative orientations to the heat flux Q have been analyzed. The objective, Fig. 2, is to determine which architectures, if any, are the least susceptible to thermal stresses and strains, and hence which offer the greatest potential resistance to thermal fatigue cracking.

Material, Properties, Composite Cubes

A continuous fiber (silicon carbide, SCS6, 33% by vol.) reinforced titanium matrix (Ti-15-3) composite was analyzed. Pertinent time-independent, temperature-dependent material properties of the constituent materials are given in Fig. 3. Figure 4 lists discrete ply properties vs. temperature, computed from METCAN (ref. 3). The composite cubes consist of symmetric 12 ply lay ups with each ply having the dimensions 0.262 x 0.262 x 0.022 cm (0.665 x 0.665 x 0.0559 in). Several laminated architectures were selected to represent the extreme combinations of plies relative to the x -direction of heat flux, Fig. 5. One of the 12 cubes represents the stand-alone matrix material (Case 0). Four distinct laminate lay-ups (labelled I, II, III, and IV) are positioned in three orientations (A, B, and C) relative to a heat flux in the x -direction. Case IA is equivalent to Case IC, so Case IA is dropped and Case 0 is shown in its place. The Case indexing scheme follows a progression to a thinner center laminate and thicker laminate faces, Fig. 6

Thermal Loading, and Structural Finite Element Analyses

Elementary cubes were thermally loaded (Fig. 5) with temperature rising from 21°C (70°F) to a maximum on the heated face while the opposite face was maintained at 21°C (70°F). Side faces were insulated. Maximum temperatures for the stand-alone matrix and composite cubes were determined by assuming both to be subjected to the same heat flux. For the arbitrarily prescribed maximum temperature of 800°C (1471°F) for the stand-alone matrix, thermal conductivity calculations based on a constant heat flux resulted in a maximum temperature of 910°C (1670°F) for the composite cubes owing to their lower thermal conductivity. Both continuum (Unit Cube with 1728 elements, 2197 nodes) and micromechanical (Unit Cell with 3072 elements, 3689 nodes) elastic finite element structural analyses were performed using MARC (ref. 4) with 8-noded, solid hexagonal elements, Fig. 7. The micromechanical model is a sub-element of the continuum. Parallel faces in both models were forced to remain parallel during thermal loading. The elastic analyses enables generalization of results to other ranges of thermal cycling. Sensitivity studies (varying α and E by factors of 2) permit extrapolation of results to other MMC systems.

Results

Stand-alone matrix results (Case 0) are shown in Figs. 8 and 9. The maximum thermal stress range (428 Mpa (62 ksi)) and mechanical strain range (0.48 %) are in the transverse (y and z) directions. The effects of increasing or decreasing α and E by factors of two are as expected and are also displayed. Figure 10 displays the maximum continuum stress range (and corresponding orthogonal stress ranges) found in each of the 11 composite Cases. The location of the maximum stress ranges are shown by the big X in fig. 5. In every composite Case, there is a transverse stress that is greater than the maximum stress in Case 0. The maximum ranges are always at the cube face whose temperature cycled between the maximum and the minimum. The most benign case (I-B) has a stress 25% higher than that found in Case 0. Unfortunately, the direction perpendicular to a fiber is the weakest possible direction in any composite. Combining the highest thermal stresses with the weakest directions will invariably give rise to much poorer thermal fatigue resistance than the stand-alone matrix, thereby negating any potential structural benefit of the composite for thermally-loaded components. The extent of the poorer performance, while not experimentally evaluated herein, is indicated by the following observations of others. Tensile strengths of [90] composites are less than the tensile strength of stand-alone matrix material, and isothermal fatigue strengths of [90] composites can be as low as 10% of [0] fatigue strengths (ref. 5). Furthermore, thermal fatigue resistances of composites are expected to be even less than their isothermal fatigue resistance (ref. 6). To better understand why this can be so, it is necessary to examine the thermal stresses and strains inside the composite using a micromechanical structural analysis (Fig. 7). Figure 11 shows the mechanical component of the cyclic thermal strain range developed within the matrix material for each of the 11 composite Cases. Comparable maximum strain ranges are also shown for Case 0 for comparison. In every Case, every strain range in every direction is higher than the maximum strain range in the stand-alone matrix material by 35 to 110%. Furthermore, the maximum strain ranges are always in a direction transverse to the local fiber direction. A summary of results, conclusions, and future research efforts are presented in Figs. 12-14.

References

1. Richards, C. W.: *Engineering Mats. Science.*, Wadsworth, San Francisco, 1961, p. 518.
2. Halford, G. R.: Obstacles to High Temperature Cyclic Structural Durability of Continuous-Fiber Composites. *Computational Mechanics '95, Theory & Application*, S.N.Atluri, G.Yagawa, and T.A.Cruse, Eds., Springer-Verlag, 1995, pp. 1128-1133.
3. Lee, H.-J.; Gotsis, P. K.; Murthy, P. L. N. ; and Hopkins, D. A.: Metal Matrix Composite Analyzer (METCAN), *User's Manual - Version 4.0*, NASA TM-105244, 1991.
4. Anon., *MARC General Purpose Finite Element Program*. Vols. A-D, MARC Analysis Research Corp., Palo Alto, CA, 1992.
5. Hashin, Z. And Rotem, A.: A Fatigue Failure Criterion for Fiber Reinforced Materials. *Journal of. Composite. Materials.*, Vol. 7, 1973, pp 448-464.
6. Halford, G. R.; Lerch, B. A.; and Saltsman, J. F.: Proposed Framework for Thermomechanical Fatigue Life Modeling of Metal Matrix Composites. NASA TP-3320, July 1993.

INVERSE CORRELATION

Stiffness (E) versus Thermal Expansion (α)

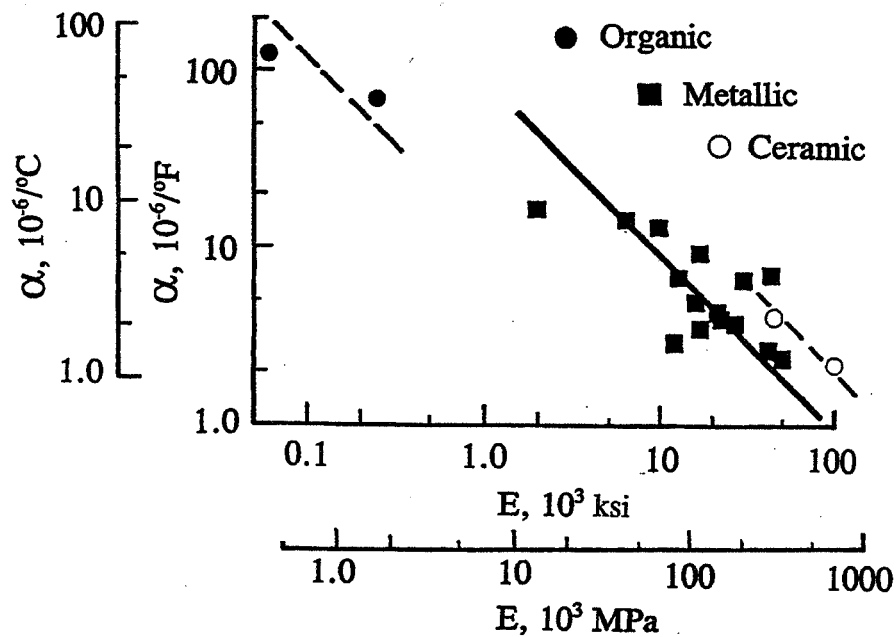


Fig. 1

OBJECTIVE

TO DETERMINE:

Which composite ply architectures suffer the lowest thermal stresses and strains and hence offer the greatest potential resistance to thermal fatigue cracking.

Fig. 2

MECHANICAL PROPERTIES OF CONSTITUENTS

Temp	°C	20.0	130.0	240.0	350.0	460.0	570.0	680.0	790.0	900.0
	°F	70.0	270.0	470.0	670.0	870.0	1070.0	1270.0	1470.0	1670.0
Fiber	E	8.98	8.88	8.79	8.68	8.58	8.47	8.36	8.23	8.11
	ν	0.1898	0.1878	0.1857	0.1835	0.1813	0.1790	0.1766	0.1741	0.1715
	α	0.1512	0.1546	0.1579	0.1616	0.1655	0.1695	0.1739	0.1786	0.1836
Matrix	E	1.78	1.67	1.56	1.44	1.30	1.15	0.98	0.78	0.48
	ν	0.3196	0.3005	0.2802	0.2582	0.2342	0.2075	0.1768	0.1395	0.0875
	α	0.2503	0.2609	0.2733	0.2811	0.3063	0.3298	0.3622	0.4160	0.5278
Units E in 10 ⁶ MPa (1MPa = 0.145 KSI); α in (10 ⁻⁵ °C ⁻¹ or 5.56 x 10 ⁻⁷ °F)										

E: Young's modulus

ν : Poisson's ratio

α : Coefficient of thermal expansion

Fig. 3

EFFECTIVE ORTHOTROPIC PROPERTIES OF THE COMPOSITE

T E M P	C	20.0	130.0	240.0	350.0	460.0	570.0	680.0	790.0	900.0
	F	70.0	270.0	470.0	670.0	870.0	1070.0	1270.0	1470.0	1670.0
E ₁₁		2.6600	2.5200	2.3600	2.2200	2.0200	1.8100	1.5700	1.2600	0.8200
E ₂₂		4.1600	4.0600	3.9500	3.8300	3.7100	3.5700	3.4200	3.2400	3.0000
ν_{12}		0.1768	0.1634	0.1492	0.1342	0.1180	0.1004	0.0810	0.0588	0.0313
ν_{23}		0.2768	0.2633	0.2490	0.2336	0.2167	0.1981	0.1767	0.1509	0.1152
ν_{31}		0.3038	0.2874	0.2697	0.2504	0.2290	0.2049	0.1768	0.1417	0.0911
G ₁₂		1.0210	0.9670	0.9080	0.8450	0.7440	0.6940	0.6000	0.4820	0.3110
G ₂₃		1.0210	0.9670	0.9080	0.8450	0.7440	0.6940	0.6000	0.4820	0.3110
G ₃₁		1.0180	0.9770	0.9310	0.8800	0.8200	0.7510	0.6600	0.5520	0.3740
α_{11}		0.2096	0.2170	0.2254	0.2352	0.2471	0.2620	0.2820	0.3128	0.3786
α_{22}		0.1797	0.1829	0.1864	0.1899	0.1936	0.1974	0.2009	0.2039	0.2034
Units E and G in 10 ⁶ MPa (1 MPa = 0.145 KSI) and α in (10 ⁻⁵ °C ⁻¹ or 5.56 x 10 ⁻⁷ °F)										

E₂₂ = E₃₃

α_{22} = α_{33}

G: Shear Modulus

Fig. 4

COMPOSITE ARCHITECTURES

Heat Flux in x-direction

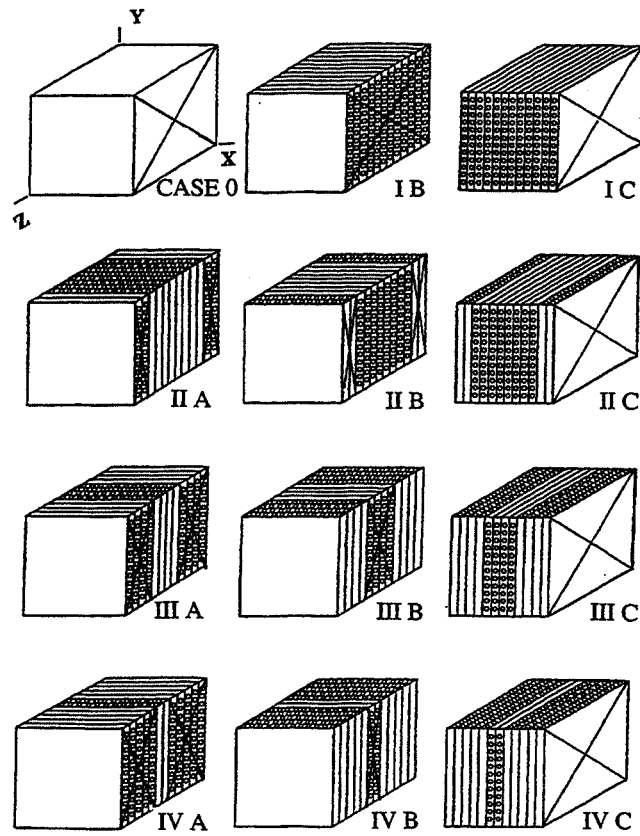


Fig. 5

INDEXING SCHEME FOR COMPOSITE CUBES

I	Center 12 ply laminate between faces of a 0 ply laminate at 90°
II	Center 8 ply laminate between faces of a 2 ply laminate at 90°
III	Center 4 ply laminate between faces of a 4 ply laminate at 90°
IV	Center 2 ply laminate between faces of a 5 ply laminate at 90°
Orientation A	Heat flux perpendicular to fibers in center laminate and parallel to fibers in face laminates
Orientation B	Heat flux perpendicular to fibers in face laminates and parallel to fibers in center laminate
Orientation C	Heat flux perpendicular to fibers in both center and face laminates

Fig. 6

FINITE ELEMENT MODELS

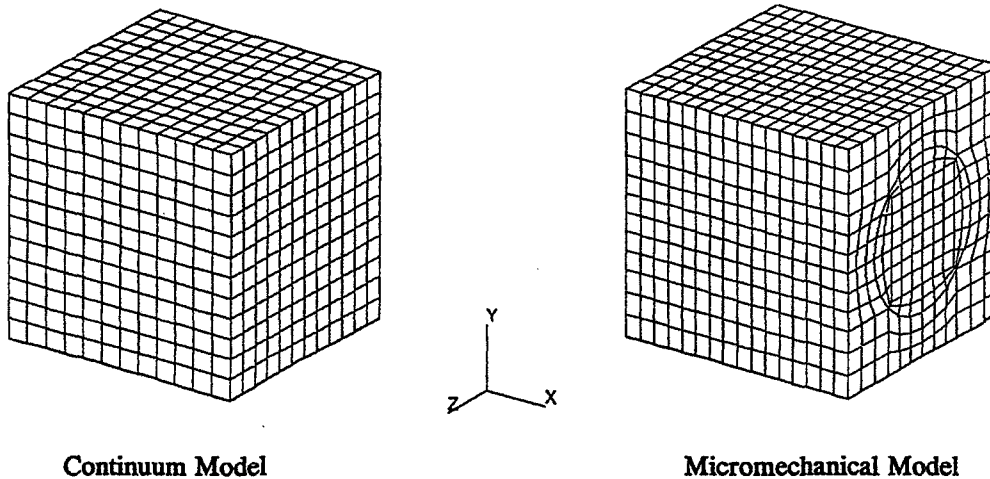


Fig. 7

Stress Ranges in Stand-Alone Matrix Cube (Case 0)

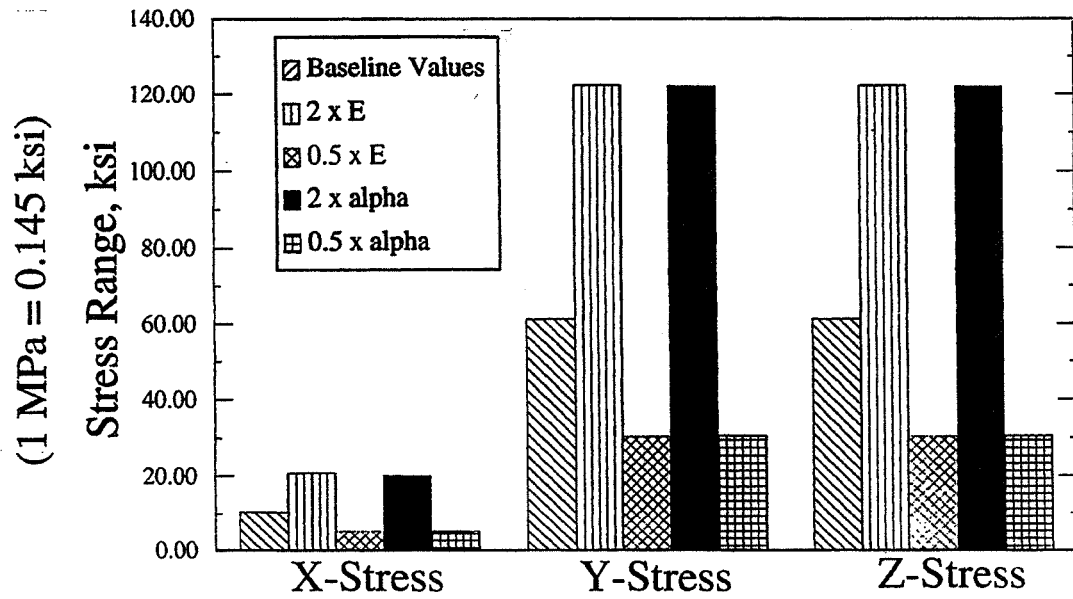


Fig. 8

Mechanical Strain Ranges in the Matrix Cube (Case 0)

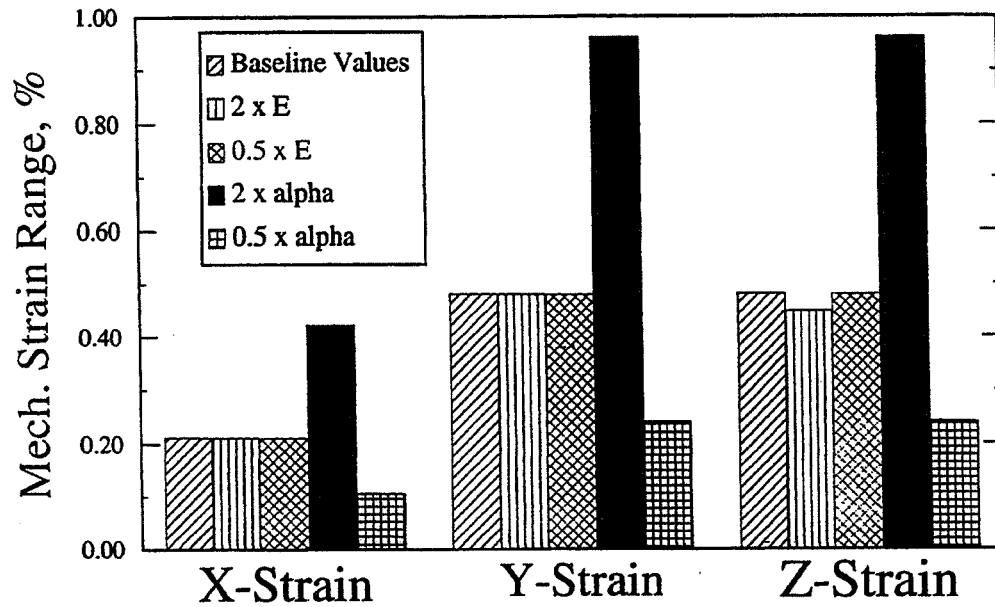


Fig. 9

Stress Ranges in Composite Cubes

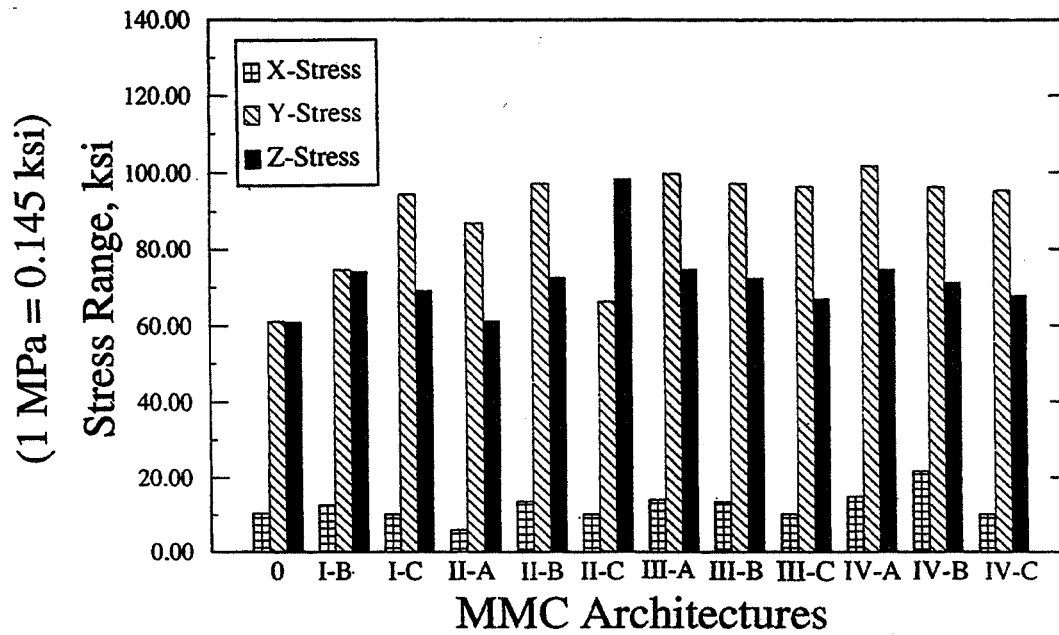


Fig. 10

Mechanical Strain Ranges in Unit Cell

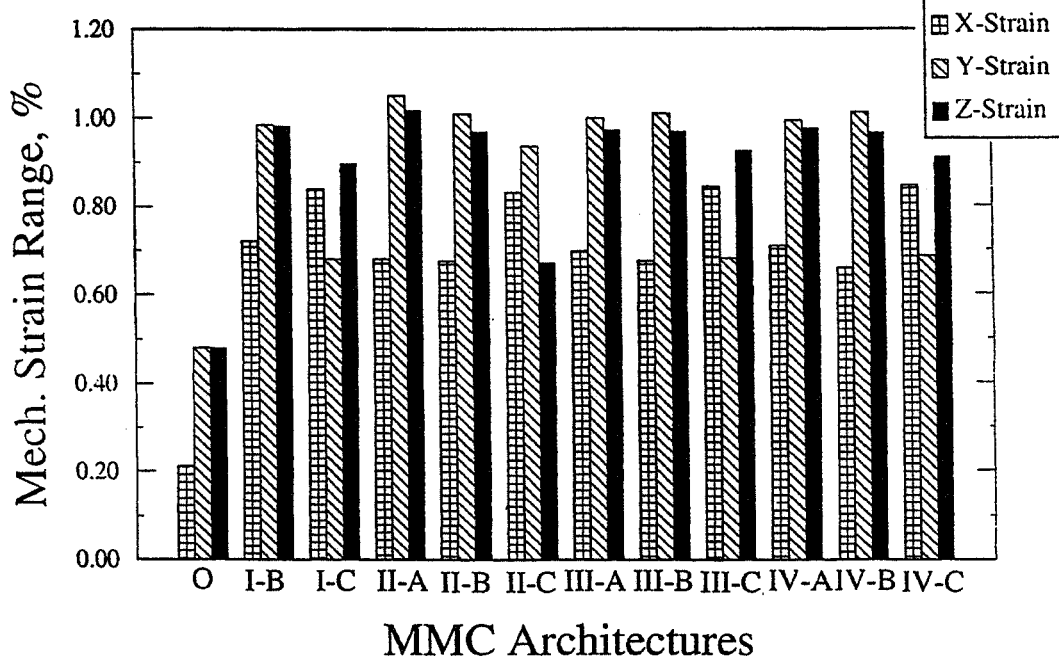


Fig. 11

SUMMARY OF RESULTS

- 0 Unit Cubes of SCS6/Ti-15-3 MMC subjected to analytic thermal gradients
- 0 Thermal stresses and strains calculated w/continuum-based, linear-elastic FEA
- 0 Inclusive range of symmetric MMC architectures analyzed
- 0 Stand-alone matrix Cubes analyzed for comparison + X2 sensitivity studies for E and α

Fig. 12a

SUMMARY OF RESULTS (Concluded)

- 0 Continuum thermal stresses in MMCs compared to stand-alone matrix material
- 0 Max. continuum composite thermal stresses always greater than for stand-alone material
- 0 Micromechanics Unit Cell analyses at critical locations in MMC Cubes reveal ranges of thermal strain transverse to fiber much greater (35 to 118% higher) than max. ranges of strain in stand-alone matrix material
- 0 Generally recognized, direction transverse to fibers is weakest

Fig. 12b

CONCLUSIONS

- 0 Thermally induced ranges of stress and mechanical strain in MMC matrix significantly greater than in stand-alone matrix material
- 0 Most benign MMC architecture is Case I-C (all plies & fibers perpendicular to heat flux)
Yet, max. mechanical range of strain is 88% higher than in stand-alone matrix
- 0 Case II-A least benign w/range of strain 118% higher than in stand-alone matrix material
- 0 High thermally-induced ranges of strain in the weakest possible direction
- 0 Thermal fatigue resistance of continuous-fiber reinforced MMCs severely compromised

Fig. 13

FOCUS OF FUTURE RESEARCH

There are no formal plans for future research on this subject matter.

Fig. 14