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METCAN Simulation of Candidate Metal Matrix Composites for High Temperature Applications

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SUMMARY

The METCAN (Metal Matrix Composite Analyzer) computer code is used to simulate the nonlinear behavior of select metal matrix composites in order to assess their potential for high temperature structural applications. Material properties for seven composites are generated at a fiber volume ratio of 0.33 for two bonding conditions (a perfect bond and a weak interphase case) at various temperatures. A comparison of the two bonding conditions studied shows a general reduction in value of all properties (except CTE) for the weak interphase case from the perfect bond case. However, in the weak interphase case, the residual stresses that develop are considerably less than those that form in the perfect bond case. Results of the computational simulation indicate that among the metal matrix composites examined, SiC/NiAl is the best candidate for high temperature applications at the given fiber volume ratio.

INTRODUCTION

High temperature metal matrix composites (HTMMC) offer great potential for use in advanced aerospace structural applications. The realization of this goal however, requires concurrent developments in (1) a technology base for fabricating HTMMC structural components, (2) experimental techniques for measuring thermal and mechanical characteristics, and (3) computational methods to predict their behavior. In the development of HTMMC's, it proves beneficial to initially simulate their behavior through computational methods. Besides providing an initial assessment of the HTMMC, this method helps to minimize the costly and time consuming experimental effort that would otherwise be required.

E-5813

Recent research into computational methods for simulating the nonlinear behavior of high temperature metal matrix composites at NASA Lewis Research Center (refs. 1 and 2) has led to the development of the METCAN (Metal Matrix Composite Analyzer) computer code. METCAN treats material nonlinearity at the constituent (fiber, matrix, and interphase) level, where the behavior of the material is modeled using a time-temperature-stress dependence of a constituent's properties in a "material behavior space." The composite properties are synthesized from the constituent instantaneous properties by virtue of composite micromechanics, macromechanics and laminate theory. Factors which affect the behavior of these composite properties include the fabrication process variables, in situ fiber and matrix properties, bonding between the fiber and matrix, and/or the properties of an interphase between the fiber and the matrix. A unique aspect of the METCAN code is an integrated cyclic arrangement which defines the computational effort for each load increment as shown in figure 1. Another feature is the use of the multifactor interaction relationship to represent the various nonlinearities and their interactions in the constituents. Figure 2 illustrates the multifactor interaction relationship and the reasons for its selection. More detailed information about METCAN can be found in references 3 to 5.

This paper presents the results of METCAN simulated properties of seven metal matrix composites in order to assess their potential for application to high temperature structures. Properties for each composite are generated at various temperatures in order to assess the temperature range of each composite and to demonstrate the versatility of the computational simulation capability in METCAN.

METCAN SIMULATION

A total of seven composites were examined for two bonding conditions for a fiber volume ratio of 0.33:

(1) A perfect bond between the fiber and matrix, so that an interphase does not develop.

(2) A weak interphase to model the fiber-matrix reaction.

Six of the seven composites were produced by taking various combinations of three fibers (Al_2O_3, TiB_2, and SiC) and two matrices (Lockalloy and NiAl). The last composite (SiC/Ti-15) is also included as a reference for comparison purposes. The constituent material properties used in METCAN for these simulations are listed in table I.

Assumptions Made in Running METCAN

Due to the lack of experimental data for the constituents and composites examined, some assumptions were made in the study. These are:

(1) Default values for exponents are used in the multifactor interaction relationship. These values were established from studies conducted on other composite systems.

(2) The consolidation temperature of the composite is initially taken as 100 °F less than the matrix melting temperature, as long as no failure occurs at room temperature due to residual stresses. If failure does occur, a progressively lower consolidation temperature is chosen which does not cause failure.

(3) For the purposes of this study, the possible chemical compatability of the various fiber and matrix combinations was not addressed.

Perfect Bond

In the perfect bond case, it is assumed that appropriate barriers exist to prevent interaction between the constituent (fiber and matrix) materials so that an interphase does not develop and there is no matrix degradation during the fabrication process. METCAN simulated composite properties for the seven composites are listed in tables II to VIII.

Some trends worth noting:

(1) An increase in longitudinal and transverse moduli with increasing temperature for the Lockalloy composites.

(2) A lack of transverse strength degradation with increasing temperature for the Lockalloy composites.

(3) "Jumps" in longitudinal and transverse moduli between 70 to 1200 °F for all of the NiAl composites except SiC/NiAl.

An explanation of the unexpected trends noted above involves residual stresses. Residual stresses result from the alpha mismatch which exists between the fiber and the matrix, and the difference between the consolidation and use temperature. The residual stresses for the perfect bond case are listed in tables IX to XI. For the perfect bond case, there is a high matrix residual stress buildup at room temperature from the consolidation process. The matrix residual stresses for the three Lockalloy composites are approximately 50 ksi. Among the three NiAl composites, Al_2O_3/NiAl has the highest matrix residual stress of around 40 ksi, while both SiC/NiAl and TiB_2/NiAl have values closer to 30 ksi. The lowest matrix residual stress exists for SiC/Ti-15, which has slightly less than 20 ksi.

Usually, the degradation of modulus and strength of a composite with increasing temperature is to be expected as in the case of SiC/Ti-15 (figs. 3 and 4). However, as the residual stresses increase, the relief of residual stresses with higher temperatures dominates the degradation in modulus and strength. Thus for two of the NiAl composites (Al_2O_3/NiAl and TiB_2/NiAl), "jumps" in the value of moduli occur as the residual stresses become higher (figs. 5 and 6). As the residual stresses become even greater in the Lockalloy composites, the moduli actually increase with higher temperatures (figs. 7 to 9). The transverse strengths of the Lockalloy composites also show no degradation effect with higher temperature, even increasing in some cases (fig. 10), which is again a result of the high matrix residual stresses.

Weak Interphase

In the weak interphase case, an interphase is allowed to develop as a result of fiber-matrix reaction. This interphase is modelled in METCAN as a separate constituent with independent properties. The interphase used in this case has a thickness of 2 percent of the fiber diameter. Moduli and strengths are taken as 25 percent of the respective matrix values. All other properties are assumed to be equal to their corresponding matrix values. METCAN results for the weak interphase case are presented in tables XII to XVIII, while residual stresses for this case can be found in tables XIX to XXI.

For the three Lockalloy composites, increasing temperatures have little affect on the longitudinal strengths (tables XII to XIV). Examination of METCAN simulations reveals longitudinal failure in the matrix during the consolidation process. A corresponding physical mechanism for this behavior may be the formation of longitudinal cracks in the matrix during the consolidation process. The longitudinal failure of the matrix indicates that the composite is unable to carry a longitudinal load. Thus the longitudinal strengths shown in tables XII to XIV correspond to METCAN generated values of the fiber bundle-strength, with the assumption that the matrix retains enough strength to help transfer load to the fiber.

Comparisons of the Perfect Bond and Weak Interphase Cases

The composites studied show a general reduction in value of all properties (except CTE) for the weak interphase case from the perfect bond case. This is a result of the matrix degradation which is allowed to occur in the weak interphase case, but not in the perfect bond case.

The increases and "jumps" in value of moduli and strengths for the perfect bond case mentioned previously do not occur for the weak interphase case. The reason for this behavior lies in the interphase. Addition of a weak interphase helps to relieve some of the residual stresses during the consolidation process. Values of matrix residual stresses for all composites fall between 10 to 20 ksi after the addition of a weak interphase. Thus, for the weak interphase case, the relief of residual stresses with increasing temperatures does not dominate as it does for certain composites in the perfect bond case. Figures 11 to 13 show the degradation of modulus and strength with increasing temperature typical of all the weak interphase composites.

RESULTS AND DISCUSSION

The two interfacial cases simulated provide two extreme conditions between which the actual properties of the composite will most likely fall. Examination of the three Lockalloy matrix composites shows the range of consolidation temperatures to be between 750 to 950 °F. This is considerably lower than the 1700 °F consolidation temperature of SiC/Ti-15 and may restrict the high temperature applications of the Lockalloy matrix composites. Other factors working against these composites is the high matrix residual stress buildup for the perfect bond case and the longitudinal failure in the matrix during the consolidation process for the weak interphase case.

The three NiAl matrix composites appear to have greater potential. For these composites, the consolidation temperatures are either close to or greatly exceed that of SiC/Ti-15. One problem of the TiB_2/NiAl composite in the presence of a weak interphase is its low transverse tensile strength. This precludes any possibility of its use at higher temperatures under transverse mechanical loads. However, if the interphase formation is somehow prevented, then this problem may not occur. This problem does not exist for the other two NiAl matrix composites. SiC/NiAl possesses a higher consolidation temperature and a generally higher strength than Al_2O_3/NiAl, giving it more flexibility for high temperature applications. This indicates that SiC/NiAl is the best candidate composite among those examined.

A comparison of SiC/NiAl with SiC/Ti-15 shows that the SiC/Ti-15 composite is much stronger than SiC/NiAl. However, SiC/NiAl can operate at higher temperature, by virtue of its higher consolidation temperature.

CONCLUSION

The computational simulation of the select properties for the different composites examined in this study demonstrates the use of METCAN to routinely assess the potential use of metal matrix composites in high temperature structures. Thus it provides valuable information in regards to the selection of those candidate composites which will meet the necessary requirements for the specified high temperature applications. In doing so, the high cost of manufacturing these new materials as well as experimental testing are minimized. From the present analysis of the seven composites, it can be concluded that for the fiber volume ratio studied the SiC/NiAl composite is the most desirable candidate for high temperature applications.

APPENDIX - SYMBOLS AND NOTATION

E	Young's modulus
fvr	fiber volume ratio
G	shear modulus
S	strength
T_c	consolidation temperature
T_m	melting temperature
α	coefficient of thermal expansion
ν	Poisson's ratio
ρ	weight density
Subscript 11	direction along the fiber
Subscript 22	direction transverse to the fiber

REFERENCES

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4. Murthy, P.L.N.; Hopkins, D.A.; and Chamis, C.C.: Metal Matrix Composite Micromechanics: In-Situ Behavior Influence on Composite Properties. NASA TM-102302, 1989.

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TABLE I. - CONSTITUENT (FIBER/MATRIX) MATERIAL PROPERTIES USED IN METCAN

Property	Fiber properties			Matrix properties		
	TiB_2	Al_2O_3	SiC	Lockalloy	NiAl	Ti-15
ρ (lb/in.^{3})	0.163	0.144	0.110	0.076	0.210	0.172
T_m (°F)	5432	3650	4870	1193	2980	1800
E_{11} (Msi)	53	55	62	27	32	12
E_{22} (Msi)	53	55	62	27	32	12
G_{12} (Msi)	22	23	24	11.8	12.3	4.7
ν_{12}	0.20	0.20	0.30	0.14	0.30	0.32
α_{11} (ppm/°F)	4.33	5.28	2.72	10.2	2.6	4.5
α_{22} (ppm/°F)	4.33	5.28	2.72	10.2	2.6	4.5
S_{11} (ksi)	250	261	500	54	42	130
S_{22} (ksi)	250	261	500	54	42	130
S_{12} (ksi)	150	157	300	32	25	78

TABLE II. - COMPOSITE (Al_2O_3/LOCKALLOY) PROPERTIES: fvr = 0.33, T_c = 950 °F FOR A PERFECT BOND

Property	70 °F	400 °F	800 °F
ρ (lb/in.^{3})	0.098	0.098	0.098
E_{11} (Msi)	18.7	21.7	22.9
E_{22} (Msi)	15.1	16.1	19.0
G_{12} (Msi)	14.1	12.1	9.1
ν_{12}	0.157	0.139	0.114
α_{11} (ppm/°F)	7.2	8.6	11.3
α_{22} (ppm/°F)	8.0	9.6	12.8
S_{11} (ksi)	120	110	95
S_{22} (ksi)	34	28	28
S_{12} (ksi)	35	29	21

TABLE III. - COMPOSITE (SiC/LOCKALLOY) PROPERTIES: fvr = 0.33, T_c = 750 °F FOR A PERFECT BOND

Property	70 °F	400 °F	700 °F
ρ (lb/in.^{3})	0.087	0.087	0.087
E_{11} (Msi)	21.3	22.2	26.2
E_{22} (Msi)	13.0	20.8	23.7
G_{12} (Msi)	14.3	12.2	10.1
ν_{12}	0.190	0.171	0.154
α_{11} (ppm/°F)	5.8	7.7	9.8
α_{22} (ppm/°F)	6.2	8.0	10.0
S_{11} (ksi)	192	184	176
S_{22} (ksi)	31	31	40
S_{12} (ksi)	35	29	19

TABLE IV. - COMPOSITE (TiB_2/LOCKALLOY) PROPERTIES: fvr = 0.33, T_c = 875 °F FOR A PERFECT BOND

Property	70 °F	400 °F	800 °F
ρ (lb/in.^{3})	0.105	0.105	0.105
E_{11} (Msi)	18.1	19.3	24.3
E_{22} (Msi)	14.6	19.2	20.5
G_{12} (Msi)	14.0	12.0	9.1
ν_{12}	0.157	0.139	0.116
α_{11} (ppm/°F)	6.6	8.2	11.1
α_{22} (ppm/°F)	7.6	9.1	12.3
S_{11} (ksi)	115	106	96
S_{22} (ksi)	34	29	34
S_{12} (ksi)	35	29	21

TABLE V. - COMPOSITE (Al_2O_3/NiAl) PROPERTIES: fvr = 0.33, T_c = 1600 °F FOR A PERFECT BOND

Property	70 °F	1200 °F	1500 °F
ρ (lb/in.^{3})	0.188	0.188	0.188
E_{11} (Msi)	29.9	31.3	29.4
E_{22} (Msi)	16.5	26.1	26.0
G_{12} (Msi)	14.5	11.6	10.7
ν_{12}	0.261	0.250	0.248
α_{11} (ppm/°F)	3.9	4.6	4.9
α_{22} (ppm/°F)	3.8	4.3	4.6
S_{11} (ksi)	110	97	92
S_{22} (ksi)	74	42	35
S_{12} (ksi)	28	21	20

TABLE VI. - COMPOSITE (SiC/NiAl) PROPERTIES: fvr = 0.33, T_c = 2800 °F FOR A PERFECT BOND

Property	70 °F	1200 °F	1500 °F	1800 °F	2100 °F	2500 °F
ρ (lb/in.^{3})	0.177	0.177	0.177	0.177	0.177	0.177
E_{11} (Msi)	33.0	29.4	28.5	27.4	26.2	23.9
E_{22} (Msi)	28.1	23.5	22.5	22.3	19.9	16.9
G_{12} (Msi)	14.7	11.8	10.9	9.9	8.8	6.8
ν_{12}	0.294	0.282	0.280	0.278	0.276	0.272
α_{11} (ppm/°F)	2.7	3.2	3.4	3.7	4.0	4.9
α_{22} (ppm/°F)	2.7	3.3	3.5	3.8	4.3	5.5
S_{11} (ksi)	187	172	164	156	152	140
S_{22} (ksi)	32	23	21	18	15	15
S_{12} (ksi)	28	21	20	17	14	11

TABLE VII. - COMPOSITE (TiB_2/NiAl) PROPERTIES: fvr = 0.33, T_c = 2300 °F FOR A PERFECT BOND

Property	70 °F	1200 °F	1500 °F	1800 °F	2100 °F
ρ (lb/in.^{3})	0.195	0.195	0.195	0.195	0.195
E_{11} (Msi)	33.3	31.7	29.8	27.9	25.8
E_{22} (Msi)	25.2	26.9	25.9	24.1	21.6
G_{12} (Msi)	14.4	11.6	10.8	9.8	8.7
ν_{12}	0.261	0.252	0.251	0.250	0.248
α_{11} (ppm/°F)	3.4	4.0	4.3	4.6	5.0
α_{12} (ppm/°F)	3.3	3.9	4.1	4.5	5.0
S_{11} (ksi)	106	96	92	88	84
S_{22} (ksi)	64	42	36	31	28
S_{12} (ksi)	28	21	20	17	14

TABLE VIII. - COMPOSITE (SiC/Ti-15) PROPERTIES: fvr = 0.33, T_c = 1700 °F FOR A PERFECT BOND

Property	70 °F	1200 °F	1500 °F
ρ (lb/in.^{3})	0.152	0.152	0.152
E_{11} (Msi)	27.6	23.1	21.3
E_{22} (Msi)	16.8	10.7	7.9
G_{12} (Msi)	6.8	4.1	3.0
ν_{12}	0.307	0.211	0.174
α_{11} (ppm/°F)	3.6	4.1	4.3
α_{12} (ppm/°F)	3.9	4.5	4.9
S_{11} (ksi)	235	192	173
S_{22} (ksi)	138	60	42
S_{12} (ksi)	66	39	27

TABLE IX. - RESIDUAL STRESSES OF THE LOCKALLOY MATRIX COMPOSITES FOR A PERFECT BOND

(a) Al_2O_3/Lockalloy

	70 °F	400 °F	800 °F
Fiber stress (ksi)	-36.7	-27.5	-7.1
Matrix stress (ksi)	49.6	37.2	9.6

(b) SiC/Lockalloy

	70 °F	400 °F	700 °F
Fiber stress (ksi)	-38.2	-23.7	-3.3
Matrix stress (ksi)	51.6	32.0	4.4

(c) TiB_2/Lockalloy

	70 °F	400 °F	800 °F
Fiber stress (ksi)	-37.1	-26.2	-2.2
Matrix stress (ksi)	50.1	35.4	3.0

TABLE X. - RESIDUAL STRESSES OF THE NiAl MATRIX COMPOSITES FOR A PERFECT BOND

(a) Al_2O_3/NiAl

	70 °F	1200 °F	1500 °F
Fiber stress (ksi)	29.1	9.3	3.4
Matrix stress (ksi)	-39.2	-12.5	-4.6

(b) SiC/NiAl

	70 °F	1200 °F	1500 °F	1800 °F	2100 °F	2500 °F
Fiber stress (ksi)	-18.9	-16.8	-15.3	-13.1	-10.1	-4.1
Matrix stress (ksi)	25.5	22.7	20.6	17.7	13.6	5.6

(c) TiB_2/NiAl

	70 °F	1200 °F	1500 °F	1800 °F	2100 °F
Fiber stress (ksi)	21.3	7.4	4.7	2.9	2.3
Matrix stress (ksi)	-28.7	-10.0	-6.4	-4.0	-3.2

TABLE XI. - RESIDUAL STRESSES OF THE SiC/Ti-15 COMPOSITE FOR A PERFECT BOND

(a) SiC/Ti-15

	70 °F	1200 °F	1500 °F
Fiber stress (ksi)	-14.2	-3.4	-1.1
Matrix stress (ksi)	19.2	4.6	1.5

TABLE XII. - COMPOSITE (Al_2O_3/LOCKALLOY) PROPERTIES: fvr = 0.33, T_c = 950 °F FOR A WEAK INTERPHASE

Property	70 °F	400 °F	800 °F
ρ (lb/in.^{3})	0.096	0.096	0.096
E_{11} (Msi)	16.0	15.6	15.1
E_{22} (Msi)	9.9	7.8	5.4
G_{12} (Msi)	13.1	11.1	8.3
ν_{12}	0.153	0.134	0.110
α_{11} (ppm/°F)	5.3	5.4	5.6
α_{12} (ppm/°F)	10.4	12.7	18.0
S_{11} (ksi)	[a]105	[a]105	[a]100
S_{22} (ksi)	22	20	12
S_{12} (ksi)	32	24	16

[a]Corresponds to the fiber bundle strength.

TABLE XIII. - COMPOSITE (SiC/LOCKALLOY)

PROPERTIES: fvr = 0.33, T_c = 750 °F

FOR A WEAK INTERPHASE

Property	70 °F	400 °F	700 °F
ρ (lb/in.^{3})	0.085	0.085	0.085
E_{11} (Msi)	18.5	18.1	17.8
E_{22} (Msi)	9.4	7.6	5.9
G_{12} (Msi)	13.2	11.2	9.2
ν_{12}	0.183	0.164	0.147
α_{11} (ppm/°F)	2.7	2.8	2.8
α_{12} (ppm/°F)	10.4	12.7	16.1
S_{11} (ksi)	[a]176	[a]176	[a]176
S_{22} (ksi)	24	19	16
S_{12} (ksi)	32	24	18

[a]Corresponds to the fiber bundle strength.

TABLE XIV. - COMPOSITE (TiB_2/LOCKALLOY)

PROPERTIES: fvr = 0.33, T_c = 875 °F

FOR A WEAK INTERPHASE

Property	70 °F	400 °F	800 °F
ρ (lb/in.^{3})	0.103	0.103	0.103
E_{11} (Msi)	14.8	14.6	14.3
E_{22} (Msi)	9.4	7.5	5.2
G_{12} (Msi)	13.0	11.0	8.2
ν_{12}	0.153	0.135	0.111
α_{11} (ppm/°F)	4.3	4.4	4.5
α_{12} (ppm/°F)	10.4	12.7	18.0
S_{11} (ksi)	[a]105	[a]105	[a]100
S_{22} (ksi)	21	19	13
S_{12} (ksi)	32	24	16

[a]Corresponds to the fiber bundle strength.

TABLE XV. - COMPOSITE (Al_2O_3/NiAl) PROPERTIES:
fvr = 0.33, T_c = 1600 °F FOR A WEAK INTERPHASE

Property	70 °F	1200 °F	1500 °F
ρ (lb/in.^{3})	0.183	0.183	0.183
E_{11} (Msi)	34.4	29.6	27.8
E_{22} (Msi)	9.9	8.7	8.2
G_{12} (Msi)	13.5	10.7	9.8
ν_{12}	0.257	0.245	0.243
α_{11} (ppm/°F)	4.3	4.7	5.0
α_{12} (ppm/°F)	2.6	3.5	3.8
S_{11} (ksi)	101	87	83
S_{22} (ksi)	11	6	5
S_{12} (ksi)	26	18	14

TABLE XVI. - COMPOSITE (SiC/NiAl) PROPERTIES: fvr = 0.33, T_c = 2800 °F FOR A WEAK INTERPHASE

Property	70 °F	1200 °F	1500 °F	1800 °F	2100 °F	2500 °F
ρ (lb/in.^{3})	0.171	0.171	0.171	0.171	0.171	0.171
E_{11} (Msi)	27.9	26.7	26.1	25.4	24.6	22.9
E_{22} (Msi)	10.9	8.6	8.0	7.2	6.4	4.9
G_{12} (Msi)	13.6	10.8	10.0	9.1	8.0	6.1
ν_{12}	0.288	0.275	0.273	0.270	0.267	0.263
α_{11} (ppm/°F)	2.7	3.1	3.0	3.1	3.7	4.3
α_{12} (ppm/°F)	2.6	3.5	3.8	4.3	4.9	6.7
S_{11} (ksi)	172	156	148	148	140	133
S_{22} (ksi)	29	13	11	10	8	5
S_{12} (ksi)	26	18	14	13	11	8

TABLE XVII. - COMPOSITE (TiB_2/NiAl) PROPERTIES: fvr = 0.33, T_c = 2300 °F FOR A WEAK INTERPHASE

Property	70 °F	1200 °F	1500 °F	1800 °F	2100 °F
ρ (lb/in.^{3})	0.189	0.189	0.189	0.189	0.189
E_{11} (Msi)	33.1	30.0	28.2	26.2	24.3
E_{22} (Msi)	10.9	8.8	8.1	7.3	6.3
G_{12} (Msi)	13.4	10.7	9.9	9.0	7.9
ν_{12}	0.257	0.247	0.245	0.244	0.242
α_{11} (ppm/°F)	3.5	4.1	4.3	4.6	4.9
α_{12} (ppm/°F)	2.6	3.5	3.8	4.3	4.9
S_{11} (ksi)	97	88	84	84	79
S_{22} (ksi)	8	(a)	(a)	(a)	(a)
S_{12} (ksi)	26	18	14	13	11

[a]Composite fails immediately upon application of a load after heat-up.

TABLE XVIII. - COMPOSITE (SiC/Ti-15) PROPERTIES: fvr = 0.33, T_c = 1700 °F FOR A WEAK INTERPHASE

Property	70 °F	1200 °F	1500 °F
ρ (lb/in.^{3})	0.147	0.147	0.147
E_{11} (Msi)	25.8	21.5	19.9
E_{22} (Msi)	13.3	8.4	6.1
G_{12} (Msi)	6.0	3.6	2.6
ν_{12}	0.301	0.205	0.168
α_{11} (ppm/°F)	3.2	3.5	3.5
α_{12} (ppm/°F)	4.1	4.8	5.3
S_{11} (ksi)	216	176	167
S_{22} (ksi)	28	12	8
S_{12} (ksi)	66	36	24

TABLE XIX. - RESIDUAL STRESSES OF THE LOCKALLOY MATRIX COMPOSITES FOR A WEAK INTERPHASE

(a) Al_2O_3/Lockalloy

	70 •F	400 •F	800 •F
Fiber stress (ksi)	-7.4	-9.9	-11.4
Matrix stress (ksi)	11.3	14.5	16.4

(b) SiC/Lockalloy

	70 •F	400 •F	700 •F
Fiber stress (ksi)	-11.3	-12.1	-12.3
Matrix stress (ksi)	16.5	17.5	17.8

(c) TiB_2/Lockalloy

	70 •F	400 •F	800 •F
Fiber stress (ksi)	-11.0	-12.8	-13.7
Matrix stress (ksi)	16.0	18.3	19.5

TABLE XX. - RESIDUAL STRESSES OF THE NiAl MATRIX COMPOSITES FOR A WEAK INTERPHASE

(a) Al_2O_3/NiAl

	70 •F	1200 •F	1500 •F
Fiber stress (ksi)	15.9	8.8	7.5
Matrix stress (ksi)	-19.0	-9.8	-8.1

(b) SiC/NiAl

	70 •F	1200 •F	1500 •F	1800 •F	2100 •F	2500 •F
Fiber stress (ksi)	-10.3	-8.5	-7.6	-6.6	-5.3	-2.9
Matrix stress (ksi)	14.1	11.8	10.7	9.3	7.6	4.5

(c) TiB_2/NiAl

	70 •F	1200 •F	1500 •F	1800 •F	2100 •F
Fiber stress (ksi)	11.4	8.1	7.7	7.5	7.7
Matrix stress (ksi)	-13.3	-9.0	-8.5	-8.3	-8.5

TABLE XXI. - RESIDUAL STRESSES OF THE SiC/Ti-15 COMPOSITE FOR A WEAK INTERPHASE

(a) SiC/Ti-15

	70 •F	1200 •F	1500 •F
Fiber stress (ksi)	-11.6	-3.1	-1.4
Matrix stress (ksi)	16.9	3.9	1.3

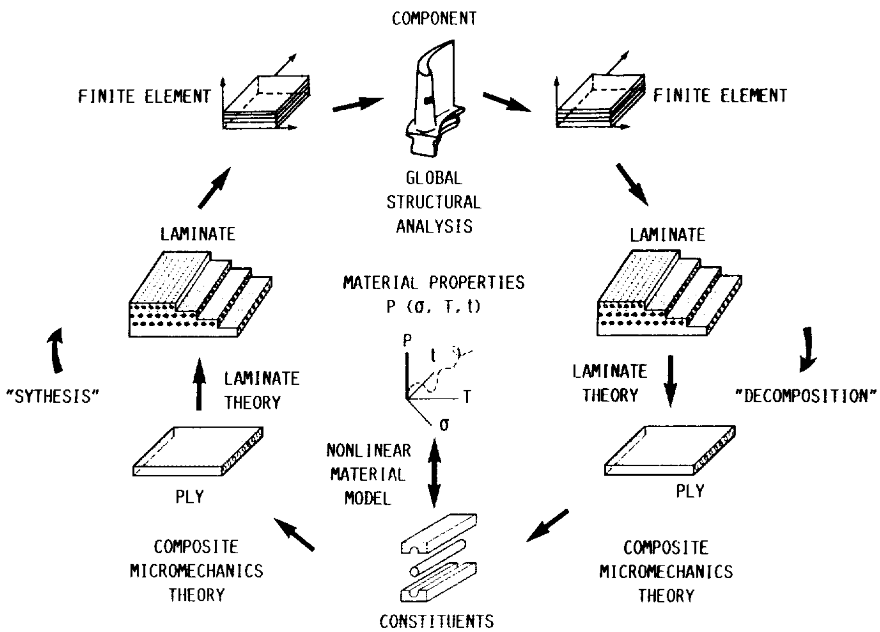
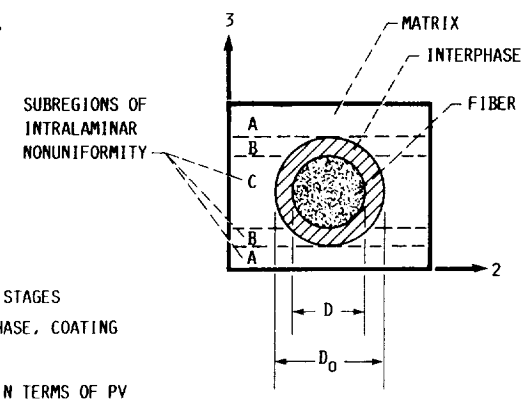


FIGURE 1. - INTEGRATED APPROACH TO METAL-MATRIX COMPOSITE ANALYSIS.

$$\frac{P}{P_0} = \left[\frac{T_F - T}{T_F - T_0}\right]^n \left[\frac{S_F - \sigma}{S_F - \sigma_0}\right]^m \left[\frac{\dot{S}_F - \dot{\sigma}_0}{\dot{S}_F - \dot{\sigma}}\right]^{\ell} \left[\frac{\dot{T}_F - \dot{T}}{\dot{T}_F - \dot{T}_0}\right]^k \left[\frac{R_F - R}{R_F - R_0}\right]^p \cdots$$

$$\cdots \left[\frac{N_{MF} - N_M}{N_{MF} - N_{MO}}\right]^q \left[\frac{N_{TF} - N_T}{N_{TF} - N_{TO}}\right]^r \left[\frac{t_F - t}{t_F - t_0}\right]^s \cdots$$



RATIONALE:

- GRADUAL EFFECTS DURING MOST RANGE, RAPIDILY DEGRADING NEAR FINAL STAGES
- REPRESENTATIVE OF THE IN SITU BEHAVIOR FOR FIBER, MATRIX, INTERPHASE, COATING
- INTRODUCTION OF PRIMITIVE VARIABLES (PV)
- CONSISTENT IN SITU REPRESENTATION OF ALL CONSTITUENT PROPERTIES IN TERMS OF PV
- ROOM TEMPERATURE VALUES FOR REFERENCE PROPERTIES
- CONTINUOUS INTERPHASE GROWTH
- SIMULTANEOUS INTERACTION OF ALL PRIMITIVE VARIABLES
- ADAPTABILITY TO NEW MATERIALS
- AMENABLE TO VERIFICATION INCLUSIVE OF ALL PROPERTIES
- READILY ADAPTABLE TO INCREMENTAL COMPUTATIONAL SIMULATION

NOTATIONS:

P - PROPERTY; T - TEMPERATURE; S - STRENGTH; R - METALLURGICAL REACTION; N - NUMBER OF CYCLES; t - TIME;

OVER DOT - RATE; SUBSCRIPTS; 0 - REFERENCE; F - FINAL; M - MECHANICAL: T - THERMAL

FIGURE 2. - ASSUMED MULTIFACTOR INTERACTION RELATIONSHIP TO REPRESENT THE VARIOUS FACTORS WHICH INFLUENCE IN SITU CONSTITUENT MATERIALS BEHAVIOR.

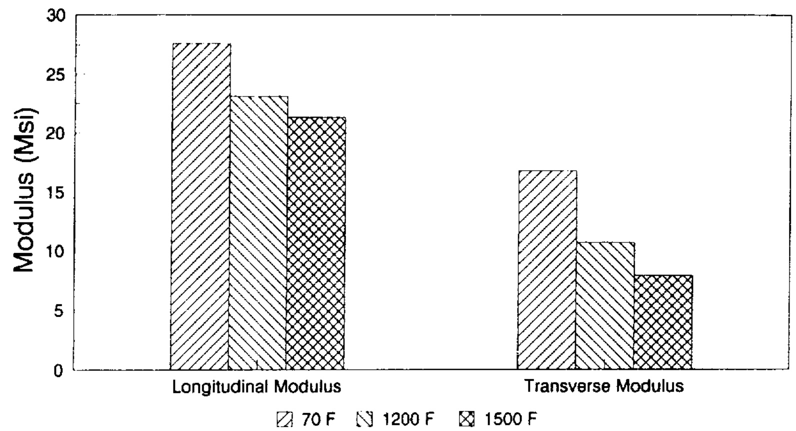


FIGURE 3. - SiC/Ti-15 MODULI FOR A PERFECT BOND.

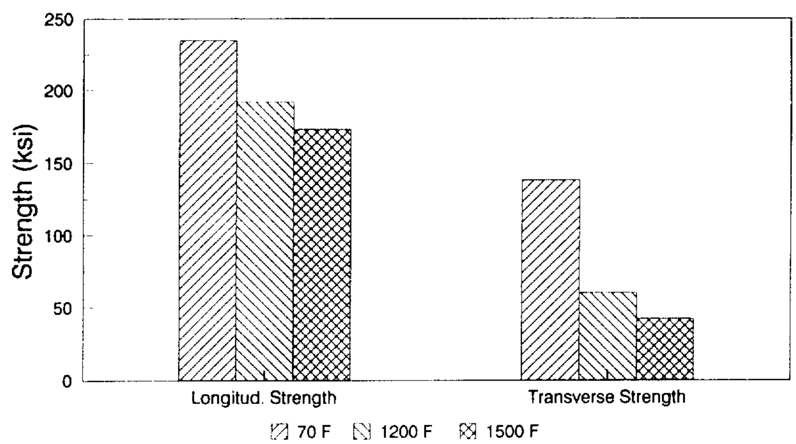


FIGURE 4. - SiC/Ti-15 STRENGTHS FOR A PERFECT BOND.

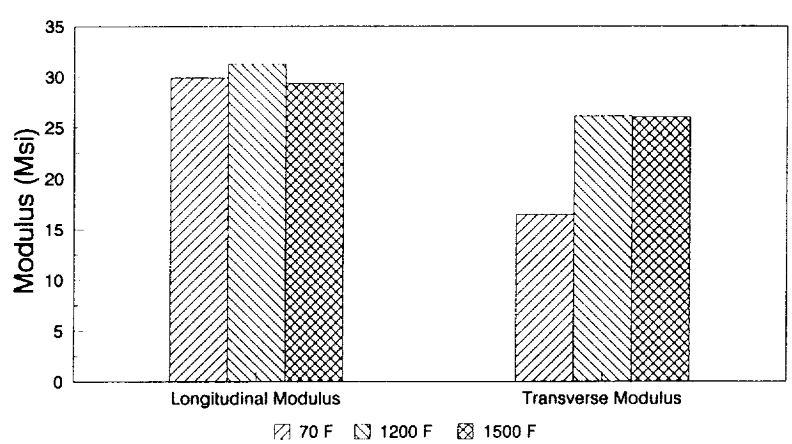


FIGURE 5. - Al_2O_3/NiAl MODULI FOR A PERFECT BOND.

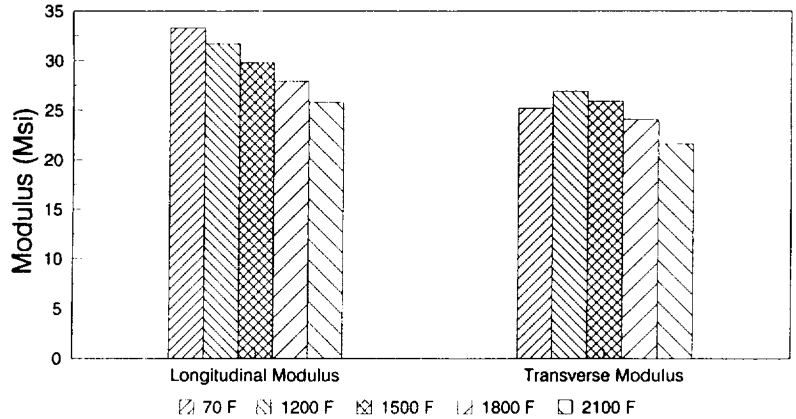


FIGURE 6. - TiB_2/NiAl MODULI FOR A PERFECT BOND.

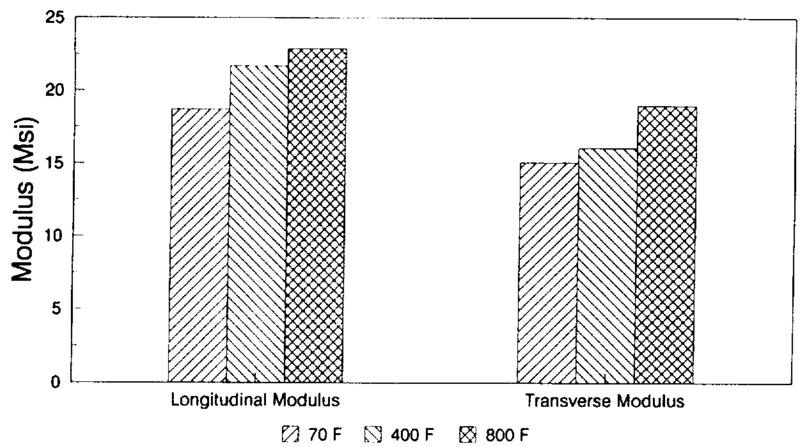


FIGURE 7. - Al_2O_3/LOCKALLOY MODULI FOR A PERFECT BOND.

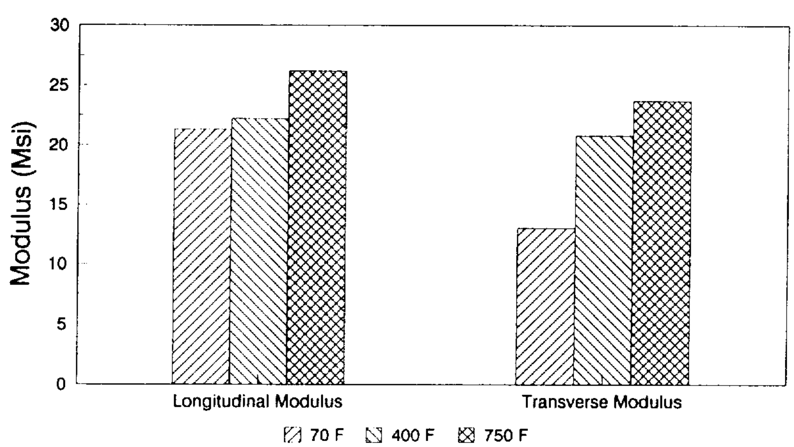


FIGURE 8. - SiC/LOCKALLOY MODULI FOR A PERFECT BOND.

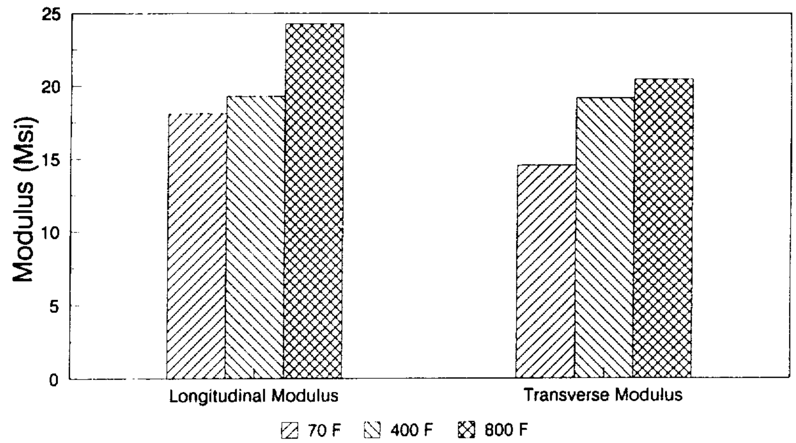


FIGURE 9. - TiB_2/LOCKALLOY MODULI FOR A PERFECT BOND.

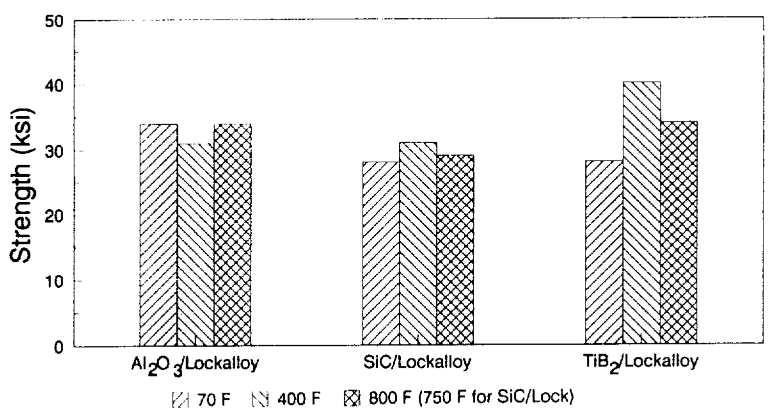


FIGURE 10. - LOCKALLOY MATRIX COMPOSITES TRANSVERSE STRENGTHS FOR A PERFECT BOND.

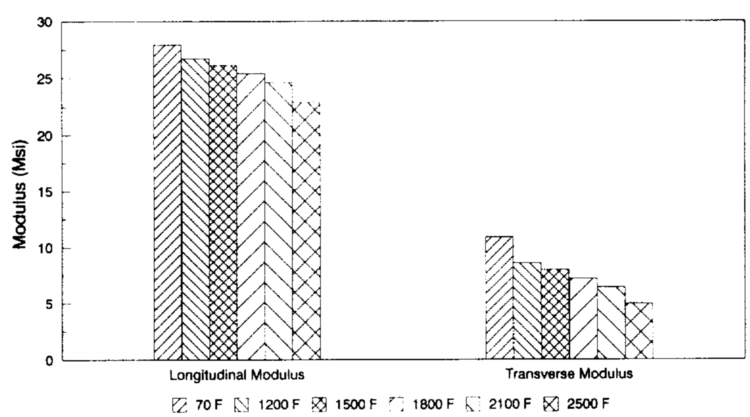


FIGURE 11. - SiC/NiAl MODULI FOR A WEAK INTERPHASE.

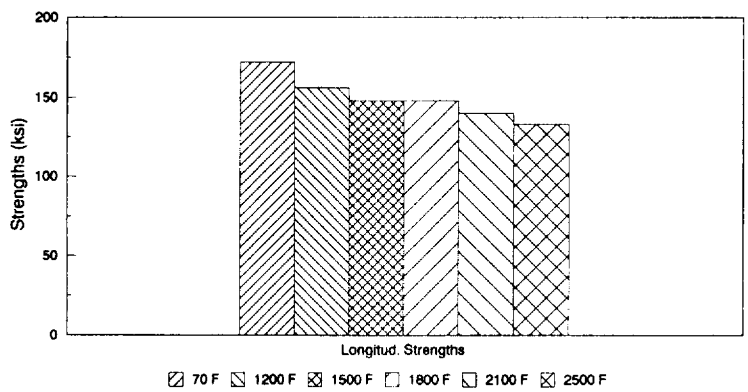


FIGURE 12. - SiC/NiAl LONGITUDINAL STRENGTHS FOR A WEAK INTERPHASE.

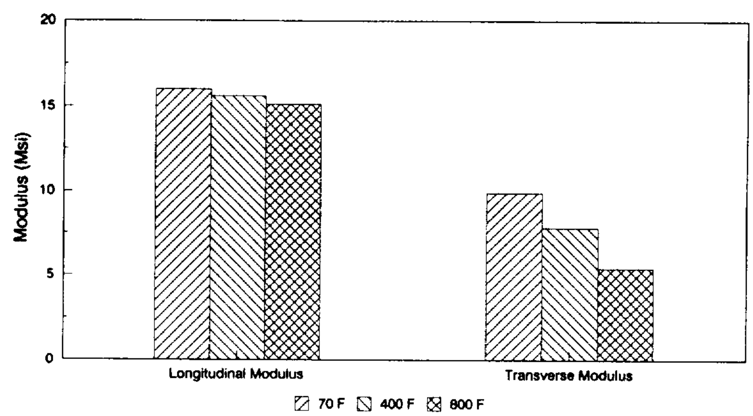


FIGURE 13. - Al_2O_3/LOCKALLOY MODULI FOR A WEAK INTERPHASE.

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15. Supplementary Notes

16. Abstract

The METCAN (Metal Matrix Composite Analyzer) computer code is used to simulate the nonlinear behavior of select metal matrix composites in order to assess their potential for high temperature structural applications. Material properties for seven composites are generated at a fiber volume ratio of 0.33 for two bonding conditions (a perfect bond and a weak interphase case) at various temperatures. A comparison of the two bonding conditions studied shows a general reduction in value of all properties (except CTE) for the weak interphase case from the perfect bond case. However, in the weak interphase case, the residual stresses that develop are considerably less than those that form in the perfect bond case. Results of the computational simulation indicate that among the metal matrix composites examined, SiC/NiAl is the best candidate for high temperature applications at the given fiber volume ratio.

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