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Tailored Metal Matrix Composites for High-Temperature Performance

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TAILORED METAL MATRIX COMPOSITES FOR HIGH-TEMPERATURE PERFORMANCE

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ABSTRACT

A multi-objective tailoring methodology is presented to maximize stiffness and load carrying capacity of a metal matrix cross-ply laminate at elevated temperatures. The fabrication process and fiber volume ratio are used as the design variables. A unique feature is the concurrent effects from fabrication, residual stresses, material nonlinearity, and thermo-mechanical loading on the laminate properties at the post-fabrication phase. For a $[0/90]_S$ *graphite/copper laminate, strong coupling was observed between the fabrication process, laminate characteristics, and thermo-mechanical loading. The multi-objective tailoring was found to be more effective than single objective tailoring. Results indicate the potential to increase laminate stiffness and load carrying capacity by controlling the critical parameters of the fabrication process and the laminate.*

1. INTRODUCTION

The demand for lower density materials with improved properties is a formidable challenge facing the aerospace industry, especially for the applications in space power and propulsion systems. Metal matrix composites (MMCs) are potential candidates to meet this challenge. However, for practical design purposes, major advancements are necessary in order to achieve desired material properties suitable for the severe in-service conditions the MMCs must undergo. Among the most challenging design requirements for these materials are their ability to sustain high strength and stiffness at elevated temperatures [1,2].

The design of MMCs is a formidable task which should include the coupled effects of residual stresses, matrix nonlinearity, elevated temperatures, material inhomogeneity, composite anisotropy, and so forth. Previous research has shown that it is possible to tailor the fabrication process, constituent materials, and laminate parameters based on a single objective function in the tailoring procedure [3-4]. For example, it was shown that residual stresses could be minimized by concurrently tailoring the processing parameters and the characteristics of an interphase layer; or maximize the thermo-mechanical (TM) load carrying capacity by tailoring the fabrication process and material parameters, namely the fiber volume ratio (FVR), simultaneously.

As a result of the increasing demand of high temperature applications on aerospace propulsion systems, a tailoring methodology is developed to simultaneously improve the properties of MMCs at elevated temperatures. Due to the complexity of the problem, a multi-objective formulation, rather than a single objective function, was used to efficiently handle the concurrent tailoring of the fabrication process and FVR to improve the stiffness and load carrying capacity of MMCs. Laminate tailoring based on a single objective function may degrade other characteristics not included in the objective function resulting in an over-designed material. For example, when maximizing the laminate stiffness in the axial direction, the transverse stiffness may decrease and vise versa.

As mentioned previously, the temperature and pressure histories of the fabrication process, and the FVR were chosen as the design variables to maximize the stiffness and strength of the MMCs. Other factors that influence the stiffness and strength of MMCs, but are not included as design variables are the constituent materials, ply orientation, and ply thickness. In this study, these variables remained constant throughout tailoring.

The objective of this paper is to describe a multi-objective method and demonstrate its effectiveness on a $[0/90]_S$ graphite (P100)/copper (Cu) laminate in order to maximize the stiffness and load carrying capacity (strength). The issues of residual stress effects, fabrication dependence, material nonlinearity, and property dependence to TM loading conditions are discussed. Finally, the strong coupling effects in the design of MMCs between the fabrication process, laminate parameters, and TM loading are demonstrated.

2. FABRICATION AND TM LOADING

A typical TM life cycle of a MMC from fabrication to failure at operational conditions (e.g. engine components) is schematically shown in Figure 1. MMCs are most often fabricated by hot-pressing the matrix onto the fiber at an elevated temperature, but at a temperature below the matrix melting point. Temperature and pressure are controlled to ensure adequate consolidation between constituents as the composite is cooled to room conditions (21°C and 0 MPa). The TM load consists of a linear increase in temperature and mechanical load which are applied until either the fiber or the matrix fails.

Residual stresses developed during the cool-down process will directly affect the performance of MMCs during its service life. The residual stresses at the end of fabrication are primarily caused by the difference in the coefficients of thermal expansion (CTE) between the constituents. Also, different laminate lay-ups may introduce supplementary residual stresses due to the variations in the CTE between the individual plies. Finally, additional effects on the build-up of stresses are the thermal stresses accumulated from the differential between room conditions and the in-service temperature. The development of residual stresses affect the TM performance of the laminate which implies that its characteristics depend on fabrication and loading parameters. Furthermore, strong linkage exists between the fabrication process and loading conditions.

3. METHODOLOGY

3.1 Composite Mechanics Composite micromechanics and laminate mechanics theories are used to capture the temperature effects, the non-linear response of the constituent materials, interaction among plies, and the residual stress build-up. The composite mechanics have been implemented into an in-house computer code, METCAN [5], which was used for simulating the thermo-mechanical response of the MMC during fabrication and TM loading. Basic elements of the composite mechanics pertinent to this work are briefly outlined herein and further details are given in reference [5].

The micromechanical theory is developed on the assumptions of constant average stresses in each micro-region of the composite (refer to Fig. 2), principles of displacement compatibility, and force equilibrium. The thermo-mechanical Hooke's law is applied at the constituent and ply level and represented by the following equation:

$$\{\sigma\}_j = [Q]_j \left(\{\epsilon\}_j - \{\alpha\}_j \, T \right) \tag{1}$$

where subscript j represents either a constituent material or composite ply (l); T, $\{\sigma\}$, and $\{\epsilon\}$ are temperature, stress, and strain increments of the materials or composite plies. $\{\alpha\}$ are the CTEs of the constituent materials or composite plies and $[Q]$ is the constituent or ply stiffness matrix. It is emphasized that $[Q]$ and $\{\alpha\}$ in eq. (1) depend on the cumulative temperature and stress states.

By integrating eq. (1) through the thickness of a laminate (Fig. 2), the relation between the incremental in-plane forces $\{N\} = \{N_x, N_y, N_{xy}\}$, moments $\{M\} = \{M_x, M_y, M_{xy}\}$, in-plane strain $\{\epsilon^o\}$, and curvature $\{k\}$ are represented by:

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & C \\ C & D \end{bmatrix} \begin{Bmatrix} \epsilon^o \\ k \end{Bmatrix} - \begin{Bmatrix} N_T \\ M_T \end{Bmatrix} \tag{2}$$

where the $[A]$, $[C]$, and $[D]$ are the extensional stiffness, coupling stiffness, and bending stiffness matrices, respectively. $\{N_T\}$ and $\{M_T\}$ represent the incremental thermal residual forces and moments due to variations in the CTE. Again, both stiffness, and thermal residual forces and moments in eq. (2) depend on the cumulative temperature and stress state through-the-thickness of the laminate.

This incremental procedure is used to simulate the nonlinear composite response with the homogenized composite and the individual constituent materials behaving elastically during each increment. The mechanical laminate loads, temperature, and resultant stresses at any increment are the cumulative quantities at the respective increment. The following equation represents theses quantities at time $t+\Delta t$, which includes the cumulative quantities at time t and their increments during step Δt;

$$\{N^{t+\Delta t}\} = \{N^t\} + \{N\} \; ; \qquad \{M^{t+\Delta t}\} = \{M^t\} + \{M\} \tag{3.1}$$

$$T^{t+\Delta t} = T^t + T \tag{3.2}$$

$$\{\sigma_j^{t+\Delta t}\} = \{\sigma_j^t\} + \{\sigma_j\} \tag{3.3}$$

where time superscripts and no superscripts indicate cumulative and incremental quantities, respectively. The subscript j indicates either ply or a material microregion.

3.2 Multi-Objective Tailoring Performance requirements set by the design of MMCs demand simultaneous improvements in many material characteristics. Laminate tailoring based on a single objective function produces only the improvement of the objective function and may degrade other characteristics resulting in over-design. Moreover, MMCs may exhibit a higher tendency to be over-designed because of the multitude of parameters involved. As a result, to achieve increases in many of the laminate characteristics a multi-objective methodology is proposed.

A constrained multi-objective problem involving minimization of n objective functions is defined in the following mathematical form:

$$\min \{ F_1(\boldsymbol{z}), F_2(\boldsymbol{z}), \ldots, F_n(\boldsymbol{z}) \} \tag{4}$$

subject to lower (L) and upper (U) bounds on the design vector $\boldsymbol{z}$ and inequality constraints $G(\boldsymbol{z})$:

$$\boldsymbol{z}^L \leq \boldsymbol{z} \leq \boldsymbol{z}^U \tag{5.1}$$

$$G(\boldsymbol{z}) \leq 0 \tag{5.2}$$

In the present paper, the tailoring objectives are focused on simultaneous maximization of the extensional or bending laminate stiffness (i.e. $\max\{A_{ii}, D_{ii}\}$ for $i=1,2,6$) and the ultimate forces and moments (i.e. $\max\{N_x, N_y, N_{xy}; M_x, M_y, M_{xy}\}$ the laminate can carry). Design variables include the temperature and pressure histories of the fabrication process, and the FVR. Though not used in this study the method is also capable of tailoring the ply orientation and thickness.

The problem defined by eqs. (4-5) does not have a unique solution but a paretto-optimum can be found by the minimization of the following objective function:

$$\min \sum_{i=1}^{n} v_i \frac{(F_i - F_i^*)^2}{F_i^{*2}} \tag{6}$$

subject to constraints (5.1 and 5.2) which define the feasible domain. Also, F_i is the ith objective function and F_i^* is the "ideal solution" resulting from the individual minimization of F_i alone subject to eq. 5. The parameter v_i, is a weighing factor defining the relative importance of this objective.

Constraints in the form of the maximum stress criterion on the fiber (f) and matrix (m) microstresses at various time steps t during the processing and TM loading

$$S_{Cm}^t \leq \sigma_m^t \leq S_{Tm}^t \tag{7.1}$$

$$S_{Cf}^t \leq \sigma_f^t \leq S_{Tf}^t \tag{7.2}$$

are used to ensure the integrity of the composite. The subscripts C and T identify compressive and tensile material strengths (S) at the corresponding thermo-mechanical state.

To ensure that the elastic properties of the tailored laminate will remain within acceptable limits, lower bounds are imposed on the diagonal terms of the extensional and bending stiffness matrices.

$$\begin{array}{l} A_{ii} \geq A_{ii}^L \\ D_{ii} \geq D_{ii}^L \end{array} \qquad i=1,2,6 \tag{8}$$

where $\boldsymbol{A}_{ii}$ and $\boldsymbol{D}_{ii}$ are the diagonal terms of the [A] and [D] stiffness matrices.

The tailoring problem described above is highly nonlinear, because the nonlinearity in the performance criteria is coupled with the nonlinear thermo-mechanical response of the material. As a result, this constrained tailoring problem is solved with non-linear programming. In the present paper the method of feasible directions [6] was used for its ability to handle the complex nature of tailoring procedure, confine the search within a feasible domain, and its computational efficiency.

An in-house computer code, MMLT (Metal Matrix Laminate Tailoring), was developed encompassing these two methodologies. In summary, METCAN was used to capture the nonlinear behavior of the MMC during fabrication and the subsequent TM loading and an optimizer using the feasible directions method performs the tailoring. By taking advantage of the unique capabilities of these two methods, the foundation of the MMLT code was established.

4. RESULTS AND ANALYSIS

A $[0/90]_S$ P100/Cu laminate composite was selected to demonstrate the method. The basic composite system was chosen because of its acceptance as a potential candidate material for aerospace applications and the availability of experimental data [1-2]. The initial FVR was 40% and the thickness of each ply was assumed to be 0.01 in. Representative constituent properties at reference conditions are shown in Table 1.

The consolidation temperature and pressure histories of the fabrication process and FVR were tailored for two biaxial loading cases: (1) an in-plane compressive load ($N_x = N_y$, $N_{xy} = 0$) ; and (2) an out-of-plane bending moment ($M_x = M_y$, $M_{xy} = 0$). Upper and lower bounds on the design variables are located in Table 2. The case of an in-plane tensile load was also investigated, but did not produce any significant improvements in the objective functions for fabrication tailoring, hence it is not presented herein. Though, improvements were observed when the FVR was used as a design variable. For example, the FVR increased to its maximum value to improve both the laminate stiffness and tensile load carrying capacity.

The post processing loading cycle consisted of a linear temperature increase to 316°C followed by application of the previously mentioned biaxial load cases. In both cases the tailoring involved two objective functions. Case 1 required maximization of the in-plane compressive load ($F_1 = N_x$) and axial laminate stiffness ($F_2 = A_{11}$) at the end of the TM cycle. Similarly, case 2 required maximization of the out-of-plane bending moment ($F_1 = M_x$) and laminate bending stiffness ($F_2 = D_{11}$) at the end of TM loading. The current fabrication process for the $[0/90]_S$ P100/Cu was obtained from reference [1].

<u>4.1 In-Plane Compressive Loading Case</u> Figure 3 shows the resultant values of both objective functions from the single-objective and multi-objective tailoring. Also, the current process (before tailoring) resultants are given as reference conditions; the maximum loading was determined when either the fiber or matrix reached failure under the given loading conditions and the current stiffness was taken at the point of maximum compressive loading. The higher compressive load was achieved when the respective objective function was individually maximized, however, this case resulted in slightly lower stiffness when compared to the other tailored cases. The highest stiffness, A_{11}, resulted when the single objective was to maximize extensional stiffness and the corresponding compressive load only increased slightly compared to the current load capacity. In contrast, by using a multiple objective function, increases in both stiffness and load carrying capacity were achieved. These results demonstrate the effectiveness of multi-objective design, as opposed to utilizing the individual objective functions.

The increase in load carrying capacity for all three objective functions can be attributed to the changes in the fabrication processes (Fig. 4) and increase in

FVRs. By increasing the consolidation pressure, thereby keeping the matrix in a "flow" state, as the temperature was decreased to room condition, the tensile residual matrix stresses are reduced and lower compressive fiber stresses are required to balance them (refer to Fig. 5). Consolidation pressure proved to be a critical parameter in the tailoring procedure. Also, shown in Fig. 4, the pressure in the maximum load case increased greater than the pressure for the multi-objective tailoring case which resulted in the favorable stress states. The critical stresses are the longitudinal fiber stresses in both 0° and 90° plies as seen in Fig. 6. This state of residual stress, lower residual compressive fiber and tensile matrix stresses, is favorable to the laminate compressive loading. This, also, explains the observed insensitivity for the tensile loading case to fabrication tailoring.

The FVR for all cases (Table 3) increased, which also contributed to the increased load carrying capacity. Since both laminate strength and stiffness is dominated by the fibers (Fig. 6), naturally higher FVRs are needed to increase stiffness and load carrying capacity. But the presence of residual stresses sets a bound on the FVR, because increased FVR results in unproportionally higher residual stresses in the matrix. More specifically, as the fiber stresses are changed due to tailoring (the combination of higher FVR and consolidation pressures), the matrix stresses are also modified to balance themselves with the fiber stresses, which results in a undesirable stress state.

Although the fabrication process and loading have only a slight effect on the fiber *in situ* properties, both affected the matrix *in situ* properties. This effect was beneficial as it enabled the control of residual stresses, but also induced a dependence of the extensional laminate stiffness to the applied load. One example of this interdependence is the "competing" effects between load and stiffness maximization. The low stiffness increase in the "maximum load" case can be particularly attributed to the matrix being strained due to the higher compressive load and higher consolidation pressure.

Even though only A_{11} was directly maximized in the objective function, A_{22} also increased and showed no sign of degradation. Interestingly, the magnitude of increase of A_{22} was not as great as the increase in A_{11} even though the laminate was symmetric and balanced. It is believed, that this resulted from not including A_{22} in the objective function in connection with the asymmetry in the application of consolidation pressure. In the multi-objective function case, a decline in the laminate shear modulus was observed and A_{66} reached the lower bound.

<u>4.2 Bending Load Case</u> The values for maximum stiffness and load capacity of the single objective functions and multi-objective function are shown in Fig. 7 for biaxial bending at a constant elevated temperature. For the current process, the maximum biaxial moment and its corresponding stiffness were determined and used as reference conditions. Similar trends to the previous case of compressive loading were attained, i.e., the single objective tailoring produced the greatest improvements for their respective objectives, but the multi-objective function provided significant simultaneous increases in both laminate stiffness and load carrying capacity. To achieve the maximum bending stiffness (D^*_{11}), the bending load capacity had to decrease, which illustrates the advantage of multi-objective tailoring in MMC laminates.

The increases in bending load capacity for the maximum load and the multi-objective tailoring can again be attributed to changes in the fabrication process (Fig. 8) and the moderately increased FVR (Table 3). Fiber and matrix residual stresses are displayed in Fig. 9. The combination of the tailored fabrication process and increased FVR led to a more favorable residual stress state when compared to the current process.

Shown in Fig. 10 are the final normalized microstresses which indicated the failure mechanism to be the longitudinal stress in the fibers of the compressed ply. As previously explained, the resultant high consolidation pressure (see Fig. 8) decreased the precompression in the fibers in the compressed 0° ply; hence it reduced the residual compressive fiber stresses, which are the controlling mechanism for laminate failure (Fig. 10). In addition, this type of tailored fabrication process reduced the matrix residual stresses. Most important was the ability to control the stress build-up during fabrication and TM loading, demonstrated by the final longitudinal stress in the bottom ply of the matrix. The current process produced a very high stress state, but due to tailoring the matrix stress was reduced to a more favorable state. In contrast, the final matrix transverse stress increased when compared to the current process but has little effect on the load carrying capacity and stiffness of the laminate.

Due to the bending load, different states of final stress exist in each ply, e.g. the top ply is in tension and the bottom ply is in compression. Even though the top ply is in tension, the reduction in compressive residual stress (Fig. 9) does not seem to affect the laminate load carrying capacity because the tensile strength $S_{f11,T}$ of the fiber is much greater than its compressive strength $S_{f11,C}$ (refer to Table 1). Also in this case there is a higher dependency on the matrix to carry the biaxial moment and provide some flexural rigidity when compared to the compressive loading case. This explains the lower FVRs (Table 3) when compared to the previous case for the different objective functions used. Interestingly, in both the "maximum stiffness" (D^*_{11}) and multi-objective designs the longitudinal matrix stress in the bottom 0° ply (compressive) has vanished (i.e. residual stresses are balanced by mechanical stresses), which increased the matrix modulus and the overall laminate flexural rigidity.

5. SUMMARY AND CONCLUSIONS

A multi-objective methodology to tailor the fabrication process and fiber volume ratio for the simultaneous maximization of the post-fabrication laminate stiffness and load carrying capacity at elevated temperatures was presented. The performance of the laminate in the post-fabrication phase included the coupled effects of processing, residual stresses, and material nonlinearity. The non-linear programming problem was numerically solved with the modified feasible directions method. A computer code MMLT (Metal Matrix Laminate Tailoring) [3-4] has also been developed incorporating this method.

Evaluations of the method were reported on a $[0/90]_S$ graphite/copper composite. The results illustrate the advantage of multi-objective tailoring rather than single objective functions. By tailoring critical fabrication parameters and ply FVRs significant increases in stiffness and load carrying capacity were achieved. The coupling between the fabrication process, laminate parameters (ply layup and FVR), and TM loading was vital to achieving the final tailored design. Overall, the results indicated the potential of controlling the constituent residual stresses in the composite to achieve increased stiffness and load carrying capacity by concurrently tailoring both fabrication process and FVR.

6. REFERENCES

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Nomenclature

A	Extensional stiffness matrix.
C	Coupling stiffness matrix.
D	Flexural stiffness matrix.
E	Young's modulus.
$F(z)$	Objective function.
G	Shear modulus.
$G(z)$	Inequality constraint.
k	Curvature.
M	Resultant bending moment.
N	Resultant force.
P	Pressure.
Q	Ply stiffness matrix.
S	Strength.
T	Temperature.
z	Design vector.
α	Coefficient of thermal expansion.
ϵ	Strain.
ν	Poisson's ratio.
ρ	Density.
σ	Stress.

Subscripts

f	Fiber.
C	Compressive.
m	Matrix.
T	Tension.
x,y,z	Laminate coordinate system.
1,2,3	Material coordinate system.

Table 1: Representative constituent mechanical properties of P100/Cu at reference conditions

P100 Graphite	Copper
E_{f11} = 724.5 GPa	E_m = 122.1 Gpa
E_{f22} = 6.21 Gpa	
G_{f12} = 7.59 Gpa	G_m = 47.0 Gpa
G_{f23} = 4.83 Gpa	
ρ_f = 2.16 g/cm$_3$	ρ_m = 8.86 g/cm^3
v_{f12} = 0.20	v_m = 0.30
v_{f23} = 0.25	
α_{f11} = -1.61 μm/m/°C	α_m = 17.5 μm/m/°C
α_{f22} = 10.0 μm/m/°C	
$S_{f11,T}$ = 2242.0 Mpa	S_{mn} = 221.0 Mpa
$S_{f11,C}$ = 1380.0 Mpa	
S_{f22} = 173.0 Mpa	
S_{f12} = 173.0 Mpa	S_{ms} = 131.0 Mpa
S_{f23} = 86.0 Mpa	

Table 2: Upper and lower bounds on the design variables, associated with Eq.(5.1)

Variable	Lower Bound	Upper Bound
Temperature (°C)	0	950
Pressure (Mpa)	0	50
FVR (%)	20	60

Table 3: Current and Tailored Fiber Volume Ratios for the Different Loading Cases

Case	Fiber Volume Ratio (%)			
	Current	Maximize Load	Maximize Stiffness	Multi Objective
Biaxial Compressive Loading	40	50	43	51
Biaxial Bending	40	43	46	44

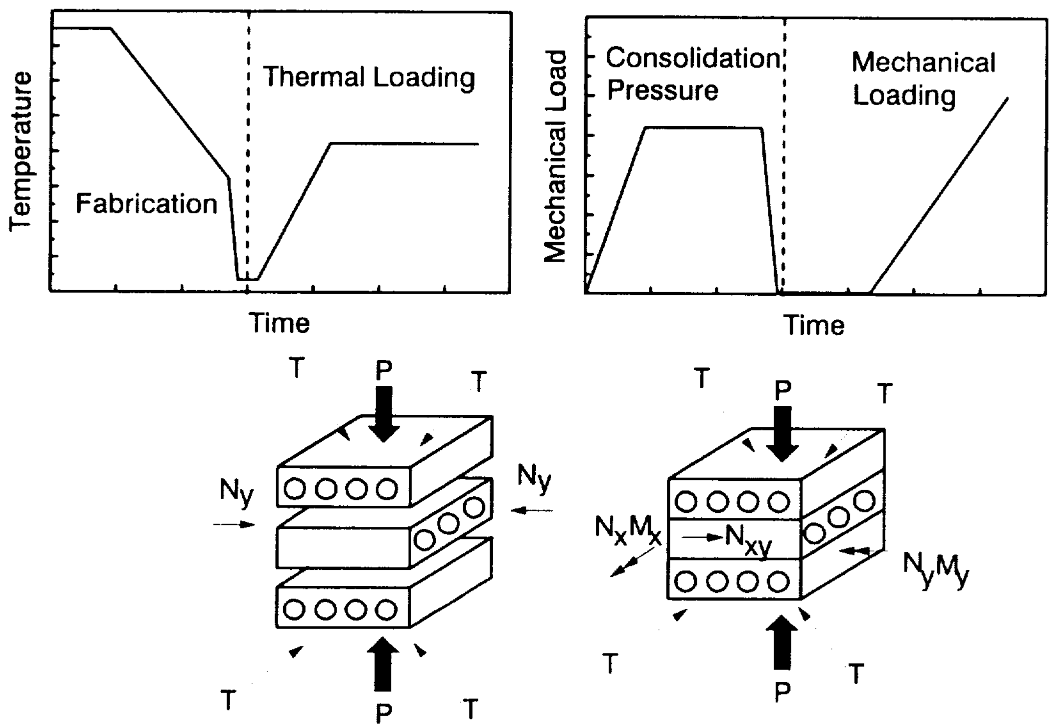

Figure 1: Typical Fabrication and Thermo-Mechanical Loading of Metal Matrix Laminates

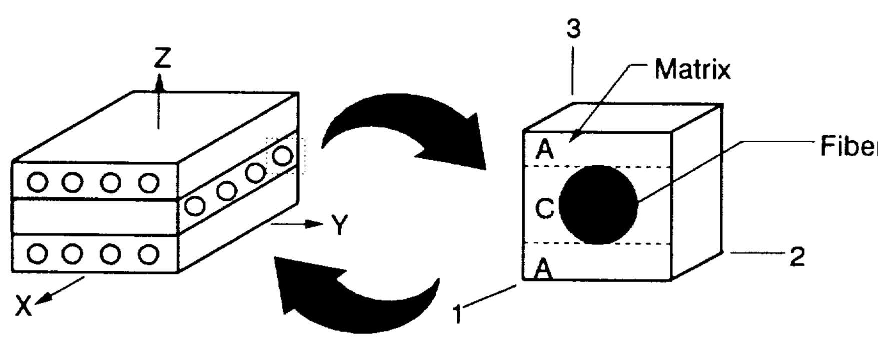

Figure 2: Coordinate Systems; (a) Laminate; (b) Material.

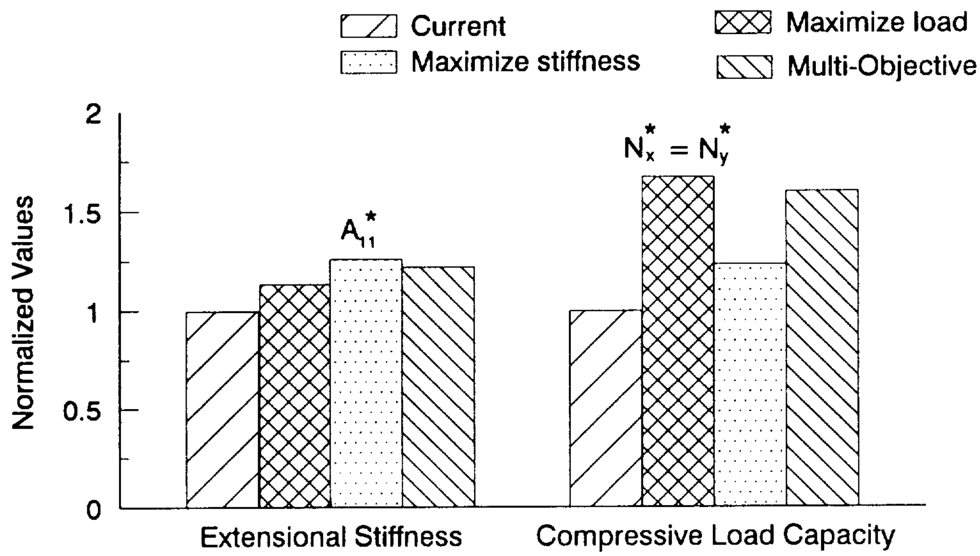

Figure 3: Comparision of Single Objective Ideal Parameters with the Multi-Objective Parameters Under a Thermal Compressive Load

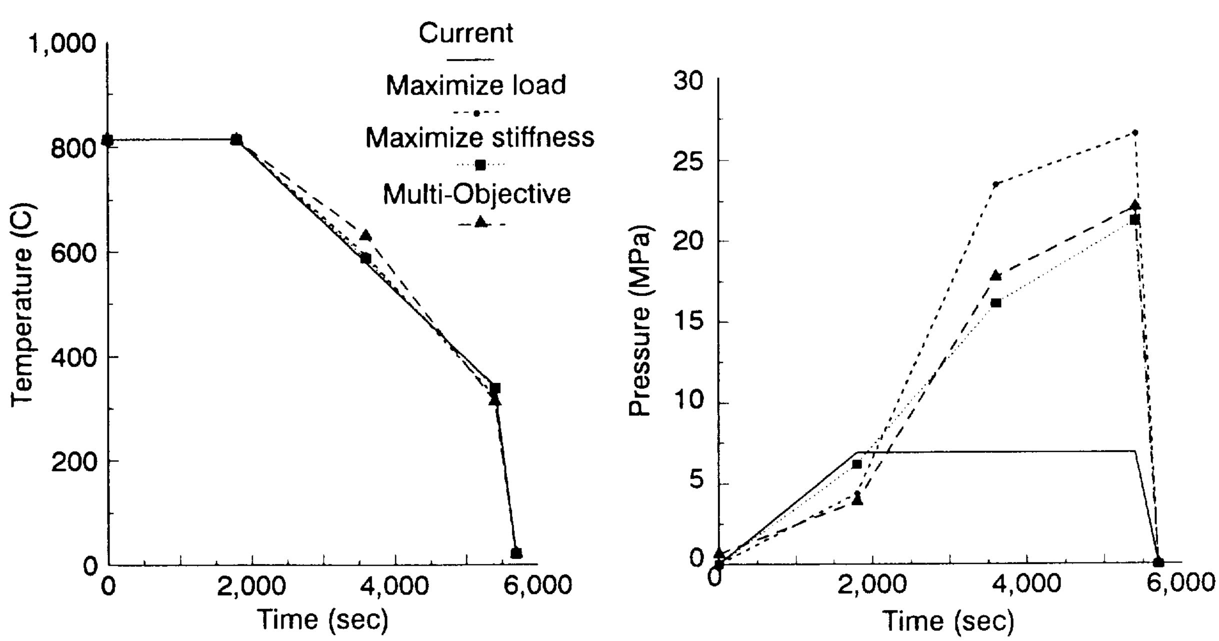

Figure 4: Current and Tailored Fabrication Process for a [0/90]s P100/Cu Laminate Under a Thermal Compressive Load

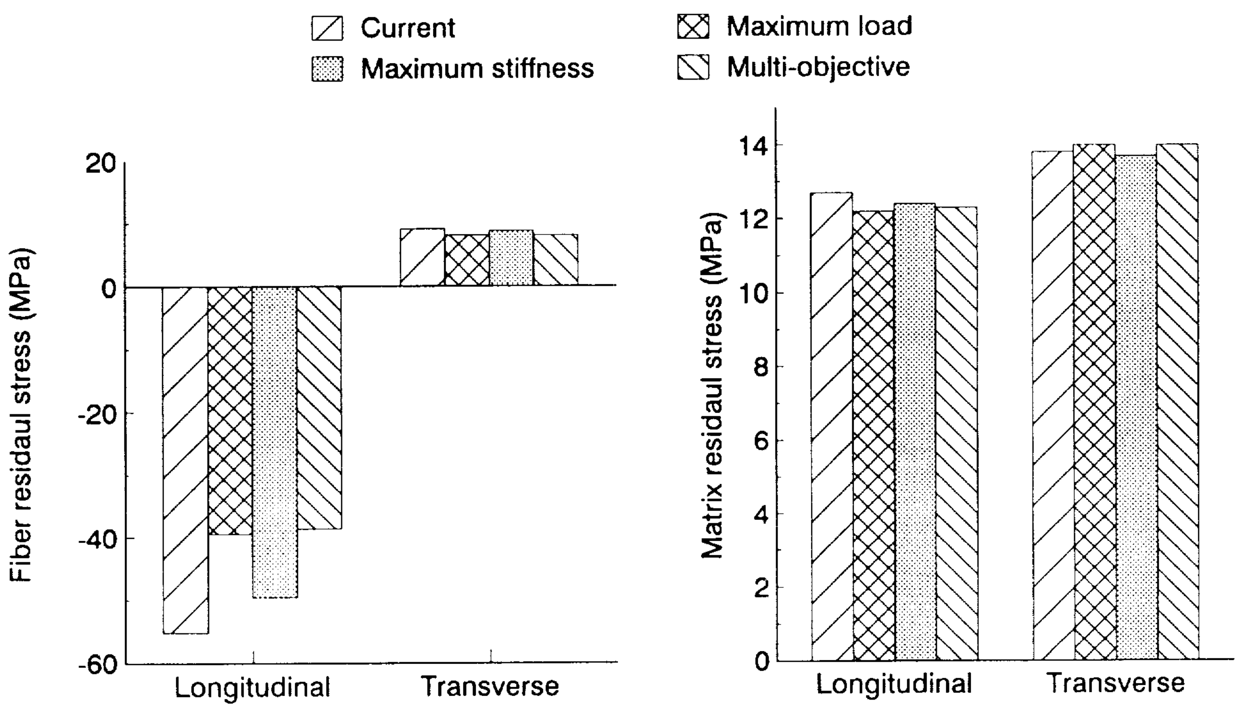

Figure 5: Residual stresses after fabrication (21 C) for [0/90]s P100/Cu (Biaxail Compressive Load Case)

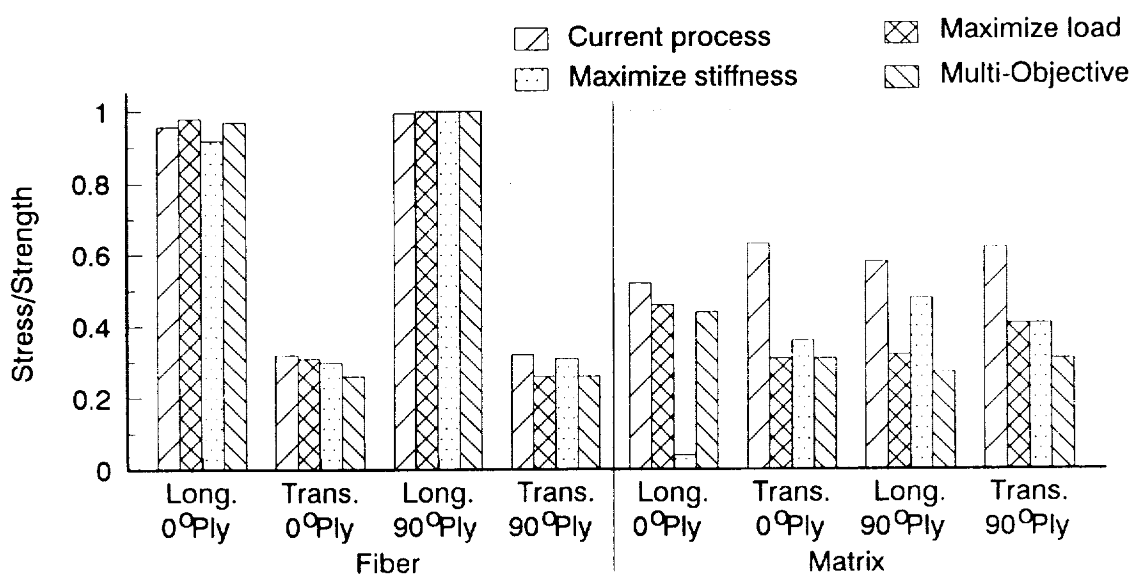

Figure 6: Final Normalized Microstresses at the End of Thermal Compressive Loading for [0/90]s P100/Cu

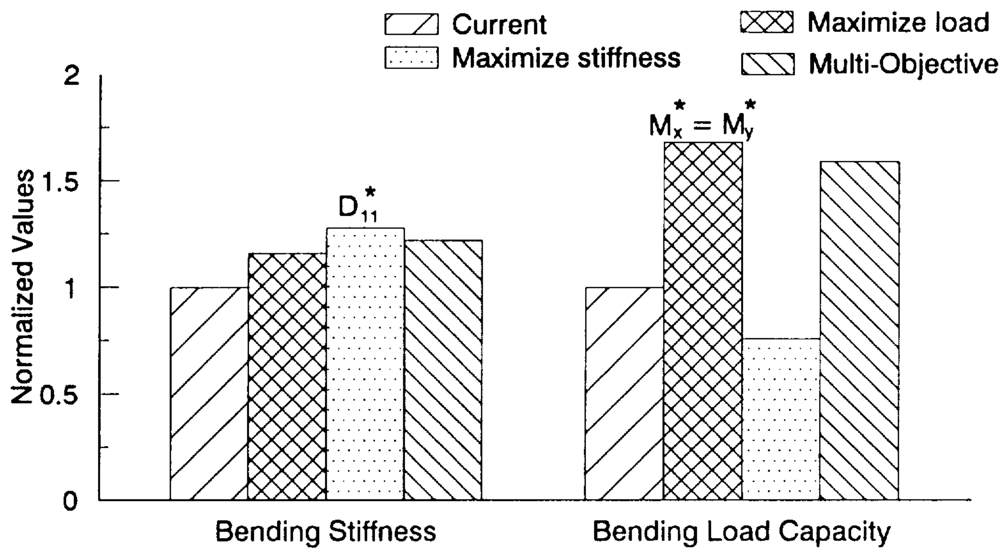

Figure 7: Comparision of Single Objective Ideal Parameters with the Multi-Objective Parameters Under a Thermal Bending Load

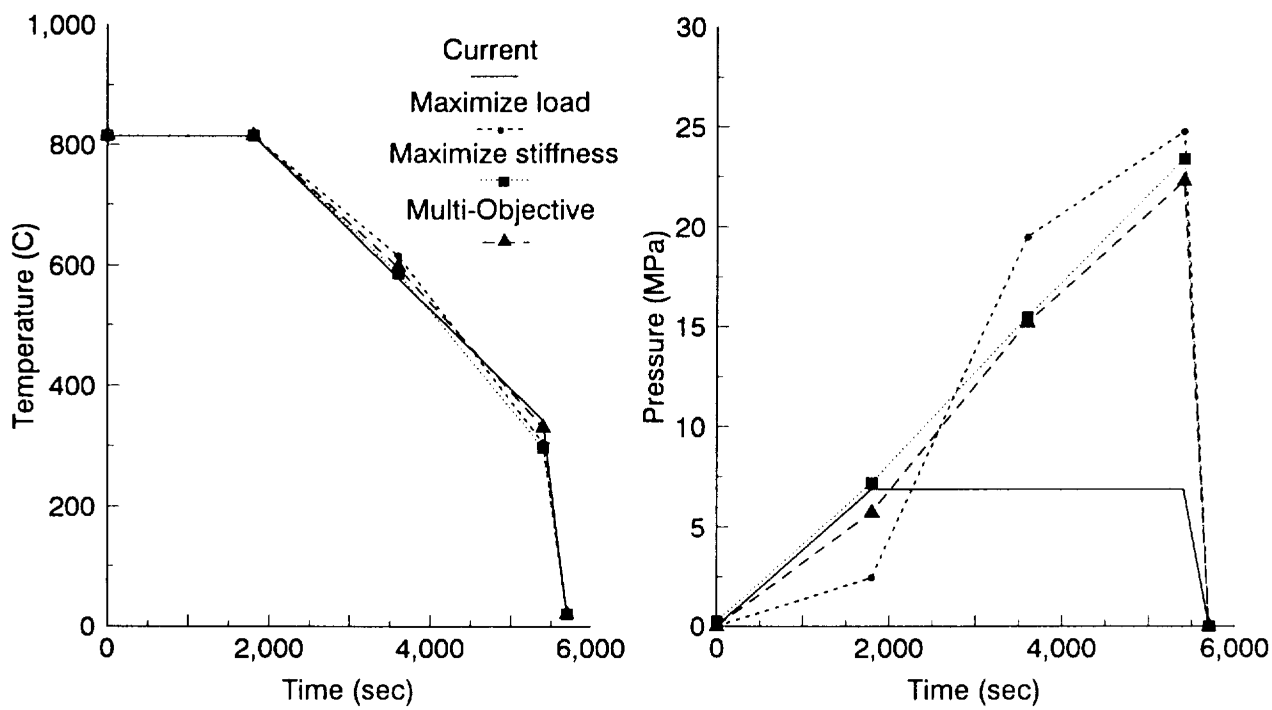

Figure 8: Current and Tailored Fabrication Process for a [0/90]s P100/Cu Under a Thermal Bending Load

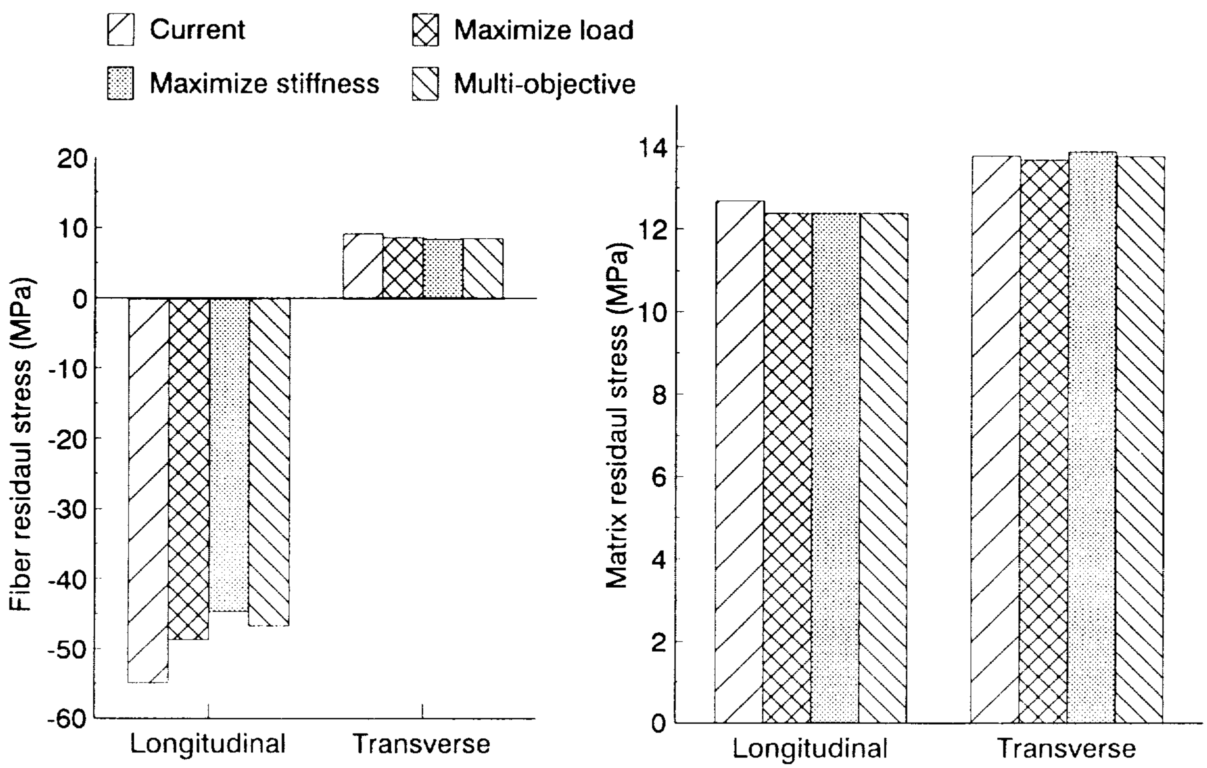

Figure 9: Residual stresses after fabrication (21 C) for [0/90]s P100/Cu (Biaxial Bending Case)

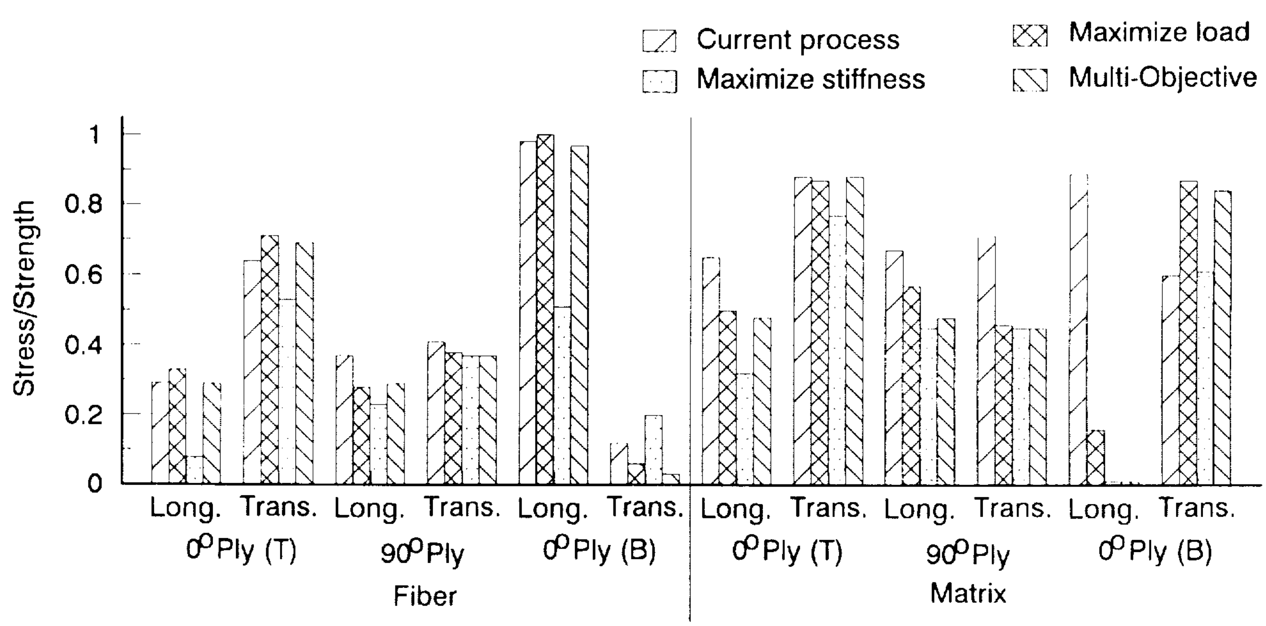

Figure 10: Final Normalized Microstresses at the End of Thermal Bending Load for a [0/90]s P100/Cu, T=Top and B=Bottom

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13. ABSTRACT ***(Maximum 200 words)***

A multi-objective tailoring methodology is presented to maximize stiffness and load carrying capacity of a metal matrix cross-ply laminate at elevated temperatures. The fabrication process and fiber volume ratio are used as the design variables. A unique feature is the concurrent effects from fabrication, residual stresses, material nonlinearity, and thermo-mechanical loading on the laminate properties at the post-fabrication phase. For a $[0/90]_S$ graphite/copper laminate, strong coupling was observed between the fabrication process, laminate characteristics, and thermo-mechanical loading. The multi-objective tailoring was found to be more effective than single objective tailoring. Results indicate the potential to increase laminate stiffness and load carrying capacity by controlling the critical parameters of the fabrication process and the laminate.

14. SUBJECT TERMS	15. NUMBER OF PAGES
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