Ultimate Tensile Strength-Processing Relationships for Metal Matrix Composites

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Abstract

Recent studies of fiber reinforced metal matrix composites (MMC's) have revealed the frequent occurrence of fiber bending and fracture in the as-processed state. It has been shown for MMC's produced from thermal spray-deposited monotapes that fibers bend and fracture due to monotape surface asperities during consolidation. A model has been developed for predicting the evolution of fiber bending and fracture as a function of consolidation processing conditions and the initial state of the monotape (D.M. Elzey and H.N.G. Wadley, Acta metall. mater., In Press 1994). By combining this model with the modified composite tensile strength model of Duva et al (J.M. Duva et al, Acta metall. mater., In Press 1994), we have been able to investigate the influence of processing conditions on strength, an important indicator of composite component performance. Detailed results are presented for the case of a Ti-24Al-11Nb/SCS-6 composite. They illustrate the value of models for the design of processing paths and the selection of materials in order to optimize performance.

Introduction

Metal and intermetallic matrix composites are manufactured via a series of processing steps which include the tape casting of metal powder slurries, the spray deposition of molten alloy droplets, and the vapor deposition of metals on unidirectional fiber arrays. In all cases, these preforms are layed up and subjected to a consolidation process to obtain a composite component with a desired final shape. The performance of the component is determined by the materials selected (e.g. fiber, matrix, interfacial coating) and microstructural features such as matrix relative density, fiber/matrix reaction products and fiber damage, which evolve along the chosen process path. This complexity and the frequent unavailability of new composite materials for testing purposes has led to a great deal of interest in the development of models able to simulate the effect of process conditions on product performance [1]. In addition to providing an inexpensive alternative to real tests, such models, once validated, could be used to optimize processes with respect to both quality and cost. In this paper, we present a process-performance model that links fiber damage occurring during the consolidation processing of MMC’s to the ultimate tensile strength of a fully dense composite. The model enables one to explore the influence of processing conditions and constituent material properties, such as fiber strength attributes, on the UTS (Ultimate Tensile Strength) of processed composite material.

Numerous experimental studies[2-6] have recently reported the susceptibility of ceramic reinforcing fibers to bending and fracture during consolidation processing of MMC’s. Groves et al[2] found that the extent of fiber damage during the consolidation of MMC monotapes produced by thermal spray deposition[7] was a sensitive function of the process conditions used (e.g. applied pressure and temperature). They also employed a simple modification of Curtin’s recent model for the ultimate tensile strength of a composite[8] to argue that a significant degradation in strength could be expected as a result of process-induced fiber fracture. Following this experimental work, Elzey and Wadley[9] developed a predictive model relating the extent of fiber damage to the process conditions used whilst more recently, Duva et al[10] have proposed a model for a composite’s ultimate strength which explicitly incorporates both fiber bending and fracture accrued as a result of processing. Here, we show how these models can be combined and used to explore the relationships between the material properties of fibers/ matrices, process conditions, and the quality of the resulting composite as characterized by its ultimate tensile strength.

Process-Structure Model

The fiber bending/fracture model[9] allows prediction of the number of fiber breaks and of the distribution of residual bending stresses in fibers following the consolidation (under arbitrary process conditions) of a laminate of spray-deposited MMC monotapes. The mechanism of fiber damage is bending caused by stress concentrations at points where the monotapes, which have rough surfaces, are in contact. Figure 1 illustrates the mechanism for a single segment of fiber: as the monotapes are compacted during consolidation, surface asperities, which are allowed to deform viscoplasticly, transmit forces to the fiber segment (elastic) which cause it to bend. The response of this unit cell (i.e. the deflection of the fiber segment as a function of time, $\nu(t)$, given the rate of densification of the cell) may be expressed by a single (nonlinear) ordinary differential equation:

$$\ddot{\nu} = \left(\frac{2}{1 + \xi}\right) \left[\frac{z_D D_0}{D(t)} - \frac{\nu(t)}{2}\right] B \left[\frac{k_s \cdot \nu(t)}{2\pi r \left(h - \frac{z_D D_0}{D(t)} + \frac{\nu(t)}{2}\right)} \right]^n - \frac{z_D D_0}{D(t)^2} \ddot{D} \right] (1)$$
where $k_s$ is the fiber bend stiffness (defined as $k_s = \left(\frac{3\pi}{4}\right) \frac{E_f}{r^3}$, with $E_f$ and $d_f$ being the fiber modulus and diameter, respectively and $l$ the length of the fiber segment), $r$ is the average asperity radius, $z_0$ is the initial monotape thickness, $h$ is the initial (undeformed) asperity height, $D_0$ and $D$ are the initial and current relative densities, respectively, $D$ is the densification rate and $\xi = \frac{k_s}{k_p}$ where $k_p$ is the effective "plastic stiffness" of the asperity ($k_p = 6\pi r \sigma_a$). The density and densification rate are obtained (for a given process cycle) using a previously developed model for the densification of MMC laminates[11].

![Figure 1](https://via.placeholder.com/150)

Figure 1 The mechanism by which fibers are damaged during consolidation of spray-deposited MMC monotapes has been captured in a micromechanics model[9]: the consolidating laminate is viewed as an assemblage of unit cells in which fiber segments undergo bending as a result of forces imposed by surface roughness asperities.

The deflection gives rise to a peak tensile stress\(^1\) in the fiber segment given approximately as

$$\sigma_f = \left(3\frac{E_f}{l^2}\right) \nu(t).$$

This stress may lead to failure of the fiber segment; the probability that failure will occur at or below this stress is given by the familiar Weibull expression

$$\Phi_f(\sigma_f) = 1 - \exp \left[ -\frac{L}{L_0} \left( \frac{\sigma_f}{\sigma_0} \right)^m \right]$$

where $\sigma_0$, $m$ and $L_0$ are Weibull parameters (the fiber’s reference strength, Weibull modulus and reference length, respectively) and $L$ is the length of fiber subjected to stress $\sigma_f$. The stress, and hence the probability of failure, increases sensitively with decreasing bend segment length, $l$.

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1. Determined from simple beam theory assuming a cylindrical fiber segment loaded pointwise at mid-span.
Since a distribution of bend lengths exists at any given density, short lengths (4-12 fiber diameters) are present which require only slight deflections in order to generate stresses likely to cause fracture.

During the densification of an MMC laminate, new asperity contacts are continually being established along the length of each fiber. With each new asperity contact, an existing bend cell is eliminated and two (shorter) bend cells are created. Thus the distribution of unit cell lengths is changing as a function of the relative density of the laminate. The fiber fracture model[9] uses a Monte Carlo approach to simulate this stochastic creation and elimination process. The overall number of fiber breaks is obtained as the sum of probabilities of failure determined for each cell using (3).

Figure 2 shows an example of the predicted dependence of the number of fiber breaks (per unit length of fiber) as a function of consolidation process conditions (temperature and applied densification rate) [9]. The map, in this case for a Ti-24Al-11Nb/SCS-6 composite, shows damage (represented by contour lines) can be reduced if consolidation is conducted at higher temperature and lower densification rates (corresponding to lower applied pressures). These conditions favor deformation of the matrix (densification) rather than fiber deflection.

![Figure 2](image1)

![Figure 3](image2)

Figure 2 The influence of consolidation processing conditions on the accumulation of fiber breaks; damage is minimized by processing at higher temperatures and lower strain rates, which promotes asperity deformation (i.e. matrix flow) rather than fiber bending.

Figure 3 The influence of fiber strength on damage (mapped for a given set of processing conditions); fiber breaks are minimized by increasing the fiber’s reference strength and reducing strength variability (i.e. by increasing the Weibull modulus, m).

The model also allows comparison of the damage susceptibility of various fibers and matrices, and enables one to evaluate their compatibility during consolidation. For example, Figure 3 shows the effect of varying the parameters characterizing fiber strength (reference strength and Weibull modulus); damage is minimized by selecting fibers of greater strength (higher $\sigma_0$) and with reduced strength variability (higher $m$). The matrix material was again Ti-24Al-11Nb and consolidation conditions were held fixed at a temperature of 900 °C and a densification rate of 0.55 hr⁻¹.
Structure-Property Model

For fibers exhibiting a Weibull distribution of strengths, the number of defects that will fail per unit length when subjected to a uniform stress, $T$, is given by

$$\rho(T) = \frac{1}{L_0} \left( \frac{T}{\sigma_0} \right)^m$$  \hspace{1cm} (4)

where $L_0$ is a reference length. Equation (4) can be modified to include the number of preexisting fiber breaks, $\rho_0$, caused by processing: $\rho(T) = \rho_0 + \frac{1}{L_0} \left( \frac{T}{\sigma_0} \right)^m$. However, in addition to fiber fracture, consolidation processing leaves many fibers in a residual state of bending, without having failed. The process model can predict the distribution of residual bend stresses, $\sigma_b(x)$, following consolidation (e.g. see Ref.[10]). The strength of a fiber in a composite is reduced because the average applied stress carried by each fiber, $T$, adds to the already existing tensile bend stress, $\sigma_b$. Letting the stress due to bending vary linearly with distance $(z)$ from the fiber's neutral axis (reaching a maximum value given by equation 3), the superposition of applied and bending stresses leads to a break density of

$$\rho(T) = \rho_0 + \frac{1}{LL_0 \pi r^2} \int_{-r_0}^{r} \int_{L \pi r^2}^{r} \left( \frac{T + z \sigma_b(l)}{\sigma_0} \right)^m dz dl.$$  \hspace{1cm} (5)

where $r$ is the radius of the fiber.

The damage, $\rho(T)$, can then be used to obtain the ultimate tensile strength of a unidirectionally reinforced composite (with fiber volume fraction, $f$) [8]:

$$\sigma = \left( \frac{T}{2 \rho(T) l} \right) \left( 1 - e^{-2 \rho(T) l} \right)$$  \hspace{1cm} (6)

where $l$ is the slip length, defined as $l = rT/2\tau$ ($\tau$ is the interfacial sliding strength). Equation (6) can also be used to predict the stress-strain behavior of a damaged composite if the composite strain is taken to be $\varepsilon = T/E$. Figure 4 shows several stress-strain curves for varying levels of initial damage, $\rho_0$, and distributions of residual stresses (corresponding to different processing conditions). The stress is plotted in dimensionless form by normalizing with respect to the characteristic strength, $\sigma_c$, defined as

$$\sigma_c = \left( \sigma_0 T L_0 / r \right)^{1/(m+1)}$$  \hspace{1cm} (7)

It can be seen that the maximum stress attainable (i.e. the UTS) is significantly degraded by the presence of process-induced damage.

![Figure 4 Fiber damage during consolidation processing has a marked effect on the stress-strain behavior of a Ti-24Al-11Nb/SCS-6 composite; process-induced breaks (per meter) and the corresponding process conditions are indicated for each curve.](image-url)
Process-Performance Prediction

The results of the two previous sections may now be combined to explore the influence of consolidation process conditions on the ultimate strength of the finished composite. Figure 5 illustrates the influence of process conditions (as given by the densification rate and consolidation temperature) on the strength of a Ti-24Al-11Nb/SCS-6 composite. Contours are shown for constant values of $\sigma_{\text{UTS}}/f_0\sigma_c$. A value of 0.81 corresponds to the case of no damage due to processing (cf. Fig. 4). It can be seen that the optimal composite strength is achieved by processing at temperatures approaching 1000°C. This can be lowered if densification is allowed to proceed more slowly (corresponding to lower applied pressures). Obviously, these guidelines must often be balanced against other considerations, for example where high consolidation temperatures lead to excessive interfacial reaction between the fiber and matrix[1]; this will be incorporated as part of work in progress.

![Figure 5 Process-performance map showing the dependence of composite strength on consolidation process conditions; highest strengths are achieved for material consolidated at higher temperatures and lower strain rates (conditions which minimize fiber damage).](image)

Next consider the effect of varying the Weibull parameters characterizing the fiber strength distribution: this will affect both the accumulation of damage during consolidation and the strength of a composite containing initially undamaged fibers. From Figure 3 we have seen that increasing $m$, i.e. decreasing the spread in fiber strengths, lowers the extent of processing damage. Curtin’s model for the ultimate strength of a composite containing initially undamaged fibers[8] also indicates the positive effect of increasing $m$, which raises the predicted strength. Thus we might expect the UTS of a consolidated composite (containing some degree of damage induced by the process) to improve as $m$ is increased. Figure 6 (obtained for constant processing conditions) reveals a more subtle dependence of strength on Weibull modulus: for $m$ above about 5, increasing $m$ lowers the strength. (The strength is now plotted in dimensional form with units of GPa, since the normalizing parameter, $\sigma_c$ (equation 7), is itself a function of the Weibull parameters, $\sigma_0$ and $m$.) Only for values of $m$ between 1 and 5 does increasing $m$ have the
anticipated effect. The reason for this behavior is the influence of stored bending stresses; although as \( m \) is increased, fewer fibers are fractured due to bending, they are bent by the same amount. This is because the bend stiffness (determined by the fiber's size and Young's modulus) and the matrix properties, which together determine the deflection, have not been altered. As the number of breaks decreases (higher \( m \)), the influence of the residual bend stresses on the strength becomes dominant (this corresponds to the region labeled “Bend Stresses”). The process-performance model leads to the perhaps unexpected conclusion that fibers having intermediate strength variability (\( m = 3-7 \)) provide the best as-processed strength.

The results shown in Figures 5 and 6 are examples of how the models may be applied to guide the selection of materials and process conditions to achieve optimal strength. Alternative approaches may also be explored, including reducing surface roughness (which is controlled by conditions during spray deposition) and lowering matrix creep resistance, both of which lead to reduced fiber bending and fracture[9].

**Concluding Remarks**

The results presented in Figures 5 and 6 are an example of the relationships between consolidation processing parameters, constituent material properties and ultimate strength which may be explored using the models presented. The influence of matrix properties (yield and creep strengths), fiber size and stiffness and surface roughness may also be investigated. There are also other links between consolidation processing and composite strength, the most important of which, the development of a reaction zone at the fiber/matrix interface, has already been mentioned. A more complete description of the relation between consolidation processing and composite strength will include these additional effects.

Both the relations between process conditions and microstructure and those between structure and performance are frequently nonlinear; combining the models (to give a process-performance relation) sometimes leads to unexpected, or perhaps even counterintuitive, results (e.g. the influence of fiber strength attributes shown in Figure 6). This observation underscores the potential hazards of relying too heavily upon a combination of few experimental data and intuition to optimize the design of processes. Process-performance simulations, such as the one presented here, offer the process engineer a means of working backwards from the designer's performance specifications to the process and specific process schedule which will ensure they are met.
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References

1 H.N.G.Wadley, R.Vancheeswaran and D.M.Elzey, “Virtual High Performance Composite Manufacturing”, also presented this volume.


