Assessing the Affordability of High Performance Composites

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Introduction

Currently available methods for analyzing the cost of materials are based on a measured (or guessed) process yield and a predefined product quality. However, cost, quality and yield are interrelated and sensitively dependent on the processing history used to produce the material. The application of process models to simulate the evolution of the material’s quality-defining attributes for a prescribed process history promises to allow the interdependencies between cost, quality and yield to be investigated for a given material system and processing technology. The approach has been dubbed ‘Quality-Cost Modeling’ (QCM). An overview of the QCM approach to composite materials is presented along with some specific examples highlighting certain features of the method.

Among the impediments to applications of advanced metal and ceramic matrix composites, one can list scientific issues (such as fiber/matrix reactivity in MMC’s), the lack of reliable design principles, limited properties database and high cost (Fig. 2). The high cost derives principally from the high cost of raw constituent materials (e.g. fine powders, continuous high strength structural fibers, whiskers, etc.), typically low process efficiency, low production volumes and an inadequate understanding of the relationships between processing and performance (Fig. 2). While scientific and technological issues remain, it has become increasingly evident (ref. 1), that attention must be concurrently focussed on both quality (i.e. performance) and cost.

The quality and cost, and thus the affordability, of a new material can be directly measured; the quality by means of mechanical property tests, metallographic investigation or by other standard means applied to material actually produced, and the cost by adding up the various contributors to the total cost of producing a given amount of material. But in situations where relatively little material is available for testing, the materials produced are often of inconsistent quality, and the factors affecting cost and quality are poorly understood, direct assessment of affordability of competing synthesis technologies is not possible. Assessing the affordability of advanced materials is also complicated by the fact that most of the available manufacturing technologies are still in a state of fairly rapid evolution; this requires that one be able to predict the potential for improvements in material quality and cost.

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A HITEMP contract awarded the University of Virginia is exploring the use of technical cost modeling (ref. 2,3) in conjunction with the application of predictive process modeling/simulation and structure-property models to perform cost analyses and to identify the critical cost- and quality-drivers during the production of continuous fiber-reinforced metal matrix composites. The QCM approach is distinguished from existing approaches to process cost analysis by its use of physical-mathematical models relating process conditions to evolving quality-defining microstructural features (such as matrix porosity, fiber damage, interfacial reaction zone growth, residual stress, etc.) which determine the performance of the final product (Fig. 3a). QCM promises to allow quantitative analysis of the cost-quality relationship during materials manufacturing processes and how this is affected by materials selection, process design and process conditions. It is intended to be applied to process steps for which cost and quality are interdependent and both are strong functions of the processing environment.1

**Quantitative Cost Modeling**

Figure 3a shows how the QCM approach combines process-structure and structure-property models to simulate the influence of processing conditions on cost and performance (i.e. affordability). The performance of the finished composite component is determined solely by the microstructural state of the material at the process exit, which in turn depends on the material’s initial state and on any microstructural changes occurring during the process. Process models are used to predict the evolution of the material’s microstructural features as a function of processing conditions. The final microstructural state is then related to its performance by means of the structure-property models.

The cost required to achieve a given product performance is obtained from the process models, which allow the rate and efficiency of material usage, labor input and energy consumption to be expressed as a function of the process conditions. Integration of these then leads to the cumulative cost for any specific process cycle. Of the cost elements, which include the cost of the raw materials, energy, labor, overhead and capital costs, only the capital cost is unaffected by the specific process schedule; the others may be strongly sensitive to the actual process cycle.

The QCM approach thus addresses several of the key cost issues mentioned previously: factors leading to the inefficient conversion of raw materials and resources into high quality material can be identified and numerical simulations used to observe the sensitivity of the process to changes in material and processing strategy. Critical cost-and quality-drivers can be identified and prioritized according to their influence on affordability. The cost/benefit ratio of various alternatives for reducing costs (including new process cycle designs, changes to the raw material, redesigning or upgrading process equipment) can be evaluated. The influence of production volume on the cost/kg of material can be estimated. Since the models serve to crystallize the current state of understanding of the relationships among process variables, evolving microstructural features, performance-defining attributes and cost-drivers, they also address the issue of understanding.

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1. Some process steps, such as fiber winding or encapsulation of material prior to HIP’ing, do not cause any microstructural changes (and therefore have no effect on final product performance), although they can have a significant impact on the final cost.
processing-performance relationships.

Figure 3b illustrates the use of optimization with the QCM models to obtain the best tradeoff between performance and cost. It is important to emphasize that detailed predictive models are not necessarily required for the application of QCM to a manufacturing process; numerically solved analytical methods (as opposed to finite element models) are appropriate, with only first-order effects considered. The models should be based on physical principles and must properly capture the sensitivity of one variable to changes in another.

**Example: Cost-Quality Analysis of Plasma Spray Deposition**

As an example of the process cost/performance analysis, the plasma spray deposition process as used to produce continuous fiber reinforced MMC's is considered. Figure 4 illustrates the steps needed to produce a composite component: first, monotapes are produced by passing a single layer of parallel, uniformly spaced ceramic fibers beneath a fine spray of plasma-melted metal/alloy droplets. Following deposition to the desired thickness, the tapes are cut and stacked to produce a laminate of specified macroarchitecture (ply orientation, stacking sequence, etc.). The laminate is then placed within a container, evacuated, and consolidated to full density and final shape by the application of pressure and heat, typically within a hot isostatic press (HIP). The performance of the end-product is determined by its shape and by the final microstructure, which is affected only by the spray deposition and consolidation steps.

Figure 5 presents a schematic illustration of the spray deposition and consolidation steps; the figure identifies the process variables (i.e., those variables which can be adjusted by the operator during the process), microstructural state variables and some of the process cost elements. The process is considered in three modeling steps: plasma spray creation, spray deposition, and consolidation. The objective of each model is to simulate the evolution of only the microstructural variables which are most sensitive to the process conditions used and which most strongly affect the final properties. The selection of critical microstructural features and first-order effects is based on experimental observations and information available in the open literature (e.g., refs. 4-6).

During plasma spraying, the metal/alloy powder which is to form the composite matrix is introduced into the plasma where the powder particles are accelerated and heated. The plasma, which is typically argon or an argon/hydrogen mixture, is generated by RF induction. Particle heating takes place by conduction and convection, with radiative losses to the surroundings. The model uses an energy balance (energy available from the plasma = energy absorbed by particle heating, melting and vaporization + radiative losses) to calculate the plasma equilibrium temperature at a given RF power and powder mass flow rate. Although the model is a one-dimensional idealization, the predicted temperature agrees well with mean temperatures obtained from more complicated 3-D mesh-type models. The plasma equilibrium temperature is then used to calculate the temperature and velocity histories of individual particles (in a powder size distribution). The temperature, velocity, diameter and liquid fraction of a given particle at impact with the substrate are predicted, which are then used as input to the deposition model.

As an example of the model's use to investigate cost-quality relationships, we consider the influ-
ence of powder size distribution during spray creation. Two key parameters are affected by the powder size distribution: the deposition efficiency ($e_D$, defined as the ratio of material actually deposited to that injected into the plasma torch) and the melting efficiency ($e_M$, defined as the ratio of molten material to deposited material). If the plasma temperature is high enough to cause complete melting of mean-sized particles, smaller particles in the powder size distribution will begin to vaporize, thus lowering the deposition efficiency. If $e_D$ were reduced to 0.5, for example, the cost of the matrix powder, which is already a significant portion of the composite cost, would be doubled. The melting efficiency on the other hand, affects not the cost, but the quality: the largest particles in the size distribution are typically deposited either unmelted or only partially melted, leading to the formation of internal porosity and increased monotape surface roughness. This has important consequences for the quality of the consolidated laminate since surface roughness has been shown to cause fiber damage and residual fiber bend stresses during consolidation.

Figure 6 shows the deposition and melting efficiencies for CP Ti as a function of RF power for three different powder size distributions. The distributions were assumed to be Gaussian for convenience (although log normal distributions are generally more appropriate for sieved powders), all with a mean particle size of 90 μm. The standard deviation was taken to be 15, 25 and 45 μm. The mass flow rate was fixed at 20 g/min (0.044 lb/min) and the gas flow rate was 60 slpm (2.12 cfm) for all cases. The deposition efficiency decreases with increasing RF power (since this increases the plasma equilibrium temperature) and, interestingly, is predicted to be insensitive to the particle distribution, at least over the range of deviations considered. The melting efficiency is more sensitive to the size distribution, with improved melting as the variability in powder size decreases. While improving the quality of the monotape, refining the powder size distribution (typically by repeated sieving) can increase the cost of the starting powder dramatically. A good combination of deposition and melting efficiency can be obtained for the smallest particle size variability ($e_D = e_M = 0.99$), but only over a very narrow range of RF power. It is unlikely that the model accurately predicts this optimal power setting, but the indication that it occurs over a limited range of settings properly reflects the difficulty of identifying optimal process conditions when spraying powders with a narrow size distribution. The intermediate size variability ($\pm 25$ μm) provides an adequate combination of efficiencies over a wider power range. It is also interesting to note that the tighter size distributions absorb less power while delivering improved efficiencies. These are observations that could not be obtained as cheaply by experiment nor as readily by intuition.

Figure 7 is a plot of melting versus deposition efficiency for the three particle size distributions shown in the previous figure. Considering the efficiencies as merit indices, matrix cost is reduced and composite quality enhanced as one moves toward the upper righthand corner of the plot.

The formation of the monotape by the impact, spreading and freezing of the droplets is too complex to be modeled in detail, at least for the present purpose. Instead, a model developed by Majdeski (ref. 7) is used to calculate the final splat diameter of molten particles selected from the particle size distribution. Majdeski’s model requires as input the temperature, velocity and diameter for each particle upon impact with the substrate (assumed flat and of known temperature). A weighted average of the splat diameters is then taken as representative of the deposit’s microstructural state. The microstructural variables of interest, e.g. relative density and surface rough-
ness, are expressed as functions of this scalar quantity (labeled $\zeta$). The functional forms for these relationships are written as polynomials in $\zeta$ whose coefficients must be determined by calibration with experimental observations. Figure 8 shows the decrease in surface roughness (as characterized by the standard deviation in surface asperity height) with increasing quality ($\zeta$), calibrated using surface profilometry data for plasma sprayed Ti-24Al-11Nb monotapes.

The surface roughness and relative density formed during the spray deposition step define the initial conditions for consolidation processing. Figures 9 - 11 show how previously developed models for the consolidation process, which simulate the evolution of relative density and fiber fracture and bending during consolidation of MMC laminates, have been used to predict the final microstructure as a function of processing conditions. Figure 12 shows the influence of consolidation process-induced fiber damage on composite ultimate strength (ref. 8). The quality index, $\zeta$, determined by the spray deposition process, can therefore be directly related to performance-defining attributes of the final product, such as the composite tensile strength (Fig. 13).

The previous discussion is an illustration of how the performance (quality) of the final material product is related to processing conditions; next, the cost of obtaining a given level of quality will be considered. Figure 14 shows the cost of spray-deposited Ti-6Al-4V (monolithic) monotape per kilogram versus the quality achieved for the three powder particle size distributions. The quality was varied for each size distribution by varying the RF power (and hence the plasma equilibrium temperature). Even though the coarse distribution does not offer the best combination of melting and deposition efficiencies (see Fig. 6), the coarsest powder size distribution possesses the best cost-quality relationship. There are several reasons for this: firstly, the raw powder costs less in this case because it can be obtained in a single sieving operation, whereas the more narrow distributions require repeated sieving. Secondly, the wider size distribution allows more efficient packing (an effect accounted for in the model), with smaller particles (droplets) more easily filling gaps created by larger particles (droplets). Lastly, the larger particles in the wide distribution are accelerated more rapidly in the plasma and therefore impact the substrate with greater velocity than smaller particles. This leads to improved tape quality because the amount of droplet spreading on impact increases sensitively with droplet velocity.

Figure 15 shows the influence of mean particle size on the cost and quality of spray-deposited Ti-6Al-4V. The plasma equilibrium temperature has been held constant at 3000 K and the coefficient of variance (i.e., the ratio of the standard deviation to mean size) has been kept constant at 0.5. Also plotted is the raw powder cost, which increases substantially as the mean particle size decreases. The figure shows that decreasing the mean particle size leads to continuous improvement in deposit quality, but at an exponentially rising cost. The inset plot of melting and deposition efficiency shows why: as the mean particle size decreases, the deposition efficiency falls because of increased vaporization. This means that in addition to the already greater cost of the smaller particles, less of the material is actually reaching the substrate.

Figure 16 shows cost versus quality for a Ti-6Al-4V/SiC fiber reinforced MMC monotape with the cost elements broken out for comparison. A fiber volume fraction of 40% was assumed. (Note that not all costs are included in the figure, such as labor, overhead, and so forth and that further costs will be incurred when the monotapes are consolidated to create a laminate.) High performance SiC fibers, such as Textron’s SCS-6 fiber, are currently only produced in small volumes
and therefore cost around 2,200 $/kg (1,000 $/lb). It is quite evident from the figure that, relative to the total cost, the additional cost required to achieve the highest quality is insubstantial. The overall cost is dominated by the high costs of the raw powder and fiber constituents. The insignificant energy costs mean that the rather low RF coupling efficiency (about 50% of the energy supplied to the plasma torch actually becomes available to process the powder) is no shortcoming of the plasma spray compositing route.

Figure 17 provides the same information, but considers the impact of a low-cost fiber (220 $/kg (100 $/lb)); now the cost of the raw powder becomes the most critical cost-driver. If large powder production volumes are considered, the cost of raw powder decreases; this effect is shown in Fig. 18. Powder cost still dominates the overall cost, but the low deposition efficiency incurred at the highest quality ($\zeta = 1.65$) now represents about 20% of the overall composite cost. Clearly, cost optimization of composite manufacturing processes can only have a significant impact on affordability once the overall costs are no longer dominated by the high cost of the constituent materials.

**Comparing Alternative Processes**

A key objective of the QCM analysis of MMC processing routes is to contrast the potential of several of the most promising processing routes for cost reduction due to the economy of scale. Figure 19 shows three composite manufacturing routes: directed vapor deposition, tape casting and plasma spray deposition. Figure 20 compares the cost versus production volume for these three process pathways. Figure 20 was obtained using a conventional cost model (quality and efficiency are therefore entered as measured or assumed quantities), and is included only to illustrate the type of result expected once the quantitative cost analyses have been completed. As shown in the figure, the cost to produce the first pound of material is very high because it includes the capital costs needed to purchase the processing facility. With continued production, the cost per pound decreases due to amortization of the initial investment. For low production volumes, the process with the lowest capital cost (e.g. tape casting) will be most economical. At large production volumes (> 1,000 lb), raw material costs and process efficiency become the cost-drivers. Figure 21 shows this regime in more detail; the vapor deposition process, because of its use of inexpensive bar stock (rather than fine powders), provides the lowest cost.

**References**


Objective

A quantitative cost modeling tool for assessing and comparing the cost of producing advanced composites

Fig. 1
Impediments to MMC Applications

Scientific issues

Design principles

Properties database

Cost

Structural fibers/alloy powders are expensive
Low process efficiency
Low production volumes
Poor understanding of process-performance relationships

Fig. 2

QCM:
PROCESS AND STRUCTURE-PROPERTY MODELS
FOR EVALUATION OF COST-QUALITY-YIELD

SIMULATION

Material / initial microstructural state

Raw materials cost ($ / kg)

Final microstructure

Material use efficiency

Performance (quality / yield)

Input a hypothetical process schedule

Resource models ($ / kg)

Operating costs:
- energy
- labor
- indirect costs

Total cost ($ / kg)

Structure - process models

OPTIMIZATION

Specify performance

Structure - process models (inverse)

Goal - state microstructure

Evolving microstructure

Process - structure models (inverse)

Process conditions

Optimization

Alternatively: include costs as an optimization parameter

Costs

Process

Actual product

Actual quality / yield

Material costs

Given initial material / microstructural state

Fig. 3
Fig. 4

PLASMA SPRAY DEPOSITION PROCESS FOR THE MANUFACTURE OF FIBER REINFORCED MMC's

Fig. 5
Fig. 6

Fig. 7
Fig. 8

MONOTAPE CONSOLIDATION
TMC HOLLOW FAN BLADE

Fig. 9
Fig. 12

Fig. 13
Fig. 14

Fig. 15
Fig. 16

Fig. 17
MMC Monotape Cost vs Quality
High volume production with low cost SiC fiber

<table>
<thead>
<tr>
<th>Fiber: low cost (200 $/kg)</th>
<th>Powder (Ti-6Al-4V)</th>
<th>Energy</th>
<th>Gas</th>
<th>Material Losses</th>
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Cost ($/Kg)

<table>
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<th>Quality Index, $\zeta$</th>
<th>1.32</th>
<th>1.43</th>
<th>1.54</th>
<th>1.65</th>
<th>1.76</th>
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SuperAlloy Cost
10 - 50 $/kg

Fig. 18

High Performance Composite Processing Pathways

Vapor deposition
- Fiber
- Alloy coating (matrix)
- Array of parallel metal coated fibers to form monotape

Slurry caster
- Fiber
- Flexible, cast fiber reinforced monotape

Plasma spray
- Fiber
- Porosity
- Array of fibers coated with a spray of molten alloy droplets

Fig. 19
Basic Comparison of the Three Processes

\[ C_p = C_m + \frac{C_c}{n} + \frac{\dot{C}_f}{n} \]

\[ C_m = \eta f C_1 + (1 - f)C_2 = \text{material cost / lb} \]

\[ C_c = \text{capital cost} \]

\[ \frac{\dot{C}_f}{n} = \text{time dependent costs} = \frac{\text{labor rate + powder consumption}}{\text{production rate}} \]

<table>
<thead>
<tr>
<th></th>
<th>RF plasma spray</th>
<th>Tape casting</th>
<th>Directed vapor deposition</th>
</tr>
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<tbody>
<tr>
<td>Equipment capital cost, ( C_a ) (x ( 10^3 ) $)</td>
<td>650</td>
<td>75</td>
<td>450</td>
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<tr>
<td>Material use efficiency, ( \eta ) (%)</td>
<td>85</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Energy cost ($ / h)</td>
<td>0.018</td>
<td>0.008</td>
<td>0.016</td>
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<tr>
<td>Rate of production, ( n ) (lb / h)</td>
<td>5.5</td>
<td>39.6</td>
<td>5.3</td>
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<tr>
<td>Cost of labor ($ / h)</td>
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<td>30</td>
<td>30</td>
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<tr>
<td>Matrix cost ($ / lb)</td>
<td>150 (powder)</td>
<td>200 (powder)</td>
<td>30 (bar)</td>
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<tr>
<td>Fiber cost ($ / lb)</td>
<td>1000</td>
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Fig. 20

Detailed Comparison of the Three Processes at Production Volumes of Greater than 1000 lb

Fig. 21
Summary

- Quantitative Cost Modeling relies on first-order, analytical process models to perform materials manufacturing cost analyses.
- QCM is distinguished from conventional production costing methods by the use of process and structure-property models which allow cost versus quality relationships to be obtained quantitatively.
- QCM is intended to aid in process optimization, cost reduction and the identification of processing pathways having the greatest potential for achieving material affordability goals.

Conclusions

- QCM can be a cost-effective method for analyzing material manufacturing costs, selecting among alternative processing pathways, identifying critical cost-drivers and assessing the potential for cost reduction through process refinement, raw material selection and processing strategy.
- The QCM approach is most effective when processing technology is rapidly evolving, when several very different yet apparently equal processing pathways exist and where final properties and cost are highly sensitive to processing conditions.