AN EXPERT SYSTEM FOR METAL MATRIX COMPOSITE SELECTION AND DESIGN

by

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ABSTRACT

This thesis summarizes the development and components of an expert system which supports engineers in the selection and design of metal matrix composites(MMCs). The system consists of a dynamic hypertext interface integrated into an expert system developed within the COMDALE/X environment.

Mechanical and thermophysical material property data for matrix alloys, reinforcement materials, and MMCs is stored in databases accessed by the expert system. Mathematical models which utilize constituent material properties to determine effective composite properties are managed by the system to design metal matrix composites and fill in property gaps. Effective elastic modulus, thermal conductivity, coefficient of thermal expansion, Poisson's ratio, shear and bulk moduli mathematical models for particulate, whisker, short fiber and fiber composites are contained in a spreadsheet managed by the system.

Although the physical and mechanical properties may often limit the constituent selection, it is the chemical reactivity of the ceramic reinforcement with the matrix alloy either during service or fabrication which will generally control the final matrix/reinforcement combination. As a result, constituent material compatibility has been

determined and incorporated in the system. A database of appropriate reinforcement coatings for applicable matrix/reinforcement systems is also included.

MMC material properties are directly influenced by manufacturing techniques. Although a variety of fabrication methods exist, they are limiting factors which control the availability of a suitable method for any given material design. As a result, a decision analysis technique has been developed to predict suitable manufacturing methods.

The system hypertext document is an on-line reference setup to allow easy access to materials information. Materials selection, effective composite property information, mathematical modeling, constituent compatibility, and manufacturing methods are among the topics covered. Relative manufacturing costs have been determined and these have been summarized in the hypertext document. A cost database of reinforcement and MMC materials has also been compiled.

Three consultation sessions have been included to demonstrate the capabilities of the expert system. Finally, system validation and evaluation are discussed.

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NOMENCLATURE

d	reinforcement diameter(μm)
e	reaction layer thermal conductivity/thickness(W/m^2K)
E	elastic modulus(GPa)
G	shear modulus(GPa)
k	thermal conductivity(W/mK)
K	bulk modulus(GPa)
L	length of elongated reinforcement axis(μm)
r	reinforcement radius(μm)
s	reinforcement aspect ratio
V	volume fraction
ν	Poisson's ratio
α	coefficient of thermal expansion(x 10^{-6}/K)

Subscripts

f, f	fiber
L	longitudinal
m, m	matrix

p, p	particulate
r, r	reinforcement
sf, sf	short fiber
T	transverse
w,w	whisker
(+)	upper
(-)	lower

Superscripts

*	effective composite property

MMC material designation standard format is A/B/Cx-TT, for example, 6061/SiC/25w-T6.

A refers to the matrix alloy, 6061 in the example

B the type of reinforcement, SiC in the example

C the reinforcement volume percent, 25 in the example

x the shape of the reinforcement(f = fiber, sf = short fiber, p = particulate, w = whisker)

TT the temper, T6 in the example

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

An important design decision in any product development is the correct choice of material[1]. Assessing new materials requires domain knowledge that is seldom available in design and engineering departments. Most published surveys indicate that few materials are familiar to design engineers in spite of the wide range of materials currently available[2]. The lack of knowledge of manufacturing limitations and materials selection are the two most common reasons for lengthy design cycles[3]. Problems dealing with material selection are paramount in design and are generally solved using the experience-based judgment of the designer.

A typical problem of materials selection usually involves one of two situations: the selection of a material for a new product or design, or the re-evaluation of an existing product or design to reduce costs, increase reliability, improve performance, and so on[4]. Material selection is a trade-off between performance and cost where the factors associated with design, fabrication and material properties must be balanced[4,5]. Specifically, a simple substitution of a new material without changing the design to exploit both the material properties and manufacturing characteristics rarely results in the optimum utilization of the material. For example, the optimum shape of a component made of brass is unlikely to be the same as one made of steel, or glass fiber reinforced plastic, or injection molded plastic with the same function[6]. Thus, true selection requires carrying out parallel design routes with different materials.

Decision making for advanced materials systems like metal matrix composites is a complex and difficult process. Performance gains which can be achieved include weight reduction, increased stiffness, tailorable thermal conductivity and coefficient of thermal expansion, wear resistance, elevated service temperatures, radiation resistance, and increased strength. The designer is not simply a materials selector but a materials designer due to the ability to select a reinforcement/matrix combination to meet the design criteria.

The tailorability of metal matrix composites for specific applications has been one of their greatest attractions and simultaneously, one of their most perplexing challenges[7]. The matrix may be any number of alloys and the reinforcements can be of a variety of types, have different surface treatments, have a range of volume fractions, or have different geometries. Although potential material candidates are vast, typically only the matrix and, to a lesser degree, reinforcement property data are adequately known. Thus, the designer has few resources to clearly define a range of metal matrix composite materials for evaluation.

In order to fill this void, an expert system has been developed to support design engineers in the selection of and design with metal matrix composites. The system consists of a dynamic hypertext interface integrated into an expert system developed within the COMDALE/X environment. Experience-based and non-quantitative information from experts necessary for selection are effectively represented with this expert system.

Numerical material property data employed in design calculations is efficiently stored in databases and managed by the system. Mathematical models which relate the properties of the constituent materials to determine effective composite properties are managed by the system to design metal matrix composites and fill in property gaps.

CHAPTER 2

SCOPE AND OBJECTIVES

An expert system prototype has been developed to aid design engineers in the selection and design of metal matrix composites. In order to accomplish this, the following objectives were pursued:

(1) To address the interdependence of material performance, manufacturing, properties and microstructure

(2) To identify gaps in the available materials information

(3) To employ mathematical modeling techniques to predict effective composite properties and infer new knowledge

(4) To provide experience-based knowledge of materials experts

(5) To effectively manage material property databases and a mathematical analysis applications tool

To accomplish this task, computer aided software engineering tools, namely an expert systems applications tool COMDALE/X and an external applications tool Microsoft EXCEL, were utilized. A prototype was constructed which in the absence of complete data sets, procedures or functions, still runs and can demonstrate pertinent system characteristics. The amount of materials information to be processed by the system was limited to fundamental material property data, simple analytical models, and heuristic information required during the early stages of the design process.

CHAPTER 3

ADVANCES IN MATERIALS SELECTION FOR DESIGN

3.1 MATERIAL DATABASES

Fundamental to all material selection systems are computerized collections of material properties organized in the form of databases with fixed record structures and search procedures. These can be multi-material databases with several different material types and properties, databases for one type of material with an extensive representation of properties, or databases for several different material types with specific types of properties. Material databases are advantageous because they have the ability to store large amounts of information in a form in which specific pieces of information can be retrieved. They are relatively easy to keep current, can link related data, and can make information available to users simply[4,13].

Table 3.1 contains representative examples of material database systems. MTDATA is a multi-material database for metallurgical thermochemistry[8]. It contains thermodynamic data which are used to calculate chemical and phase equilibria in multicomponent multiphase systems. The ALUSELECT system is a database containing material properties on 105 aluminum alloys in the full version and 28 common European alloys in the public version[9]. An MMC addition to ALUSELECT is in the early stages of development such that material properties are still being gathered from literature and commercial sources. However, the metal matrix composites contained in this database will be limited to those with aluminum alloy matrices exclusively.

The High Temperature Materials databank(HTM-DB), has been developed to store original test data and use statistical and model-based methods to evaluate tensile, creep, fatigue and fracture mechanics properties[10]. The primary role of this system is to provide materials data for computer aided engineering from raw test data. The database currently stores information on a handful of Ni alloys and can generate inputs such as the Norton creep parameters from this data for finite element code using mathematical algorithms.

M/Vision has been developed by PDA Engineering over the last 10 years to automate and improve the process of generating design allowables[1] and material processing models for use in material selection and finite element analysis[11]. An engineering spreadsheet is the controlling tool of this system which accommodates the input of raw test data, derivation of design allowables, storage of these values in the design allowables database, creation of standard material reports, and the creation of input decks for finite element codes.

The main drawback of these and other conventional material database systems is their lack of a formal material selection routine. At best, a pass-fail selection criteria is applied following database lookup and retrieval of target property values. To compensate,

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1. Design allowables are design property values derived from sets of data using statistics

material selection systems have been constructed which employ formalized selection procedures using data retrieved from material databases.

Difficulties specific to composite material databases include the diversity in quality assurance of the data and lack of standardization and quality control in test methods[15]. Although efforts are being made to establish test methods, especially by professional societies such as American Society for Testing and Materials(ASTM), these efforts seriously lag the development of metal matrix composite materials. Consequently, data frequently suffer from absent entries and suffer even more from multiple entries which differ because of the differences in methods of determination rather than because of differences associated with the material system. The ability to include a measure of the degree of belief and relevant information of property values is a necessity which will be addressed in this work.

Table 3.1 Typical Material Databases[8,12,13,22,26]

Type	General Characteristic	Example	Coverage
Database	one type of material with a wide range of properties	MATEDS	material properties of aluminum alloys
Database	one type of material with a wide range of properties	ALUSELECT	material properties for aluminum alloys and initial aluminum matrix MMCs
Database	specific properties for application specific materials	HTM-DB	mechanical properties of high temperature metals with calculations option on the data
Multi-material database	a wide range of materials and properties	M/Vision	material properties for a range of metals and composites - under development
Multi-material database	specific properties for a wide range of materials	CORSUR	mechanical properties and corrosion resistance of ferrous/non-ferrous alloys

3.2 MATERIAL SELECTION DATABASE SYSTEMS

The selection of materials is far from easy. There are many conflicting goals in representing materials information and there is not yet a generally useful model for describing materials data[17]. As a result, the majority of material selection systems simply apply a selection routine using the data obtained from their material databases.

A consensus on the approach to materials selection has not evolved and no single or small number of methods have emerged to a position of prominence[4,17,18]. Popular methods include those listed in Table 3.2, what worked before, and what the competition uses[3-5,19-21]. Academic research and database developers have concentrated on the irreducible core of material selection, where every property value is usually considered to have identical reliability or quality for a closed set of materials[17]. It is also assumed, however incorrectly, that the database property information is sufficient and appropriate for the selection task. The majority of material selection systems follow a systematic approach as follows[4, 8, 9, 16-18,20-27]:

1. Analysis of requirements and critical material properties

2. Screening of candidate materials by comparing required properties with a large materials database to select a few promising candidates

3. Selection by analyzing candidate materials in terms of tradeoffs in product performance, cost, fabricability, and availability to derive the best material for the application

4. Development of design data from reliable measures of material performance and key properties under service conditions

Examples of these systems are given in Table 3.3. The Fulmer Materials Optimizer is designed to select and specify the material and manufacturing route for a new product and to evaluate alternative materials or manufacturing routes for an existing product[24]. The selection technique employed in this system is the weighted property factors method. For each material, the user specifies critical properties and their weighting factors. The system then determines a merit rating for each material and those with the highest ratings are selected.

Mat.DB contains data on carbon and alloy steels, thermoplastics, tool steels, titanium and aluminum alloys[4]. Mat.DB can search the database by material group, UNS number, common name, manufacturer, specification designation, ranges of chemical composition, product form, heat treated condition, and up to 40 properties.

The major disadvantages of these two systems is that formal design analysis must be conducted before the pre-selection stage in order to establish material requirements. Furthermore, complete and detailed material property information is simply not readily available for screening[29-32]. If a database is complete, then simple and powerful indexing and search techniques are possible; however, sparse databases are far less easy to use since searches conducted for particular property values reject materials whose properties are absent or not yet measured[33]. This is the case of metal matrix composites where a lack of material property measurements is one factor which limits their widespread use.

The Cambridge Materials Selector(CMS) is a multi-material CAD software package for the selection of materials for design[26]. The addition of a limited number of metal matrix composites to the database has recently been completed[27]. The user performs a series of selection stages in which a pair of material properties or performance indices of interest is specified. The user then sets the attribute threshold graphically. The database stores ranges of values for a given property to account for potential inaccuracies and null values in the data[4,28]. No distinctions between well characterized and less characterized values are given in keeping with the intent of the system to deliver only approximate data on the broadest possible range of materials.

All three of these systems use relative rankings for properties such as machinability, weldability, corrosion resistance, and average processing cost. However, the use of pass/fail, maximizing performance or utility function approaches have a major drawback based on the need to represent all performance criteria as stable properties with equal value. Ranking values of 1 to 10, typically assigned to properties such as processability or weldability, are generally incomplete and potentially inaccurate leading to erroneous results. For example, value judgments on qualities such as corrosion resistance are extremely difficult to make.

Difficulties inherent to material class selection systems such as the CMS are also apparent. Ashby has analyzed material selection and design problems with the goal of achieving desired mechanical and thermal properties[26]. However, once a material class is selected, many aspects of the component design and manufacture are dictated or constrained. As a result, potential candidate materials are eliminated prematurely.

When material selection was analyzed as part of the design process, it became apparent that[34,35]: (1) There is no agreed point where the material is selected. Each selection is subjected to evaluation and review in an iterative fashion. For example, it is necessary to define the material properties to determine the stresses, while the stresses often determine the material. (2) Material selection is neither routine or easy. For example, many materials are chosen not for their intrinsic properties but by their properties when linked to other components, as in welding and spray coating. (3) The restraints on the use of a material extend beyond it own behavior. For example, an ideal choice may have such superior corrosion resistance that is causes catastrophic galvanic corrosion in an adjacent component.

The major disadvantage of relying solely on data compiled in databases is that the data types which can be represented are limited. Experience-based and other pertinent material selection information, such as the effect of adjoining components in an assembly on a material, cannot be adequately represented. Many end-users of materials data claim that maintaining either actual data on parts in service or at least laboratory simulations of actual service conditions provide more useful measures of properties and performance than standard lab procedures currently used[5]. Databases do not give enough information to permit detailed evaluation of a material which is necessary before design decisions are reached and the manufacturing method is chosen[14,16]. A quantitative approach is needed to combine material behavior and experience-based information to fill in the gaps.

Table 3.2 Material Selection Methods[1,4,5,24,25]

Method	Description
Cost versus Performance Indices	express trade-off between cost and properties
Weighted Property Factors	performance requirements are weighted with respect to their importance
Value Analysis	least expensive way to manufacture product without compromising quality or reliability
Failure Analysis	minimize risk of failure, e.g. Weibull Analysis
Benefit-Cost Analysis	incorporates lifecycle costs, reliability, etc. in decision
Hanley-Hobson Method	algebraic approach using minimization of the sum of deviations of properties from their target
Linear Programming Method	optimize objectives while satisfying constraints
Target Properties & Database Lookup	pass-fail criteria
Reasoning with Descriptions and Constraints	artificial intelligence methods

Table 3.3 Material Selectors[16-18,21]

Type	**General Characteristic**	**Example**	**Coverage**
Multi-material database with selection routine	a wide range of materials and properties	Mat.DB	material properties and processing procedures of steels, composites, plastics, and titanium, magnesium, aluminum and copper alloys
Multi-material database with selection routine	a wide range of materials and properties	Fulmer Materials Optimizer	material properties of metals, ceramics, plastics, manufacturing processes, and costs
Multi-material database with semi-systematic selection routines	a wide range of materials and properties with performance indices	CMS	material properties of metals, ceramics, plastics, wood, composites and processability, shape and cost factors

3.3 MATERIALS SELECTION EXPERT SYSTEMS

Material selection is a proven area of expert system application if the knowledge can be represented by clear rules[22,36-40]. Expert systems utilize knowledge bases which are relatively small compared to most databases, are considerably more complex in structure, and are by necessity, highly focused in specific domains[36,37]. This is evident in Table 3.4 where all of the expert systems share the general characteristic of specific properties for application specific materials.

One highly successful expert system is SOCRATES from Cortest Laboratories[8]. This system is designed to help select corrosion resistant alloys based on mechanical, environmental and metallurgical considerations. Two databases, one of alloy composition and the other of material behavior based on lab and field data, are integrated within this system.

An advisory program called PAL is designed to help a user select an adhesive or sealant for a particular application[8]. The user is asked a series of specific questions such as the nature and surface finish of the materials to be joined, temperature of use, and lifetime required. Users are required to know exactly what they want to do in order to successfully use this system.

A materials selector expert system for advanced ceramics is under development to assist users in identifying candidate ceramic materials for high temperature heat exchangers and recuperators[41]. The demonstration system will integrate expert system capabilities with the Structural Ceramics Database at NIST. This undertaking follows the philosophy of focusing on one application area to keep the problem tractable. Currently, only the software tools are under development.

The Center for Intelligent Processing of Materials is developing modular software for intelligent, integrated, and interactive design, called I^3D[42]. The software uses an artificial intelligence system approach which allows communication among the various databases and modules. The modules themselves may use an expert system or an analytical methodology. Currently, a powder-processing application is under development.

These expert systems utilize existing knowledge of established materials in well-defined applications. They do not have the means to consider information relating to new materials. The rules are constructed for the materials contained within the respective system databases and any new information or data requires major system revision.

The potential of expert systems to create new or revised inferences and rules as new databases are developed or existing databases updated has the potential of expanding the knowledge envelope. Material selection expert systems which employ this concept are not yet commercially available and have not been published in the open literature. However, this area of expert system application is conducive to metal matrix composites where limited experience is available but knowledge may be inferred using predictive modeling and analytical techniques in conjunction with material databases and decision analysis techniques using generic rules.

Table 3.4 Expert Systems[27,34,41]

Type	**General Characteristic**	**Example**	**Coverage**
Expert system question and answer interface with database	specific properties for application specific materials	PAL	properties of adhesives and sealants with option to perform elastic stress analysis of joint
Expert system question and answer interface with database	specific properties for application specific materials	SOCRATES	material properties and cost of corrosion resistant alloys with option for cost comparisons and sensitivity analysis

3.4 DATABASE MANAGEMENT SYSTEMS

Database management systems are the tools which organize and maintain the data stored in a database[15]. Computer aided design, geographic information systems and knowledge-based systems require databases which can store large quantities of information having complex structures. As databases become more varied in their applications, many of the data processing requirements exceed the capabilities provided by conventional database management systems. For example, an engineering design system may have to store data in the form of technical design diagrams and descriptions which can not be accommodated by conventional database systems.

Currently, research into extended relational database models has led to the development of the nested relational model(NRM)[78]. This model allows the attributes of a relation which have been restricted to tabular values, to be a number of abstract data types. It is suggested that this model may be appropriate for use in scientific and engineering databases[78]. Since conventional database management systems based on relational, network, or hierarchic data models cannot effectively meet requirements for representing and manipulating complex information, it is doubtful the nested relational model is in fact the solution[12-15,17,75,79,80]. As a result, the expert system in this work has been designed to function as the database management system. In order to use databases effectively, a knowledge base is necessary so that an intelligent approach to the search can be performed. Therefore, an approach has been formulated in this work to combine an elimination process common to these selection databases with a semi-qualitative method of a knowledge base and on-line hypertext interface.

3.5 USER INTERFACES

The importance of a flexible user interface to satisfy all user requirements has been identified[17,75]. A layered approach has been proposed which would allow various levels of access with the data partitioned horizontally by application area and vertically by amount of detail[75]. The NSF Workshop on scientific databases suggests that both menu-driven and command language interfaces be provided. However, these approaches are only effective for conventional databases, not expert systems.

Many databases incorporate graphical and computational capabilities which can be invoked by the user as aids for data interpretation but expert guidance in their selection and use is generally lacking. Well designed interfaces are expected to provide expert guidance allowing for the itemizing of additional data for known relationships which might not be apparent to the non-expert user[13]. An example of this type of system is the specialized polymer database Natural Rubber Formulary and Property Index[8]. This database operates within the MORPHS information retrieval system which uses artificial intelligence to produce a user friendly interface. MORPHS is designed for use with textual information together with a limited amount of quantified data.

In practice, the question and answer approach of expert system interfaces can make them frustrating to use. The inability to view the total system contents inhibits the user in obtaining specific information due to the constraints of the knowledge formulation. To address this shortcoming, the integration of hypertext documents and expert systems is being pursued[76,77]. Although initially developed for text information, the versatility and potential of a well designed user interface using hypertext is an effective technique to conduct specialized data manipulation and viewing. This approach has been undertaken in this work.

CHAPTER 4

EXPERT SYSTEM DESIGN

4.1 INTRODUCTION

Expert systems are a part of the field of knowledge engineering. The approach is to apply a number of techniques to capture and imitate the decision making behavior of human experts in certain narrow domains of knowledge. Although this is a separate field of endeavor, knowledge based or expert systems can be viewed as a special case of information systems and are developed in a similar manner[79].

4.2 SYSTEM DEVELOPMENT

In its simplest form, the development of an information system, or expert system, can be seen as a list of procedures requiring iteration and overlapping known as the information systems development life cycle[80]. This simple model has been used extensively in information systems development due to its simplicity. However, this model does possess shortcomings as a result of its principles; namely, that the goal is known before beginning, that it is possible to proceed along a straight line towards the goal, and that a complete and correct system can be delivered[79,80]. These assumptions are to a certain degree unrealistic. A method of overcoming these problems is to use the approach of a working model or prototype shown in Figure 4.1[79].

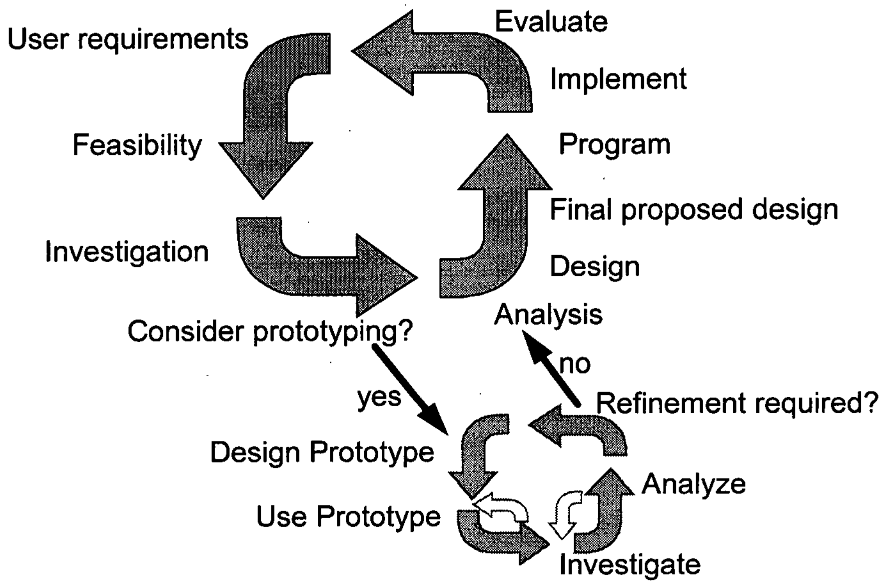


Figure 4.1 Prototype Model of Information Systems Development[81]

The development of this system has followed the prototyping approach which is based on the ability to construct and revise information systems rapidly, where speed is achieved through the use of computer aided software engineering(CASE) tools such as expert system shells, databases and so on[81].

4.3 SYSTEM DESIGN

Four major perspectives are considered during the analysis and design of an information system[80]: (1) the functional activity of the system, (2) the system's technical components (3) the organizational role of the system and (4) the users' interests and requirements.

4.3.1 SYSTEM FUNCTION In this study, an expert system has been developed to aid design engineers in acquiring and utilizing metal matrix composite materials information in their product design. As discussed in Chapter 1, current materials databases and selection systems do not give enough information to permit detailed evaluation of a material which is necessary before design decisions are reached and they do not have an effective means to consider information relating to new materials. Consequently, this system is designed to supply material behavior combined with experience-based information on current MMCs and to infer new knowledge using predictive and analytical techniques to design new MMCs.

4.3.2 ORGANIZATIONAL ROLE Information systems are either designed to aid a whole organization or perform specific tasks within it. This system design is unique in that it functions both as a design tool performing specific tasks and as an advisor guiding firms in their new product design. For example, a packaging materials research group would employ this system in their product development strategy. Specifically, they would identify candidate metal matrix composite solder materials with coefficient of thermal expansion values matching those of assembly components. On the other hand, design engineers would also employ the system to fill material property gaps and understand material behavior as part of their on-going material selection and design function.

4.3.3 USER REQUIREMENTS The identification and fulfillment of user requirements is fundamental to the success and acceptance by designers of this expert system. Table 4.1 is a list of requirements which have been gathered from user critiques of current materials databases and selection systems[6,8,15-18,21,29,30]. The system design incorporates these requirements in the various components as listed in Table 4.1.

4.3.4 TECHNICAL COMPONENTS This system, shown in Figure 4.2, has been developed using the expert system shell Comdale/X linked to Microsoft Excel spreadsheet and databases running in the Microsoft Windows operating environment on a personal computer. Comdale/X is an expert system applications tool comprised of a knowledge base, inference engine, user interface, and utilities[82].

The knowledge base consists of facts and heuristics about the domain in the form of rules, procedures, objects, and classes. Objects represent factual information, classes embody structural relationships of facts in a hierarchical classification, rules are the complex relationships formed between the facts and procedures are used to apply rules and manipulate classes and objects. The inference engine processes belief in facts contained in the knowledge base to make decisions through inference and control strategies that select and execute rules.

The Comdale/X inference engine can be embedded in an application, thereby having no user interface, or can be customized by the developer. The customization of the inference engine was employed using the Hypertext and Form utilities to provide a more robust and flexible user interface allowing access to on-line interactive documentation, knowledge acquisition, and the ability to freely navigate and view the system contents.

Table 4.1. Materials Selection System Requirements

User Requirement:	Met by System:
Simple/User friendly	User interface
Relate to real world materials e.g. material designations	Databases
Compatible with quantitative design analysis	Databases, Mathematical Modeling Spreadsheet
Material constraints available	Knowledge Base, Hypertext Document
Reliable information, data sources	Databases, Hypertext Document
Accessible at different levels, move around quickly without lengthy or complicated procedures	User interface
Consistent data quality	Databases, Knowledge Base, Hypertext Document
Knowledge of system limitations	Knowledge Base, Hypertext Document
Data/Information relationships presented	Knowledge Base, Databases, Mathematical Modeling Spreadsheet, Hypertext Document
Indication of data/information contained	User interface, Databases, Hypertext Document
Textual and graphical information	Knowledge Base, Hypertext Document, Databases, Mathematical Modeling Spreadsheet
Manufacturing information	Knowledge Base, Hypertext Document, Databases
Cost information	Hypertext Document, Databases
Relevant supporting materials' information available	Databases, Knowledge Base, Hypertext Document

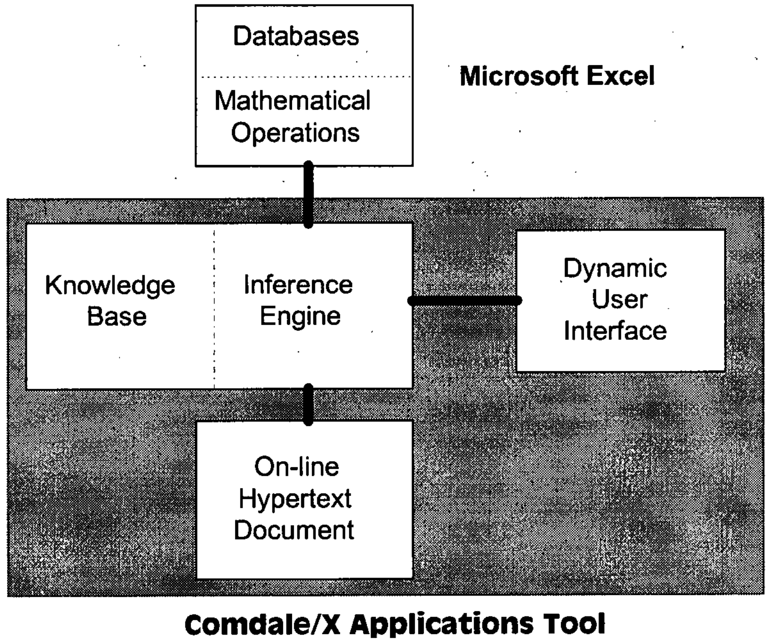


Figure 4.2 Expert System Architecture

An external applications tool, Microsoft Excel, has been employed to speed up the development process given its compatibility with Comdale/X and elaborate data handling capabilities which include database functions. The large amount of discrete information which is needed by the expert system is much more efficiently stored in an external database which can then be accessed by the expert system or the user as required. The spreadsheet used to perform mathematical modeling is the most efficient means of handling what-if scenarios, a major demand for new material design.

An on-line hypertext document describing material behavior, the theoretical background of the knowledge base and inferencing strategies, and other pertinent materials information is also a fundamental part of the expert system. The hypertext document may be accessed during a consultation as an aid to material selection or independently as a tutorial document to provide MMC materials information.

4.4 SYSTEM STRUCTURE

The expert system structure consists of five modules. The first encompasses database search and retrieval routines with the expert system accessing the external Microsoft Excel databases to search and retrieve information in an intelligent manner. The flexibility to access the databases independently of the expert system interface by switching Microsoft Windows applications during a consultation or when running Excel independently is provided. This allows the user control of the database and the ability to update and add new information simply using the database functions of Excel.

The second module predicts effective composite properties using matrix and reinforcement constituent properties. The constituent properties utilized by the system are either obtained from the results of the matrix and reinforcement database searches in module one, or from user input. The mathematical models contained in the Excel spreadsheet are managed by the expert system to ensure the appropriate models are run depending upon the input parameters and the effective property of interest. Like the databases, the mathematical modeling worksheet can be accessed independently of the expert system interface.

The third module determines the compatibility of a matrix and reinforcement combination selected by the user. This information is contained within the knowledge base and is of fundamental importance to achieving successful design and manufacture of metal matrix composites.

The fourth module advises the user on available manufacturing techniques for a selected metal matrix composite. The knowledge base employs linguistic variable constraints, such as matrix/reinforcement compatibility, reinforcement type and volume fraction to make this recommendation.

The fifth module contains the on-line hypertext document. This source of metal matrix composite materials information captures expert knowledge, experience and observation which can not be adequately represented in the database structure. The document contains the theoretical basis for the many intelligent functions performed by the system such as mathematical modeling, the determination of constituent compatibility and the recommendation of suitable manufacturing techniques.

For a simple but fundamental example of the hypertext document's importance, the screen view of the hypertext section on thermal conductivity of aluminum alloys is shown in Figure 4.3. Information about the effects of precipitates on high silicon alloys is important particularly for aluminum MMCs reinforced with SiC particulates. A higher measured thermal conductivity value is obtained when compared to the predicted theoretical value. For other aluminum alloys reinforced with SiC particulates, for example 6061, the measured value is consistent with the theoretical value. This type of information provided by the hypertext document is essential to materials selection and the design of new MMCs with accurately predicted thermal conductivity values.

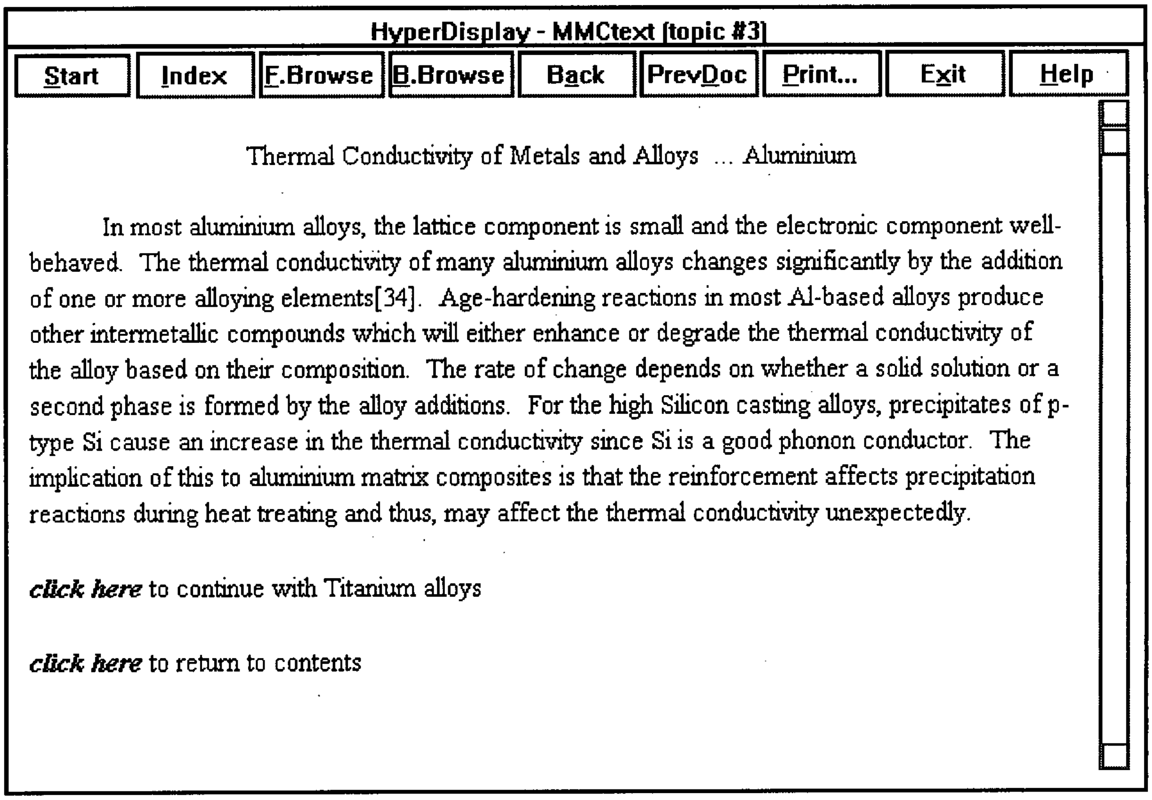


Figure 4.3 Screen View of Thermal Conductivity - Aluminum Alloys Topic

CHAPTER 5

KNOWLEDGE DOMAIN PART I

5.1 MATERIAL PROPERTY DATABASES

The representation of measured material property data has been subdivided into metal matrix composite(MMC), matrix alloy and reinforcement material databases based on the alloys and reinforcements listed in Table 5.1. Density, thermal conductivity, coefficient of thermal expansion and mechanical properties which include tensile, compressive, and shear properties, have been compiled. Also present is metadata, or information about the data, which includes data sources, notes on the manufacture and applications of the materials, degrees of belief in the data, and equations describing the temperature dependence of properties. Appendices A, B and C list MMCs, reinforcements and alloys contained in the databases. Tables 5.2 - 5.4 give the specific pieces of compiled information in each database.

5.1.1 <u>DESIGN PROPERTY VALUES</u> Material property data used directly in design is generally compiled in a database as design allowable property values. These are the minimum material properties likely to be observed in a particular alloy or product form[83]. They are typically represented with uncertainties determined by statistical approaches with mean values and standard deviations[7,84]. However, unlike isotropic metals for which design allowables are readily available from standard sources(e.g. Military Handbook Volume 5E), MMC values are notably absent. Once a material can be produced reliably and cost effectively, a long and costly qualification process is necessary which can take from 10-15 years.

An extensive amount of characterization testing must be done to determine design allowables for anisotropic composite materials[97]. In addition, a lack of quality control in test methods and diversity of quality assurance of the data compound this problem. Test methods and specimen preparation are not fully developed or standardized for the industry. For every test, there are a number of test methods available and often these are modified by individual companies.

To address this problem, degrees of belief associated with each property value have been assigned. Property values which are proposed design allowables or are manufacturers' data have a higher degree of belief than experimental values measured with unknown conditions or values obtained from indirect sources. For example, it is difficult to measure the properties of reinforcements and as a result, many of the data sources employ theoretical techniques[85]. Difficulties in this approach are evident leading to uncertainty in many published values and consequently, low degrees of belief are necessary.

Table 5.1 Matrix Alloy and Reinforcement Materials

Alloys				
Aluminum:		Magnesium	Titanium	Copper
2XX	6XXX			
3XX	7XXX			
2XXX	8XXX			

Reinforcements			
Particulate	Whisker	Short Fiber	Fiber
Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3
AlN	B_4C	Al_2O_3-SiO_2	Al_2O_3-SiO_2
B_4C	Carbon(graphite)	Boron	Boron
Carbon(graphite)	Si_3N_4	Carbon(graphite)	Carbon(graphite)
Si_3N_4	SiC	SiC	SiC
SiC		TiB_2	TiB_2
TiB_2		Tungsten	Tungsten
TiC			

Table 5.2 Metal Matrix Composite Database

Mechanical Properties		Thermal Conductivity	Coefficient of Thermal Expansion
Material Designation	Shear Strength	Material Designation	Material Designation
Manufacturer/Source of information	Shear Modulus	Manufacturer/Source of information	Manufacturer/Source of information
Notes	Longitudinal Compressive Strength	Notes	Notes
Longitudinal UTS value and equation as a F(temp)	Transverse Compressive Strength	Longitudinal Value	Longitudinal value
Transverse UTS value and equation as a F(temp)	Longitudinal Compressive Modulus	Transverse value	Transverse value
Longitudinal yield strength value and equation as a F(temp)	Transverse Compressive Modulus	Equation as a F(temp)	Temperature Range if value is an average
Transverse yield strength	Bearing Ultimate Strength	Degrees of Belief	Equation as a F(temp)
Longitudinal Elastic Modulus value and equation as a F(temp)	Bearing Yield Strength		Degrees of belief
Transverse Elastic Modulus value and equation as a F(temp)	Bearing (e/D) ratio		
Poisson's Ratio	Degrees of Belief		
elongation %			
exponent n or shape of stress/strain curve			

Table 5.3 Reinforcement Materials Database

Mechanical Properties	**Thermal Conductivity**	**Coefficient of Thermal Expansion**
Material Designation	Material Designation	Material Designation
Manufacturer/Source of information	Manufacturer/Source of information	Manufacturer/Source of information
Notes	Notes	Notes
Density	Longitudinal Value and equation as a f(Temp)	Longitudinal Value
length, diameter, aspect ratio	length, diameter, aspect ratio	length, diameter, aspect ratio
Tensile Strength value and equation as a f(Temp)	Transverse value and equation as a f(Temp)	Transverse value
Elongation %	Degrees Of Belief	Degrees Of Belief
Longitudinal Elastic Modulus value and equation as a f(Temp)		Temperature Range if value is an average
Transverse Elastic Modulus value and equation as a f(Temp)		CTE Equations as a f(Temp)
Longitudinal Shear Modulus		
Transverse Shear Modulus		
Poisson's Ratio		
Compressive Strength(MPa)		
Degrees of Belief		

Table 5.4 Matrix Materials Database

Mechanical Properties	**Thermal Conductivity**	**Coefficient of Thermal Expansion**
Material Designation	Material Designation	Material Designation
Manufacturer/Source of information	Manufacturer/Source of information	Manufacturer/Source of information
Notes	Notes	Notes
Yield Strength value and equation as a f(Temp)	Thermal conductivity value	CTE value
Tensile Strength value and equation as a f(Temp)	Thermal conductivity as a function of temperature	Temperature Range if value is an average
Elongation %	Degrees of Belief	CTE as a function of temperature
Elastic Modulus value and equation as a f(Temp)		Degrees of Belief
Poisson's ratio		
Exponent n or shape of stress/strain curve		
Shear Modulus		
Shear Strength		
Compressive Modulus		
Compressive UTS		
Bearing Yield Strength		
Bearing UTS		
Bearing e/D ratio		
Degrees of Belief		

5.1.2 <u>METADATA</u> The inclusion of textual metadata in the databases is necessary to analyze and interpret the data effectively. For example, numerous mechanical properties have been measured for a typical extruded whisker reinforced MMC, namely 6061/SiC/25w-T6 extrusion product. The Aluminum Association Designation and product type fall short of explaining the multiple entries for this material. An increase in the extrusion ratio of whisker reinforced MMCs increases the composite tensile strength and elastic modulus, due to whisker alignment, in the extrusion direction. However, at higher extrusion ratios whisker damage occurs and the strength and modulus decrease. Qualifying information, which includes extrusion ratio and reinforcement aspect ratio(ideally both before and after extrusion) in this example, is necessary to discern multiple property entries and capture material property behavior not obvious to non-expert users.

5.1.3 <u>NULL VALUES</u> The number of null values, or gaps in the data, is substantial in the metal matrix composite and reinforcement databases. Typically, the only consistently measured mechanical properties are yield strength, ultimate tensile strength, modulus, and strain to failure. Even these values are incomplete because transverse properties, temperature dependencies, characterization of the microstructure, residual stresses and so on are absent. Compressive and shear properties remain essentially unmeasured and statistically significant data needed to establish design allowables is still lacking. Important information which is absent in all but a few materials is the fundamental uniaxial stress-strain curve. The shape of the curve and the effect of temperature and strain rate on the flow stress have not been characterized. The uniaxial stress-strain curve is the basis for computer simulation of inelastic behavior of joints, components or systems and therefore of fundamental importance.

5.1.4 MMC DATABASE The majority of MMCs in the database contain aluminum matrix alloys with SiC particulate, whisker or fiber reinforcements. This can be attributed to the availability of SiC, its relative low cost, and early research objectives of (1) increasing both room and high temperature properties of aluminum alloys in weight critical applications, (2) providing dimensionally stable(i.e. controlled CTE) and thermal management(i.e. controlled thermal conductivity) materials for electronic and optical applications, and (3) introducing light-weight wear and abrasion resistance materials.

Other matrix alloys and reinforcements have been introduced to deliver increased overall room and high temperature performance without increasing material weight. These MMCs include aluminum alloys with B_4C particulates, graphite fibers, TiC particulates, and Al_2O_3 particulates, short and continuous fibers; titanium alloys with SiC fibers; magnesium alloys with SiC particulates, graphite fibers and Al_2O_3 short fibers; and copper alloys with graphite and tungsten fibers. Although research is ongoing to design new combinations of matrix alloys and reinforcements(e.g. aluminum matrix alloys with Si_3N_4 whiskers), the focus still remains on aluminum/SiC and aluminum/ Al_2O_3 systems.

For thermal management and stability applications in electronic and optical systems, copper matrices reinforced with graphite and tungsten fibers are being introduced. These composites exploit the conductivity advantages of the copper matrix with the strength, stiffness, thermal conductivity and coefficient of thermal expansion properties of the reinforcement.

5.1.4.1 Ultimate Tensile Strength Measured MMC ultimate tensile strength(UTS) values are plotted in Figure 5.1. The major contributing factors are matrix strength, reinforcement shape, orientation, and volume fraction.

The contribution of matrix strength is illustrated by the higher strength values of aluminum 2014/Al_2O_3 particulate composites compared to aluminum 6061/Al_2O_3 particulate composites. Reinforcement orientation effects are demonstrated by lower transverse strengths as compared to longitudinal strengths of aligned fiber and whisker reinforced MMCs.

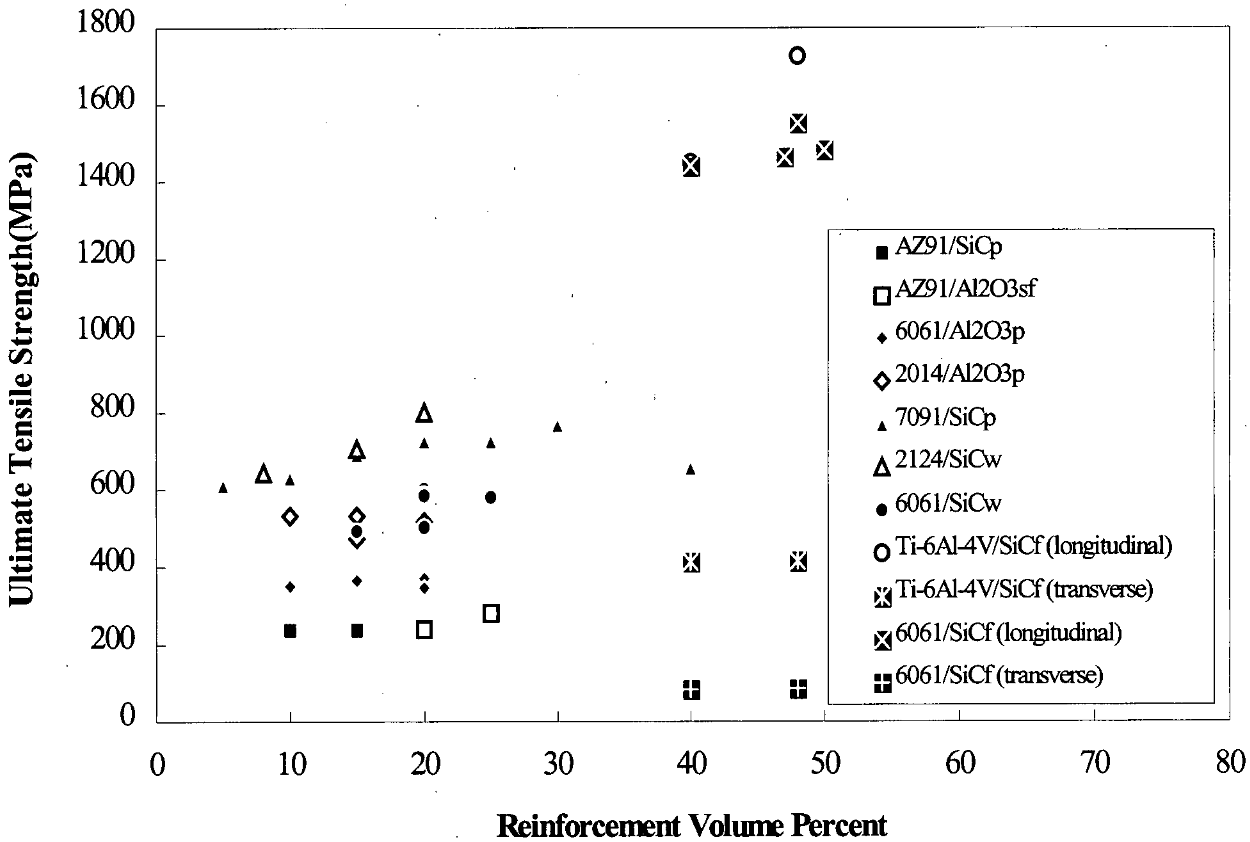


Figure 5.1 MMC Ultimate Tensile Strength as a Function of Reinforcement Volume Percent

The effects of orientation and reinforcement shape are evident in Figure 5.2. For a constant reinforcement volume fraction, an increase in reinforcement aspect ratio(from particulate to fiber) results in an increase in tensile strength.

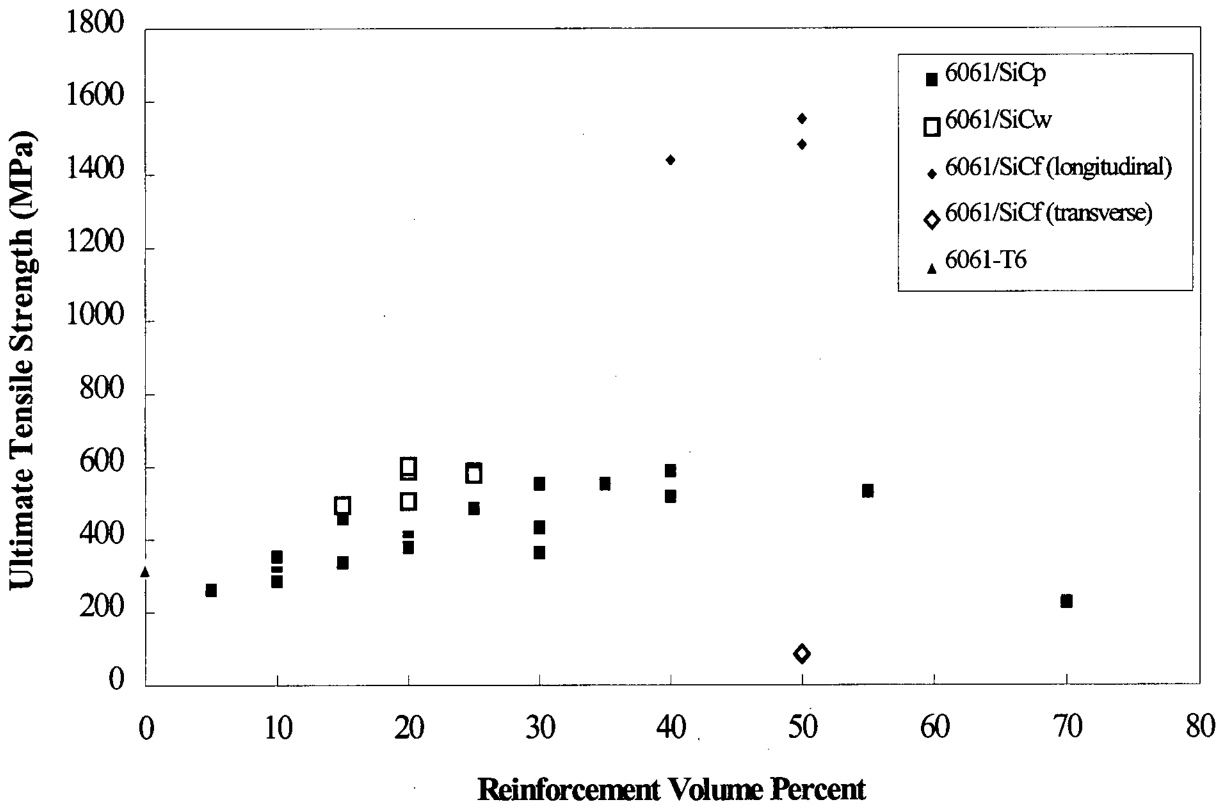


Figure 5.2 Ultimate Tensile Strength of 6061 Aluminum MMCs as a Function of Reinforcement Volume Percent

Unlike particulate, short fiber and whisker MMCs, the matrix strength of fiber reinforced MMCs is a small contributor to longitudinal strength. For example, the similar longitudinal UTS values for SiC fiber reinforced titanium and aluminum matrix composites is due to the load carrying capacity of the aligned fibers. However, this is not the case in the transverse direction as seen in Figure 5.1. The transverse strength of the titanium MMC is greater than the equivalent aluminum MMC due to the higher matrix strength.

For all particulate, whisker and short fiber composites, the ultimate tensile strength reaches a peak value and falls off at high volume fractions. Inadequate processing methods and poor matrix/reinforcement interfaces are the main cause for this drop in strength and consequently, highly loaded composites are currently designed for wear and abrasion resistant applications only.

5.1.4.2 Yield Strength Measured yield strength values are shown in Figure 5.3. The primary factors which determine MMC yield strength are matrix yield strength, reinforcement volume fraction and alignment. Secondary factors which include the matrix/reinforcement interface and reinforcement shape are also significant. Scattering in the particulate, whisker, and short fiber data is evident and the current inability to accurately predict MMC yield strengths is most likely due to the secondary effects.

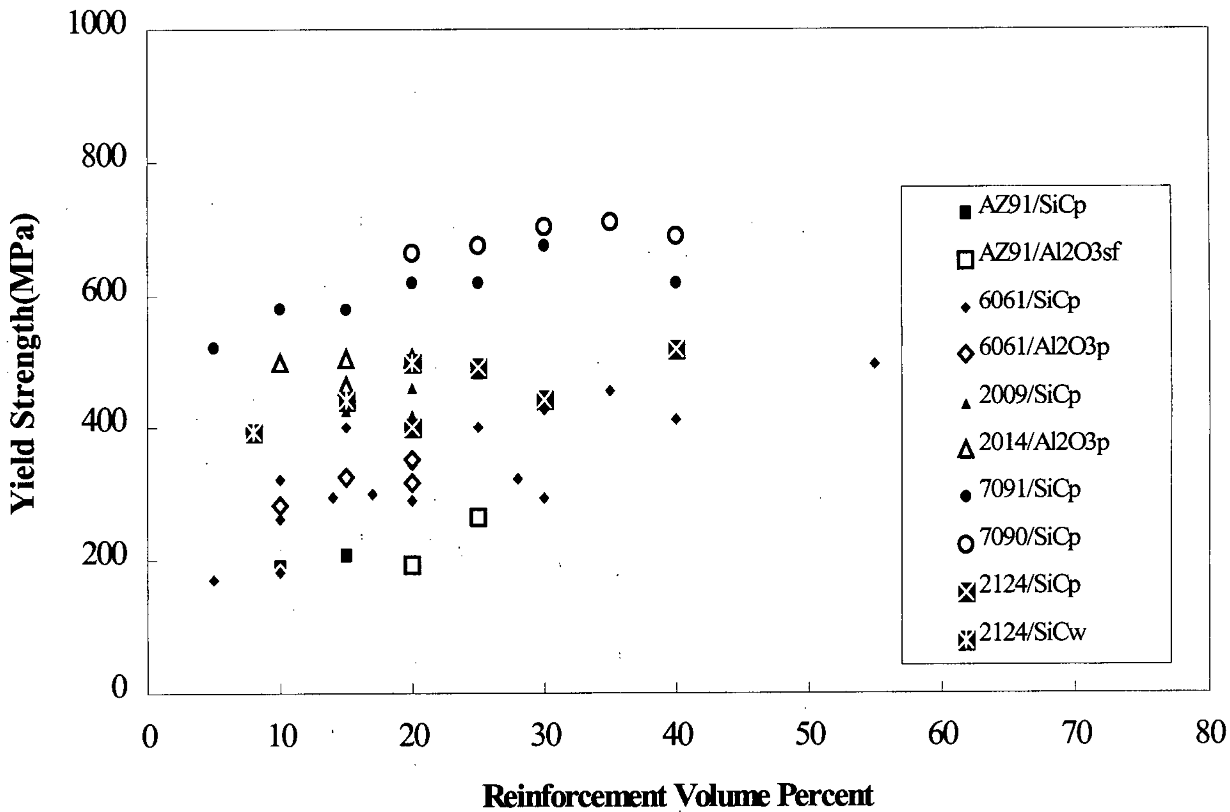


Figure 5.3 MMC Yield Strength as a Function of Reinforcement Volume Percent

Figure 5.4 shows the result of different reinforcements with an aluminum 6061 matrix alloy. Although the yield strength increases with volume percent and aspect ratio, few higher volume fraction MMCs are present and a high degree of variation, particularly for the SiC particulate reinforced composites, is evident.

The absence of values for aligned fiber reinforced MMCs is due to the failure mechanism of continuous fiber composites. Like plastic reinforced composites, fiber reinforced MMCs do not exhibit matrix yielding as the load is carried by the fibers up to fracture. In addition, measured yield strength values for randomly oriented fiber reinforced

MMCs could not be found in the published literature. It is expected that some yielding will occur but without measurements, predictions can not be validated.

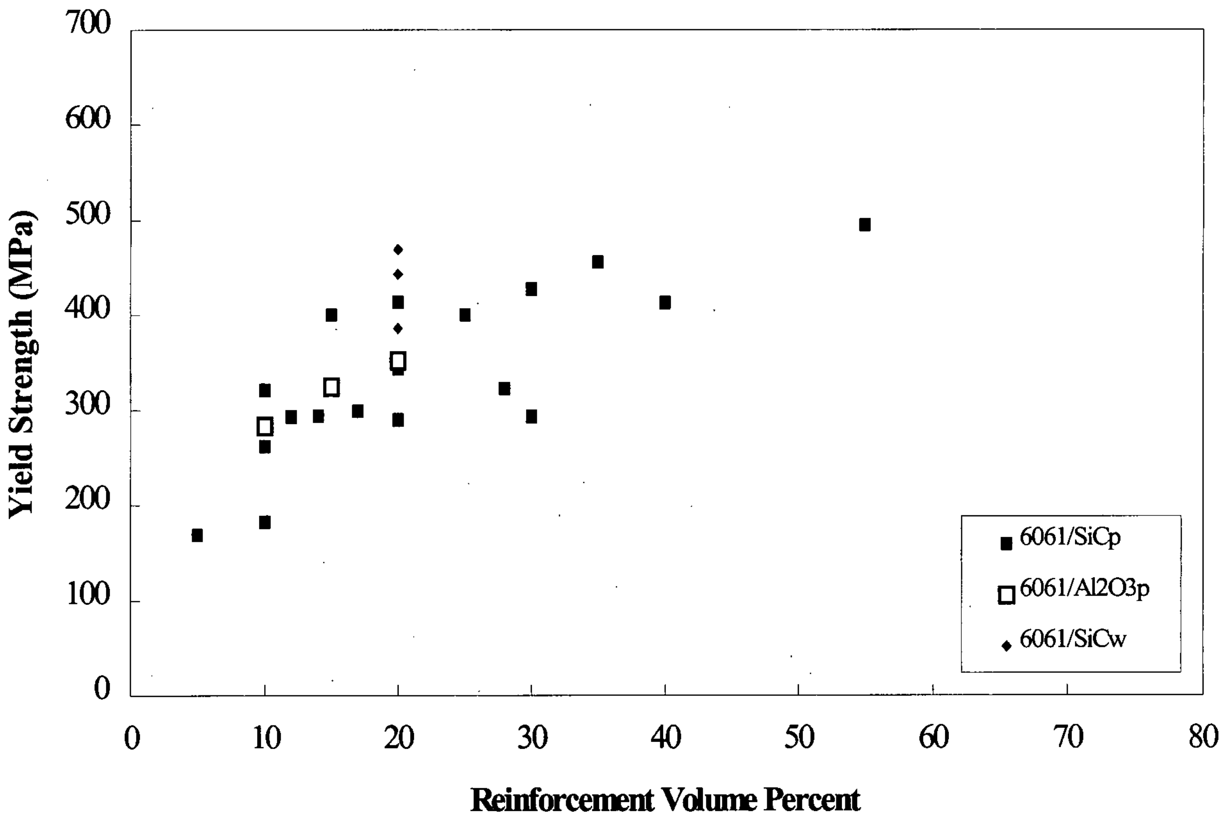


Figure 5.4 Yield Strength of 6061 Aluminum MMCs as a Function of Reinforcement Volume Percent

5.1.4.3 Ductility Measured percent elongation to failure versus reinforcement volume fraction is presented for a number of MMCs in Figure 5.5. The ductility falls off rapidly such that at relatively low reinforcement volume fractions(20 v/o), the elongation of the majority of MMCs is below 5 %.

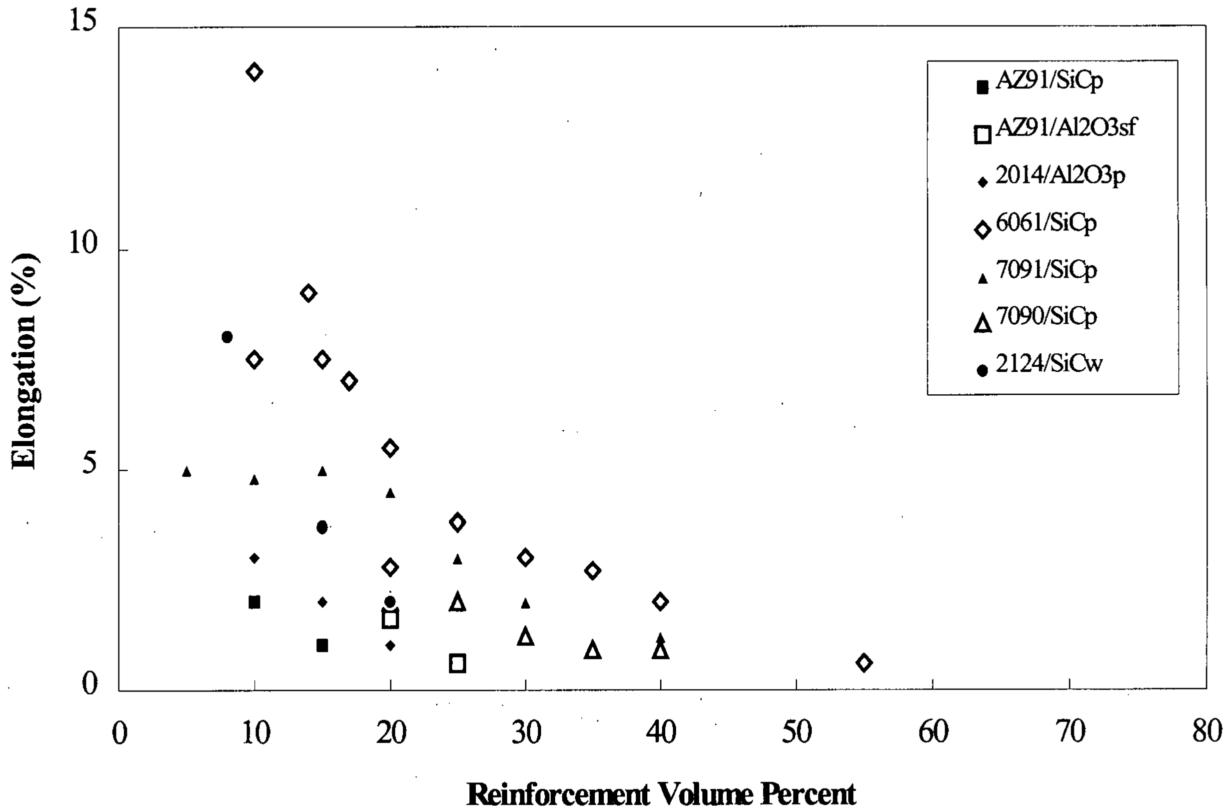


Figure 5.5 Percent Elongation as a Function of Reinforcement Volume Fraction

Figure 5.6 highlights this rapid decline for aluminum 6061 matrix MMCs. The primary controlling variable for particulate and whisker reinforced MMCs is the level of reinforcement. For MMCs with short and continuous fibers, the ductility is further limited by the aspect ratio. Thus for high aspect ratio reinforcements like fibers, the MMC ductility does not generally rise above 1 %.

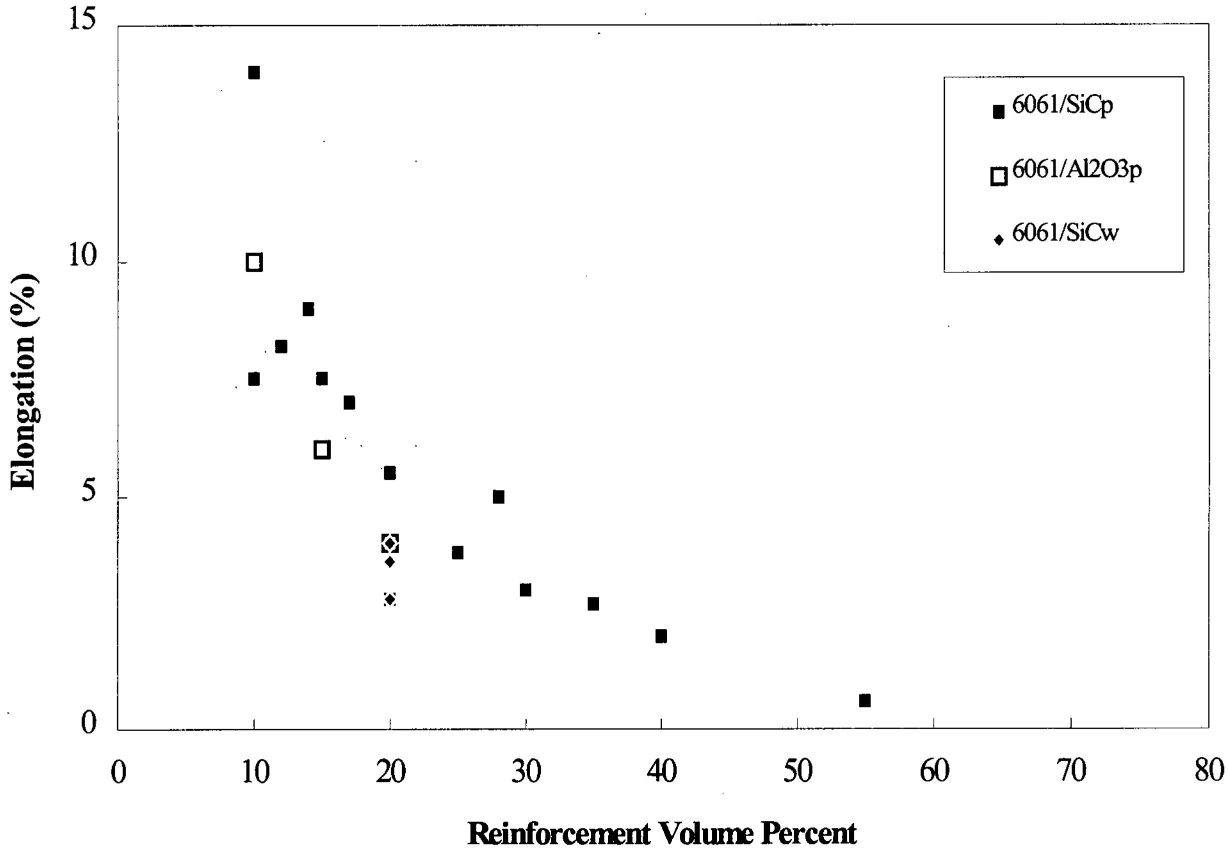


Figure 5.6 Percent Elongation of 6061 Aluminum MMCs as a Function of Reinforcement Volume Fraction

A rule of thumb of aerospace designers is that a metallic material should exhibit at least 5% elongation for structural applications. As seen in Figure 5.5, the majority of MMCs are below this threshold. A minimum 2 - 4 % ductility is required for less critical applications but this is still beyond many MMCs.

5.1.4.4 <u>Elastic Modulus</u> Measured elastic moduli are plotted for a number of MMCs in Figure 5.7. The primary controlling factors are matrix alloy modulus, reinforcement aspect ratio, volume fraction and alignment. Variations in particulate and whisker reinforced

MMC elastic moduli are common. This results from the difficulty in obtaining accurate measurements due to the short proportional regime.

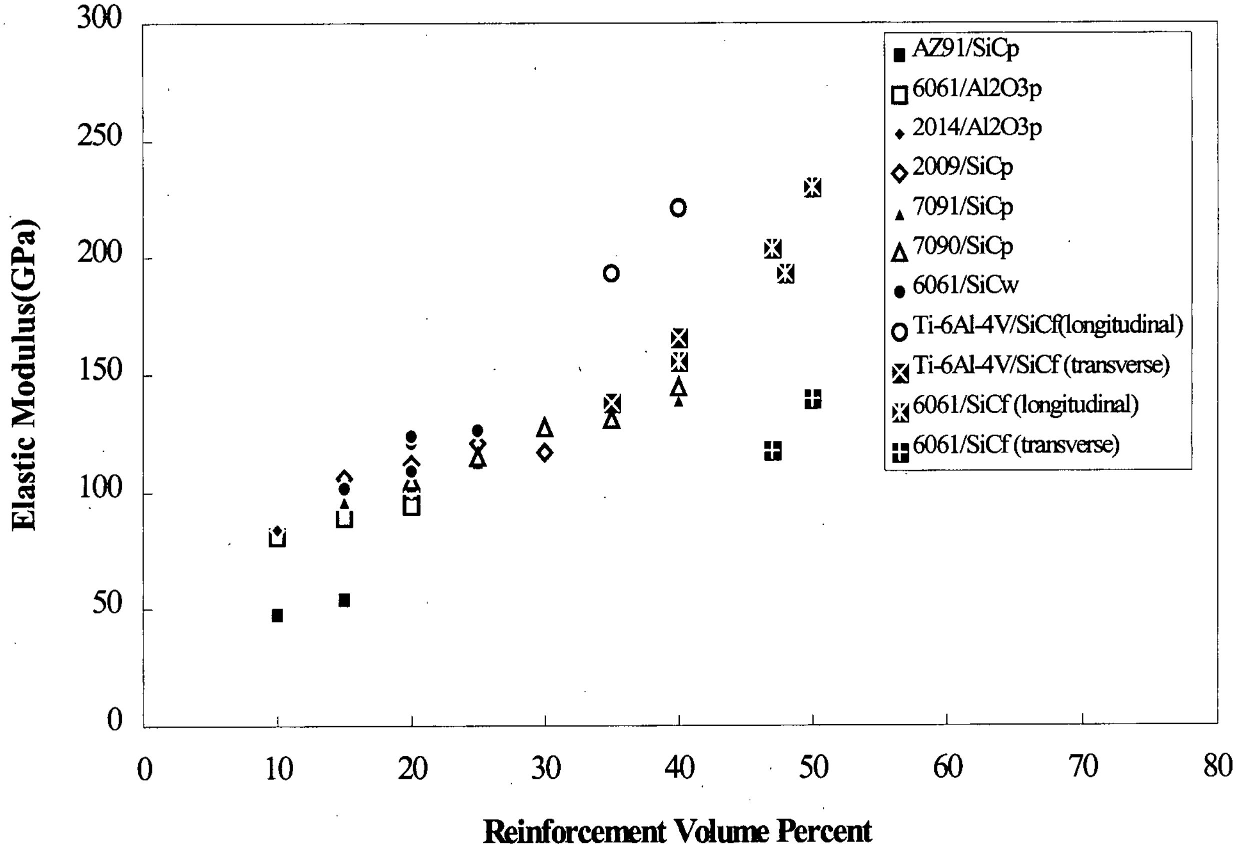


Figure 5.7 MMC Elastic Modulus as a Function of Reinforcement Volume Percent

As the volume fraction and reinforcement aspect ratio increases(from particulate to fiber), the longitudinal modulus increases. However, fiber reinforced MMC transverse modulus remains low. This is also the case for aligned whisker, short fiber and to a lesser degree, particulate reinforced MMCs. The presence of interfacial reaction layers also lower the transverse moduli of many aligned fiber composites. Despite this, elastic modulus is one of the properties least sensitive to microstructural features(Poisson's ratio and shear moduli are the others)[93,95,96]. The effect of volume fraction and reinforcement aspect ratio on elastic modulus is further demonstrated in Figure 5.8 for aluminum 6061 matrix alloy MMCs.

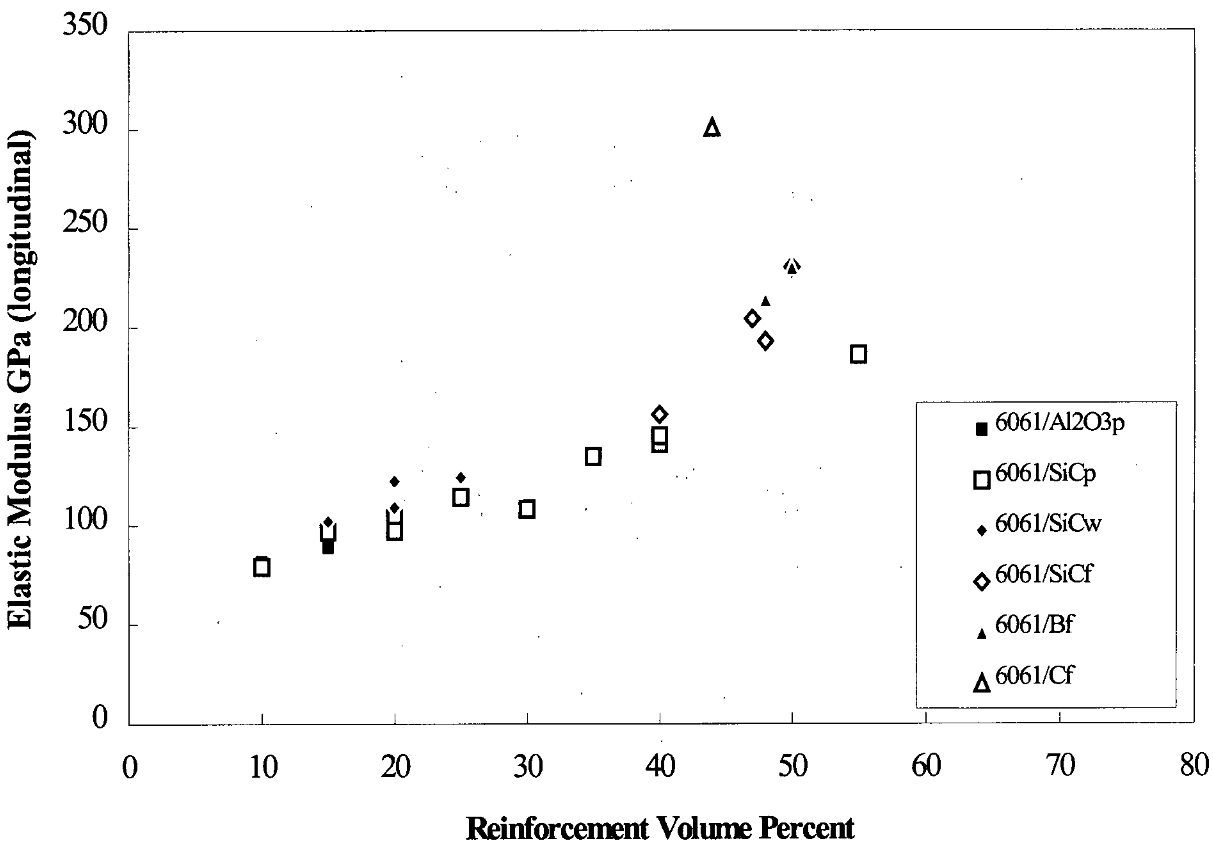


Figure 5.8 Elastic Modulus of 6061 Aluminum MMCs as a Function of Reinforcement Volume Percent

5.1.4.5 <u>Coefficient of Thermal Expansion</u> Measured MMC coefficients of thermal expansion(CTE) are shown in Figure 5.9. Reinforcement coefficient of thermal expansion, aspect ratio, volume fraction, and alignment are the main elements used to control MMC effective CTE. The tailorability of CTE is exploited in thermal stability design applications. For example, in order to replace beryllium in electronic devices, the substitute material must have a CTE value of 11.5×10^{-6}/C. A dashed line representing 11.5×10^{-6}/C is shown in Figure 5.9, illustrating that a number of different MMCs are either equivalent or within close proximity of this value.

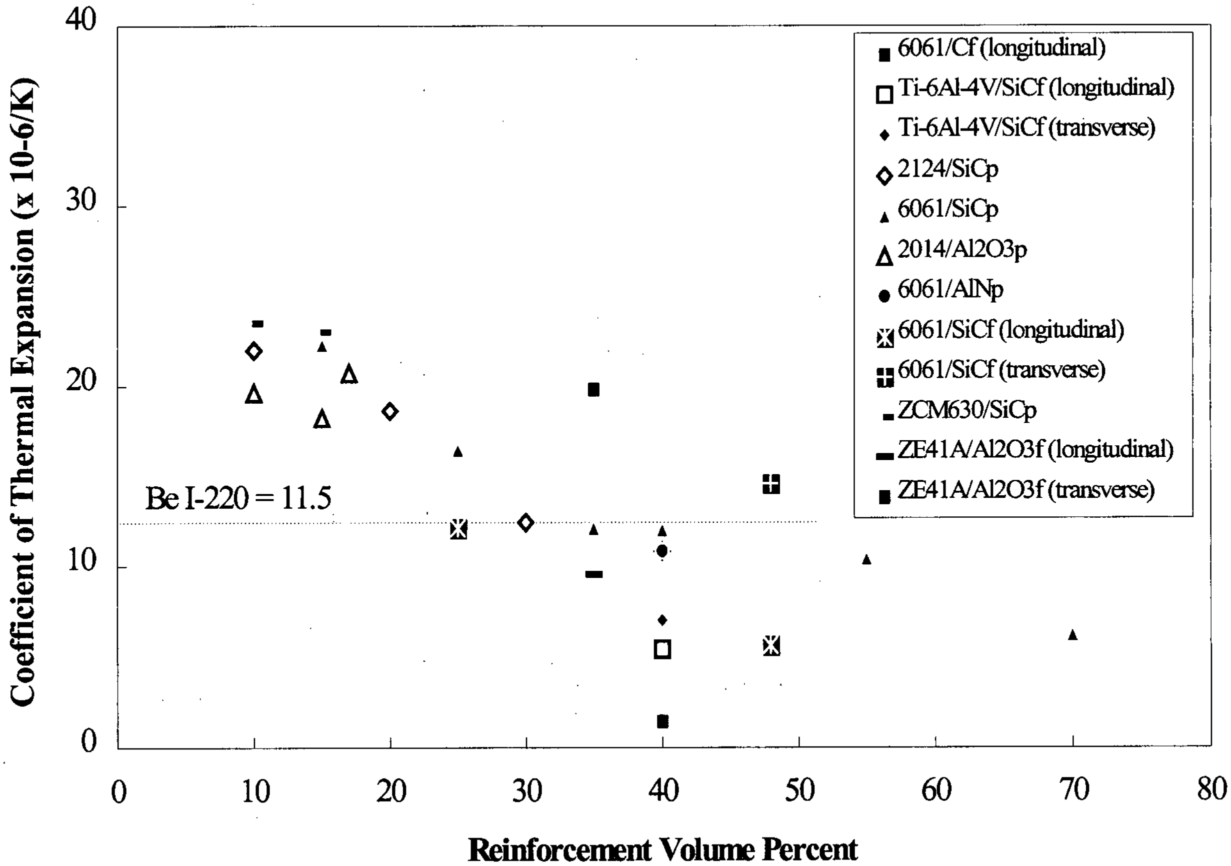


Figure 5.9 MMC Coefficient of Thermal Expansion as a Function of Reinforcement Volume Percent

Figure 5.10 contains measured CTE data for a number of aluminum 6061 matrix MMCs. The lower values of SiC fiber versus SiC particulate reinforcements is due to the larger aspect ratio of the fiber. The effect of orientation is demonstrated by the high transverse fiber values. The large difference between the longitudinal and transverse CTE of the carbon fiber is due to the higher transverse fiber value exhibited by many carbon fiber reinforcements.

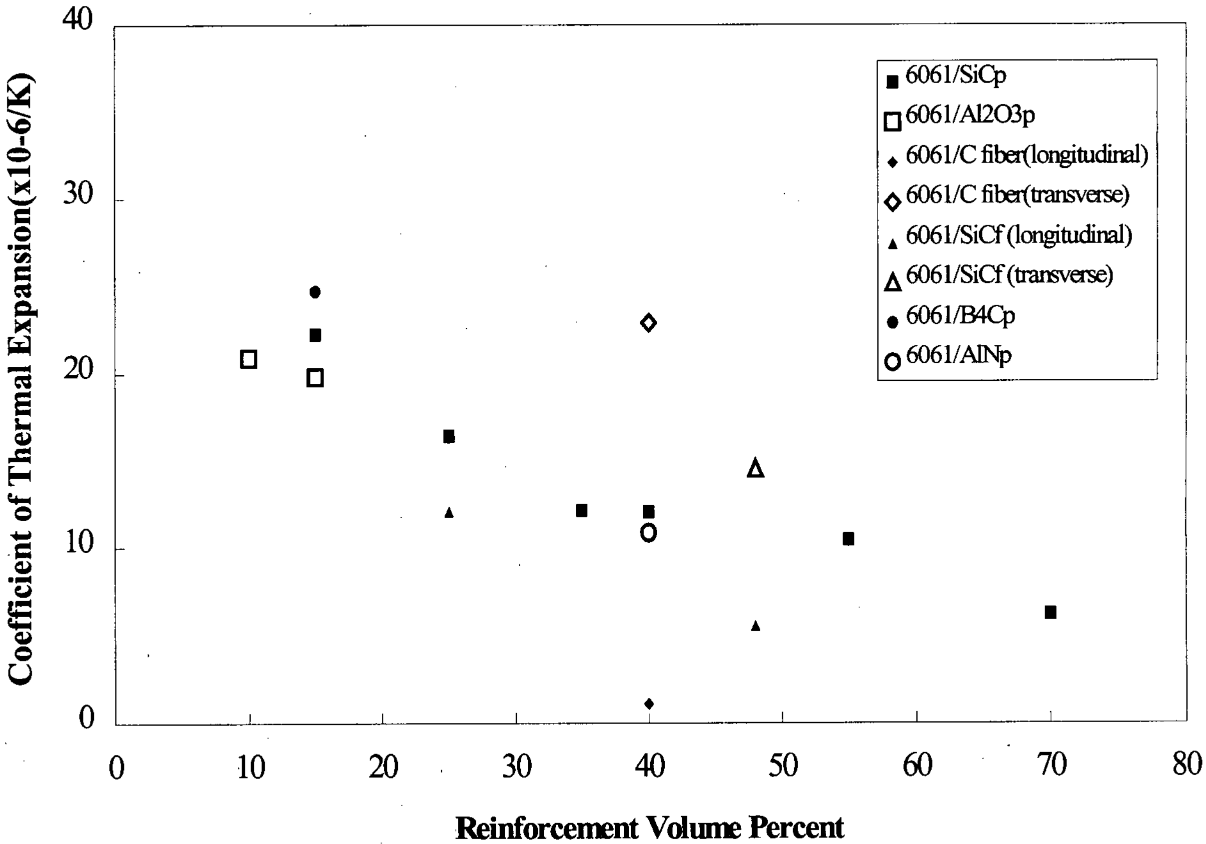


Figure 5.10 Coefficient of Thermal Expansion for 6061 Aluminum MMCs as a Function of Reinforcement Volume Percent

Coefficient of thermal expansion may also be influenced by the presence of an interfacial reaction layer. Depending upon the interfacial reaction products, either an increase or decrease in CTE will result. For example, during heat treatment of reactive systems such as aluminum/carbon reinforcements, carbides form at the interface which reduces the CTE. Conversely, aluminum/Al_2O_3 is a non-reactive system and the CTE remains unaffected by heat treatment.

The composition of the matrix alloy is also significant in many cases. For instance, the 3XX series of aluminum alloys contain varying amounts of Si and Ni. As the levels of these additions are increased, the CTE decreases. However, at levels of Si greater than 12%, primary crystals of Si form which then increases the CTE.

5.1.4.6 Thermal Conductivity Measured MMC thermal conductivity values are illustrated in Figure 5.11. MMC thermal conductivity is a function of matrix and reinforcement thermal conductivity, reinforcement aspect ratio, orientation, and volume fraction. As volume fraction increases, the decrease in respective thermal conductivity values is small(relative to elastic moduli) because matrix and reinforcement values are similar. This similarity in constituent values also reduces the influence of aspect ratio such that whisker and particulate reinforced MMC values are comparable.

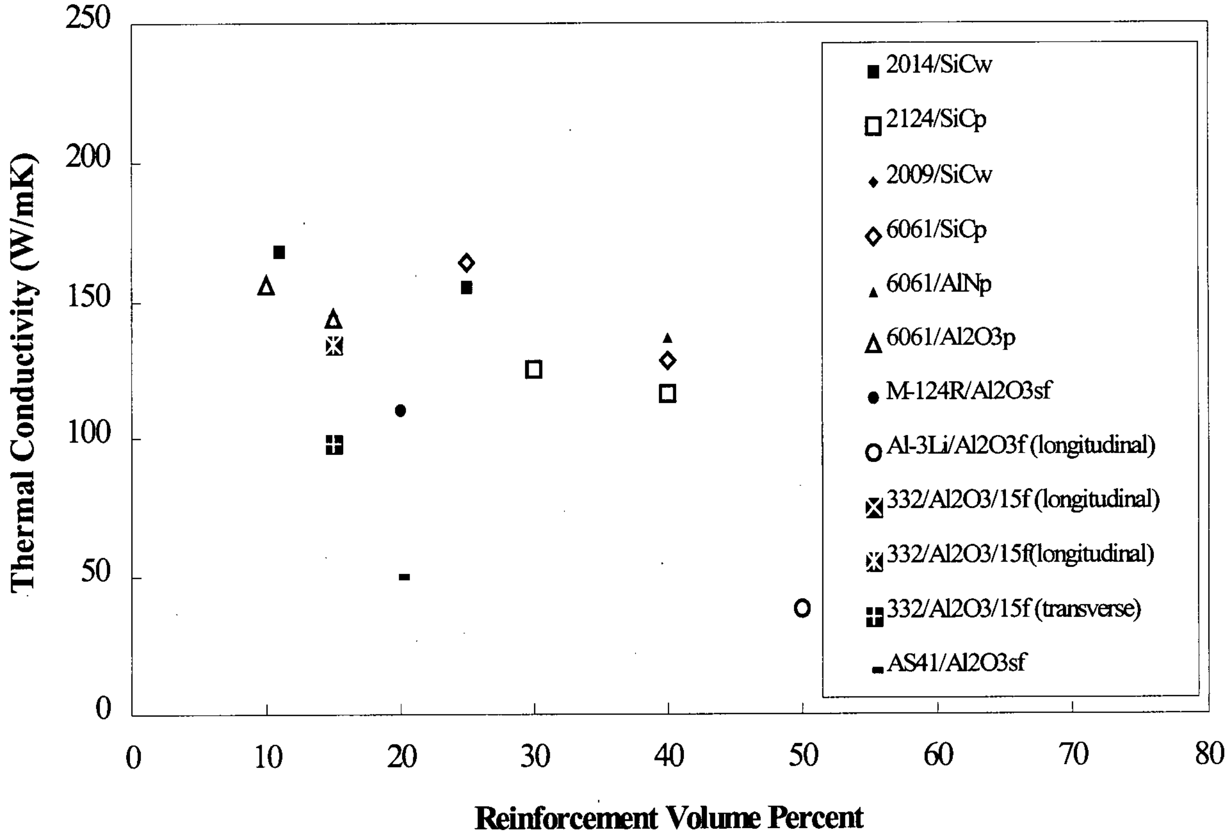


Figure 5.11 MMC Thermal Conductivity as a Function of Reinforcement Volume Percent

The use of high thermal conductivity reinforcements in MMCs for thermal management is a major design objective. For example, heat sinks in microelectronic devices require thermal conductivities greater than 100 W/mK but with an equivalent CTE of the ceramic substrate. By using a low CTE and high thermal conductivity reinforcement, many candidate MMCs can be manufactured. In fact, of the MMCs in Figure 5.11, all but two have thermal conductivities greater than 100 W/mK.

Thermal resistance at the matrix/reinforcement interface due to a reaction layer or porosity also affects thermal conductivity. For example, the effect of the presence of a reaction layer has been well documented for titanium SiC particulate composites[58]. A reduction in the thermal conductivity value occurs as the reaction layer thickens. For most composite systems however, reaction layer thickness and heat transfer properties are unknown. Research is currently underway to characterize these interfaces, particularly for aluminum reinforced with SiC.

For MMCs with heat treatable matrix alloys, the thermal conductivity is expected to follow the recovery and recrystallization profiles of the matrix alloy provided there are no interfacial reaction products being formed[86]. The effect of temper on 359/SiC/20p is shown in Figure 5.12. The thermal conductivity is similar to the monolithic alloys even though this system is known to form carbides at the interface.

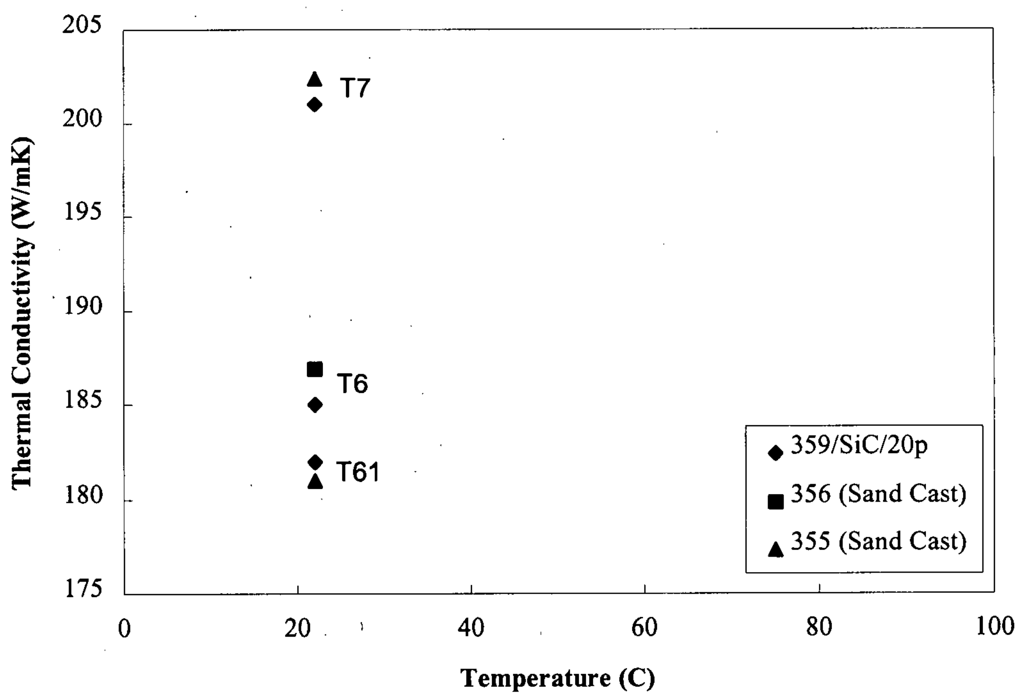


Figure 5.12 Effect of Heat Treatment on Thermal Conductivity of 359/SiC/20p

5.1.5 REINFORCEMENT DATABASE Compilation of measured property values for the ceramic reinforcements uncovered significant material variations. These variations occur not only for reinforcements manufactured by different companies but for the same material when measured by different researchers. Wide ranges in property values for one type of reinforcement material are evident in Figures 5.13 to 5.15. For example, SiC reinforcements have elastic modulus values from 150 up to 700 GPa, carbon fiber thermal conductivity values from 10 to well over 500 W/mK, and Al_2O_3 reinforcement coefficient of thermal expansion values from 3.5 to 9.5 (x 10^{-6}/C).

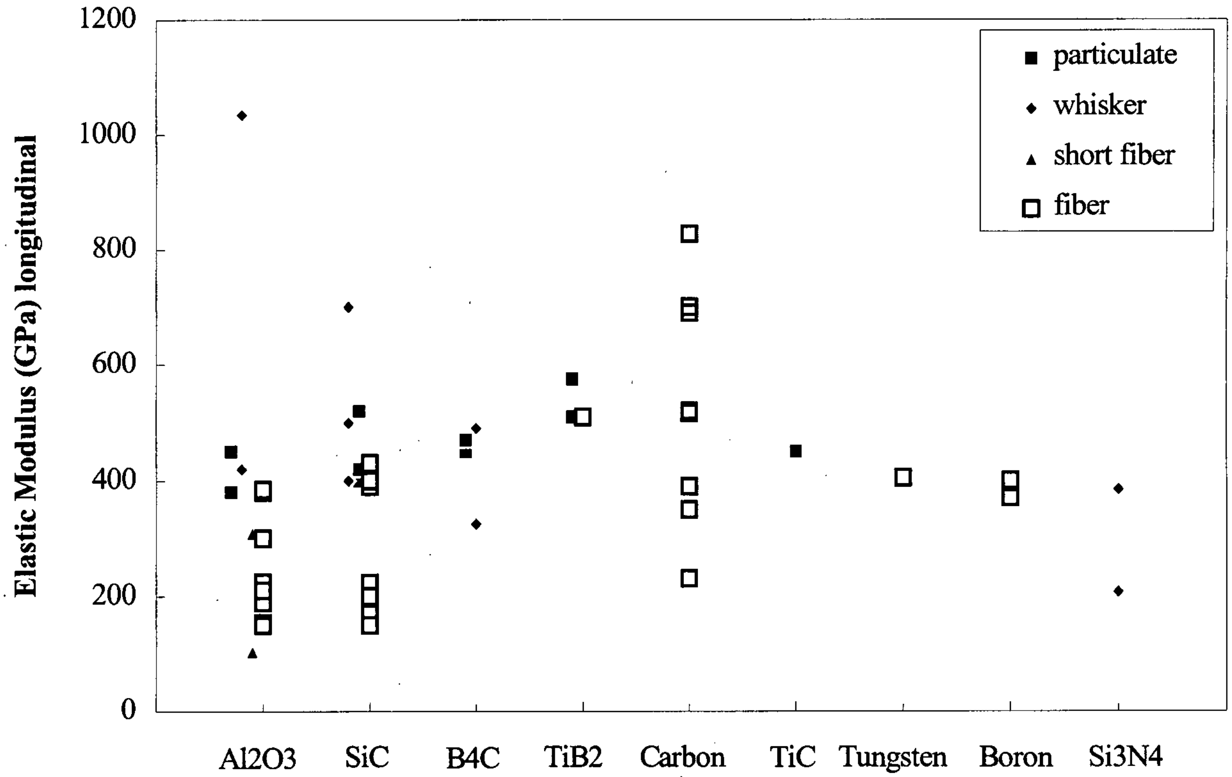


Figure 5.13 Measured Reinforcement Elastic ModulusValues

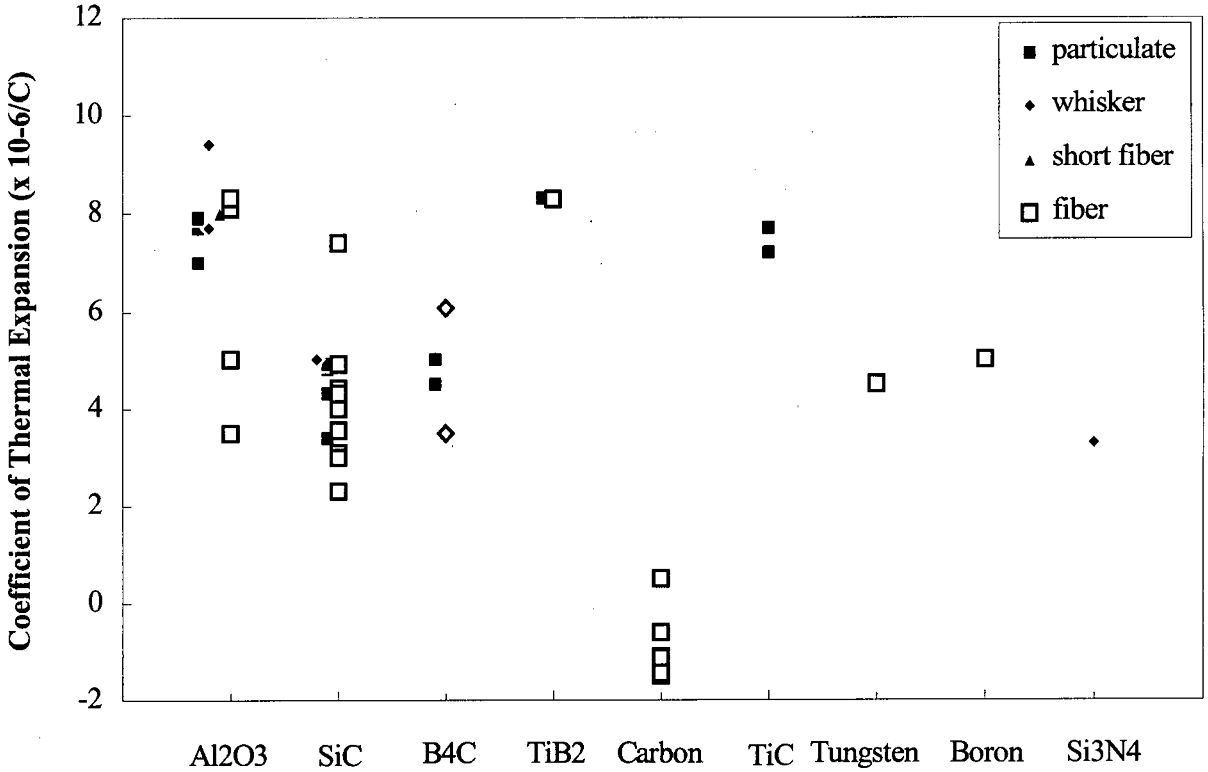


Figure 5.14 Measured Reinforcement Coefficient of Thermal Expansion Values

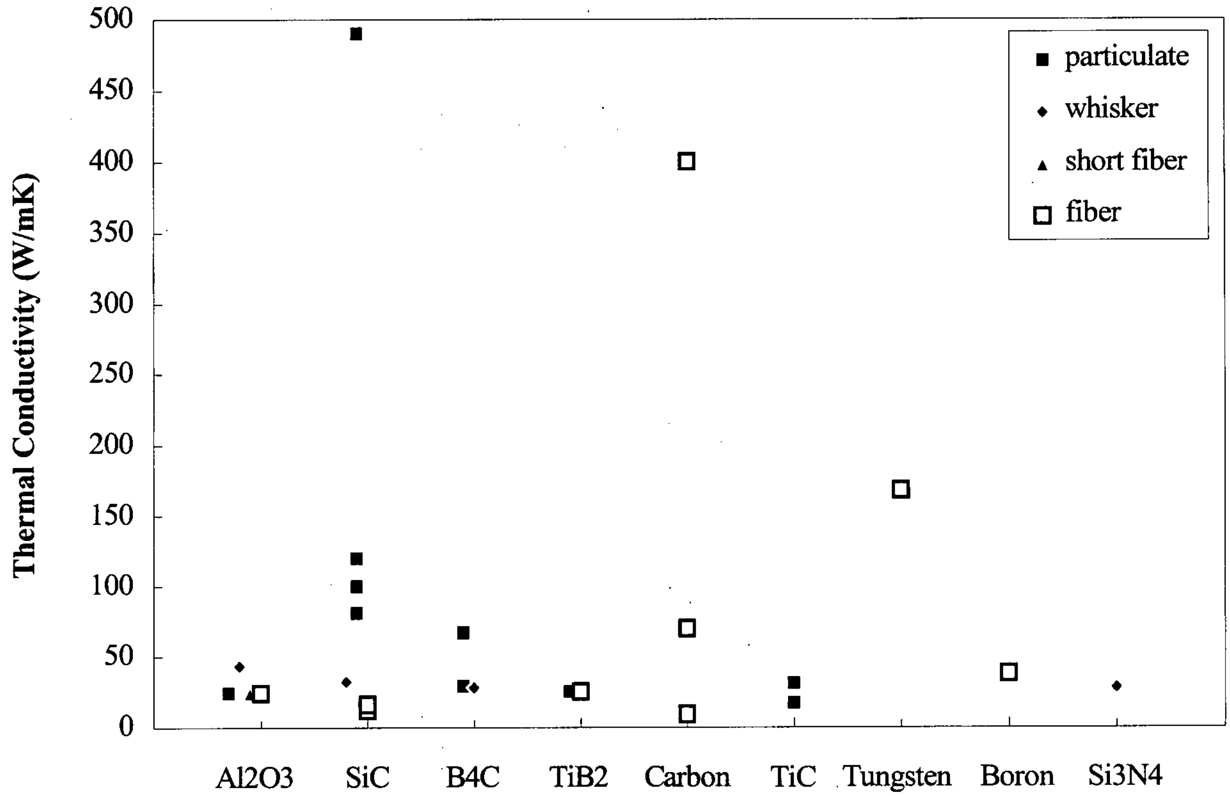


Figure 5.15 Measured Reinforcement Thermal Conductivity Values

Property variations result from contamination, impurities, surface coatings, phase differences, measurement errors, and so on[85,90,92]. Although the theoretical thermal conductivity of single crystal AlN is 320 W/mK, the practical value is between 150 and 220 having been lowered by impurities, primarily oxygen. For SiC fibers, the elastic modulus ranges from 175 to 450 GPa due to variations in surface coatings and core fiber material. Particularly susceptible reinforcements are those which are difficult to fabricate as pure materials such as SiC, AlN, and graphite[92].

Due to their stability at high temperatures, most ceramic reinforcements exhibit small decreases in thermal conductivity and elastic modulus, and correspondingly small increases in coefficient of thermal expansion[89,90,91]. Reinforcement strength decreases are minimal compared to matrix alloys thus the limiting factor to high temperature MMC service is the matrix.

Reinforcement transverse property values are generally not characterized and isotropy is assumed. However, reinforcement anisotropy, particularly for carbon fibers and graphite crystalline reinforcements, is present[89]. For example, the transverse CTE of P100 carbon fiber is 30 versus -1.5 (x 10^{-6}/C) longitudinally. The elastic modulus of PAN E-75 carbon fiber is 520 GPa longitudinally and 6.9 transversely. These results suggest that carbon core fibers(e.g. SiC and Boron) should exhibit transversely isotropic behavior. Transverse property measurements could not be found in the published literature for confirmation. Despite this, measured transverse elastic moduli for Ti-6Al-4V/SiC/40f and 6061/SiC/47f are lower than most model predictions supporting the belief that the transverse modulus is lower than the longitudinal modulus.

5.1.6 <u>TEMPERATURE DEPENDENT PROPERTIES</u> Temperature dependent equations for material properties in conjunction with their valid temperature range, data source, and any pertinent notes have been compiled. For most design curves, analytical expressions fitted to the data is desired; however, due to the absence of analytical laws, curve fitting using regression analysis has been employed. For equations determined from data points, the data points themselves are listed in a separate database.

Ultimate tensile strength versus temperature is plotted in Figure 5.16. The decrease in MMC strength parallels matrix alloy strength decreases at elevated temperatures. The curves of Figure 5.16 support the generally accepted premise that the matrix alloy is the main contributor to high temperature strength[93]. The exception to this is the longitudinal strength of aligned fiber reinforced MMCs since the thermally stable fibers carry the load.

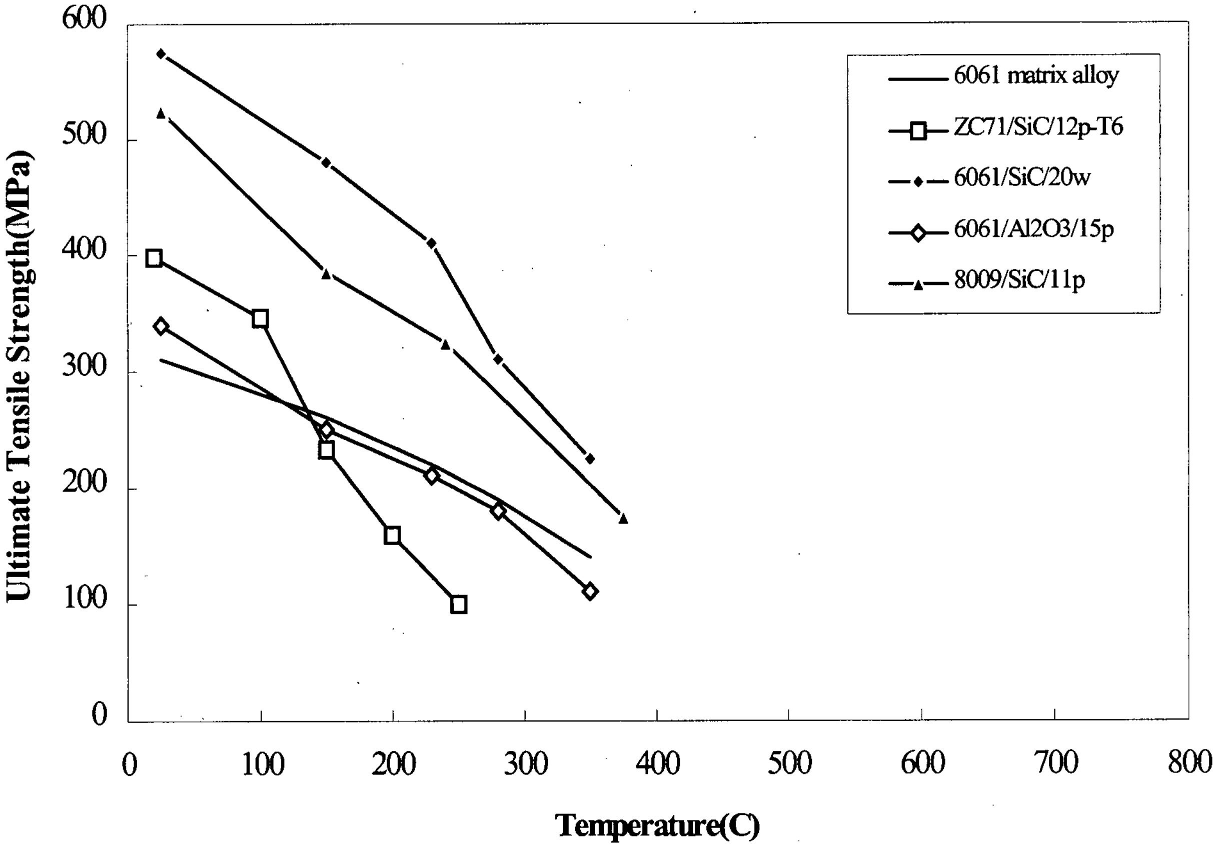


Figure 5.16 Ultimate Tensile Strength at Elevated Temperatures

The elevated temperature dependence of MMC moduli also mirror the monolithic matrix alloys as shown in Figure 5.17[94,95]. The elevated temperature curves of Ti-6Al-

4V/SiC/40f follow the Ti-6Al-4V matrix alloy curve. Despite having a different type and shape of reinforcement, 6061/Al_2O_3/20p and 6061/SiC/20w curves both decrease in a similar manner. This further confirms the matrix as the limiting factor to high temperature modulus.

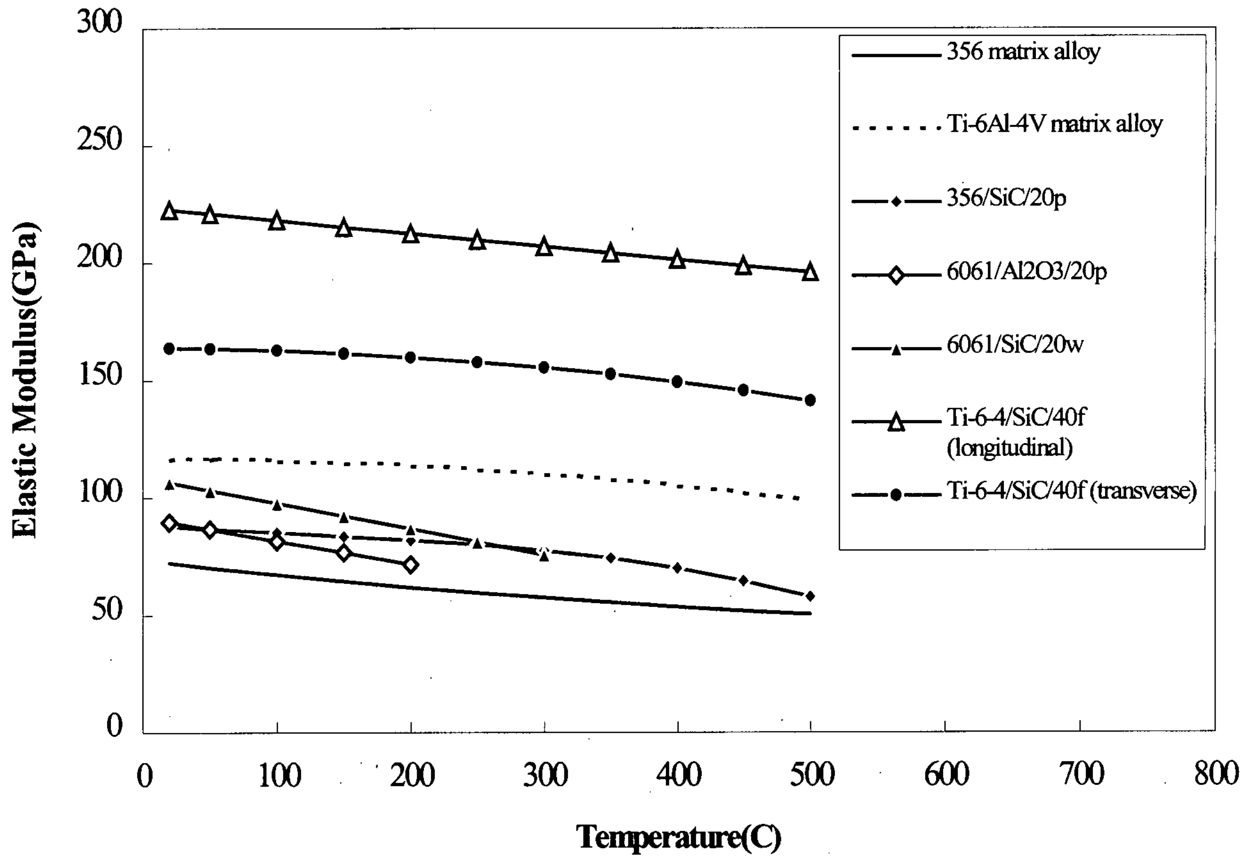


Figure 5.17 Elastic Modulus at Elevated Temperatures

MMC high temperature thermal conductivity also matches monolithic matrix alloy behavior. Figure 5.18 illustrates elevated temperature thermal conductivity. Like elastic modulus, the MMC thermal conductivity curves follow their respective matrix alloys. For metals and alloys, there has been a great deal of theoretical work done in the 1960s and

1970s to establish equations which would predict thermal conductivity values at elevated temperatures[87]. Many of these equations are consistent with the Smith-Palmer model and allow for a large amount of variability in magnitude and behavior[87,88].

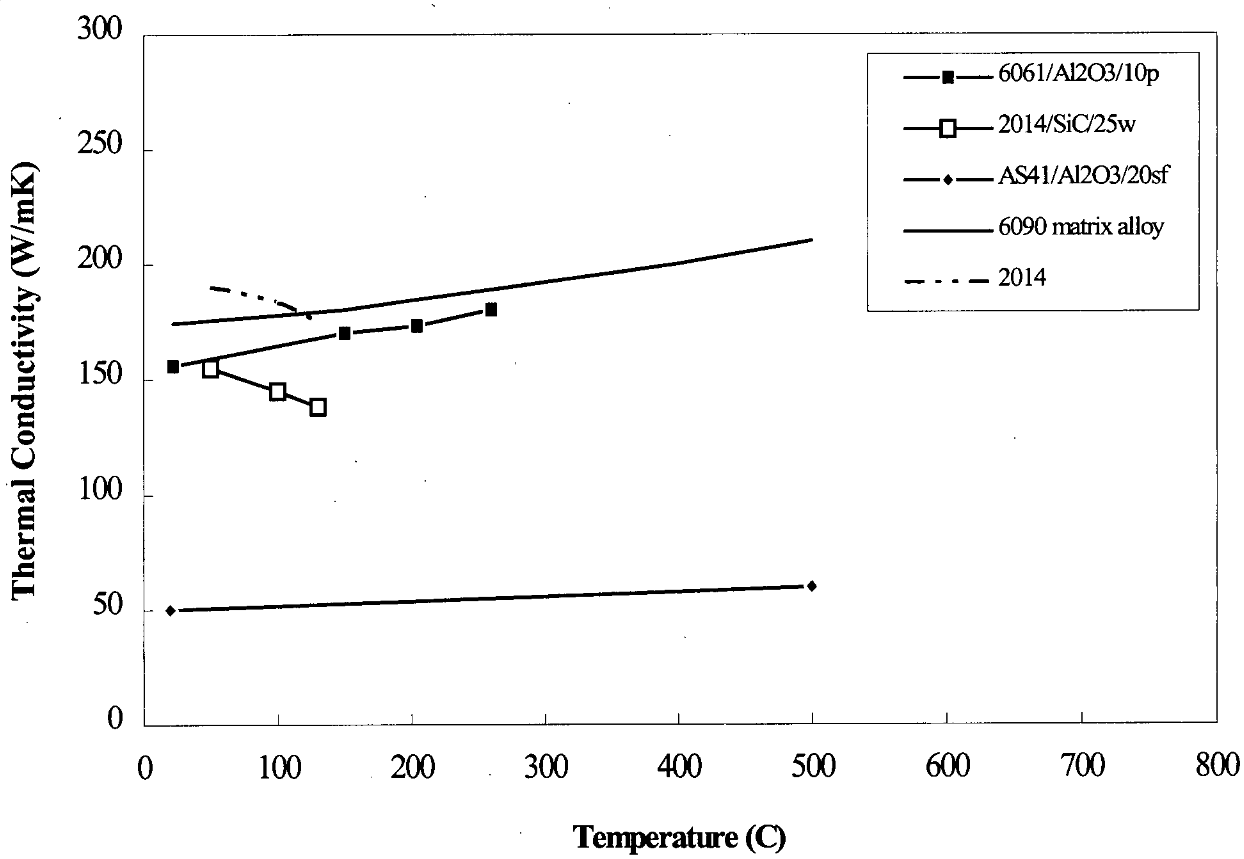


Figure 5.18 Thermal Conductivity at Elevated Temperatures

Figure 5.19 contains MMC high temperature coefficient of thermal expansion(CTE). The trend in behavior is also similar to that of elastic modulus and thermal conductivity. Poorer correlation between the shape of the MMC and corresponding matrix alloy curves are obtained. Insufficient data was found in the published literature to give a full explanation.

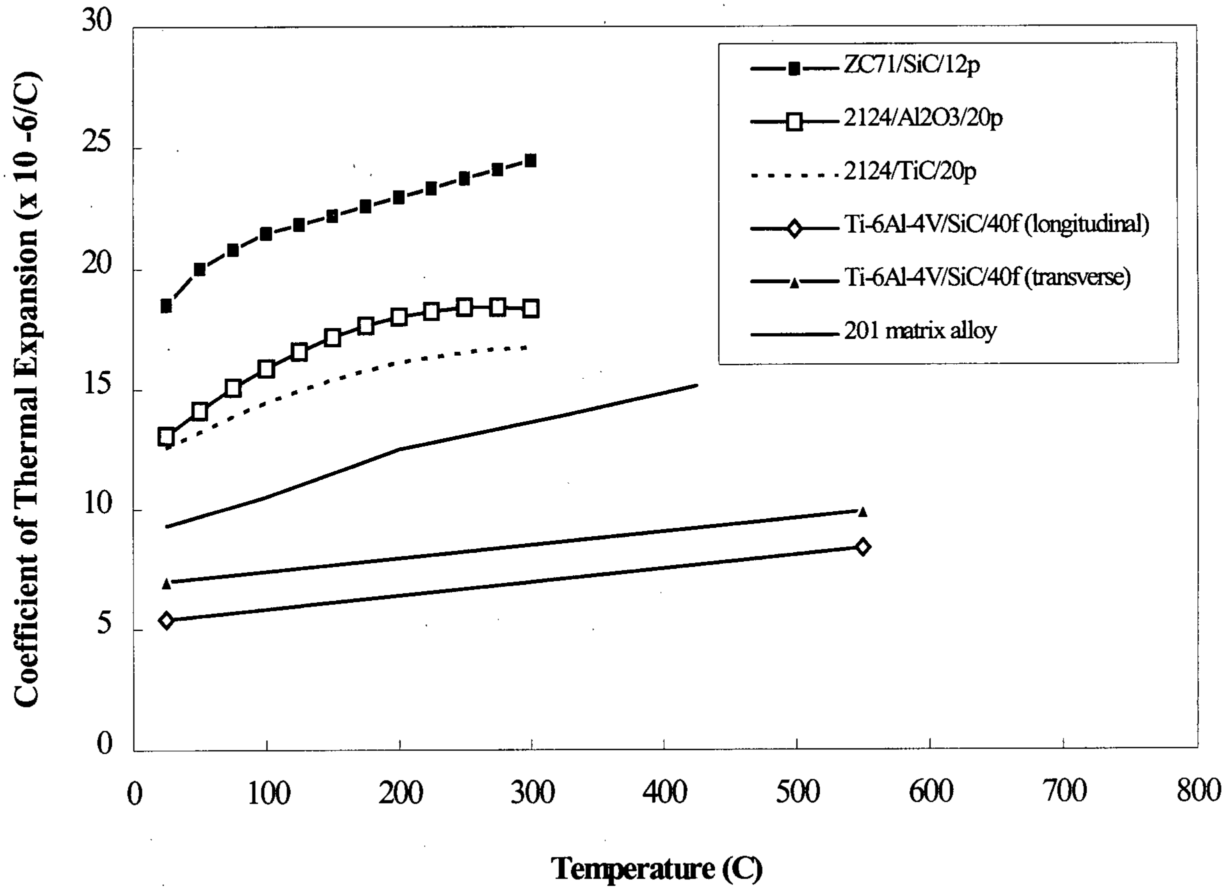


Figure 5.19 Coefficient of Thermal Expansion at Elevated Temperatures

It is evident from these results that MMC elevated temperature behavior generally follows that of the matrix alloy. This rule of thumb coupled with equations compiled in the databases allow for extrapolation and prediction of high temperature properties for new materials.

5.2 REINFORCEMENT COATINGS

Reinforcement coating information is important to aid the designer in selecting the most appropriate reinforcement from the database depending upon the matrix alloy, service environment and/or manufacturing method. Currently coatings are employed to control interfacial reactions and thereby increase operating temperatures and reduce reinforcement/matrix interactions during manufacturing. A reinforcement coatings database has been compiled and is illustrated in Table 5.5. Included are the reinforcement/matrix alloy systems for which the coatings or reinforcement surface treatments have been designed. A typical example is the Ti/SiC system in which unprotected SiC fibers are rapidly degraded by titanium at processing temperatures. A number of coatings have been developed for this system, notably carbon, TiB_2 and TiC.

For reinforcement coatings, it is desirable to have[60,99]: (1) a material which will not react with the reinforcement or matrix during fabrication or service (2) thermodynamic stability or at least slow reaction kinetics (3) highly stable oxides(from a thermodynamic point of view) (4) a barrier which impairs transport of reactants through it(i.e. migration through grain boundaries and other defects such as porosity in the barrier layer) (5) protection for fibers prior to processing(i.e. SiC on C fibers for oxidation resistance) (6) wetting agents(stimulation or modification of some local reaction) and (7) a material which promotes desirable mechanical behavior at the interface(i.e. encourage interfacial sliding or provide compliant or soft layer in contact with the fiber).

Predominance area diagrams at processing temperatures have been examined to predict the composition of reaction zones at the reacting interface[98]. This in turn has been used to suggest protective coatings based on the concept of pre-designing interfacial transition layers. Kinetic considerations are also important when selecting barrier coatings[99]. It is very difficult to make useful quantitative predictions because the reaction kinetics are highly dependent on process specific microstructural factors such as defects which provide short circuit diffusion paths.

Table 5.5 Reinforcement Coatings

Reinforcement	Coatings	Matrix Alloys
C, SiC, and Al_2O_3 particulates	Ni, Cu, Ti	Al and Cu
Al_2O_3 and SiC particulates	BN, TiN	Cu and Mo
Carbon particulate	Mg, P Cr, Ti Ca	Al Cu Fe
B fiber	B_4C TiB_2 SiC	Al and Ti Al Al
C fiber (PAN)	W_2C, Cr_3C_2, TiC Ni	Al Al
Carbon fiber	SiO_2, SiC HfB, TiB_2, ZrB SiO_2 + SiC	Cu and Mg Al, Mg, and Cu Al, Mg, Ti, and Ni
Carbon and SiC fibers	K_2ZrF_6	Al
SiC fiber	C TiB_2, TiC C/TiB_2	Ti Ti Ti
Al_2O_3 fiber	B, Ti, TiB immersed in molten Na	Al Al
Al_2O_3 short fiber/fiber	SiO_2 additions	Al

5.3 COST

Modest performance improvements are worthwhile if the MMC cost and processing requirements remain within the range of those encountered in conventional alloy development[99]. For automotive applications, components are affordable if the material costs are in the range of 0.90 - 1.35 US$/kg[100]. However, current prices for MMCs are estimated as 4-6 US$/kg for molten metal cast products, 100 US$/kg for powder metallurgical products(should reduce with scale up), and for continuous fiber reinforcement MMCs, costs are currently dominated by the cost of the fibers which can be in excess of 2000 US$/kg. Tables 5.6 - 5.8 list typical MMC, competing material, and reinforcement costs. MMC constituent materials, fabrication and final component costs are all much higher than conventional materials. These high costs have proved to be a major obstacle to commercialization. It is very difficult to convince customers that down-stream savings based on parts consolidation or longer life is worth the additional cost[100].

To establish a framework for cost comparison, a cost database of reinforcement and MMC materials has been compiled. This information is time dated, referenced and qualified such that anticipated changes are recorded. For example, new SiC whisker technology and the implementation of large scale production is set to reduce the cost of these reinforcements. This information is included with the current entry for SiC whiskers.

The estimation of manufacturing costs is very complex. In addition, a lack of experience with large scale production runs for many manufacturing processes complicates the issue further. As a guide, relative manufacturing costs have been determined and presented in the hypertext document. Figure 5.20 is an illustration taken from the hypertext document. Here the process costs are ranked relative to each other such that at the low cost end of the scale is molten metal mixing and at the high cost end is diffusion bonding.

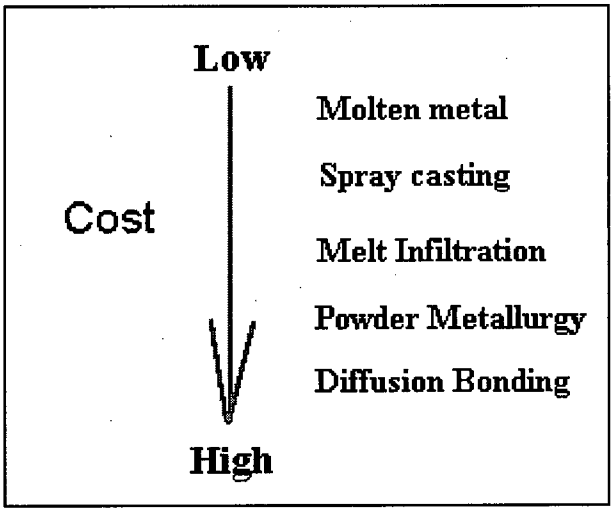


Figure 5.20 Relative Processing Costs

Table 5.6 Typical Metal Matrix Composite Costs

Metal Matrix Composite	Cost (1991 $US/kg)
Duralcan F3B & F3A particulate composites	9
Pechiney A357 + 15 v/o SiCp	10
Al/SiC whisker P/M	16-18
Al/SiC particulate P/M large runs	16-18
Al/SiC particulate P/M small runs	30-36
Martin Marietta 201 XD	30
Cu/Graphite fiber	115+
Al/SiC whisker high performance	115+
Al/B fiber MMCs	90-225

Table 5.7 Typical Competing Material Costs

Material	Cost (1991 $US/kg)
6061-T6	0.91
2014 T6	1.80
Al-Li alloys	2.30
316 Stainless Steel	1.50
Ti-6Al-4V titanium	3.50
PEEK Epoxy/graphite fiber	45-68
Fiberglass using S glass	5
Woven epoxy/graphite cloth	9-23
Woven epoxy/aramid cloth	4-12

Table 5.8 Typical Reinforcement Costs

Reinforcement	Cost (1991 $US/kg)
Al_2O_3 powder	0.13 - 2.57
B4C powder	20 - 225
SiC powder	10 - 40
SiC whisker	200-800
Si3N4 powder	25 - 125
TiB2 powder	35 - 65
Saffil Al_2O_3 fiber	40
Safimax Al_2O_3 fiber	120
Sumitomo Al_2O_3-SiO_2 fiber	550
Fiber FP Al_2O_3	250
Fiberfax Al_2O_3-SiO_2 short fiber	2.2
Fibermax Al_2O_3-SiO_2 fiber	37.5
Tyranno SiC fiber	650
Nicalon SiC fiber	350
Tokamax SiC whisker	150
Hi Mod grafil C fiber	32
SNW Si_3N_4 whisker	735
NX Si_3N_4 whisker	600
Avco SiC/C fiber	1000
Berghof SiC/W fiber	280
SCS SiC fiber	2200
ICI Safimax preforms	1000
Boron fiber	575
Carbon fiber PAN	38 - 1000
Carbon fiber Pitch	5 - 2750
Al_2O_3 fiber Nextel 312 (3M)	22
ICI Saffil alumina preforms 25 v/o	22
Tokai SiC whisker preforms 40 v/o	330

CHAPTER 6

KNOWLEDGE DOMAIN PART II

6.1 METAL MATRIX COMPOSITE DESIGN

The decision to employ advanced materials like metal matrix composites is a complex and difficult process. The designer is not simply a materials selector but a materials designer who must choose the appropriate reinforcement/matrix combination to meet the design needs. The MMC matrix may be based on any number of alloy systems. The reinforcement can be of a variety of types, have different surface treatments, have a range of volume fractions, and have different geometries. In addition, continuous reinforcements can be used in laminates to give another class of MMCs.

The myriad of potential MMCs far outdistance the limited number of materials which have been developed to date. In addition, a lack of material property measurements on these materials limit their widespread use. Mathematical modeling which relates the properties of the constituent matrix and reinforcement to that of the composite material can be used in the design of materials to meet specific requirements, fill in property gaps, reduce the cost of essential development work and shorten development lead times.

In the late 1980s, the field of new material design was being pursued[43]. To accomplish this, all relevant material behavior must first be numerically predictable. This has been difficult to achieve except for pure materials or new materials that are defined mixtures or composites of experimentally well-characterized material components, such as metal matrix composites[17].

The application of analytical and semi-empirical techniques to predict effective composite properties has found widespread acceptance and a significantly large number of models have been derived[44-74]. The majority of theoretical models have concentrated on plastic matrix composites. However, models which are accurate predictors for plastic composite systems are not necessarily applicable to MMCs. Plastic composites have non-conducting matrices, high reinforcement volume fractions, and significantly higher reinforcement to matrix strength and elastic modulus ratios. In addition, factors affecting the prediction of effective composite properties due to matrix/reinforcement chemical reactivity are not a consideration in plastic composites. As a result, an analysis of the mathematical models to select the most applicable MMC models was undertaken in this work.

Previous studies on composite materials generally either compare model predictions without measured data, have a limited number of actual data points, or are system specific(i.e. same matrix/reinforcement)[45-50,126]. In addition, Laws has shown that the experimental data used by many researchers to validate their models is outside of accepted theoretical bounds[88].

The major obstacle preventing a comprehensive study before now has probably been the lack of databases for both reinforcement and MMC material properties. Without accurate constituent and composite properties, this endeavor has not been feasible. Therefore, the selection and incorporation of MMC models in this system is a first study.

6.2 PREDICTION OF EFFECTIVE MMC PROPERTIES

The major theoretical techniques used to predict effective thermomechanical properties are based on applied mechanics[48]. This approach begins with a simple model, exploits fundamental principles of continuum mechanics(especially linear elasticity and associated extremum principles) and computes the overall properties and associated property bounds[45]. Prominent micro-mechanical models of this type include the Differential Method, Composite Spheres(Cylinders) Model, Self Consistent Method, Generalized Self Consistent Method(Three Phase Model), Mori-Tanaka Method, and the Eshelby Method[47].

Semi-empirical models, for example Halpin-Tsai equations, and models which use approximations have also found widespread acceptance[63]. These expressions are generally associated with whisker and short fiber composites due to the geometric complexity of these materials.

Finite difference and finite element methods have been used extensively in analyzing composite mechanics particularly in studying materials with various constitutive relationships, clusters of particles, and composites with imperfect interfaces[101-104]. However, these methods have difficulty in dealing with multiparticle random systems because of the complexity associated with generating an appropriate discrete model(i.e. forming an appropriate finite element mesh) and the large size of the resulting discrete problem. Finite element analysis is complicated and the results are not significantly better than the simpler analytical models derived for the corresponding geometries[46,51,105-107]. In some cases, the finite element prediction has proven to be worse than the simpler analytical model[108]. Consequently, complex numerical methods have been excluded from consideration in this work.

To model thermal cycling and high temperature behavior, models must account for the elastic-plastic nature of the matrix. In these cases, numerical methods are necessary because they can account for the simultaneous effects of anisotropic fibers, plastic deformation in the matrix and microcracking.[109]. An analytical model recently developed by Klemens for thermal expansion was examined, but the elastic regime solution was found to be inadequate[110]. As a result of the necessity for complex numerical methods, thermal cycling and high temperature modeling have not been included in the system.

6.3 EFFECTIVE PROPERTY MODEL SELECTION

The mathematical analogy which exists between thermal conduction, electrical conduction, electrostatics, magnetostatics, and elasticity means that any models obtained in one area are readily applicable to the other. Few critical evaluations have been made and consequently, a standard set of MMC models have not been identified. Models for specific matrix/reinforcement systems have been established but many perform poorly when applied to other matrix/reinforcement combinations. To date, only a few studies which compare different model predictions with measured data have been performed. Johnson and Birt compared Paul, Cox and Halpin-Tsai elastic modulus models using 6061/SiC/15p, 6061/SiC/15w and 6061/SiC/30w composites[52]. Bowles and Tompkins compared a number of CTE models with finite element analysis for unidirectional fiber reinforced composites[51]. Unfortunately, the experimental data consisted of a single 2024/Graphite/40f MMC and a few carbon reinforced epoxy and ceramic composites.

Vaidya and Chawla compared Kerner and Turner models for particulate reinforced aluminum composites; and Schapery, Chamis, and Rosen & Hashin equations for fiber reinforced MMCs[61]. Again, only a handful of data points were used.

Comparison of model predictions with experimental data has historically been done at very low reinforcement volume fractions[53]. In this range, the better models are within experimental error and only the rule of mixtures or those containing errors show large variations. The maximum difference between models occur at high volume fractions and large mismatch in constituent properties(i.e. highly loaded ceramic reinforced MMCs). Therefore, these conditions were employed to assess and select appropriate system models.

Many of the equations which have been developed using different theoretical approaches are equivalent or within close proximity of each other. For example, the lower Hashin-Shtrikman bound for a randomly distributed particulate composite is equivalent to the Rayleigh-Maxwell equation(thermal conductivity), Kerner model(coefficient of thermal expansion), Composite Spheres Model, Generalized Self Consistent Scheme(spherical reinforcement), Behrens' model, Mori-Tanaka equation(harder, spherical reinforcement), Halpin-Tsai equation(spherical reinforcement), Eshelby equation(spherical reinforcement) and so on. This feature is generally unreported in the literature.

6.3.1 <u>MODEL CATEGORIZATION</u> The composite models are first divided into three categories: fiber, whisker/short fiber, and particulate reinforced MMCs based on elongated reinforcement aspect ratio and that the analysis of properties is different for each group[45,46]. Next, since only closed form solutions are acceptable, reinforcement distribution categories are necessary. The configurations which are readily accommodated by analytical models and represent the two boundaries on orientation are random and aligned reinforcement distributions. The aligned reinforcement orientations are represented by property values transverse and longitudinal to the aligned reinforcement axis. Maximum property values are obtained in the aligned longitudinal direction, minimum in the transverse direction and random orientation values are in-between.

To distinguish between particulate, whisker/short fiber, or fiber reinforcements, valid ranges of reinforcement average aspect ratios for each category need to be set. To determine the aspect ratio which separates particulates from whiskers, analytical equations were compared with experimental observation. Lloyd has observed that aspect ratios of ≤ 5 are typical of particulate reinforced MMCs[111]. For aligned short fiber composites, only at low aspect ratios of ≤ 5 are the numerous models significantly different[112,113]. In addition, at these low aspect ratios the predictions are generally poor and experimental results are more consistent with the particulate models. Consequently, 5 has been established as the maximum particulate/whisker threshold aspect ratio.

Figure 6.1 shows coefficient of thermal expansion(CTE) predictions for ZC63/SiC/30w. The particulate to whisker/short fiber boundary is clearly evident at an aspect ratio of 5. At this point, the CTE for both randomly distributed particulate and whisker/short fiber models are equivalent.

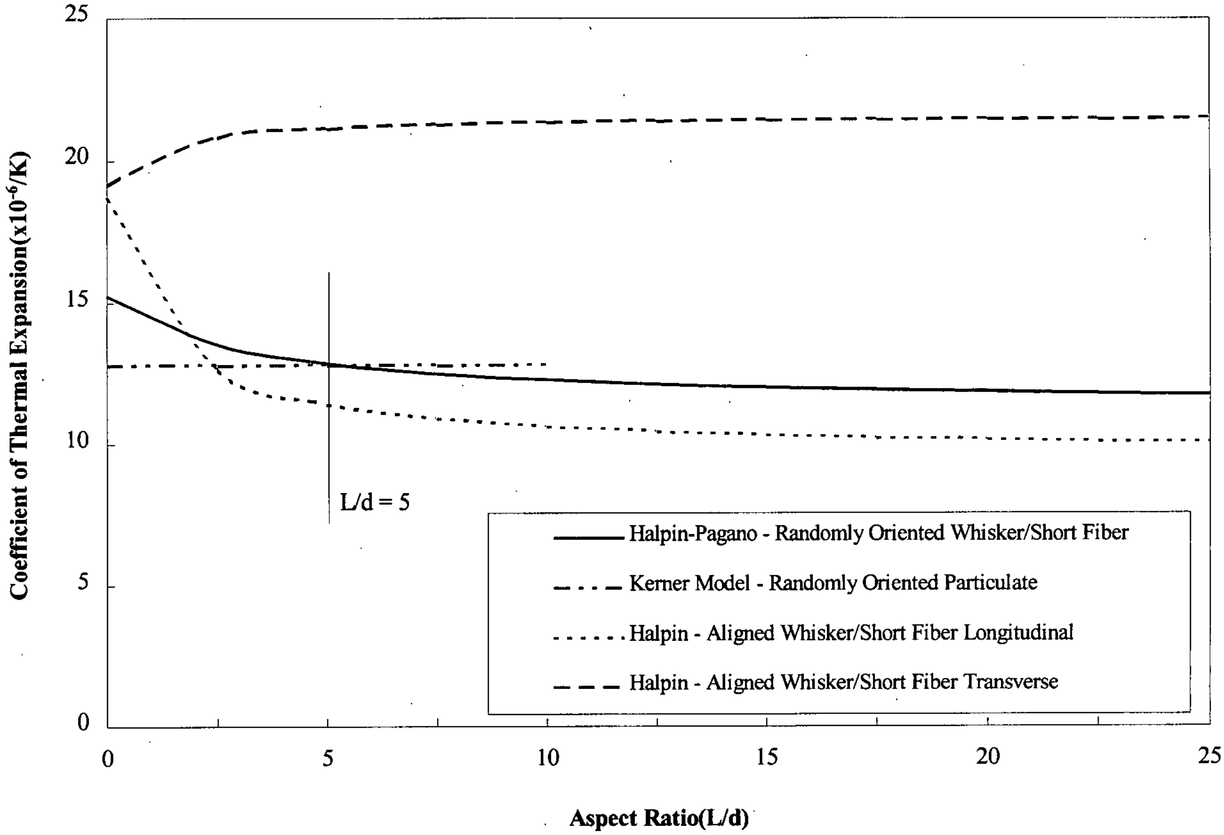


Figure 6.1 CTE Prediction for ZC63/SiC/30w(sf) as a function of Aspect Ratio

The establishment of a definitive whisker/short fiber to continuous fiber transition aspect ratio is more difficult. Figure 6.2 demonstrates how whisker/short fiber prediction curves converge to continuous fiber curves. The whisker/short fiber prediction curves approximate the continuous fiber values at surprisingly low aspect ratios particularly in the transverse direction. This behavior is independent of reinforcement volume fraction. Whisker and short fiber reinforcements with aspect ratios of 50 or more(e.g. Fiberfrax) are common. Therefore, although theoretically the transition is as low as 30, the actual constituent reinforcement values are higher and a value of 100 has been selected to avoid user confusion.

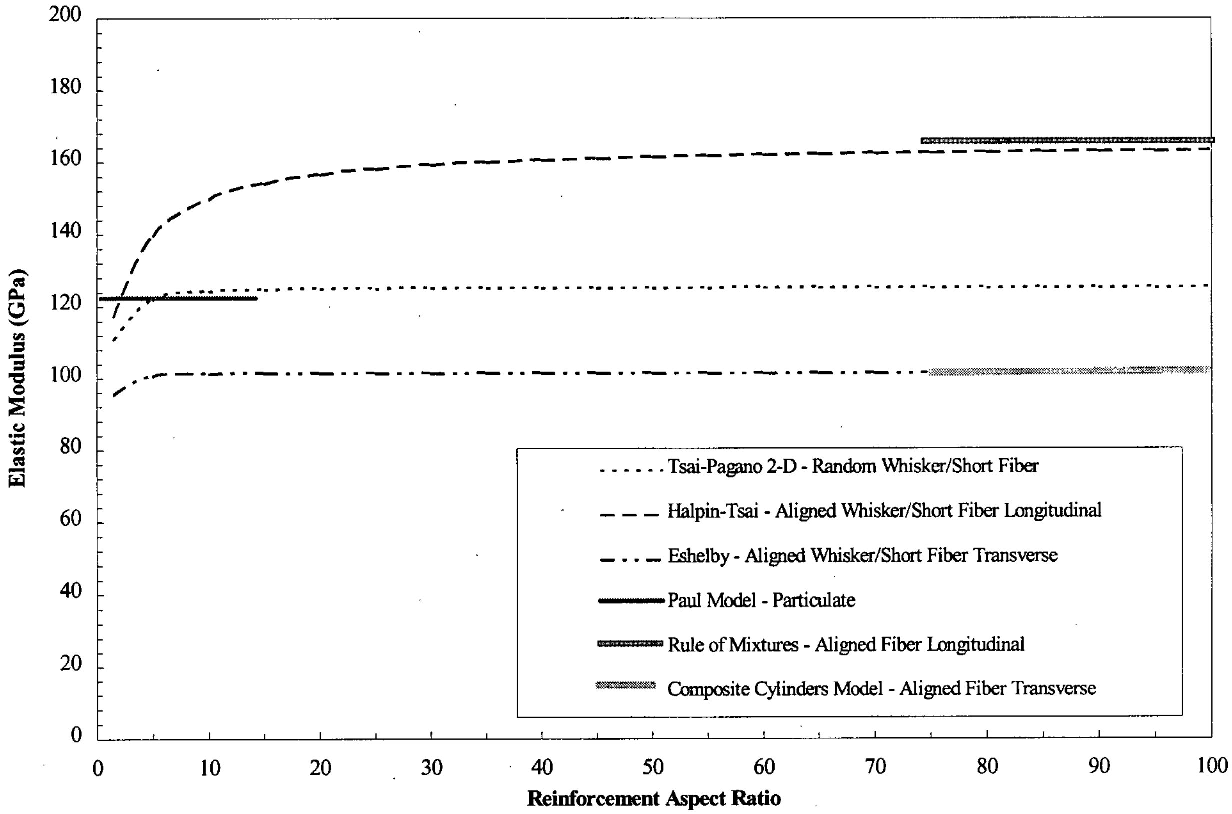


Figure 6.2 Elastic Modulus versus Aspect Ratio for 6061/SiC/25w

6.3.2 <u>MODEL ASSUMPTIONS</u> The majority of models, including finite element and boundary element techniques, are formulated with a basic set of assumptions, compiled in Table 6.1, to keep the problem tractable. In many instances, they do not represent real MMC systems and coupled with poor constituent characterization, contribute to poor correlation with experimental data. Specifically, numerous models which only consider a dilute reinforcing phase, such as the Differential model, are poor predictors at high reinforcement volume fractions[114]. Models of this type were not considered. In addition, equations which require iteration based on experimental measurements, such as Bruggeman's equation, were also not considered[115].

Table 6.1 Model Assumptions

Model Assumptions
Linear elastic behavior of matrix and reinforcement(plastic regime not considered)
Volume fraction limitations(reinforcement distribution)
No chemical reactions occur at the matrix/reinforcement interface
Bonding between reinforcement and matrix is perfect and purely mechanical in nature
The reinforcement is typically uniformly distributed in the matrix (a few specific models consider randomly distributed reinforcements)
Uniform shape and size of reinforcement
Transverse isotropy for aligned continuous fiber reinforced composites
Unreinforced matrix properties equivalent to those of the composite
Dilute case such that reinforcement/reinforcement interactions are neglected
Composite statistically homogeneous such that while representative unit cell or volume element may be regular or irregular, isotropic or anisotropic, the element is representative of the whole sample
Thermal convection and radiation are negligible and consequently neglected
Models are generally based on 1-D or 2-D, with a handful on 3-D heat conduction

6.3.3 INFLUENCE OF MATERIAL PROPERTY VALUES ON MODEL ACCURACY To determine the accuracy of the models, model predicted values were compared with the analogous measured values. Experimental data was obtained from the MMC database and the respective constituent properties from the reinforcement materials and matrix alloys databases. Caution was employed since one model may seem better than others depending upon the input values when compared to experimental results[116]. Specifically, non-direct methods of obtaining material property values are prone to error, (i.e. extrapolation, calculation, and estimates) variations are inherent in experimental and test methods, and variations can be considerable with different alloy compositions, heat treatments and processing routes. In addition, the matrix in a MMC is not in the same state as the monolithic alloy which is generally unaccounted for in the constituent properties[117]. This can be due to the difference in thermal stress history, segregation of matrix additions to the interface, or the presence of reinforcements which influence matrix solidification and solid-state matrix transformations like precipitation and recrystallization.

Figure 6.3 contains thermal conductivity predictions for 6061/SiCp and 6090/SiCp using the Rayleigh-Maxwell equation(Hashin-Shtrikman upper bound). The thermal conductivities of 6061-T6 and 6090-T6 are 167 and 174 W/mK respectively. SiCp thermal conductivity values range from 81, a relatively inexpensive commercial particulate, to a high of 490 W/mK, a high purity material. This extreme difference has a substantial effect on the predicted MMC thermal conductivity. For example, at 50 volume percent, the disagreement is 175 W/mK.

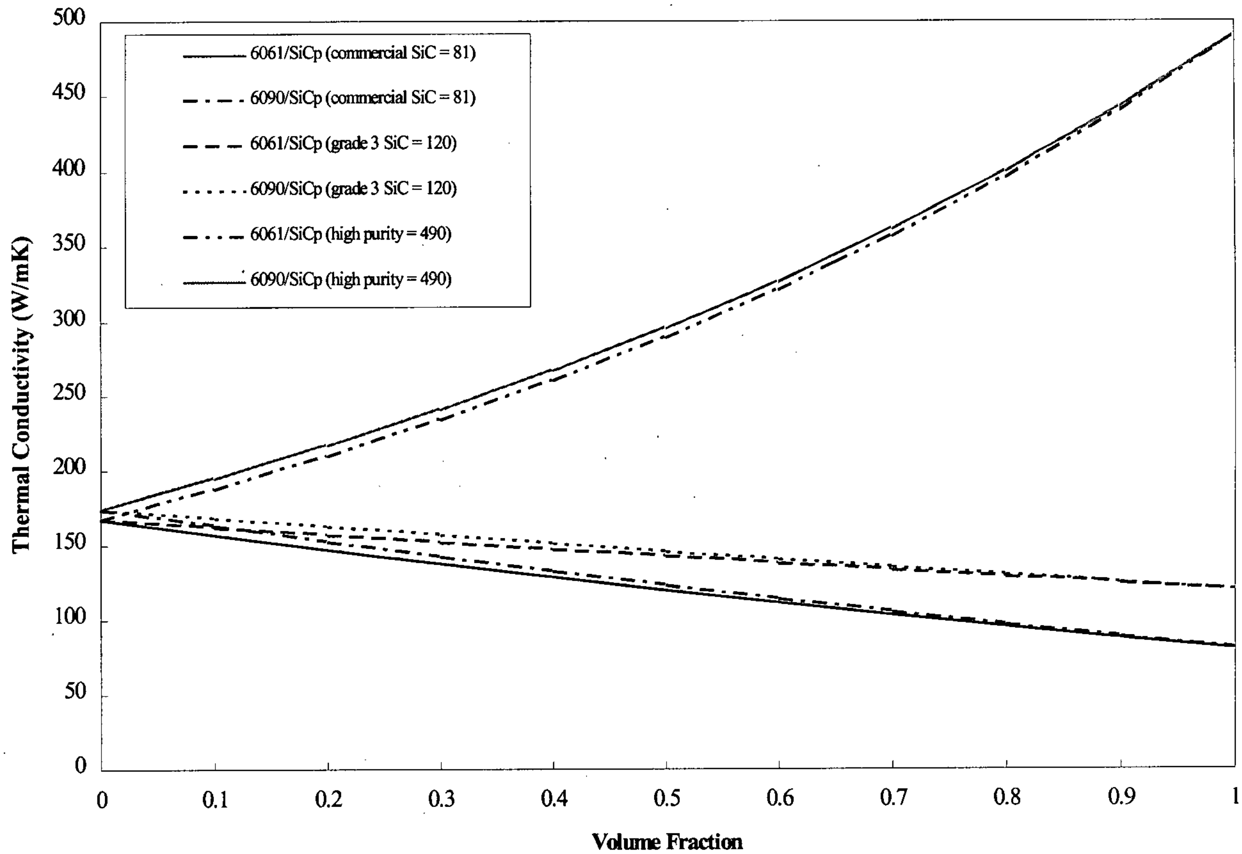


Figure 6.3 Thermal Conductivity Predictions using Rayleigh-Maxwell Equation

6.4 EXPERT SYSTEM MODELS

6.4.1 <u>BOUNDS</u> Specific bounds are included because they are valuable in certain situations[44,47,48]. First, they are invaluable when it is not possible to obtain a direct model solution for the effective property of interest[44]. For example, when the phase geometry is unknown or constituent properties are inaccurate. They are used to test the predictions of new models such that if a particular model violates relevant bounds then the model is useless[48,49].

The most general and basic set of bounds developed for the dielectric constant of a two-phase isotropic material are given by Weiner's bounds[123]:

$$k_{lower} = \frac{1}{\dfrac{V_r}{k_r} + \dfrac{(1 - V_r)}{k_m}} \quad \text{.....(6.1a)}$$

$$k_{upper} = V_r k_r + (1 - V_r) k_m \quad \text{.....(6.1b)}$$

These bounds correspond to those obtained by Brown using minimization theories and are identical to the equations for a composite with alternating laminae or the spring model of fibers acting in parallel(Voigt equation) and in series(Reuss equation)[48,60]. Only the reinforcement volume fraction and constituents' property of interest are used in this equation.

Hashin & Shtrikman derived second order bounds without specifying the phase geometry using variational principles[55]:

$$k_{lower} = k_r \left\{ 1 + \frac{(1 - V_r)}{\dfrac{k_r}{(k_m - k_r)} + \dfrac{V_r}{S}} \right\} \quad \text{.....(6.2a)}$$

$$k_{upper} = k_m \left\{ 1 + \frac{V_r}{\dfrac{k_m}{(k_r - k_m)} + \dfrac{(1 - V_r)}{S}} \right\} \quad \text{.....(6.2b)}$$

where: S = 3 for an isotropic two-phase composite
S = 2 for transversely isotropic cylindrical assemblage

These bounds incorporate a variable field of admissible stress and strain rather than the uniform fields of stress and strain[47,48,55].

Torquato et al compared third and fourth order bounds for random, impenetrable spheres of uniform size and a random array of equisized circular cylinders to those of Hashin-Shtrikman[44,124,125]. The main improvement seen was the lowering of the upper elastic modulus bounds while the lower bounds remained closely approximated by the Hashin-Shtrikman lower bound. Since most metal matrix composites follow the lower bound(due to the reinforcement phase having a significantly higher elastic modulus), improvements to the upper bound using these methods generally does not result in significant improvements to the predicted effective composite CTE, elastic modulus, shear modulus and bulk modulus. A more effective technique to improve bounds is to use a specific composite model.

Tighter bounds are possible when the structural geometry, shape and orientation of the reinforcement is available through the use of statistical information. Nomura & Chou have developed simple bounds on effective thermal conductivity and elastic modulus for specific composite models[59]. A perturbation expansion of the local field gradient is developed using Green's function tensor. The correlation of the thermal conductivity/elastic modulus are evaluated based upon the characteristics of the geometry and distribution of the matrix and reinforcement. The bounds are then determined from a variational treatment of the correlation functions up to the third order term. For thermal conductivity, the Nomura & Chou bounds are as follows:

$$\left\{\frac{V_r}{k_r}+\frac{V_m}{k_m}-\frac{V_rV_m\left(\frac{1}{k_r}-\frac{1}{k_m}\right)^2 h(s)}{(V_m-V_r)\left(\frac{1}{k_r}-\frac{1}{k_m}\right)h(s)+\frac{V_r}{k_r}+\frac{V_m}{k_m}}\right\}^{-1} \leq k_{11}^* = k_L \leq$$

$$V_rk_r + V_mk_m - \frac{V_rV_m(k_r - k_m)(1 - h(s))}{(V_m - V_r)(k_r - k_m)(1 - h(s)) + V_rk_r + V_mk_m} \quad \text{.....(6.3a)}$$

$$\left\{\frac{V_r}{k_r}+\frac{V_m}{k_m}-\frac{V_mV_r\left(\frac{1}{k_r}-\frac{1}{k_m}\right)^2\left(1-\frac{h(s)}{2}\right)}{(V_m-V_r)\left(\frac{1}{k_r}-\frac{1}{k_m}\right)\left(1-\frac{h(s)}{2}\right)+\left(\frac{V_r}{k_r}+\frac{V_m}{k_m}\right)}\right\}^{-1} \leq k_{22}^* = \quad \text{.....(6.3b)}$$

$$k_{33}^* = k_T \leq V_rk_r + V_mk_m - \frac{V_mV_r(k_r - k_m)h(s)}{(V_m - V_r)(k_r - k_m)h(s) + 2(V_rk_r + V_mk_m)}$$

where:

$$h(s) = \frac{s^2}{s^2-1}\left[1-\frac{1}{2}\left\{\left(\frac{s^2}{s^2-1}\right)^{1/2}-\left(\frac{s^2-1}{s^2}\right)^{1/2}\ln\left(\frac{s+\sqrt{s^2-1}}{s-\sqrt{s^2-1}}\right)\right\}\right]$$

s = reinforcement aspect ratio L/d

Spherical inclusions, $h(s) = 2/3$

Long continuous fibers, $h(s) = 1$

Figure 6.4 demonstrates how the bounds become tighter as successively more microstructural information is incorporated. One of the bounds can typically provide a relatively accurate estimate of the property even when the reciprocal bound diverges from it[54]. To demonstrate the advantage of using specific bounds developed for a reinforcement category, consider the approach employed by Ashby et al[28]. Weiner bounds are used to predict elastic moduli for all particulate, whisker, short fiber and fiber composites[28]. For the SiC particulate reinforced aluminum 2124 system of Figure 6.4, the improvement in accuracy using Nomura & Chou model specific bounds is evident particularly at higher reinforcement volume fractions.

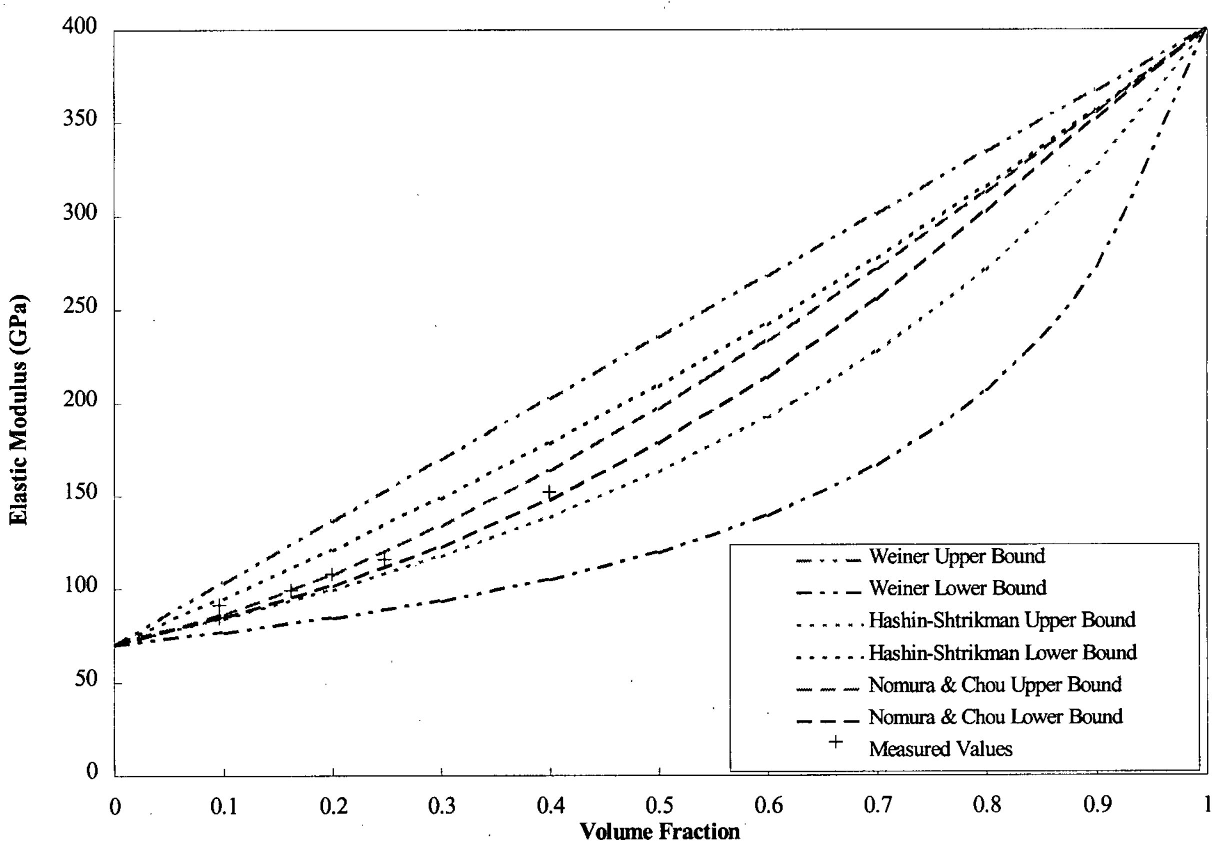


Figure 6.4 Comparison of Elastic Modulus Prediction for 2124/SiCp

Correlation functions which incorporate statistical and probability information have been incorporated by Beran, Silnutzer, Miller, Brown, Milton, Torquato, and others to give even tighter bounds[3,5,7,23,25,34,38,44]. However, experimental determination of the required probability functions is an involved and time-consuming task and it is easier to determine effective properties experimentally. The multipoint probability functions cannot in general distinguish between matrix and reinforcement phases. This leads to bounds being far apart when the difference in constituent properties is large. As a result, these complex models are of limited value and not incorporated in the system.

6.4.2 PARTICULATE MODELS Many mathematical models and approaches have been introduced in order to predict an effective thermal conductivity or elastic modulus value for particulate reinforced composite materials[47,50,52,60,121,126-129]. A majority of these models reduce to the Rayleigh-Maxwell equation (lower Hashin-Shtrikman bound) when the reinforcement phase is spherical. However, particulates are generally not spherical in shape thus the Lewis & Nielsen and Paul models are necessary.

The Rayleigh-Maxwell equation was derived using potential theory for randomly distributed and non-interacting homogeneous spheres in a homogeneous continuous medium[130,131]. This model is particularly effective for low volume fractions of spherical reinforcements with a negligible interfacial reaction layer.

The effect of the presence of a reaction layer has been well documented for Ti-SiCp composites where a reduction in the thermal conductivity value occurred as the reaction layer thickened[58]. Complicated models have been derived to account for reinforcements with coatings or interfacial reaction layers but these require characterized boundary conditions(i.e. interface/coating characteristics)[86]. The Hasselman & Johnson model is a simple analytical model to account for a thermal resistance at the particulate/matrix interface due to porosity or a reaction layer as follows[58,60]:

$$k = k_m \left[\frac{2V_r\left(\frac{k_r}{k_m} - \frac{k_r}{re} - 1\right) + \frac{k_r}{k_m} + \frac{2k_r}{re} + 2}{V_r\left(1 - \frac{k_r}{k_m} + \frac{k_r}{re}\right) + \frac{k_r}{k_m} + \frac{2k_r}{re} + 2} \right] \quad .....(6.4)$$

where r = particulate radius
e = reaction layer (thermal conductivity/thickness)

This equation is equal to the Rayleigh-Maxwell equation in the absence of a thermal barrier. The major difficulty in applying this and any other model is the current lack of interfacial knowledge and consequently, the reaction layer thickness and heat transfer properties are unknown. Research is currently underway to characterize interfaces, particularly for aluminum alloys reinforced with silicon carbide.

The Paul model, given by equation (6.5), is a simple approximation for a material with cube shaped inclusions, which are assumed to have a finite length[57].

$$k = k_m \left[\frac{k_m + (k_r - k_m)V_r^{1.5}}{k_m + (k_r - k_m)V_r^{1.5}\left(1 - V_r^{1/3}\right)} \right] \quad .....(6.5)$$

where: k can be replaced by E

The equation is not a function of the particulate size and may be applied to nonspherical shaped particulates with or without varying size distributions.

Hashin-Shtrikman bounds are employed to determine shear modulus using equation (6.6) and bulk modulus with equation (6.7)[55,65].

$$G^*_{(-)} = G_1 + \frac{V_2}{\frac{1}{G_2 - G_1} + \frac{6V_1(K_1 + 2G_1)}{5G_1(3K_1 + 4G_1)}} \quad .....(6.6a)$$

$$G^*_{(+)} = G_2 + \frac{V_1}{\dfrac{1}{G_1 - G_2} + \dfrac{6V_2(K_2 + 2G_2)}{5G_2(3K_2 + 4G_2)}} \qquad .....(6.6b)$$

$$K^*_{(-)} = K_1 + \frac{V_2}{\dfrac{1}{K_2 - K_1} + \dfrac{3V_1}{3K_1 + 4G_1}} \qquad .....(6.7a)$$

$$K^*_{(+)} = K_2 + \frac{V_1}{\dfrac{1}{K_1 - K_2} + \dfrac{3V_2}{3K_2 + 4G_2}} \qquad .....(6.7b)$$

where: $G_2 > G_1$
if $G_1 > G_2$, bounds are reversed
if $G_1 = G_2$, bounds coincide

The bulk and shear moduli of the Mori-Tanaka method correspond to the lower Hashin & Shtrikman bound if the inclusion is the harder phase and the upper bound if the inclusion is the softer phase[47]. Kerner developed a model for packed spherical particles which accounts for both the shear and isostatic stresses developed in the component phases[119]. By using an averaging process for finding the bulk modulus of the composite, he obtained the same equation as the lower bound of Hashin and Shtrikman. Wakashima et al have also derived the Hashin & Shtrikman lower bound equation using the equivalent-inclusion method introduced by Eshelby and additionally developed by Mura[118,120,132].

It has been shown that the effective Poisson's ratio is given by the following relationship[47-49,55,57]:

$$\upsilon^* = \frac{3K^* - 2G^*}{2(3K^* + G^*)} \qquad .....(6.8)$$

Hashin and Shtrikman have established Poisson's ratio bounds by substituting in shear and bulk modulus bounds from equations (6.7) and (6.8). Paul's bounds, for a two-phase material of irregular geometry, are equivalent to Weiner's(Reuss-Voigt) thermal conductivity bounds[57]. Bounds are currently used in the system due to an absence of measured values for model validation.

A basic relationship for an effective coefficient of thermal expansion for an isotropic composite with two isotropic phases has been established by Levin and others as follows[55,133-135]:

$$\alpha^* = \bar{\alpha} + \frac{\alpha_1 - \alpha_2}{\left[\left(\frac{1}{K_1}\right) - \left(\frac{1}{K_2}\right)\right]}\left[\frac{1}{K^*} - \overline{\left(\frac{1}{K}\right)}\right]$$

where: .....(6.9)

$$\bar{\alpha} = V_1\alpha_1 + V_2\alpha_2 \qquad \overline{\left(\frac{1}{K}\right)} = \frac{V_1}{K_1} + \frac{V_2}{K_2}$$

$$K^* = \frac{E^*}{3(1 - 2v^*)}$$

General bounds are based on the expression of strain or stress energy in terms of effective elastic moduli and average strains or stresses[65]. For the case of uniform strain, with no elastic interactions between the constituents, substitution of an effective bulk modulus in the general equation gives the Rule of Mixtures.

Turner considered each component of the composite to be constrained to change dimensions with temperature equal to the aggregate dimensional change with temperature using a force balance criteria[136]. This model is based on uniform hydrostatic stresses existing in the phases giving an effective bulk modulus which is substituted into the generalized equation above[136].

substitute $K^* = K_p V_p + K_m V_m$

$$\alpha^*_{(-)} = \frac{\alpha_m V_m K_m + \alpha_p V_p K_p}{V_m K_m + V_p K_p} \qquad \text{.....(6.10a)}$$

substitute $K^* = \dfrac{1}{\dfrac{V_p}{K_p} + \dfrac{V_m}{K_m}}$

$$\alpha^*_{(+)} = V_p \alpha_p + V_m \alpha_m \qquad \text{.....(6.10b)}$$

Tighter bounds on effective coefficient of thermal expansion are derived by substituting Hashin-Shtrikman bulk modulus bounds into the generalized equation to give the following[48]:

$$\alpha^*_{(-)} = \alpha_1 - \frac{(\alpha_1 - \alpha_2)K_2(3K_1 + 4G_1)V_2}{K_1(3K_2 + 4G_1) + 4(K_2 - K_1)G_1V_2} \qquad \text{.....(6.11a)}$$

$$\alpha^*_{(+)} = \alpha_2 - \frac{(\alpha_2 - \alpha_1)K_1(3K_2 + 4G_2)V_1}{K_2(3K_1 + 4G_2) + 4(K_1 - K_2)G_2V_1} \qquad \text{.....(6.11b)}$$

where: $\frac{\alpha_2 - \alpha_1}{K_2 - K_1} > 0$ and $G_2 > G_1$

when: $\frac{\alpha_2 - \alpha_1}{K_2 - K_1} < 0$ or $G_2 < G_1$ the bounds are reversed

$\alpha_1 = \alpha_2$ or $G_1 = G_2$, the bounds coincide

The composite spheres model of Hashin & Shtrikman is representative of the behavior of a wide variety of composite systems, not just those with exactly spherical particles[65]. The effective properties relate to global averages of stress and strain, which themselves are more dependent on the volume fractions of various phases, rather than on the details of the local geometry of phases. This model assumes that each composite sphere is surrounded by composite material rather than matrix and incorporates an element of randomness into the phase geometry. So long as the particles are not greatly different in shape from the spherical configuration, the model would be expected to give a reasonable prediction.

Figure 6.5 illustrates the prediction of coefficient of thermal expansion for 6061/SiCp. The lower Hashin-Shtrikman bound gives the best fit to the measured values, consistent with Vaidya and Chawla's result, and is employed to predict CTE of randomly oriented particulate MMCs.

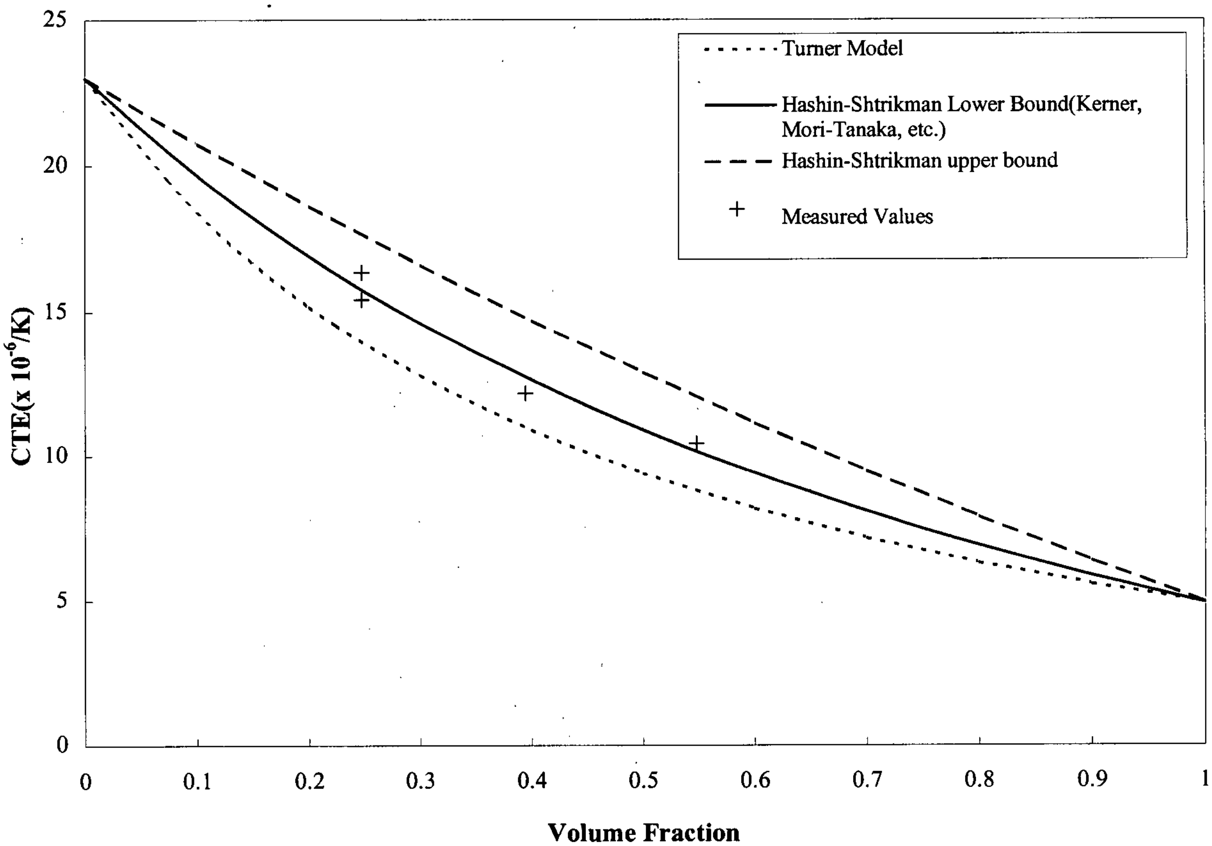


Figure 6.5 6061/SiCp Coefficient of Thermal Expansion

Figure 6.6 shows the prediction of elastic modulus for 6092/SiCp. The Paul model, consistent with Johnson and Birt's result, is used to predict elastic modulus of randomly distributed particulate reinforced MMCs. At low reinforcement volume fractions, all of the models are within close proximity of one another and can equally be used. For aligned particulate MMCs, typically extruded or rolled material, the upper Nomura & Chou bound is used to predict longitudinal modulus and the lower bound predicts transverse modulus.

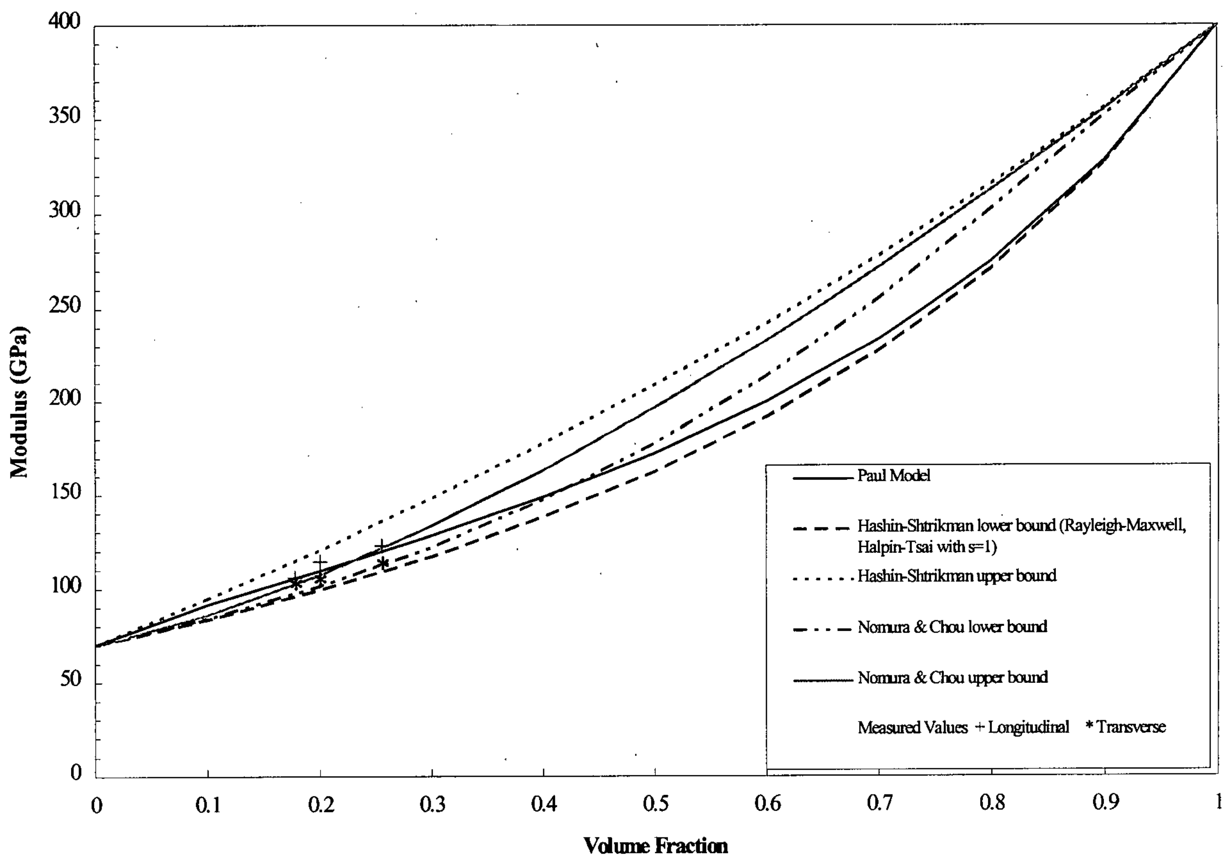


Figure 6.6 6092/SiCp Elastic Modulus

The elastic modulus of aluminum/SiCp composites reach 110 GPa, characteristic of titanium alloys, at relatively moderate reinforcement levels. This is a driving force in their development to replace titanium alloys in weight critical structural applications.

Figure 6.7 demonstrates the prediction of elastic modulus for Mg-6Zn/SiCp. The Hashin-Shtrikman and Nomura & Chou bounds are wider when compared to 6092/SiCp due to a larger reinforcement to matrix alloy elastic modulus ratio. Like aluminum MMCs, stiffness improvements of particulate reinforced magnesium alloys are also important for light-weight substitution of aluminum alloys. At reinforcement volume percent levels of 25, the effective magnesium composite elastic modulus is equivalent to aluminum alloys.

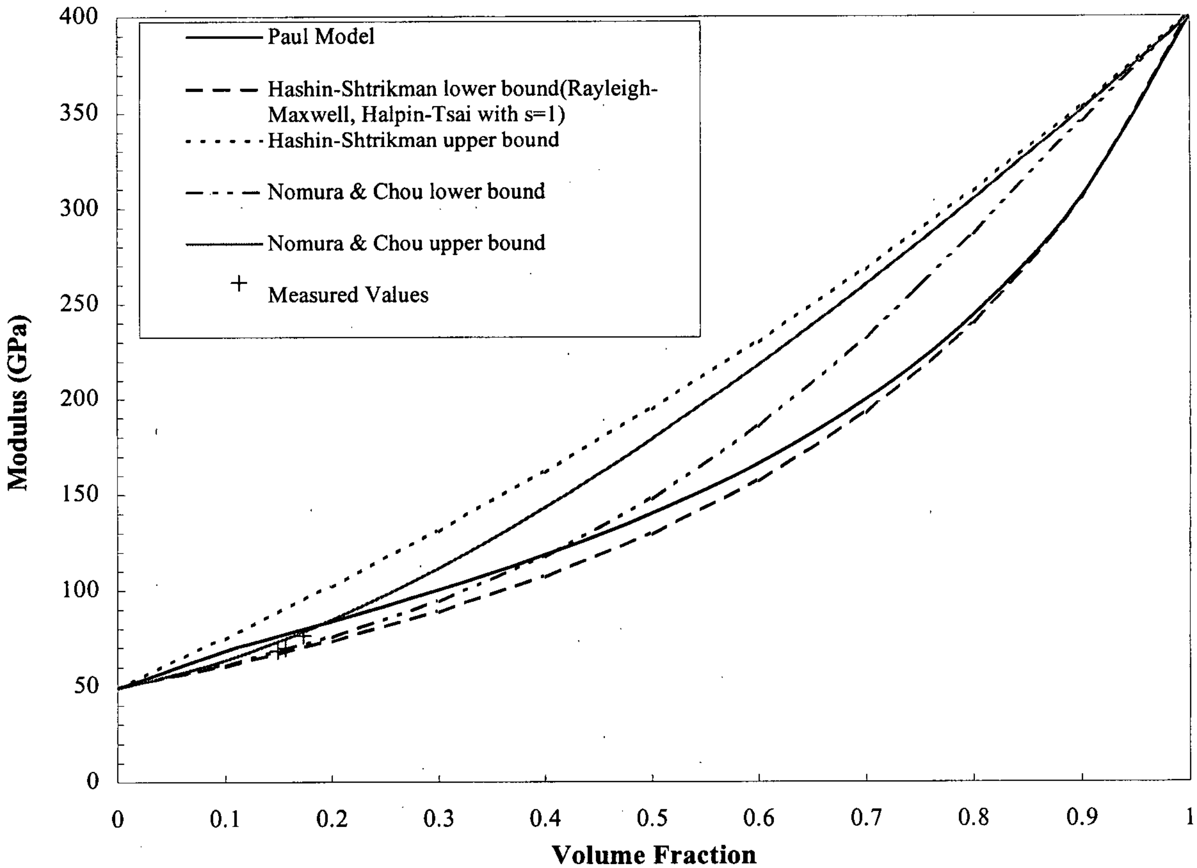


Figure 6.7 Mg-6Zn/SiCp Elastic Modulus

Bulk and shear moduli for 6061/SiCp are shown in Figure 6.8. Hashin-Shtrikman lower bounds are typically used for predicting bulk and shear moduli of randomly oriented particulate reinforced MMCs. In general, shear and bulk modulus are considered as part of elastic modulus. A lack of experimental data makes independent validation of these equations impossible therefore bounds are used in the system at this time.

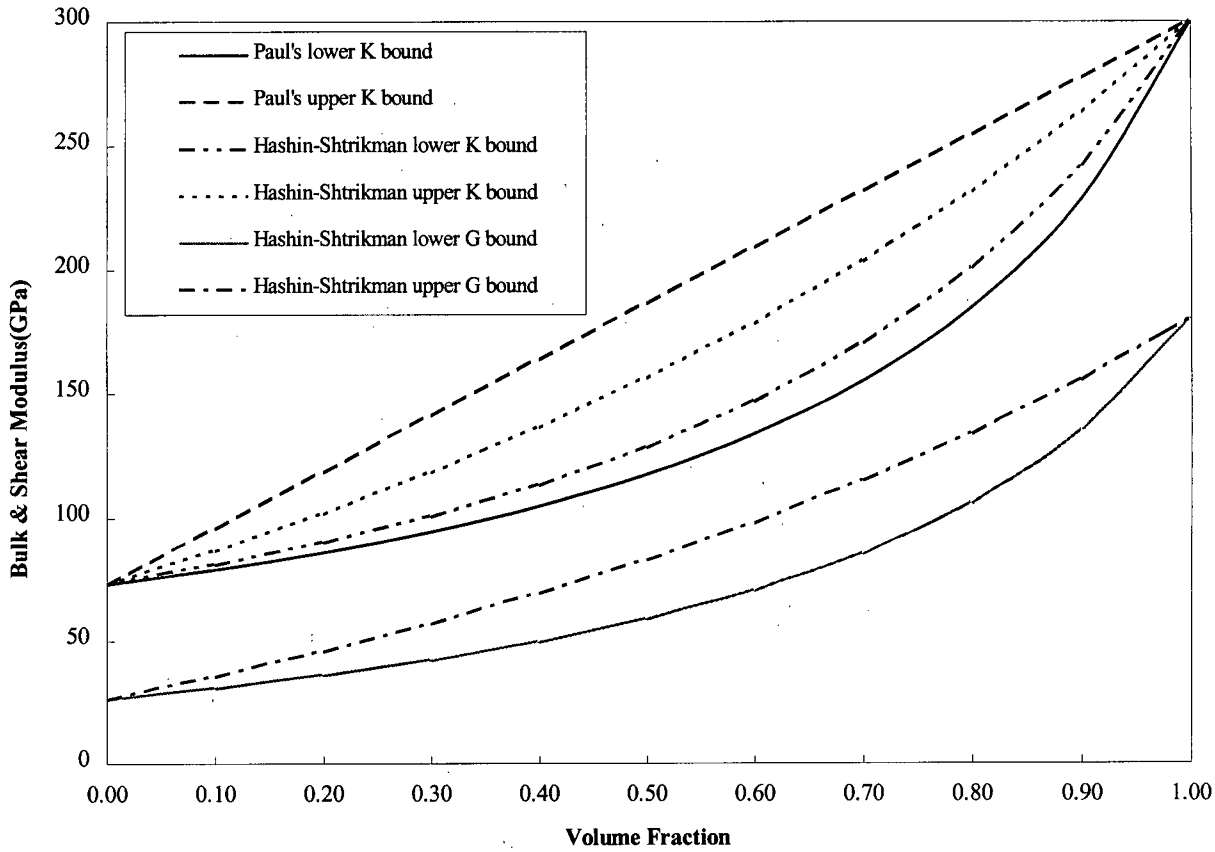


Figure 6.8 6061/SiCp Bulk and Shear Moduli

6.4.3 CONTINUOUS FIBER MODELS Unidirectional fiber composite materials have two principal properties, namely transverse and longitudinal to the fiber axis. The longitudinal effective thermal conductivity and elastic modulus are approximated by the Rule of Mixtures[45-50,56,60-65,114,118,126]. Longitudinal coefficient of thermal expansion is calculated using Schapery's equation, the Composite Cylinders Model(equivalent to Generalized Self Consistent method) and the Modified Eshelby method[47-49,51,65,67,70,71,121]. The transverse effective properties are more difficult than longitudinal to represent and numerous analytical, numerical and semi-empirical techniques have been developed[45-50,56,61-65,70,71,74,114,118,126]. The major difficulty in applying any of these formulae is the lack of experimental data on the constituents themselves, specifically transverse fiber properties. Hashin-Shtrikman bounds(lower bound equivalent to Eshelby method and Composite Cylinders Model), Kural & Min equation and Nomura & Chou bounds are used to calculate the transverse thermal conductivity and elastic modulus[46-50,59,64,65,114,118]. The Eshelby method, Composite Cylinders model(equivalent to Generalized Self Consistent method), and Schapery equation(with Strife & Prewo modification) are employed to approximate the transverse coefficient of thermal expansion[47-49, 65,67,70,71,121]. Poisson's ratio, shear and bulk moduli are approximated by the Generalized Self Consistent method, the mechanics of materials approach(Kural & Min and Schoutens), and Hashin & Hill bounds[47-49,55,65].

Rosen and Hashin extended the work of Levin to derive expressions for the effective coefficient of thermal expansion for multiphase composites with their Composite Cylinders model as follows[134,138]:

$$\alpha_L = \bar{\alpha} + \frac{(\alpha_f - \alpha_m)}{\left(\frac{1}{K_f} - \frac{1}{K_m}\right)}\left[\frac{3(1-2\nu_{12})}{E_{11}} - \left(\frac{\bar{1}}{K}\right)\right] \quad .....(6.12a)$$

$$\alpha_T = \alpha_c + \frac{(\alpha_f - \alpha_m)}{\left(\frac{1}{K_f} - \frac{1}{K_m}\right)}\left[\frac{3}{2K_{23}} - \frac{3(1-2\nu_{12})\nu_{12}}{E_{11}} - \left(\frac{\bar{1}}{K}\right)\right] \quad .....(6.12b)$$

where:

$$\bar{\alpha} = \alpha_f V_f + \alpha_m V_m$$

$$\left(\frac{\bar{1}}{K}\right) = \frac{V_f}{K_f} + \frac{V_m}{K_m}$$

$$\nu_{12} = V_f \nu_f + V_m \nu_m + \frac{V_f V_m (\nu_f - \nu_m)\left[\dfrac{G_m}{K_m + G_m/3} - \dfrac{G_m}{K_f + G_f/3}\right]}{\dfrac{V_m G_m}{K_f + G_f/3} + \dfrac{V_f G_m}{K_m + G_m/3} + 1}$$

This model is the two-dimensional counterpart of the three-dimensional Composite Spheres model, for a transversely isotropic composite with isotropic phases. Through the analysis of an individual composite cylinder, this model determines four of the five effective moduli for the representative volume element.

Christensen and Lo extended the spherical inclusion problem to the corresponding cylindrical inclusion problem using the Generalized Self-Consistent scheme[53]. The Self-Consistent model assumes the cylinder is embedded in an effective homogeneous medium which is transversely isotropic and allows for the full range of volume fraction of fibers[47]. The solutions of the model lead to closed form, exact solutions for five properties which correspond to solutions of the Composite Cylinders model. These are the axial modulus, axial Poisson's ratio, plane strain bulk modulus, axial shear modulus, and the property not determined by the composite cylinders model, the transverse shear modulus.

$$E_{11} = V_f E_f + V_m E_m + 4V_f V_m G_m \left[\frac{(\nu_f - \nu_m)^2}{\dfrac{V_m G_m}{K_f + G_f/3} + \dfrac{V_f G_m}{K_m + G_m/3} + 1} \right] \quad .....(6.13)$$

$$\nu_{12} = V_f \nu_f + V_m \nu_m + \frac{V_f V_m (\nu_f - \nu_m) \left[\dfrac{G_m}{K_m + G_m/3} - \dfrac{G_m}{K_f + G_f/3} \right]}{\dfrac{V_m G_m}{K_f + G_f/3} + \dfrac{V_f G_m}{K_m + G_m/3} + 1} \quad .....(6.14)$$

$$K_{23} = K_m + \frac{G_m}{3} + \frac{V_f}{\dfrac{1}{K_f - K_m + (G_f - G_m)/3} + \dfrac{V_m}{K_m + 4G_m/3}} \quad .....(6.15)$$

$$G_{12} = G_m \left[\frac{G_f(1 + V_f) + G_m(1 - V_f)}{G_f(1 - V_f) + G_m(1 + V_f)} \right] \quad .....(6.16)$$

$$G_{23} = G_m \left[1 + \frac{V_f}{\dfrac{G_m}{G_f - G_m} + \dfrac{V_m\left(K_m + \frac{7}{3}G_m\right)}{\left(2K_m + \frac{8}{3}G_m\right)}} \right] \quad .....(6.17)$$

Schapery established bounds on effective thermal expansion coefficients of isotropic and anisotropic composite materials consisting of isotropic phases by employing extremum principles of thermoelasticity[70]. Simple formulae, equations (6.18a) and (6.18b), are deduced for the transverse and longitudinal thermal expansion coefficients of unidirectional, fiber-reinforced materials in which the fiber and matrix are both considered to be isotropic.

Strife and Prewo have modified the transverse Schapery equation for transversely isotropic fibers by replacing the fiber coefficient of thermal expansion by the transverse fiber value[72].

$$\alpha_L = \frac{\alpha_f V_f E_f + \alpha_m V_m E_m}{E_f V_f + E_m V_m} \qquad .....(6.18a)$$

$$\alpha_T = (1 + \nu_m)\alpha_m V_m + (1 + \nu_f)\alpha_f V_f - \alpha_L \nu_c \qquad .....(6.18b)$$

where: $\nu_c = \nu_f V_f + \nu_m V_m$

The modified Eshelby method is a well known approach used to predict a number of composite properties[60,118]. The equivalent inclusion method in steady-state heat conduction is analogous to Eshelby's equivalent inclusion method in elasticity[60]. One of the significant features of the modified model is that it considers the temperature gradient disturbance by the interaction of the reinforcements, the nondilute case. Consequently, this model can be applied to all reinforcement volume fractions.

Wakashima et al have applied Eshelby's method to predict the overall thermal expansion characteristics of a heterogeneous solid containing a dispersion of elastic aligned inclusions in an elastic matrix[118,120]. The calculation is carried out by applying Eshelby's theory on the strain transformation of an ellipsoidal inclusion(assumed to be ellipsoidal for simplicity). The elastic interactions due to the effect of a finite concentration of inclusions are accounted for in an approximation method and closed form solutions are obtained for fiber shaped inclusions as follows:

$$\alpha_L = V_f\alpha_f + V_m\alpha_m + V_fV_m(\alpha_f - \alpha_m)\left[\frac{C - D}{AC - BD}E_f - 1\right] \quad .....(6.19a)$$

$$\alpha_T = V_f\alpha_f + V_m\alpha_m + V_fV_m(\alpha_f - \alpha_m)\left[\frac{A - B}{AC - BD}E_f - 1\right] \quad .....(6.19b)$$

where:

$$A = V_m\frac{2\nu_m\nu_fG_f + 2(1 - 2\nu_f)G_m}{1 - \nu_m} + 2V_f(1 - \nu_f)G_f$$

$$B = V_m\frac{\nu_mG_f + (1 - 2\nu_f)\nu_mG_m}{1 - \nu_m} + 2V_f\nu_fG_f$$

$$C = V_m\frac{G_f + (1 - 2\nu_f)G_m}{1 - \nu_m} + 2V_fG_f$$

$$D = V_m\frac{2\nu_fG_f + 2(1 - 2\nu_f)\nu_mG_m}{1 - \nu_m} + 4V_f\nu_fG_f$$

The mechanics of materials approach of Schoutens and Kural & Min, equations (6.20) to (6.24), uses a generalization into two-dimensional space[74]. Perfect interfacial bonding is assumed under plane stress conditions. The fiber and matrix are assumed to have identical longitudinal strain and identical transverse and shear stresses. When the reinforcing fiber is isotropic, the transverse coefficient of thermal expansion is equal to the Schapery expression. The derived expression for the longitudinal coefficient of thermal expansion is the same as Schapery.

$$E_L = E_{f_1}V_f + E_{m1}V_m \quad .....(6.20)$$

$$\frac{1}{E_T} = \frac{V_f}{E_{f_2}} + \frac{V_m}{E_{m_2}} - \frac{V_f V_m (\nu_{f_{12}} E_{m_1} - \nu_{m_{12}} E_{f_1})^2}{E_{f_1} E_{m_1} (V_f E_{f_1} + V_m E_{m_1})} \qquad .....(6.21)$$

$$\nu_{12} = \nu_{f_1} V_f + \nu_{m_1} V_m \qquad .....(6.22)$$

$$\nu_{23} = -\frac{E_L}{E_T} \nu_{12} \qquad .....(6.23)$$

$$\frac{1}{G_{12}} = \frac{V_f}{G_{f_{12}}} + \frac{V_m}{G_{m_{12}}} \qquad .....(6.24)$$

The transverse thermal conductivity and elastic modulus are determined using the Composite Cylinders model. This equation is equivalent to the lower Hashin-Shtrikman bound(S = 2) and the Modified Eshelby Method. Hashin & Hill bounds are employed to predict bulk and shear moduli.

$$K_{23\ upper} = K_2 + \frac{V_1}{\frac{1}{K_1 - K_2} + \frac{V_2}{K_2 + G_2}} \qquad .....(6.25a)$$

$$K_{23\ lower} = K_1 + \frac{V_2}{\frac{1}{K_2 - K_1} + \frac{V_1}{K_1 + G_1}} \qquad .....(6.25b)$$

$$G_{12\ upper} = G_2 + \frac{V_1}{\frac{1}{(G_1 - G_2)} + \frac{V_2}{2G_2}} \qquad .....(6.26a)$$

$$G_{12\,lower} = G_1 + \frac{V_2}{\dfrac{1}{(G_2 - G_1)} + \dfrac{V_1}{2G_1}} \qquad .....(6.26b)$$

$$G_{23\,upper} = G_2 + \frac{V_1}{\dfrac{1}{G_1 - G_2} + \dfrac{V_2(K_2 + 2G_2)}{2G_2(K_2 + G_2)}} \qquad .....(6.27a)$$

$$G_{23\,lower} = G_1 + \frac{V_2}{\dfrac{1}{G_2 - G_1} + \dfrac{V_1(K_1 + 2G_1)}{2G_1(K_1 + G_1)}} \qquad .....(6.27b)$$

where: $G_2 > G_1,\ K_2 > K_1$

Craft & Christensen and Christensen & Waals' equations, derived from the Generalized Self Consistent Scheme, are used in conjunction with Hashin-Shtrikman bounds(S=2) to predict properties of randomly distributed fiber MMCs[47,48,53,55,114]. Christensen & Waals developed effective composite property equations for three-dimensional and two-dimensional random fiber composites[114]. This was accomplished by orientation averaging of the effective properties of a randomly oriented composite cylinder.

$$E^*_{3D} = \frac{\left[E_{11} + (4\nu_{12}^2 + 8\nu_{12} + 4)K_{23}\right]\left[E_{11} + (4\nu_{12}^2 - 4\nu_{12} + 1)K_{23} + 6(G_{12} + G_{23})\right]}{3\left[2E_{11} + (8\nu_{12}^2 + 12\nu_{12} + 7)K_{23} + 2(G_{12} + G_{23})\right]}$$

.....(6.28)

$$E^*_{2D} = \frac{(U_1^2 - U_2^2)}{U_1} \quad \{\text{plane stress}\} \qquad .....(6.29)$$

$$\nu^*_{3D} = \frac{E_{11} + (4\nu_{12}^2 + 16\nu_{12} + 6)K_{23} - 4(G_{12} + G_{23})}{4E_{11} + (16\nu_{12}^2 + 24\nu_{12} + 14)K_{23} + 4(G_{12} + G_{23})} \qquad .....(6.30)$$

$$\nu^*_{2D} = \frac{U_2}{U_1} \quad \{\text{plane stress} \qquad .....(6.31)$$

$$K^* = \frac{1}{9}\left[E_{11} + 4(1 + \nu_{12})^2 K_{23}\right. \qquad .....(6.32)$$

$$G^* = \frac{1}{15}\left[E_{11} + (1 - 2\nu_{12}^2)K_{23} + 6(G_{12} + G_{23})\right. \qquad .....(6.33)$$

where:

$$U_1 = \frac{3E_{11}}{8} + \frac{G_{12}}{2} + \frac{K_{23}G_{23}(3 + 2\nu_{12} + 3\nu_{12}^2)}{2(G_{23} + K_{23})}$$

$$U_2 = \frac{E_{11}}{8} - \frac{G_{12}}{2} + \frac{K_{23}G_{23}(1 + 6\nu_{12} + \nu_{12}^2)}{2(G_{23} + K_{23})}$$

and ν_{12} , K_{23} , E_{11}, G_{12}, G_{23} are either known or predicted from the Generalized Self Consistent / Composite Cylinders model

Craft and Christensen derived the effective coefficient of thermal expansion for fiber composites in three-dimensional isotropic form[67]. The coefficient of thermal expansion is given in terms of the thermal-mechanical properties of the corresponding aligned fiber system. This is derived through a three-dimensional randomizing process, comparable to that employed in the mechanical case with no thermal effects.

$$\alpha_{3D} = \frac{\alpha_L \left[E + 4\nu_{12}(1 + \nu_{12})K_{23}\right] + 4(1 + \nu_{12})K_{23}\alpha_T}{E_{11} + 4(1 + \nu_{12})^2 K_{23}} \qquad .....(6.34)$$

where: α_L , α_T , ν_{12} , K_{23} , E_{11} are either known or predicted from the Generalized Self Consistent / Composite Cylinders model

Figure 6.9 illustrates the prediction of elastic modulus for Ti-6Al-4V/SiCf. The Rule of Mixtures is generally a good predictor of longitudinal modulus. Since matrix/fiber interfaces still need to be adequately characterized, transverse elastic moduli remain difficult to predict. At low volume fractions, all curves(except Kural & Min) are close to one another and the difference between them is insignificant. The Nomura & Chou bounds are generally used when the matrix/fiber interface is assumed to be close to perfect. The lower Hashin-Shtrikman bound(equivalent to the Generalized Self Consistent, Composite Cylinders, and Eshelby methods) is good for MMCs with a moderate matrix/fiber interfacial layer. For composites with poor interfaces and transversely isotropic fibers such as carbon/graphite, the Kural & Min equation is used.

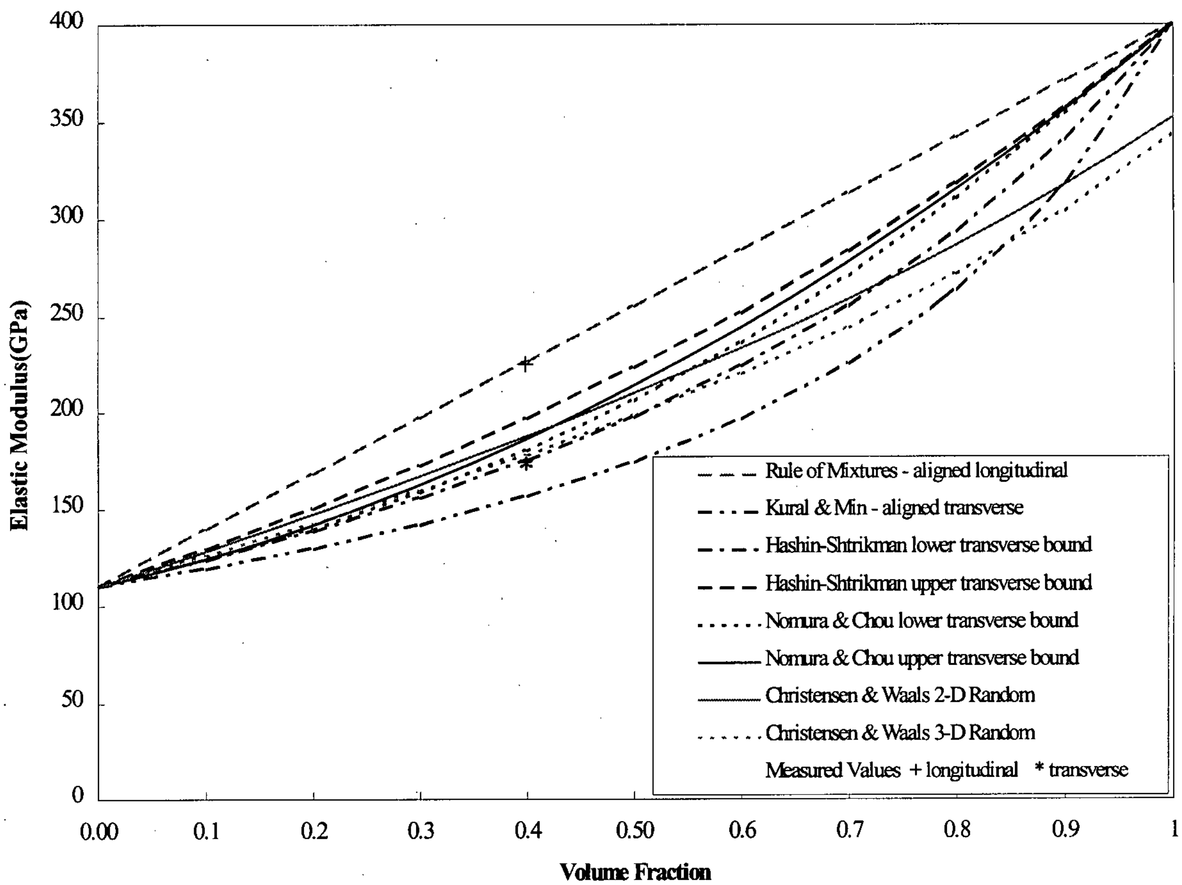


Figure 6.9 Ti-6Al-4V/SiC_f Elastic Modulus

For randomly distributed fiber composites, simple analytical equations and experimental data is scarce. As a result, validation of the random equations is limited to comparisons with property bounds and aligned fiber longitudinal and transverse equations. The randomly oriented fiber curve of Christensen & Waals falls between the lower Nomura & Chou bound and the Rule of Mixtures up to a reinforcement level of 55 v/o. Beyond this point the curve falls below the transverse prediction and is of little value. As a result, at high volume fractions, the Hashin-Shtrikman bounds are the best alternative.

Thermal conductivity predictions for 2014/TiB_2f are shown in Figure 6.10. The Rule of Mixtures is utilized to predict longitudinal property values, Hashin-Shtrikman and Nomura & Chou lower bounds predict transverse values and the upper bounds predict randomly distributed values.

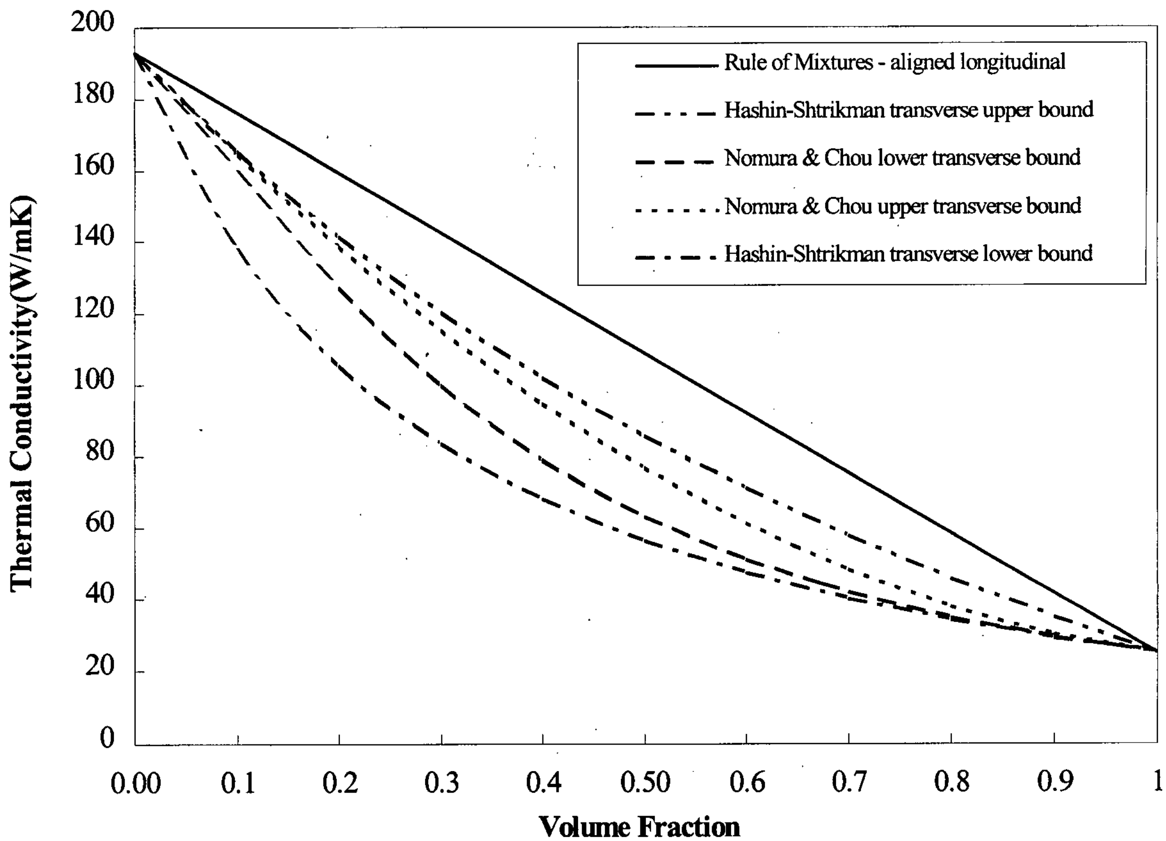


Figure 6.10 2014/TiB_2f Thermal Conductivity

Coefficient of thermal expansion for ZE41A/Al_2O_3f is displayed in Figure 6.11. The longitudinal curves of Schapery and the Composite Cylinders model(and Generalized Self Consistent method) are within close proximity of each other thus either equation is suitable for predicting longitudinal CTE. The Composite Cylinders model is adequate as a predictor of transverse CTE if there is not a significant matrix/fiber interface present, as in this example. The transverse Schapery equation is a better predictor for those MMCs with significant interfacial reaction products.

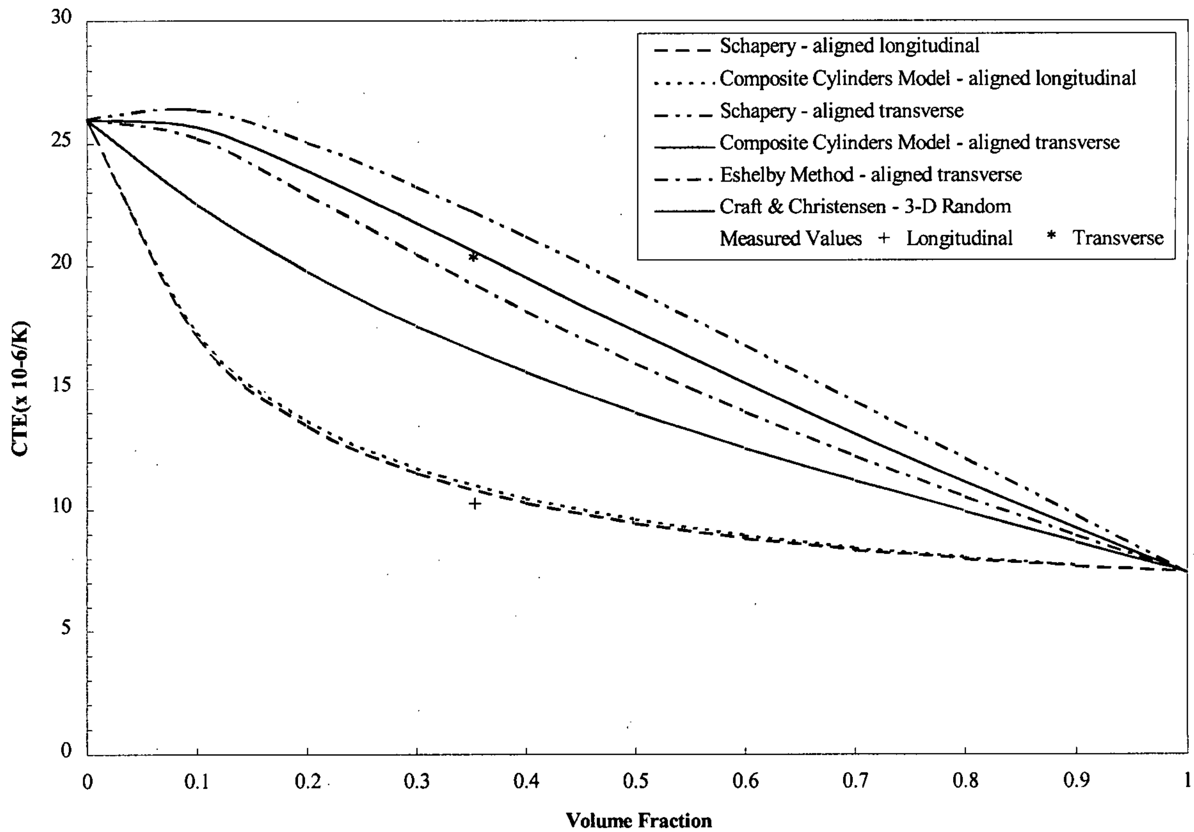


Figure 6.11 ZE41A/Al_2O_3f Coefficient of Thermal Expansion

The prediction of Poisson's ratio for a 6061/SiCf system is shown in Figure 6.12. The upper Hashin & Hill υ_{12} bound is adjacent to Kural & Min's equation. At low volume fractions, the random orientation curve of Christensen & Waals is approximated by υ_{12}.

Measured data to test the validity of these equations is scarce. Consequently, Poisson's ratio predictions given by the system at this time are not expected to be very accurate.

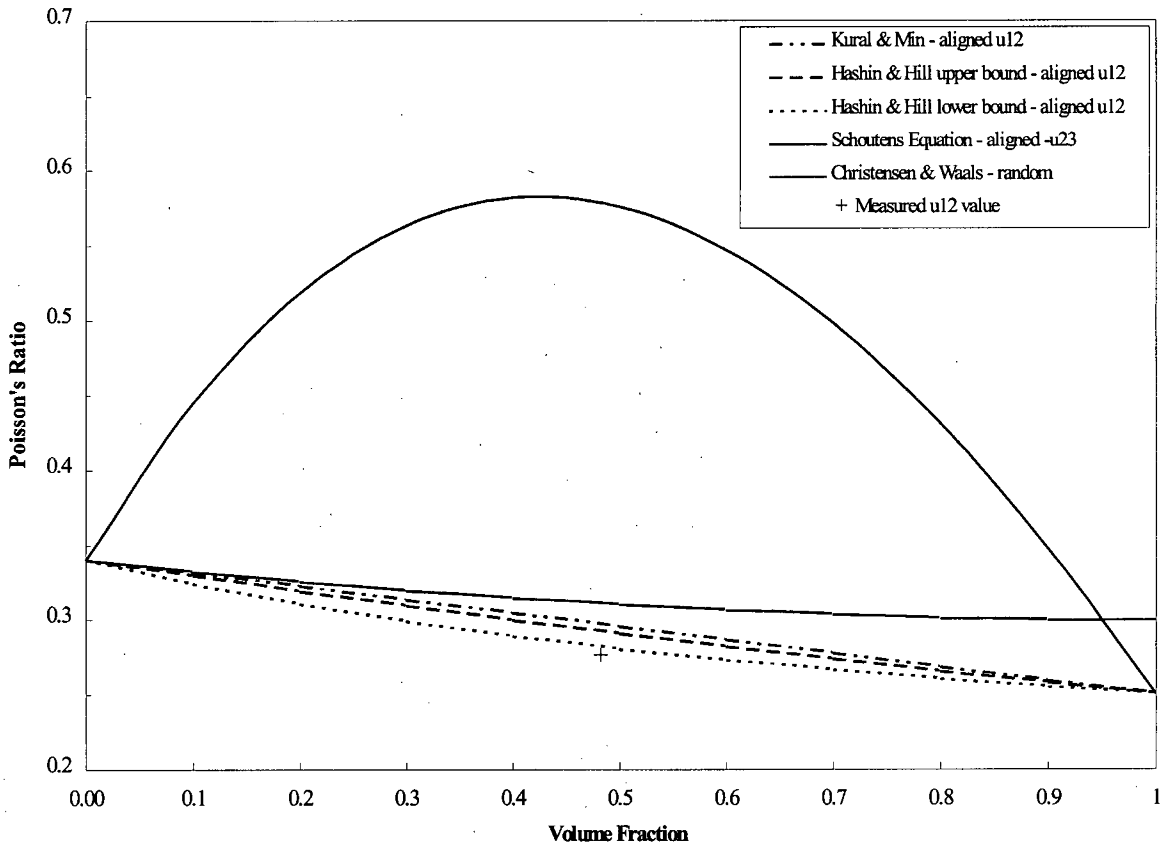


Figure 6.12 6061/SiCf Poisson's Ratio

6.4.4 <u>WHISKER/SHORT FIBER MODELS</u> The analytical models which have been developed to predict effective MMC thermomechanical properties have primarily focused on particulate and aligned continuous fiber composites. Short fiber and whisker reinforced composites are more difficult to model analytically, and coupled with a lack of metal matrix composite experimental data for model verification, have led to slower model development[105,106].

For aligned whiskers or short fibers, effective properties are calculated by the Halpin-Tsai equation, Modified Eshelby method, Hashin-Shtrikman bounds, Halpin equation, and Marom & Weinberg's modified Schapery equation[47-50,55,61,63,65,68,69,118,121].

The Halpin-Tsai model was originally developed to predict shear moduli, Poisson's ratios, longitudinal and transverse elastic moduli of continuous fiber reinforced composites[63,69]. The equations for whisker/short fiber reinforced composites have been obtained from the original equations which accounted for different fiber cross-sectional shapes and packing geometry[66]. The equation for longitudinal thermal conductivity of aligned reinforcements was formulated for fibers packed in a diamond array with rectangular cross sections.

$$E_{L,T} = E_m \frac{(1 + \xi\eta V_w)}{(1-\eta V_w)} \qquad .....(6.35)$$

$$\nu_{12} = \nu_w V_w + \nu_w V_w \qquad .....(6.36)$$

where:

$$\eta = \frac{\frac{E_w}{E_m} - 1}{\frac{E_w}{E_m} + \xi}$$

$\xi = 2\frac{L}{d}$ for E_L and $\xi = 2$ for E_T

$$G_{12} = G_m \frac{(1 + \xi\eta V_w)}{(1-\eta V_w)} \quad .....(6.37)$$

where:

$$\eta = \frac{\dfrac{G_w}{G_m} - 1}{\dfrac{G_w}{G_m} + \xi}$$

$$\xi = 1$$

Marom & Weinberg have modified Schapery's aligned continuous fiber equations for short fiber composites[68,70]. An efficiency factor K is introduced to account for the dependence of longitudinal and transverse coefficient of thermal expansion on the fiber/whisker length due to the shear transfer process at the interface. This shear transfer affects the thermal strains in a similar way as mechanical strains. The efficiency factor K is a function of the fiber/whisker length and critical fiber length. The critical fiber length is dependent on the fiber/whisker diameter, strength, and the fiber/matrix shear strength. The major drawback with this approach is the lack of information needed to determine the efficiency factor K and the random nature of fiber/whisker lengths.

$$\alpha_L = \frac{E_m \alpha_m V_m + k E_w \alpha_w V_w}{E_m V_m + k E_w V_w} \quad .....(6.38a)$$

$$\alpha_T = (1 + \nu_m)\alpha_m V_m + (1 + \nu_w)\alpha_w V_w - \alpha_L(\nu_m V_m + \nu_w V_w) \quad .....(6.38b)$$

where:

$$k = \frac{l}{2l_c} \quad (l \le l_c,\ 0 \le k \le 0.5)$$

$$k = 1 - \frac{l_c}{2l} \quad (l \ge l_c,\ 0.5 \le k \le 1)$$

$$l_c = \frac{d\sigma_w}{2\tau_i}$$

Halpin obtains approximate values for CTE of oriented short fiber composites by estimating the stiffness in the fiber direction from that of the corresponding continuous fiber composite(first given by Schapery) and assuming that the Poisson's ratio for the matrix is the same for the reinforcement[69]. For the case when the Poisson's ratios are not equivalent, the bulk modulus K is used in place of modulus E in the longitudinal approximation. The transverse CTE is assumed to be independent of the aspect ratio and is given by Schapery's equation for transverse CTE of aligned continuous fiber composites.

$$\alpha_L = \bar{\alpha} + \left(\frac{\overline{E\alpha}}{\bar{E}} - \bar{\alpha}\right)\frac{\left(\frac{1}{E_l} - \frac{1}{E_{11}}\right)}{\left(\frac{1}{E_l} - \frac{1}{E_u}\right)} \qquad \text{.....(6.39a)}$$

$$\alpha_T = (1 + \nu_w)\alpha_w V_w + (1 + \nu_m)\alpha_m V_m - \alpha_a^{*}\bar{\nu} \qquad \text{.....(6.39b)}$$

where: $\bar{\alpha} = V_w \alpha_w + V_m \alpha_m$ $\qquad \alpha_a^* = \dfrac{\bar{E\alpha}}{\bar{E}}$

$$\frac{\bar{E\alpha}}{\bar{E}} = \frac{E_w V_w \alpha_w + E_m V_m \alpha_m}{E_w V_w + E_m V_m} \qquad E_u = V_w E_w + V_m E_m$$

$$E_{11} = E_m \frac{(1 + \xi \eta V_w)}{(1 - \eta V_w)} \qquad \frac{1}{E_l} = \frac{V_w}{E_w} + \frac{V_m}{E_m}$$

$$\eta = \frac{E_w / E_m - 1}{E_w / E_m + \xi} \qquad \xi = 2\frac{L}{d}$$

Eshelby's equivalent inclusion method is used to predict elastic modulus, thermal conductivity and coefficient of thermal expansion of aligned whisker or short fiber composites. The elastic and temperature gradient disturbances due to the interaction of the reinforcements is accounted for in an approximation method. The resulting closed form solutions can then be applied for all reinforcement volume fractions.

$$k_{L,T} = k_m + \frac{V_w (k_w - k_m) k_m}{(k_w - k_m)(1 - V_w) S + k_m} \qquad \text{.....(6.40)}$$

where:

$S = S_{33}$ for k_L

$S = S_{11} = S_{22}$ for k_T

$S_{33} = 1 - 2S_{11}$

$$S_{11} = \frac{a_3 a_1^2}{2(a_3^2 - a_1^2)^{\frac{3}{2}}} \left[\sqrt{\left(\frac{a_3^2}{a_1^2} - 1 \right)} - \cosh^{-1}\left(\frac{a_3}{a_1} \right) \right]$$

$a_3 > a_1 = a_1$ prolate spheroid

Properties for randomly oriented whiskers or short fibers are calculated using Hashin-Shtrikman bounds, Hatta & Taya, Lewis & Nielsen, Halpin-Pagano, Tsai-Pagano, and Lim & Han equations[48,55,56,62,63,66,69,139,140]. Hatta & Taya have used Eshelby's equivalent inclusion method to predict the effective thermal conductivity of misoriented short fiber composites[62,140]. The method is analogous to the Eshelby equivalent inclusion method in elasticity and the formulation of the problem and its computation are synonymous. The equation used by this system is based on three-dimensional short fiber misorientation with the aspect ratio of the reinforcements remaining constant and a rod or fiber shape assumed.

$$k = k_m \left[\frac{V_w(k_m - k_w)\left[(k_w - k_m)(2S_{33} + S_{11}) + 3k_m\right]}{3(k_w - k_m)^2(1 - V_w)S_{11}S_{33} + k_m(k_w - k_m)R + 3k_m^2} \right] \quad .....(6.41)$$

where:

$$R = 3(S_{11} + S_{33}) - V_w(2S_{11} + S_{33})$$

$$S_{33} = 1 - 2S_{11}$$

$$S_{11} = \frac{a_3 a_1^2}{2\left(a_3^2 - a_1^2\right)^{\frac{3}{2}}}\left[\sqrt{\left(\frac{a_3^2}{a_1^2} - 1\right)} - \cosh^{-1}\left(\frac{a_3}{a_1}\right)\right]$$

$a_3 > a_1 = a_1$ prolate spheroid

Halpin & Pagano and Tsai & Pagano treat the properties of a homogeneous random or nearly random material as a laminated solid[66]. In this two-dimensional approximation, the homogeneous material is considered to be mathematically equivalent to a material composed of layers of oriented short fiber material. The percentage of fibers in each layer corresponds to the volume fraction of fibers of the particular orientation in the material being molded, known as a quasi-isotropic laminate in laminated plate theory. Lim & Han then considered the corresponding three-dimensional case to predict effective elastic modulus using a transformed laminate analogy[139].

$$E_{2\text{-}D} = \frac{3(E_L + 5E_T)}{8} \quad .....(6.42)$$

$$E_{3\text{-}D} = \frac{(3E_L + 5E_T) - (E_L + E_T)^2}{8(2E_L + 3E_T)} \quad .....(6.43)$$

$$\alpha = \frac{1}{2}\left(\alpha_L + \alpha_T\right) + \frac{E_{11} - E_{22}}{2\left[E_{11} + (1 + 2\nu_{12})E_{22}\right]}(\alpha_L - \alpha_T) \quad .....(6.44)$$

where:

$$E_{11} = E_m \frac{(1 + \xi\eta V_w)}{(1-\eta V_w)} \qquad \nu_{12} = V_w\nu_w + V_m\nu_m$$

$$E_{22} = E_m \frac{(1 + 2\eta V_w)}{(1 - \eta V_w)} \qquad \eta = \frac{E_w/E_m - 1}{E_w/E_m + \xi}$$

$$\xi = 2\frac{L}{d}$$

E_L, E_T, α_L, α_T are either known or predicted from aligned whisker / short fiber models

Lewis and Nielsen have taken the general equations derived by Halpin & Tsai for elastic moduli of composite materials and applied them to thermal conductivity[56]. The randomly oriented equation has been modified for the specific case of one phase being dispersed in another continuous phase. Factors A and n have been introduced to take into account the shape of the particles, their orientation and distribution.

$$k = k_m \left[\frac{1 + \varepsilon \beta V_w}{1 - \beta m} \right] \qquad .....(6.45)$$

where:

ε = 1.58 to 8.38

$$\beta = \frac{\frac{k_w}{k_m} - 1}{\frac{k_w}{k_m} + \varepsilon}$$

$$m = \frac{1 + 0.48V_w}{0.27}$$

Figure 6.13 illustrates the prediction of thermal conductivity for M-124R/SiCw. The equivalence of the aligned transverse Eshelby curve and the upper Hashin-Shtrikman bound in addition to the longitudinal Halpin-Tsai and Eshelby curves is shown. This is a result of both a low reinforcement/matrix thermal conductivity ratio and a higher reinforcement aspect ratio.

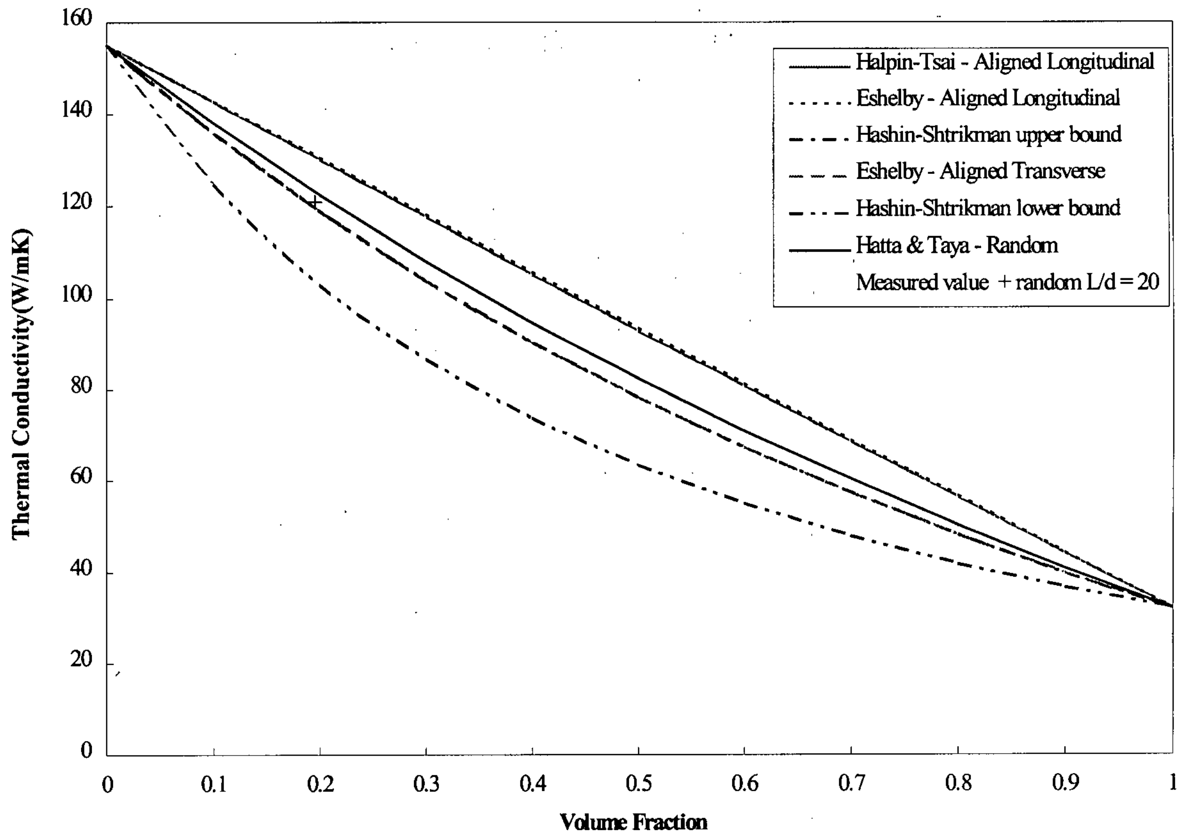


Figure 6.13 M-124R/SiCw Thermal Conductivity

The prediction of elastic modulus for 5456/SiCw is shown in Figure 6.14. Since the reinforcement/matrix ratio is large and the whisker aspect ratio is low, the aligned longitudinal and transverse curves are not equivalent as in the thermal conductivity example. The Eshelby curves more closely approximate aligned continuous fiber composites and are prone to overprediction in these circumstances. The two and three-dimensional randomly oriented curves are also shown. The Tsai-Pagano curve better approximates measured randomly oriented MMC values.

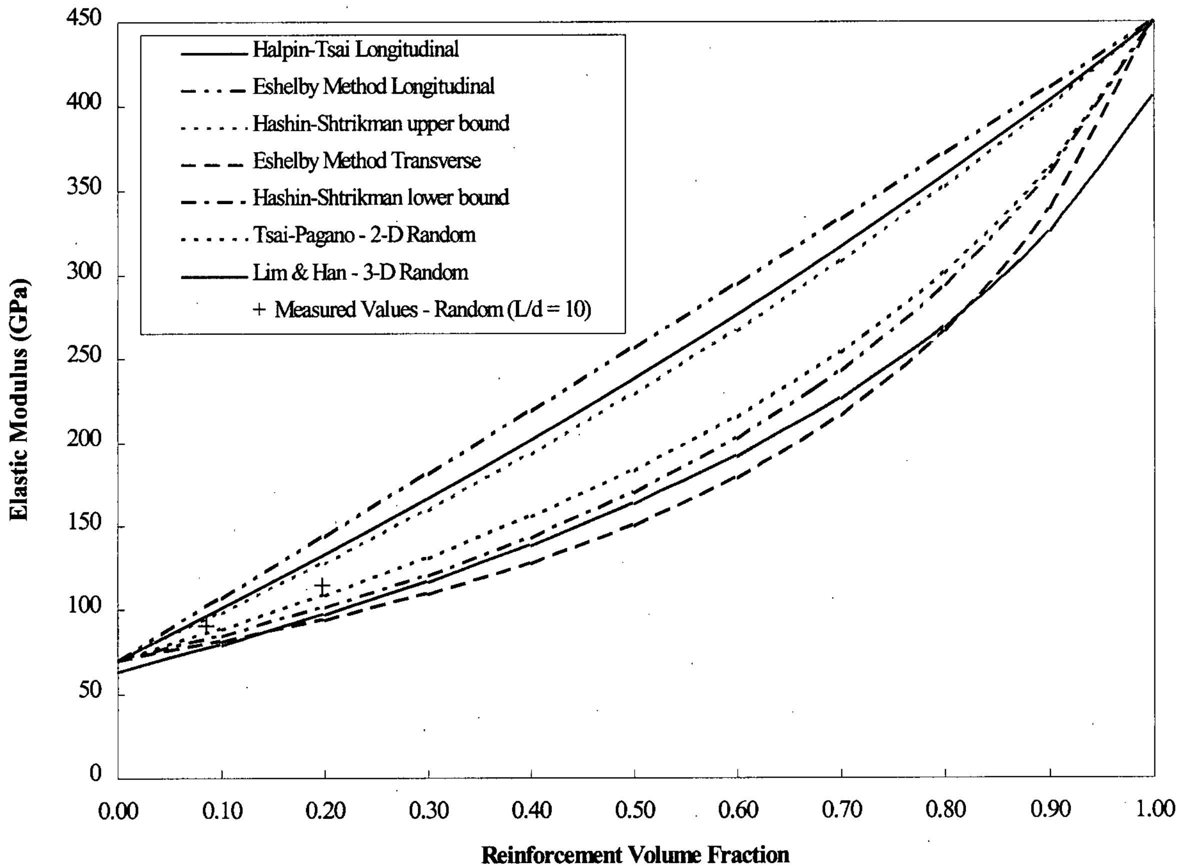


Figure 6.14 5456/SiCw Elastic Modulus

Coefficient of thermal expansion prediction for the 2009/SiCw system is shown in Figure 6.15. The aligned transverse equations of Marom & Weinberg and Halpin are in close proximity of each other although they generally overpredict transverse values. The upper Hashin-Shtrikman bound is used for systems with a significant interface. Halpin's equation is typically used to predict longitudinal CTE. Random orientations are generally predicted using Halpin & Pagano's equation.

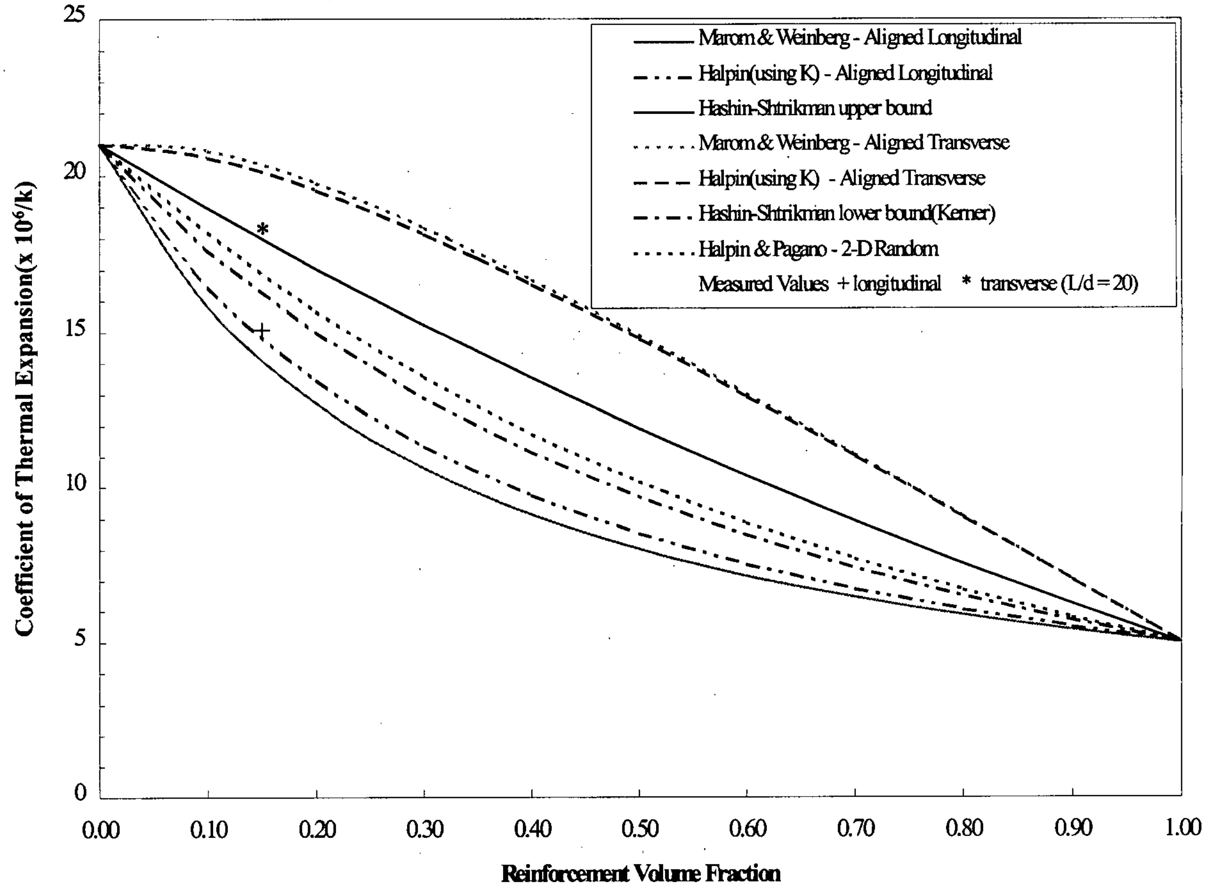


Figure 6.15 2009/SiCw Coefficient of Thermal Expansion

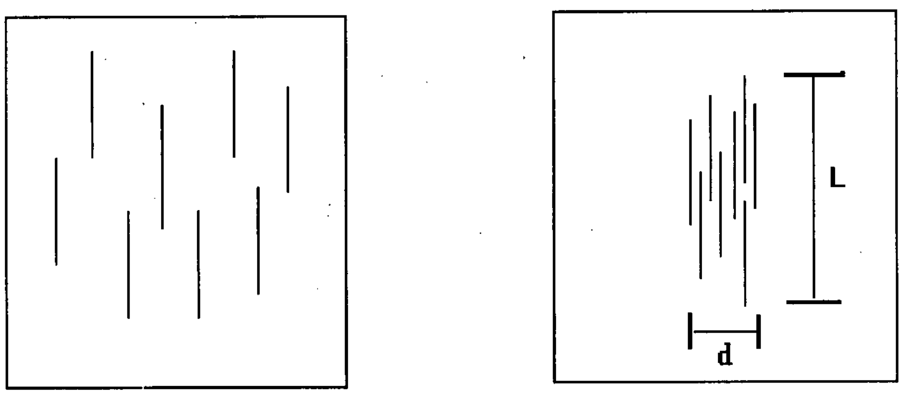
6.4.5 SENSITIVITY STUDIES Knowledge of the sensitivity of input model parameters and major model assumptions on the effective property predictions is essential. Not only is this information critical to the selection of appropriate models but also to determining the accuracy of the predicted values and what parameters contribute the most to controlling the composite property of interest.

Most models assume all reinforcements in a MMC have the same length or aspect ratio. For an aligned short fiber composite, Yakao et al examined the effect of variable aspect ratio[141]. They found that the effect of fiber misorientation has a much stronger influence on composite properties than variable fiber aspect ratio. The use of a mean value has given good predictions of elastic modulus, Poisson's ratio and coefficient of thermal expansion for short fiber composites. Consequently, the use of a mean aspect ratio value is adequate unless the distribution of variable aspect ratios and the degree of misorientation is very large.

The effect of reinforcement size on effective composite properties is not considered by the models. For particulate and continuous fiber reinforced composites, it is assumed that given a constant volume fraction, altering the size of the diameter is of little consequence. Similarly for whisker/short fiber composites, as long as the aspect ratio remains constant, varying the diameter has no effect on the predicted effective properties.

Only a few studies have been conducted to examine this phenomenon, primarily for particulate reinforced MMCs[144,145,146]. Contradictory results were found but as yet, no explanation for this discrepancy has been given. At particulate diameters greater than 10-15 microns, elastic modulus and thermal conductivity values remain relatively constant. However, below this threshold, an increase in modulus and decrease in thermal conductivity are measured as the diameter decreases. Two probable explanations for this effect are: (1) matrix microstructural refinement due to dispersion of particulates with diameters less than 10 microns and (2) increased surface area for interfacial reactions to occur depending upon the matrix/reinforcement compatibility[94,99]. As a result, for small diameter reinforcements poor correlation between predicted and measured property values may occur and require the use of specific bounds.

A uniform reinforcement distribution is also a common assumption[108]. However, inhomogeneous distribution, or clustering of reinforcements, is a major manufacturing problem. Areas with higher volume fractions of particulates have higher local modulus and lower Poisson's ratios. Alternatively, for aligned whisker or short fiber composites a cluster would yield a smaller effective aspect ratio, demonstrated in Figure 6.16, thereby reducing the local elastic modulus. Researchers are studying the effect of local clusters using numerical techniques such as finite element modeling but the majority of particulate finite element models still assume a uniform distribution[108]. Studies suggest that global thermomechanical effective properties are generally unaffected but properties such as fracture toughness, where crack initiation is a function of the local stress, are influenced by inhomogeneous distributions[108,142,143].



L/d = 30 L/d = 4

Figure 6.16 Effect of Clustering on Aspect Ratio

The sensitivity of model predicted property values to the input parameters was examined. The single most important factor is the reinforcement volume fraction. For aligned whisker/short fiber and continuous fiber composites, the transverse property value is less sensitive to an increase in volume fraction than the longitudinal values. Not until a large volume fraction of over 0.6 is reached does a noticeable effect occur.

For particulate reinforced composites, at low volume fractions the matrix properties dominate and at high volume fractions the reinforcement properties dominate. For aligned whisker/short fiber and continuous fiber composites, the longitudinal properties are most sensitive to the reinforcement properties and conversely, transverse properties are most sensitive to the matrix properties.

Shape or aspect ratio and alignment of the reinforcements are also important factors. The significance of the aspect ratio varies depending upon the orientation of the reinforcement phase and its volume fraction. For random reinforcement orientations, a minor difference is seen between different reinforcement types, particularly at low volume fractions, as shown in Figure 6.17 for elastic modulus.

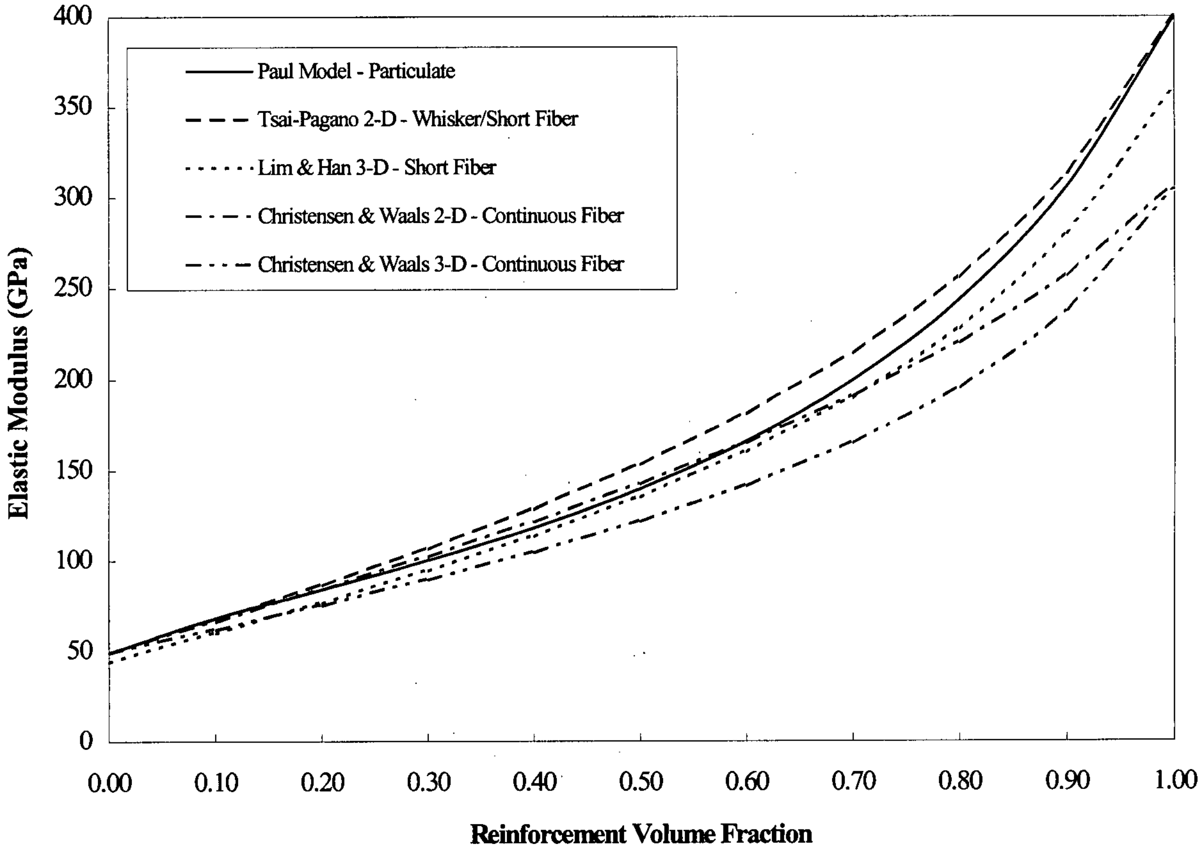


Figure 6.17 Comparison of Randomly Oriented(L/d = 5) Elastic Modulus Predictions

For aligned whisker/short fiber and continuous fiber reinforced composites, only at low aspect ratios does the shape of the whisker/short fiber significantly influence the effective composite property. The aspect ratio value at which longitudinal properties of aligned whisker/short fiber composites approach those of continuous fibers is surprisingly low. This is significant since a typical short fiber or whisker has an aspect ratio between 20 and 50. Consequently it is possible to achieve whisker/short fiber MMC effective property values of the same magnitude as continuous fibers.

A complicating factor of low threshold aspect ratio is the consistent overprediction of properties for aligned whisker reinforced MMCs[147][148]. Specifically, extrusion of whisker reinforced MMCs result in a significant reduction of aspect ratio due to damage. Table 6.2 shows the measured and predicted values of an aligned whisker composite. Using the initial whisker aspect ratio of 20 overpredicts the longitudinal elastic modulus, particularly by the Eshelby equation. It is therefore important that manufacturing and processing effects on the composite microstructure, especially reinforcement aspect ratio, be determined in order to achieve accurate predictions.

Table 6.2 Effect of Aspect Ratio on Prediction of Elastic Modulus

	Elastic Modulus (GPa)	
Model	Aligned Longitudinal	Aligned Transverse
6061/SiC/20w-T6 extrusion product [147]	122	91
Halpin-Tsai Equation		
L/d = 5	119	
L/d = 10	126	-
L/d =20	130	
Modified Eshelby Method		
L/d = 5	131	92
L/d = 10	134	93
L/d = 20	135	93

6.4.6 SUMMARY OF SYSTEM MODELS Tables 6.3 to 6.8 list the effective elastic modulus, thermal conductivity, coefficient of thermal expansion, Poisson's ratio, shear modulus and bulk modulus mathematical models currently contained in the expert system. For composites where there is a high degree of belief in the property values of the matrices and reinforcements and when they have well characterized reinforcement shapes, volume fractions and orientations, and exhibit a negligible interfacial reaction layer, good predictions are obtained using the analytical models. For composites where there are low degrees of belief in the constituent values, the phase geometry is unknown, the volume fraction is inaccurate, the reinforcement shape is unknown, or a significant interfacial reaction layer is present, selected bounds are necessary.

Table 6.3 Effective Thermal Conductivity Models[53,55-60,62-64,118]

Reinforcement Shape	Randomly Distributed	**Phase Geometry** Aligned Longitudinal	Aligned Transverse
Particulate	Paul Model Hashin-Shtrikman bounds[1] Hasselman & Johnson	Nomura & Chou Bounds	Nomura & Chou Bounds
Whisker or Short Fiber	Hashin-Shtrikman bounds Hatta & Taya Equation Lewis & Nielsen Modified Halpin-Tsai	Modified Eshelby Method Halpin-Tsai Equation Hashin-Shtrikman Bounds	Modified Eshelby Method Hashin-Shtrikman Bounds[2]
Continuous Fiber	Hashin-Shtrikman Bounds	Rule of Mixtures[3]	Nomura & Chou Bounds Hashin-Shtrikman Bounds[2]

Notes:

1. Upper bound equivalent to Composite Spheres Model, Generalized Self Consistent Scheme, Rayleigh-Maxwell, Mori-Tanaka, Behrens, etc.
2. Upper bound equivalent to Composite Cylinders Model and Eshelby Method
3. All models reduce to Rule of Mixtures

Table 6.4 Coefficient of Thermal Expansion Models[53,55,61,65-73,118-121,125,132-136]

Reinforcement Shape	Randomly Distributed	**Phase Geometry** Aligned Longitudinal	Aligned Transverse
Particulate	Turner Equation Hashin-Shtrikman bounds[1]	Hashin-Shtrikman bounds[1]	Hashin-Shtrikman Bounds[1]
Whisker or Short Fiber	Hashin-Shtrikman Bounds Halpin & Pagano Equation	Halpin Equation Marom & Weinberg Modified Schapery Modified Eshelby Method	Halpin Equation Marom & Weinberg Modified Schapery
Continuous Fiber	Craft & Christensen Hashin-Shtrikman Bounds	Schapery Equation[3] Composite Cylinders Model[2]	Composite Cylinders Model[2] Schapery(Strife & Prewo) Modified Eshelby Method

Notes:
1. Lower bound equivalent to Kerner and Mori-Tanaka models
2. Equivalent to Generalized Self Consistent Scheme
3. Equivalent to Chamis, Chamberlain, and Levin equations

Table 6.5 Elastic Modulus Models[45-48,52-55,57,59-63,65-67,70,73,74,118]

Reinforcement Shape	Randomly Distributed	**Phase Geometry** Aligned Longitudinal	Aligned Transverse
Particulate	Hashin-Shtrikman Bounds[1] Paul Model Nomura & Chou Bounds	Nomura & Chou Bounds	Nomura & Chou Bounds
Whisker or Short Fiber	Hashin-Shtrikman Bounds Lim & Han 3D Equation Tsai-Pagano 2D Equation	Halpin-Tsai Equation Modified Eshelby Method Hashin-Shtrikman Bounds	Hashin-Shtrikman Bounds Modified Eshelby Method
Continuous Fiber	Hashin-Shtrikman Bounds Christensen & Waals	Rule of Mixtures[3]	Kural & Min Equation Nomura & Chou Bounds Hashin-Shtrikman lower Bound[2]

Notes: 1. Lower bound equivalent to Composite Spheres Model, Generalized Self Consistent Scheme, Rayleigh-Maxwell, Mori-Tanaka, Behrens, etc.
2. Lower bound equivalent to Composite Cylinders Model, Eshelby Method
3. All models reduce to Rule of Mixtures

Table 6.6 Poisson's Ratio Models[47,48,53,63,65,69,74,114,122]

Reinforcement Shape	Randomly Distributed	**Phase Geometry** Aligned υ_{12}	Aligned υ_{23}
Particulate	Paul Bounds[1]		
Whisker or Short Fiber		Halpin Method[2]	
Continuous Fiber	Christensen & Waals Model	Generalized Self Consistent Method[3] Schoutens Method[4]	Schoutens Method

Notes: 1. Upper bound equivalent to Rule of Mixtures
2. Equivalent to Rule of Mixtures
3. Equivalent to Composite Cylinders Model
4. Equivalent to Kural & Min

Table 6.7 Shear Modulus Models[47-49,53,63,65,69,74,114,122]

Reinforcement Shape	Randomly Distributed	**Phase Geometry** Aligned G_{12}	Aligned G_{23}
Particulate	Hashin-Shtrikman Bounds[1]		
Whisker or Short Fiber		Christensen Halpin Method	Christensen
Continuous Fiber	Christensen & Waals Model	Generalized Self Consistent Method[2] Hashin & Hill Bounds Kural & Min	Generalized Self Consistent Method[2] Hashin & Hill Bounds

Notes: 1. Lower bound equivalent to Mori-Tanaka
2. Equivalent to Composite Cylinders Model

Table 6.8 Bulk Modulus Models[47-49,53,55,65,67,69,114,122]

Reinforcement Shape	Phase Geometry Randomly Distributed	 Aligned K_{23}
Particulate	Hashin-Shtrikman Bounds[1]	
Whisker or Short Fiber		
Continuous Fiber	Christensen & Waals Model	Generalized Self Consistent Method[2] Hashin & Hill Bounds

Notes: 1. Lower bound equivalent to Generalized Self Consistent Method
2. Equivalent to Composite Cylinders Model

CHAPTER 7

KNOWLEDGE DOMAIN PART III

7.1 CONSTITUENT COMPATIBILITY

Although the physical and mechanical properties may often limit the constituent selection, it is the chemical reactivity of the ceramic reinforcement with the matrix alloy either during service or fabrication which will in most cases control the final reinforcement/matrix combination[98]. The primary factors which contribute to matrix/reinforcement compatibility are listed in Table 7.1.

The interface can be a preferential precipitation location because of its higher energy content due to structure, point defect concentrations or residual strains, its enhanced local dislocation content due to the accommodation of forces arising from the mismatch in constituent thermal expansion, or its association with segregation arising from processing[99].

These phenomena are diffusion dependent and are more of a factor with increasing temperature and time of exposure. This dictates the selection of a manufacturing process with low temperatures and times, and modifications to the matrix, reinforcement or both. The presence of an interface with local segregation of matrix elements and local dislocation density gradients can markedly influence the kinetics of reactions taking place during thermomechanical processing and heat treatment.

Thermodynamic assessment can indicate whether or not a matrix/reinforcement system is thermodynamically stable. In practical MMC systems this is never the case, either because of the heterogeneous nature of most reinforcements or matrices, or because of the presence of more than the minimum interfacial area for the system. Specifically, the rate of the diffusion processes are sensitive to the reinforcement radius because the interfacial area per unit volume of fiber available for interaction is inversely proportional to the radius[73]. Thus, fibers with diameters less than 10 microns and whiskers are potentially very sensitive to interactions.

Simple relative stability arguments can be used to predict whether a system is unstable under anticipated conditions of processing or use[60,99]. For example, an oxide Ellingham diagram indicates that alumina fibers would be unstable in a magnesium matrix at processing temperatures[99]. In the case of solutions, the concept of activity is used to delineate compositional ranges of stability and instability[99]. This approach has been used predictively in preventing the formation of interfacial carbide reaction products in Al-Si casting alloys reinforced with SiC particulates.

Table 7.1 Factors Contributing to Constituent Compatibility[98,99]

Factors
Attack of reinforcement by matrix - dissolution of the reinforcement - reprecipitation or coarsening processes
Chemical reaction products
Precipitation of matrix constituents at the interface
Segregation of matrix constituents to the interface
Interface presence leads to local dislocation density gradients
Interface acts as a preferential precipitation location

7.1.1 <u>COMPATIBILITY DETERMINATION</u> The determination of matrix/reinforcement compatibility has been undertaken for the matrix alloys and reinforcements listed in Table 7.2. The subdivision of aluminum into selected alloy series has been made due to the availability of additional experimental data for these matrix alloys. Current magnesium and titanium matrix alloy research will permit the subsequent subdivision of these materials in the near future.

To determine compatibility, experimental observations, expert knowledge and experience from numerous sources including research literature and MMC manufacturers was examined. Matrix/reinforcement chemical reactivity and its driving forces were investigated. Successes, failures and particulars of MMC manufacture in relation to compatibility were recorded. Effects of matrix alloy changes and reinforcement coatings on MMC microstructure and properties were examined. Comparisons of composite systems and reinforcement types were made. Collectively, general heuristic information was assembled despite a lack of quantitative data.

To represent this knowledge, linguistic descriptions with associated textual statements were constructed. These linguistic and textual or string variables are structured in the knowledge base. The representation of the linguistic compatibility variables is shown in Figure 7.1. Depending upon the matrix/reinforcement system selected, a compatibility of negligible to high is given to represent the best expected performance in relation to the other alternatives. The textual information given by the string variables aid in the explanation of the constituent compatibility by providing information on the chemical reactivity of the matrix/reinforcement combination. Examples of the compatibility knowledge are shown in Table 7.3. For cases where compatibility is unknown or has yet to be determined, a default of "*not known*" is supplied.

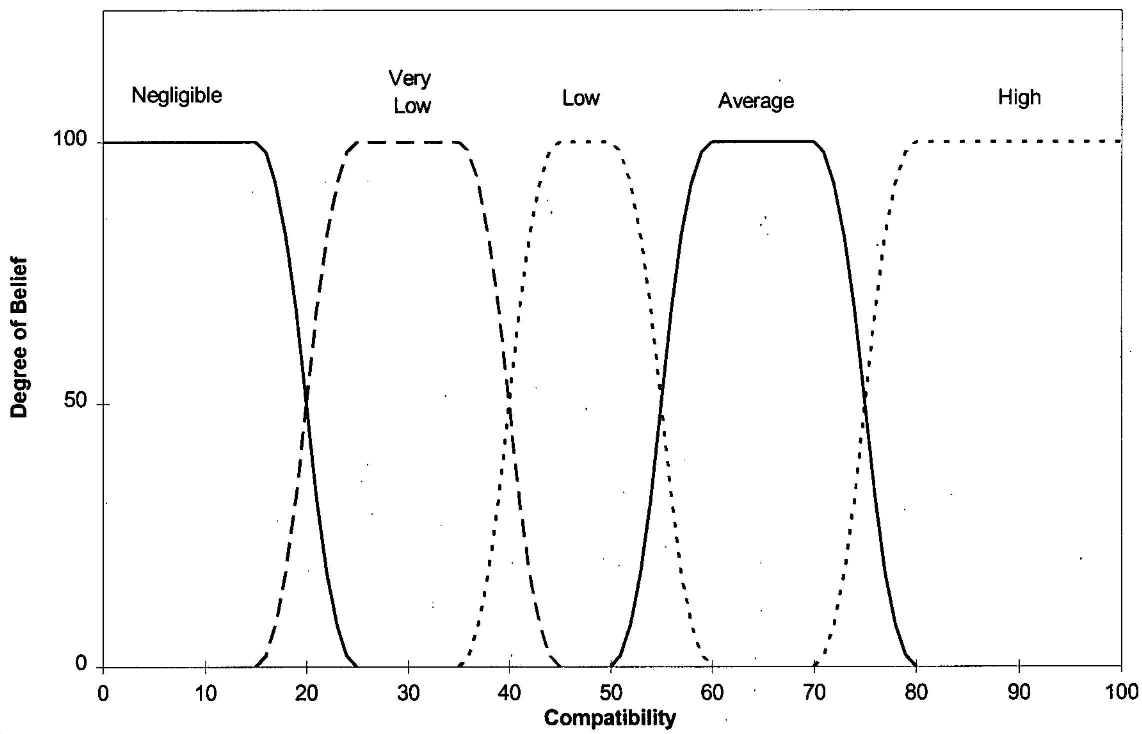


Figure 7.1 Linguistic Representation of Matrix/Reinforcement Compatibility

Table 7.2 Matrix Alloy and Reinforcement Materials

Alloys				
Aluminum:		Magnesium	Titanium	Copper
2XX 3XX 2XXX	6XXX 7XXX 8XXX			

Reinforcements			
Particulate	Whisker	Short Fiber	Fiber
Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3
AlN	B_4C	Al_2O_3-SiO_2	Al_2O_3-SiO_2
B_4C	Carbon(graphite)	Boron	Boron
Carbon(graphite)	Si_3N_4	Carbon(graphite)	Carbon(graphite)
Si_3N_4	SiC	SiC	SiC
SiC		TiB_2	TiB_2
TiB_2		Tungsten	Tungsten
TiC			

Table 7.3 Examples of Constituent Compatibility Knowledge

		Compatibility	
Matrix	**Reinforcement**	Linguistic Variable	String Variable
Al 3XX	Si3N4 particulate	low	Si3N4 reacts exothermically with liquid Al. Unsuitable for liquid metal processing unless reinforcement coated.
Al 6XXX	Carbon/graphite particulate	low	Al4C3 forms quickly at processing temp. > 550C degrading reinforcement. Reinforcement coatings necessary.
Al 2XX	Al2O3 short fiber	average	Al2O3 nonwetting thus SiO2 commonly added. Al alloys which contain appreciable amounts of elements whose oxides are more stable than Al2O3 will attack the reinforcement(e.g. Li & Mg)
Al 2XXX	B4C whisker	low	Thermodynamically unstable in molten Al. Complex reaction. Reinforcement coatings necessary for liquid metal processing.
Al 8XXX	Al2O3 fiber	average	Al2O3 nonwetting thus Li added to alloy to achieve adequate bonding.
Ti	Al2O3 fiber	very low	Al2O3 is not compatible with pure Ti or Ti3Al alloys. It is compatible with TiAl alloys. Fibers containing SiO2 attacked by solid Ti.
Mg	SiC whisker	average	Mg has no stable carbide so SiC stable in pure Mg. Alloying additions can react during processing(e.g. Al)
Al 7XXX	SiC fiber	very low	SiC is attacked by molten Al. Fiber surface coatings necessary.
Cu	TiB2 fiber	not known	The compatibility is not known at this time.
Mg	AlN	high	AlN does not react with metals at processing temperatures.

7.2 MANUFACTURING

Unlike traditional materials, commodity shapes of MMCs are seldom available. This is due to the limited number of material manufacturers and limitations on MMC fabrication resulting from the incorporation of a ceramic reinforcement in a metal matrix. In addition, traditional forming operations such as machining, forging and welding which are performed on standard shapes cannot be performed on the majority of MMCs due to material constraints. Therefore, the traditional approach of sequential design is not feasible where the material is first selected, the product shape is then specified and the part fabricated.

Composite material properties and performance are directly influenced by the manufacturing method as demonstrated in Figure 7.2[7]. This interdependence dictates that manufacturing must be considered in combination with desired mechanical and thermal properties when designing a new MMC material.

Current MMC manufacturing methods are listed in Table 7.4 and summarized in the hypertext document. The advantages of solid state processing over liquid-state processes include lower processing temperatures which reduce matrix/reinforcement chemical interaction and beneficial matrix microstructures which can be transferred to the composite. However, the disadvantages of higher matrix and processing costs favor liquid metal techniques.

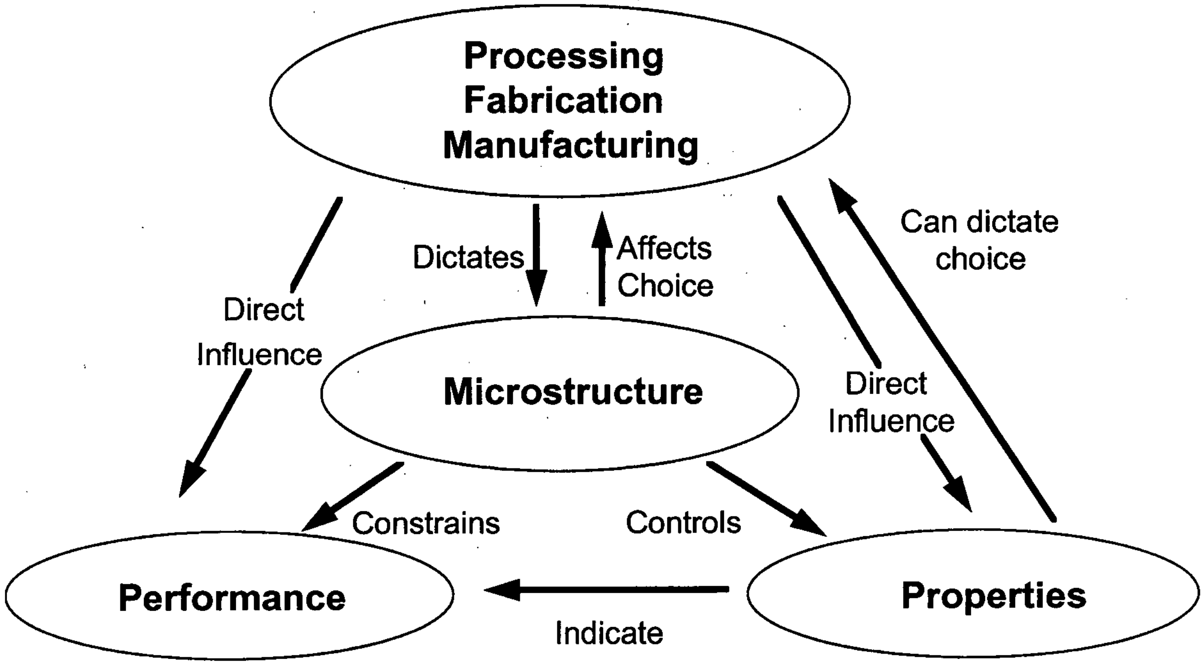


Figure 7.2 Interdependence of Manufacturing, Properties and Performance[7]

Although a variety of manufacturing processes exist, there are limiting factors which control the availability of a suitable method for any given material design. These constraints include matrix/reinforcement compatibility, matrix microstructure(and reinforcement if formed during in-situ processing), type of reinforcement, its distribution, aspect ratio, and volume fraction. For example, Table 7.5 gives reinforcement volume fraction limitations of different shape and size reinforcements for melt infiltration techniques. However, composites based on many high temperature alloys such as titanium cannot be manufactured by melt infiltration because of the severity of the reactions in the melt. For other matrix/reinforcement systems, melt infiltration is only possible with reinforcement coatings and/or matrix alloy modifications. Important factors such as these must be accounted for before a manufacturing route can be established and a material designed.

Table 7.4 Manufacturing Methods

Solid State	**Liquid Metallurgy**	**Rapid Solidification**
Powder metallurgy Fiber/foil Consolidation of Matrix Coated Fibers Powder/cloth	Molten metal mixing Melt infiltration Rheocasting/Compocasting	Dual spray deposition Osprey deposition Vacuum plasma spray co-deposition Fiber winding and plasma spray coating Melt spinning

Table 7.5 Melt Infiltration Reinforcement Volume Fraction Limits

Technique	**Volume Percent Limitation**
cast preforms	70 v/o (distributed particulates)
pressed preforms	55 v/o particulate, whisker or short fiber
die casting(with vacuum)	75 v/o particulates
pressure infiltration	spherical particles(ave. dia = few μm) - 50 v/o bent fibers and whiskers - 40 v/o aligned fibers - 50 - 60 v/o(e.g. alumina fibers) for small dia. non-wetting fibers(e.g. 6 μm C) - 30 v/o
ceramic injection molding	80 v/o particulates (55-60 v/o high pressure and ≥ 80 v/o low pressure)

Notes: (1) Appropriate reinforcement coatings and alloy modifications are assumed to have been made
(2) Specific examples include: Cercast preforms of particulate, whisker, short fiber SiC & Al_2O_3 in Al alloys : 15 - 70 v/o; Ceramic Injection molding Al alloys with 80 v/o B_4C, 82 v/o AlN, 73 v/o TiB_2 & 75 v/o SiC

7.2.1 DETERMINATION OF MANUFACTURING TECHNIQUE In order to construct a decision analysis technique to predict manufacturing methods appropriate for new materials, individual process constraints must first be established. The first step is the subdivision of processing routes based on reinforcement shape categories as used to predict effective composite properties. Next, these processes are further subdivided based on reinforcement orientation and volume fraction limits. Finally, matrix/reinforcement compatibility is taken into account.

The categorization of applicable manufacturing processes for the different reinforcement shapes has been completed and shown for particulate reinforced MMCs in Table 7.6. Volume fraction limitations on the processes of Table 7.4 have been examined. In order to represent levels of reinforcement consistent with manufacturing limitations, linguistic descriptions are employed. These linguistic variables, designated as low, medium and high, are shown in Figure 7.3.

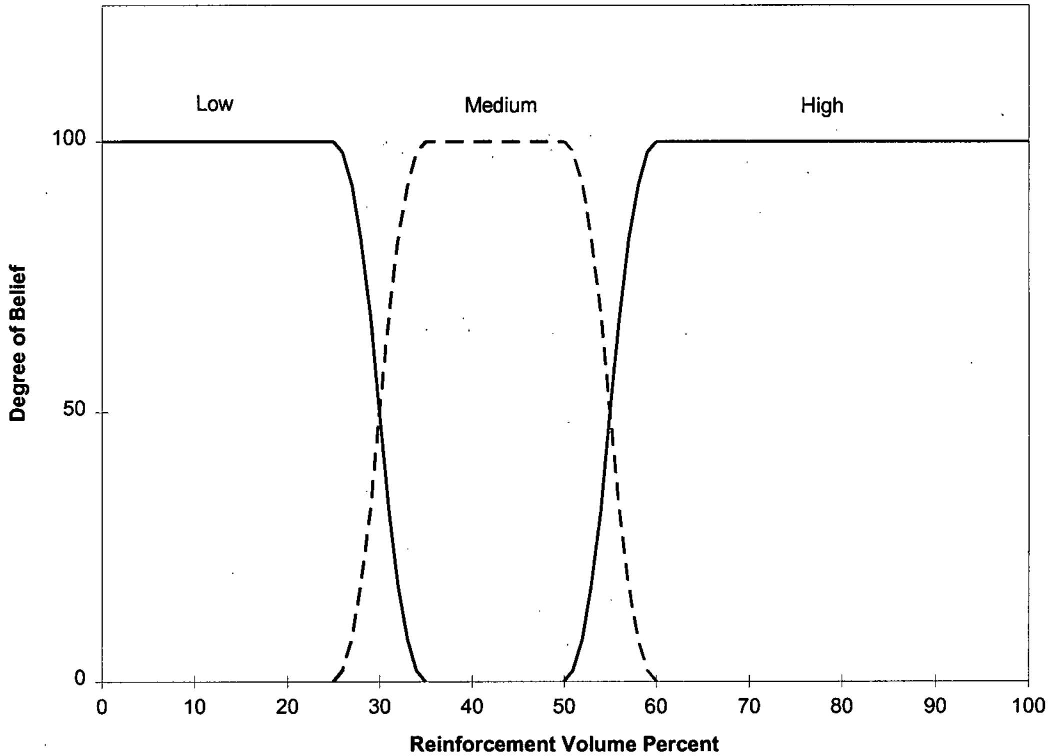


Figure 7.3 Linguistic Representation of Reinforcement Volume Fraction

The determination of processing restrictions due to reinforcement alignment has not be completed for all processes due to the absence of available information. In many instances, orientation constraints have yet to be studied. Therefore, orientation will not be accounted for and as a result, only particulate reinforcements are considered. Particulate alignment is not a restrictive factor for manufacturing since these composites are designed for random orientations and any alignment is introduced as a result of the manufacturing or fabrication process.

Table 7.6 Manufacturing Techniques for Particulate Reinforced MMCs

Particulate Reinforcement Methods
Powder metallurgy
Molten metal mixing
Rheocasting(compocasting)
Spray casting
Melt infiltration
Melt spinning

Constituent compatibility is the major factor which determines what manufacturing method is available for a specific matrix/reinforcement combination. This knowledge in combination with reinforcement volume fraction for particulate reinforced MMCs is used to determine suitable manufacturing techniques.

A decision table, shown in Table 7.7 was constructed. Absent from the table is melt spinning. Since this is still an experimental technique, processing constraints are unavailable and cannot be included at this time. Validation of the decisions was made using current practices in conjunction with expert knowledge. Since few commercial MMCs are being produced, many of the decisions by the system represent new knowledge. This is significant for the rapid development of new materials and the identification of alternative methods to current practices which are potentially more cost effective techniques. For example, the powder metallurgical processing of SiCp reinforced aluminum composites may be replaced by one or more melt infiltration techniques if appropriate matrix alloy modifications or reinforcement coatings are made.

Table 7.7 Decision Table for Particulate Reinforced MMCs

Constituent Compatibility	Level of Particulate Reinforcement		
	Low	**Medium**	**High**
negligible	B	A	A
very low	B,C	C	A
low	B,C,D	C,D	A
average	B,C,D,E,G,I	C,D,E	E
high	B,C,D,E,F,G,H,I	C,D,E,F	E,F

where: A = absence of appropriate method
B = rapid solidification(spray cast)
C = solid state(powder metallurgy) with modifications
D = solid state
E = melt infiltration with modifications
F = melt infiltration
G = molten metal mixing with modifications
H = molten metal mixing
I = rheocasting/compocasting
Modifications include matrix alloy additions and/or reinforcement coatings

CHAPTER 8

KNOWLEDGE ENGINEERING

8.1 KNOWLEDGE ACQUISITION

Knowledge acquisition refers to the process of developing a base of subject knowledge whose use by the expert system can demonstrate a behavior comparable to that of a human expert[149]. This involves interpreting the subject domain, the types of knowledge required, the types of reasoning to be employed and the different knowledge to be used in the reasoning process[150]. Information from experts, books, journals, and manufacturers has been used to construct this system's knowledge about metal matrix composites as illustrated in Figure 8.1.

A direct result of the subject knowledge and materials information together with the role of the system(selection and design) was that the domain had to be structured such that the capacity to use the knowledge adequately was more important than the accumulation of a large amount of information. Specifically, the same materials knowledge can be used to accomplish different goals depending upon the requirements of the user, so the system had to be multi-functional. In addition, in some instances, the same goal can be attained by following a variety of strategies of utilizing the subject knowledge. So, to enable different inferencing and lines of reasoning within a common subject domain, the inference knowledge(reasoning, problem solving and procedural methods) were separated from the factual, quantitative and qualitative subject knowledge.

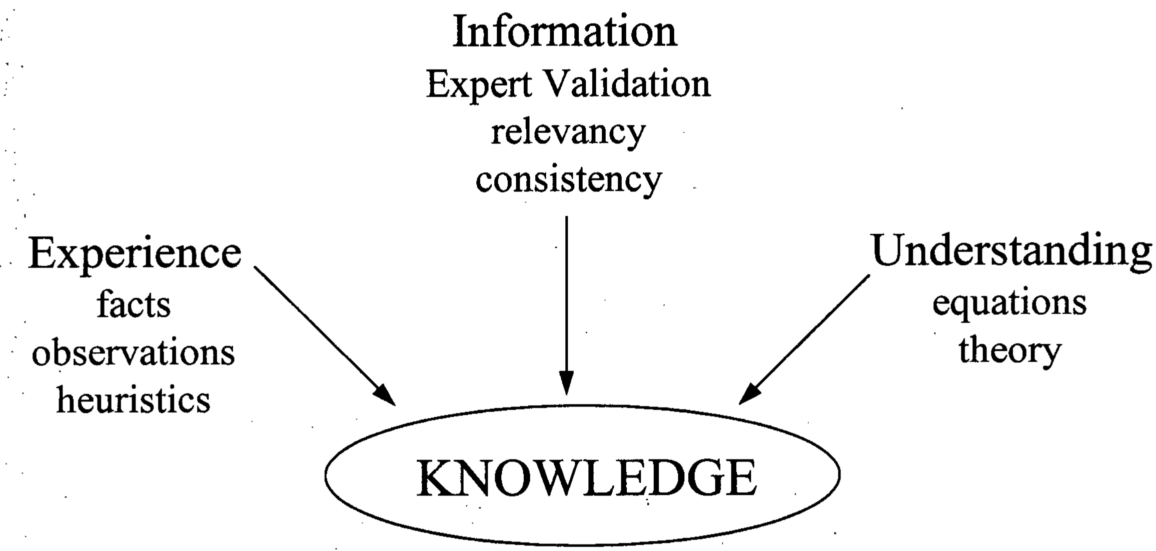


Figure 8.1 Knowledge Acquisition[12]

8.2 KNOWLEDGE REPRESENTATION

Knowledge representation is the process whereby specific devices such as formal logic, semantic networks, hierarchical frames, objects, rules and procedures are employed to capture the subject knowledge. The representation scheme must accommodate the available knowledge, allow the search and inferencing strategies required to provide effective materials information, and store the knowledge in an explicit manner such that it is always available and maintainable[151,152].

The knowledge units of Comdale/X, shown in Figure 8.2, have been utilized to implement the representation of knowledge where the subject domain is contained in the knowledge base as classes, objects, rules, and procedures[153]. Classes represent relationships that exist among similar objects in a hierarchical and schematic manner. This enables reasoning about and representing groups of objects without specifying the individual members of the group. Figure 8.3 is a representation of the class **Compatibility** with its public attributes which are inherited by all member objects of this class.

Objects represent the facts(physical or conceptual entities) of the subject domain. All objects have at least one attribute and an associated value. This object.attribute.value combination is called a keyword triplet. Associated with each keyword triplet are a set of facets used to describe its properties. Examples of keyword triplets are given in Figure 8.4 where the logical keyword triplet **MMCxpert.excel.activated** is used to control the launching of Excel from the expert system. The **conversation.*.@integer** integer keyword triplets are used to control the exchange of data between various Excel spreadsheets. The numeric **calc_E.*.@float** keyword triplets represent the values of elastic modulus calculated by the mathematical models. Objects which are created during the inferencing process by linking strings is a technique also employed. For example, the statement:

compatibility.information.@string =
<matrix.selected.@string>.<reinforcement.selected.@string>.@string

assigns the value of the global keyword triplet **compatibility.information.@string** based upon the matrix alloy and reinforcement material selected by the user.

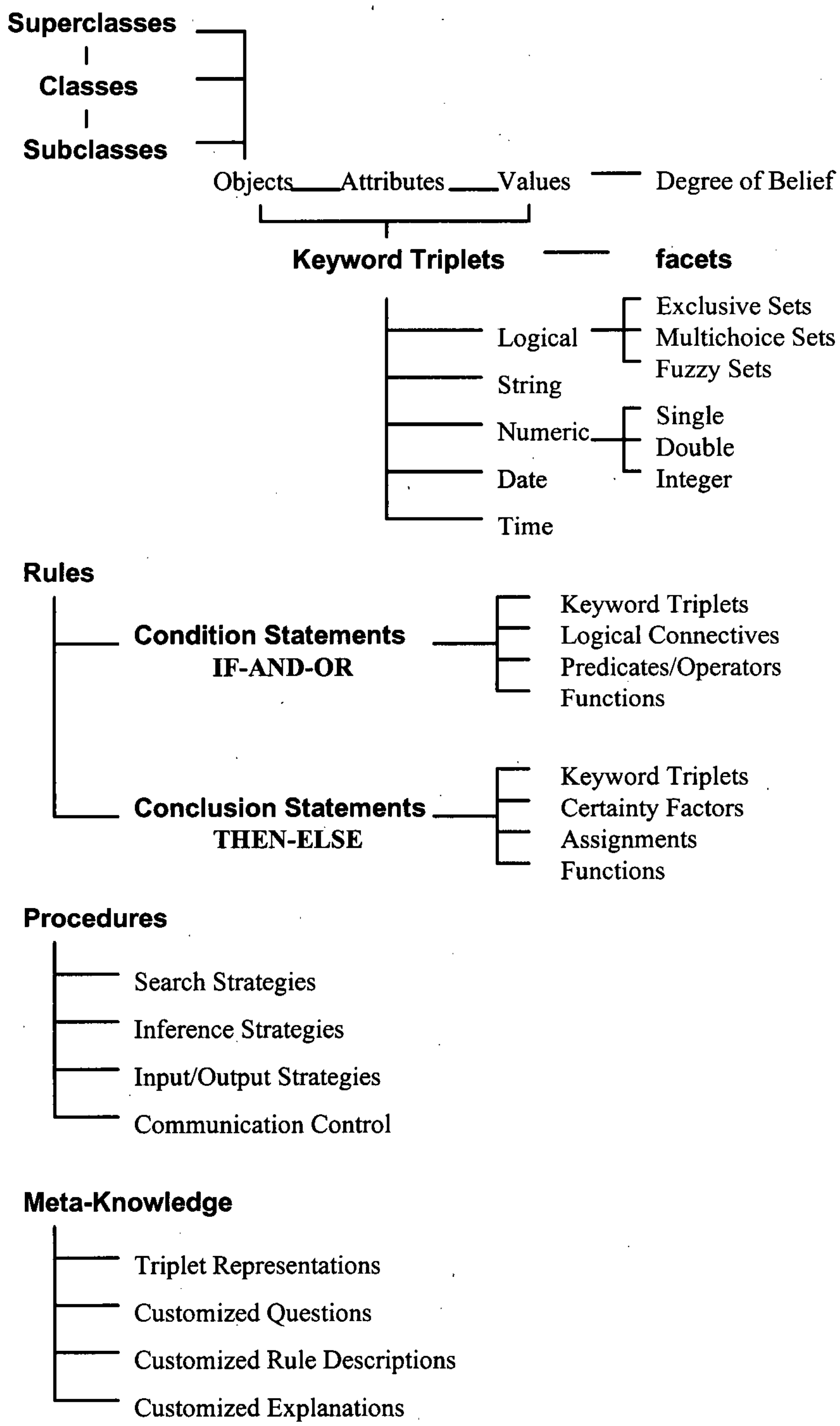


Figure 8.2 Knowledge Units in Comdale/X[153]

```
Class
@name = Compatibility
@object = Al2XX, Al2XXX, Al3XX, Al6XXX, Al7XXX, Al8XXX, CuXXX, MgXX, TiXX
@public = Al2O3_fiber.compatible, Al2O3_fiber.@string, Al2O3_particulate.compatible,
        Al2O3_particulate.@string, Al2O3_short_fiber.compatible, Al2O3_short_fiber.@string,
        Al2O3_whisker.compatible, Al2O3_whisker.@string, AlN_particulate.compatible,
        AlN_particulate.@string, B4C_particulate.compatible, B4C_particulate.@string,
        B4C_whisker.compatible, B4C_whisker.@string, Boron_fiber.compatible,
        Boron_fiber.@string, Carbon_fiber.compatible, Carbon_fiber.@string,
        Carbon_particulate.compatible, Carbon_particulate.@string, Carbon_short_fiber.compatible,
        Carbon_short_fiber.@string, Carbon_whisker.compatible, Carbon_whisker.@string,
        Si3N4_particulate.compatible, Si3N4_particulate.@string, Si3N4_whisker.compatible,
        Si3N4_whisker.@string, SiC_fiber.compatible, SiC_fiber.@string,
        SiC_particulate.compatible, SiC_particulate.@string, SiC_short_fiber.compatible,
        SiC_short_fiber.@string, SiC_whisker.compatible, SiC_whisker.@string,
        TiB2_fiber.compatible, TiB2_fiber.@string, TiB2_particulate.compatible,
        TiB2_particulate.@string, TiC_particulate.compatible, TiC_particulate.@string,
        Tungsten_fiber.compatible, Tungsten_fiber.@string
endClass
```

Figure 8.3 ASCII Text of Compatibility Class Knowledge Unit

```
Object                              Object
@name = MMCxpert_excel              @name = conversation
@attribute = is.activated           @attribute = eight.@integer, eleven.@integer, fifteen.@integer,
endObject                                   five.@integer, four.@integer, fourteen.@integer,
                                            nine.@integer, one.@integer, seven.@integer,
                                            six.@integer, sixteen.@integer, ten.@integer,
                                            thirteen.@integer, three.@integer, twelve.@integer,
                                            two.@integer
                                    endObject

Object
@name = calc_E
@attribute = behrens_whisk_trans.@float, christensen_2D.@float, christensen_3D.@float,
        eshelby_whisk_long.@float, eshelby_whisk_trans.@float, halpin_tsai_whisk_long.@float,
        hash_shtrik_lower.@float, hash_shtrik_random_lower.@float,
hash_shtrik_random_upper.@float,
        hash_shtrik_trans_lower.@float, hash_shtrik_trans_upper.@float, hash_shtrik_upper.@float,
        hash_shtrik_whisk_lower.@float, hash_shtrik_whisk_upper.@float, hatta_taya_random.@float,
        kural_min.@float, nom_chou_lower.@float, nom_chou_trans_lower.@float,
        nom_chou_trans_upper.@float, nom_chou_upper.@float, paul.@float,
        ROM.@float, tsai_pagano_random.@float
endObject
```

Figure 8.4 ASCII Text of Keyword Triplets

Facets are used to describe the properties of the keyword triplets. Each keyword triplet has a facet called the degree of certainty. This is a numerical value ranging from 0 to 100 representing how sure the system is that the attribute value is true. A value of 0 is equivalent to FALSE and 100 to TRUE. The exclusive set facet **Alloy**, shown in Figure 8.5, is used to allow the selection of one alloy type from the set of alloys listed during a consultation. This ensures that the user can choose only one option. Factors which are difficult to quantify or too complex to model mathematically or algorithmically are represented using fuzzy sets. The fuzzy set facet **Volume_low**, shown in Figure 8.5, determines the condition when the keyword triplet **reinforcement.volume_level.low** is true based upon the value of the reinforcement volume percent, keyword triplet **reinforcement.volume_percent.@float,** and its degree of belief. Since reinforcement volume levels are not well defined, the use of linguistic variables such as **low** capture this knowledge in a more appropriate fashion.

```
Facets                                          Exclusive
@triplet = reinforcement.volume_level.low       @name = Alloy
@default = 0.000000                             @state = Al2XX, Al2XXX, Al3XX,
@fuzzy = Volume_low                                 Al6XXX, Al7XXX, Al8XXX,
endFacets                                           CuXXX, MgXX, TiXX
                                                endExclusive
Fuzzy
@name = Volume_low
@source = reinforcement.volume_percent.@float
@range = 12
@value = 0.000000, 25.000000, 26.000000, 27.000000, 28.000000, 29.000000, 30.000000, 31.000000,
32.000000, 33.000000, 34.000000, 35.000000
@rank = 100.000000, 100.000000, 98.000000, 92.000000, 82.000000, 68.000000, 50.000000,
32.000000, 18.000000, 8.000000, 2.000000, 0.000000
endFuzzy
```

Figure 8.5 ASCII Text of Comdale/X Facets

Reasoning and decision-making heuristics are structured as rules. Rules are written in an **IF-THEN-ELSE** format whereby the IF-AND-OR part of the rule is the premise and the THEN-ELSE part is the conclusion. There are no limits to the number of condition statements in the premise or conclusion statements which can be used in a rule. Figure 8.6 shows the rule used to control the activation of Excel. Rules are also used to represent relationships between facts. For example, the dependence of the value of the constant A,

reinforcement.constA.@float, from the Lewis & Nielsen equation on the value of the fiber aspect ratio, **fiber.aspect_ratio.@float,** is demonstrated by the rule **LewNiel_constA_Rule4** in Figure 8.6.

```
Rule
@name = Rule_Excel
IF   MMCxpert.excel.activated is FALSE
THEN ACTIVATE ( "c:\excel\excel.exe c:\final\TcMatrix
c:\final\TcReinf4.xls c:\final\TcPartdB.xls c:\final\CTEdB.xls
c:\final\mechprop.xls c:\final\XprtPred.xls" )
THEN MMCxpert.excel.activated is T
ELSE TEXT ( "Excel will not be activated. ", "Excel Status" )
endRule

Rule
@name = LewNiel_constA_Rule4
IF   6 < fiber.aspect_ratio.@float
AND  fiber.aspect_ratio.@float   <= 10
THEN reinforcement.constA.@float   = 4.930000
endRule
```

Figure 8.6 ASCII Text of Comdale/X Rules

Procedures contain a set of instructions pertaining to rules, objects or classes. They mimic the algorithmic actions of conventional programs by performing a top-down sequence of statement execution. For example, Figure 8.7 is the ASCII text listing of the procedure **ReinfCTEWr**. This procedure acquires the name of the reinforcement for which a search is required for the coefficient thermal expansion; makes the assignment to run the appropriate Excel macro program; opens a connection to Excel; writes the name of the reinforcement to the database and finally closes the Excel connection.

```
Procedure
@name = ReinfCTEWr
@do =
 FREERULE ( $Rule, "ReinfdB_control" )
 reinforcement.database.search is TRUE
 letter.value.@string = "a"
 ASK ( "Enter reinforcement name for CTE search", reinforcement.name.@string )
 conversation_6.TYPE.@string is "DDE"
 conversation_6.MAPFILE.@string is "c:\final\ctereinf.mpf"
 conversation.six.@integer = CONNECT ( "conversation_6", "Excel TcReinf4.xls" )
 WRITE ( CONVERSATION.six.@integer, "reinforcement.name.@s" )
 DISCONNECT ( CONVERSATION.six.@integer )
endProcedure
```

Figure 8.7 ASCII Text of Comdale/X Procedure

8.3 KNOWLEDGE PROGRAMMING

Knowledge programming is the process of building the knowledge base and coding the rules and procedures applied by the inference engine. These components convert expert heuristics and assertions into lines of reasoning and decision-making processes of the system.

This system uses a goal directed strategy where rules and procedures are selected to reach a conclusion. The user interface was customized to permit immediate inferencing due to user action. Since the system supports multiple decision-making processes in addition to managing external applications tools and user input, a traditional question and answer approach was inadequate. Therefore, a dynamic hypertext interface has been integrated into the system to give a comprehensive means of navigating through the knowledge base and the on-line hypertext documents. Excel databases and spreadsheets are accessed through hypertext nodes and links.

The modular design of the system is based on the separate lines of reasoning followed within each module. Figure 8.8 is a simple illustration of the modules and their knowledge sharing linkages, Figure 8.9 their locations, and Figures 8.10-8.14 their structures. Although not shown, they are all interconnected such that the user can move from one to another through a series of links incorporated into the hypertext interface.

An important consideration in placing the nodes which link the modules is to ensure that lines of reasoning are not disrupted by the user action of jumping from one module to another. To accomplish this, exit nodes are available at all levels but are generally linked to other modules at the top level.

Links between modules which share knowledge are available at lower levels but are designed to maintain coherence. For example, the determination of manufacturing methods suitable for a particulate reinforced MMC performed in Module 4 requires matrix/reinforcement compatibility. This can be determined in Module 3 thus a link to matrix/reinforcement compatibility determination is provided. The prediction of effective composite properties by Module 2 can be performed using constituent property data from the databases. Lower level linkages to Module 1 are provided to enable database retrieval of the appropriate property values. Although these modules are linked to share data, they can reason independently(with user input) and it is not necessary to follow a single approach.

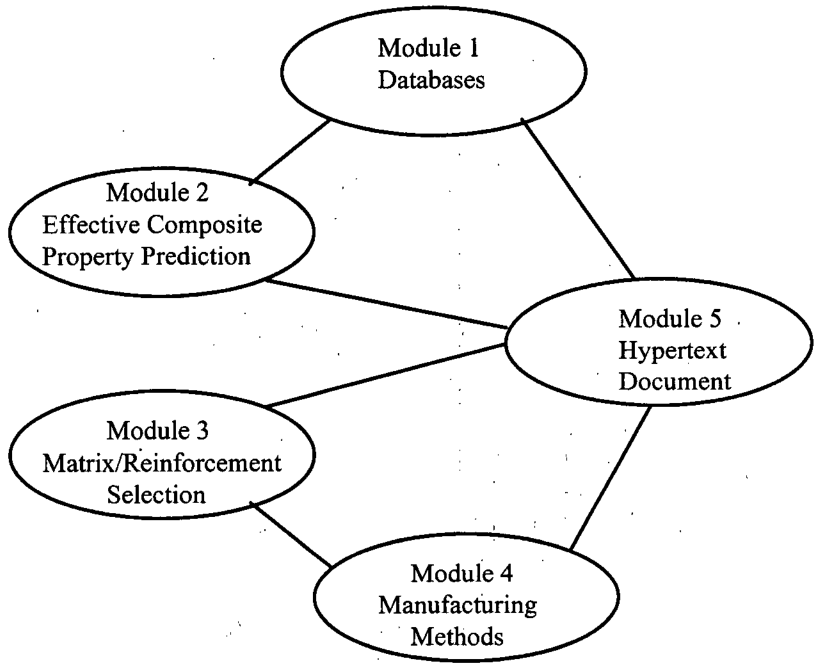


Figure 8.8 System Modules and Linkages

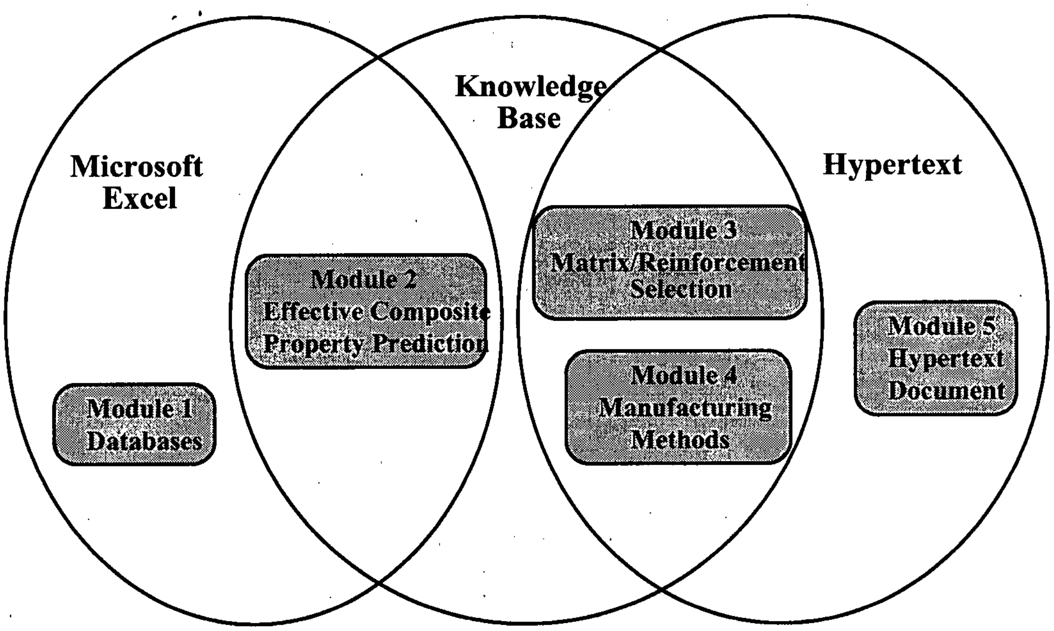


Figure 8.9 Module Location

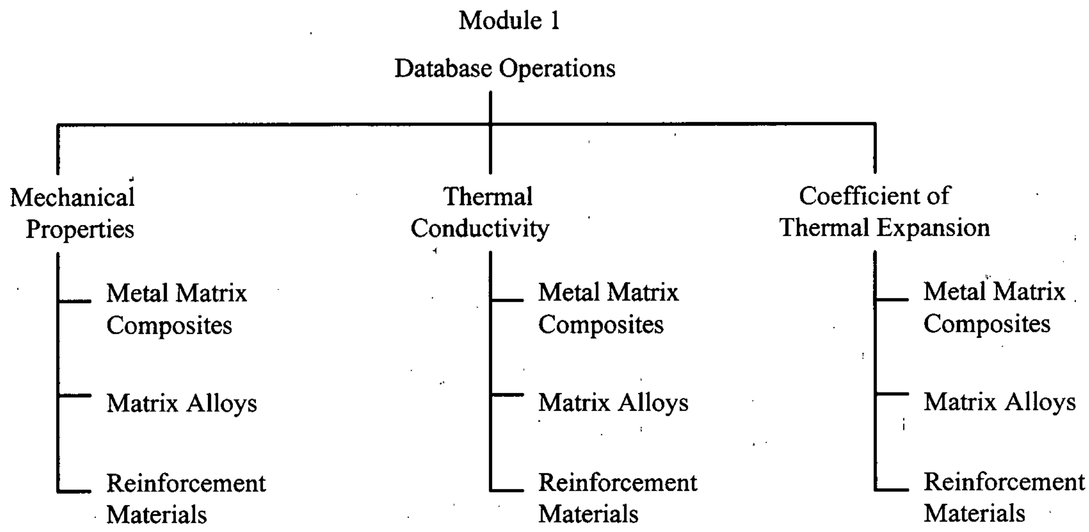


Figure 8.10 Structure of Module 1

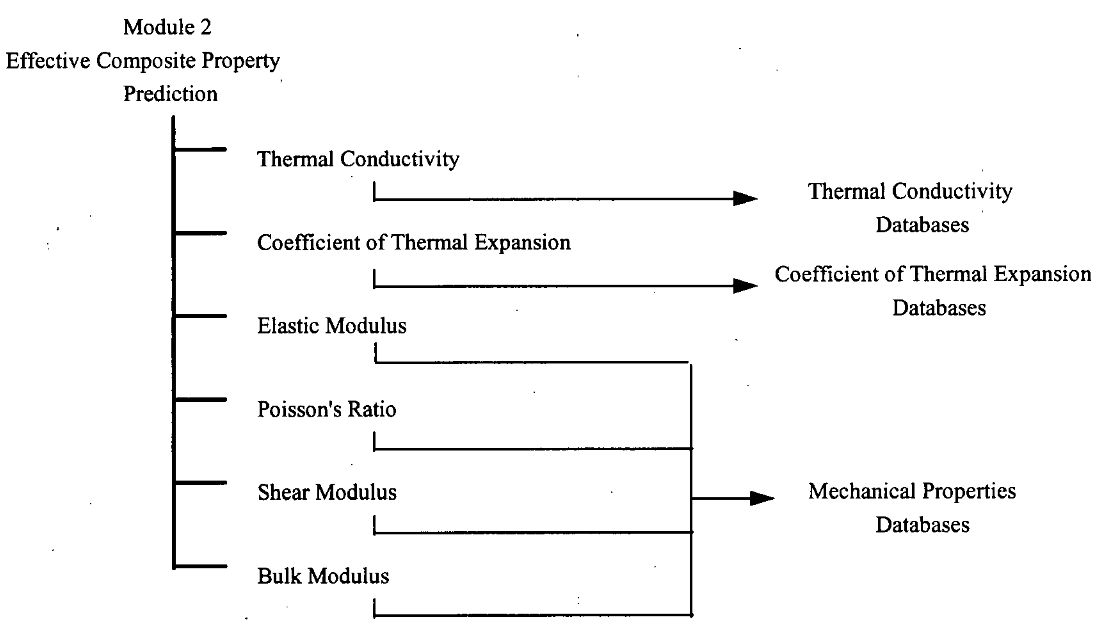


Figure 8.11 Structure of Module 2

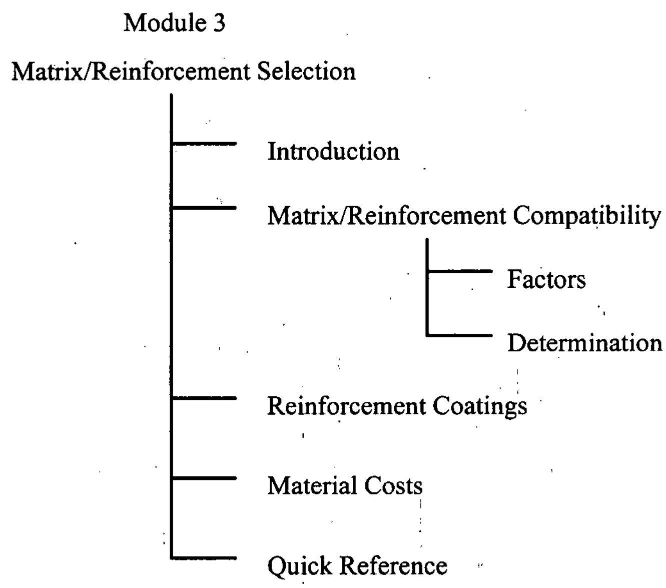


Figure 8.12 Structure of Module 3

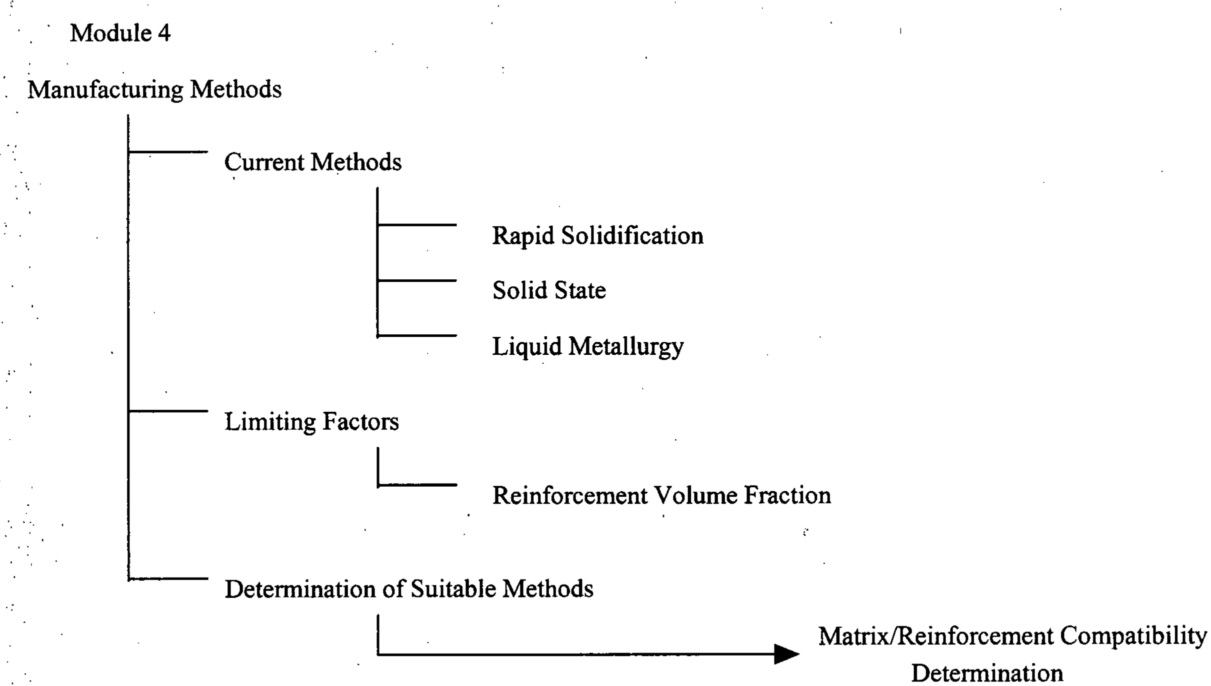


Figure 8.13 Structure of Module 4

Module 5

Hypertext Document

- MMC Properties
  - Thermal Conductivity
    - Overview
    - Determination
    - Effect of Temperature
    - Effect of Heat Treatment
    - Metals and Alloys
    - Reinforcements
  - Coefficient of Thermal Expansion
    - Overview
    - Effect of Temperature
    - Effect of Heat Treatment
    - Metals and Alloys
    - Reinforcements
  - Elastic Constants
    - Elastic Moduli
    - Poisson's Ratio
- Effective Property Prediction
  - Thermal Conductivity
    - Particulate Reinforcement
    - Whisker/Short Fiber Reinforcement
    - Fiber Reinforcement
  - Coefficient of Thermal Expansion
    - Particulate Reinforcement
    - Whisker/Short Fiber Reinforcement
    - Fiber Reinforcement
  - Elastic Moduli and Poisson's Ratio
    - Particulate Reinforcement
    - Whisker/Short Fiber Reinforcement
    - Fiber Reinforcement

Figure 8.14 Structure of Module 5

The interactive user interface allows the user to go back to any point within any module and revise a previous input or value. This is important because the linking of the modules also includes transfer of knowledge. Rules and procedures are designed for consistency such that facts derived by the expert system can always be followed back to the premise which yielded those conclusions. This consistency ensures that all subsequent inferencing from that point on includes the revised input no matter how the user jumps around the system.

8.3.1 <u>APPROXIMATE REASONING</u> Inferencing with linguistic variables, as logical keyword triplets, which represent inexact knowledge is performed by the system in the determination of suitable manufacturing routes for particulate reinforced MMCs. Reasoning under such approximate conditions leads to rational decisions although the conclusions may not be exact[154]. Multiple rules are prevented from firing by the setting of a system confidence level of 50 %. This gives a crisp boundary between variables such as low and medium reinforcement volume fractions, shown in Figure 7.3.

Figure 8.15 is the rule which determines the manufacturing route for a particulate MMC with a medium level of reinforcement and a very low matrix/reinforcement compatibility. The system advises on Powder Metallurgy but does not give any specific details. For more precise information such as alloy or reinforcement modifications, the user can consult the hypertext document or contact a manufacturer.

```
Rule
@name = Manuf_Route_Rule9
IF   reinforcement.type.particulate is True
AND  reinforcement.volume_level.medium is True
AND  material.compatibility.very_low is True
THEN manufacture.process_available.@string = "Powder Metallurgy with modifications
 to matrix and/or reinforcement phases."
endRule
```

Figure 8.15 Approximate Reasoning Rule

8.3.2 <u>EXTERNAL APPLICATIONS</u> Information contained in the external databases and calculated by the mathematical models is transferred through a dynamic data exchange(DDE) link with keyword triplets assigned the addresses of respective worksheet cells by Comdale/X mapping files. The interaction between the expert system and the Excel applications takes place dynamically with the databases and mathematical modeling spreadsheet acting as servers to the expert system supplying information on demand. The databases and mathematical modeling spreadsheets have been configured such that they can be used independently in Excel. The worksheets are documented such that by entering appropriate input values in the highlighted cells, the user can utilize the models to predict effective composite properties and access the databases. In addition, Excel charts containing plots of the model predictions are also accessible.

8.3.3 DATABASE MANAGEMENT The coupling of the expert system and Excel databases was achieved using Excel database management functions under the control of the expert system. Macro programs have been written in Excel which manage the databases based on instructions from Comdale/X. Figure 8.16 displays the Comdale/X rule **ReinfdB_control** which signals the Excel macro program **MacRun** to run the applicable database functions depending on the value of the keyword triplet **letter.value.@s**. Keeping the database management functions in Excel and the inferencing rules in Comdale/X maintains efficiency and keeps the operations simple.

```
Rule
@name = ReinfdB_control
IF   reinforcement.database.search is TRUE
THEN conversation_8.TYPE.@string is "DDE"
THEN conversation_8.MAPFILE.@string is "c:\final\global.mpf"
THEN conversation.eight.@integer = CONNECT ( "conversation_8", "Excel macctrl.xls" )
THEN WRITE ( CONVERSATION.eight.@integer, "letter.value.@s" )
THEN DISCONNECT ( conversation.eight.@integer )
endRule


MacRun
=ACTIVATE("macctrl.xls")
=SELECT("R4C3")
=IF(ACTIVE.CELL()="a",RUN(GLOBAL.XLM!CTEReinf),)
=IF(ACTIVE.CELL()="c",RUN(GLOBAL.XLM!MechReinf),)
=IF(ACTIVE.CELL()="b",RUN(GLOBAL.XLM!TcReinf),)
=IF(ACTIVE.CELL()="d",RUN(GLOBAL.XLM!MatCTE),)
=IF(ACTIVE.CELL()="e",RUN(GLOBAL.XLM!MatMech),)
=IF(ACTIVE.CELL()="f",RUN(GLOBAL.XLM!TcMatrix),)
=RETURN()
```

Figure 8.16 Coupling of Comdale/X Rule and Excel Macro Program

Traditional database options are available in Excel giving the user control over the compiled information. The databases can be modified and new information added without affecting the integrity of the expert system. In addition, as the databases grow in size, the operational efficiency of Comdale/X remains unchanged.

8.4 USER INTERFACE

Optimization of the dialogue structure together with customization of the inference engine was used to design the user interface. The Hypertext and Form utilities of Comdale/X were employed. Dynamic hypertext allows the knowledge base to be organized into procedures and rules that run in response to user requests for real-time results. This avoids redundancy and provides an efficient inferencing process. In addition, the user can access different options much more efficiently without lengthy procedures particularly when the results of a completed task indicate a change or new direction in the system consultation procedure.

The Form utility allows the input or modification of information, as keyword triplets, by the user. Figure 8.17 is a sample Form for coefficient of thermal expansion. If the user has used the expert system to retrieve constituent properties from the databases in module 1 or previously entered data during the consultation, the boxes would contain this information. If not, the boxes are blank and the user is prompted for the data. Restrictions have been employed in many instances to prevent the entry of foolish information.

Output or conclusions are provided to the user by embedding keyword triplets into the text contained in hypertext or on Forms. Figure 8.18 shows the structure of the hypertext page which presents the results of the determination of matrix/reinforcement compatibility.

This method allows for the delivery of unlimited and variable textual information in a coherent, user-friendly manner.

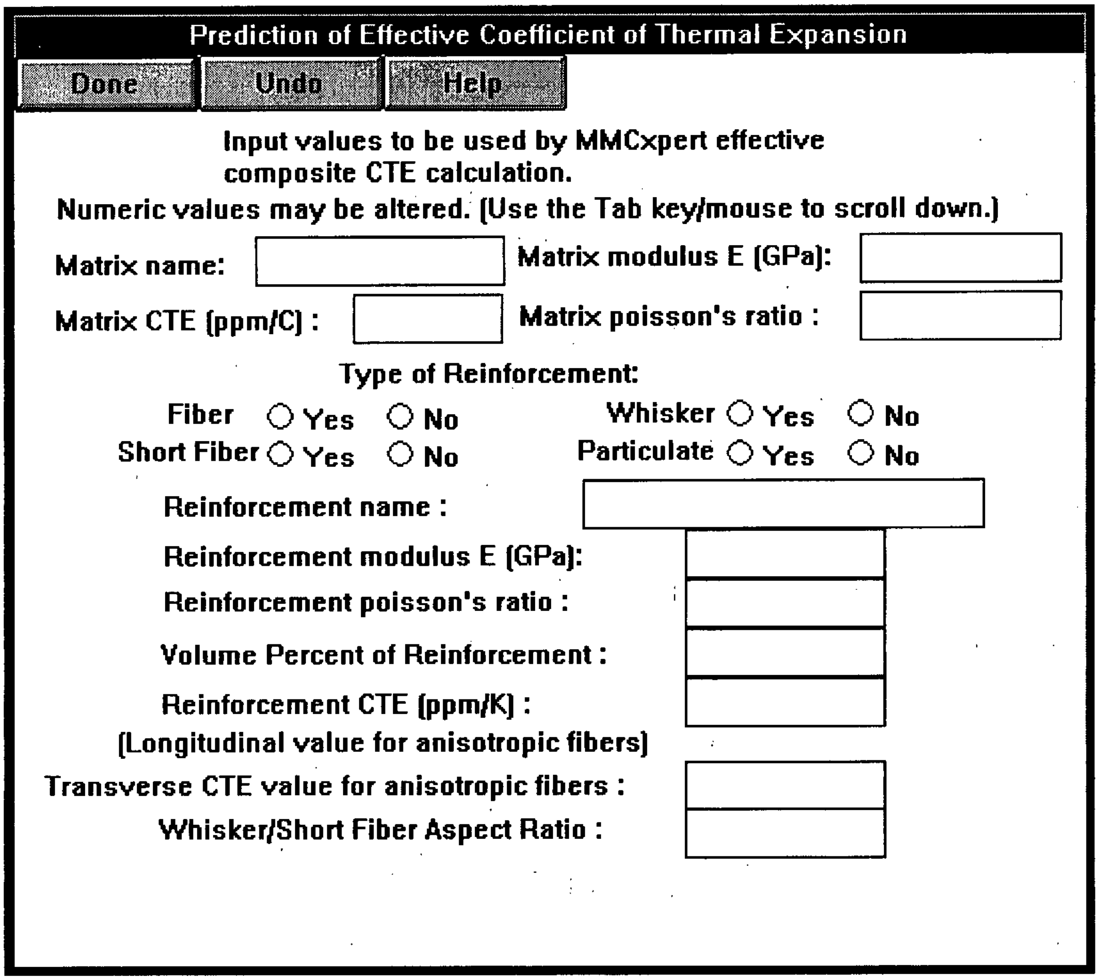


Figure 8.17 Comdale/X Form for Coefficient of Thermal Expansion

```
\bt\
\nt[Manuf4]\
                    \h2. Determination of Manufacturing Route\
                      \h2. for Particulate Reinforced MMCs\

Given the following conditions:

    1. Particulate volume fraction is !$reinforcement.volume_message.@s$!

    2. The compatibility of !$matrix.selected.@s$! and !$reinforcement.selected.@s$!
       is !$compatibility.message.@s$!.

Suitable manufacturing route(s) : !$manufacture.process_available.@s$!

    !$compatibility.information.@s$!

\jt[process1].click here to return to start of module 4\

\jt[Index].click here to return to beginning of MMCxpert\
```

Figure 8.18 Hypertext Display Topic With Embedded Keyword Triplets

8.5 HYPERTEXT DOCUMENT

The hypertext document is an on-line reference which has been setup to allow easy access to materials information. Information is organized into topics which contain information, link and embedded operation objects. These objects can interact with each other although they are separate items within a topic. Information objects include text and pictures, links are the paths to other topics in the hypertext document and embedded operation objects are executable Comdale/X functions.

Finding information and navigating through the hypertext document has been enhanced by using tables of contents, quick reference guides and links arranged in a similar manner as in the system modules. A top-down approach has been used such that general information is available first and more specific pieces of information can be accessed using link objects.

CHAPTER 9

SYSTEM VALIDATION AND EVALUATION

9.1 VALIDATION

The purpose of validation is to ensure that the system reaches the right decisions and that it does so for the right reasons. This means that not only are the inferencing rules and keyword triplets examined, but the information contained in the databases, knowledge base and the mathematical modeling spreadsheet must also be tested for accuracy. The simplest and most logically means of testing is to examine the system module by module. For modules which are interdependent, joint testing was performed for consistency.

9.1.1 <u>MODULE 1 - DATABASES</u> During database construction, the information to be input was closely examined for accuracy. Cross-referencing was made and sources and degrees of belief were included. For the MMC and reinforcement databases, specific commercial products were listed and the majority of information came from manufacturers to ensure accuracy. For products which are sensitive to contamination or subject to varying surface treatments, data ranges and descriptions of anticipated behavior were included. Finally, proof reading of the database entries after they were keyed-in was performed to identify any typing errors.

9.1.2 MODULE 2 - MATHEMATICAL MODELS As part of the selection of the mathematical models to be included in the system, model accuracy and validation were closely examined as described in Chapter 6. The precision of the spreadsheets themselves and the transfer of data from Excel to Comdale/X were also reviewed. The focus was to ensure that the Comdale/X mapping file and keyword triplet assignments corresponded to the correct spreadsheet cells and that model parameters were given the correct cell assignments.

A tedious process of inputting test values and examining their cell assignments and model calculation results was followed. Errors were quickly identified and corrected. Correct reading of cell values into Comdale/X was ensured by following the same process with test values assigned to spreadsheet cells.

Since the input for the models can be obtained from database searches in addition to the user, the correct transfer of values from Module 1 needed to be assured. This was handled with a scenario approach where database searches were conducted prior to running Module 2.

9.1.3 MODULE 3 - MATRIX/REINFORCEMENT SELECTION The testing of this module is more difficult due to the use of linguistic variables to describe matrix/reinforcement compatibility. Quantitative data with which to validate these variable assignments does not exist. As a result, validation was confined to comparing the relative assignments to one another for consistency and ensuring that the assignment of linguistic and string keyword triplets was correct.

The reinforcement coatings and material cost information was checked for accuracy and sufficient documentation. This information is very dynamic as the drive to reduce costs and develop new reinforcements and surface treatments keeps changing the accuracy of the information available. To deal with this, time dating was incorporated and the information moved into Excel databases. The use of databases permits user modification simply and independently of the expert system.

9.1.4 <u>MODULE 4 - MANUFACTURING METHODS</u> The testing of this module is particularly challenging due to the decision-making process which recommends suitable manufacturing routes for particulate reinforced MMCs. Since there is a lack of information to verify the decisions, i.e. the majority of matrix/reinforcement combinations have yet to be manufactured, a number of recommendations present new knowledge. Since many of the decisions are verifiable, a high level of confidence is imparted to all decisions.

The verification method compares system recommended routes to current practice techniques. This was done during the module development cycle where the decision table, Table 7.7, was refined based on these results.

This module will require periodic review to maintain its accuracy. New manufacturing routes can be incorporated in future versions of the hypertext document. In addition, creation of MMCs not presently manufactured but recommended by the system will require verification.

9.1.5 <u>MODULE 5 - HYPERTEXT DOCUMENT</u> Validating the hypertext document primarily concerns ensuring the links between topics function properly. A systematic method of scanning the document was employed to detect any logical errors after the document was compiled. In terms of the accuracy of the information provided, the hypertext document will always require updating and the addition of more information to provide materials information. The document will never be complete and should be viewed in this capacity.

9.2 EVALUATION

Evaluation generally encompasses both an informal process with experts, novices and system developers and a formal process which involves field testing the prototype. For this system, only informal testing has occurred. This is due primarily to time constraints and also the proprietary nature of the system data. Strong interest to purchase the system as is have been received with significant value placed on the contents of the Excel spreadsheets and databases which cannot be protected from copying. Although methods are in place to ensure confidentiality, the time-line involved versus the need to complete the project resulted in only informal testing being performed.

The aim of the evaluation was to discover any bugs in the system, acquire feedback on the usability of the system and on the information provided by the system. In general, the users were satisfied with the result of their consultations. Useful suggestions to improve the prototype were given.

One expert familiar with material information systems and design was encouraged to comment on the system design and content. This expert suggested using a method to select one MMC from a group of materials by applying an optimization or objective function routine. The addition of strength prediction capabilities was suggested as a priority in the next phase of development.

Two experts familiar with the subject domain but not expert systems also examined the system prototype. They suggested more detailed cost information should be included as it is the primary consideration for selection in the automotive industry. A method to store information obtained from each consultation, particularly the prediction of values in Module 3, was recommended. Minor errors which occur when the user enters incorrect data were also detected.

A novice user unfamiliar with either the subject domain or expert systems was also observed testing the system prototype. Introductory screens which describe the structure of the modules were recommended. Minor errors, such as misprints, in the hypertext document were uncovered.

Features such as visual clarity, user guidance and support, and explicitness were questioned. The interface was generally considered to be user-friendly with individual likes and dislikes mentioned. For example, some users were happy with the jump text format while others would prefer buttons. These items do not impact on the operation of the system and can be customized for each user. The use of help files or direct links into appropriate hypertext document topics from all levels of all modules was suggested to aid novice users.

The incorporation of changes suggested by the evaluators' comments should be considered for future versions of the prototype. In addition, field testing should be undertaken to complete the evaluation process.

CHAPTER 10

CONSULTATION SESSIONS

10.1 SUBSTITUTION OF AISI 304 SS IN CRYOGENIC SERVICE

The most commonly used alloys for cryogenic applications are austenitic stainless steels, nickel steels, and aluminum alloys[154]. Some typical alloys and their properties are shown in Table 10.1[154-157]. For service temperatures down to 4 K, the austenitic stainless steels and aluminum alloys are the preferred alloys [155]. The wider application of aluminum alloys has been hampered by their low modulus of elasticity and strength, high thermal conductivity, and high coefficient of thermal expansion[154]. A low ratio of thermal conductivity to elastic modulus reduces refrigeration costs whenever the components are subjected to a temperature gradient. A low coefficient of thermal expansion(CTE) is also an important design parameter since additional stresses are introduced into the structure in the presence of a temperature gradient. The advantages of aluminum alloys include their low density, nonmagnetic behavior, weldability, compatibility with cryogens; and retained strength, fracture toughness and elongation at low temperatures.

In practice, welded austenitic stainless steel assemblies are widely used but they are expensive; the toughness of the welds is usually significantly lower than the base metal; and there is an increased sensitivity to hydrogen embrittlement in the welds[154,155].

Substitution of these welded assemblies by machined and bolted high strength aluminum alloys has been proposed. However, the coefficient of thermal expansion mismatch between the aluminum alloys and the steel bolts is a major barrier. The mismatch in CTE of aluminum and steel alloys is also a problem in the design of double-wall vessels and in many instances is the deciding factor in the selection of the inner and outer tank material[156]. The substitution of austenitic stainless steel is the goal of this consultation.

10.1.1 <u>METAL MATRIX COMPOSITE DATABASE SEARCH</u> The necessary requirement for all candidate MMCs will be a CTE equivalent to austenitic stainless steels, a lower thermal conductivity, and an increase in the elastic modulus. In this case, a room temperature CTE value of 15.8 $\times 10^{-6}$/K, equivalent to AISI 304 SS is selected. The first step in the consultation is to search the MMC database to identify possible candidate materials. It was decided to access the database independent of the expert system interface since the number of entries is relatively small and can be browsed efficiently using the features of Microsoft Excel. The system is designed with this flexibility so that the user can easily switch to other Microsoft Windows applications during a consultation, or can update and add new information to the Excel databases either during a consultation or when running Excel independently.

A list of materials retrieved from the MMC database search are shown in Table 10.2. Thermal conductivity values retrieved from the database for these materials reveal an increase over the monolithic matrix alloy thereby precluding their further consideration. At this juncture the option to explore designing a composite with a matrix/alloy combination meeting the design objectives is undertaken.

Table 10.1. Typical Properties of Cryogenic Materials at Room Temperature[7,9,10]

Material Designation	Density (g/cm^3)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Poisson's Ratio	Thermal Conductivity (W/mK)	Coefficient of Thermal Expansion ($x 10^{-6}/K$)
Steels							
ASTM A203 grade D alloy steel	7.86	255	448	204	0.28	35	11.9
ASTM A516 grade 55 carbon steel	7.83	207	379	195	0.28	50	11.75
ASTM A240 AISI 304 austenitic s.s.	8.03	207	517	193	0.29	17	15.8
Aluminum Alloys							
2219-T87	2.84	395	475	73	0.33	120	23
5083-O	2.66	145	290	72	0.33	117	23
6061-T6	2.7	275	310	70	0.34	167	23

10.1.2 METAL MATRIX COMPOSITE MATERIAL DESIGN The first task is to select appropriate alloy matrices. In this consultation, two aluminum alloys currently used at cryogenic temperatures namely, the high strength alloy 2219-T87 and the medium strength alloy 6061-T6 will be used. Alternatively, other matrix alloys may be selected from the matrix alloy database of this system which includes properties for many copper, aluminum, titanium, and magnesium alloys. Selection of reinforcement materials is more complex. Browsing through the reinforcement database of the system, it is evident that the majority of the reinforcements possess superior stiffness(relative to the aluminum matrices) and low coefficients of thermal expansion.

The thermal conductivity of reinforcements varies widely. In order to prepare a short-list of potential reinforcements, their value will be subjectively limited to 30 W/mK or less. This threshold value is selected by the user to generate the list shown in Table 10.3. Due to uncertainty associated with many published values, degrees of belief associated with the property values are given in the database to aid in the selection process. Property values of different materials do not have the same reliability and cannot be compared simply based on one database entry. For example, the average value of thermal conductivity for B_4C particulate is 48 W/mK; however, the range is approximately 29 - 67 W/mK. With a database entry of 48 W/mK, B_4Cp would have been overlooked by the majority of database management systems.

Table 10.2. Materials Retrieved From MMC Database

Material Designation	**Coefficient of Thermal Expansion ($x10^{-6}/K$)**
X2080/SiC/15p	15.5
2024/SiC/25f-T6	14.9L 16.4T
6092/SiC/25p-T6	15.3
6090/SiC/25p-T6	15.3
6090H/SiC/25p	15.3

Table 10.3. Reinforcements Retrieved From Database

Particulates	**Whisker/Short Fibers**	**Fibers**	
Al_2O_3	Al_2O_3	Al_2O_3 - Nextel 312	C fiber PAN E-34
B_4C	Al_2O_3-SiO_2 Fiberfrax	Al_2O_3 - Nextel 440	SiC fiber SCS
Si_3N_4	Al_2O_3-Saffil RF Grade	Al_2O_3 -Safimax	SiC fiber on W
TiB_2	B_4C	Al_2O_3 -Fiber FP DuPont	SiC fiber on C
TiC	SNW Si_3N_4 whisker	Al_2O_3 - SiO_2 Sumitomo	SiCf Nicalon NL = 200
		Al_2O_3 - SiO_2 Fibermax	TiB_2
		C fiber PAN HTS(T300)	

The final selection of reinforcements for consideration is made qualitatively. The expert system is employed to examine information on matrix/reinforcement compatibility, reinforcement cost and elastic modulus. Table 10.4 lists typical costs and Table 10.5 elastic modulus values retrieved from the databases. Table 10.6 provides constituent compatibility information for the 2219 matrix alloy determined by the expert system. The highest moduli are obviously owned by the most expensive reinforcements and this high cost prevents their consideration. The Al_2O_3 and Al_2O_3-SiO_2 reinforcements possess the highest compatibility but lower cost alternatives have substantially lower elastic moduli. An Al_2O_3 particulate, TiB_2 particulate, Al_2O_3 Saffil short fiber and Al_2O_3-SiO_2 Nextel 310 fiber were selected for comparison given their all-round qualities of acceptable constituent compatibility, high elastic moduli, and moderate cost.

Table 10.4 Reinforcement Costs as Retrieved from Database

Reinforcement	Cost $US/Kg
Al2O3 powder	0.68 - 2.57
B4C powder	20 - 225
Si3N4 powder	25 - 125
TiB2 powder	35 - 65
Saffil Al2O3 fiber	40
Safimax Al2O3	120
Sumitomo Al2O3-SiO2	550
Fiber FP Al2O3	250
Fiberfrax	2.2
Fibermax	37.5
Al2O3 Nextel 312 (3M)	22
Nicalon SiC	350
SNW Si3N4 whisker	735
Avco SiC/C	1000
Berghof SiC/W	280
SCS SiC fiber	2200

Table 10.5 Reinforcement Elastic Moduli

Name of Reinforcement	Elastic Modulus (GPa)
Al2O3 particulate	380 - 450
SiC fiber Nicalon, NL-200	220
Al2O3-Saffil RF Grade ICI	310
SiC fiber SCS-6 Textron	400
SiC fiber SCS-2	400
Al2O3-Safimax ICI fiber	300
Al2O3-Fiber FP DuPont	380
Al2O3 - Nextel 312 3M	154
Al2O3 - Nextel 440 3M	189
Al2O3 whisker	420
B4C whisker	450 - 490
B4C particulate	450
Si3N4 whisker SNW	385
Si3N4 Mitsubishi/Tateho	207
TiB2 fiber	510
TiB2 particulate	510 - 575
TiC particulate	450
Graphite PAN HTS(T300)	228
Al2O3-SiO2 short fiber Fiberfrax	105
C fiber PAN E-34	230
Al2O3-SiO2 fiber Sumitomo	210
Al2O3-SiO2 Fibermax	150
Avco SiC/C	428
Berghof SiC/W	420

Table 10.6. Selected Constituent Compatibility Results

Matrix	Reinforcement	Compatibility	
		Linguistic Variable	String Variable
2XXX	Al_2O_3 particulate	high	Al_2O_3 is nonwetting thus SiO_2 commonly added. Al alloys which contain appreciable amounts of elements whose oxides are more stable than Al_2O_3 will attack the reinforcement(e.g. Li & Mg)
2XXX	B_4C particulate	low	Thermodynamically unstable in molten Al. Complex reaction. Reinforcement coatings necessary for liquid metal processing.
2XXX	Si_3N_4 particulate	low	Si_3N_4 reacts exothermically with liquid Al. Reinforcement coatings necessary for liquid metal processing.
2XXX	TiB_2 particulate	average	TiB_2 resists molten metal attack, especially Al.
2XXX	TiC particulate	low	TiC thermodynamically unstable in molten Al, complex reaction. Reinforcements formed in-situ.
2XXX	C fiber	low	Carbide formation a problem. Fiber surface coatings necessary. Al_4C_3 forms quickly at processing temperatures > 550C degrading fiber.
2XXX	SiC fiber	very low	SiC attacked by molten Al. Fiber surface coatings necessary.

10.1.3 <u>EFFECTIVE MMC PROPERTY PREDICTION</u> The reinforcement volume fraction giving a target coefficient of thermal expansion of 15.8 x 10^{-6}/K, equivalent to the austenitic stainless steel, is determined by the CTE mathematical models. The resulting composites and their predicted values are shown in Tables 10.7 to 10.9. A volume percent of 29 is optimum for both the Al_2O_3 and TiB_2 particulates, 32 v/o for Al_2O_3 Saffil short fiber, and 35 v/o for Al_2O_3 Nextel 310 fiber. The variability in predicted CTE values as a function of geometry is evident.

The effective composite values of elastic modulus and thermal conductivity are next determined. The decision to examine only randomly distributed reinforcements is made for simplicity. Figure 10.1 is a screen view of the elastic modulus input interface for the aluminum 2219 reinforced with 32 v/o Al_2O_3 Saffil short fibers. The input constituent values are those retrieved from the databases by the system. Figure 10.2 is the next screen view showing the resulting model predictions.

The results of the randomly distributed reinforcement model predictions are shown in Table 10.10. It is evident that the benefit of using high aspect ratio reinforcements is lost when a random distribution is used and that the properties of the matrix alloy have a strong influence on the composite properties at these reinforcement levels.

Table 10.7 Particulate Reinforced MMC CTE(x 10^{-6}/K)

Material Designation	Turner Equation	Hashin-Shtrikman Bounds	
		lower[a]	upper
2219/Al2O3/29p	13.8	15.7	17.6
6061/Al2O3/29p	13.8	15.8	17.7
2219/TiB_2/29p	14.1	15.7	17.8
6061/TiB_2/29p	14.2	15.8	17.9

a = Kerner, Mori-Tanaka,Eshelby Method etc.

Table 10.8 Short Fiber Reinforced MMC CTE(x 10^{-6}/K)

Material Designation	**Randomly Distributed**	**Aligned Longitudinal**		**Aligned Transverse**		
	Halpin & Pagano	Halpin Equation	Marom & Weinberg	Halpin Equation	Hashin Strikman Bounds	
2219/Al_2O_3/32sf L/d = 20 (Saffil)	15.8	14.9	14.8	19.5	16.2	17.4
6061/Al_2O_3/32sf L/d = 20 (Saffil)	15.8	15	14.7	19.6	16.3	17.5

Table 10.9 Fiber Reinforced MMC CTE(x10^{-6}/K)

Material Designation	**Randomly Distributed**	**Aligned Longitudinal**			**Aligned Transverse**		
	Craft & Christensen	Schapery	CCM[a]	Eshelby	Schapery	CCM[a]	Eshelby
2219/Al_2O_3/35f (Nextel 310)	15.7	12.6	13	14.8	17.6	17	15.9
6061/Al_2O_3/35f (Nextel 310)	15.7	12.4	12.9	14.7	17.7	17.1	16

a = Composite Cylinders Model

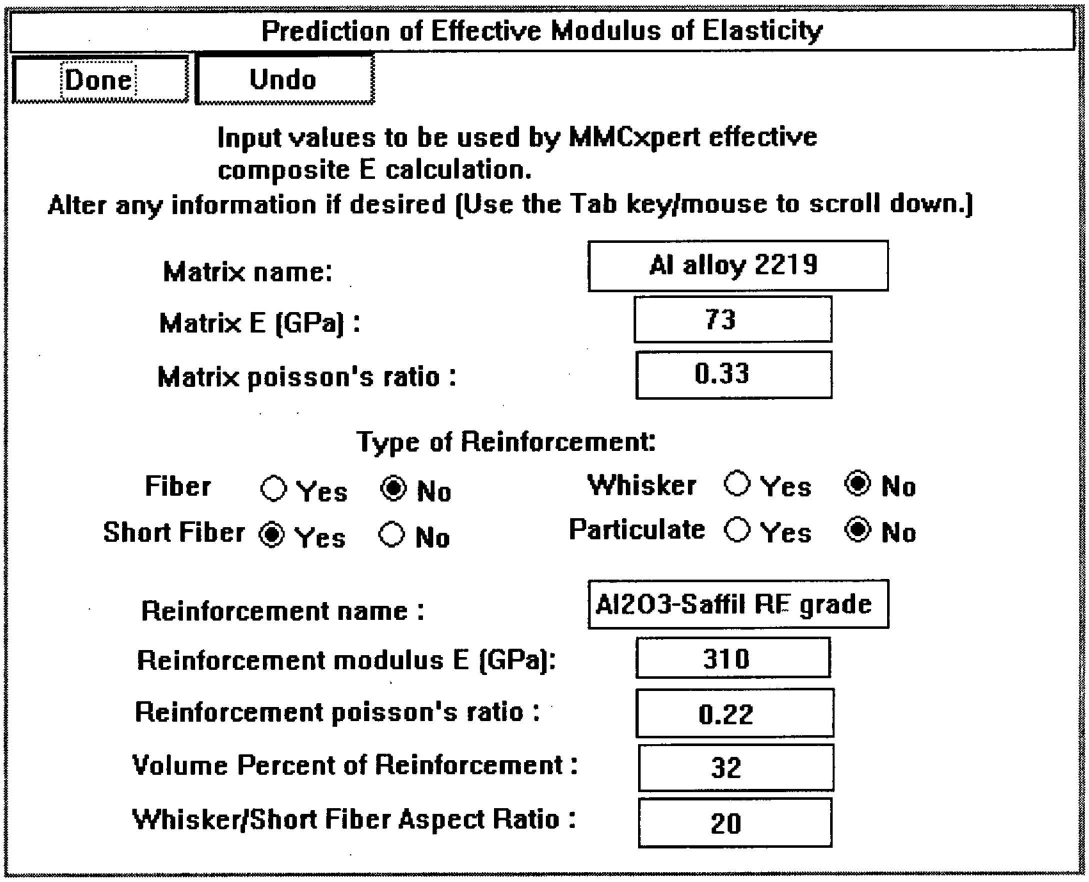


Figure 10.1 Screen View of Input for Effective Modulus Prediction

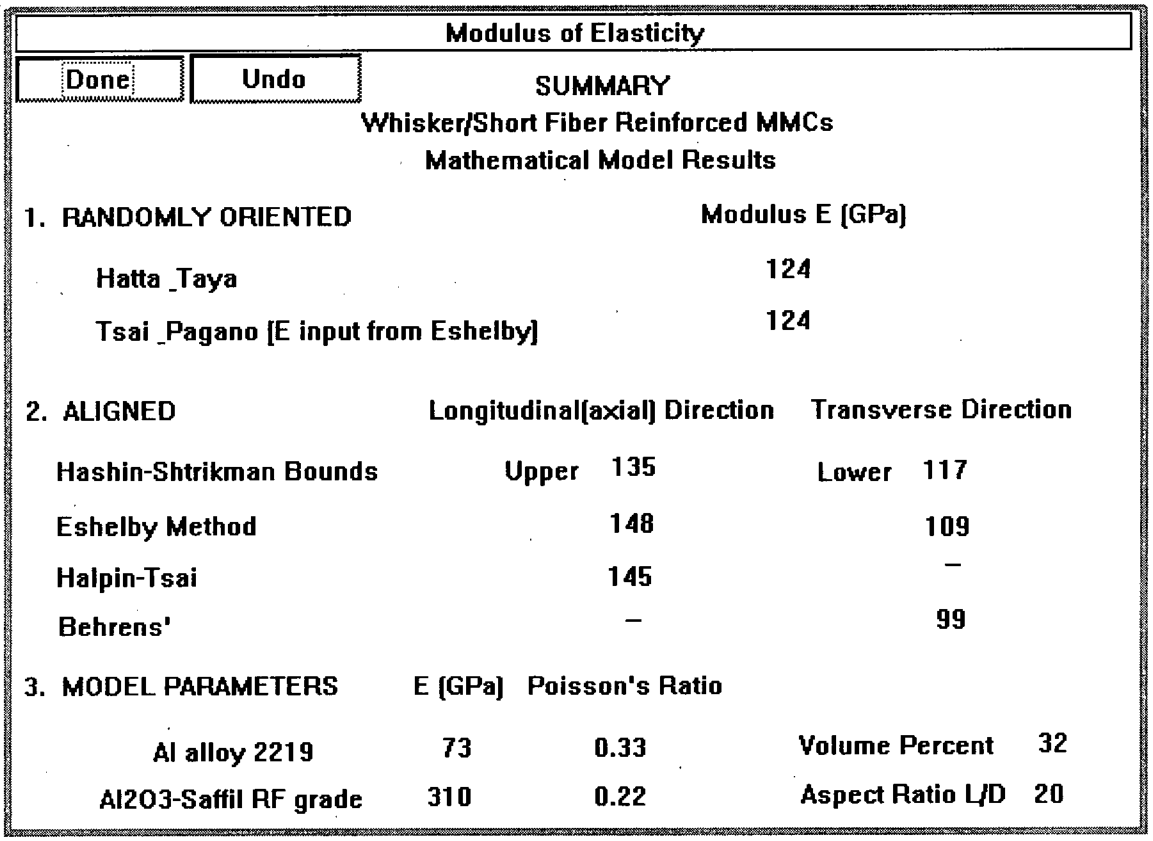


Figure 10.2 Screen View of Effective Modulus Prediction Results

Table 10.10. Thermal Conductivity and Elastic Modulus Predictions for Randomly Oriented Reinforcements

Material Designation	Elastic Modulus E [a] (GPa)	Thermal Conductivity K [b] (W/mK)
2219/Al_2O_3/29p	130	81
2219/TiB_2/29p	140	82
2219/Al_2O_3/32sf L/d = 20(Saffil)	124	76
2219/Al_2O_3/35f (Nextel 310)	96	79
6061/Al_2O_3/29p	126	109
6061/TiB_2/29p	136	109
6061/Al_2O_3/32sf L/d = 20(Saffil)	122	100
6061/Al_2O_3/35f (Nextel 310)	93	106

a = particulate: Paul Model, short fiber: Hatta & Taya, fiber: Christensen & Waals 2D
b = particulate: Lewis & Nielsen, short fiber: Lewis & Nielsen, fiber: Hashin-Shtrikman upper bound

10.1.4 FINAL SELECTION The selection of candidate materials in effect is a trade-off between performance and cost. Manufacturing methods influence both material cost and effective composite properties and must be examined. Figure 10.3 is a screen view of the input interface and Figure 10.4 the hypertext output for 6061/TiB_2/29p. The input descriptions shown in Figure 10.3 have been inferred by the system although the user has the option to change them.

The Al_2O_3 particulate composites are limited to the same processing routes as the TiB_2 particulate composites, namely powder metallurgy and melt infiltration. The system advises that Al_2O_3 is nonwetting in aluminum. SiO_2 additions are typically made and aluminum alloys containing appreciable amounts of elements whose oxides are more stable than Al_2O_3(e.g. Mg & Li) will attack the reinforcement. The system lists Ni, Cu, Ti, B, Ti, TiB, immersion in molten Na and SiO_2 as potential coatings for Al_2O_3 in aluminum. The Al_2O_3 particulates will need coating whereas Saffil Al_2O_3 already contain SiO_2. The prediction of manufacturing routes for short fibers and continuous fibers is not complete thus, the on-line hypertext on manufacturing methods is examined. Al_2O_3 Saffil short fiber composites are currently manufactured using melt infiltration with Saffil preforms. Specific information on the manufacture of composites with Nextel 310 fibers is absent. However, methods listed for fiber composites in general include melt infiltration, fiber/foil diffusion bonding, powder/cloth methods, plasma spray coated fiber winding, and consolidation of matrix coated fibers. The melt infiltration technique is the lowest cost option and produces a random distribution of fibers.

It is evident that the complexity of the comparisons and trade-offs make a clear decision difficult. The final step is to determine what other information is needed. Specific components must be identified and design parameters established to determine the suitability of aligned versus randomly distributed reinforced materials. Material constraints such as reinforcement geometry and shape due to manufacturing methods must be established. The selection of less expensive alloys or reinforcements for comparison may be in order. Consequently, an iterative consultation process is necessary to determine the full potential of alternative MMC candidates.

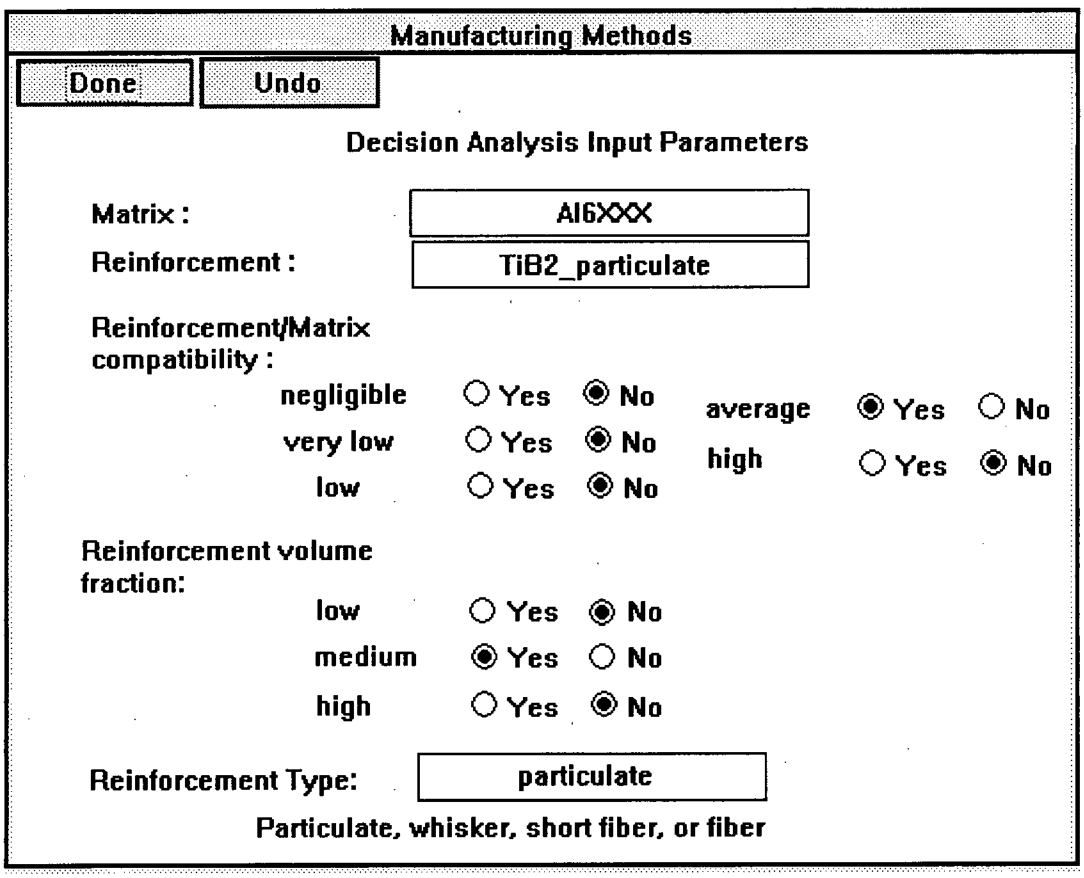


Figure 10.3 Screen View of Input Manufacturing Form

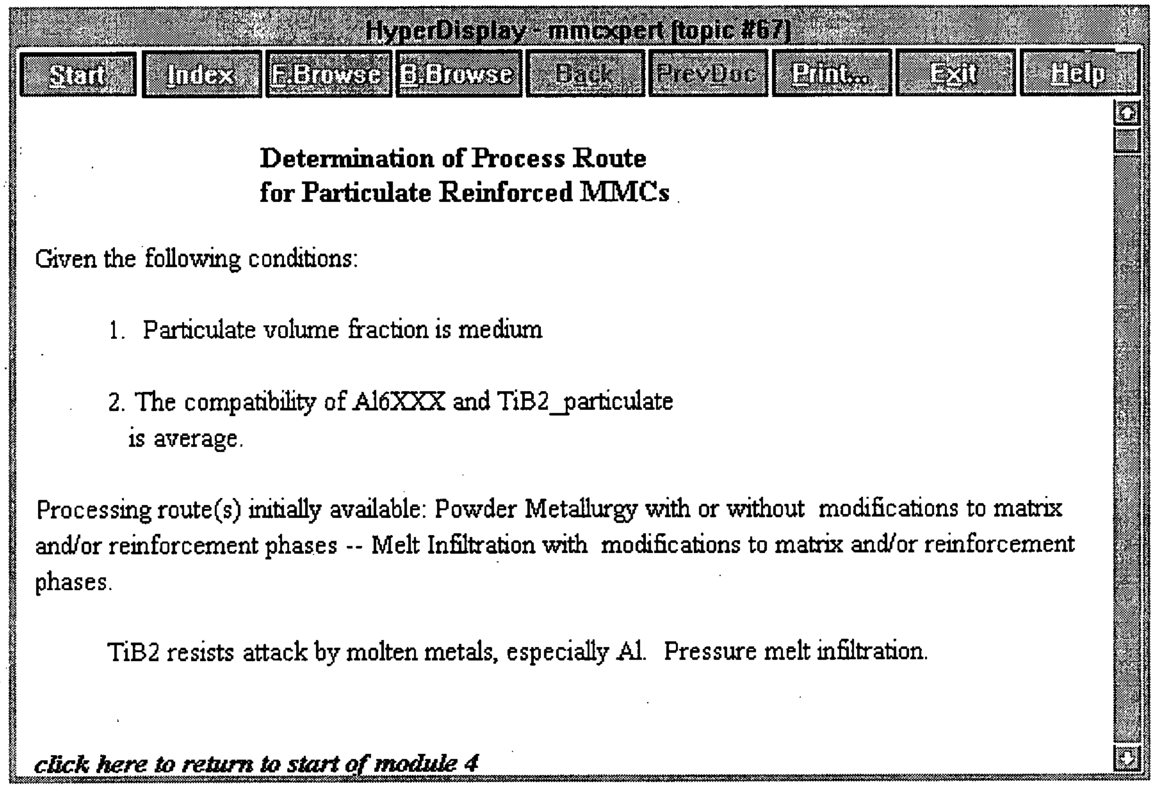


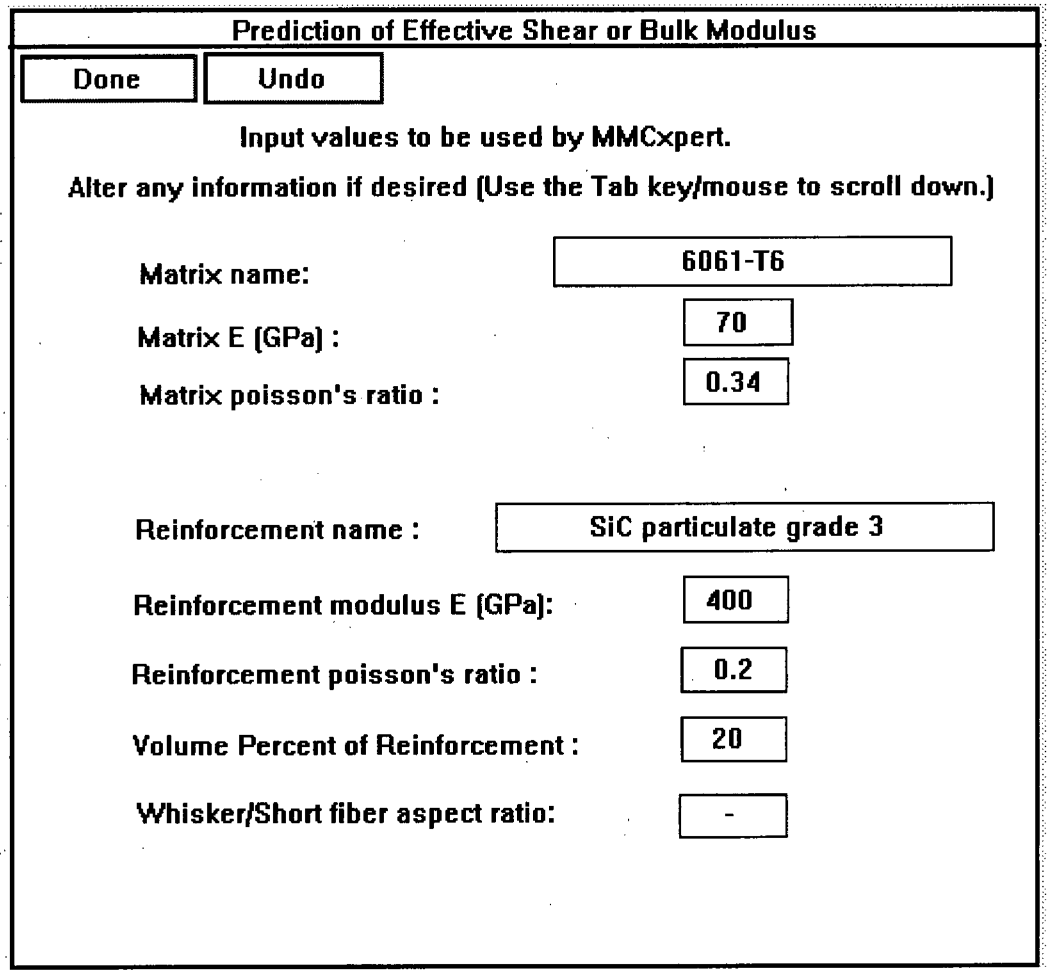
Figure 10.4 Screen View of Hypertext Interface Output

10.2 ACQUISITION OF SHEAR MODULUS FOR 6092/SiC/20p-T6

Advanced Composite Materials manufactures an extrusion product of aluminum 6092 reinforced with 20 volume percent SiC particulates. A design calculation requires the value of its shear modulus. The designer enters the Aluminum Association Designation 6092/SiC/20p-T6 to perform a search of the mechanical properties database. The system returns with **not known** as the value is not contained in the database. A decision to predict a value for this composite's shear modulus is made.

Two database searches are performed to obtain the constituent properties for the matrix alloy and reinforcement. The reinforcement search is successful however 6092 aluminum is not present in the matrix alloy database and the system returns with **Search unsuccessful for this alloy. Try a more general alloy designation**. A new search is performed with an input of material name equal to 6* which retrieves all 6XXX series alloys contained in the database. Properties of alloy 6061 are retrieved as the best alternative.

The designer then selects the shear modulus option in Module 2. The input Form with the constituent properties retrieved from the databases is displayed in Figure 10.5 and Figure 10.6 gives the calculated results. A large difference in value for the upper and lower bound requires further explanation, consequently, the on-line hypertext document is selected. The lower bound is the accurate value in this case and discussed in the topic on **General Modeling** under **Bounds.**


Prediction of Effective Shear or Bulk Modulus

Done | Undo

Input values to be used by MMCxpert.

Alter any information if desired (Use the Tab key/mouse to scroll down.)

Matrix name: 6061-T6

Matrix E (GPa) : 70

Matrix poisson's ratio : 0.34

Reinforcement name : SiC particulate grade 3

Reinforcement modulus E (GPa): 400

Reinforcement poisson's ratio : 0.2

Volume Percent of Reinforcement : 20

Whisker/Short fiber aspect ratio: -

Figure 10.5 Screen View of Shear Modulus Input Form

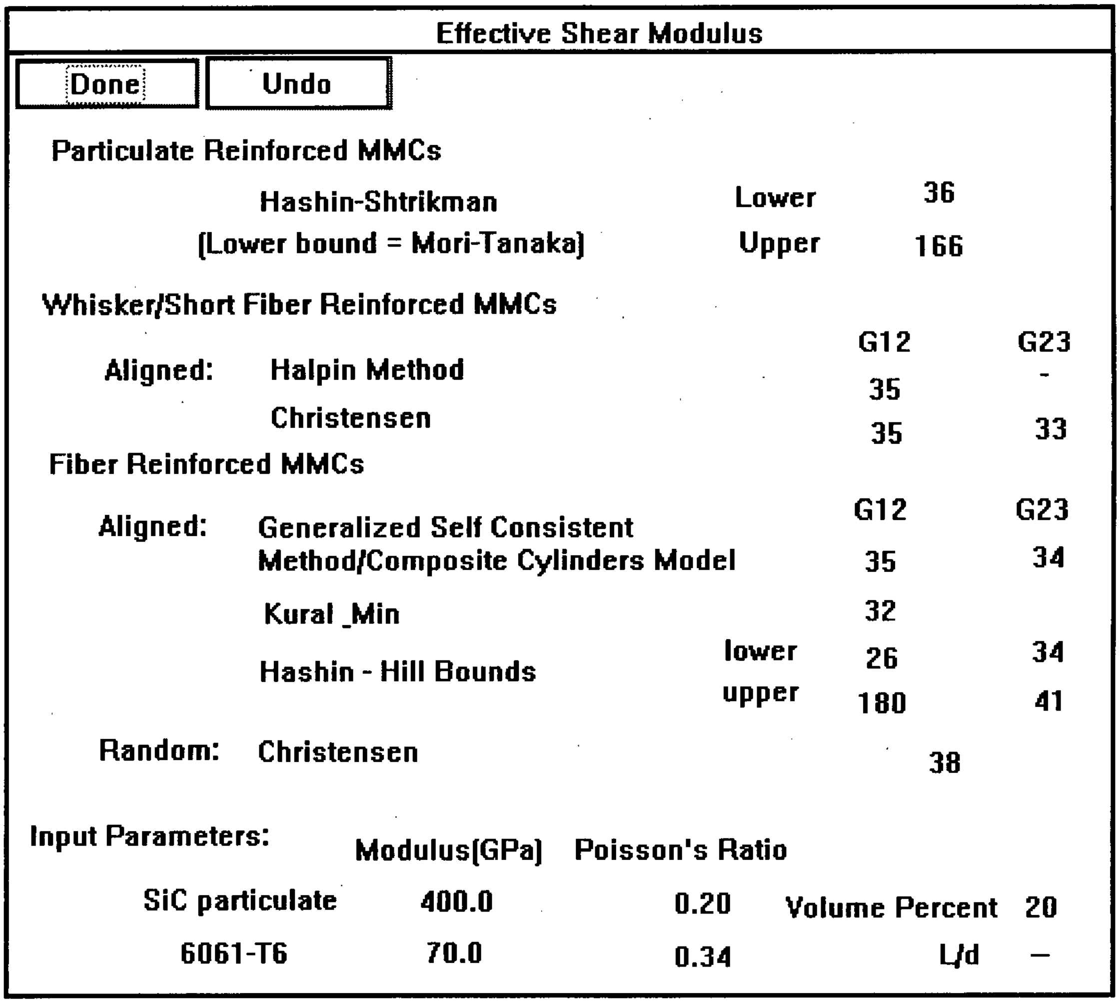


Figure 10.6 Screen View of Shear Modulus Output Form

10.3 EFFECT OF EXTRUSION ON ELASTIC MODULUS

The objective in this consultation is to ascertain whether a MMC reinforced with particulates can achieve an effective elastic modulus of the same order of magnitude as a whisker reinforced MMC after extrusion processing. Extrusion of whisker and particulate reinforced MMCs causes an alignment of the reinforcements in the extrusion direction and a reduction in the average whisker aspect ratio due to damage. A comparison in predicted elastic moduli is undertaken to see whether an extruded particulate MMC can compete with the equivalent whisker MMC.

An aluminum 2009 alloy with elastic modulus of 73 GPa and Poisson's ratio of 0.34 is selected for the matrix. The reinforcement is SiC with an elastic modulus of 400 GPa and Poisson's ratio of 0.2. The volume percent of reinforcement is 25. An extrusion ratio of 10 is utilized resulting in the average whisker aspect ratio being reduced from 30 before to 6 after extrusion.

The elastic modulus option of Module 2 is selected to perform this analysis. A blank Form is displayed to accept user input values. The user inputs constituent elastic modulus values, Poisson's ratios, reinforcement volume percent, and whisker aspect ratio(after extrusion). Both the particulate and whisker reinforcement options are selected.

The aligned longitudinal elastic modulus of the particulate MMC is given by the Nomura & Chou upper bound as 123 GPa and the whisker MMC by the Halpin-Tsai equation as 136 GPa. The longitudinal whisker value is higher however the transverse values returned by the system are the opposite. A value of 115 GPa for the particulate MMC and 103 GPa for the whisker MMC is predicted. Consequently, the transverse value is the limiting factor in this consultation.

CHAPTER 11

CONCLUDING REMARKS AND FUTURE WORK

11.1 CONCLUDING REMARKS

An expert system prototype which aids in the selection and design of metal matrix composites has been developed in this work. An effective and efficient system design was accomplished using the expert system applications tool Comdale/X coupled to an external applications tool Microsoft Excel. The modular design of the system's inferencing structure allows separate lines of reasoning to be followed within each module or jointly with all modules taking part.

The use of databases to store material property data has been successfully completed using Excel database management functions under the control of Comdale/X. The databases and inferencing rules and keyword triplets are designed to allow new data entries and the modification of current entries by the user.

The use of a spreadsheet for mathematical calculations exploits its ability to perform what-if scenarios common in design iteration cycles. The spreadsheet acts as a server to Comdale/X providing effective composite properties on demand. In addition, the spreadsheet contains graphical representations of the models and these can be accessed as an additional tool in examining the effects of altering material design parameters.

The inclusion of experience-based information and the inferencing ability to determine constituent compatibility is fundamental to the success of the matrix/reinforcement selection module. Matrix/reinforcement compatibility controls manufacturing and material performance. This information is critical to making selection decisions and has been successfully represented using linguistic variables in this system.

The incorporation of manufacturing techniques and their effect on metal matrix composite properties is also an important module. Information is provided which advises on the limitations of many manufacturing routes and ensuing metal matrix composite design. The determination of appropriate manufacturing methods for new particulate reinforced metal matrix composites is an important tool in the design process.

The last module contains the on-line hypertext document which provides easy access to materials information. This information can be used in support of information provided by the system's decision-making or to augment it. The navigation through the hypertext document has been designed to be as efficient as possible and is structured to provide information in a top down manner with general information at the top and more specific pieces available at the bottom.

Finally, the customized user interface brings the whole system together. The dynamic hypertext allows immediate response to a user action. The use of links allows the user to follow many lines of reasoning or just one using all of the knowledge available in the system. The three consultation sessions presented demonstrate the potential of the expert system in a design environment and its value to metal matrix composite design.

11.2 FUTURE WORK

The first task necessary in any future work is the completion of the formal evaluation with prototype field testing. The prototype and a users' questionnaire should be sent to a number of design organizations to obtain user feedback and identify any further programming errors.

In terms of building the system, the manufacturing module needs to be completed to predict appropriate whisker, short fiber, and fiber reinforced metal matrix composite methods. Information has been gathered and constraints identified such that only the decision tables need to be completed and the computer code written. The incorporation of a knowledge link between module 2, effective property prediction, and module 3, compatibility determination, needs to be made. This would eliminate the need to repeat the input of constituent material names by the user.

The addition of a strength prediction module is also a priority. Mathematical models are available which are relatively accurate for predicting ultimate tensile strength but methods to predict yield strength are inadequate. Analytical and numerical techniques have proven to be inaccurate and other techniques such as neural networks may be the solution. Yield strength is a widely measured property thus significant amounts of data are available in which patterns can be identified. Using appropriate inputs such as constituent yield strength, reinforcement volume percent, aspect ratio and alignment in a neural network may prove to be a simple and effective method.

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APPENDIX A

METAL MATRIX COMPOSITES IN DATABASE

Material Designation	Manufacturer/Source of Data	Qualifying Information
6061/SiC/40f as fabricated SCS-2	Textron	pultruded tube 2.54cm dia x 5 plies (0.111cm)
6061/SiC/40f annealed SCS-2	Textron	pultruded tube 2.54cm dia x 5 plies (0.111cm)
6061/SiC/40f -T6 SCS-2	Textron	pultruded tube 2.54cm dia x 5 plies (0.111cm)
Ti-6-4/SiC/40f SCS-6	Textron	preliminary design data
Ti-6-4/SiC/35f SCS-6	Textron	hot pressed
6061/SiC/48f SCS-2	Textron	hot molded
2009/SiC/15w-T8	Advanced Composite Materials	proposed design data, sheet
2009/SiC/30p-T6	Advanced Composite Materials	SXA optical grade
6092/SiC/20p--T6	Advanced Composite Materials	extrusions
6091/SiC/25p-T6	Advanced Composite Materials; JOM, Jan. 1993, p. 26	extrusions
2009/SiC/15p-T6	Advanced Composite Materials	typical properties, extrusions
2009/SiC/20p-T6	Advanced Composite Materials	typical properties, extrusions
2009/SiC/25p-T6	Advanced Composite Materials	typical properties, extrusions
6013/SiC/15p-T6	Advanced Composite Materials	typical properties, extrusions
6013/SiC/20p-T6	Advanced Composite Materials	typical properties, extrusions

6013/SiC/25p-T6	Advanced Composite Materials	typical properties, extrusions
2009/SiC/20p-T6	Advanced Composite Materials	typical properties, forgings
2009/SiC/25p-T6	Advanced Composite Materials	typical properties, forgings
2009/SiC/15w-T6	Advanced Composite Materials	typical properties, forgings
6061/SiC/15p	Eng Mats Hndbk: Composites vol. 1	
6061/SiC/20p	Eng Mats Hndbk: Composites vol. 1	
6061/SiC/25p-T6	DWA C. Zweben(1992), JOM, Jul, p.15 Eng Mats Hndbk: vol. 1	
6061/SiC/30p-T6	Advanced Composite Materials	typical properties, forgings
6061/SiC/35p	Eng Mats Hndbk: Composites vol. 1	
6061/SiC/40p-T6	Advanced Composite Materials	SXA instrument grade
6061/SiC/55p-T6	C. Zweben(1992), JOM, Jul, p.15 (source DWA)	
6061/SiC/70p-T6	C. Zweben(1992), JOM, Jul, p.15 (source DWA)	
6061/SiC/20w-T6	Advanced Composite Materials	typical properties, forgings
380/SiC/10p-F	Duralcan F3D.10S-F	typical properties, die castings
380/SiC/20p-F	Duralcan F3D.20S-F	typical properties, die castings
380/SiC/10p-O	Duralcan F3D.10S-O	typical properties, die castings
380/SiC/10p-T5	Duralcan F3D.10S-T5	typical properties, die castings
380/SiC/20p-O	Duralcan F3D.20S-O	typical properties, die castings
380/SiC/20p-T5	Duralcan F3D.20S-T5	typical properties, die castings
360/SiC/10p-F	Duralcan F3N.10S-F	typical properties, corr. resistant applications
360/SiC/10p-O	Duralcan F3N.10S-O	typical properties, corr. resistant applications
360/SiC/10p-T5	Duralcan F3N.10S-T5	typical properties, corr. resistant applications
360/SiC/20p-F	Duralcan F3N.20S-F	typical properties, corr. resistant

		applications
360/SiC/20p-O	Duralcan F3N.20S-O	typical properties, corr. resistant applications
360/SiC/20p-T5	Duralcan F3N.20S-T5	typical properties, corr. resistant applications
6061/Al2O3/10p-T6	Duralcan W6A.10A-T6	typical properties, extrusion 20:1, room temp applications
6061/Al2O3/15p-T6	Duralcan W6A.15A-T6	typical properties, wrought products, room temp applications
6061/Al2O3/20p-T6	Duralcan W6A.20A-T6	typical properties, wrought products, room temp applications
6061/Al2O3/20p-T6	Comalco Comral-85	J.Mats Sc, 29, p.3906 regression from curves
339/SiC/10p-F	Duralcan F3K.10S-F	typical properties, permanent mold, elevated temp use
339/SiC/10p-O	Duralcan F3K.10S-O	typical properties, permanent mold, elevated temp use
339/SiC/10p-T5	Duralcan F3K.10S-T5	typical properties, permanent mold, elevated temp use
339/SiC/10p-T6	Duralcan F3K.10S-T6	typical properties, permanent mold, elevated temp use
339/SiC/20p-F	Duralcan F3K.20S-F	typical properties, permanent mold, elevated temp use
339/SiC/20p-O	Duralcan F3K.20S-O	typical properties, permanent mold, elevated temp use
339/SiC/20p-T5	Duralcan F3K.20S-T5	typical properties, permanent mold, elevated temp use
339/SiC/20p-T6	Duralcan F3K.20S-T6	typical properties, permanent mold, elevated temp use
357/SiC/20p	Cercast (Duralcan)	investment castings
6092/SiC/17.5p-T6	DWA	preliminary design, extrusions t=0.5 in
6092/SiC/25p-T6	DWA	preliminary design, extrusions t=0.5 in

ZC71/SiC/12p	Magnesium Elektron	preliminary data
2014/Al2O3/15p-T6	Duralcan W2A.15A-T6	stuctural shapes & forgings, med - high strength composites
2014/Al2O3/10p-T6	Duralcan W2A.10A-T6	stuctural shapes & forgings, med - high strength composites
2014/Al2O3/20p-T6	Duralcan W2A.20A-T6	stuctural shapes & forgings, med - high strength composites
6061/SiC/20w-T6	W.R. Mohn et al, J. Mats Eng, 10(3),p.225	1/2 in rod
6061/SiC/20w-T6	W.R. Mohn et al, J. Mats Eng, 10(3),p.225	2.54cm OD 1.25mm t tube
2124/SiC/20w-T6	W.R. Mohn et al, J. Mats Eng, 10(3),p.225	1.27cm xsection bar
6061/SiC/40p-T6	W.R. Mohn et al, J. Mats Eng, 10(3),p.225	
2124/SiC/17.8p-T4	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from tables, low DOB
2124/SiC/20p-T4	D. Lloyd(1994), Int Mats Rev, 39(1), p.1 T.S. Srivatsan et al, J Mats Sc, 28, p. 611(1993)	from tables, low DOB [exp.]
2124/SiC/25p-T4	D. Lloyd(1994), Int Mats Rev, 39(1), p.1 T.S. Srivatsan et al, J Mats Sc, 28, p. 611(1993)	from tables, low DOB [exp.]
2124/SiC/30p-T6	W.R. Mohn et al, J. Mats Eng, 10(3),p.225 T.S. Srivatsan et al, J Mats Sc, 28, p. 611(1993)	from tables, low DOB [exp.]
2124/SiC/40p	Eng Mats Hndbk: Composites vol. 1	from tables, low DOB
6061/SiC/20w-T6	Nardone et al, Scripta Met, 20, p.43 , UTS eqn-R.B. Bhagat et al, ICCM VIII	ARCO material
6061/SiC/20w	Nardone et al, Scripta Met, 20, p.43	aligned, extrusion
6061/SiC/20w	A. Wolfenden et al(1988), ASTM STP 964, p.207	plate
Ti-6-4/SiC/35-40f SCS-6	Textron	developmental stage, typical properties
Ti-6-4/SiC/35-40f SCS-9	Textron	developmental stage, typical properties
Ti-15-3-3-3/SiC/35-40f SCS-6	Textron	developmental stage, typical

		properties
Ti-15-3-3-3/SiC/35-40f SCS-9	Textron	developmental stage, typical properties
Beta21S/SiC/35-40f SCS-6	Textron	developmental stage, typical properties
Ti-14-21/SiC/35-40f SCS-6	Textron	developmental stage, typical properties
ZC71/SiC/12p-T6 9 um grit	T.E. Wilks, Adv Mats Proc, 8, p.27	extruded
AZ91/Al2O3/20sf as cast Saffil	K. Purazrang et al, Composites, 22(6), p.456	preform die casting
AZ91/Al2O3/25sf as cast Saffil	K. Purazrang et al, Composites, 22(6), p.456	preform die casting
AZ91/Al2O3/25sf saffil(380 C heat treat)	K. Purazrang et al, Composites, 22(6), p.456	preform die casting
AZ91/Al2O3/25sf saffil(420 C heat treat)	K. Purazrang et al, Composites, 22(6), p.456	preform die casting
359/SiC/20p-T6	Duralcan F3K.10S	
2618/SiC/12p-T6	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
7075/SiC/15p-T651	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
7049/SiC/15p-T6	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
7090/SiC/20p-T6	D. Lloyd(1994), Int Mats Rev, 39(1), p.1 [Eng Mats Hndbk: Composites vol. 1]	from table, low DOB
7090/SiC/25p	Eng Mats Hndbk: Composites vol. 1	from table, low DOB
7090/SiC/30p-T6	Eng Mats Hndbk: Composites vol. 1	from table, low DOB
7090/SiC/35p	Eng Mats Hndbk: Composites vol. 1	from table, low DOB
7090/SiC/40p	Eng Mats Hndbk: Composites vol. 1	from table, low DOB
8090/SiC/13p-T4	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
8090/SiC/13p-T6	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB

8090/SiC/17p-T4	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
8090/SiC/17p-T6	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
201/TiC/20p-T7	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
356/SiC/10p-T61	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
356/SiC/15p-T61	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
356/SiC/20p-T61	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
AZ91/SiC/9.4p	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
AZ91/SiC/15.1p	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
AZ61/SiC/20p	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
2124/SiC/15p	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	from table, low DOB
2024/G/50f (81.3 um)	Handbook of Ceramics and Composites	
2024/G/60f (142 um)	Handbook of Ceramics and Composites	
6061/SiC/50f	Handbook of Ceramics and Composites	
201/FP/50f	Handbook of Ceramics and Composites	
6061/B on W/50f (142 um)	Handbook of Ceramics and Composites	
201/G T50/30f	Handbook of Ceramics and Composites	
201/G T50/49f	Handbook of Ceramics and Composites	
201/G GY 70/34f	Handbook of Ceramics and Composites	
201/G GY70/30f	Handbook of Ceramics and Composites	
AZ31/G HM pitch/38f	Handbook of Ceramics and Composites	

Ti/BorSiC/45f	Handbook of Ceramics and Composites	
Ti/SiC/35f	Handbook of Ceramics and Composites	
Al/SiC/20w	Handbook of Ceramics and Composites	
Ti/B4C on B/38f	Handbook of Ceramics and Composites	
6061/SiC/5p-T6	H.J. Kim et al(1992), Mats Sc & Eng A, A154, p.35	
6061/SiC/10p-T6	H.J. Kim et al(1992), Mats Sc & Eng A, A154, p.35	
6061/SiC/20p-T6	H.J. Kim et al(1992), Mats Sc & Eng A, A154, p.35	
6061/SiC/30p-T6	H.J. Kim et al(1992), Mats Sc & Eng A, A154, p.35	
M124R/Al2O3-SiO2/20f (fiberfrax)	A. Afonso & G. Ferran, SAE 910632	
M124R/Al2O3/20f (saffil)	A. Afonso & G. Ferran, SAE 910632	
M124R/SiC/20w	A. Afonso & G. Ferran, SAE 910632	
X2080/SiC/15p-T4	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
X2080/SiC/15p-T6	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
X2080/SiC/15p-T8	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
X2080/SiC/20p-T4	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
X2080/SiC/20p-T6	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
X2080/SiC/20p-T8	W.H. Hunt et al, SAE 910834	P/M extrusion(Al-3.8Cu-1.8Mg-0.2Zr)
7091/SiC/15p	Eng Mats Hndbk: Composites vol. 1	
7091/SiC/20p	Eng Mats Hndbk: Composites vol. 1	
7091/SiC/25p-T6	Eng Mats Hndbk: Composites vol. 1	

7091/SiC/30p	Eng Mats Hndbk: Composites vol. 1	
7091/SiC/40p	Eng Mats Hndbk: Composites vol. 1	
8009/SiC/5p	M.S. Zedalis, JOM, Aug 91, p. 29 (Allied Signal)	P/M, Vac Hot Pressed, extruded to bars, rolled to sheet 0.23 cm gauge, SiC- Sohio grade 1500 green SiCp ave 3 um
8009/SiC/10p	M.S. Zedalis, JOM, Aug 91, p. 29 (Allied Signal)	P/M, Vac Hot Pressed, extruded to bars, rolled to sheet 0.23 cm gauge, SiC- Sohio grade 1500 green SiCp ave 3 um
8009/SiC/11p	M.S. Zedalis, JOM, Aug 91, p. 29	P/M, extruded, rolled, sheet (ave. dia 3 um)
8009/SiC/15p	M.S. Zedalis, JOM, Aug 91, p. 29 (Allied Signal)	P/M, Vac Hot Pressed, extruded to bars, rolled to sheet 0.23 cm gauge, SiC- Sohio grade 1500 green SiCp ave 3 um
5456/SiC/8w-W	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
5456/SiC/20w-W	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
5456/SiC/8p-W	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
5456/SiC/20p-W	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
2124/SiC/8w-T4	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/8w-T6	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/8w-T8	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)

2124/SiC/8w-O	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/20w-T4	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/20w-T6	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/20w-T8	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/20w-O	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCw-F9 grade dia= 0.52 um L/d=26 (aves)
2124/SiC/8p-T4	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
2124/SiC/8p-T8	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
2124/SiC/20p-T4	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
2124/SiC/20p-T8	J.M. Papazian & P.N. Adler(1990), Metall Trans A, 21A, p.401	P/M, extruded, ARCO material, SiCp- Carborundum grade 3, alpha SiC geometric shapes < 3 um
356/SiC/20p	D. Lloyd(1994), Int Mats Rev, 39(1), p.1	
356/SiC/10p-T61	Duralcan F3A.xxs-T61, D.O. Kennedy, Adv. Mats. Proc., 6, p.42(1991)	
356/SiC/15p-T61	Duralcan F3A.xxs-T61, D.O. Kennedy, Adv. Mats. Proc., 6, p.42(1991)	
356/SiC/20p-T61	Duralcan F3A.xxs-T61, D.O. Kennedy, Adv. Mats. Proc., 6, p.42(1991)	
356/SiC/10p-T61	Duralcan F3A.10S-T61	permanent mold casting, versatile, general purpose for room temp

		applications
356/SiC/10p-T61	Duralcan F3A.10S-T61	investment cast, versatile, general purpose for room temp applications
356/SiC/10p-T61	Duralcan F3A.10S-T61	sand cast, versatile, general purpose for room temp. applications.
356/SiC/15p-T61	Duralcan F3A.15S-T61	permanent mold casting, versatile, general purpose for room temp applications
356/SiC/15p-T61	Duralcan F3A.15S-T61	investment cast, versatile, general purpose for room temp applications
356/SiC/15p-T61	Duralcan F3A.15S-T61	sand cast, versatile, general purpose for room temp. applications.
356/SiC/20p-T61	Duralcan F3A.20S-T61	permanent mold casting, versatile, general purpose for room temp applications
356/SiC/20p-T61	Duralcan F3A.20S-T61	investment cast, versatile, general purpose for room temp applications
356/SiC/20p-T61	Duralcan F3A.20S-T61	sand cast, versatile, general purpose for room temp. applications.
356/SiC/10p-T6	Duralcan F3S.10S-T6	permanent mold casting, foundry friendly general purpose for room temp. applications.
356/SiC/20p-T6	Duralcan F3S.20S-T6	permanent mold casting, foundry friendly general purpose for room temp. applications.
Al-4.5Cu/SiC/6sf (Nicalon)	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	Squeeze casting, chopped fibers vortex mixing)
Al-4.5Cu/SiC/10sf (Nicalon)	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	Squeeze casting, chopped fibers vortex mixing)
Al-2Cu-1.2Mg-0.9Ni-1.2Fe/Al2O3/20sf-T6 (saffil)	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	squeeze casting
Al-3Cu-3Mg/Al2O3/20sf (saffil)	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	squeeze casting
Al-4.5Cu-3Mg/Al2O3/20sf (saffil)	R.B. Bhagat, Casting Fiber-	squeeze casting

	Reinforced Metal Matrix Composites, 1991	
2014/SiC/15p-T6	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	cast, extruded
6061/SiC/10p-T6	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	cast, extruded
6061/SiC/20p-T6	R.B. Bhagat, Casting Fiber-Reinforced Metal Matrix Composites, 1991	cast, extruded
6061/SiC/10p-T4 (3 um beta SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/SiC/10p-T6 (3 um beta SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/SiC/14p-T4 (3 um alpha SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/SiC/14p-T6 (3 um alpha SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/Sic/17p-T6 (3 um alpha SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/SiC/11.5p (single crystal alpha SiC)	Y.W. Wu & E.J. Lavernia, JOM, Aug. 1991, p. 16	spray atomization & codeposition
6061/SiC/28p-T4 (15 um alpha SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/SiC/28p-T6 (15 um alpha SiCp)	I.A. Ibrahim et al, Conf. Mg & Al Alloys,	spray atomization & codeposition, extruded
6061/B/48f	Metals Handbook, vol. 2, 10th ed., 1990	
6061/SiC/47f (SCS-2)	Metals Handbook, vol. 2, 10th ed., 1990	
6061/C/43.5f (Gr P100)	Metals Handbook, vol. 2, 10th ed., 1990	
Al-2Li/Al2O3/55f (FP)	Metals Handbook, vol. 2, 10th ed., 1990	
Al-4Cu-1.5Mg/SiC/20p	Metals Handbook, vol. 2, 10th ed., 1990	12.7 mm plate, ACMC material
Al-4Cu-1.5Mg/SiC/15w	Metals Handbook, vol. 2, 10th ed., 1990	1.8 - 3.2 mm sheet, ACMC material

8090/SiC/12p	J. White et al, Aluminium-Lithium Alloys V(1989), p. 1635	spray cast and extruded
8090/B4C/11p	J. White et al, Aluminium-Lithium Alloys V(1989), p. 1635	spray cast and extruded
Mg-6Zn/SiC/15p (3.2 um)	Adv. Mats. Proc., 11, p. 71(1990)	powder metallurgy
Mg-6Zn/SiC/17p (10-15 um)	Adv. Mats. Proc., 11, p. 71(1990)	ingot metallurgy
Mg-6Zn/SiC/14p (10-15 um)	Adv. Mats. Proc., 11, p. 71(1990)	rapid solidification process
356/SiC/15p (10-15 um)	Adv. Mats. Proc., 11, p. 71(1990)	rapid solidification process
356/SiC/15p (10-15 um)	Adv. Mats. Proc., 11, p. 71(1990)	ingot metallurgy
2124/SiC/15w-T6	Y. Kim et al, Metall. Trans. A, 23A, p.2589 (1992) ACMC material	powder metallurgy, extruded
2124/SiC/20w-T4	P.L. Boland et al, ASTM STP 964, p. 346(1988)	hot rolled, tested in whisker axial direction
2124/SiC/25p-T4 (ave. 3 um, L/d=2)	R. Da Silva et al, Conference Proceedings: Riso 88, p.333	powder metallurgy, extruded
7091/SiC/5p-T7 (ave. 3 um, L/d=2)	R. Da Silva et al, Conference Proceedings: Riso 88, p.333	powder metallurgy, extruded
7091/SiC/10p-T7 (ave. 3 um, L/d=2)	R. Da Silva et al, Conference Proceedings: Riso 88, p.333	powder metallurgy, extruded
7090/SiC/25p-T7 (ave. 3 um, L/d=2)	R. Da Silva et al, Conference Proceedings: Riso 88, p.333	powder metallurgy, extruded
7090/SiC/25p-T6	P.L. Boland et al, ASTM STP 964, p. 346(1988)	hot rolled, tested in final roll direction
6061/SiC/15w	J.Awerbuch et al, ASTM STP 964, p. 121 (1988)	powder metallurgy, extruded ER=10:1
6061/SiC/25w	J.Awerbuch et al, ASTM STP 964, p. 121 (1988)	powder metallurgy, extruded ER=10:1
6061/SiC/25w	J.Awerbuch et al, ASTM STP 964, p. 121 (1988)	powder metallurgy, extruded ER=5:1

APPENDIX B

REINFORCEMENT MATERIALS IN DATABASE

Name	
Al2O3 whisker	Si3N4 Mitsubishi/Tateho
Al2O3 particulate	W fiber
SiC fiber ceramic grade Nicalon	TiB2 fiber
SiC fiber Nicalon, NL-200 Nippon Carbon	TiB2 particulate
SiC - Nicalon NLM-202	TiC particulate
Al2O3-Saffil RF Grade ICI short fiber	TiC bulk
SiC - Tokawhisker	SiC particulate commercial
SiC whisker TWS-100 Tokawhisker	SiC particulate high purity
SiC whisker TWS-200 Tokawhisker	SiC particulate grade 3
SiC whisker TWS-300 Tokawhisker	SiC particulate
SiC whisker TWS-400 Tokawhisker	AlN particulate
SiC fiber SCS-6 Textron	AlN-4Y2O3
SiC fiber SCS-2	Graphite PAN fiber HMS
B- on W Textron	Graphite PAN HTS(T300)
B- on W Avco	Graphite pitch P-120 (Amoco Thornel P-120) MP type
B- on C Textron	Graphite rayon T50
Al2O3-Safimax ICI fiber	Al2O3-SiO2 short fiber Fiberfrax Sohio Carborundum
Al2O3-Fiber FP DuPont	SiC fiber - C/TiB2 coated BP
Al2O3 - Nextel 312 3M	Graphite pitch E-120 DuPont
Al2O3 - Nextel 440	Graphite pitch E55
Al2O3 - Nextel 480	Graphite pitch E100
Al2O3 Nextel 610 fiber	Celion GY-70 BASF PAN type C fiber
B- W core, SiC coated (Borsic) CTI	Graphite IM6
B - B4C coated	Graphite IM6
Al2O3 whisker	C Fiber P100

Name	
BeO whisker	Carbon fiber
B4C whisker	C fiber PAN E-34
B4C particulate	C fiber PAN E-75
C - graphite whisker	C fiber vapour phase
SiC whisker	Alumina (96%) monolithic
SiC whisker TWS-100 Tokawhisker	monolithic, polycrystalline AlN particulate
SiC whisker TWS-200 Tokawhisker	monolithic, polycrystalline AlN particulate
SiC whisker TWS-300 Tokawhisker	BeO particulate
SiC whisker TWS-400 Tokawhisker	B4C particulate
SiC monolithic	TiB2 particulate
SiC fiber on W	C fiber PAN type T-50 Amoco
SiC fiber on C	C fiber Thornel P100 (MP type)
Avco SiC/C	Al2O3-SiO2 fiber Sumitomo
Berghof SiC/W	Al2O3-SiO2 Fibermax Sohio Carborundum
Tyranno SiC fiber (O + Ti)	Hi Mod grafil C fiber Courtaulds
SiC fiber HPZ Dow Corning/Celanese	Hi T.S. grafil C fiber Courtaulds
NX Si3N4 whisker	Torayca T300 C fiber
Si3N4 whisker SNW	Torayca M40 C fiber

APPENDIX C

MATRIX ALLOYS IN DATABASE

Name	
Aluminum Alloys	**Titanium Alloys**
201	Al-3Cu-3Mg
201-T6	Commercially Pure Ti
6061-T6	Ti-3Al-2.5V
356-T6	Ti-6Al-4V Textron material
357-T6	Ti-6Al-4V BP material
2014-T6	Ti-10V-2Fe-3Al
6061-T4 spray cast	Ti-15V-3Cr-3Al-3Sn
6061-T6 spray cast	Ti-3Al-8V-6Cr-4Mo-4Zr
339	Beta-21S
332	Ti-24Al-11Nb
356	
2124-T6	
2024-T4	
7005	
7050-T6	**Magnesium Alloys**
7050-T74	ZC71
7075-T6	AS41
8090	AZ91
M124-R	Commercially Pure Mg
6013	AZ31B
6090	Mg-6Zn
5052	QE22
Al-2Cu-1.2Mg-0.9Ni-1.2Fe	ZC63
Al-7Si-0.6Mg-T6	
Al-4.5 Cu	
8009	**pure Cu**
2124-T4	
2124-T6	
2124-T8	
2219-T87	
5083-O	
Al-2Cu-1.2Mg-0.9Ni-1.2Fe	
Al-7Si-0.6Mg-T6	
Al-4.5 Cu	