Concurrent Materials and Process Selection in Conceptual Design

Stephen D. Kleban

Sandia National Laboratories
Albuquerque, NM 87185
sdkleba@sandia.gov

Abstract

The sequential manner in which materials and processes for a manufactured product are selected is inherently less than optimal. Designers' tendency to choose processes and materials with which they are familiar exacerbate this problem. A method for concurrent selection of materials and a joining process based on product requirements using a knowledge-based, constraint satisfaction approach is presented.

Introduction

It is estimated that decisions made in the design phase determine as much as 70 or 80 percent of the cost of a manufactured product (Boothroyd, Dewhurst, and Knight 1991). Most often these decisions are made based on the designers' familiarity with a small set of materials and processes. The product designer commonly selects a material they are familiar with, and then some time later, the process designer selects a process that they are familiar with or that is available in-house. This restrictive sequential procedure of choosing a material first in isolation without consideration of the impacts of the processes results in a far less than optimal solution. In addition, new materials and processing techniques emerge constantly and even focused specialists have difficulty keeping current.

In conceptual design, the designer should be open to a wide variety of materials and processes to explore alternatives while meeting the constraints imposed by performance requirements, production schedule, and deployment service conditions. With this freedom, the designer could better address today's demands of higher performance, lower costs, and faster production rates. There are several projects that address materials and shaping process selection (Dargie, Parmeshwar, and Wilson 1982, Boothroyd, Dewhurst, and Knight 1991, Abel Edwards, and Ashby 1994) but none that specifically address the joining processes. This paper addresses the issues with material and joining process selection and describes the knowledge-based Materials and Joining Advisor (MJA).

Materials and Joining Advisor Overview

To address the limitations of sequential, isolated materials and joining process selection, the Materials and Joining Advisor was conceived, designed, and built by a team of materials scientists, joining process engineers, and computer scientists. The success of the Welding Advisor (Kleban 1996) demonstrated the advantages of thoroughness, repeatability, and improvability by using a knowledge-based approach for complex problem solving in manufacturing. The MJA solves a simultaneous constraint satisfaction problem regarding the requirements for each piece part and the requirements for the joint and deployed service conditions.

There are numerous commercial tools for material selection based solely on performance requirements. Unfortunately, they tend to be specialized for a single material group such as metals or polymers. Many of them do not have reliable search mechanisms because much of the data are in text format (not numeric) or the data are simply incomplete. However, the Cambridge Material Selection System (CMS) (Granta 1994) has a database that is complete and includes the material categories: metals, ceramics, polymers, natural, and composites. It contains general, electrical, mechanical, and thermal data (thirty property values) on every material. Since no data are missing, a material will not be omitted for not containing data on a property that is included in the criteria for a search.

The basic mechanism for the MJA is a three step procedure that specifies the requirements for the first piece part, specifies the requirements for the second piece part, and specifies the requirements for joint and deployed service conditions. Figure 1 shows the input screen for specifying the functional requirements for the material of a piece part. Notice that the requirements are for "Piece Part 1" as indicated by the button at the top of the screen. The user selects a property and a histogram is displayed with the range of values for that property on the x-axis, and the number of materials on the y-axis. The user can either type in upper and lower bounds in the edit boxes or they can slide the arrow/edit boxes left or right to set the values.

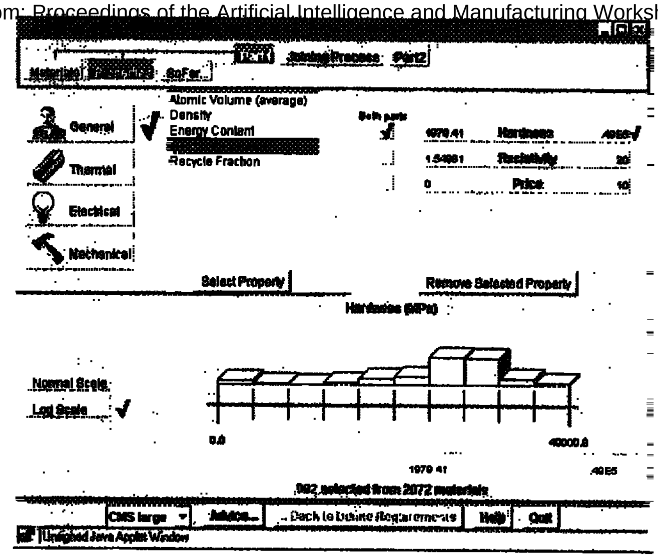


Figure 1. The screen for specifying bounds on material properties. In this example, a hard, highly resistive, relatively inexpensive material is required.

Setting upper and lower bounds for properties results in a set of materials that fall with that range. The number of materials that fall within the specified range is displayed at the bottom of the histogram. This process of setting property values can be repeated for a number of properties, each time resulting in a new set of materials for each bounded property. Following the convention of CMS, the "SoFar" button performs the intersection of these sets to determine if we are in a reasonable search dimension or if no materials satisfy the requirements and we are specifying "unobtainium[1]". This part of the MJA, in and of itself, provides a useful method for material selection.

Once the user is satisfied with the specification of "Piece Part 1" they repeat the procedure for "Piece Part 2". Notice in Figure 1 the "Both Parts" check box is checked for the Hardness property. This is a convenience for the user so that they do not have to re-enter the property constraints twice if they pertain to both piece parts.

An alternative scenario may be that the material for "Piece Part 2" is known and the material selection for "Piece part 1" is open. To anchor "Piece Part 2" to a specific material, the user clicks on the "Materials" button at the top of the screen for "Piece Part 2". A material hierarchy is displayed where the user can manually browse the hierarchy or they can perform a search for a particular material. Once the material is located in the hierarchy, the "Details" button to the right of the material can be pressed to display a wealth of information about the material including composition, all the property values, suppliers, typical uses, etc. A red check mark indicates that a material is selected for consideration. As shown in Figure 2, both 6061-T4 and 6061-T6 are selected as options for "Piece Part 2".

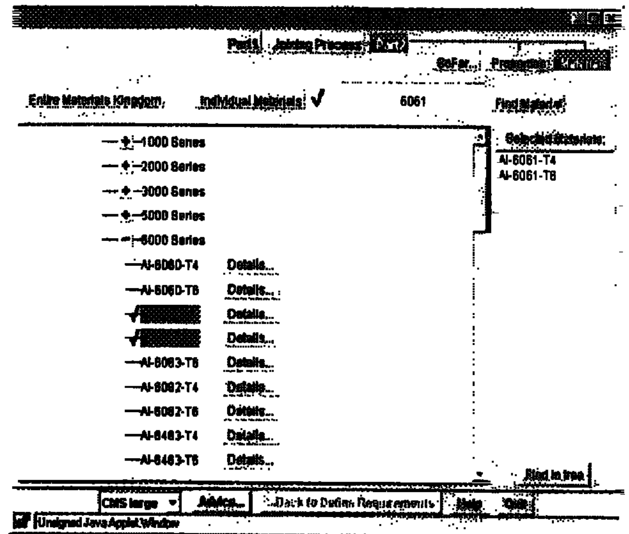


Figure 2. The materials hierarchy. The user specified aluminum 6061-T4 or 6061-T6 as material options for "Piece Part 2".

Once the requirements for "Piece Part 1" (hard, high resistance, cheap) and "Piece Part 2" (Al-6061-T4 or Al-6061-T6) are in place, the final constraint specifications are for the joint and the deployed service conditions. As shown in Figure 3, the user inputs parameters pertaining to Purpose, Service Loading, Service Environment, etc.

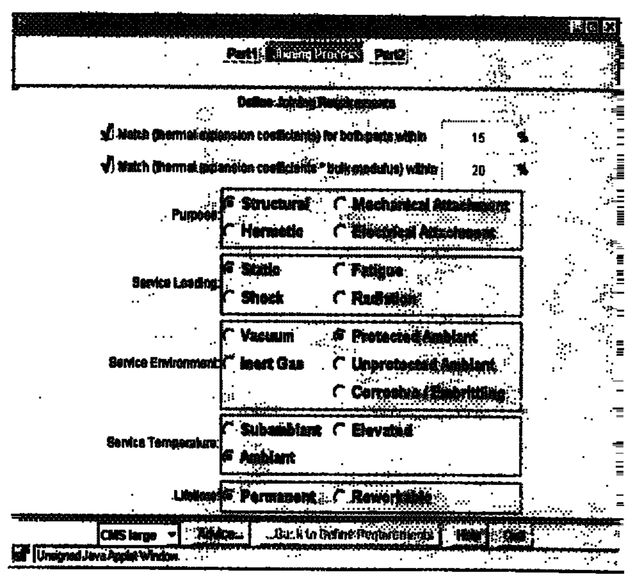


Figure 3. Constraints for the joint and deployed service conditions.

[1] Manufacturing slang for a set of requirements that is so restrictive that no existing material can satisfy it.

In addition, the user can specify to match the Thermal Expansion Coefficient of the two materials within a certain percent and/or to match the Thermal Expansion Coefficient multiplied by the Bulk Modulus (a measure of stress) within a certain percent. In this example, the Thermal Expansion Coefficient is matched within 15% and the Thermal Expansion Coefficient multiplied by the Bulk Modulus is matched within 20%.

Knowledge-based Constraint Satisfaction

With all the constraints now specified, the task of simultaneously satisfying the constraints is presented to the knowledge-based advisor. The joining processes it evaluates are welding, soldering, brazing, adhesives, glaze bonding, diffusion bonding, and mechanical fastening. Initially, much of the work done by the advisor is database search, retrieving materials that satisfy the constraints for each of the piece parts. When the database search is completed, all combinations of materials and joining process scenarios are generated.

Maximum number of joining scenarios equals
$x \bullet y \bullet z$ where

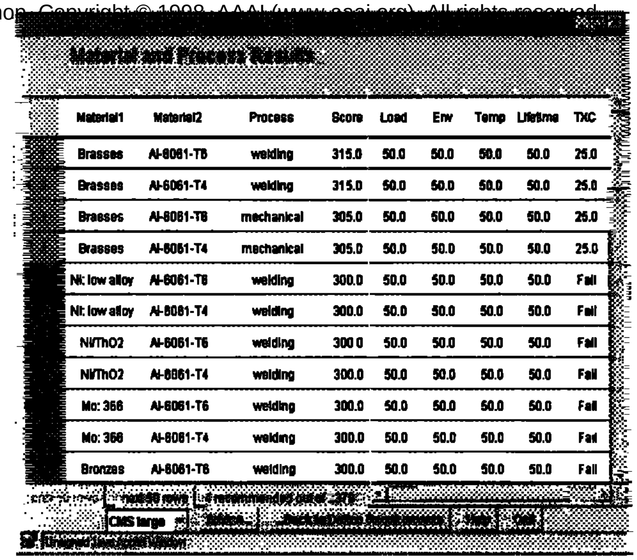
x = size of set of materials satisfying constraints for piece part 1,

y = size of set of materials satisfying constraints for piece part 2,

z = max number of joining process options = 7.

In fact, not all possible combinations are generated. The advisor has the intelligence not to propose scenarios that are totally infeasible. It knows, for example, not to join a ceramic to a polymer by welding. Finally, the advisor attempts to satisfy the constraints imposed on the joint (e.g. joint purpose, analyzing the thermal fluctuation impacts, etc) and by the deployed service conditions. The results are displayed as a scored and ranked ordered table of results as shown in Figure 4.

Each row in the table is a possible scenario for materials and process selection. An explanation of the reasoning process and the determination of score and rank are available for every scenario by clicking on the particular scenario in the table. There are four recommended scenarios in this example, as indicated by the light background (green) color for rows 1 – 4. All others have failed a major requirement as indicated by the dark (red) color.



Material1	Material2	Process	Score	Load	Env	Temp	Lifetime	TXC
Brasses	Al-6061-T6	welding	315.0	50.0	50.0	50.0	50.0	25.0
Brasses	Al-6061-T4	welding	315.0	50.0	50.0	50.0	50.0	25.0
Brasses	Al-6061-T6	mechanical	305.0	50.0	50.0	50.0	50.0	25.0
Brasses	Al-6061-T4	mechanical	305.0	50.0	50.0	50.0	50.0	25.0
Ni: low alloy	Al-6061-T6	welding	300.0	50.0	50.0	50.0	50.0	Fail
Ni: low alloy	Al-6061-T4	welding	300.0	50.0	50.0	50.0	50.0	Fail
Ni/ThO2	Al-6061-T6	welding	300 0	50.0	50.0	50.0	50.0	Fail
Ni/ThO2	Al-6061-T4	welding	300.0	50.0	50.0	50.0	50.0	Fail
Mo: 366	Al-6061-T6	welding	300.0	50.0	50.0	50.0	50.0	Fail
Mo: 366	Al-6061-T4	welding	300.0	50.0	50.0	50.0	50.0	Fail
Bronzes	Al-6061-T6	welding	300.0	50.0	50.0	50.0	50.0	Fail

Figure 4. The table of results for material selection for each piece part and for selection of a joining process.

Architecture

The MJA is implemented as a three tier architecture. It is entirely implemented using Java™ technology. The client (Java applet) is downloaded from a web server to the web browser on the desktop of the user. It communicates back to the server (Java application) using Java's RMI distributed object communication mechanism. The server, which encompasses the knowledge base, accesses the materials database through Java's JDBC relational database access protocol. The database is implemented in Sybase® SQL Anywhere.

Benefits

One indisputable benefit from the MJA is timesaving. For a materials scientist to research all material categories (metals, ceramics, polymers, composites, and natural) for applicable materials based on functional requirements of a part can be quite time consuming. In addition, performing the thermal expansion and stress analysis potentially increases the time by an order of magnitude.

The simultaneous materials and joining process selection method allows for a much better solution than performing either of these in isolation first. A "good" material and a "good" process is much better than an "excellent" material and a "poor" process or "no" process and a trip back to the drawing board. Also, considering the entire materials kingdom allows for novel material usage, pushing the designer to look beyond their narrow set of habitual options. This method of simultaneous materials and process selection can be no worse than its sequential counterpart.

Furthermore, the thorough and repeatable process of simultaneous material and process selection is much easier for a computer to perform than a human. Database lookup is much faster and thorough than a set of materials handbooks on a shelf. Of course, the experts will always have gems of knowledge that the MJA does not, but the knowledge in the MJA can constantly be updated and improved. The simultaneous considerations of all materials and all joining processes allows for product performance optimization, innovation, cost and schedule improvements, and better response to forces of change.

Future Work

Work has begun on developing a Materials and Process Design Environment (MPDE) of which the MJA is a portion. The MPDE vision is to have an integrated environment where all the tools share information under a common ontology. This way, the Shaping Advisor (Rivera, Stubblefield, and Ames 1997) communicates with the Materials and Joining Advisor, which in turn communicates with the Welding Advisor. The workspace of information that is continually modified is accessed and shared by all.

More specifically for the MJA, work is planned to build a multi-base architecture so that a number of materials databases can be queried simultaneously including in-house, proprietary materials data. Some thought has also been given to a fuzzy logic approach for materials constraint satisfaction. Finally, general performance measures, such as "light and stiff," may be added for easier, more intuitive material constraint specification.

Acknowledgements

The author acknowledges the program support and direction of Louie Tallerico and John Mitchiner, the team of experts including Jerry Knorovsky, Brian Damkroger, Sandy Monroe, Doug Adolf, Gary Pressly, and design issues discussions with Bill Stubblefield. This work was performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract numbers DE-AC04-76DP00789 and DE-AC04-94AL85000.

References

C. A. Abel, K. L. Edwards and M. F. Ashby, 1994. Materials, processing and the environment in engineering design: the issues. *Materials & Design* 15(4):179-193.

G. Boothroyd, P. Dewhurst and W. A. Knight, 1991. Research program on the Selction pf Materials and Processes for Component Parts. *International Journal of Advanced Manufacturing Technologies.* 6:98-111, London: Springer-Verlag.

P. P. Dargie, K. Parmeshwar and W. R. D. Wilson, 1982. *MAPS-1: computer-aided design system for preliminary material and manufacturing selection.* ASME Transactions 104:126-136.

Granta 1994. Granta Design Limited, 20 Trumpington Street, Cambridge CB2 1QA, United Kingdom.

S. D. Kleban, 1996. Design Issues of a Knowledge-based Welding Advisor. Proceedings *Artificial Intelligence and Manufacturing Research Planning Workshop*, 98-102. Albuquerque, New Mexico: AAAI Press.

J. J. Rivera, W. A. Stubblefield, and A. L. Ames 1996. Critics and Advisors: Heuristic Knowledge and Manufacturability. *Proceedings Artificial Intelligence and Manufacturing Research Planning Workshop*, 146-152. Albuquerque, New Mexico: AAAI Press.