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AN INTEGRATED APPROACH TO DESIGN, MANUFACTURE AND MATERIALS SELECTION IN ENGINEERING

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ABSTRACT

The introduction of a new product or changing an old model involves reaching economic decisions, making designs, selecting materials and choosing manufacturing processes. These activities are interdependent and should not be performed in isolation from each other. This is because the materials and processes used in making the product can have a large influence on its shape, cost and performance in service. If a certain design and economic analysis are based on a particular material and process it will be difficult to introduce widely different alternatives. The further the product development activities progress the more difficult it will be to consider alternative materials and processes.

With the increasing pressure to produce cheaper and more reliable components and with the greater number of new engineering materials and manufacturing processes that are now available, there is a growing need for an integrated approach to economic analysis, design, and materials and process selection. The integrated approach will make it easier to achieve the optimum component that will combine the functional requirements with reliability at a competitive cost.The increasing use of computers in the various aspects of product development has made the integrated approach easier to attain. Computer aided design, computer aided manufacture, computer aided economic analysis and computerized material properties data banks are among the tools that are now available to the engineer.

This paper presents a proposed integrated approach to the processes of design, economic analysis, manufacture and materials selection that are involved in introducing an engineering product. A simple case study is presented to illustrate the proposed approach.

STAGES OF PRODUCT DEVELOPMENT

Generally, the development of a new product goes through a series of major phases, that begin with ideas or concepts, and culminates in a finished product or system. The four broad stages of development of a new product are shown in figure 1.

Stage (1)
- Recognition of need and decision to investigate
- Assessment of market and competition
- Preliminary selection of design, materials and manufacturing processes

Stage (2)
- Development of design
- Selection of materials and processes
- Testing of a prototype

Stage (3)
- Optimization of design, materials and processes to achieve maximum economy
- Refining of design materials and processes

Stage (4)
- Manufacturing the product on a large scale
- Possible materials modification to suit large scale production
- Possible design modification to suit large scale production and new materials

Fig.1 Stages of product development

In the first stage of product development, main design and materials requirements are broadly outlined and on this basis certain classes of materials and processes are eliminated and others chosen as likely candidates. Another important part of first stage is feasibility study where the concept is examined economically in terms of market assessment and competition appraisal. In the second stage,a practical and workable design is developed and the major part of materials and process selection should be performed concurrently. This is because the materials and processes used in making the product can have a large influence on its shape, cost and performance in service. If a component form and cost are based on a particular material and process it will be difficult to introduce widely different alternatives such as for example, using injection molded thermoplastic instead of formed sheet metal. The further the design process proceeds the more difficult it is to consider alternative materials and processes.

In the third stage, optimization techniques are performed to select the optimum design, materials and processing route. At this stage design modifications may be made to achieve production economy or to fit existing facilities and equipment. These modifications could require significant changes in materials, or the design may be refined to conform with the exact properties of the selected materials.

The final stage is the manufacture of the product. Even at this stage, materials selection may still continue. Manufacturing problems may arise causing the replacement of an otherwise satisfactory material. For example, heat treating, joining and finishing difficulties may require a material substitution which in turn, results in different service performance characteristics requiring some redesign.

Although the design and materials selection processes are often thought of in the framework of new product development, there may be reasons for material changes in existing products. Some of the most important changes are made to take advantage of new materials or processes or to improve service performance, including longer life and higher reliability.

ECONOMIC CONSIDERATIONS

In a competitive industrial environment, costs play an important role in the evaluation of a product. It is not enough that a component or a machine should function properly as a physical unit; it must also function properly as an economic unit. The various factors that affect the economic behavior of a product include initial cost, running and maintenance costs, repair and breakdown costs as well as insurance costs. To take the product life into account, the above cost factors should be presented either as cost per unit service life or cost per service performed by the product. In consumer industries compromises of physical perfection may be suggested by the cost of the materials and processes which will be needed for production. Further compromises of physical perfection may be dictated by the economic climate in which the product will be marketed.

FACTORS AFFECTING MATERIALS AND PROCESS SELECTION

With the large number of materials that are available to the engineer and with the more stringent demands for safety and reliability coupled with the demand for lower costs, the materials selection process has become a complex one. The selection process is further complicated by the fact that material properties are affected by the manufacturing processes and by the geometry of the component as well as the type of forces acting on it, as shown in Fig.(2). Frequently the behavior of the material in the finished product is quite different from that of the stock material involved in making it.

As the material behavior is directly affected by the component geometry and the type of forces acting on it, proper design criteria should be used. For example, the presence of sharp corners is known to affect the behavior of high strength steels to a greater extent than mild steels, and surface roughness can affect the material under fatigue loading to a greater extent than under static loading.

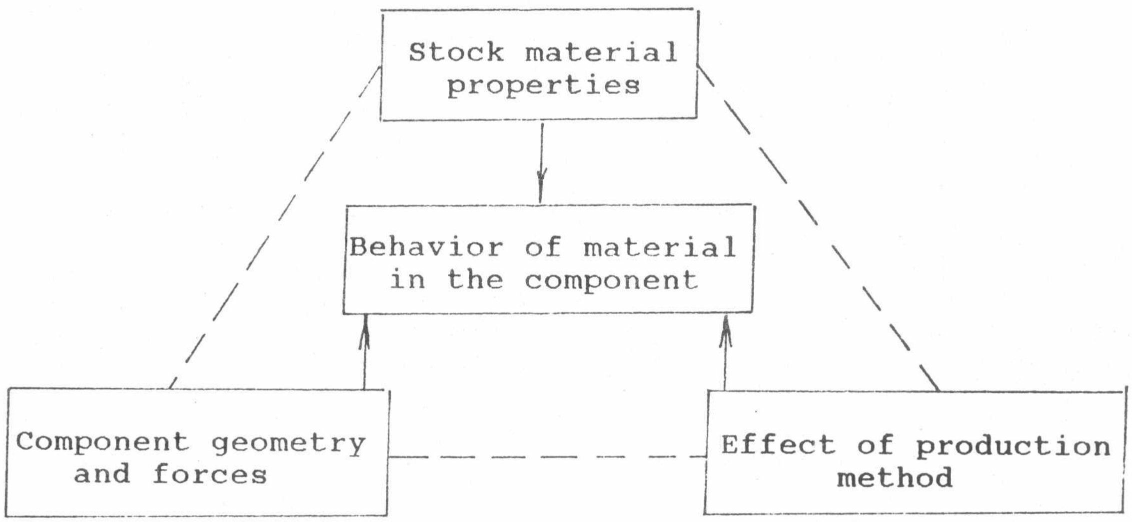

Fig.(2) Factors affecting the behavior of materials in the finished component(1).

Very frequently, alternative materials do not come in the same stock size. This may affect the efficiency of utilizing materials. Likewise the resulting scrap may differ for different materials. This factor may have serious economic implications especially if the materials cost represents a large proportion of the total cost of the product.

In the cases where several designs and materials may serve a purpose equally well from a functional point of view, the cost of processing may be a factor that determines which material is chosen. Some designs contain features that are more costly to produce than others while some materials are more expensive to process than others. Aluminum which is more easily machinable and in addition has a lower density, is being used in increasing amounts as a replacement for steel and other metals whose cost per unit weight is considerably less.

From the consumer point of view, it is the performance of the component in service rather than the behavior of material in the component that counts. Service conditions and component properties in terms of weight, volume, etc. can directly affect the performance, as shown in Fig.(3).

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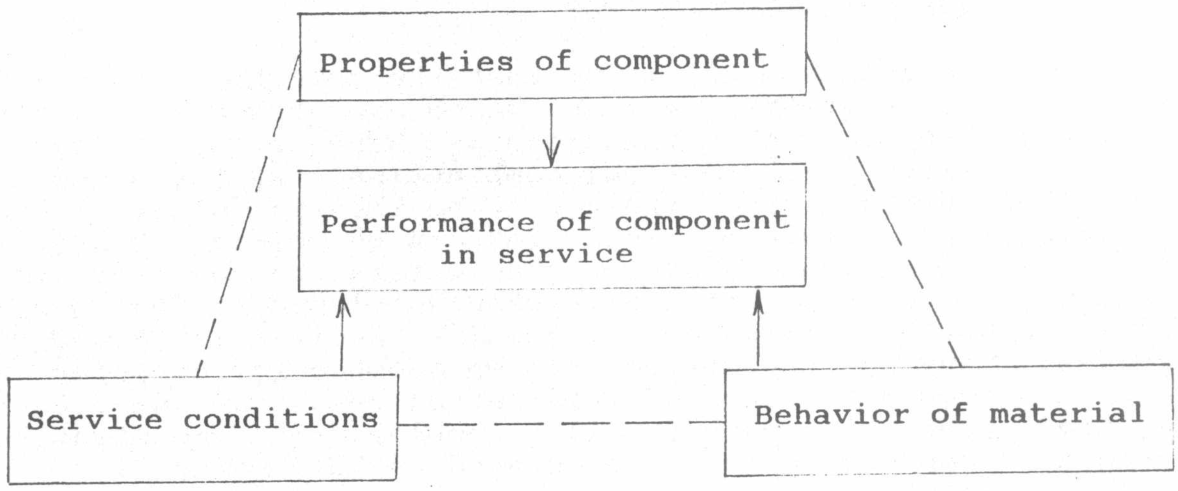

Fig.(3) Factors affecting the performance of a component in service (1).

ANALYSIS OF REQUIREMENTS

The various designs involved in the different stages of product development are normally based certain specifications of material properties. These are based on the desired function and the expected performance of the product, as well as the environment in which it will operate. The performance requirements of a product can generally be divided into the following broad categories:

1- Functional requirements which are directly related to the required characteristics of the product.

2- Processability requirements which are related to the possibility of shaping the selected material in a finished component. With reference to a specific manufacturing process, processability can be defined as castability, weldability, machinability, etc.

3- Cost which is usually an important factor in evaluating a product.

4- Reliability which can be defined as the probability that the product will perform the intended service for the expected life without failure. Failure analysis techniques are usually used to predict the different ways in which a product can fail and can be considered as a systematic approach to reliability evaluation. The causes of failure of a component in service can usually be traced back to defects in materials and processing or to unexpected service conditions.

5- Resistance to service conditions. Corrosive environments as well as high or low temperatures can alter the service performance of most materials and whenever more than one material is involved in an application, compatibility becomes a selection consideration.

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THE SELECTION PROCESS

The above discussion has shown that the selection process is a complex one. Various designs which are based on different materials and manufacturing processes have to be compared in order to arrive at the optimum combination. If the selection is carried out haphazardly, there will be the risk of overlooking a possible viable solution. This risk can be reduced by adopting a systematic selection procedure. The literature contains various quantitative methods which have been developed to deal with the large amount of data which are usually involved in the selection process. Many of the methods can be adopted for computer aided selection from data banks or information retrieval devices. The weighted properties method will be employed in demonstrating the integrated approach which is presented in this paper (1).

The weighted properties method can be used in evaluating complicated combinations of materials and properties. In this method each material property is assigned a certain weight (a), depending on its importance. A weighted property value is obtained by multiplying the scaled value of the property by the weighting factor. The individual weighted property values of each material are then summed to give a comparative merit value (M). The combination of material and process with the optimum (M) is selected.

CASE STUDY - DESIGN, MATERIALS SELECTION AND MANUFACTURE OF A TURNBUCKLE

A turnbuckle is a loop with opposite internal threads in each end for the threaded end of two ringbolts, forming a coupling that can be turned to tighten or loosen the tension in the members attached to the ringbolts. The turnbuckle is used in different applications involving widely different requirements of forces, reliability, and service conditions. The forces acting on the turnbuckle are usually tensile although fatigue and impact loading can be encountered. Corrosion becomes a problem in aggresive environments especially if the loop is made of a material other than that of the ringbolts.The possible forms of failure in service involve yielding of the loop material, yielding of the ringbolt, shearing of the threaded part of the loop or the ringbolt and corrosion. Other possible failure modes are fatigue, brittle fracture or creep.

The materials strength requirements of the turnbuckle components could involve yield strength, shear strength, fatigue strength, impact strength and creep strength. Processability requirements include castability for casting alloys, workability for wrought alloys and machinability for any selected material. Cost of the finished turnbuckle consists of the costs of stock materials, processing and finishing. Reliability requirements are related to toughness and homogeneity of the materials involved. Resistance to service conditions is mainly related to corrosion resistance in this case. If the loop and ringbolt materials are different, compatibility then becomes an important factor.Galvanic corrosion will take place if the two materials are far apart in the galvanic series. Differences in thermal expansion coefficient can cause difficulties in operation if widely different service temperatures are encountered in service.

Possible materials for turnbuckle components include ferrous alloys, nonferrous alloys, polymers and composite materials. Normally selection would be carried out from a data bank containing the relevant material properties, processability information, available stock shapes and cost (2). For the purpose of this case study, a small data bank containing 5 types of steel, 2 types of cast iron, 5 nonferrous alloys and one composite material was constructed. The information included in the bank was: yield strength, shear strength, endurance limit, impact strength, specific gravity, corrosion resistance, position in the galvanic series, possible manufacturing processes, cost of stock material and cost of manufacturing.

A computer program can easily be written to perform the selection process. At AUC such a program was developed for use with the IBM microcomputer (3). The input data supplied by the user describes the function to be performed by the turnbuckle, the expected loading and performance requirements and service conditions. In the present case it is assumed that the ringbolt is manufactured by working while the loop can be shaped by either casting or working.The threads are assumed to be made by machining.

The sequence of design and selection processes in the present case study is as follows :

1- A wrought alloy is used to design the ringbolt. Based on this design, thread dimensions are determined in addition to other dimensions which will be needed to manufacture it and determine its weight and cost. An appropriate factor of safety is used in the calculations.
2- Materials in the data bank are then screened to eliminate all the materials that are more than a specified distance away from the ringbolt material. One of the possible candidate materials is then used to design the nut part of the loop on the basis of the ringbolt designed in step 1. The rest of the loop is then designed to accommodate the nut and carry the load. The weight of the loop is determined followed by its cost. Calculations are then repeated for all the other loop candidate materials.
3- Another wrought alloy is then selected to design a ringbolt and steps 1 and 2 are repeated.
4- Computations carried out in the above steps yield dimensions, weight and cost of all possible material combinations in the data bank.
5- Selection of the optimum material combination is then based on its merit value (M).For the present case study :

$$M = a1 * W + a2 * C + a3 * R .$$

a1, a2, a3 are the weighting factors of W, C, and R respectively. W is the weight of the turnbuckle. C is the cost and R is the rate of corrosion of the less resistant material in the combination. The optimum material combination is the one with least M.

It should be noted that in its simple form, the weighted properties method has the drawback of combining unlike units which could lead to irrational results. This is particularly true when different mechanical, physical and chemical properties with widely different numerical values are combined. The property with higher numerical value will have more influence than is warranted by its weighting factor. This draw back is overcome by introducing scaling factors. Each property is so scaled that its highest numerical value does not exceed 100. When evaluating a list of candidates, one property is considered at a time. The best value in the list is rated as 100 and the others are scaled proportionally.

A sample of the results obtained with the present simple computer program is shown in Fig.(4) for the case of a turnbuckle for marine applications.

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                 TURNBUCKLE FOR MARINE APPLICATIONS

WEIGHTING FACTORS:
       Cost= 0.4, Corrosion resistance= 0.5, Weight= 0.1
LOADING CONDITIONS:
       Applied force= 20000 N
       Fatigue loading    Yes
       Impact loading     Yes
MAXIMUM ALLOWABLE DISTANCE IN GALVANIC TABLE     5
NUMBER REQUIRED               5000
SELECTED MATERIAL COMBINATIONS IN DECREASING PREFERENCE
       Ringbolt material                    Loop material
    Stainless steel    (405)   with   Stainless steel    (405)
    Manganese  bronze (B124)   with   Commercial bronze (B134)
    Phosphor bronze   (B139)   with   Commercial bronze (B134)
OPTIMUM COMBINATION
    Ringbolt material                 Stainless steel (405)
    Loop material                     Stainless steel (405)
    Ringbolt manufacturing            Forging
    Loop manufacturing                Forging
    Ringbolt nominal diameter         19  mm.
    Loop nut length                   30  mm.
    Loop cross sectional area         170 sq. mm.
    Total turnbuckle weight           910 gm.
    Total turnbuckle cost             2.8 * Cost of 405 per Kg.
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Fig. (4) Output of computer program for turnbuckle design, costing and materials and process selection.

CONCLUSION.

The proposed integrated approach to design, selection of materials and manufacturing processes should be of help to engineers to find optimum solutions that satisfy the various requirements for a given application. More sophisticated programs are being developed at AUC to solve more complicated problems.

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