Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 10, Issue 3, 2015, 141–146 ISSN 2067-9238

# MATERIALS SELECTION FOR AN ENGINEERING APPLICATION USING MULTIPLE-CRITERIA DECISION ANALYSIS

**Cătălin GHEORGHIȚĂ[1,*], Vlad GHEORGHIȚĂ[2]**

[1)] PhD, Lecturer, University "Politehnica"of Bucharest Romania, Department of Manufacturing Technology, Bucharest, Romania,
[2)] PhD Student, University "Politehnica" of Bucharest Romania, Department of Manufacturing Technology, Bucharest, Romania.

***Abstract:*** *The process of choosing materials for one part is always a difficult task, due to the large variety of materials and manufacturing processes. The complex list of requests defining the appropriate material leads to a multicriterial problem. The selection methods must have materials databases and resources for comparing objectively specific materials according to a set of requests. Systematic methods for material selection were developed and implemented in selection programs. The interaction between function, material, shape and process is an important issue in the material selection process. All materials and processes are candidates, requiring a procedure which allows access to data. At the beginning of the design process, the goal of the selection softwares is to establish the best materials. The material for components of machine tools requires special attention for the coefficient of expansion, vibration absorption and strength. Decisions for a given problem are made by using methods of decision making to eliminate unsuitable alternatives and to select the most suitable alternative. A decision matrix method is a formalized procedure by which materials are classified considering the selection decision. In this paper a method is used to identify the best solution for conventional and alternative materials used in machine tool structures.*

***Key-words:*** *material selection, machine tool, multiple criteria decision, subjective weight, Topsis method.*

## 1. INTRODUCTION

Choosing the material is an important step in the design process because it is the crucial decision linking a project engineering calculations in an effective performance of a product. The vastness of this decision can be appreciated if we consider the more than 40,000 commonly used metal alloys and perhaps as many nonmetallic materials that can form a product. Methods of choice of materials are: depending on their physical, thermal, rheological and tribological and by destination (specific uses).

The process of selecting materials for a technical application should consider two principles: selected materials must possess physico-chemical, mechanical and technological appropriate requirements imposed by the application in which they are used; chosen materials must lead to technical solutions to solve application that is economically convenient, that can be put into practice with acceptable expenditure on materials development and manufacturing of products required by the application.

In order to facilitate the selection for various applications, it is required to divide the materials into two main classes. Structural materials (construction materials) are those designed for manufacturing elements (parts, components) subject to mechanical stress; metallic materials (steel, cast iron and alloys), materials based on macromolecular substances, ceramics and glasses, wood and composite materials. Functional materials must ensure that the functional role of some elements for electrical, electronics, automation and computer science, technique measurement, signal detection and recording of different physical nature. To achieve a product consists in knowing all the technical conditions that define its functionality and its behavior in operation.

## 2. MATERIAL SELECTION

During the process of materials selection, the chosen materials must have suitable properties with the application of the product produced. This is to ensure that the product can operate safely and have long life cycle.

Systematical methods of materials selection have been introduced in various programs of selection. The main goal of these programs is to establish from the beginning of the design process, the best material. These methods require materials databases and a set of procedures aiming materials comparing with taking into account the designing requests. The selection procedures structures have to allow an easy adjustment to a large variety of situations. Materials databases have to be organized so that the designer to choose the most adequate selection procedure. Requested information is different in every stage of the design process. From the beginning of the process it must consider all the possible materials so that the database has to contain all materials classes. At this level, the requested accuracy of the

[*] Corresponding author: Splaiul Independeței, No. 313, 060042, Bucharest, Romania;
Tel.: 0723212477;
E-mail addresses: *catalin.gheorghita@upb.ro* (C. Gheorghiță).

material properties values is low. The amount of information concerning materials properties is enlarging.

Fatigue Property Charts were used by Garton et al. [6] to choose the optimal material with minimum weight design for infinite fatigue life. Topsis and Electre II methods were developed by Chatterjee et al. [4] for the determination of the optimum material for an application. Weighting factor approach is developed for material selection with combination of linearization of non-linear models and modified digital logic method [9]. The methodology used by Pecas et al. [10] is a combination between a product development process and a classic material selection process that uses information generated in both processes. To decide the ranking among candidate materials according to some requirements, Yoon's algorithm Technique for Order Preference by Similarity to Ideal Solution is utilized [5]. A number of criteria are simultaneously considered to select a material for a part. Few studies have been done to provide a basis on managing some criteria and ranking the materials. An approach to choose the optimal material for a given component is described, and material properties are classified into qualitative and quantitative properties according to Ashby [5].

Material design defines many degrees of freedom regarding an optimization of machine frames and components. It gives an overview of the material selection and exploitation for high performance, precision and high efficiency machine tools. To achieve high precision components, equipment used for processing must ensure: thermal stability, repeatability of results and the possibility of moving axes to achieve minimum travel and very small feeds.

In case of machine tools must be controlled friction, regular movement and positioning at low speeds, static stiffness, damping capacity and execution cost. In modern machine tool structures a variety of materials are used: steel, cast iron, fiber reinforced composite materials and hybrid structures. Economic issues related to the use of materials depend on the design and for this reason it is very important that the designer take into account the possibilities for processing this specific material.

For very small feeds without variation, it is necessary to eliminate areas of contact between fixed parts of the machine and the mobile structure, which allows optimum dynamic accuracy and a minimum displacement.

## 2.1. CASE STUDY

To select the material for the design of a machine-tool was used Multi-Criteria Decision Analysis. This is a valuable tool that can be applied to many complex decisions. It is applicable at the choice between alternatives. This analysis has an approach used to solve problems involving selection from among a finite number of alternatives. A method specifies how attribute information is to be processed in order to arrive at a solution.

The attributes considered are Young's modulus, tensile strength, compressive strength, damping ratio, coefficient of thermal expansion and density. The first four attributes are beneficial with higher values, while the others two are useful with lower values. It was argued that multiobjective methods should be used only when the decision attributes can be expressed in identical units of measure. For application of these methods were used data, according to Table 1, for conventional and alternative materials used in machine tool structures.

It has been shown that the multi-criteria methods should be used when the decision attributes can be expressed in identical units of measure. If all the elements of the decision table are normalized, then a method can be used for any type of attributes.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is based on the concept that the chosen alternative should have the shortest Euclidean distance from the ideal solution and the farthest from the negative ideal solution. The ideal solution is a hypothetical solution for which all attribute values correspond to the maximum attribute values in the database comprising the satisfying solutions; the negative ideal solution is the hypothetical solution for which all attribute values correspond to the minimum attribute values in the database [5]. This method considers three types of attributes or criteria: qualitative benefit attributes, quantitative benefit attributes or cost attributes. The main procedure of this method for the selection of best alternative from among those available is described below. In order to make a comparison between properties, the elements of the matrix are normalized as in equation 1.

*Table 1*

**Objective data of the attributes [8]**

| **Material** | **Material properties** | | | | | |
|---|---|---|---|---|---|---|
| | ***E*** **[GPa]** | $\sigma_{T,S}$ **[MPa]** | $\sigma_{C,S}$ **[MPa]** | **Damping ratio** | $\alpha$ **[10$^6$/K]** | $\rho$ **[Kg/m$^3$]** |
| Cast Iron | 80 | 150 | 600 | 0.001 | 10 | 7150 |
| Cement Concrete | 20 | 3 | 20 | 0.001 | 10 | 2300 |
| Polymer Concrete | 30 | 25 | 70 | 0.001 | 11.5 | 2260 |
| Epoxy granite | 60 | 25 | 65 | 0.01 | 8 | 2850 |
| E-glass epoxy | 45 | 1020 | 620 | 0.001 | 30 | 2076 |
| E-glass polyester | 37.9 | 903 | 357 | 0.001 | 22 | 1850 |

*Table 2*

**The values normalized for candidate materials properties**

| **Material** | **Material properties** | | | | | |
|---|---|---|---|---|---|---|
| | ***E*** **[GPa]** | **$\sigma_{T,S}$ [MPa]** | **$\sigma_{C,S}$ [MPa]** | **Damping ratio** | **α [$10^6$/K]** | **ρ [$Kg/m^3$]** |
| M1 | 0.293 | 0.070 | 0.346 | 0.066 | 0.109 | 0.3867 |
| M2 | 0.073 | 0.001 | 0.011 | 0.066 | 0.109 | 0.124 |
| M3 | 0.109 | 0.011 | 0.040 | 0.066 | 0.125 | 0.122 |
| M4 | 0.219 | 0.011 | 0.037 | 0.666 | 0.087 | 0.154 |
| M5 | 0.164 | 0.479 | 0.357 | 0.066 | 0.327 | 0.112 |
| M6 | 0.138 | 0.424 | 0.206 | 0.066 | 0.240 | 0.100 |

$$r_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \, . \quad (1)$$

The values normalized of the six material properties are listed in Table 2

The entropy $E_j$ of the normalized values of an attribute $j$ is defined as follows [11]:

$$E_j = -k \sum_{i=1}^{m} r_{ij} \cdot log r_{ij}, \quad (2)$$

where $k = 1/\log m$ and $m$ is the number of candidate materials. $E_j$ is also in the range of (0, 1). The weight factor $w_j$ for the attribute $j$ is defined as [11]:

$$w_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)}, \quad (3)$$

where $n$ is the number of material properties or performance indices. If $r_{ij}$ for an index has wide scatter, that yields a small value of $E_j$, which gives the large weight factor in turn.

If one wants to add the subjective weight $s_j$, particular constraints of design, the weight factor is revised as:

$$w_j^* = \frac{s_j \cdot w_j}{\sum_{j=1}^{n} s_j \cdot w_j}. \quad (4)$$

Four cases of the subjective weight $s_j$ are considered. In cases where the specified number of material properties and relative importance is not clear, the importance coefficients are determined using an assessment procedure, named Digital Logic Method. When comparing two properties, the most important receives the value 1 and the other one – 0 (Table 3). The total number of possible decisions is: $N = n \cdot (n-1)/2$ where $n$ is the number of properties under consideration. The coefficient of importance $s_j$, $j$ = 1, 2, ..., $n$, is obtained by dividing the number of positive decisions for each property at the total number of positive decisions ($N$).

In Digital Logic Method, properties are compared regarding superiority of one property to another and then number of positive decisions are listed and scaled to obtain weight fractions so as to have a sum of 1 for each property.

In case 1, the weights are distributed as follows with this method: $s_1$ = 0.06; $s_2$ = 0.2;   ; $s_3$ = 0.14; $s_4$ = 0.26; $s_5$ = 0.2; $s_6$ = 0.14. In case 2, Young's modulus is most weighted $s_1$ = 0.3. In case 3, tensile strength and compressive strength are most weighted $s_2$ = $s_3$ = 0.3. In case 4, all weights are equal, expect $s_1$ = $s_6$ = 0.1.

In case 1, the damping ratio is most weighted $s_4$ = 0.26, while in case 3 is least weighted $s_3$ = 0.1. In case 3, the compressive strength is most weighted $s_3$ = 0.3, while in case 1 is least weighted $s_3$ = 0.14. $E_j$, $w_j$, $s_j$ and the revised weights factor $w_j$ are listed in Table 4.

*Table 3*

**Digital Logic Method**

| **Properties** | **Number of decisions N = n·(n-1)/2** | | | | | | | | | | | | | | | **Positive decision** | **Relative coefficient** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | | |
| Property 1 | 1 | 0 | 0 | 0 | 0 | | | | | | | | | | | 1 | 0.06 |
| Property 2 | 0 | | | | | 0 | 1 | 1 | 1 | | | | | | | 3 | 0.2 |
| Property 3 | | 1 | | | | 1 | | | | 0 | 0 | 0 | | | | 2 | 0.14 |
| Property 4 | | | 1 | | | | 0 | | | 1 | | | 1 | 1 | | 4 | 0.26 |
| Property 5 | | | | 1 | | | | 0 | | | 1 | | 0 | | 1 | 3 | 0.2 |
| Property 6 | | | | | 1 | | | | 0 | | | 1 | | 0 | 0 | 2 | 0.14 |
| Total number of positive decisions | | | | | | | | | | | | | | | | **15** | **Σ $s_j$ =1** |

*Table 4*

**Entropy and weight factors for each material properties**

| Calculation of weighting factor | | Material properties | | | | | |
|---|---|---|---|---|---|---|---|
| | | *E* [GPa] | $\sigma_{T,S}$ [MPa] | $\sigma_{C,S}$ [MPa] | Damping ratio | α [$10^{-6}$/K] | ρ [Kg/m$^3$] |
| $E_j$ (entropy) | | 0.262 | 0.558 | 0.407 | 0.491 | 0.276 | 0.284 |
| $w_j$ (objective weight factor) | | 0.115 | 0.244 | 0.178 | 0.215 | 0.121 | 0.124 |
| $s_j$ (subject weight) | Case 1 | 0.06 | 0.2 | 0.14 | 0.26 | 0.2 | 0.14 |
| | Case 2 | 0.3 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| | Case 3 | 0.2 | 0.3 | 0.3 | 0.1 | 0.05 | 0.05 |
| | Case 4 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| $w_j^*$ (modified weight factor) | Case 1 | 0.038 | 0.274 | 0.141 | 0.313 | 0.135 | 0.097 |
| | Case 2 | 0.208 | 0.296 | 0.216 | 0.131 | 0.073 | 0.075 |
| | Case 3 | 0.125 | 0.399 | 0.291 | 0.117 | 0.032 | 0.033 |
| | Case 4 | 0.065 | 0.278 | 0.203 | 0.244 | 0.137 | 0.071 |

With the weight factors, the material properties matrix is defined as [11]:

$$v_{ij} = w_j^* \cdot r_{ij} \qquad (6)$$

For the j-th material property or performance index is defined as the ideal $v_j^+$ and the element with the least preferred value is defined as the non-ideal $v_j^-$.

$$s_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2}\ , \qquad (7)$$

$$s_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}\ . \qquad (8)$$

Finally, selection of combination from Tables 5–8 should be made upon the separation measures, $S_i^+$ and $S_i^-$, the ideal combination has a maximum $S_i^-$ and minimum $S_i^+$. For the purpose the relative closeness $C_i^+$ is introduced and defined as follows [11]:

$$C_i^+ = \frac{s_i^-}{s_i^+ + s_i^-}\ . \qquad (9)$$

when $C_i^+$ is close to 1, the combination is regarded as ideal; and when $C_i^+$ is close to 0, the combination is regarded as non-ideal.

*Table 5*

**The separation measures and the relative closeness (case 1)**

| Material / Case 1 | Separation measure / relative closeness | | |
|---|---|---|---|
| | Separation measure ($S_i^+$) | Separation measure ($S_i^-$) | Relative closeness ($C_i^+$) |
| **Cast Iron** | 0.222 | 0.051 | 0.187 |
| **Cement Concrete** | 0.236 | 0.025 | 0.098 |
| **Polymer Concrete** | 0.233 | 0.026 | 0.103 |
| **Epoxy granite** | 0.141 | 0.189 | 0.575 |
| **E-glass epoxy** | 0.188 | 0.146 | 0.437 |
| **E-glass polyester** | 0.191 | 0.124 | 0.395 |

*Table 6*

**The separation measures and the relative closeness (case 2)**

| Material / Case 2 | Separation measure / relative closeness | | |
|---|---|---|---|
| | Separation measure ($S_i^+$) | Separation measure ($S_i^-$) | Relative closeness ($C_i^+$) |
| **Cast Iron** | 0.146 | 0.088 | 0.375 |
| **Cement Concrete** | 0.184 | 0.019 | 0.097 |
| **Polymer Concrete** | 0.178 | 0.022 | 0.112 |
| **Epoxy granite** | 0.156 | 0.085 | 0.354 |
| **E-glass epoxy** | 0.082 | 0.163 | 0.664 |
| **E-glass polyester** | 0.092 | 0.135 | 0.594 |

*Table 7*

**The separation measures and the relative closeness (case 3)**

| Material / Case 3 | Separation measure / relative closeness | | |
|---|---|---|---|
| | Separation measure ($S_i^+$) | Separation measure ($S_i^-$) | Relative closeness ($C_i^+$) |
| **Cast Iron** | 0.178 | 0.105 | 0.371 |
| **Cement Concrete** | 0.229 | 0.008 | 0.037 |
| **Polymer Concrete** | 0.221 | 0.013 | 0.058 |
| **Epoxy granite** | 0.209 | 0.073 | 0.259 |
| **E-glass epoxy** | 0.072 | 0.216 | 0.751 |
| **E-glass polyester** | 0.088 | 0.178 | 0.671 |

*Table 8*

**The separation measures and the relative closeness (case 4)**

| Material / Case 4 | Separation measure / relative closeness | | |
|---|---|---|---|
| | Separation measure ($S_i^+$) | Separation measure ($S_i^-$) | Relative closeness ($C_i^+$) |
| Cast Iron | 0.189 | 0.072 | 0.276 |
| Cement Concrete | 0.212 | 0.018 | 0.081 |
| Polymer Concrete | 0.208 | 0.021 | 0.091 |
| Epoxy granite | 0.149 | 0.148 | 0.497 |
| **E-glass epoxy** | 0.146 | 0.155 | 0.514 |
| **E-glass polyester** | 0.151 | 0.127 | 0.457 |

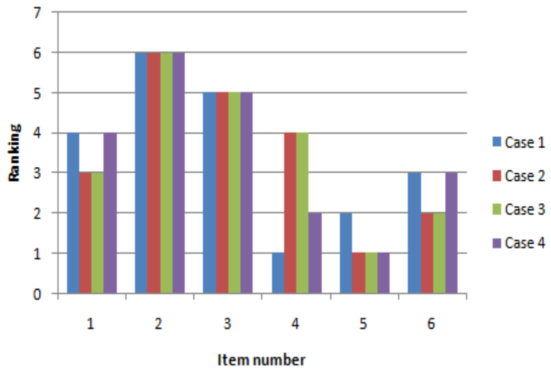


**Fig. 1.** Ranking established by Topsis method.

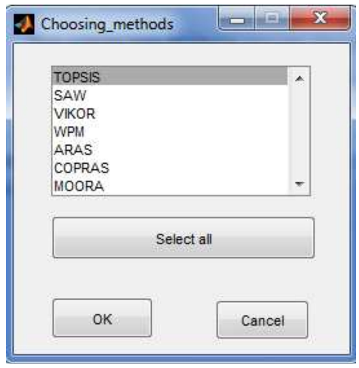


**Fig. 2.** Choice of multicriteria methods.

The values required for each method are calculated in order to achieve a hierarchy. The ranking of the 4 cases are presented in Fig. 1.

## 3. SOFTWARE APPLICATION

The material properties considered are determined by functional requirements. Furthermore, minimum constraints on materials under question should be applied to candidate materials from the database. With the materials and the related properties, the procedure can go through the final selection of a material.

The calculation provided by Topsis Method was made with a Matlab program in which all the data of materials and their properties have been stored. The method was implemented into an application that allows the choice of multicriteria methods (Fig. 2).

Within each class of material, data are defined for a representative set of materials, chosen both to span the full range of behaviour for the class and to include the most common and most widely used members of it. Each class shows a characteristic range: metals have high conductivities; polymers have low conductivities; ceramics have a wide range, from low to high. Material classes used in this application are: engineering alloys, engineering polymers, engineering ceramics, porous ceramics, woods, elastomers, polymer foams.

Classes of materials and material performance characteristics are based on physical, electrical, nuclear, mechanical, thermal, chemical and fabrication properties (Fig. 3).

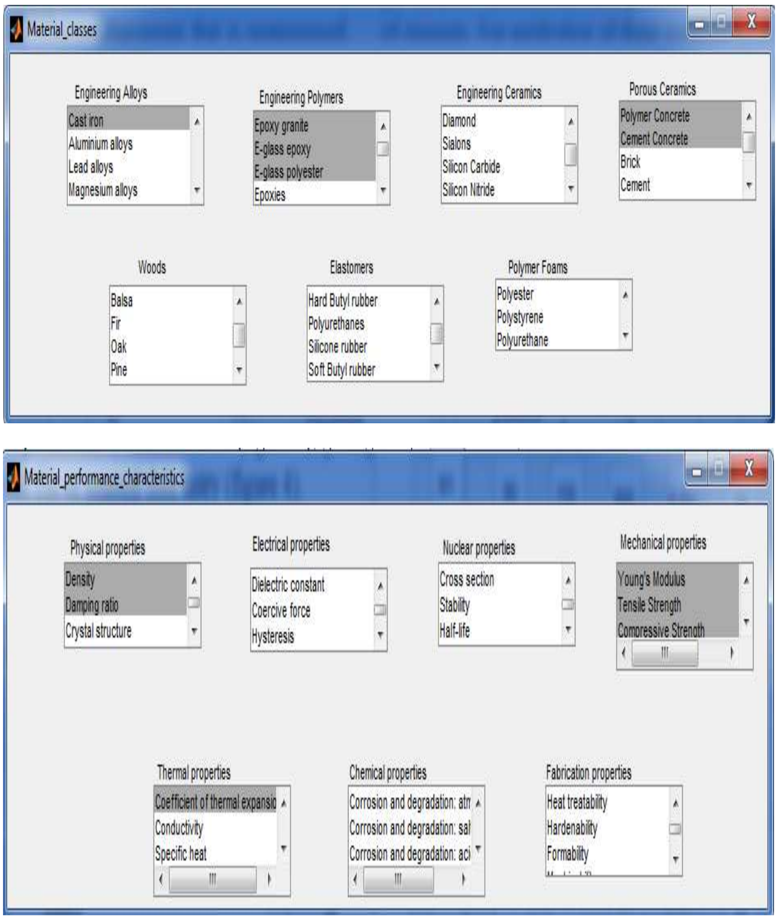


**Fig. 3.** Classes of materials with material performance characteristics.

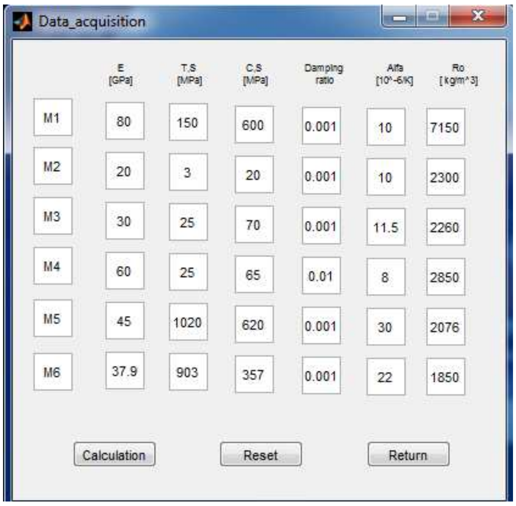


**Fig. 4.** Data from files.

The application was used to verify data, reducing the time needed to process them. The use of computer-aided tools allows the engineer to minimize the materials selection information overload. A computerized materials search can accomplish in minutes what may take hours or days by manual search. Over a hundred materials databases are available worldwide. However, the data contained in most of them are limited to numerical values and text [1].

Data necessary can be obtained from file or can be introduced manually (Fig. 4).

For a product which is composed of many parts, no one can provide all of the information necessary to select the optimum material for each part. To shorten the design time for a new product, a design engineer should benefit from the help of a tool. The procedure should be objective so as to minimize personal opinions. The user can adjust the relative priority among design requirements using the subjective weight. Also if the user does not have the required experience and knowledge to decide the subjective weight, the objective weight is evaluated through the procedure.

## 4. CONCLUSIONS

The application presented is intended for educational purpose, allowing filling the database with new information, and also the use of multi-criteria analysis methods. Advantages of this application are: material choice established during early-stage of the product development, avoiding later costs and delays, generate ideas through a systematic search of materials, apply a repeatable process for validating the results.

Four illustrative cases have been considered to demonstrate Topsis method and validated it. In three of the cases, it is observed that the top-ranked material is E-glass epoxy. Regardless of subjective weights given, materials with the best relative closeness ($C_i^+$) are the following: E-glass epoxy, Epoxy granite, E-glass polyester.

## REFERENCES


[1] M. Ashby, *Materials Selection in Mechanical Design Second Edition*, Butterworth Heinemann, Great Britain, 1999.

[2] M. Ashby, *Materials and the Environment: Eco-Informed Material Choice*, Butterworth-Heinemann, Canada, 2009.

[3] *ASM Handbook Materials Selection and Design*, Vol.20, The Materials Information Society, United States of America, 1997.

[4] P. Chatterjee, V.M. Athawale and S. Chakraborty, *Selection of Materials Using Compromise Ranking and Outranking Methods*, Materials & Design, Vol. 30, No. 10, 2009, Elsevier, pp. 4043–4053.

[5] D.H. Jee, K.J. Kang, *A method for optimal material selection aided with decision making theory*, Journal of Materials and Design, Vol. 21, No. 3, June 2000, Elsevier, pp. 199–206.

[6] D.A. Garton, K.J. Kang, N.A. Fleck, M.F. Ashby, *Materials Selection for Minimum Weight Fatigue Design. Theoretical Concept and Numerical Analysis of Fatigue*, Engineering Materials Advisory Services Ltd, pp. 359-376, 1993.

[7] M. Holly, *Matlab for Engineers*, Third Edition, Pearson Education, pp. 581–598, New Jersey, 2000.

[8] N. Mahendrakumar, S. Syathabuthakeer, *Study of Alternative Structural Materials for Machine Tools*, 5th International & 26th All India Manufacturing Technology, Design and Research Conference, pp. 645–652, India, 2014.

[9] B.D. Manshadi, H. Mahmudi, A. Abedian and R. Mahmudi, *A Novel Method for Materials Selection in Mechanical Design: Combination of Non-Linear Linearization and a Modified Digital Logic Method*, Materials & Design, Vol. 28, No. 1, 2007, Elsevier, pp. 8–15.

[10] P. Pecas, I. Ribeiro, A. Silva and E. Henriques, *Comprehensive Approach for Informed Life Cycle-Based Material Selection*, Mater Design, Vol. 43, 2013, pp. 220–232.

[11] R.R. Venkata, *Decision Making in the Manufacturing Environment*, Springer, pp. 27–42, India, 2007.