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An Approach to Selection of Material and Manufacturing Processes for Rocket Motor Cases Using Weighted Performance Index

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Material selection is a very critical design decision, which has a profound influence on the entire development program for rocket motor cases. In the selection process, the main performance parameters and the most appropriate fabrication technology with proven processes must be considered. Many years of practical experience in material selection process with a thorough understanding of materials behavior under various loading environments and hands-on experiences with various available manufacturing processes are of immense help to the design and development engineer for successful completion of the development program. In this paper, an attempt has been made to present an approach for selecting appropriate material and manufacturing process for rocket motor case based on method of Weighted Performance Index (WPI) with the hope that this approach will also provide additional aid to the design engineer for the selection of material and manufacturing process for rocket motor cases. In this method, different properties are assigned a certain weight depending upon their importance to the service requirements. Different properties are normalized using a scaling factor, and finally a weighted property index is computed. The material that scored the maximum numerical value is chosen as the material for fabrication. This approach closely matches with the actual performance. Maraging steel and D6AC are found to be the preferred materials for rocket motor cases for critical missions. HSLA steels are appropriate for less-critical applications, in which rocket motor cases are required in very large numbers (e.g., flow-formed AISI 4130 motor cases[8]). For the selection of an appropriate manufacturing method, the major parameters considered are dimensional accuracy, cost of production, minimum material waste, and flexibility in design. Again, these properties are given a relative grading, which is then converted into a scaled property. Finally, the weighted performance indices are estimated. The flow-forming method has emerged as the manufacturing method of choice for motor tubes.

Keywords maraging steel, materials behavior, rocket motor case, Weighted Performance Index (WPI)

1. Introduction

The motor case is the main load-bearing structural member of a solid propellant rocket. It functions as a container for the propellant, acts as the combustion chamber during propellant burning, and performs as the main structural member of the flight vehicle. However, the primary function of the rocket motor case is its function as a pressure vessel. In addition to its function as the main structural member, it is desirable to aim for minimum structural weight for performance enhancement of the rocket in terms of range as per the formula [1]

$$\text{Range in vacuum, } R_{\max} = Isp^2 g\left[I_n \frac{1}{1 - M \cdot F}\right]^2 \qquad \text{(Eq 1)}$$

where

g = acceleration due to gravity, m/s^2
Isp = specific impulse of propellant or fuel, s
M.F = mass fraction

$$\text{M F} = \frac{M_p}{M_p + M_s + M_{Pl}}$$

M$_p$ = mass of propellant, kg
M$_s$ = mass of structure, kg
M$_{pl}$ = mass of payload, kg.

2. Objective

This paper represents an attempt to present a methodology for selection of material and manufacturing processes appropriate for the design and development of rocket motors with the hope that such an approach will also become a tool for selection of material and manufacturing processes for the practicing engineers in the field.

3. Property Spectrum

Materials cannot be evaluated by comparison with an idealized model, which possesses all the required properties to the

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degree demanded. There is generally no limit to the demands of design engineers. A large number of high-strength materials have been developed, which supposedly have several advantages for application in rocket motor cases. It is important to know which properties can be sacrificed with the least impairment. If the relative weight of the material parameters can be estimated, a feasibility factor can be calculated which will determine the suitability of materials for each specific purpose.[2] This could possibly act at best as a design aid for the design and development engineer.

The longitudinal-circumferential stress ratio is 1:2 in a cylindrical pressure vessel. Homogeneous materials such as metals seem to be at a disadvantageous and nearly in a competitive position compared to composite materials in which the properties can be tailor-made to meet this requirement. However, due to lack of well-established manufacturing methods, lack of reliable quality control and quality assurance methods, absence of foolproof inspection and testing methods, unknown reliability, and limitations in manufacturing complicated shapes with joints, composite materials will not be considered in this paper. Only metal alloys will be considered for construction of rocket motor cases. However, the attractive features of composite materials will be of immense importance in the near future.

4. Material Selection for a Solid Rocket Motor Case

The material selection for a rocket motor case is generally being evaluated on the basis of[2]

- Specific strength: The maximum poteneial strength-weight ratio cannot be fully utilized because of the tendency to brittle failure increases with higher strength. Hence, yield strength-weight ratios will be utilized in the performance evaluation.
- Fracture toughness: This factor determines to what strength limit material can be reasonably utilized in the presence of small flaws, which are often unavoidable and undetectable.
- Specific stiffness: Elastic modulus is a structure-insensitive property and cannot be changed as readily as the other properties by heat treatment, alloying, and cold working. Its main importances is for stiffness consideration. Specific stiffness is a better way of compairng the stiffness properties of candidate materials.
- Fabricability: No material can be considered adequate for rocket motor cases unless it can be fabricated without excessive cost.
- Cost: Overall cost is the most important criterion in selecting a material. Cost is a more usefull parameter when it can be related to a critical material property that controls the performance of the design.
- Coefficient of thermal expansion: The material has to have a minimum thermal expansion coefficient to minimize the effect of dimensioal changes and thermal stress due to fluctuation in operating temperatures.

5. Material Selection Approach

The material selection approach shall be taken at two levels. The first approach considers the selection of rocket motor material for very critical mission applications, such as strap-on motors for satellite launch vehicles, intercontinental ballistic missiles, and other missiles for strategic applications where the quantity of motor cases is limited. In such cases, the material properties are of paramount importance. The cost of raw materials is only a secondary criterion in such cases.

However, in less critical application areas, such as free-flight artillery rockets, which are required on the order of thousands with recurring requirements, availability of the materials in bulk quantity and their cost become significant considerations; often the latter becomes the overriding consideration for the selection of the raw material.

6. Weighted Property Index

In most applications, it is necessary that a selected material satisfy more than one performance requirement. Compromise is needed in material selection. The requirements can be separated into three groups: (i) GO/NO GO parameters, (ii) non-discriminating parameters, and (iii) discriminating parameters.[3] GO/NO GO parameters are those requirements that must meet a certain minimum value. Any merit in exceeding the fixed value will not make up for a deficiency in another parameter. Non-discriminating parameters are requirements that must be met if a material is to be used at all. Discriminating parameters are those requirements to which quantitative values can be assigned.

A decision matrix is well suited to materials selection with discriminating parameters. In this method each material property is assigned a certain weight depending on its importance to the required service performance.[3] Since the different properties are expressed in different units, the best procedure is to normalize these differences by using a scaling factor. The scaling is a simple technique to bring all the different properties within one numerical range. Since different properties have widely different numerical values, each properly must be scaled so that the largest value does not exceed 100.

$$\beta = \text{Scaled property} = \frac{\text{Numeric value of property}}{\text{Largest value under consideration}} \times 100 \quad \text{(Eq 2)}$$

When it is desirable to have low value of certain properties, such as density, cost, corrosion etc., the scale factor is formulated as follows[3]:

$$\beta = \text{Scaled property} = \frac{\text{Lowest value under consideration}}{\text{Numeric value of property}} \times 100 \quad \text{(Eq 3)}$$

For properties that are not readily expressed in numerical values, e.g., weldability and wear resistance, some kind of subjective rating is preferred.

The material performance index γ is

$$\gamma = \Sigma\beta_i W_i \qquad \text{(Eq 4)}$$

where i is summed over all the properties.

Cost can be considered as one of the properties with a high weighting factor. When large numbers of material properties are to be considered, cost can be applied as a moderator to the material performance index

$$\gamma' = \frac{\gamma}{m\rho} \qquad \text{(Eq 5)}$$

where

m = material cost/kg
ρ = density, kg/m^3.

When there are N properties to be considered, then there are

$$N\left(\frac{N-1}{2}\right)$$

possible combinations of pairs to be compared.

The process of rank ordering can be facilitated by using a digital logic approach. Each design objective is listed and is compared to every other objective, two at a time. When the comparison is made, the property considered the more important of the two is given a 1 and the less important property is given 0 value. The total number of possible combinations is

$$N = n\,\frac{(n-1)}{2},$$

where n is the number of objectives under consideration. This approach is shown in Table 1 to find the rank order. The possible design combinations against the most important parameters to be considered are first worked out. In Table 1 a total of 5 properties are considered. A total of

$$\frac{5\,(5-1)}{2} = 10$$

design combinations are shown.

Based on the weighted property index chart presented in Table 2, a clear picture emerges regarding material selection.

Table 1 Possible Design Combinations

Serial No.	Properties Considered	1 (1)(2)	2 (1)(3)	3 (1)(4)	4 (1)(5)	5 (2)(3)	6 (2)(4)	7 (2)(5)	8 (3)(4)	9 (3)(5)	10 (4)(5)	Positive Decisions	Weighting Factors Wi
1	Strength to weight ratio	1	1	1	1	0	0	0	0	0	0	4	0.4
2	Fracture toughness	0	0	0	0	0	0	1	0	0	0	1	0.1
3	Specific stiffness	0	0	0	0	1	0	0	0	0	0	1	0.1
4	Thermal expansion	0	0	0	0	0	0	0	0	1	0	1	0.1
5	Cost	0	0	0	0	0	1	0	1	0	1	3	0.3

Table 2 Weighted Property Index Chart for Selection of Material for a Pressure Vessel

	Go/No Go Screening									
Material	Corrosion Resistance	Fabricability	Availability	Specific Strength 0.4	Fracture Toughness 0.1	Specific Stiffness 0.1	Thermal Expansion 0.1	Cost 0.3	WPI Without Cost Factor $\gamma = \Sigma\beta_i w_i$	WPI with Cost $\gamma = \Sigma\beta_i w_i$
304 Stainless steel	S(a)	S	S	83	32	61	53	50	47.8	62.86
Maraging steel	S	S	S	89	80	74.25	99	10	**61.82**	64.82
15CDV 6	S	S	S	66.5	100	81	100	15	54.7	59.82
D6AC	S	S	S	91.34	70	80	98	15–	**61.4**	66.6
Ti alloy (Ti-6A-4V)	S	S	S	100	35	79	93	9.3	60.7	63.5
Al Alloy	S	S	S	78.8	17	100	42	50	47.72	62.42
HSLA Steels (AISI 4130, AISI 4140, AISI 4340)	S	S	S	49	56.	80	71	100	40.3	**70.3**

(a) S, Satisfactory

As discussed earlier, for critical applications like rocket motor cases for strap-on boosters for space shuttle, motor cases for satellite launch vehicles, and missiles for strategic applications, cost of raw material is not a major concern. The performance of flight vehicle to meet the mission goal is the primary concern. From this point of view, as can be seen from Table 2, the preferred materials are Maraging steel and D6AC. This choice of materials closely matches with the existing solutions, which are reported in literature and is presented in Table 3.

However, for less-critical missions, such as free-flight artillery rockets, which are manufactured in hundreds of thousands with recurring requirements to meet the operational requirements of the artillery units, easy availability and cost of raw material become very significant considerations; often the later dictates the choice of the material. Hence High Strength Low Alloy (HSLA) steels like AISI 4130 and AISI 4340 steels find applications for rocket motor case manufacture.[2,4]

Table 3 Materials Used in Large Solid Rocket Motors

Material	Heat Treatment
PS-1(PSLV) Maraging Steel	Aging at 480 °C
Titan III Booster D6AC	Harden and Temper
Minuteman D6AC	Harden and Temper
Space Shuttle (Strap-on Booster) D6AC	Harden and Temper

5. Selection of Manufacturing Process for Motor Cases

The ease of processing a material has a major influence on the cost of a component. If the scrap rate is high because of cracks, poor surface finish, or failure to meet specified dimensions and tolerances, the cost of the manufacture goes up. Hence, the process should be improved or changed. Difficulty in working or fabricating a material can often be overcome by a change in the manufacturing process. Thus, an alloy that is difficult to work may be more successfully extruded than drawn. There has been increasing emphasis on chipless machining processes by which a part is made to final or near-net shape. Precision forging, precision investment casting, powder-processing techniques, etc. are good examples of this.

As the mineral resources of the world are running out at an alarming rate, the price of engineering materials will continually rise in the future. The percentage of the cost of a manufactured component that is due to cost of raw materials is also rising. Thus, there is strong economic incentive to conserve material through processing.[3]

Rocket motor cases must be manufactured with excellent specific strength, close dimensional tolerances, good surface finish, and minimum mass unbalance so that excellent performance in flight can be achieved. Therefore, the selection of the appropriate manufacturing process from a large number of manufacturing methods available is a difficult task. Hence the concept of a Weighted Property Index (WPI) can be employed in the selection of the most satisfactory manufacturing method for motor cases. For properties that are not readily expressed in numerical values, e.g., fabricability and wear resistance, some

Table 4 Comparison Chart for Various Metal-Forming Processes for Manufacture of Tubes Based on Weighted Property Index Based on Subjective Rating

Serial No.	Manufacturing Process	Dimensional Accuracy	Minimum Thickness Possible	Force Requirement	Material Waste	Production Cost	Design Flexibility	Weighted Performance Index
Scaled property of relative grading								
1	Rolling and Welding	40	40	80	80	100	40	380
2	Rotary Tube Piercing	60	40	60	60	60	20	300
3	Hot Extrusion	20	40	80	60	60	20	280
4	Cold Extrusion	60	60	60	80	60	20	340
5	Hydrostatic Extrusion	80	60	80	80	80	20	400
6	Tube Drawing	60	40	60	80	60	20	320
7	Deep Drawing	60	60	40	60	60	20	300
8	Pilger Process	60	40	60	60	60	20	300
9	Flow Forming	100	100	100	100	80	100	580

Dimensional Accuracy, Minimum Thickness Formable, Design Flexibility:

Relative Rating	Scaled Property
Excellent: 5	5–100
Very Good: 4	4–80
Good: 3	3–60
Fair: 2	2–40
Poor: 1	1–20

Production Cost, Force Requirement, Material Waste:

Relative Rating	Scaled Property
Lowest: 5	5–100
Low: 4	4–80
High: 3	3–60
Very High: 2	2–40

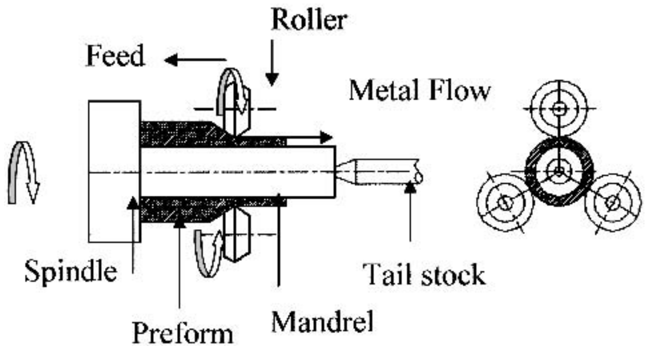

Fig. 1 Flow-forming process

Table 5 Percent Saved Using the Flow Forming Method Compared to Machining Methods

		Percent Saved		
Serial No.	Component	Material Cost	Machining Cost to Common Stage of Manufacture	Total per Engine Cost
1	Pneumatic Ram Cylinder	84.3	…	50.0
2	Low-Pressure Compressor Drive Shaft	50.7	66.7	54.3
3	High-Pressure Compressor Drive Shaft	15.9	30.5	18.4
4	Rear Flange of Stator Support Cone	19.7	42.2	20.8
5	Turbine Bearing Housing Diaphragm	41.0	45.5	41.4

Table 6 Deformation of Materials Possible in Flow Forming

Serial No.	Material	Percentage of Thickness Reduction
1	Stainless Steel, AISI 304 (Cr: 18%, Ni: 8%, C: 0.08% maximum)	95
2	Maraging Steel, MDN 250 (Equivalent to ASTM A 579-70 Grade 72 and DIN Werkstoff No. 1.6359.4)	96
3	42 Cr Mo4, UNI (Italian Specification), Equivalent to AISI 4140	80
4	15CDV6 (French Specification for Alloy Steel), Equivalent to DIN 14CrMoV6-9 (C: 0.10–0.16%, Mn: 0.80–1.10%, Cr: 1.25–1.50%, Mo: 0.8–1.0%, Ni: 0.5%, P: 0.03%, S: 0.03%, Si: 0.20%, Fe: balance)	82
5	Low-Carbon Steels	90
6	Al Alloys	60–80

kind of subjective rating is required. These are presented in Table 4,[2,5-7] which helps in selecting the most suitable manufacturing method for rocket motor cases.

It can be seen from Table 4 that the flow-forming technique has emerged as the most favorable manufacturing method for motor cases. Further, to highlight the order of percent saved that can be achieved using flow forming compared to machining methods, the following example is given in Table 5.[8] Rocket motor cases have been manufactured by flow forming using D6AC and HP-11 steels.[4] PHENIX rocket motor cases (by CELERG Company, France) are manufactured from 15CDV6 steel by flow forming.

Flow forming is essentially a point-deformation rotary metal-forming process. The material (preform) is elasticized by the localized application of heavy compressive forces exerted by conical rollers. The deformed metal takes the shape of the mandrel contour and proper wall thickness following the principle of equal volume. Figure 1 shows a reverse flow-forming technique. In reverse flow forming, the deformed material flows in the direction opposite that of roller feed, whereas feed and material flow directions are the same in forward flow forming.

Flow forming increases the ultimate tensile strength, yield strength, and hardness, and reduces ductility due to work hardening. It offers excellent strength, dimensional tolerances, and surface finish, and minimum material waste by chipless forming.

Flow forming has several other remarkable advantages over conventional tube-forming methods. Conventionally, tubes are produced by hot extrusion followed by drawing or pilgering. However, it is not practicable to hot extrude thin wall tubes beyond a specified limit. As drawing is an easier and cheaper process, a thick wall tube is cold extruded and finished on a draw bench or pilger mill. The drawing process is essentially a tensile process. Microcracks inside the material tend to propagate, leading to failure of the material, and therefore the area reduction in the case of hard materials is limited to 10%, while the total reduction before annealing that must be carried out to restore the ductility of the material is limited to about 50-60%.[9] The number of passes needed to obtain the area reduction for producing a finished tube is considerably larger, involving a number of processing cycles, and consequently increases the cost of production. It is obvious that using drawing operation for producing tubes from difficult to form materials is very expensive. Theoretically, a seamless tube represents the ultimate in reliability.[10] The resulting component has a stretched crystalline structure with a resulting increase of hardness, yield strength, and ultimate tensile strength, followed by a corresponding reduction in ductility.

In reverse flow forming reductions up to 90% and above are obtained[11] depending on material, which is quite high compared to drawing operation. Some of the deformations possible are given in Table 6.

Apart from these advantages, the other remarkable advantages are

- Difficult to work materials can be easily flow formed.
- Low-strength, low-cost materials can be used for high strength application due to work hardening in flow forming.
- The manufacturing method is eco-friendly.

- Extremely thin tubes (0.15 mm) can be formed.
- Fatigue resistance increased, especially in notch-sensitive materials due to smoothness of surface, which is burnished rather than cut, and due to an increase in surface harness.
- Flares in metals show up during power spinning; the process acts as its own inspector.
- Pressure vessels can be formed with integral closures.
- Tubes with diameters of 600 mm can be formed accurately.
- Monolithic components offer high reliability and reduce the fabrication cost as much as 20%.[12]

6. Conclusions

Selection of materials for motor cases for critical application from a large number of candidate materials is a challenging task. There is no limit to the demands of a design engineer. In the method suggested in this paper, a decision matrix is generated in which each material property is assigned a certain weight depending upon its importance to the service requirements. The different properties are normalized using a scaling factor. Based on this approach, a weighed property index is computed. The material, which yields the maximum weighted property index, is selected for fabrication. It has been shown in this study that for strategic rocket applications, the preferred materials are Maraging steel and D6AC steels, which closely match with the existing solutions. For other less-critical applications, HSLA steels are recommended

In view of the many advantages offered by flow forming over conventional tube forming methods enumerated in the preceding pages and also based on the comparative performance index (see Table 4), the flow forming technique stands out as the most attractive method for manufacture of high-strength, high-precision tubes required for critical applications in very large numbers. The entire production process can be automated with the availability of advanced heavy-duty Computer Numerical Control (CNC) flow-forming machine centers.

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