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Appropriate Selection of Material for Rocket Motors used in Aerospace Applications

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Abstract

This paper focuses on appropriate selection of material for manufacturing of rocket motor case used in aerospace applications. Motor case should be light weight, stiff, strong, resistant to crack growth and allows minimum heat flux. Initially, respective properties and material indices have been derived by making certain assumptions. The appropriate range of materials has been identified in first step with help of derived material indices. These material indices are plotted in Cambridge Education System software with their appropriate slopes. By finding and putting the appropriate slopes the suitable materials are screened. These screened materials are further analyzed by novel heuristical approach. Finally, material/s is proposed for manufacturing of rocket motor case on the basis of analysis supported by available literature.

Keywords: Materials, Manufacturing, Material indices, Heuristical Approach

1. Introduction

In aerospace applications, rocket motor is the main component for any spaceship launching rockets [1].This motor assembly basically encloses propellant [2]. Propellant burns and creates thrust. To balance thrust a reaction force causes rocket to lift the aerospace rocket.

Burning of propellant causes extremely severe conditions i.e., higher pressures and temperatures [3].

High internal pressures or buckling phenomenon beyond a specified limit may fail the rocket motor [4]. Inadequate materials and design selection can cause abrupt failure of motor. Improper adiabatic condition can also damage the rocket motor [1,5]. Besides, additional requirement for motor case needs to be moisture resistant [6]. Improper liner and motor interface also causes problems during flight [7]. Therefore, motor case needs to have the adequate strength and heat resistance.

Several materials have been used in manufacturing of rocket motor cases. These materials include phenolic or thermoset based epoxies as matrices. Materials mostly used as reinforcements are asbestos, carbon black and carbon fibers [8,9]. Phenolic resins are much more erosion resistant due to proper char formation during propellant burning [10,11]. In contrast, phenolic resins matrices cannot survive higher strains [12]. Similarly, ablation resistance of carbon black is insufficient to endure erosion and higher stresses during combustion of propellant. Additionally, carbon black has been declared as carcinogenic by international agency for research on cancer [13]. Health hazards related to asbestos also makes this an unsuitable candidate for rocket motor application [14]. Maraging steels are also used in manufacturing of rocket motors. However, assembly of maraging steel based rocket motor is performed by welding. Higher number of welds increases residual stresses which ultimately affects the strength of the motor [15,16]. Furthermore, carbon fiber and carbon- carbon composites both have relatively higher thermal conductivity. Higher thermal conductivity makes thermal gradient less steeper. Ultimately, the objective of manufacturing high efficiency and efficient motor case becomes difficult. Moreover, adequate material needs to be selected. Although several materials have been analyzed previously by finite element analysis and other related techniques and softwares however, to the best of our knowledge, proper optimal selection of material for rocket motor case which is light weight, strong, stiff, resistant to crack growth and allows minimum heat flux has not been performed using combinatorial analysis of material indices and novel heuristics.

This paper emphasizes on the selection of appropriate material for manufacturing high quality rocket motor. The appropriate selection of materials has been performed by deriving the respective material indices. These material indices are plotted in Cambridge Education System (CES) software with their appropriate slopes. By finding and putting the appropriate slopes the suitable materials are screened. These screened materials are further analyzed by novel heuristical approach. Finally, material/s is proposed for manufacturing of rocket motor case.

2. Methodology

2.1 Deriving the material indices

Material indices need to be derived by considering the high tension and buckling stress in the motor. Initially, rocket motor can be considered as a light weight pressure vessel which should withstand higher pressures without failure [17]. Afterwards, rocket motor filled with propellant is assumed to be a light and stiff column. This column resists axial or compression loading on the motor case. Moreover, in this application proper insulation and maximum adiabatic condition needs to be maintained.

2.2 Plotting material indices

Material indices are plotted on *x* and *y*-axis respectively. Slope of the curve depends on ratio of the quantity on *y*-axis divided by quantity on *x*-axis. Non-linear material indices are converted into linear relations. Materials having higher specific strength, modulus and less crack growth are screened in first step. After that materials having higher thermal diffusivity are further screened out.

2.3 Final selection by heuristics

Finally, heuristics have been employed to select the best possible candidate. All the materials are assigned weights based on their respective properties. The values of properties are converted into another scale ranging between zero to one. Minimum value is zero and maximum value of this scale is one. Furthermore, two cases exist in heuristical based approach. In first case maximum value of a property is desired. In that case the general formula is written as follows:

$$P_{iE} = \frac{V_{Ei}}{V_{\max}} \tag{1}$$

In abovementioned relation P_{iE} is the normalized scale value of a material obtained by ratio of respective value of property (V_{Ei}) of respective material i divided by material having maximum value of that property (V_{max}). Conversely, the relation for minimizing a certain property becomes:

$$P_{iE} = \frac{V_{\min}}{V_{Ei}} \tag{2}$$

Aforementioned relation normalized scale is ratio of minimum value of that property (V_{min}) and respective value of property (V_{Ei}) of material i. Normalized values of each property of these finally screened materials were calculated from Eqns. (1) and (2) depending on the requirement. Furthermore, value of P_{iE} is multiplied with respective weight factor. Finally, relation can be written as follows:

$$MSA_i = \sum_{E=1}^{r} P_{iE} w_E = w_E P_{1E} + w_{E+1} P_{2E} + w_{E+2} P_{3E} + \ldots\ldots + w_r P_{iE} \tag{3}$$

Where weight assigned to individual property ranges from w_E to w_r.

3. Extracting material indices

3.1 Deriving material index for light and strong motor

Rocket motor almost resembles thin walled pressure vessels in geometry. Therefore, the relation for mass of rocket motor can be written as:

$$m = 4\pi R^2 t\rho \tag{4}$$

In abovementioned relation, t is wall thickness, R is the radius and ρ is density of material used to construct motor. However, motor failure of motor mostly depends upon hoop stress. Hoop stress is written mathematically as:

$$\sigma = \frac{pR}{2t} \tag{5}$$

To prevent motor from failure, the applied stress σ should be smaller than yield stress of wall σ_y i.e., $\sigma < \sigma_y$. To achieve higher σ_y the wall thickness t is mathematically given as:

$$t \geq \frac{pR}{2\sigma_y} \tag{6}$$

Mass is main objective function in this case whose final relation becomes:

$$m \geq 2\pi R^3 \rho \left(\frac{\rho}{\sigma_Y} \right) \tag{7}$$

However, the mass shall be minimized to make the motor light weight. Hence, the index is written in inverse order.

$$M_1 = \left(\frac{\sigma_Y}{\rho} \right) \tag{8}$$

3.2 Deriving material index for light and stiff motor

Rocket motor can be approximated as a column in axial direction. Thus, the relation for mass of the column is:

$$m = Al\rho \tag{9}$$

The motor can buckle elastically in axial direction only if applied load (F) during flight exceeds Euler critical load (F_{crit}). Hence, to avoid buckling applied force should be less than Euler critical load i.e., $F \leq F_{crit}$

$$F \leq F_{crit} = \frac{\pi^2 EI}{L^2} \tag{10}$$

(E) is elastic modulus and (L) is length of the column. (I) represents moment of area in Eq. (10). In addition, I is mathematically expressed as:

$$I = \pi r^4 / 4 = A^2 / 4\pi \tag{11}$$

$$A^2 = \frac{4FL^2}{\pi E} \tag{12}$$

By putting value from Eqn. (12) into Eqn.(10) the relation of mass can be rewritten in the form:

$$m \geq \left(\frac{4FL^2}{\pi}\right)^{1/2} L\left(\frac{\rho}{E^{1/2}}\right) \tag{13}$$

Material index for light and stiff motor is written as:

$$M_2 = \left(\frac{E^{1/2}}{\rho}\right) \tag{14}$$

3.3 Deriving material index to avoid rapid fracture

Rapid fractures can develop in rocket motors due to harsh operating conditions. To avoid fracture, applied stress (σ) should be less than failure stress (σ_f). Furthermore, relation of σ_f with fracture toughness (K_{Ic}) and flaw or crack diameter a_c^* is given as:

$$\sigma_f = \frac{K_{Ic}}{C\sqrt{\pi a_c^*}} \tag{15}$$

C is a constant term in Eqn. (15). In addition, by putting Eqn. (15) into Eqn. (6) yields:

$$t = \frac{pR}{2K_{Ic}}\sqrt{\pi a_c^*} \tag{16}$$

Further putting Eqn. (16) into Eqn. (4), mass of the motor can be expressed as:

$$m \geq 2\pi R^3 \rho\sqrt{\pi a_c^*}\left(\frac{\rho}{K_{Ic}}\right) \tag{17}$$

Material index for light weight and fracture resistant rocket motor becomes:

$$M_3 = \left(\frac{K_{Ic}}{\rho} \right) \tag{18}$$

3.4 Deriving material index for maximizing temperature shock wave travel time

During burning of propellant temperature of the internal surface of motor case increases very rapidly which generates temperature wave. This temperature wave travels distance (*X*) inside the motor case wall in time *t*. Flight time of rocket motor usually ranges up to few seconds depending upon composition and impulse generated by propellant. *X* is related to wall thickness of motor case by formula:

$$X^2 = CW^2 \tag{19}$$

Where *C* is the constant whose value is one or unity. However, *X* is further mathematically related with time (*t*) taken by temperature wave to propagate inside motor case and thermal diffusivity (*a*) as:

$$X = \sqrt{2at} \tag{20}$$

Putting Eqn. (20) in Eqn. (19) and the resulting relation can be written as:

$$t = \frac{CW^2}{2a} \tag{21}$$

t is maximized by choosing minimum value of *a*. *a* is also related with thermal conductivity (λ), specific heat capacity (C_p) and ρ [see Eqn. (22)].

$$a = \frac{\lambda}{C_p \rho} \tag{22}$$

4. Results

4.1 Specific strength and modulus

Initially composites, fibers, particulates, metal, alloys and thermosetting polymers were selected for analysis (these included a total of 2868 materials) [see Fig.1]. High internal pressure i.e., more than 103bars may lead to failure of rocket motor. To bear this internal pressure material should have higher specific strength. After plotting the curve between σ and ρ approximately 550 elements were screened out which are having relatively higher specific strength [see Fig.2]. Moreover, relatively higher specific modulus is also required to prevent motor from buckling. Hence, plot between E and ρ having a slope of ½ further screens down only 300 materials. Fig. 3 further indicates that these 300 materials are having relatively higher specific strength and modulus. Both these properties are needed in materials used to manufacture rocket motor.

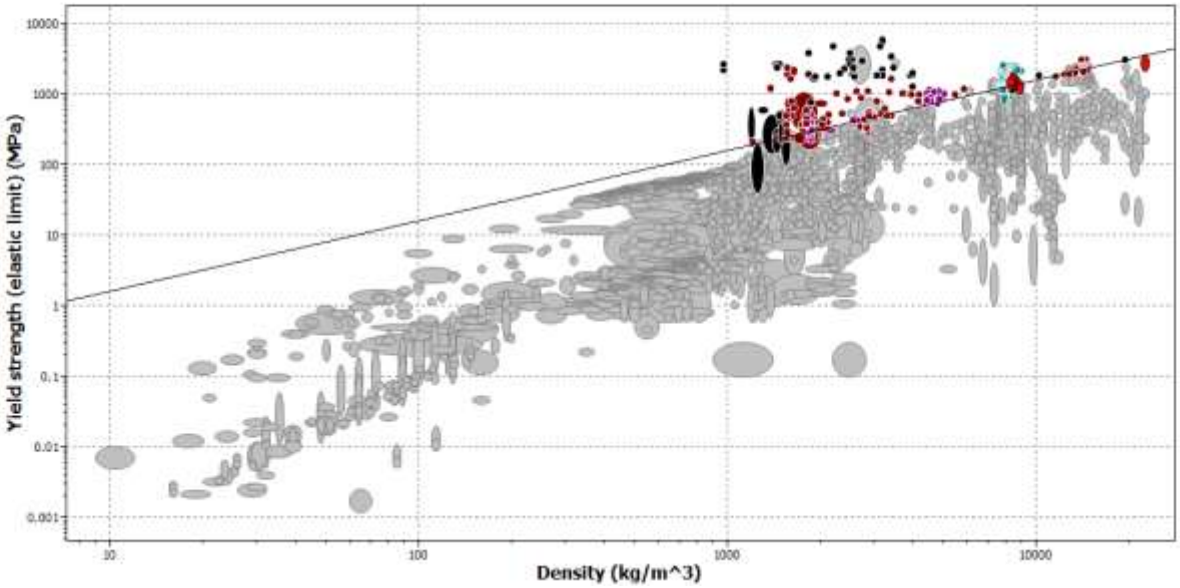

Fig. 1. Plot between density and yield strength

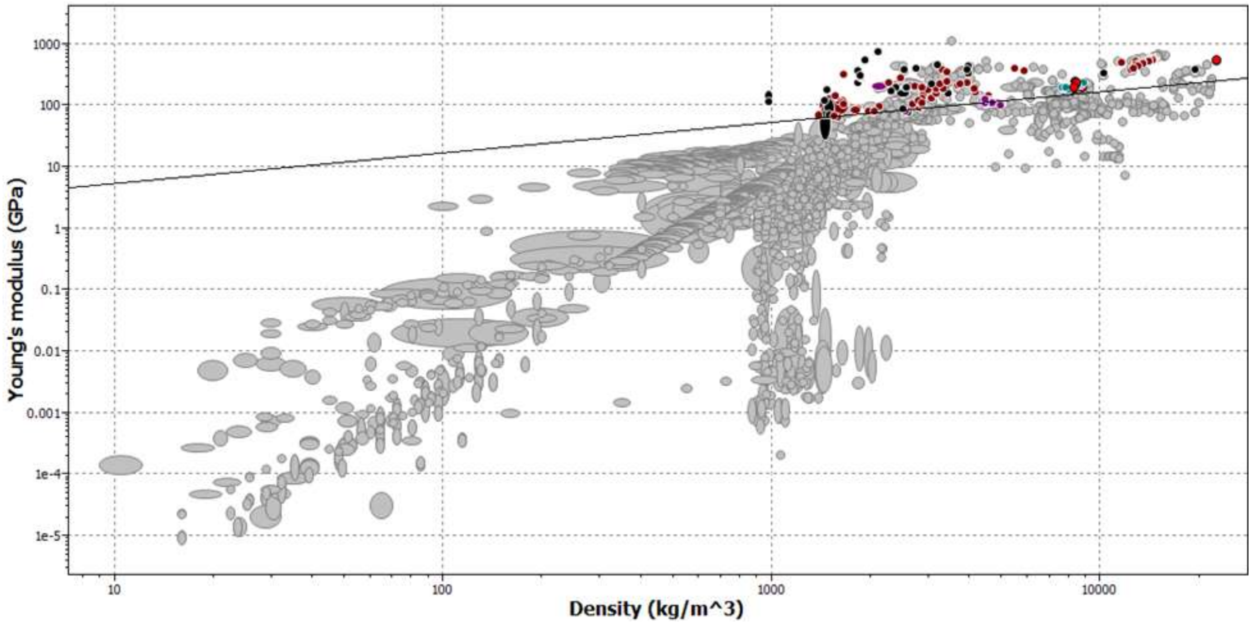

Fig. 2. Material indices plot between density and young modulus.

4.2 Specific fracture toughness

To screen the materials having higher crack resistance against propogation, graph is plotted between K_{Ic} and ρ. Fig. 4 shows that only nineteen have been further screened out of 300 materials. These nineteen materials include ten alloys i.e., alloy steel AF 1410, nickel-beryllium alloy (alloy 440), nickel-cobalt-chromium alloy (AEREX-350), nickel-iron-chromium alloy (UDIMET 630), six titanium alloys. In addition, nine composites are also screened by this index which includes Poly ether ether ketone (PEEK) with carbon fiber, cyanate ester with high modulus carbon fiber, bismaleimide (BMI) with high strength carbon fiber, epoxy carbon fibres, epoxy with simple carbon fibre, epoxy with aramid fiber respectively. To further screen out of these nineteen materials thermal diffusivity needs to be analyzed.

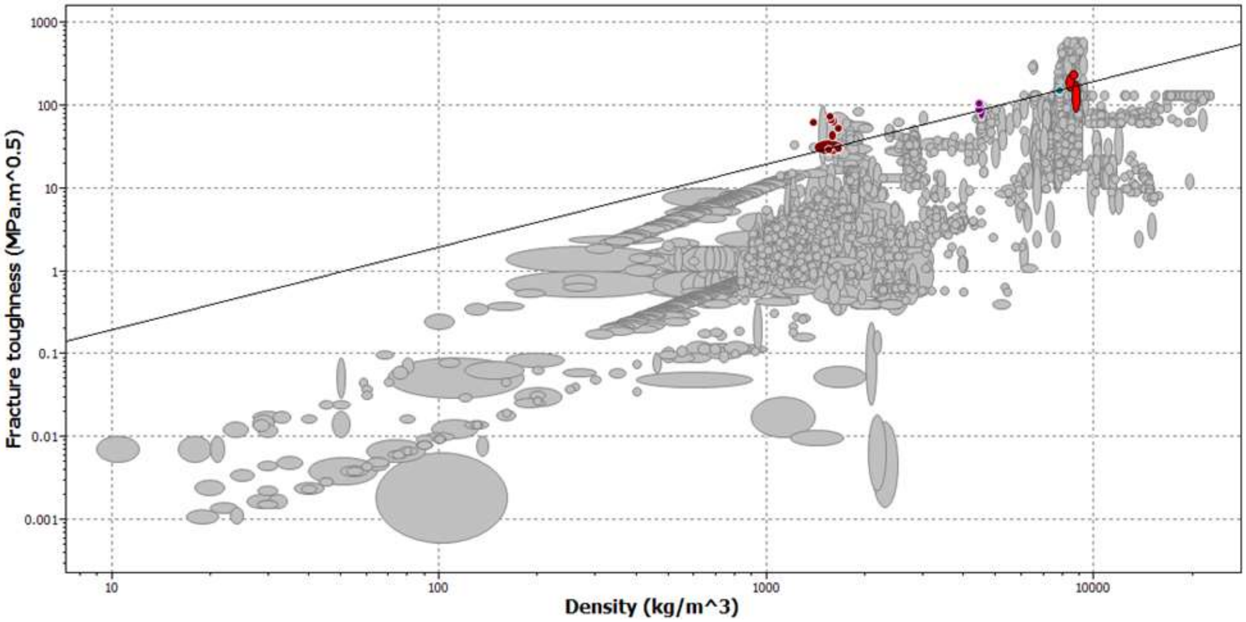

Fig. 3. Material indices plot between density and fracture toughness.

4.3 Minimizing thermal diffusivity

Minimizing thermal diffusivity means to select those materials which have minimum thermal conductivity. Only four materials are left after this analysis which includes cyanate ester with high modulus carbon fiber, bismaleimide (BMI) with high strength carbon fiber, epoxy carbon fibres, epoxy with aramid fiber respectively [see Fig. 5]. These four materials have relatively less thermal conductivity and diffusivity when compared with previously screened fifteen elements [see Fig. 4 and 5]. This further means that these materials can resist the sudden temperature wave for longer period of time.

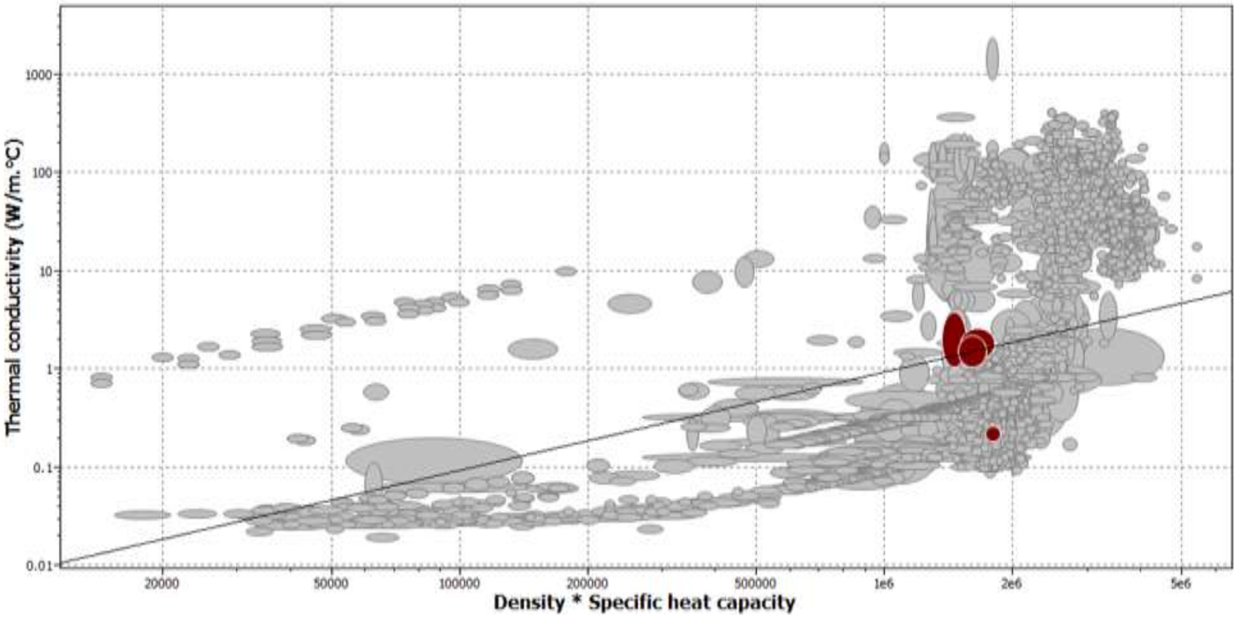

Fig. 4. Material indices plot between density and heat capacity versus fracture toughness.

4.4 Heuristical approach

Normalized values of each property of these four finally screened materials were calculated from Eqns. (1) and (2) [Consult Table 1 & Table 2]. Density, strength, Afterwards, each property was also given an equal weight factor and the values were put in Eqn. (3) [As shown in Table 1]. Material selection heuristical (MSA) relation suggests that epoxy composite with aramid or Kevlar fibers shall be selected. Therefore, epoxy and aramid (Kevlar) fiber composite shall be major constituent for manufacturing of rocket motor.

Table. 1. Respective values of density, yield strength, fracture toughness and thermal conductivity of four screened materials.

Material	**Density (Kg/m^3) (0.25)**	**Yield Strength (MPa) (0.25)**	**Fracture Toughness ($MPa.m^{0.5}$) (0.25)**	**Thermal Conductivity (W/m ℃) (0.25)**
BMI + Carbon fiber	1510	507	26.5	1.06
Cyanate ester + High Modulus Carbon Fiber	1620	607	27.7	1.28
Epoxy + Aramid Fiber	1380	1100	56.3	0.19
Epoxy + High Strength Carbon Fiber	1540	627	37.9	1.08

Table. 2. Conversion of properties to their respective relative scales using Eq. (1) and (2).

Material	**Density (Kg/m^3) (0.25)**	**Yield Strength (MPa) (0.25)**	**Fracture Toughness ($MPa.m^{0.5}$) (0.25)**	**Thermal conductivity (W/m ℃) (0.25)**
BMI + Carbon fiber	0.914	0.461	0.469	0.179
Cyanate ester + High Modulus Carbon Fiber	0.852	0.552	0.492	0.148
Epoxy + Aramid Fiber	1.000	1.000	1.000	1.000
Epoxy + High Strength Carbon Fiber	0.896	0.570	0.673	0.176

Table. 3. Determination of Material selection analysis (MSA) factor's value for each of four material using Eq. (3).

Material	**Density (Kg/m³)**	**Yield Strength (Mpa)**	**Fracture Toughness (MPa.m $^{0.5}$)**	**Thermal Conductivity (W/m ℃)**	**Commutative Weight Factor**
BMI + Carbon fiber	0.228	0.115	0.117	0.045	0.506
Cyanate ester + High Modulus Carbon Fiber	0.213	0.138	0.123	0.037	0.511
Epoxy + Aramid Fiber	0.250	0.250	0.250	0.250	1.000
Epoxy + High Strength Carbon Fiber	0.224	0.143	0.168	0.044	0.579

5. Discussions

Although based on material indices and heuristical approach epoxy aramid composite is proposed however, only using suggested material has some limitations in aerospace applications. Inspite of minimum heat conductivity, Kevlar fibers usually degrade up to temperature of 1450 °C. In contrast, final decomposition temperature for carbon fiber is 3450°C [18]. Furthermore, heat insulation or liner usually made of ethylene propylene diene monomer (EPDM). Moreover, interface bonding of liner with motor case also plays significant role. Improper bonding between liner or insulation and motor case can detach the motor case, liner and propellant causing catastrophic failure [19].

Previous study suggested maraging and AISI-4130 steels for manufacturing rocket motor cases [20]. However, welding joints increases the probability of failure due to higher residual stresses in welded portions [16, 21]. Additionally, higher flame can cause problems in steel based rocket motors. Hence, composite manufactured rocket motor is preferred over steel made motor case. Composite motor case can be made possible by filament winding process [22].

Initially, first layer of carbon fiber or carbon-carbon composite must be used for manufacturing motor case. Both the aforementioned materials possess higher thermal resistance. Afterwards, Kevlar fiber must be wound to desired thickness in hoop and helical patterns. At first, hoop winding should be accomplished followed by helical pattern. Optimum angle for helical winding pattern ranges from 51^o to 55^o.

6. Conclusion

Most appropriate material for manufacturing rocket motors has been proposed based on material indices and heuristical relations. On the basis of both these analysis Kevlar or aramid fiber and epoxy composite has been suggested. However, due to decomposition of Kevlar at 1450^oC first layer attached to liner or insulation shall be of carbon fiber or carbon- carbon composite. Afterwards, hoop and helical windings of Kevlar epoxy composite shall be performed to desired thickness. Manufactured motor case will have higher specific strength, specific modulus and fracture resistance. Minimum heat transfer is achieved using Kevlar epoxy composite. In addition, future experimental studies can focus on optimum blend of epoxy and phenolic resins with Kevlar to achieve more superior erosion and ablation resistance characteristics.

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