

Solid Rocket Motor Case: A Review of Existing Design and Composite Material Criteria

Padala Murali Krishna¹, Ramesh Velumayil^{2,*}, Karthik Krishnasamy², Manikandan Kannan¹, Prabhu Kishore³, M. Ganesh⁴

Abstract

Solid propulsion systems are an integral part of inaugural vehicles for many space agencies because of their relatively simple design and high reliability. The solid propulsion rocket motor case design, including the material used for fabrication, is an important aspect as it affects the solid rocket motor's performance, reliability, and safety. In this abstract, an attempt has been made to review the most commonly used materials in the manufacture of solid rocket motor cases worldwide, including ultra-Superior-strength steels and composites. Discussion of the manufacturing process used for construction has also been touched upon. This paper also highlights the design considerations of a solid propulsion rocket motor case. Solid rocket motor cases can typically be modelled as cylindrical, thin-pressure vessels to estimate the overall design configuration. The design process involves optimizing various parameters, including the case diameter, length, and material for fabrication, to meet the flight mission requirements. The motor case design must take into account the internal pressures generated during the combustion of the propellant. The aerodynamic load experienced in flight, including the maximum dynamic pressure phase, must also be accounted for. In conclusion, Using a rocket case that is properly constructed with suitable material would be beneficial in maximising the payload's fraction of mass for the liftoff vehicle. The continued enhancement of solid rocket motor casing design is facilitated by the continuous progress in materials and production processes.

Keywords: Solid propulsion; composites; combustion; aerodynamic load; payload mass fraction

INTRODUCTION

A solid propulsion rocket motor uses solid propellants to generate thrust, burning from the inside with a casing, creating high-temperature gases [1-2]. These gases are expanded through a nozzle at the rear of the rocket motor generating a reactive force known as thrust, as per Newton's third law of motion. Solid rocket motors are regarded for their reliability and simplicity in design, and they find applications in various fields, including missiles, launch vehicles, and emergency crew escape system of a human space flight and in spacecraft propulsion systems. Important components of a solid rocket motor include the solid propellant, a motor casing, a nozzle for controlling gas flow, an ignition system to start the combustion, and thrust control system for control of pitch, yaw and roll motion in flight. Following describes the key component of a solid propulsion rocket motor:

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Received Date: January 25, 2024

Accepted Date: April 29, 2024

Published Date: September 28, 2024

Citation: Padala Murali Krishna, Ramesh Velumayil, Karthik Krishnasamy, Manikandan Kannan, Prabhu Kishore, M. Ganesh. Solid Rocket Motor Case: A Review of Existing Design and Composite Material Criteria. Journal of Polymer & Composites. 2024; 12(Special Issue 6): S224–S232.

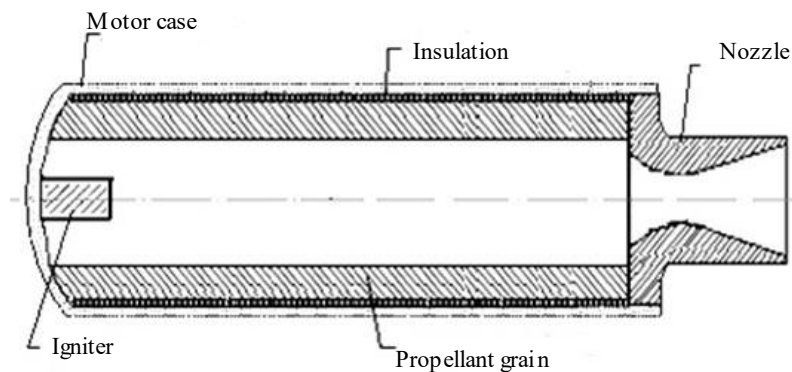


Figure 1. Section view of solid rocket casing.

1. *Propellant*: The solid rocket propellant is a mixture of fuel and oxidizer bound together in a solid, stable form. Common fuel and oxidizer combinations include ammonium perchlorate with powdered metals like aluminium or other additives. Binders like Hydroxy Terminated Poly-Butadiene are added to bind the oxidizing agent, fuel and other ingredients into a solid but elastic mass in most composite propellant systems. The propellant is cast or extruded into a specific shapes like cylindrical, star shaped etc. within the motor casing. Shape of the propellant grain majorly decides the thrust time history of solid rocket propellant. A propellant grain, in the context of rocket propulsion, is the solid, shaped component of a rocket motor that contains the propellant and is designed to burn in a controlled manner to produce thrust (Figure.1)
2. *Motor casing*: The casing of a solid propellant rocket motor is a strong, heat-resistant cylindrical structure that contains the solid propellant. It provides structural integrity and protection for the burning propellant. Materials like steel or composite materials are normally used for the casing.
3. *Nozzle*: At the rear end of the motor, there is a nozzle that directs the flow of hot gases produced by the burning propellant. The nozzle's design affects the performance and efficiency of the motor by controlling the rate at which exhaust gases are expelled.
4. *Igniter*: An igniter initiates the combustion process of the solid propellant and could be in the form of a smaller rocket (pyrogen) or using electrical squibs (pyrotechnic). It provides the energy for sustained combustion inside the motor case.
5. *Insulation*: A sheet of insulation which is usually a rubber of high tensile strength and high specific heat is bonded to the inside of the casing to protect the casing from high temperature generated during the combustion process. The insulation rubber also holds the propellant in place during processing and storage.

Functioning of a Solid propellant Rocket Motor

Initially, the propellant is ignited using the igniter, leading to a rapid combustion that generates gases. These gases create pressure within the combustion chamber, forcing them to exit through the nozzle. Subsequently, the nozzle's area expands to further increase the velocity, as per the principle that an increase in area at supersonic speeds results in a rise in velocity [3-4].

Historical Perspective

The Chinese invented the first real rockets by accident in the first century. It was packed inside bamboo tubes with a type of gunpowder made only of saltpetre, sulphur, and charcoal dust. It was thrown into flames during religious celebrations to produce explosions. Through experimentation, it was found that these bamboo tubes filled with gunpowder could propel themselves only by the thrust generated by the escaping gas, leading to the development of the first real solid-propellant rocket [5-6]. Earlier rockets with solid propellants were used for the first time in Year of 1232. Because solid rockets are more reliable and straightforward than liquid engines, they are still in use today. Solid-propellant rockets are widely used in military applications such as missiles because they can be stored for long periods and safely launched at short notice. Because solid propellants behave differently from liquid

propellants, they are used for unique applications. Compared to solid propellants, liquid propellants have a higher specific impulse, but a lower overall impulse. Boosters using solid rockets to improve payload capacity are common. Solid rockets are difficult to switch on and off or adjust the throttle on. Spacecraft employed Solid Rocket Boosters (SRBs). Solid rocket motors typically consist of several key materials: The propellant in solid rocket motors is a mixture of fuel and oxidizer, often in a rubbery or plastic-like form. Common propellant ingredients include ammonium perchlorate, powdered metals (such as aluminum), and a polymer binder (such as hydroxyl-terminated polybutadiene, or HTPB). The casing of a solid rocket motor is typically made of a strong, heat-resistant material such as steel or a composite material like carbon fiber reinforced polymer (CFRP). The casing contains the propellant and withstands the pressure and heat generated during combustion. The nozzle is usually made of a heat-resistant material like graphite or a composite material. It is designed to withstand the high temperatures and pressures of the exhaust gases exiting the motor.

SOLID ROCKET PROPELLANT MOTOR CASING

The casing of a solid rocket motor is a pressure vessel designed to handle external stresses as well as internal combustion pressure during handling, storage, and in-flight. [7]. According to NASA SP-8025 [4], motor Case internal dimensions are among the fundamental motor case-design factors, length-to-diameter ratio, pressure, motor case inertia and flight loads internal and exterior envelope limitations, propellant mass fraction etc. The following are the primary considerations in casing design:

1. The rocket motor casing must be minimized in size while still maintaining an optimal contour to fulfill the specifications of the propellant grain design and provide for auxiliary equipment. The construction of the rocket motor casing can be conceptualized as a slender cylindrical pressure container subject to cylindrical stresses, which include a) hoop stress, or circumferential stress, a conventional stress in the tangential direction; b) axial stress, a conventional stress running parallel to the axis of cylindrical symmetry; and c) radial stress, a conventional stress in directions that are coplanar but perpendicular to the symmetry axis as depicted in Figure. 2. Typically, the wall thickness of rocket motor casings does not exceed approximately one-tenth (frequently quoted as $\text{Diameter} / t \gg 20$), hence sustaining the validity of the thin pressure vessel theory. The hoop stress, axial stress, and radial stress can be roughly calculated as PxR/t , $PxR/2t$, and P , respectively. [8].
2. The material used for the casing should have mechanical properties that meet or exceed the requirements for structural integrity at the critical operating temperature. This includes resistance to thermal, moisture, corrosive effects, and other potential hazards.

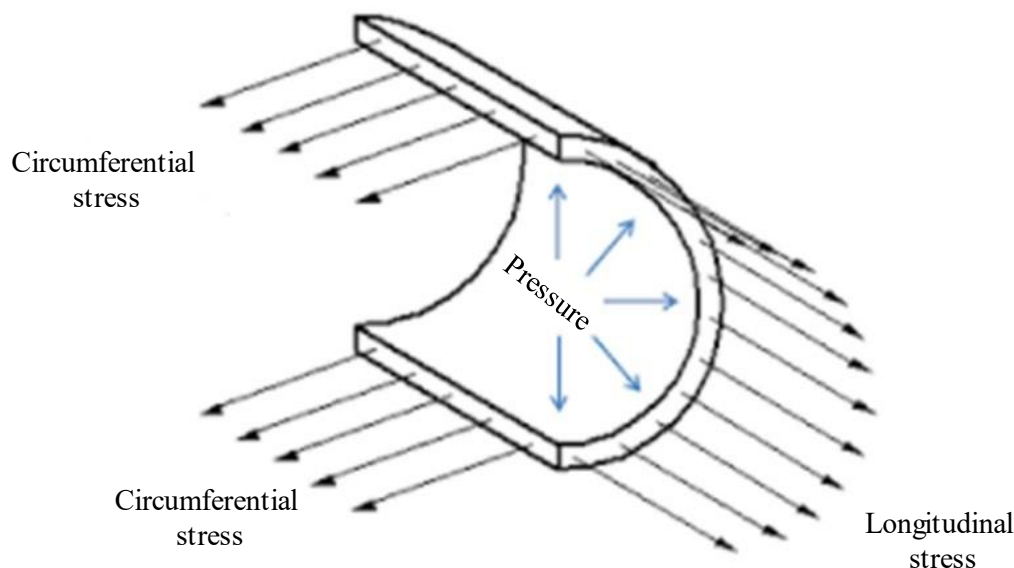


Figure 2. Different stress are acting inside of solid rocket casing.

MATERIALS USED IN SOLID ROCKET PROPELLANT MOTOR CASING AND ITS MANUFACTURING

The selection of materials for a solid rocket motor casing is critical as the motor case should be able to provide structural integrity to support the rocket, contain the high-pressure burning propellant, and withstand the extreme heat and mechanical stresses generated during the combustion of propellant. Some of the important factors which are considered when selecting materials solid rocket motor case include strength, thermal conductivity, weight and cost. Details on the material characteristics for the different solid rocket motors are provided in NASA SP-8025. The material for the solid propellant rocket motor is chosen based on these material characteristics in order to survive the pressures will be applied to the motor casing. NASA has provided information on the structural study of the solid rocket motor manufacturing joint, which includes both metallic and non-metallic components. A structural study is carried out to confirm the solid rocket motor's structural integrity at a specific working temperature. Post the fabrication, the motor casing usually undergoes a proof pressure test at a higher pressure than the pressure experienced by a rocket propellant motor case during combustion to qualify the motor casing integrity including the weld joints. Some of the common materials used for solid rocket motor casings are described in the following section [9-13]:

Steel Alloys

Due to Superior -strength steel alloys utilised in the fabrication of solid rocket motor casings are selected for their exceptional mechanical properties, which allow them to withstand the high pressures, temperatures, and mechanical stresses experienced during motor burn. These may include stainless steels, maraging steels, and other specialized alloys with high strength and heat resistance. High-strength steels exhibit exceptional strength, both in terms of yield strength (the point at which the material begins to deform plastically) and ultimate tensile strength (the maximum stress it can withstand without failing) [14-16]. These alloys are chosen for their ability to withstand the high internal pressures of the rocket motor without structural failure. Some of the most commonly used steel are as-follows:

Maraging steel

Maraging steels belong to an exclusive category of ultra-high-strength steel alloys, which are low-carbon variants. These steels demonstrate superior resilience and toughness compared to the majority of other steels, while maintaining a comparable ductility. The term 'Maraging' is a combination of 'martensitic' and 'ageing', indicating the method through which the steel's strength is enhanced. Distinctively, maraging steel does not rely on carbon to harden. Instead, it utilizes the precipitation of a unique blend of other intermetallic compounds. The lack of carbon, coupled with the use of intermetallic precipitation, facilitates maraging steel in achieving a balance of high strength and toughness, while still preserving a relatively high ductility. Below Table -1 shown in chemical composition of maraging steel .

Table 1. Chemical composition by weight of 18Ni-M250 Maraging Steel.

Chemical composition	Ni	Mo	Co	Ti	Al
Maraging Steel 18Ni-M250	18	5.0	8.5	0.4	0.1

D6AC

D6AC steel is a high-strength alloy made of carbon, manganese, chromium, molybdenum, vanadium, nickel, and tungsten [17]. It is known for its good physical and mechanical characterisation, including strength, toughness, and wear resistance. The alloy is utilised in various structural and mechanical applications, including aircraft landing gear, engine components, missile parts, and high-stress knife blades. Additionally, D6AC steel can be heat-treated to enhance its hardness and mechanical characterisation, and it is moderately weldable utilising standard welding techniques. Though it is more corrosion-resistant than standard carbon steel, it can rust when exposed to acidic or caustic environments. D6AC steel is a versatile and highly durable material that can withstand high loads and stresses, making it a popular choice in various industries. Its chemical composition is shown below in Table – 2.

Table 2. Chemical composition by weight of D6AC.

Chemical Composition	C	Si	Mn	Cr	Ni	Mo	V
D6AC	0.46	0.25	0.75	1.10	0.60	1.00	0.10

Composites Including Kevlar and Graphite-Epoxy Resins

Composite materials are often used in solid rocket motors because to their inherent material qualities, including a high strength-to-weight ratio, superior temperature tolerance, and the ability to be customised according to specific needs. Although these materials perform better than metals, advanced analytical techniques are frequently needed to evaluate their behaviour in situations with complicated mechanical and thermal loading [18-20]. Additionally, they could also develop defects while being manufactured, stored, handled, or transported. Some of the most commonly used composite material in solid rocket motor casings is discussed below.

Kevlar

Kevlar, a member of the aromatic polyamide family, is an organic fibre known for its exceptional strength and lightweight properties. Despite being a synthetic polymer, Kevlar can be woven into a fabric that surpasses the strength of steel by five times when compared at an equal weight. Moreover, its tensile strength is eight times more formidable than that of steel wire. The composite materials made from Kevlar fibres are seeing increasing use in the aerospace industry, being integrated into the construction of aircraft, missiles, and even rocket motor casings and nozzles. Kevlar fibre composites, when combined with aluminium, form superior hybrid composites. A unique quality of Kevlar is its ballistic resistance, which is attributed to the fibre's ability to withstand longitudinal splitting. This characteristic becomes particularly effective when Kevlar is combined with suitable matrices. The ongoing growth of Kevlar composites, which boast high strength, stiffness, and proven toughness, is incredibly relevant in today's technological climate. There is a growing demand for materials with excellent damage tolerance, superior strength and stiffness, good wet-hot properties, extended fatigue life, and low density. Kevlar, with its impressive portfolio of characteristics, meets these requirements admirably. [21].

Carbon Fibre

The majority of carbon atoms make into carbon fibres, which have a diameter of 5 to 10 micrometres. A few advantages of carbon fibres are their superior stiffness, excellent tensile strength, lightweight, outstanding chemical resistance, high temperature tolerance, and minimum thermal expansion. Carbon fibre's properties utilised in various applications such as, civil engineering, aerospace, and military [22]. However, they are a little more expensive than other fibres like glass or plastic. Strong, thin carbon crystalline filaments—basically, extended chains of carbon atoms joined together the building blocks of carbon fibre. Among the many advantages of carbon fibres are:

- Superior rigidity and an impressive ratio of rigidity to weight
- Superior tensile strength and the ratio of strength-to-weight
- High-temperature tolerance with special resins
- Minimum Thermal Expansion
- Superior chemical resistance

Table - 3 below illustrates the Material properties of Kevlar and Carbon Fibre comparison. Kevlar has a lower tensile strength than carbon fibre. However, Kevlar is of minimal density. Kevlar is also better in extreme temperatures than carbon fibre. Figure 3 shows the fibre texture of Kevlar and Carbon Fibre respectively.

Table 3. Material properties of Kevlar and Carbon Fiber Composites

Fibre material	Young's modulus (GPa)	UTS (MPa)	Density (g/cc)
Kevlar	30	480	1.44
Carbon fiber	70	600	1.9

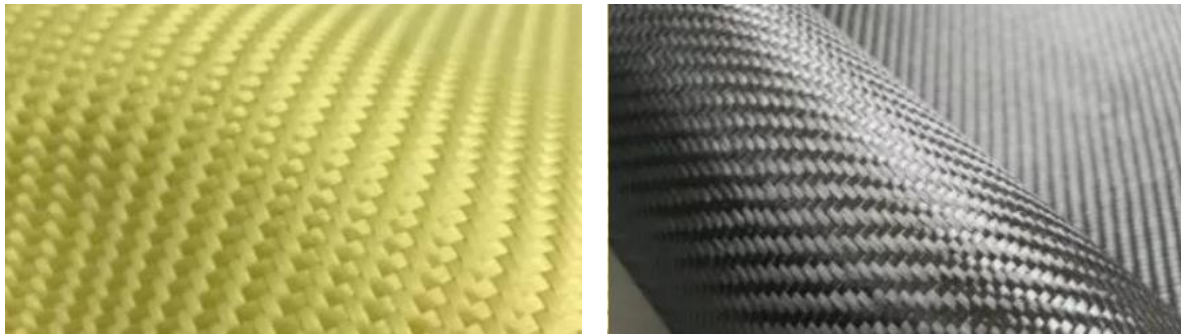


Figure 3. Kevlar fibre (Left) sheet vs carbon fibre sheet (Right)

Advantages of Composite over Typical Metallic Cases

High tensile strength and high compressibility allows composites them to be utilised in a variety of applications. The better characteristics of composite materials such as weight, stiffness, strength, etc. cannot be attained independently by their constituent components [22]. The following parameter lists the advantages that the composite has over traditional materials:

1. Superior weight ratio to strength: Superior weight ratio to strength implies that strong and lightweight applications can be made using composite materials. Because of this property, large rocket casings with extremely high strength and relatively light weight can be fabricated.
2. Complex metal components may be easily replaced by composite structures because composite materials enable easy part overlap. These approaches help shorten the production cycle.
3. High specific stiffness indicates a high stiffness to density ratio providing stiffness comparable to steel at a fifth of the weight of steel.
4. The high degree of corrosion and chemical resistance due to the inert properties of the exterior surface of the composites.

The material selection is based on the particular needs of the rocket motor. Stronger materials, such as titanium or steel, may be needed for big or high-performance motors in order for them to withstand the high temperatures and pressures. Lighter materials like composites or aramid fibers are often used in smaller, lightweight motors. In addition to material selection, the casing design and manufacturing processes also play a critical role in ensuring the reliability and safety of a solid rocket motor. The choice of material is made in consideration of the overall performance, structural integrity, and cost-effectiveness of the rocket motor casing.

Manufacturing Process of Solid Rocket Motor Casing

The solid rocket motor metallic case is usually fabricated using the forming-rolling-welding route for a safe and functional container motor case capable of withstanding internal pressure. Here's an overview of the typical fabrication process for a motor casing:

The cylindrical body of the motor case is formed by rolling the cut sheets into a cylinder shape. The end rings with tang and clevis joints are formed separately. The longitudinal seam of the cylinder is welded to create a continuous, cylindrical shell. Heat treatment techniques including annealing, precipitation hardening, tempering, normalizing and quenching are used for different metals based on the constituents and the mechanical properties desired. Post the heat treatment process, machining processes including drilling, reaming and tapping are carried out to end rings for manufacturing the assembly interfaces. In order to qualify the casing, proof pressure test is conducted by pressurising the motor case using hydraulically or pneumatically at a pressure slightly higher the maximum expected operating pressure. It is performed to validate the vessel's ability to withstand the specified internal pressure safely. They undergo a rigorous non-destructive inspection process to confirm each motor's Readiness for flight. The fabrication process of a cylindrical thin pressure vessel demands precision and adherence to established standards and safety protocols. Following these steps ensures the vessel's structural integrity and safety, making it suitable for various applications, including industrial storage tanks, pressure vessels, and more. NASA Space Shuttle's SRB [8].

The Solid Rocket Booster (SRB) motor case of the Space Shuttle was a crucial component of the shuttle's propulsion system. In this section, an outline is given on the motor case design of SRB.

The SRB motor case was a large, cylindrical structure that housed the solid propellant of the boosters. It had a length of approximately 149.16 feet (45.5 meters) and a diameter of 12.17 feet (3.7 meters). The motor case was segmented, consisting of several cylindrical sections that were assembled before each launch. These segments were made of a steel alloy called CRES (Corrosion-Resistant Steel), which provided the necessary structural strength and durability.

CHALLENGES AND FUTURE DIRECTIONS

The solid rocket motor case materials and manufacturing will face several challenges, as the space industry continues to mature. Some of the key challenges are included below:

1. *Improved performance and efficiency:* There is a growing demand for more efficient and high-performance solid rocket motors. Future materials and manufacturing methods will need to meet these demands by achieving higher specific impulses and better thrust-to-weight ratios.
2. *Reducing weight:* Weight reduction is a perpetual goal in rocket as lower the inert mass of the solid propulsion Rocket motor case, higher will be the payload which can be carried to space. Designing materials and manufacturing processes that allow for lighter but equally strong motor casings will remain a challenge.
3. *Innovative materials:* The development of novel materials with superior properties, such as higher temperature resistance and improved strength-to-weight ratios, will be crucial. Integrating these materials into manufacturing processes is a challenge.
4. *Composite materials:* The using of composite materials in solid propulsion rocket motor cases is increasing. The challenge lies in optimizing composite material design, ensuring consistent quality, and reducing production costs. Forming a seamless interface between the metallic flanges and the composite casing
5. *Advanced manufacturing techniques:* Embracing cutting-edge manufacturing techniques, such as 3D printing and additive manufacturing, while maintaining the reliability and consistency of motor casings is a challenge, especially for the metallic cases.
6. *Adaptation to emerging technologies:* Staying current with emerging technologies, such as smart materials and Industry 4.0 advancements, is a challenge for the solid rocket motor industry. Being an industry meeting the diverse needs of different rocket motor applications, from small launch vehicles to large space launch systems, requires customization in materials and manufacturing processes and is intense capital intensive. Integrating the modern emerging technologies is only going to enhance the manufacturing costs.

Addressing these challenges will be essential to meet the evolving requirements of the solid rocket motors, improve the performance and environmental impact of solid rocket motor casings, and ensure the continued growth and innovation of this critical technology.

CONCLUSION

In conclusion, the paper "Solid Rocket Motor Case: A Review of Existing Design and Material Criteria" has explored the critical aspects of solid rocket motor case design and material selection. Functioning of solid rocket motor, its components and historical significance has been touched upon in the initial section. Later, design of solid rocket motor casing has been discussed with various significant structural parameters. The paper moves to discussing the material utilised in the manufacturing of solid propulsion rocket motor cases including high strength metals like M250, D6AC and composites like Kevlar and Carbon Fibre. The article also addresses some difficulties and prospects. Simply said, the specifications for solid rockets motor casings involve several characteristics and are now the subject of ongoing research and development. As space exploration and commercial ventures increase in numbers, the importance of robust, cost-effective, and environmentally safe material is increased. This paper aimed to review some of the design and material criterion for solid rocket motor cases while also offering some challenges and opportunities in this area of space technology.

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