

Design and manufacturing of a composite solid motor casing using filament winding technology

Dinh Van Hien, Bui Van Am*, Tran Ngoc Thanh

Institute of Missile, Academy of Military Science and Technology, 17 Hoang Sam, Nghia Do, Hanoi, Vietnam.

*Corresponding author: kimam1994offich@gmail.com

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ABSTRACT

Composite materials are increasingly adopted in the fabrication of solid motor casings due to their low density, high specific strength, and excellent pressure resistance. This study presents a design methodology for a composite motor casing manufactured via filament winding technology. The study has successfully designed and fabricated a small-scale motor casing with a maximum operating pressure of 12 MPa using the filament winding method to directly wind T700 carbon fiber/epoxy matrix onto a mandrel made from RSI-12M propellant grains. The manufactured casing was evaluated through hydrostatic pressure testing, X-ray inspection for defect detection, and motor firing experiments. The experimental results demonstrated that the motor casing operated stably throughout the firing test, thereby confirming the feasibility of developing and mastering filament-wound composite solid motor casing manufacturing technology in Vietnam.

Keywords: Composite solid motor casing; SRM; Firing test.

1. INTRODUCTION

In recent years, composite materials have been increasingly adopted in the fabrication of solid rocket motor (SRM) casings due to their superior specific strength compared with conventional metallic materials and their excellent performance under high-temperature operating conditions. The application of composite materials enables a substantial reduction in structural mass while increasing the propellant mass fraction, thereby enhancing the overall efficiency and range of rocket systems. Owing to these advantages, the design and manufacturing of composite SRM casings have attracted significant research interest worldwide, leading to notable technological achievements. A representative example is the casing of the Russian Topol-M rocket motor, which is fabricated from glass fiber-reinforced composite materials [1].

Despite these advancements, the design of composite SRM casings remains a challenging research area because of its highly specialized nature and the limited availability of published technical references. Existing studies primarily focus on the theory and design of filament-wound cylindrical pressure vessels, which share certain geometric similarities with SRM casings. Typical references include Vasiliev (2009) [2] and Liang et al. (2002) [3], which mainly address methods for determining dome geometry and thickness for pressure vessels with a single polar opening. However, SRM casings differ fundamentally in that they possess two open polar ends and operate under distinct structural and loading conditions. Consequently, the material selection, structural design, and manufacturing technologies for SRM casings require specialized approaches beyond those developed for conventional pressure vessels.

Several accessible recent studies on composite SRM casings [4-7] have primarily employed constant winding-angle strategies to optimize laminate configurations. Although effective to some extent, this approach often results in non-uniform stress distributions across the casing surface, leading to localized stress concentrations and incomplete utilization of the material's load-bearing capacity. Furthermore, performance evaluations in these studies have largely been limited to numerical simulations and hydrostatic pressure testing, while experimental validation under actual motor firing conditions has rarely been reported.

In Vietnam, existing research has predominantly focused on the design and manufacture of composite pressure vessels [8], whereas studies addressing the fabrication, structural optimization, and full-scale testing of composite SRM casings remain limited.

To address these gaps, this study proposes a novel design methodology for composite SRM casings based on filament winding technology using both geodesic and non-geodesic roving trajectories to achieve a more uniform stress distribution throughout the casing structure. Unlike previous studies relying on constant winding angles, the proposed approach enhances structural efficiency by minimizing local stress concentrations and improving material utilization. Based on this methodology, a composite SRM casing compatible with RSI-12M propellant was successfully designed and manufactured, featuring a maximum operating pressure of 12 MPa. The novelty and practical applicability of the proposed design were comprehensively validated through hydrostatic pressure testing, X-ray inspection for defect detection, and, importantly, motor firing tests under real operating conditions. These results demonstrate the feasibility and effectiveness of the proposed approach for advancing composite SRM casing technology in Viet Nam.

2. DESIGN OF A COMPOSITE SOLID MOTOR CASING

2.1. Design basis of a composite solid motor casing

2.1.1. Assumptions and internal loads acting on the composite SRM casing

During operation, the SRM is subjected simultaneously to mechanical and thermal loads. When designing the casing, the following assumptions are used:

- The pressure in the motor chamber is considered to be uniformly distributed;
- When designing the SRM, a thermal protection layer of sufficient thickness is designed to ensure that the casing temperature remains below the temperature at which the material's mechanical properties are affected. To ensure stable engine operation, the design pressure is determined by $p = np_{max}$, where $n=2-3$ is the safety factor and p_{max} is the maximum pressure in the engine [9].

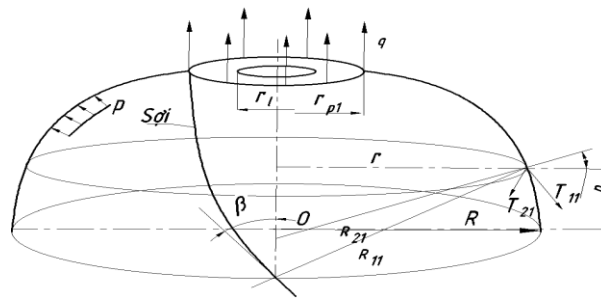


Figure 1. The geometry of a dome profile of the SRM casing.

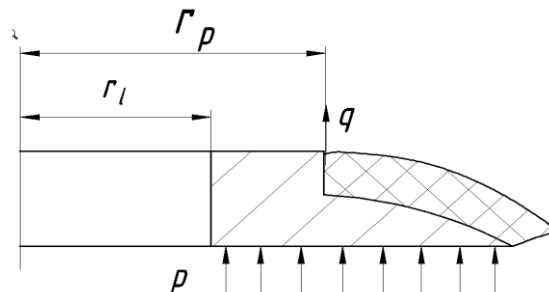


Figure 2. Force balance at the polar hole connected to the nozzle.

Consider the motor casing with inner radii r_{p1} and r_{p2} as shown in Figure 1, in which one dome is connected to the nozzle section, while the other dome is sealed by the igniter. Consider the end

connected to the nozzle as shown in Figure 1. Some geometric and physical characteristics of the first end in Figure 1 are as follows:

- R the radius of the cylindrical section; r_l is the radius of the nozzle throat section, $r_l = 0$ - for the remaining dome, h - SRM casing' thickness.

- β is the winding angle, which is the angle formed by the tangent of the fiber trajectory with the tangent of the shell meridian.

- T_l and T_2 are the internal forces in the meridional and parallel directions; R_l and R_2 are respectively the radii of curvature in the meridional and parallel directions [3].

$$R_l = -\frac{\sqrt{(1+r'^2)^3}}{r''} \quad (1)$$

$$R_2 = r \cdot \sqrt{1+r'^2} \quad (2)$$

where r', r'' - are respectively the first and second derivatives of r with respect to z .

- p is the calculated pressure in the engine, and q is the force distribution at the polar hole.

Under the effect of pressure p , internal force components appear in the casing T_l and T_2 [3].

$$T_l = \frac{pR_2}{2} \left(1 - \frac{r_l^2}{r^2}\right) = \sigma_l \cdot h \quad (3)$$

$$T_2 = \frac{pR_2}{2} \left(2 - \frac{R_2}{R_l} \left(1 - \frac{r_l^2}{r^2}\right)\right) = \sigma_2 \cdot h \quad (4)$$

Consider the force balance of the SRM, assumed to be a unidirectional material. Under the action of pressure p , along the fiber axis, the average stress along the fiber axis σ_d will be determined as follows [3]:

$$\sigma_l = \sigma_d \cdot \cos^2 \beta \quad (5)$$

$$\sigma_2 = \sigma_d \cdot \sin^2 \beta \quad (6)$$

where σ_l, σ_2 are the stresses and strains in the meridional and parallel directions, respectively; σ_d are the stress and strain in the direction longitudinal to the fiber axis;

Equation of force balance at the polar hole:

$$2\pi r_p q = (\pi r_p^2 - \pi r_l^2) \cdot p \quad (7)$$

From equation (7) we obtain the force distribution at the polar hole:

$$q = \frac{(r_p^2 - r_l^2) \cdot p}{2r_p} = \frac{p \cdot r_p}{2} \left(1 - \frac{r_l^2}{r_p^2}\right) \quad (8)$$

2.1.2. The system of equations describing the dome profile of the composite SRM casing.

From Equations (1) - (6), we obtain the equation:

$$\tan^2 \beta = \sigma_2 / \sigma_l = \frac{2 - \frac{R_2}{R_l} \left(1 - \frac{r_l^2}{r^2}\right)}{1 - \frac{r_l^2}{r^2}} = \frac{2 + \frac{r \cdot r''}{1 + r'^2} \left(1 - \frac{r_l^2}{r^2}\right)}{1 - \frac{r_l^2}{r^2}} \quad (9)$$

For the wound dome of the SRM case based on non-geodesic roving trajectories, according to [5], the non-geodesic wound trajectory equation is as follows:

$$\beta' = \frac{d\beta}{dz} = \lambda \cdot \left(\frac{\sin \beta \cdot \tan \beta}{r} - \frac{r'' \cdot \cos \beta}{1 + r'^2} \right) - \frac{r' \cdot \tan \beta}{r} \quad (10)$$

where λ is the slip coefficient between the fiber and the mandrel. To ensure the fiber does not slip, the slip coefficient needs to be smaller than the allowable slip coefficient value.

Combining Equations (8), (9), (10) gives the system of equations describing the dome profile of the SRM connected to the nozzle, following a non-geodesic winding roving trajectory:

$$\begin{cases} r'' = \left(\tan^2 \beta - \frac{2 \cdot r^2}{r^2 - C_p \cdot r_{p1}^2} \right) \frac{1 + r'^2}{r} \\ \beta' = \lambda \cdot \left(\frac{\sin \beta \cdot \tan \beta}{r} - \frac{r'' \cdot \cos \beta}{1 + r'^2} \right) - \frac{r' \cdot \tan \beta}{r} \end{cases} \quad (11)$$

where $C_p = (r_l / r_p)^2$ - coefficient nozzle radius.

For the dome closed by the igniter case ($r_l = 0$), the system of equations describing the dome profile becomes:

$$\begin{cases} r'' = (\tan^2 \beta - 2) \frac{1 + r'^2}{r} \\ \beta' = \lambda \cdot \left(\frac{\sin \beta \cdot \tan \beta}{r} - \frac{r'' \cdot \cos \beta}{1 + r'^2} \right) - \frac{r' \cdot \tan \beta}{r} \end{cases} \quad (12)$$

For the dome wound based on the geodesic roving trajectories, the winding angle follows Clairaut's equation [11]. Thus, the second equation of the system (10), (11) is replaced by:

$$r \sin \beta = r_p = \text{const} \quad (13)$$

To ensure a uniform stress distribution on the casing surface, composite structures are typically manufactured based on geodesic or non-geodesic roving trajectories. For casings with $r_{p1} = r_{p2}$, the entire casing is wound based on geodesic roving trajectories; in cases $r_{p1} \neq r_{p2}$ where one of the domes or the cylindrical section must be wound based on non-geodesic roving trajectories. The boundary conditions for solving the system of equations describing the dome profile are: $\bar{z}(0) = 0, \bar{r}(0) = 1, \bar{r}'(0) = 0, \beta(0) = \beta_{xd}$, where β_{xd} - the winding angle at the equator.

2.1.3. Determination of the composite SRM casing' thickness.

By combining Equations (3), (4), the thickness at the equator of the dome is determined by the following formula:

$$h_{xd} = \frac{p \cdot R \cdot (1 - r_l^2)}{2 \cdot [\sigma_d] \cdot \cos^2(\beta_{xd})} \quad (14)$$

where $[\sigma_d]$ is the longitudinal tensile strength composite materials.

In determining the composite thickness at the dome, we assume a constant fiber count across any section; thus, the thickness of the dome is determined by:

$$2 \cdot \pi \cdot R \cdot h_{xd} \cdot \cos \beta_{xd} = 2 \pi r \cdot h \cdot \cos \beta \quad (15)$$

From Equation (15), we determine the thickness of the helical winding layer:

$$h = h_{xd} \cdot \frac{\cos \beta_{xd}}{r \cdot \cos \beta} \quad (16)$$

To ensure the structural integrity of the shell, a hoop winding layer with a thickness of h_n is added to the cylindrical section. In this case, the forces in the parallel directions are defined as follows:

$$T_2 = \sigma_d \cdot (h_{xd} \cdot \sin^2 \beta_{xd} + h_n \cdot \cos^2 \beta_{xd}) \quad (17)$$

By combining Equations (16) and (17), we obtain the thickness of the hoop winding layer:

$$h_n = \frac{pR - [\sigma_d] \cdot h_{xd} \cdot \sin^2 \beta_{xd}}{[\sigma_d]} \quad (18)$$

2.2. Design of the SRM casing made of composite materials

Design requirements of the SRM were specified as follows: the outer diameter must not exceed 123 mm; the total motor length, including the nozzle, must not be less than 330 mm; the loading factor must be no less than 0.55; the maximum operating pressure must be at least 12 MPa and the operating time must not be less than 18 s. From the design requirements, after performing internal ballistics calculations, the maximum pressure inside the motor is determined $p_{\max}=12$ MPa. The authors design the casing with a polar opening radius $r_{p1}=r_{p2}=29\text{mm}$, the radius of the cylindrical section $R=58\text{mm}$, and select the design pressure inside the motor $p=3p_{\max}=36$ MPa with safety factor $n=3$. The material used to manufacture the motor casing is T700 carbon fiber–reinforced epoxy composite, with the longitudinal tensile strength $[\sigma_d] = 1997\text{ MPa}$ [12].

Based on the input design requirements of the motor, geodesic roving trajectories were adopted for the entire casing due to the equal radii of the two polar openings. The system of equations (11), (12), (14), (16) and (18) is solved using the Odesolve function in Mathcad software with boundary conditions $\bar{z}(0)=0, \bar{r}(0)=1, \bar{r}'(0)=0, \beta(0)=30^\circ$. The results yield the geometric profile of the casing and the thickness distribution as shown in Figure 3, and also determine the winding angle of the dome as shown in Figure 4.

Based on the obtained geometric configuration, the structural design of the casing was completed and the corresponding technical drawings were developed, as presented in Figure 5. The SRM casing was manufactured by filament winding directly onto a mandrel consisting of the propellant grain and an internal thermal insulation layer. The thermal protection layers for the forward and aft domes were fabricated from E-glass fiber reinforced with phenolic resin and molded to conform to the external contour of the dome sections. The cylindrical thermal protection layer was manufactured using T300 carbon fiber and epoxy resin via filament winding technology, and subsequently bonded to the dome sections using epoxy adhesive. A sealing layer of UG-2D rubber was then applied by spray coating. Finally, the structural casing was formed over the sealing layer using four double composite layers, each with an approximate thickness of 0.5 mm.

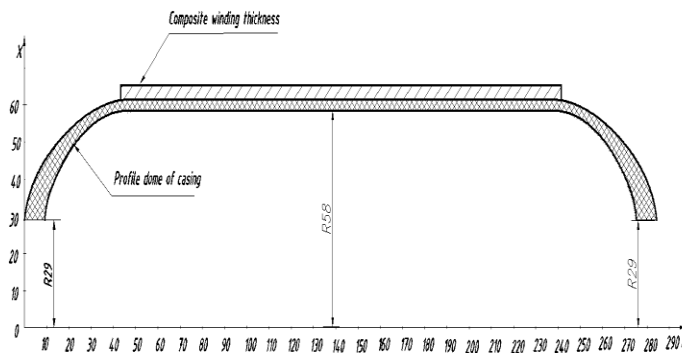


Figure 3. Geometry and thickness distribution of the composite SRM casing.

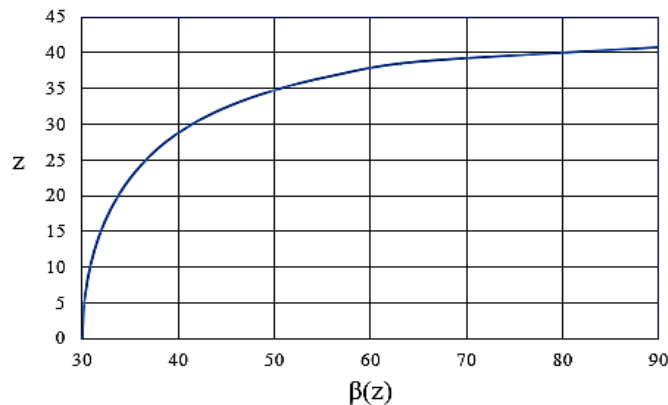


Figure 4. Winding angle of the casing dome along the height z .

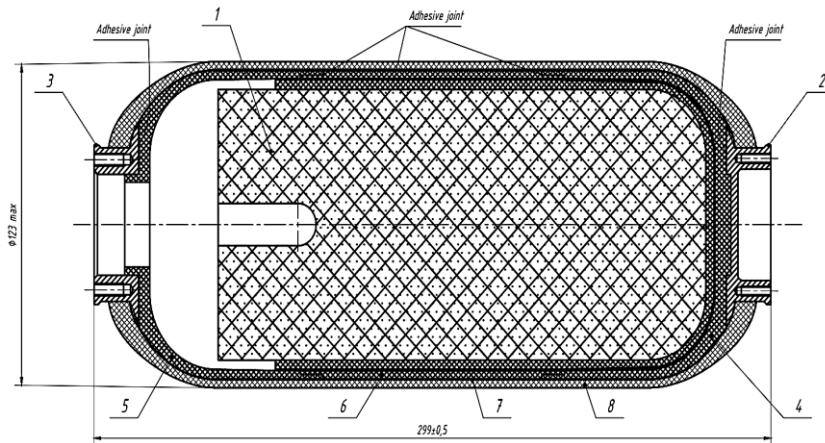


Figure 5. Technical drawing of the composite motor casing with propellant.

1- Propellant, 2 – Front flange, 3 – Rear flange, 4, 5, 6 – Thermal protection layers of the front dome, rear dome, and cylindrical section, 7 – Sealing layer, 8 – Composite motor casing.

3. MANUFACTURING AND TESTING OF COMPOSITE SRM CASINGS

3.1 Manufacturing of the composite SRM casings

Based on the casing design presented in section 2.2, the following materials are required to manufacture the SRM casing.

Table 2. Materials for manufacturing the composite SRM casing.

No	Name and function	Material code	Origin	Physical form
1	Resin (Epoxy)	ED20	Russia	Liquid
2		EDG-1	Russia	Liquid
3	Polyester	P9-14	Viet Nam	Liquid
4	Curing agent	m-Phenylenediamine	China	Flakes
5		Absolute acetone	China	Liquid
6	Defoamer	Pharaphin	Viet Nam	Liquid
7	Rubber (TPA)	UG-2D	Russia	Liquid
8	Curing agent of rubber (TPB)		Russia	Liquid
9	Carbon fiber T700	T700 12K	China	Solid

The technological process for manufacturing the SRM consists of the following main steps:

Step 1. Assembly of the winding mandrel

The front flange, front dome thermal protection layer, and cylindrical thermal protection layer were bonded using a specialized adhesive, while the rear flange was similarly assembled with the rear thermal protection layer. The propellant grain was subsequently bonded to the front assembly and cured under ambient conditions for 48 h. The rear assembly was then adhesively joined to the front assembly. After complete curing, excess adhesive was removed, and the fully assembled mandrel was mounted onto the filament winding machine.

Step 2. Manufacturing of the sealing layer

The curing agent was prepared by mixing m-phenylenediamine and absolute acetone at a mass ratio of 1:1. The resin matrix solution was formulated using ED-20, DEG-1, and P9-14 at a ratio of 9:6:1, respectively. Subsequently, the resin matrix solution and curing agent were mixed at a ratio of 10:1.5 to obtain the bonding solution, which was spray-coated onto the mandrel surface to a thickness of approximately 0.05 mm.

The UG-2D rubber layer was prepared by mixing TPA rubber and TPB at a ratio of 3:1 under processing conditions of 15 - 30 °C and relative humidity below 75%. The mixture was then spray-applied onto the mandrel surface to a thickness of approximately 0.5 mm and allowed to cure naturally for 4 h (Figure 6).



Figure 6. Manufacturing of the sealing layer.



Figure 7. Composite SRM after winding.

Step 3. Winding of the casing

The T700 carbon fibers were dried at 60 °C for 2 h to eliminate moisture prior to processing. The winding resin system was prepared by mixing the curing solution, resin matrix, and defoaming agent at a weight ratio of 10:1.5:0.05, respectively. The prepared resin mixture was then maintained at 60 °C for 15 min to reduce the acetone content and remove entrapped air bubbles.

The filament winding parameters were established using a 4VFW-600 winding machine at the Missile Institute. The motor casing was subsequently cured at 40 °C for 12 h after manufacturing. The assembled SRM with the composite casing and nozzle section is presented in Figure 7. The total motor mass was 4.9 kg, including a propellant mass of 2.73 kg. The resulting loading factor reached 0.56, exceeding the initial design requirement.

3.2. Testing composite SRM casings

- **Durability test:** To evaluate the structural performance of the composite casing, casing specimens without propellant were fabricated and subjected to hydrostatic pressure testing. According to the testing conditions specified in [13], the test pressure was defined as $p = 1.5p_{max} = 18 \text{ MPa}$, with a pressure holding duration of 1 min. The acceptance criteria required no pressure loss during the holding period and no observable defects on the outer surface of the casing, including cracking, surface damage, or resin exudation. The pressure testing process is illustrated in Figure 8. Experimental results demonstrated that all three tested casings successfully satisfied the prescribed structural strength requirements. The measured burst pressure reached 38 MPa, exceeding the design pressure and confirming the high load-bearing capability of the composite structure. These findings indicate that the developed casing possesses adequate structural integrity and sealing performance for application in complete motors and subsequent static firing tests.

- **X-ray defect inspection:** Since the propellant was directly used as the mandrel for filament winding, inspection of casing defects before firing tests is mandatory to ensure safety. X-ray images of the casing after fabrication are presented in Figure 9. The observations indicate that the inhibitor layer, propellant grain, and composite motor casing were well bonded. No structural defects, voids, or delamination affecting strength and sealing performance were detected. The fabricated structure satisfies the safety requirements for subsequent firing tests.



Figure 8. Pressure strength testing of the SRM without propellant.



Figure 9. X-ray images of a SRM.

- **Firing test:** After X-ray inspection, 05 motor was assembled with the nozzle and igniter units, and then mounted on the test stand for firing. The firing test results showed that two composite motor casings operated stably for 20 s. Post-test observations of the outer surface indicated that the structure retained its original shape, with no evidence of cracking, blistering, or thermal deformation. The maximum outer surface temperature measured was approximately 40 °C at 30 s after the start of the firing process. These results confirm that the developed SRM casing satisfies the design requirements regarding structural strength, sealing capability, and operational reliability under practical firing conditions.



Figure 10. Composite SRM casing before and after the firing test.

4. CONCLUSIONS

This study presented the theory for the design of composite SRM casings manufactured by filament winding using both geodesic and non-geodesic roving trajectories. A composite SRM casing was designed with a maximum operating pressure of $p_{max}=12$ MPa, a cylindrical diameter of 123 mm, and a loading factor of 0.56. In addition, a manufacturing process based on direct filament winding of T700 carbon fiber/epoxy composite onto mandrels fabricated from RSI-12M propellant grains was developed and implemented.

Five fabricated casings were experimentally evaluated through hydrostatic pressure testing, X-ray nondestructive inspection, and static firing tests under practical operating conditions. Experimental results demonstrated that the composite casings satisfied the requirements for structural strength, sealing capability, and operational stability, with no observable damage or structural degradation during testing. The results confirm the feasibility and reliability of the proposed design and manufacturing approach, thereby providing a scientific and technological foundation for further research, development, and practical application of composite SRM casing technologies in Vietnam.

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TÓM TẮT

Thiết kế và chế tạo vỏ động cơ nhiên liệu rắn từ vật liệu composite sử dụng công nghệ quấn

Vật liệu composít được sử dụng ngày càng nhiều trong chế tạo thân vỏ động cơ nhờ khối lượng nhẹ, độ bền riêng cao và khả năng chịu áp suất tốt. Bài báo trình bày cơ sở thiết kế thân vỏ động cơ nhiên liệu rắn từ vật liệu composít bằng công nghệ quấn. Trên cơ sở đó, nghiên cứu tiến hành thiết kế và chế tạo thân vỏ động cơ cỡ nhỏ có áp suất làm việc lớn nhất 12 MPa bằng phương pháp quấn trực tiếp sợi cacbon T700/ nền epoxy lên khuôn quấn chế tạo từ thỏi thuốc phóng RSI-12M. Thân vỏ sau chế tạo được thử nghiệm thủy tĩnh, kiểm tra khuyết tật bằng tia X và thử nghiệm đốt động cơ nhằm đánh giá khả năng làm việc. Kết quả thực nghiệm cho thấy vỏ động cơ hoạt động ổn định trong suốt quá trình thử nghiệm đốt, qua đó khẳng định tính khả thi của việc phát triển và làm chủ công nghệ sản xuất vỏ động cơ rắn từ vật liệu composít tại Việt Nam.

Từ khoá: Động cơ nhiên liệu rắn làm từ vật liệu composít; SRM; Thử nghiệm động cơ.