

Research on Universal Clamping Technology for Automatic Assembly of Small Solid Rockets

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Abstract

Based on an analysis of clamping methods for the automatic assembly of small solid rockets, clamping force calculation, simulation, and experimental verification were carried out for different clamping solutions. The results show that when using a three-jaw chuck fitted with a 0.5 mm thick graphite rubber pad between the chuck jaws and the rocket shell, a clamping pressure of 0.5 MPa can prevent slippage even under the maximum torque load of 390 N·m. The resulting deformation has no adverse impact on product quality and assembly performance. Considering the profile characteristics of the clamping surface of small solid rockets and economic efficiency, a universal clamping tooling was designed. This work lays a foundation for the automatic assembly of small solid rockets.

Keywords

Clapping, Solid Small Rockets

1. Introduction

Solid small rockets are a type of small solid rocket engine, featuring a simple structure, large impulse, and ease of use [1]. They have a wide range of applications and a large total volume, and are an indispensable part for fulfilling the predetermined functions of space missions [2]. Solid small rockets mainly use threaded connections between the nozzle and the shell for sealing [3] [4].

Solid small rockets have the production characteristics of “multiple varieties and small batches”, which leads to high costs for achieving automation [5] [6]. Therefore, the current production of solid small rockets mainly relies on manual assembly. However, as the demand for production capacity increases, the require-

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ment for production efficiency becomes more prominent, and the demand for the automation of small solid rocket assembly is becoming increasingly strong [7]. Based on the currently available technologies, the bottleneck process in the assembly of small solid rockets is the torque loading of the threads between the nozzle and the housing [8] [9]. Therefore, to achieve the automated assembly of small solid rockets, the problem of automatic torque loading of the threads between the nozzle and the housing needs to be solved [10].

During the moment loading process, one of the two types of parts, the solid small rocket nozzle or the shell, needs to be clamped, and the other part needs to be subjected to moment loading. At present, the torque automatic loading technology has become relatively mature [11]-[13]. However, due to the wide variety of small solid rockets and their different sizes and shapes, it is difficult to design the clamping fixtures [14]. The design of the clamping fixtures has become the key to whether solid small rockets can achieve automatic assembly [15].

This paper analyzes the clamping methods of the automatic assembly of solid small rockets, calculates, simulates, and verifies the clamping force for different clamping methods, and designs the corresponding universal clamping fixture based on the shape characteristics of the clamping surface of the automatic assembly of solid small rockets and the principle of economic applicability, laying a foundation for the automatic assembly of solid small rockets.

2. Selection of Clamping Method

As shown in **Figure 1**, according to their shape characteristics, small solid rockets are classified into three types: those with supporting lugs on the nozzle, those with supporting lugs on the shell, and those without supporting lugs.

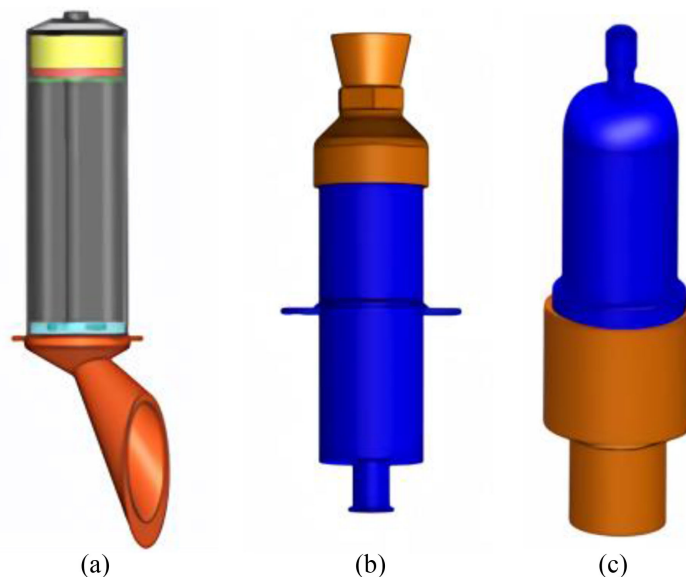


Figure 1. Shows the shape of a typical small solid rocket: (a) The nozzle is equipped with lugs; (b) The shell is equipped with lugs; (c) Without lugs.

As shown in **Figure 2**, the manual assembly torque loading is achieved by designing a special fixture to fix the rocket lugs, shell lugs, or clamp shell, and then manually loading the nozzle or shell with a torque wrench until the gasket is compressed to the design requirement value. Due to the wide variety of small solid rockets and the different sizes and positions of the lugs, the tooling design is overly complex, and it is not convenient to achieve the universality of the tooling.

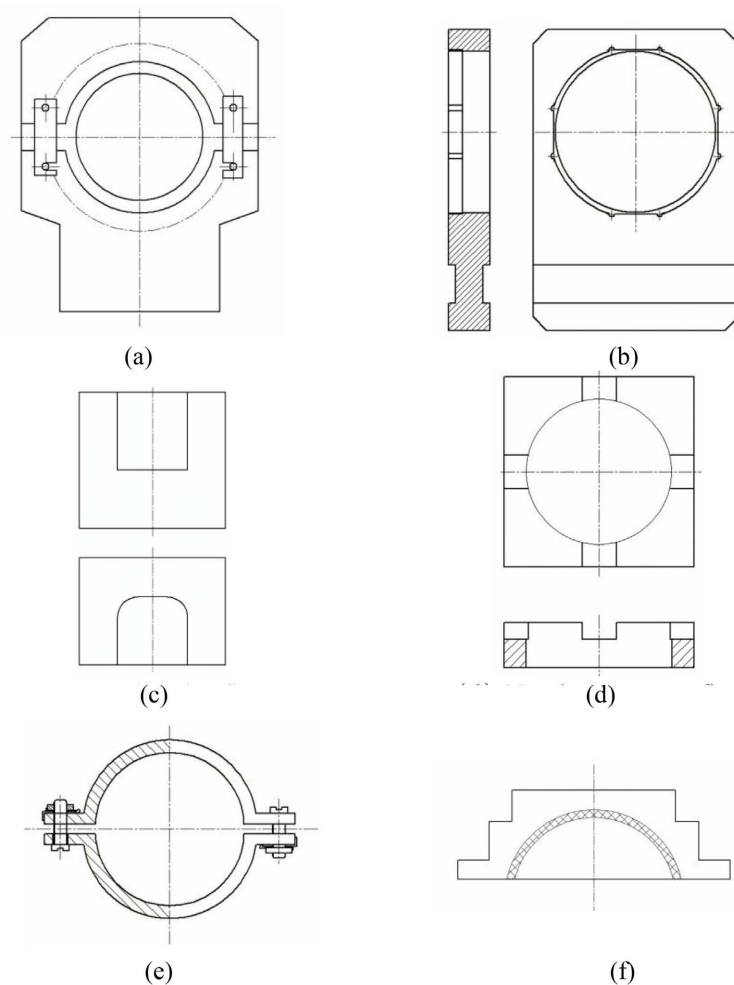


Figure 2. Typical torque loading fixture for small solid rockets. (a) Cylindrical three-jaw clamping fixture 1; (b) Shell support ear clamping fixture 1; (c) Shell support ear clamping fixture 2; (d) Nozzle ear support fixture 1; (e) Shell support ear clamping fixture 3; (f) Nozzle ear support fixture 2.

It can be seen from the profile characteristics of small solid rockets that they come in various types, yet all feature cylindrical shells with identical shell materials and surface treatment processes. The main parameters are listed in **Table 1**.

Table 1. Shell parameter table.

Shell Outer Diameter (mm)	Shell Wall Thickness (mm)	Shell Material	Shell Surface Treatment	Shell Hardness
35 - 300	1.5 - 2.5	PCrNi2Mo	Electroless nickel plating	HRC 45 - 50

Based on the degree-of-freedom analysis for fixture positioning, positioning, and clamping are required to restrict three degrees of freedom of the cylindrical profile. Experience suggests that a three-jaw hoop structure clamping the shell is suitable to achieve positioning and clamping. With three-point clamping, the resultant of the three clamping forces acts through the circle center. This not only firmly holds the small solid rocket, but also counteracts deformation in all directions to prevent shell distortion. This three-point clamping scheme allows designing dedicated tooling according to the rocket shell diameter. It maximizes the force-bearing area and minimizes clamping force, thus reducing shell deformation to the lowest level and standardizing the loading mode. Replacing the jaws enables rapid loading and unloading of small solid rockets.

As the shell is a thin-walled cylindrical barrel-shaped part, the problem that needs to be solved by adopting the three-claw clamp shell method is:

- 1) What clamping force should be adopted to hold the solid small rocket and prevent slippage during the moment loading process, which would affect the moment loading?
- 2) Whether the deformation of the shell during clamping will be too large, thereby causing damage to the shell?
- 3) Will the deformation of the shell opening affect the tightening torque?

3. Design of Universal Clamping System

3.1. Calculation of Clamping Force

The solid small rocket housing is cylindrical. To facilitate torque loading and clamping, it is placed vertically during the tightening process, and the clamping mechanism is a three-jaw chuck. The main function of clamping is to prevent the solid small rocket body from rotating during the tightening process due to the tightening torque M .

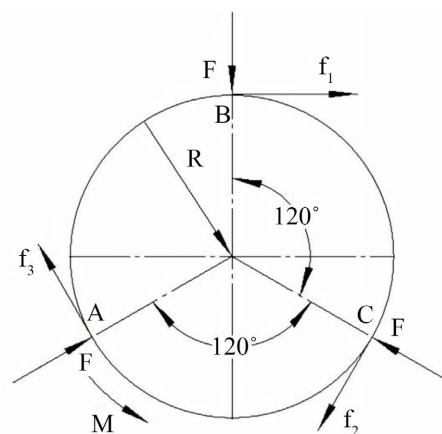


Figure 3. Force analysis diagram of the clamped shell under torque loading.

As shown in **Figure 3**, to simplify the calculation, the force F on the three claws is approximately regarded as being of the same magnitude and distributed at 120°

in space, and the radius of the solid small rocket shell is R . To facilitate automatic torque loading, the solid small rocket is set to be placed vertically. Therefore, when clamping the cylinder, the influence of its own gravity is not considered.

Therefore, taking point A as an example, the critical force that makes the rocket body rotate at each clamping point is:

$$F = \frac{M}{3R} \quad (1)$$

The frictional force generated by the clamping force at each point is:

$$f_3 = \mu F \quad (2)$$

To prevent the rocket body from rotating, the frictional force must satisfy the following relationship:

$$f_3 = \mu F \geq F = \frac{M}{3R} \quad (3)$$

In addition, considering the differences between theoretical calculations and the actual tightening process, as well as the influence of other factors, a safety factor K_3 should also be multiplied by the clamping force. Generally, K_3 is taken as 1.2 to 1.5. To distinguish from the axial preload F mentioned above, the clamping force is changed to F_j . The conditions that need to be met are:

$$F_j \geq K_3 \cdot \frac{M_{\max}}{3\mu R} \quad (4)$$

Among them, $M_{\max}$ represents the maximum tightening torque during the tightening process.

In addition, during the clamping process, it is necessary to ensure that the rocket body does not move, rotate, or vibrate, and no plastic deformation or damage should occur to the surface coating of the small solid rocket. Therefore, the next step should be to consider the relationship between the clamping force and the deformation of the rocket shell, and compare it with the clamping force F that prevents the small solid rocket body from rotating. If F causes plastic deformation of the solid small rocket body, the clamping force needs to be adjusted, such as increasing the direct friction coefficient μ between the clamping mechanism and the rocket body, or increasing the direct contact area between the clamping mechanism and the rocket body. Or change the three-jaw clamping mechanism to four-jaw or six-jaw, etc.

3.2. Simulation Research on Shell Clamping

Take a small solid rocket with a shell diameter of 90 mm as an example to calculate the minimum required clamping force. Meanwhile, this paper analyzes the stress distribution of the rocket shell under this clamping force, and conducts calculations and experimental measurements on the deformation at the shell end. To increase friction and protect the shell surface, graphite rubber pads are installed between the rocket shell and the clamping mechanism. The friction coefficient between steel and graphite rubber pad is found to range from 0.2 to 0.8, and a value of $\mu = 0.5$ is adopted for calculation. The safety factor is set to 1.2. For the

selected small solid rocket with a seal ring compression rate of 30%, the maximum required torque $M_{\max}$ is 390 N·m, which is also the maximum torque load for all types of small solid rockets. Substitute the above parameters into Equation (4):

$$F_j \geq \frac{K_3 \cdot M_{\max}}{3\mu R} = \frac{1.2 \times 1300 \times 1 \times 0.3}{3 \times 0.5 \times 45 \times 10^{-3}} \approx 6933 \text{ (N)} \quad (5)$$

Since hydraulic or pneumatic chucks generally express pressure in terms of pressure, pressure-pressure conversion is required. This subsequent verification test plans to use the hydraulic chuck of a certain machine tool for the test. After consulting relevant technical data, it is learned that the inner diameter of this hydraulic cylinder is 140 mm, the minimum pressure is 0.5 MPa, and the maximum pressure is 16 MPa.

$$P \geq \frac{F_j}{A} = \frac{6933}{\pi \times 70 \times 70} \approx 0.45 \text{ (MPa)} \quad (6)$$

So when using this hydraulic chuck and adjusting to a minimum pressure of 0.5 MPa, the small solid rocket remains stationary when tightened with a maximum torque of 390 N·m.

The clamping force of each claw of the triangular chuck when $P = 0.5$ MPa:

$$F = \pi \times 70 \times 70 \times 0.5 \approx 7697 \text{ (N)} \quad (7)$$

As shown in **Figure 4**, the rocket casing is directly clamped with three claws, with a cross-section of approximately 20 mm × 60 mm. The clamping area is shown in **Figure 4**.

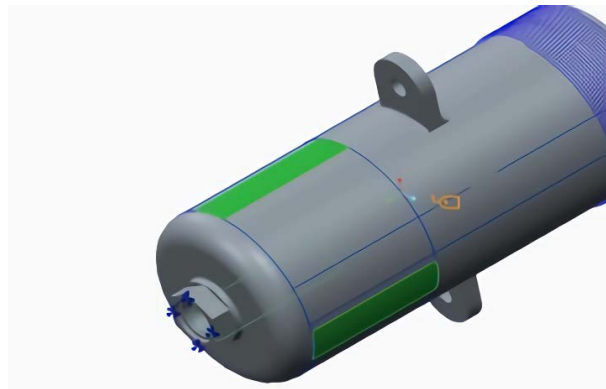


Figure 4. Illustration of the clamping area.

It can be calculated that:

$$P = \frac{F}{S} = \frac{7697}{20 \times 60} = 6.41 \text{ (Mpa)} \quad (8)$$

That is, the pressure acting on the clamping part of the small rocket shell is 6.41 MPa.

The stress analysis was performed in Pro/E by inputting parameters such as the clamping cross-section of the three-jaw chuck, clamping pressure, and shell material characteristics, see **Figures 5-7**.

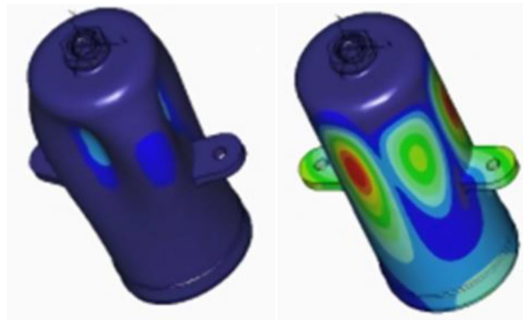


Figure 5. Displacement and stress cloud map.

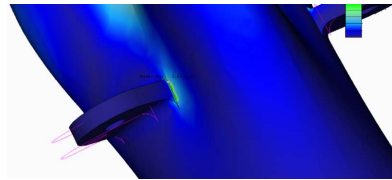


Figure 6. The position with the maximum stress.

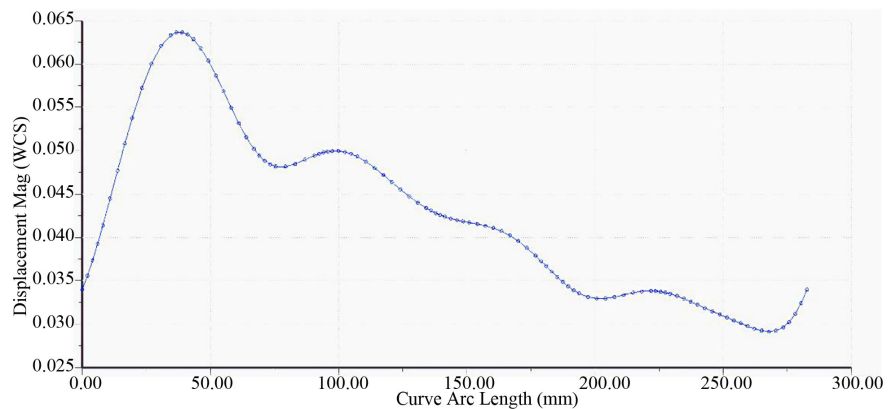


Figure 7. Displacement curve of the outer circle of the shell thread.

It can be obtained that the displacement of the part held by the three claws is the maximum, which is 0.16 mm. The part with the greatest stress is located at the ear branch, at 563 MPa, which is less than the yield strength of the shell at 785 MPa. The maximum displacement of the outer circle curve of the thread is 0.0637 mm, which has little impact on the thread assembly.

3.3. Typical Shell Clamping Verification Test

The above theoretical calculations and simulation analyses were conducted on the magnitude of the clamping force, stress distribution, and deformation of the solid small rocket. A typical small solid rocket with a 90 mm diameter shell and lugs was used for verification tests.

Test specimen preparation: 1) Twenty small solid rockets of the lug-mounted shell type with an outer diameter of 90 mm were selected and divided into two groups. The first group was tested by direct clamping with a three-jaw chuck, while the second group was tested with a 0.5 mm thick graphite rubber pad (Material

Grade: 66-2, Standard: Ji Q/CSMQ6131-90) installed between the three-jaw chuck and the shell; 2) Six marking points were evenly arranged on the outer circular surface and the threaded end of each shell.

The main purpose of the test is: 1) To verify the differences between rubber gaskets with graphite and those without; 2) To verify the minimum clamping force that ensures the product does not rotate when a torque of 390 N·m is applied to the solid small rocket nozzle; 3) Measure the magnitude of the deformation at the nozzle housing opening during clamping.

Test content: 1) Use the hydraulic three-jaw chuck of the CNC machine tool to hold the housing with a clamping force of 0.5 MPa (where the chuck and the product are divided into two states: direct clamping and wrapping with graphite rubber); 2) Measure the deformation of the six points marked at the shell opening; 3) Can it achieve no slippage when loading with a 390 N·m torque after adopting three-jaw clamping? 4) After the torque loading is completed and the shell is removed, observe whether there is any damage or an appearance defect at the clamping part of the shell.

The process of the test part is shown in **Figure 8**.



Figure 8. Shows part of the test process.

The test results are shown in **Table 2** and **Table 3**.

Table 2. Test records of direct clamping of the shell with three claws.

The three claws directly hold the shell	Test Piece Serial Number									
	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Can a torque loading of 390 N·m be achieved	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping	No, it's slipping

Table 3. Test results of adding 0.5 mm graphite rubber pads between the three claws and the shell.

Add a 0.5 mm graphite rubber pad between the three claws and the shell	Test Piece Serial Number									
	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Can a torque loading of 390 N·m be achieved	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Deformation at the shell opening	0.02	0.04	0.03	0.06	0.05	0.06	0.01	0.04	0.04	0.05
	0.05	0.03	0.02	0.02	0.10	0.09	-0.01	-0.05	0.09	0.04
	-0.02	-0.02	-0.02	-0.10	-0.07	-0.08	-0.07	0.01	-0.06	-0.07
	-0.02	-0.02	-0.06	-0.08	-0.08	-0.08	-0.04	0.07	-0.05	-0.08
	0.04	0.06	0.04	0.09	0.09	0.09	-0.04	-0.05	0.10	-0.02
	-0.01	-0.02	-0.03	-0.01	-0.01	-0.05	-0.09	-0.10	-0.03	0.03

Continued

Average deformation of shell end	0.027	0.032	0.033	0.060	0.067	0.075	0.043	0.053	0.062	0.048
Maximum deformation of shell end	0.04	0.06	0.06	0.09	0.09	0.09	0.09	0.1	0.1	0.08
Is there any damage or appearance defect after removing the shell	No	No	No	No	No	No	No	No	No	No

By analyzing the above test data, it can be known that.

1) As shown in **Table 1** and **Table 2**, under a clamping pressure of 0.5 MPa, slippage occurs when a torque of 390 N·m is applied without the graphite rubber pad. After installing the graphite rubber pad, no slippage takes place under the same 390 N·m torque load.

2) It can be concluded from **Table 2** that the maximum deformation is 0.1 mm and does not affect the torque loading.

3) It can be concluded from **Table 2** that a clamping force of 0.5 MPa will not cause any damage or appearance defects to the product.

4. Design and Verification of Universal Clamping Systems

Calculations and experimental verification demonstrate that after attaching graphite rubber pads to the three jaws, a clamping pressure of merely 0.5 MPa is sufficient for the three-jaw chuck to firmly grip the shell. It effectively prevents slippage under the maximum torque load of 390 N·m while causing no shell deformation. For cost efficiency, a simple pneumatic three-jaw structure is adopted for clamping. Its adjustable clamping force enables one set of jaws to clamp shells with different outer diameters. Accordingly, the three-jaw assembly and a universal clamping system are designed, as illustrated in **Figure 9** and **Figure 10**.

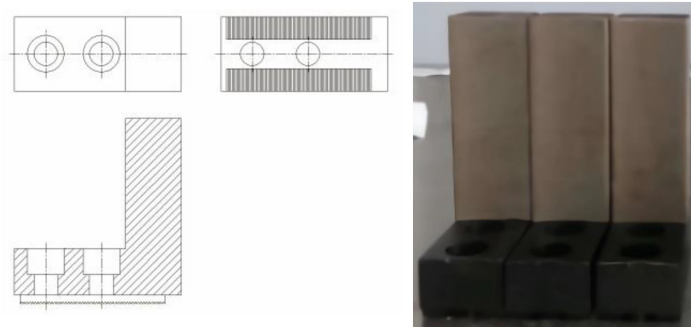


Figure 9. Three-pronged design drawing and physical object.



Figure 10. Design drawing and physical view of the universal clamping system.

5. Conclusion

This paper conducts theoretical analysis and experimental research on the feasibility of clamping small solid rocket shells with a three-jaw hoop. The results show that when using a three-jaw chuck fitted with a 0.5 mm thick graphite rubber pad between the jaws and the shell, a clamping pressure of 0.5 MPa can completely avoid slippage under the maximum torque load of 390 N·m, and the resulting deformation will not affect product quality and assembly performance. On this basis, a universal clamping system with a three-jaw hoop structure for the shell is developed. This system realizes rapid loading and unloading of small solid rockets, and provides technical support for their automatic assembly.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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