Exhausted jet caused the deformation of front metal seal covers in a multiple launch rocket system

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Abstract. During the launch tests of a Multiple Launch Rocket System (MLRS), the front metal seal covers on unlaunched tubes had plastic deformation and felled to the ground. More seriously, the rocket exhausted jet directly caused damage to some of the unlaunched rockets projectiles. As the rocket exhausted jet impinged on the cover, high temperature and high pressure jet caused plastic deformation of the covers. So the temperature and pressure of exhausted jet acting on the surface of the cover were measured. Then pressure data were used to estimate the strain of front cover on adjacent launch tube caused only by pressure. And temperature data were used for thermal stress analysis of the cover. Furthermore, the triaxial strain curves of the cover were obtained during a flight test in which a 252-mm diameter rocket projectile was launched from the MLRS. The results demonstrated that plastic deformation of the covers is mainly due to the thermal deformation caused by the high temperature, which provided guidance for optimal design of front seal covers. No plastic deformation was found in the modified covers during subsequent launch tests of the MLRS.

1. Introduction

The front covers of Multiple Launch Rocket System (MLRS) launch tubes protect the rocket projectiles from external damage during storage, marching, and launching, which should be opened in time during launch. The materials made for seal covers are metals, composites, and ceramics. For the reason that its surrounding environment is extremely harsh, the mechanical strength and ablative resistance must be guaranteed and further studied.

The front covers of the missile tubes are easy to break under the effects of high temperature and high velocity jet flow. Depending on the results by CFD calculation, the pressure and temperature distributions of the former cover exit great difference [1]. After the rocket projectile slides out of the launch tube, the high temperature and high pressure exhausted jet produced by the solid rocket engine impact the front seal cover. The temperature in the core area of the exhausted jet is generally above 2000 °C [2]. The pressure field distribution of exhausted jet is complicated [3]. In recent decades, a large number of researchers have studied the working process of solid rocket motors, including engine combustion process, nozzle tail flow field calculation and experimental measurements [4-7].
deformation of the front covers on unlaunched tubes during the launch is a combined effect of the pressure and temperature.

Several front seal covers on unlaunched tubes fell to the ground during multiple launch tests of the MLRS, making the unlaunched rocket projectiles directly subject to the impact of the exhausted jet. All covers on unlaunched tubes that fell to the ground have plastic deformation. The purpose of this study is to confirm the reason of plastic deformation of the front cover and improve its design to protect the unlaunched rocket projectiles. Dynamic measurements were conducted to obtain characteristic parameters of exhausted jet and stress-strain curves of front metal cover during launch tests. The theoretical deformation of the exhausted jet was calculated by using the pressure curve and temperature curve information. The theoretical calculation results were compared with the measured strain curves, and the real cause of plastic deformation of the front cover was obtained.

2. Experimental Investigation

The paper is divided into three stages. The first stage is phenomenal observation. The ablative and plastic deformation of the seal covers are presented in figure 1. Front covers on unlaunched tubes fell to the ground due to deformation and vibration.

Figuring out the main cause of plastic deformation of covers is the main task of the second stage. The front seal covers are inevitably impacted by the exhausted jet during launch, so the ablation effect is inevitable. However, a properly designed cover can reduce the deformation and avoid such accident. A series of experimental measurements and theoretical analysis have been completed. The temperature and pressure curves of exhausted jet acting on the surface of the cover were obtained. The experimental data of exhausted jet flow field was extracted and used as the input conditions for theoretical analysis. The triaxial strain curves of cover on an adjacent launch tube were used for stress analysis and compared with theoretical analysis results. The main causes of plastic deformation of the seal covers were determined by experimental measurements and theoretical analysis. According to the results of this study, the structural design and material of the front seal covers were modified in the third stage.

![Figure 1a](image1a.png) **Figure 1a.** The front metal seal cover on adjacent launch tube was ablated and plastic deformation occurred after impact of exhausted jet after a single launch.

![Figure 1b](image1b.png) **Figure 1b.** The front metal seal cover on adjacent launch tube was ablated and plastic deformation occurred after multiple launching.

Rocket Projectiles in launch tubes 14, 15 and 19 were launched at intervals of two seconds. Figure 2 shows the distribution of launch tubes 14, 15, 19 and 27. Thermocouples and pressure sensors were installed on the front cover of launch tube 27 when rocket projectiles in launch tubes 14, 15 and 19
were launched. Figure 3a shows the mounting location of pressure sensor and thermocouples. Figure 3b shows the mounting location of triaxial strain gauge.

![Figure 2. Launch tubes number distribution.](image)

Piezoelectric pressure sensors were used to measure the pitot pressure of exhausted jet, and W-Re5/26 thermocouples were used to measure the temperature of exhausted jet. The range and dynamic characteristics of the pressure sensors meet the pressure testing requirements of the exhausted jet. The diameter of tungsten-rhenium thermocouple wires are 0.2 mm, and the time constant is 30 ms [8]. The triaxial strain gauge was used to measure the deformation of seal cover under the impact of the exhausted jet as the direction of principal stress is unknown.

3. Results
During the experiments, a piezoelectric pressure sensor was used to measure the pressure of exhausted jet, and two W-Re5/26 thermocouples were used to measure the temperature of exhausted jet.

3.1. Experimental results
The temperature curves and pressure curve of exhausted jet acting on the front cover on launch tube 27 were obtained. The temperature data for rocket projectiles in tubes 14, 15 and 19 are presented in figure 4. The maximum temperature and acting time of exhausted jet acting on the front cover on launch tube 27 for rocket projectiles during tubes 14, 15 and 19 launched are listed in Table 1. The maximum operating temperature of W-Re5/26 thermocouple can reach 2800 °C. The maximum temperature for calibration of the W-Re5/26 thermocouple is 2300 °C. The data is dispersed at
temperatures above 2300 °C during the calibration process. The pressure curve contains data for rocket projectile during launch tubes 15 launched is presented in figure 5.

The measured strain curves in figure 6 are divided into different stages by reference line L. The physical significance of data on the left and right sides needs to be confirmed by theoretical analysis results. According to the curves, the data on the left side of reference line L is the result of pressure action, and the data on the right side is greatly affected by the heat conduction temperature. Theoretical calculation results can determine the degree of temperature influence.

![Figure 4](image4.png)

**Figure 4.** Temperature of exhausted jet acting on the front cover of launch tube 27. Line A represents the maximum value of W-Re5/26 thermocouple indexing meter.

![Figure 5](image5.png)

**Figure 5.** Pressure of exhausted jet acting on the front cover of launch tube 27.

![Figure 6](image6.png)

**Figure 6.** Triaxial strain curve.

| Tubes | Temperature in the ablation zone/°C | Acting time/ms | Temperature in the central area/°C | Acting time/ms |
|-------|-------------------------------------|----------------|-----------------------------------|----------------|
| 14    | 1439                                | 93             | 586                               | 144            |
| 15    | Over 2300°a                        | 165            | 1238                              | 159            |
| 19    | Over 2300°a                        | 126            | 1335                              | 167            |

Note: The maximum temperature for calibration of the W-Re5/26 thermocouple is 2300 °C
3.2. Theoretical calculations results

The input conditions for theoretical calculations are determined by the results of temperature and pressure measurements. The theoretical calculation object is a circular metal plate of 250 mm in diameter and 1 mm in thickness. The metal plate is a simplified model of the front metal seal cover on launch tubes. It is made of 45# steel.

The stress states of metal plate under two different working conditions were calculated. In the first working condition, the maximum pressure on the front of the whole metal plate was 0.99 MPa. In the strain test results, the time from the beginning of deformation to the beginning of temperature to affect the strain measurement was 120 ms. In the second condition, the surface temperature distribution of the whole metal plate was not uniform. The temperature of the exhausted jet in the upper edge of the metal plate was set at 2300 °C. The temperature of the exhausted jet in the center of the metal plate was set at 1238°C. It is assumed that the temperature distribution of the gas jet on the front of the metal plate was distributed in a certain gradient and temperature action time was 160 ms. The thermal deformation and thermal stress of metal plate under this condition were calculated.

![Deformation and stress results](image)

**Figure 7.** Deformation and stress results.
At the left of the reference line L in figure 7c is the stress curves in each direction of the triaxial strain gauge. The maximum principal stress to the left of the reference line L in figure 7a can be calculated from the following equation

\[
\sigma_i = \frac{E}{2(1-\nu)} \left[ \left( \varepsilon_{i0} - \varepsilon_{i1} \right)^2 + \left( \varepsilon_{i1} - \varepsilon_{i2} \right)^2 + \left( \varepsilon_{i2} - \varepsilon_{i0} \right)^2 \right]^{\frac{1}{2}}
\]

where E is the elastic modulus, \( \nu \) is the Poisson ratio, \( E=206 \) GPa and \( \nu=0.3 \). The experimental maximum principal stress \( \sigma_1=71 \) MPa, the minimum principal stress \( \sigma_2=34 \) MPa and the experimental maximum principal strain \( \varepsilon_1=3.4\times10^{-6} \). The theoretical maximum principal stress at the measuring point is 80.9 MPa (Extracted from figure 7d) and theoretical maximum principal strain \( \varepsilon_1=3.6\times10^{-6} \) (Extracted from figure 7b). The maximum deformation of the cover in the z-axis still under the action of high temperature exhausted jet reached 0.17mm, far exceeding the elastic deformation limit of the material (Extracted from figure 7e and 7f).

4. Conclusions

Previously, scholars usually measure or calculate characteristic parameters of rocket exhausted jet to check the strength of some launch system components. Deformation of some components is the result of both thermal and mechanical effects. The deformation at each moment can be known by this method, but it is not easy to figure out the influence of each factor on the deformation at each stage. Compared with previous method, a triaxial strain gauge was added to measure the strain of the cover in this study. Although the strain gauge was burnt after the test, important conclusions still can be drawn by comprehensive analysis of the measured strain curves, pressure curve, temperature curves and theoretical calculation.

| Table 2. Strain and stress errors caused only by the action of pressure. |
|---------------------------------------------------------------|
| Maximum principal Strain | Experimental value | Calculated value | Errors   |
|--------------------------|--------------------|------------------|---------|
|                         | 3.4×10^{-6}       | 3.6×10^{-6}      | 5.6%    |
| Maximum principal Stress, MPa | 71               | 89               | 20.2%   |

The experimental and theoretical results showed that pressure action of the exhausted jet alone can only cause the elastic deformation of the cover. Strain and stress errors caused only by the action of pressure are listed in table 2. The main reason for the large error was that the pressure measurement result of the measuring point is taken as the input of the deformation calculation of the whole cover.

The results of thermal deformation analysis demonstrated that high temperature was the main cause of plastic deformation of front metal seal covers. Despite a thin coat of paint on the surface of the front cover, it was still severely deformed by the impact of exhausted jet up to 2300 °C. This study provides a direction for the front cover optimization. To prevent the front covers on unlaunched tubes from dropping out during launch, the design of the front cover was modified. The material of the new cover was engineering plastic with low thermal conductivity. To ensure the structural strength of the cover, the thickness was increased to 15 mm. No plastic deformation was found in the modified covers during subsequent launch tests. The ablation effect of rocket exhausted jet should be fully considered in the design of the MLRS in the future.

Acknowledgments

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