Simulation Study of a Crack Test Equipment for Solid Rocket Motor Propellant

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Abstract. To establish safety assessment criteria for solid rocket motors with cracked propellant. In this paper, a specific test equipment was designed using UG NX software. The purpose of this equipment is to simulate the flow field and structural field inside the crack when the cracked propellant was impacted by the ignition gas flow. Using FLUENT and ABAQUS software to investigate the flow field and structure field of the equipment in the process of work, thus verifying the feasibility of the experimental equipment. The result shows: There is a certain regularity in the transmission process of the pressure peak inside the crack. The transmission direction of the pressure peak does not represent the flow direction of the gas flow inside the crack. The propellant in the middle of the crack is subjected to twice the number of impacts as the crack tip. The material in the middle of the crack may fail earlier than the crack tip, and the branch of the crack may occur.

1. Introduction

It is important to find the crack size threshold of the cracked solid propellant inside the motor. The threshold of crack size means when the crack size is less than a certain value, the cracks in the propellant will not propagate, and the extra pressurization due to increased crack surface can be ignored at the time of ignition. This threshold value can be utilized to establish the safety assessment criteria for solid rocket motors with cracked propellants. Han et al. [1] pointed out that the coupling of combustion and fracture is likely to lead to the DDT (Deflagration-to-Detonation transition) process, and the composite solid propellant strain has a direct effect on the burning rate. Frederick et al. [2] quantitatively explained the crack tip propagation speed from the simulated radiographic image of a burning, centrally perforated motor, and believed that the measurement results of RTR (real-time radioscopy) can be accepted. Butt et al. [3] quantitatively explained the crack tip growth rate from a burning, centrally perforated propellant, and obtained the dynamic process of surface motion. In the case of crack propagation, the intensity distribution at the centerline grows faster. Kuo et al. [4-5] conducted some experiments. Their experiment showed that at a relatively low pressure increase rate, crack combustion in the propellant will not occur. Liu et al. [6-8] also studied the crack tip local characteristics and crack growth behavior under many loading conditions. The results show that the crack growth resistance curve is similar to the crack growth curve, and the crack growth rate is taken as a function of the type I stress intensity factor. It was found that the crack growth behavior in the pre-damaged specimens was highly dependent on strain rate.
According to the introduction above, there is no suitable theory for explaining or simulating the propagation behavior of cracked propellant when it is impacted by ignition gas. Therefore, this paper designed a specific test equipment to simulate the change of the flow field and structural field inside the crack when the cracked propellant is impacted.

2. Design of Test Equipment
This paper uses UG NX software to design the test equipment, as shown in Figures 1 and 2, it’s working principle is the following: First, high-pressure gas or fuel gas is introduced into the gas box through the gas tube, and these gases will impact the simulated crack. Then, by installing sensors at three positions of the simulated crack, the pressure of the shock wave on the crack entrance, middle and tip positions can be measured separately, and finally the control parameters of the crack threshold can be constructed using the measured parameters in subsequent work. As shown in Figures 3, there are two mid-boards, and the propellant is stuck on both mid-boards. By installing two mid-boards, a simulated crack is formed between the two pieces of propellant.

![Figure 1](image1.png)

Figure 1. The crack test equipment for solid rocket motor propellant

![Figure 2](image2.png)

Figure 2. Exploded view of test equipment

![Figure 3](image3.png)

Figure 3. Section view of test equipment
As shown in Figures 2 and 3, by making mid-boards of different thicknesses, it is possible to simulate cracks with different sizes, thereby simulating the change in internal pressure of different cracks when the motor ignites. The obtained parameters can be used as a criterion for judging whether the crack will propagation.

3. Simulation of Transient Flow Field
In order to verify the feasibility of the test equipment, this paper uses Fluent software to simulate the flow field during the test equipment working process, and mainly discusses the change of pressure in different positions of the simulated crack.

3.1. Case 1: Set Mass Flow Rate Inlet Boundary Conditions
As shown in Figure 4, the boundary conditions of the two-dimensional flow field of the test equipment are as follows:

![Figure 4](image)

![Figure 5](image)

The gas tube is set as the mass flow rate inlet, the mass flow rate is 0.8kg/s, the exhaust tube is set as the pressure outlet, and the initial pressure of the entire flow field is 101325Pa, with three monitoring points at the entrance, middle and tip of the crack.

The calculation results are shown in Figure 5, which includes the pressure change curve at three locations of crack entrance, crack middle and crack tip with time. In this paper, the letter A represents the peak pressure point of the crack entrance, the letter B represents the peak pressure point in the middle of the crack, and the letter C represents the peak pressure point of the crack tip and the different peak points corresponding to different moments are indicated by foot marks.

As shown in Figure 6, the gas flow first reaches the crack entrance, and the crack entrance reaches the first pressure peak as point A at 0.761 ms. Then, as the gas flows into the crack, the pressure in the middle of the crack gradually increases. As shown in Figure 7, the pressure in the middle of the crack reaches the first pressure peak as point B at 0.909 ms. Finally, as the gas flows into the crack tip, the crack tip pressure gradually increases. As shown in Figure 8, the crack tip pressure reaches the first pressure peak as point C at 1.070 ms. In this paper, the gas impact process following the above-mentioned internal pressure transfer sequence of the crack is called the "sequential impact" mode, that is, the pressure increase sequence is \( A \rightarrow B \rightarrow C \). It can be seen that in the sequential impact, the internal pressure increase sequence of the crack follows the sequence from the crack entrance to the crack tip.
When the first sequential impact ends, as shown in Figure 5, the pressure in the middle of the crack will reach a pressure peak point $B_{X_1}$. The reasons for this phenomenon are explained as follows:

As shown in Figure 9, before the pressure in the middle of the crack reaches the peak point $B_{X_1}$, the pressure at the crack tip and the entrance have a tendency to decrease. This means that the gas at both ends of the crack is flowing to the middle of the crack at the same time. The gas is compressed in the middle of the crack, resulting in a sudden pressure increase in the middle of the crack, as shown in Figure 10.
As shown in Figure 5, after the first sequential impact of $A_1 \rightarrow B_1 \rightarrow C_1 \rightarrow B_{x1}$ is over, the next sequential impact $A_2 \rightarrow B_2 \rightarrow C_2 \rightarrow B_{x2}$ will occur inside the crack. But during the second sequential impact, the direction of the gas flow in the crack is different from the first sequential impact. In the first sequential impact, those pressure peak points $A_1$, $B_1$ appears due to the gas flows into the crack, but in the second sequential impact, those pressure peak points $A_2$, $B_2$ appears due to the gas flows out of the crack. Therefore, the transition point at which the flow direction of the instantaneous gas flow changes at point $B_x$ at each sequential impact can be obtained, and a larger pressure will be generated in the middle of the crack. In the second sequential impact, the airflow direction changes again. It can be concluded that there is a certain difference between the appearance sequence of the peak pressure inside the crack and the change sequence of the flow direction of the gas flow inside the crack.

To find the law of the pressure change inside the crack, this paper will conduct another simulation study by changing the boundary conditions of the flow field.

3.2. Case 2: Set Pressure Boundary Conditions

In case 2, as shown in Figure 11, Set a pressure of 6MPa on the right side of the gas tube, and the exhaust tube was set as the pressure outlet, the initial pressure of the entire flow field was 101325Pa, and three monitoring points were set at the entrance, middle and tip of the crack.

![Figure 11. Flow field initialization of case 2](image)

![Figure 12. The result of case 2](image)

The results are shown in Figure 12. The pressure level in case 2 is significantly greater than the pressure level in Case 1. Due to the increase in pressure, two distinct sequential impact modes $A_1 \rightarrow B_1 \rightarrow C_1 \rightarrow B_{x1}$ and $A_2 \rightarrow B_2 \rightarrow C_2 \rightarrow B_{x2}$ appear in this case. However, there is a set of sequential $A_3 \rightarrow C_3 \rightarrow B_3$ that are different from the sequential impact mode. The peak pressure point $C_3$ of the crack tip appears before the peak pressure point $B_3$ of the middle of the crack. This process is called the "oscillating impact" mode. Before the oscillating impact process, the peak pressure value at the crack tip was significantly greater than the middle and the entrance of the crack, and during the oscillating impact process, the pressure values at the three locations of the crack tended to be stable. From the above simulation results, it can be concluded that during the sequential impact, the pressure at the crack tip is always the largest, and the pressure at all locations inside the crack will continue to increase. The pressure inside the crack will gradually stabilize when the oscillating impact occurs. In case 1, the second sequential impact $A_1 \rightarrow B_1 \rightarrow C_1 \rightarrow B_{x1}$ has a tendency to change into oscillating impact, and in case 2 where the overall pressure is increased, two complete sequential impacts appear, which shows that as the pressure increases, the number of sequential impacts will increase.

Finally, it is worth noting that during the sequential impact process, when the crack tip shows 2 peaks, the corresponding crack middle will have 4 peaks. Therefore, the material in the middle of the crack may even fail earlier than the crack tip, that is, the branch of the crack may appear.
4. Simulation of Transient Structure Field

Through the aforementioned flow field simulation of the crack simulation test equipment, the pressure change inside the crack when impacted by the gas flow is obtained, and the deformation of the propellant in the test equipment after being impacted by the gas flow can be simulated.

In this paper, the ABAQUS software is used to simulate the structural field. The case material is steel, the Young's modulus is 123GPa, and the Poisson's ratio is 0.33. The model of propellant material is a linear viscoelastic constitutive model. According to the relaxation test data [9], as shown in Table 1, the relaxation modulus data of the propellant material is obtained.

|   |   |   |   |   |
|---|---|---|---|---|
| E_i (MPa) | 2.7344 | 1.7712 | 1.3064 | 0.3504 | 0.3168 |
| τ_i (s) | 0.1000 | 1.0000 | 10.000 | 100.00 | 1000.0 |

In the analysis of the flow field, the sequential impact process in case 2 is more obvious, therefore, using the data in case 2 (Figure 12) to set the boundary conditions of the structural field. Because of the test equipment has symmetry, the half structure is analyzed, while ignoring bolts and other connectors. The structural field meshing method is shown in Figure 13. The pressure load is applied inside the crack, and its value is consistent with case 2 in the flow field analysis.

![Structure field meshing method](image1)

Through the analysis of the structural and flow fields, it can be found that in the first sequential impact, the peak pressure of the crack tip is greater than the pressure at other locations, and the propellant strain is also greater than the other locations. However, in the second sequential impact, although the maximum pressure point in the fluid field still appears at the crack tip, the strain in the middle of the crack is greater than the crack tip. Due to the small internal pressure of the crack in case 2, the plastic deformation of the propellant material is extremely small, while the elastic deformation dominates. Due to the extremely short time, the propellant material did not exhibit viscoelastic behavior, so the strain inside the crack did not continue to increase but decreased after two sequential impacts. However, when a real solid rocket engine is ignited, the pressure inside the crack will continue to rise, and the irreversible plastic deformation will occur inside the crack.

5. Conclusion

The crack test equipment designed in this paper can effectively simulate the change of the internal flow field and structural field of cracks in the cracked propellant when subjected to gas impact, and can provide experimental data for the study of crack size threshold of solid rocket motors.
By simulating the flow field during the operation of the crack simulation test equipment, it was found that when the crack is impacted by the gas flow, firstly, it will produce a sequential impact on the crack, that is, the sequence of pressure peaks is “crack entrance → crack middle → crack tip → crack middle”. During the sequential impact process, the pressure at the crack tip is always maximum. Secondly, when the sequential impact ends, oscillating impact will occur inside the crack, that is, the sequence of pressure peaks appearing is “crack entrance → crack middle → crack tip”. Finally, during the oscillating impact, the internal pressure value of the crack will tend to be stable, and at the same time, the increasing sequence of the pressure value at the three locations of the crack will no longer follow the sequential impact mode. As the overall impact pressure increases, the number of sequential impacts will also increase. During the sequential impact process, the material in the middle of the crack is subjected to twice the number of impacts as the crack tip. The material in the middle of the crack may fail earlier than the crack tip, and the branch of the crack may occur. There is a certain difference between the sequence of the pressure peak and the change sequence of the flow direction inside the crack. The transmission direction of the pressure peak does not represent the flow direction of the gas flow inside the crack.

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