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Study on a Method to Determine the Transverse Impact Strength of Propellants Based on Impact Absorbing Energy

Ji-Hua Liu,[a] Chang-Hui He,[a] Rui-Hua Zhang,[a] Hong-Li Zhao,*[a] and Qiong-Lin Wang[a]

Abstract: In this paper, a measurement method of the transverse impact strength of propellant based on the initial fracture impact absorbing energy in the drop weight impact test is proposed. According to the relationship between load and time, displacement was deduced. The correctness and reliability of the displacement were confirmed by comparing it with the displacement by the digital image correlation method (DIC). Combined with a high-speed camera, the impact process image was collected, and the initial fracture point was determined by the load-displacement curve. Then the impact absorbing energy corresponding to the initial fracture point was obtained by integrating the displacement with a load. The transverse impact strength of the propellant can be acquired based on the initial cross-sectional area of the sample. By comparison, it is found that the coefficient of variation and dispersion degree of the measurement results by the proposed method at low and room temperature are significantly less than those by the traditional pendulum test. That is, the consistency and repeatability of the proposed method are better. The result proves the feasibility and reliability of the method based on the initial fracture impact absorbing energy to measure the transverse impact strength of propellants.

Keywords: Propellant · Coefficient of variation · Dispersion degree · Impact absorbing energy · Digital image correlation

1 Introduction

The impact resistance performance has always been a necessary topic in the research of high-energy propellants, which is directly related to the launching safety of high-performance artillery and other barrel weapons [1–6]. The main factors determining the impact resistance of propellant are the formula and processing technology. Therefore, accurate measurement of the impact strength of propellant is of great practical significance for regulating the formula design and process control.

The impact strength is the main characteristic parameter of the impact resistance of the propellant. The measurement method is usually the pendulum test (PT) and axial drop weight test (ADWT) [7–11]. The basic principle of the former is to calculate the transverse impact strength based on the difference between the initial potential energy and the residual potential energy. The principle is simple and the operation is fast, but there are some problems: (1) the deformation process of propellant sample in the impact process can not be known; (2) the impact absorbing the energy of propellant cannot exclude the kinetic energy when the fracture sample flies out, which leads to the calculation result more large than the actual value; (3) due to the process problems, the performance of propellant is dispersive. So there is a great difference in fracture mode under the impact, resulting in poor repeatability of impact strength. The latter determines the impact strength in an axial direction through a mid-value, which is acquired when 50% propellants occur cracks or complete fracture by measuring enough samples. This method is too general. In this paper, a method based on the initial fracture impact absorbing energy in the drop weight test (DWT) is proposed to measure the transverse impact strength of propellants. According to the load-time curve obtained in the impact process, the initial fracture point of the propellant is determined. The displacement of the drop hammer is obtained using the kinematic equation, and the load-displacement curve is established. The energy consumption corresponding to the initial fracture point is derived by integration, which is used as the impact absorbing the energy of the propellant. In the light of the initial cross-sectional area, the transverse impact strength can be got. This method can not only know the deformation process of propellant during the impact process but also eliminate the influence of kinetic energy of fracture sample. At the same time, the proposed method can avoid the problem of poor repeatability of impact strength measurement due to different fracture modes to a certain extent.

[a] *J.-H. Liu, C.-H. He, R.-H. Zhang, H.-L. Zhao, Q.-L. Wang*
High energy gun propellant department
Xi'an Modern Chemistry Research Institute
Zhangbadong Road, Yanta District, 710065, Xi'an, P. R. China
**e-mail: webzhl@126.com*

2 Experimental

2.1 Experimental Procedure

The samples used in this paper are SF-3 double-base propellants, ADI, and DAG triple-base propellants, which are provided by Xi'an Modern Chemistry Research Institute. The main components of SF-3 propellants are nitrocellulose and nitroglycerin (the weight percentages of them are 52% and 27%), while ADI and DAG propellants mainly contain nitrocellulose, nitroglycerin, and high energy solid explosive particles. The weight percentages of nitrocellulose and nitroglycerin of ADI and DAG propellants respectively are 35% and 9%, 43% and 11%. The CEAST (Compagnia Europea Apparecchi Scientifici Torino, Italy) 9340 drop weight impact system is supplied by Instron Limited; The VEO710 high-speed camera comes from York Limited; Analysis software used in the digital image correlation method is GOM Correlate 2018.

(1) Displacement reliability verification test. First of all, this paper deduces the displacement according to the load-time curve and establishes the load-displacement curve to obtain the impact absorbing energy. In order to verify the accuracy of the displacement, combining the high-speed camera with the digital image correlation method [12–14] measures the axial deformation of ADI propellant, which is compared with the deformation derived above to prove the effectiveness and accuracy of the latter. Of course, before the comparison, it is necessary to verify the measurement accuracy of the digital image correlation method by zero deformation test. The specific operation is as follows: The propellant sample was pasted under the hammer. Nine images were collected before the hammer impacting sample stage. The first image was taken as the reference image and other images as the deformation images. The strains in the *x* and *y* directions were calculated. As shown in Figure 1, the analysis process of the digital image correlation method is illustrated. The test process referred to Ref. [15]. The test parameters are shown in Table 1. No. 0 is the zero deformation test, and No. 1 is the displacement reliability verification test. The calculation parameters of the digital image correlation method are set as follows: sub-area size is 9×9 pixels; step size is 7 pixels.

(2) DWT. Before the test, the propellant samples with a length of 60 mm were processed, as shown in Figure 2. The samples were set into an incubator for more than 2 hours and then placed on the simply supported beam with a span of 40 mm. The test parameters are shown in Table 1. During the tests, a high-speed camera is used to capture the deformation images of propellants. The test system is shown in Figure 3. The fracture samples at low temperature are shown in Figure 4.

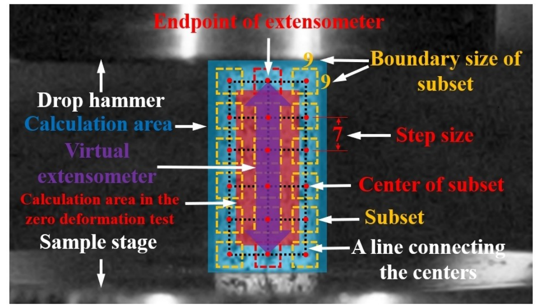
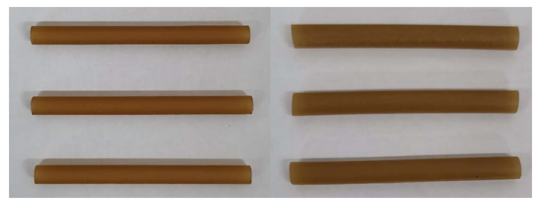


Figure 1. Diagram of the deformation calculation of ADI propellant by DIC.



(a) SF-3 propellants (b) DAG propellants

Figure 2. SF-3 and DAG propellants before testing.

2.2 Data Processing

2.2.1 Calculation of the Transverse Impact Strength

In this paper, according to the load-time data, the velocity of a hammer is calculated and the change of displacement

Table 1. Test parameters settings.

Test code	Type	External diameter/ mm	Internal diameter/ mm	Length/ mm	Span/ mm	Temperature/ °C	Impact velocity/ $m \cdot s^{-1}$	Frequency/ kHz
No. 0	ADI	5.9	2.3	12.0	–	room	3.8	20
No. 1	ADI	5.9	2.3	12.0	–	room	2.9	20
No. 2	SF-3	5.2	1.6	60.0	40.0	room	2.9/3.8	20
No. 3	SF-3	5.2	1.6	60.0	40.0	−40	2.9/3.8	20
No. 4	DAG	6.0	2.2	60.0	40.0	room	2.9/3.8	20
No. 5	DAG	6.0	2.2	60.0	40.0	−40	2.9/3.8	20

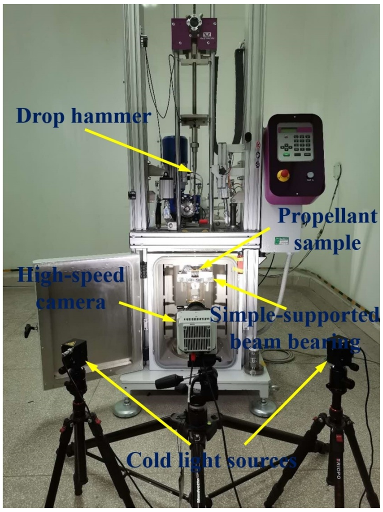


Figure 3. Drop weight test system.

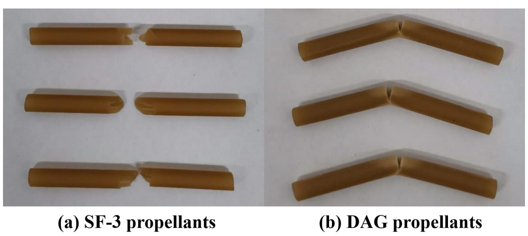


Figure 4. SF-3 and DAG propellants after testing at low temperature.

with time is obtained. Then the relationship between load and displacement is established. The work of hammer on the propellant sample corresponding to the initial fracture point is calculated, which is used as the impact absorbing energy. Finally, the transverse impact strength of the propellant is determined. The specific calculation steps are as follows:

First, according to the kinematic equation, the relationship between the velocity of hammer and impulse is as follows

$$v(t) = v_0 - I(t)/m \tag{1}$$

Where, $v(t)$ is the velocity of the hammer; v_0 is the maximum velocity before the hammer contacting the propellant sample; $I(t)$ is the impulse of the hammer; m is the mass of hammer; t is the time from the moment when the hammer contacts propellant. Then, the displacement of the hammer can be obtained by integration according to Eq. (2).

$$u(t) = v_0 t - \left[\int_0^t I(t)dt\right] \Big/ m \tag{2}$$

Where, $u(t)$ is the displacement of the hammer. Other parameters are the same as the above equation. The work of hammer is obtained by Eq. (3), which can be regarded as the impact absorbing energy (as the shadow area shown in Figure 5). Then the transverse impact strength corresponding to the initial fracture point can be acquired.

$$\alpha_k = \left[\int_0^{t_0} F(t)du(t)\right] \Big/ S_0 \tag{3}$$

Where, α_k is the transverse impact strength of the propellant; $F(t)$ is the load; S_0 is the initial cross-sectional area of the propellant; t_0 is the moment corresponding to the initial fracture point; other parameters are the same as the above equations.

2.2.2 Determination of the Initial Fracture Point

The purpose of this paper is to determine the impact absorbing energy corresponding to the initial fracture point in the impact test. In order to achieve this goal, the high-speed camera is used to collect the test images of propellant, which is compared to the load-displacement curve. Then the characteristic point of the curve corresponding to

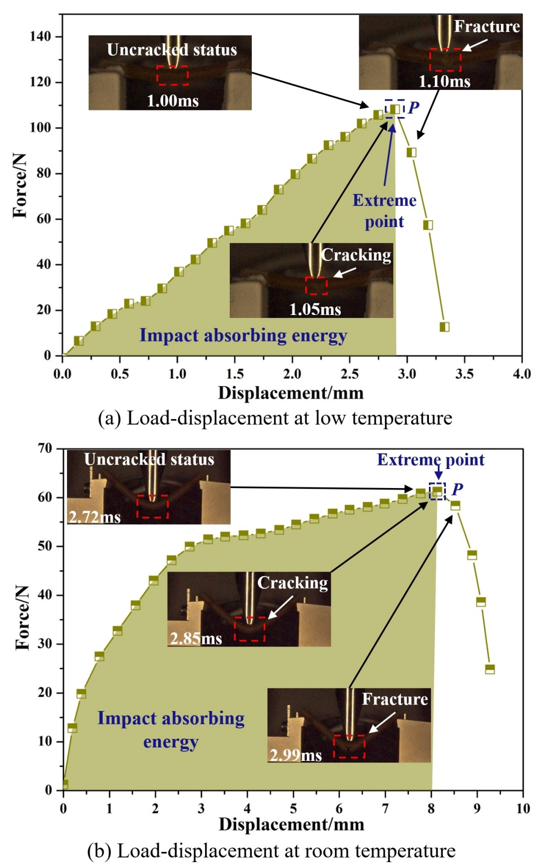


Figure 5. Typical loading-displacement curves of SF-3 propellant.

the initial fracture point is determined. Figure 5 shows the typical load-displacement curves of SF-3 propellants at low temperature and room temperature. It can be found that the load-displacement curves have an obvious characteristic inflection point. Through comparing with the test images, it can be clearly seen that the propellant samples were cracked near the maximum load point, which can be taken as the initial fracture point.

3 Results and Discussion

3.1 Zero Deformation Test

In the drop weight test, the size of the propellant perpendicular to the load direction is small, due to the transverse placement of the sample. So the pixels occupied by the sample in the field of view of a high-speed camera are small at high frame rate, which results in low resolution. The phenomenon makes it difficult to directly measure the displacement of propellant in the impact test. However, the axial dimension of the propellant is large enough. So this paper will use the axial drop weight impact test combining with a high-speed camera and digital image correlation method to carry out zero deformation and displacement reliability verification tests.

Before the displacement reliability verification, the measurement accuracy of the digital image correlation method was analyzed under high-speed impact. Compared with the quasi-static test, due to the high acquisition frequency, the image definition is insufficient. The image noises result in errors during the correlation calculation, which leads to decrease in the measurement accuracy of the digital image correlation method. Through the zero deformation test, the measurement accuracy of the analysis method and the influence on the subsequent measurement results can be determined. As shown in Figure 6, the evolution process of surface deformation of propellant before impacting was obtained. As can be seen from Figure 6, numerically the maximum average strain in the x direction is 1.541% and 2.568% in the y direction. This result namely is the random measurement error of the digital image correlation method in this test (the measurement accuracy will increase with the decrease of measurement error). Besides, during the displacement reliability verification test, the deformation in the y direction is the main object of study. As shown in Figure 7, when the maximum load is reached, the strain of ADI propellant is about 35%. So when the deformation is small, the errors of this method exist. But with the increase of deformation, the influence of measurement errors on the deformation analysis gradually decreases. By comparison, the measurement error of the digital image correlation method is small in general. It is proved that the digital image correlation method is accurate enough to analyze the axial deformation of propellant in the drop weight impact test.

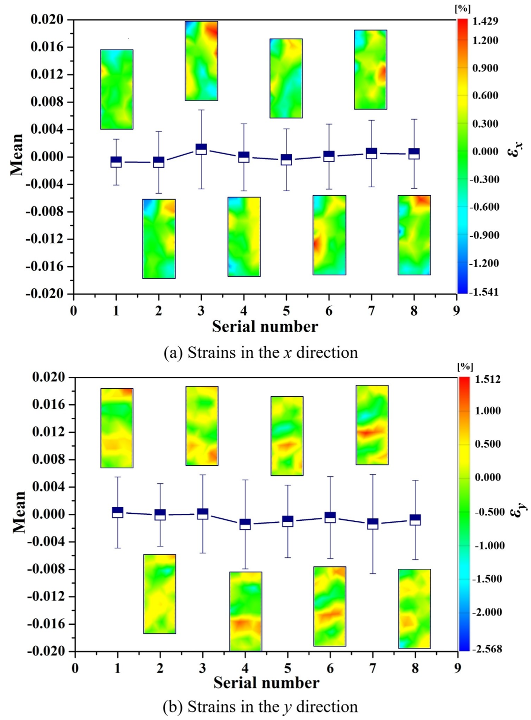


Figure 6. Average strains and standard deviations in the x and y direction obtained by DIC in the zero tests.

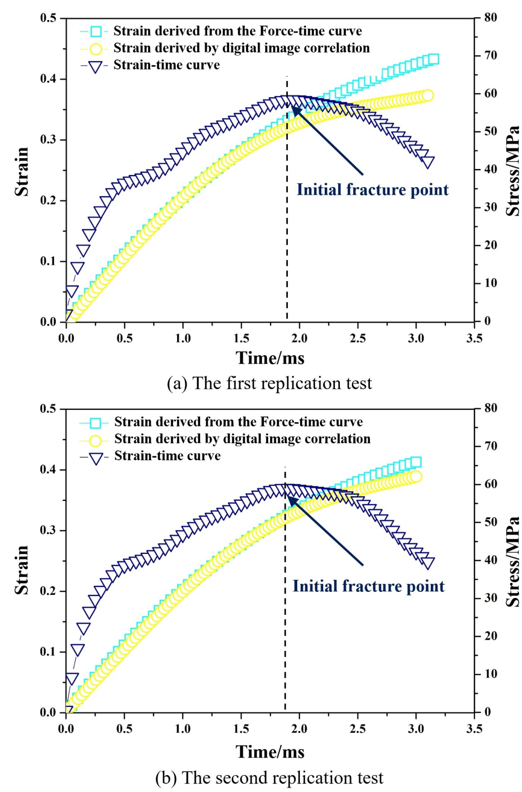


Figure 7. The axial strains of ADI propellants in the replication tests.

3.2 Displacement Reliability Verification

It is known that the displacement used in this paper is derived from the load-time relationship. The accuracy and reliability of calculating the impact absorbing energy with displacement need to be discussed. The test process has been described above. One point needs to be specially explained: this part is to explain the accuracy of displacement calculation through verifying the reliability of strain measurement. The reason is as follows: the displacement obtained by load represents the change of the whole axial dimension of a propellant sample, while the digital image correlation method often takes the middle region of a sample as the deformation calculation area. Since the boundary effect will cause the inaccuracy of calculation results, so the middle region is usually used to carry out the correlation calculation. Namely, there is no comparison between the displacements obtained by the two calculation methods above. However, strain represents relative deformation and is a dimensionless parameter. Therefore, strain can be used to indirectly explain the reliability of displacement calculation. According to Eq. (4), the axial strain ε_1 is obtained by the displacement. Based on the principle of virtual extensometer, the axial strain ε_d is acquired by the digital image correlation method. Figure 7 shows the axial strain of ADI propellant in the repeatability tests.

$$\varepsilon_1 = \text{-ln}(1 - [u(t)]/h \tag{4}$$

Where, ε_1 is the strain obtained from the load-displacement data, h is the initial height of the propellant sample, and $u(t)$ has the same meaning as the above equation.

As can be seen from Figure 7, generally speaking, ε_1 and ε_d before the initial fracture point is very similar. The two strains almost coincide between 0 ms to 1.5 ms, and then there is a little deviation. From the numerical point of view, at the initial fracture point in Figure 7 (a), ε_d is 3.9 % smaller than ε_1. The former is 0.8 % smaller than the latter in Figure 7 (b). It can be seen that the strain from the load-displacement data is very close to the strain by the digital image correlation method. The phenomenon illustrates sufficiently the accuracy and reliability of the displacement derived from the load-time relationship.

3.3 Drop Weight Test

3.3.1 SF-3 Double-Base Propellant

Table 2 shows the transverse impact strength of SF-3 double-base and DAG triple-base propellants obtained by DWT and PT (standard deviation is denoted by Std Dev and coefficient of variation is denoted by c_v in Table 2). Firstly, for the former, it can be seen from table 2 that when the impact velocity is 2.9 m/s, the average impact strength by DWT is 6.14 kJ/m^2 (at low temperature) and 21.83 kJ/m^2 (at room temperature) respectively. Meanwhile, the average impact strength by PT is 9.82 kJ/m^2 (at low temperature) and 29.71 kJ/m^2 (at room temperature). No matter at room or low temperature, it is worth noting that the results by PT are generally larger than those by DWT. The former is 1.60 times of the latter at low temperature and 1.36 times at room temperature. It is well known that the impact absorbing energy is obtained by PT after the complete fracture of a propellant sample, which includes the kinetic energy of the sample after a fracture. But the impact absorbing energy corresponding to the initial fracture moment by DWT doesn't contain the kinetic energy. So it is inevitable that the latter is greater than the former. Figure 8 shows the impact strength measurement results of SF-3 propellant including average values and deviations. It is apparent that the repeatability and stability of DWT are better than those of PT. In order to explain the consistency of test results and further determine the stability and reliability of the two methods, the coefficient of variation c_v is introduced to characterize the dispersion of results. From table 2, the coefficients of variation of SF-3 propellant in DWT at low and room temperature are 1.14 % and 6.92 % re-

Table 2. The transverse impact strengths of SF-3 and DAG propellants by DWT and PT.

Test	Type	Length/ mm	Cross section area/ mm^2	Temperature/ °C	Impact velocity/ m·s^{-1}	Impact strength/kJ·m^{-2} 1	2	3	Mean	Std Dev	c_v/%	Φ/rad
DWT	SF-3	60.00	17.48	room	2.90	21.91	20.29	23.30	21.83	1.51	6.92	0.07
					3.80	26.52	25.16	28.53	26.74	1.70	6.36	0.06
			17.48	−40	2.90	6.11	6.08	6.22	6.14	0.07	1.14	0.01
					3.80	9.25	9.18	8.00	8.81	0.70	7.95	0.07
	DAG	60.00	23.37	room	2.90	–	–	–	–	–	–	–
					3.80	–	–	–	–	–	–	–
			23.37	−40	2.90	9.91	9.44	8.60	9.32	0.66	7.08	0.07
					3.80	12.55	14.82	15.12	14.16	1.41	9.96	0.09
PT	SF-3	60.00	17.48	room	2.90	36.33	23.74	29.06	29.71	6.32	21.27	0.21
			17.48	−40	2.90	11.79	9.27	8.41	9.82	1.76	17.92	0.17
	DAG	60.00	23.37	room	2.90	–	–	–	–	–	–	–
			23.37	−40	2.90	13.05	9.41	10.78	11.08	1.84	16.61	0.16

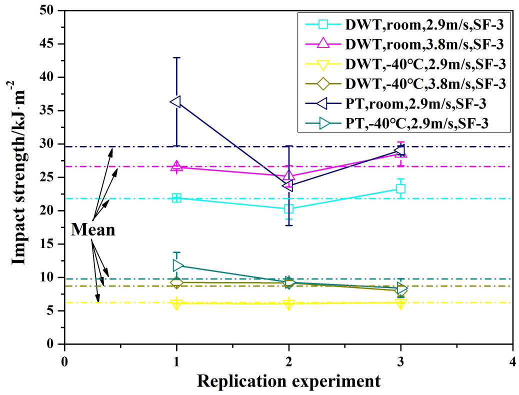


Figure 8. The transverse impact strengths of SF-3 propellants by DWT and PT.

spectively, while the coefficients in PT are 17.92% (at low temperature) and 21.27% (at room temperature). By comparison, it is easily found that the coefficient of variation of impact strength measurement results at room temperature is generally greater than that at low temperature. The coefficient in PT is 15.72 (at low temperature) times and 3.07 (at room temperature) times of that in DWT, respectively. The above results show that the dispersion of impact strength measurement results in PT (especially at low temperature) is much greater than that in DWT.

In order to have a more specific and visual understanding of the consistency of test results, the dispersion degree Φ is introduced. The definition is as follows: take the ratios of the maximum value and minimum value to the average value as the slope a of the line $y=a\cdot x$, respectively. Then two straight lines can be made in a Cartesian coordinate system. So the angle between the two straight lines represents the dispersion degree Φ, as shown in Figure 9. The physical meaning is as follows: it is known that all the straight lines obtained pass through the origin of the coordinate system. The straight line with the slope of 1 repre-

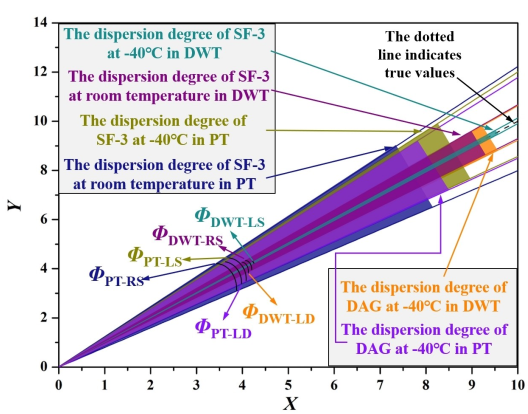


Figure 9. The measurement dispersion degrees of the impact strengths by DWT and PT.

sents the average value of each test. When the test result is more discrete, the straight line obtained above will deviate more from the line where the average value is located. The sector area with the origin as the center and two straight lines as the radius will be larger. It is well known that the sector area is determined by the radius and central angle. For the convenience of comparison, the radius is assumed to be 1. Then the only factor determining the sector area is the central angle, which is namely the dispersion degree Φ described in this paper. This parameter can be got through Eq. (5). In Figure 9, $\Phi_{DWT\text{-}LS}$, $\Phi_{DWT\text{-}RS}$, and $\Phi_{PT\text{-}LS}$, $\Phi_{PT\text{-}RS}$ respectively represents the dispersion degree of impact strength measurement of SF-3 propellant in DWT/PT at low/room temperature when the impact velocity is 2.9 m/s.

$$\Phi = \mathrm{artan}\left(\alpha_{max}/\alpha_m\right) - \mathrm{artan}\left(\alpha_{min}/\alpha_m\right) \tag{5}$$

Where, Φ is the dispersion degree of impact strength measurement in rad; α_{max} is the maximum of impact strengths obtained in the repeatability tests; α_{min} is the minimum of impact strengths; α_m is the average of impact strengths. Table 2 lists the calculated dispersion degree of each impact test. It can be seen that when the impact velocity is 2.9 m/s, the dispersions degree of SF-3 propellant measured in DWT is 0.01 rad (at low temperature) and 0.07 rad (at room temperature). The dispersions in PT are 0.17 rad (at low temperature) and 0.21 rad (at room temperature), which are significantly larger than those in DWT. The comparison results of dispersion degree and coefficient of variation show that DWT has better consistency than PT test for the measurement of transverse impact strength of double-base propellant.

In order to further illustrate the reliability of DWT, the impact test with a velocity of 3.8 m/s was carried out. The results are shown in Figure 8 and table 2. It's obvious that the coefficients of variation and dispersion degrees of impact strength of SF-3 propellants at low and room temperature are 7.95% and 0.07 rad, 6.36% and 0.06 rad, respectively. Compared to DWT at low temperature with a velocity of 2.9 m/s, the coefficient of variation and dispersion degree increase by 6.97 times and 7.00 times. But the results are still far less than those of PT with a velocity of 2.9 m/s. At room temperature, the coefficient of variation and dispersion degree are slightly lower than those of DWT with a velocity of 2.9 m/s. The above results further prove the reliability and stability of DWT compared with PT. In addition, it should be noted that the impact strengths of SF-3 propellants increase with the increase of impact velocity. The phenomenon indicates that the impact strength of propellant has a strain rate effect within the described velocity range.

3.3.2 DAG Triple-Base Propellant

Table 2 lists the impact strengths of DAG triple-base propellants obtained in DWT and PT at low temperatures. Figure 10 shows the average values and standard deviations of impact strengths. It is apparently found that when the impact velocity is 2.9 m/s, the average impact strengths of DAG at low temperature in the two tests are 9.32 kJ/m^2 and 11.08 kJ/m^2, respectively. The latter is greater than the former, which is similar to that of SF-3 double-base propellant. Besides, it can be found from Table 2 that the impact strengths of DAG propellant at room temperature are missing. The reason is that DAG propellant has excellent plastic properties at room temperature. The DWT and PT cannot make the DAG propellants crack or fracture and only produce large irreversible deformation, as shown in Figure 11. For the consistency of DAG impact strength measurement results, as shown in Table 2, when the impact velocity is 2.9 m/s, the coefficients of variation and dispersion degrees in DWT and PT are 7.08 % and 0.07 rad, 16.61 % and 0.16 rad, respectively. The results indicate that DWT has better consistency than PT for the measurement of impact strength of triple-base propellant. When the impact velocity is 3.8 m/s, the coefficient of variation and dispersion degree in DWT are 9.96 % and 0.09 rad, respectively. Compared to the tests with 2.9 m/s, there is a slight increase, but the results still far less than those obtained in PT. This phenomenon is sufficient to explain the reliability and stability of DWT.

To sum up, after careful thinking and analysis, it can be concluded that the main reasons for the results obtained above are as follows: (1) due to the influence of process, the propellant as a kind of energetic polymer has some problems, such as poor consistency of configuration, uneven distribution of components, density inconsistency or local agglomeration. These problems can cause the differences in mechanical properties between propellant grains; (2) the impact absorbing energy at the moment of initial fracture is used in DWT to calculate the impact strength. The difference in impact strengths is mainly caused by the inconsistency of sample properties and the test process. Meanwhile, the impact absorbing energy after complete fracture of the propellant sample is used to obtain the impact strength in PT. The reasons for the differences in impact strengths in PT include not only the two inconsistencies mentioned above in DWT but also the difference of absorbing energy caused by the inconsistency of fracture mode and the inconsistency of kinetic energy of the fracture sample. The above reasons cause the results in PT to be larger than those obtained in DWT, and the consistency and reliability of DWT are better.

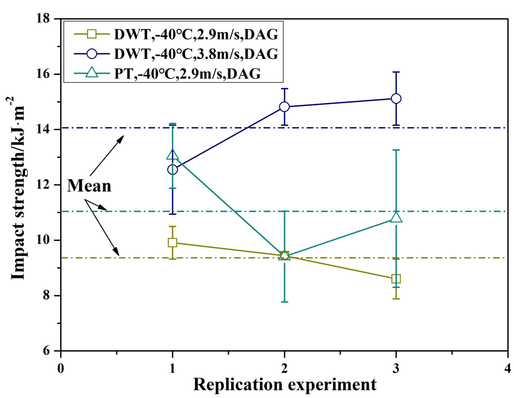


Figure 10. The transverse impact strengths of DAG propellants by DWT and PT.

Figure 11. DAG propellants after the impact test.

4 Conclusions

In this paper, a measurement method of transverse impact strength of propellant based on initial fracture impact absorbing energy in DWT is proposed. The impact resistances of SF-3 double-base and DAG triple-base propellants are studied. Compared with the traditional pendulum impact (PT), the main conclusions are as follows:

(1) Due to the different calculation principles and influence factors, the impact strengths of SF-3 and DAG propellants in DWT at low and room temperature are generally less than those obtained in PT. And the impact strengths increase with the increase of temperature and impact velocity;

(2) By analyzing the coefficient of variation and dispersion degree of impact strengths in the repeatability tests, it can be found that the coefficient of variation and dispersion degree in DWT are significantly less than those obtained in PT. The results are sufficient to illustrate that DWT has smaller dispersion, better repeatability, better consistency, and reliability for measuring the transverse impact strength of propellant.

Data Availability Statement

No data available.

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