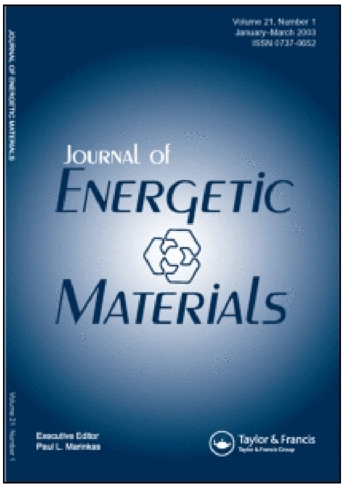

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Mechanical properties of azide polymer propellant at ignition stage

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MECHANICAL PROPERTIES OF AZIDE POLYMER PROPELLANT AT IGNITION STAGE

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SUMMARY

The rates of pressure increase for the 6.8 grams of the igniter powder and the igniter pellets at an ignition stage are measured by using dummy rocket motors. The mechanical properties of high burn rate azide polymer propellant at low temperature and at simulated ignition condition are also studied here. Although the effect of the pressure increase on the deformation of the propellant surface is smaller than that caused by the thermal stress, it becomes important when the rate of pressure increase is very high. The rates of pressure increase are for powder, 1.9×10^7 kgf/cm ^{2} /min, and for pellets, 2.6 to 7.5×10^5 kgf/cm ^{2} /min. The high speed tensile test well simulates the ignition condition in a view point of the viscoelasticity. The propellant used here has excellent mechanical properties even at a low temperature.

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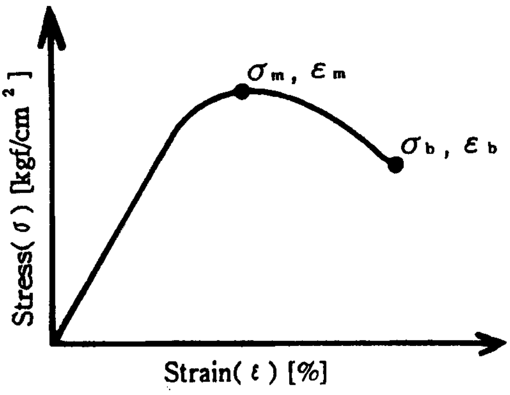
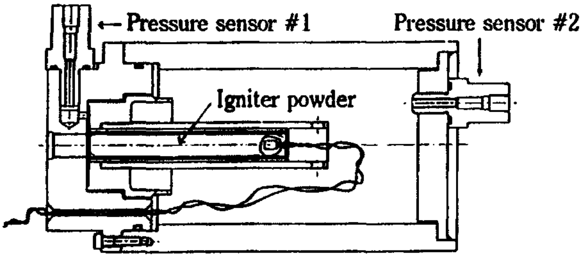


FIGURE 1 Typical stress–strain curve of a solid rocket propellant.

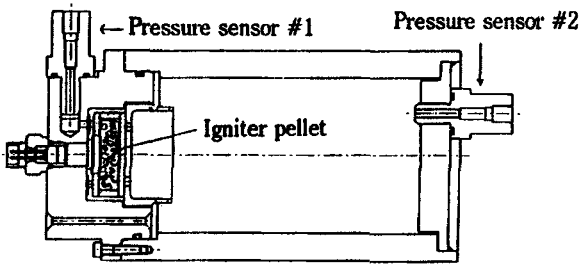
INTRODUCTION

Typical stress–strain curve of a solid rocket propellant measured by using a dog–bone specimen is shown in Figure 1. The propellant is a viscoelastic material and shows maximum stress (σ_m) and then yields till a break point. The mechanical properties of the propellant depend on a temperature and a strain rate. The propellant becomes brittle at low temperature or high strain rate and is soft at hot condition or low strain rate. Taking time–temperature superposition principle into consideration, the condition at low strain rate is equivalent to that of at hot temperature and a large strain rate is consistent with the cold day 1) . Therefore, the phenomenon occurred in a rocket motor is able to simulate with changing a temperature and a strain rate in a view point of stress–strain.

The igniter is designed to initiate the solid rocket propellant within tens of milliseconds and the amount of powders or pellets is depend on a burning surface area of the propellant grain and a free volume of the rocket chamber. The ignition peak pressure is carefully controlled to diminish the motor case safety margin but the effect of the pressure increase rate on the propellant mechanical properties is



Dummy motor case #2



Dummy motor case #1

FIGURE 2 The cut views of dummy motor case #1 and #2.

less reported. Azide polymer propellants show excellent thermal properties and combustion characteristics 2-5) but mechanical properties at below −35 ℃ are relatively inferior to those of hydroxyterminated polybutadiene, which is commonly used in a composite propellant. Therefore, it is important to estimate the mechanical properties of azide polymer propellant at low temperature range in the view point of grain design. The objective of this study is to analyze the mechanical properties of high burn rate azide polymer propellant at low temperature ignition stage.

EXPERIMENTAL

Rate of Pressure Increase At Ignition

The cut views of dummy motor case #1 and #2 are shown in Figure 2. The free volume is adjusted to the full size L/D = 16 rocket motor 6) . Two pressure

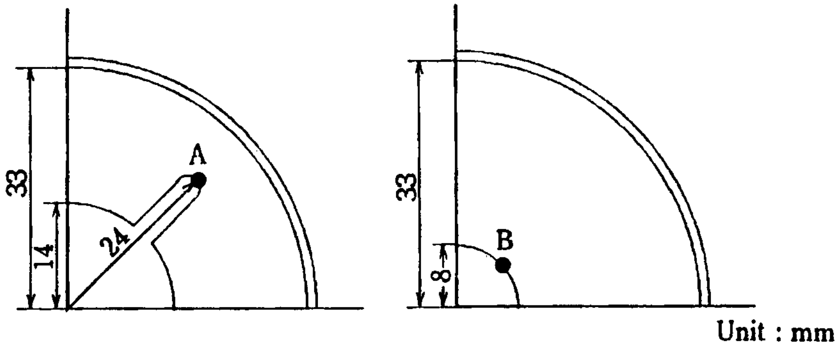


FIGURE 3 The propellant grain of the slot type and the center–perforated type.

sensors are installed to measure the pressures at the forward cap and the aft end. The effect of pellet size is observed in the dummy motor case #1 at temperatures of −33 ℃, 20 ℃, and 60 ℃. The amount of pellet used in this study is 6.8 grams. Sample 1, which is a large pellet, weighs 440 mg. Sample 2 and Sample 3 are 150 mg and 27 mg, respectively. The powder of 6.8 g is used in the dummy motor case #2 at 20 ℃.

Mechanical Properties Measurement

The mechanical properties at −30 ℃ are obtained at cross head speeds of from 5 mm/min to 2937 mm/min. The effect of prestrain is also monitored at 14% and 25%, which simulate the conditions of block bonding and case bonding, respectively.

RESULTS AND DISCUSSION

Rate of Pressure Increase At Ignition

The stress and strain occurred in the propellant depend on the grain shape and their estimation methods have been established and reported elsewhere [7, 8]. The slot grain and center–perforated grain, as shown in Figure 3, shows the maximum strain at points A and B, respectively. The strain related to temperature ($\varepsilon_{\theta T}$) is obtained by the equation (1) and that caused by the pressure ($\varepsilon_{\theta P}$) is calculated by the equation (2).

$$\varepsilon_{\theta T} = -K_{\theta T} \times (1+\nu_P)(M^2-1)/\{(1-2\nu_P)M^2+1\} \times \alpha_P \times \Delta T \qquad (1)$$

$$\varepsilon_{\theta P} = -K_{\theta P} \times (1+\nu_P')(M^2-1)/\{(1-2\nu_P')M^2+1\} \times Pi(t) \times Jc(T,t) \qquad (2)$$

where, $K_{\theta T}$: thermal stress factor (A = 2.8, B = 1.0), ν_P : propellant poisson's ratio (0.495), M: grain ratio (A = 66/48, B = 66/16), α_P : propellant thermal expansion ratio (1.3×10^{-4} ℃$^{-1}$), ΔT: temperature difference between the operation and the curing condition, $K_{\theta P}$: pressure stress factor (=$K_{\theta T}$), ν_P': propellant poisson's ratio at compression (0.498), Pi: internal motor pressure, Jc: propellant creep compliance, T: temperature, t: time.

These equations indicate that the strain depends on M and ΔT and the strain should be large when M and ΔT are large . The strain decreases with the web thickness decrease. ΔT depends on the curing temperature and the propellant loading condition. Therefore, the strain condition is severe in the case bonding, then the block bonding, and the strain is lowest in the cartridge loading. If the propellant is case-bonded at 60 ℃ , $\varepsilon_{\theta T}$ at −35 ℃ is 4.5% at the point A and is 25% at the point B. Since the strain is severe at a thick web section, the point B is focused in the study.

At an ignition stage, a deformation of the propellant surface is generated by $\varepsilon_{\theta T}$ and $\varepsilon_{\theta P}$. If it is assumed that $\varepsilon_{\theta P}$ is independent to the time factor, Pi = 230 kgf/cm^2 , and Jc= 10^{-4} cm^2/kgf, $\varepsilon_{\theta P}$ is calculated to be 0.2%. It is very smaller than $\varepsilon_{\theta T}$ of 25%. But when the pressure increases very steeply, the time factor becomes to be very effective on the $\varepsilon_{\theta P}$. The rate of pressure increase at

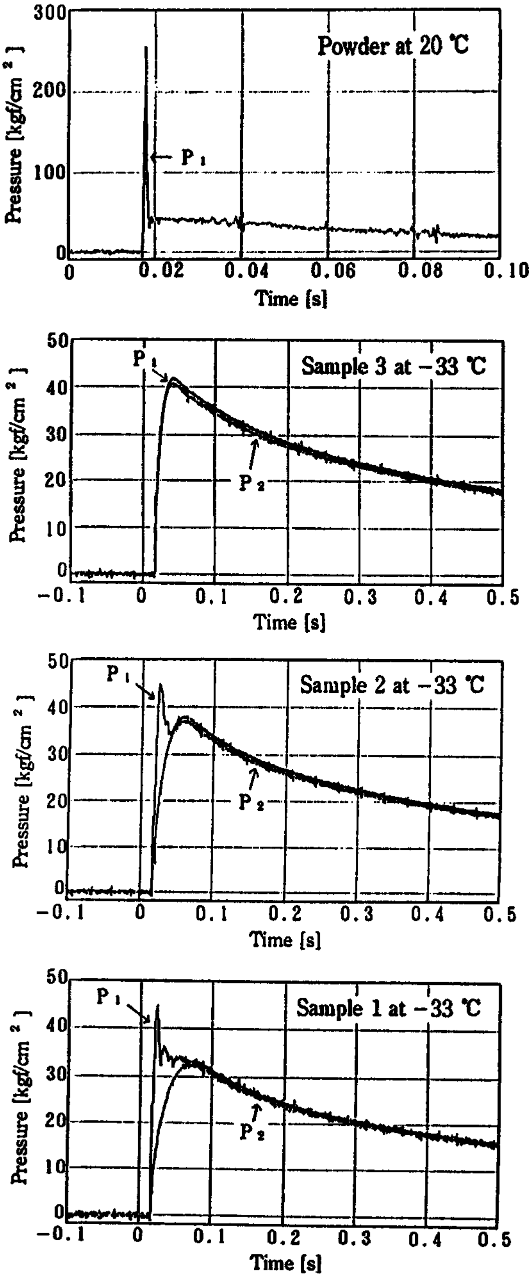


FIGURE 4 Typical pressure curves measured by the dummy motor case.

Table 1 Rate of Pressure Increase at Ignition

Sample	Temp [°C]	t_d [ms]	t_r [ms]	P_{max} [kgf/cm^2]	$\dot{P}$ [kgf/cm^2/min]
1	60	16.04	3.96	39.75	4.52×10^5
	60	16.04	3.56	44.63	5.64×10^5
	20	15.84	2.58	38.56	6.73×10^5
	20	16.24	6.14	51.55	3.78×10^5
	−33	15.84	3.57	44.90	5.66×10^5
	−33	16.04	2.97	53.72	8.14×10^5
2	60	15.84	2.77	46.73	7.59×10^5
	60	16.04	1.98	48.32	10.0×10^5
	20	15.84	2.38	51.24	9.69×10^5
	20	15.84	5.55	40.22	3.26×10^5
	−33	15.84	2.18	47.97	9.90×10^5
	−33	16.04	4.36	44.95	4.64×10^5
3	60	16.04	7.92	41.77	2.37×10^5
	60	16.04	6.93	41.61	2.70×10^5
	20	16.04	7.33	41.95	2.58×10^5
	20	15.84	6.93	42.72	2.77×10^5
	−33	16.04	6.73	43.17	2.89×10^5
	−33	16.04	7.92	42.15	2.39×10^5
Powder	20	17.03	0.59	249.1	1.90×10^7

t_d : ignition delay time, t_r : the time to reach to the pressure of 75% P_{max} ,
P_{max} : maximum pressure, $\dot{P}$: rate of pressure increase at ignition (= $0.75P_{max}/t_r$)

ignition ($\dot{P}$) is calculated by the equation of which 75% of maximum pressure devided by the time. For example, when ignition peak pressure goes to 230 kgf/cm^2 in 100 ms, $\dot{P}$ is 1.38×10^6 kgf/cm^2/min. The $\dot{P}$ depends on igniter nozzle design, pellet size, loading density, etc., and usually is in a order of 10^4 to 10^7 kgf/cm^2/min.

Typical results obtained by the dummy motor case #1 at −33 °C are shown in Figure 4. The pressure profiles at 20 °C and 60 °C are similar to those of at −33 °C . A pressure difference between the forward cap (P_1) and the aft end (P_2) exists and it is largest in Sample 1. The pressure difference diminishes with the pellet size decrease. The ratio of burning surface area to throat area of igniter nozzle is 44 in the dummy motor case #1 and the combustion of a smaller pellet may not complete in the igniter case. Most of Sample 3 pellets may pass through a nozzle throat of the igniter and burn in the dummy motor case. The relationship between pellet size of Sample 3 and the nozzle throat diameter plays an important role in diminishing the pressure difference. As shown in Figure 4, however, powder sample shows steep peak pressure at initial phase and it indicates that the pressure difference relates the burning surface area. P_{max} of P_2 becomes to appear in early stage and its value also becomes large with the particle size decrease. These results indicate that the combination of pellet size and the igniter nozzle throat area is the best in Sample 3.

The test results are listed in Table 1. Although there are some scatterings in the data because that the ignition occurs in a very short period of time, the order of $\dot{P}$ for powder is 10^7 kgf/cm ^{2} /min and that of pellet is 10^5 kgf/cm ^{2} /min. The powder sample has very large burning surface area and produces a large amount of combustion gases in a very short time. Therefore, $\dot{P}$ of powder tends to be large. Sample 1 indicates that the $\dot{P}$ increases with temperature decrease. Generally speaking, chemical reaction is faster in high temperature. But this temperature effect is not observed in Table 1. Especially, Sample 3 shows no temperature dependence on $\dot{P}$. Although the igniter powder is not recommended to use for the azide polymer propellant, there is few difference in the $\dot{P}$ of the igniter pellets.

As of equation (2), $\varepsilon_{\theta P}$ relates $\dot{P}$ and may change in the order of 10^2 , if the time factor changes drastically. The properties of the solid propellant turn to be glassy at low temperature condition. There is few additional safety margin in the grain design of the high performance rocket motor. Therefore, the increase of $\varepsilon_{\theta P}$ is serious at low temperature. The selection criteria of igniter pellet is not only ignitability, minimum smoke, and ignition peak pressure but also the rate of

TABLE 2 Mechanical Properties of Azide Polymer Propellant

ε_0 [%]	R [mm/min]	$\dot{\varepsilon}$ [min^{-1}]	σ_m [$\mathrm{kgf/cm}^2$]	σ_b [$\mathrm{kgf/cm}^2$]	ε_m [%]	ε_b [%]
0	5	0.076	24.7	13.4	27.0	66.1
0	30	0.455	37.0	25.7	24.8	39.7
0	100	1.52	49.3	39.5	21.2	32.3
0	300	4.55	63.0	54.6	22.1	32.1
0	500	7.58	72.1	60.9	18.6	29.2
0	1435	21.7	94.0	89.1	14.4	18.5
0	1643	24.9	92.5	87.2	12.1	16.6
14	1161	17.6	74.1	68.9	11.8	18.5
14	1782	27.0	80.9	80.9	12.6	12.6
14	1850	28.0	79.2	71.3	11.6	16.8
14	2535	38.4	82.6	76.8	11.7	15.4
25	487	7.4	49.0	46.1	16.6	18.3
25	1878	28.5	70.1	64.2	12.0	18.5
25	2213	33.5	61.3	61.3	10.0	10.0
25	2937	44.5	70.2	70.2	10.5	10.5

ε_0 : prestrain (block bonding = 14%, case bonding = 25%), R: cross head speed, $\dot{\varepsilon}$: strain rate, σ_m : maximum stress, σ_b : stress at break point, ε_m : elongation at σ_m, ε_b : elongation at σ_b

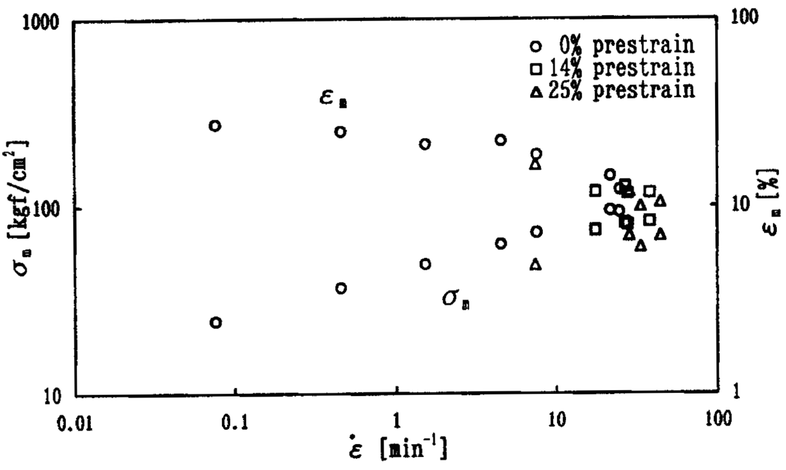


FIGURE 5 Mechanical properties versus strain rate at −30 ℃ .

pressure increase.

Mechanical Properties at Ignition Stage

The mechanical properties of solid propellant at a ignition stage depend on a deformation rate of a propellant surface, which relates to the $\dot{P}$. The deformation rate is approximately 1,000 – 10,000 mm/min, whose deviation is caused by the type of igniter pellet and diameter of an inner bore or shape of the grain. Therefore, it is important to evaluate the mechanical properties at a condition which simulates the deformation rate occurred at an ignition.

The mechanical properties measured by the high speed single axis tensile test are listed in Table 2. the relationship between ε_m, σ_m and the strain rate, $\dot{\varepsilon}$, are shown in Figure 5. When $\dot{\varepsilon}$ increases, ε_m decreases with increase of σ_m. It indicates that the propellant becomes brittle with $\dot{\varepsilon}$ increase. The expected $\dot{\varepsilon}$ is approximately 30 min^{-1} in the flight weight rocket motor and these results indicate that the high speed tensile test well simulates the ignition condition.

The propellant used here is bis(azidemethyl)oxetane/nitratomethylmethyl oxetane/ammonium perchlorate composite propellant and shows high burn rate with a favorable plateau burn chatacteristic (6). This propellant has 10% of ε_m even at −30 °C with 25% prestrain.

CONCLUSIONS

Although the effect of pressure increase occurred at an ignition stage on the deformation of the propellant surface is usually smaller than that of thermal stress, it influences the grain when the rate of pressure increase is very steep.

The powder type igniter tends to show very large peak pressure and it is not recommended to use a powder type in a small free volume rocket chamber. There is few difference in the $\dot{P}$ of igniter pellets, therefore large pellet is recommended to control the ignition peak pressure and the $\dot{P}$.

The high speed tensile test is a good tool to evaluate the propellant mechabical properties at a simulated ignition condition.

The propellant used here has excellent mechanical properties even at a low temperature.

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