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Temperature Measurement of a Burning Surface by a Thermocouple

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A thermocouple has been used to measure the temperature profile near the surface of a burning solid propellant. An inverted U-shaped thermocouple was better than an inverted V-shaped one in this situation, because there was less heat loss through the leads. However, producing an efficient inverted U-shaped thermocouple and embedding it perfectly parallel to the burning surface are difficult. In this study, the error introduced by heat conduction through the thermocouple leads was examined experimentally, using ammonium perchlorate. The decrease in temperature due to heat conduction through the leads of a 50-μm thermocouple was estimated using a simple expression. The results showed that for a 50-μm thermocouple, a lead angle greater than 120 deg is necessary to prevent errors due to heat conduction losses from causing a deviation that exceeds the normal experimental scatter in the data. In addition, it was found that the temperature of the burning surface of ammonium perchlorate is between 460 and 470°C at atmospheric pressure.

Introduction

BOTH the temperature and the temperature gradient near a burning surface are important in modeling the combustion of solid propellants, because the temperature of the burning surface provides a critical boundary condition for models that are used to predict the regression rate of the propellant. To date, the use of imbedded microthermocouples has been the only successful method for measurement of temperature profiles through the entire combustion waves of solid propellants. Thermocouples may remain the best method for measurement in the condensed phase for the foreseeable future. However, temperature measurements using thermocouples introduce systematic errors such as time lag in the response, limited spatial resolution, catalytic effects, radiation losses from the junction, and heat conduction through the leads.

The use of imbedded thermocouples in solid propellants was first described by Klein et al.,[1] who discussed the catalytic effect that occurs when platinum wires are used in double-base propellant flames. They also recognized the value of temperature profiles in providing heat release distributions through flames. The surface temperature of a burning surface was derived graphically from a plot of $\log(T - T_0)$ vs distance. The point of departure of this plot from linearity is taken to be the surface temperature. They measured the surface temperature of a double-base propellant to be about 250°C, which is significantly lower than the value of 300°C[2,3] obtained in other studies.

Suh et al.[2] and Suh and Tsai[3] measured the temperature profile near the burning surface of a double-base propellant at pressures of 5, 10, and 15 psi (0.034, 0.069, and 0.103 MPa) and observed the emergence of the thermocouple bead from the solid phase into the gas phase, using high-speed motion pictures. In their study, Pt–Pt10%Rh thermocouples with wire diameters of 12.7, 25.4, 51, and 76 μm were used. A V-shaped thermocouple with a lead angle of 40 deg was imbedded in a double-base propellant. Some of the temperature–time records showed the plateau region at the burning surface. Although the thermocouple they used was relatively large compared with the temperature gradient in the propellant, they concluded, by using one-dimensional heat transfer analysis, that the surface temperature of a double-base propellant was between 300 and 330°C.

Strittmater et al.[4] modeled leads as insulated conductors with an exponential heat input at the hot end. The analysis concluded that the conduction error increases as the thermocouple wire diameter decreases. Thus the ratio of heat input into the junction to heat loss by conduction through the leads increases for small beaded thermocouples. However, this conclusion seems unreasonable for microthermocouples, because the error introduced by the leads should decrease for thinner thermocouple wire. Thus, the assumption of insulated conductors is not good in the limit of small wire diameters.

Miller[5] examined the effect of lead angle in the thermal wave near the burning surface in a triple-base nitrate–ester propellant experimentally. In his experiment, Pt–Pt10%Rh thermocouples with 50-μm beads were used. The angle was varied from 150 to 30 deg at 1 MPa. The results of the temperature measurement at 1 MPa show that the angle of the leads affects the temperature profile, because of heat conduction from the junction site. However, he does not report the burning surface temperature; only temperature profiles are shown. In addition, it is apparent that the thermocouple does not have adequate spatial resolution to examine the thermal wave near the combustion surface.

Zenin[6,7] is one of the preeminent practitioners of this kind of experiment. He discusses the errors in temperature measurements inside flames with a thermocouple.[6] Furthermore, Zenin et al.[7] use a U-shaped ribbon thermocouple with very small thickness to gain the appropriate space and time resolution for temperature measurements.

In a previous paper,[8] the surface temperature of ammonium perchlorate (AP), a major ingredient in composite solid propellants, was measured using thermocouples. In that study, the thermocouple leads were aligned parallel to the burning surface to reduce heat conduction along the leads. However, in some cases the thermocouple leads cannot be aligned parallel to the surface.

Though a numerical simulation of the thermocouple is required for accurate estimation of heat loss through the leads, the objective of this study is to primitively and experimentally evaluate the measurement error associated with an inverted V-shaped thermocouple in measuring the burning surface temperature of a propellant.

Experiment

The experimental apparatus used in this study is the same as that described in Ref. 8. A propane gas stream impinged on the AP specimen. Heat from the propane/air diffusion flame sustained the combustion of the AP below its pressure deflagration limit. The regression rate was adjusted by controlling the flow rate of propane.

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The specimen was moved at a rate such that the burning surface remained in the same relative position. The temperature profile near the burning surface was measured using Pt–Pt10%Rh thermocouples with wire diameters of 50 and 12.7 μm. The thermocouple was sandwiched between two AP pellets without any glue. The effect of the poor contact between the thermocouple and AP was confirmed to be negligible.[8]

As shown in Fig. 1, the angle between the thermocouple leads is defined by θ. A photo of the thermocouple is shown in Fig. 2. The diameter of the bead was from 1.5 to 3 times larger than the diameter of the lead. The lead angle θ was determined from the equation

$$\theta = \tan^{-1}\{\tan(\theta'/2)\cos\varphi\} \times 2 \tag{1}$$

where θ' is the lead angle measured on a television monitor and φ is the angle between the horizontal plane and the optical axis of a charge-coupled device (CCD) camera.

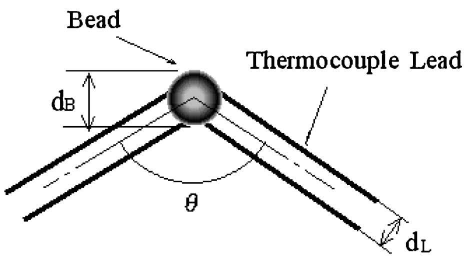


Fig. 1 Thermocouple and lead angle.

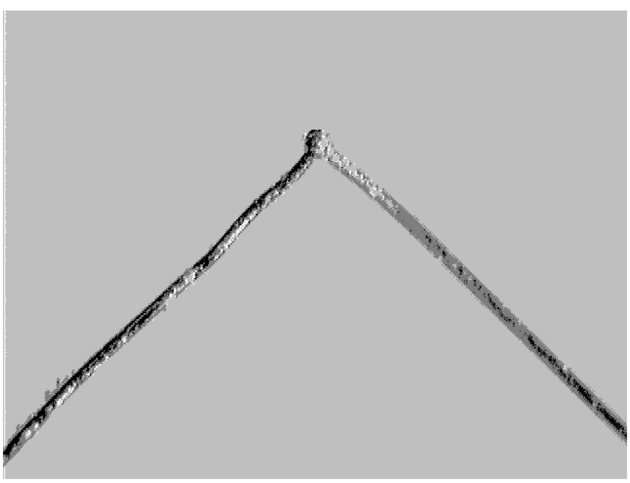


Fig. 2 Typical thermocouple.

Results and Discussion

Surface Temperature and Heating Rate

Figure 3 shows the thermocouple near the burning surface. The thermocouple in Fig. 3 is illustrated in Fig. 4. In Figs. 3a and 4a, the top of the thermocouple bead has just appeared on the burning surface. In Figs. 3b and 4b, the bottom of the thermocouple bead has reached the burning surface. In Fig. 3c, the lead angle can be measured using Eq. (1).

Figure 5 shows a typical temperature–time diagram for $\theta = 90$ deg. The photos in Figs. 3a and 3b were taken at the times indicated by the letters A and B, respectively, in Fig. 5. The temperature at point A in Fig. 5 is defined as T_{smin}, and that at points B

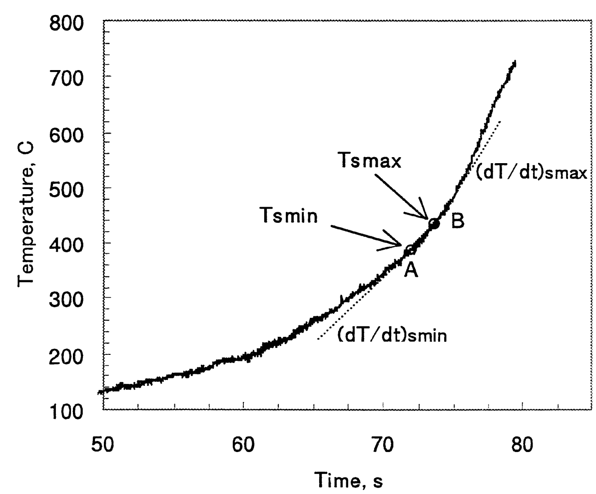
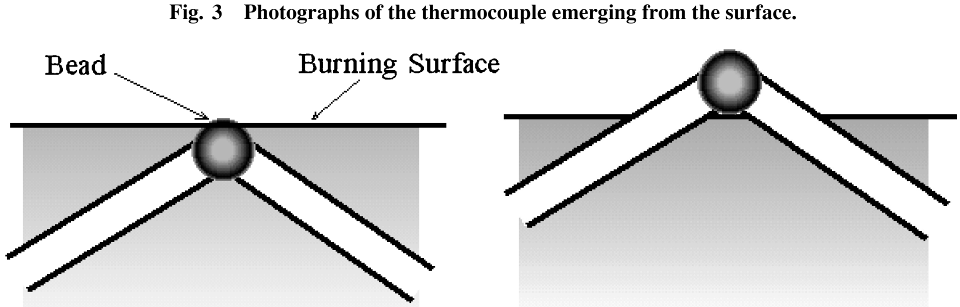


Fig. 5 Temperature–time diagram obtained by thermocouple.

a) b) c)

Fig. 3 Photographs of the thermocouple emerging from the surface.



a) b)

Fig. 4 Schematic side view of the thermocouple emerging from the surface.

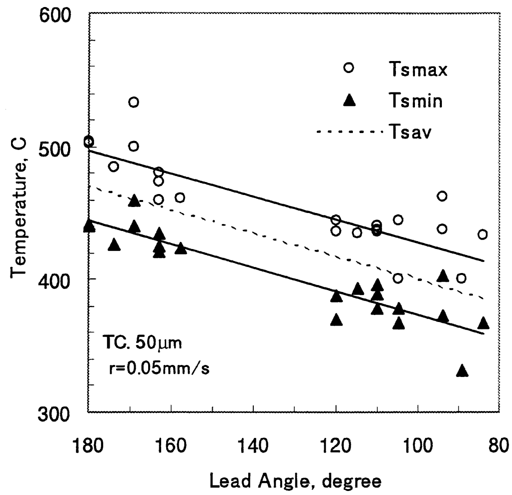


Fig. 6 Correlation between the lead angle and thermocouple temperature (50-μm-diam wire).

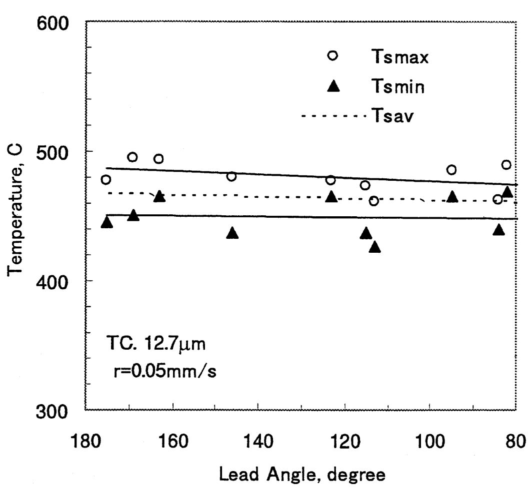


Fig. 7 Correlation between the lead angle and thermocouple temperature (12.7-μm-diam wire).

is defined as T_{smax}. In the temperature–time diagram, no flat region can be seen near the burning surface.

When the thermocouple has an inverted U-shape, the true burning surface temperature is clearly between T_{smin} and T_{smax} (the temperatures of points A and B in Fig. 5), whereas when the thermocouple has an inverted V-shape, the true burning surface temperature may not be between T_{smin} and T_{smax}.

The relationship between the measured temperature and the lead angle θ is shown in Figs. 6 and 7. In these figures, the regression rate is approximately 0.05 mm/s. The dashed lines in Figs. 6 and 7 are averaged temperatures as defined in the following equation:

$$T_{sav} = (T_{smin} + T_{smax})/2 \tag{2}$$

In the case of the thermocouple with 50-μm-diam wires, the measured temperature decreases as the lead angle θ decreases, as shown in Fig. 6. The temperature was affected by the lead angle due to heat loss through the leads. On the other hand, for the thermocouple with 12.7-μm-diameter wire, the burning surface temperature does not decrease as the angle θ decreases, as shown in Fig. 7. In addition, the difference between T_{smin} and T_{smax} in Fig. 7 is smaller than that in Fig. 6. Therefore, the heat loss of the 12.7-μm thermocouple can be considered to be smaller for a pressure of 0.1 MPa and $r = 0.05$ mm/s. Because the burning surface temperature of AP has been shown to be independent of the regression rate,[8] the true burning surface temperature of AP is taken to be close to T_{sav} (460–470°C), as obtained with the 12.7-μm thermocouple. This temperature is a little lower than the value obtained by the study.[9]

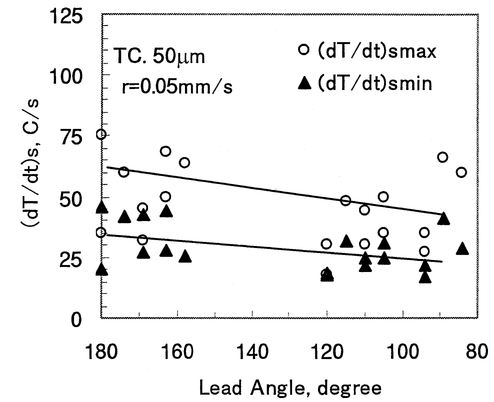


Fig. 8 Effect of lead angle on heating rate (50-μm-diam wire).

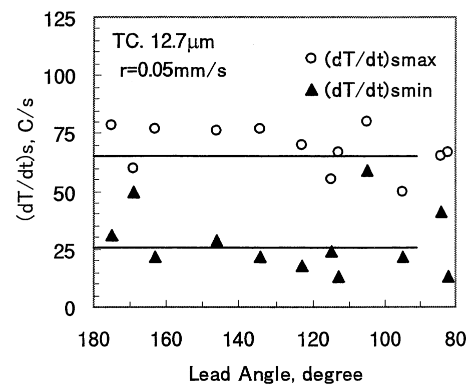


Fig. 9 Effect of lead angle on heating rate (12.7-μm-diam wire).

Figure 6 shows that for $\theta > 140$ deg, T_{smin} is lower than the actual burning temperature, and T_{smax} is higher than the actual burning surface temperature. On the other hand, when $\theta < 140$ deg, T_{smax} is lower than the actual burning surface temperature, and the actual burning surface temperature cannot be found between T_{smin} and T_{smax}.

Using the temperature–time diagram shown in Fig. 5, the temperature gradient at the burning surface $(\mathrm{d}T/\mathrm{d}x)_s$ can be estimated by the equation

$$\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_s = \left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)_s \Big/ r \tag{3}$$

where $(\mathrm{d}T/\mathrm{d}t)_s$ is the heating rate at the surface and r is the regression rate. Figures 8 and 9 show the relationship between the heating rate and the lead angle. In these figures, the values of $(\mathrm{d}T/\mathrm{d}t)_{smin}$ and $(\mathrm{d}T/\mathrm{d}t)_{smax}$, which correspond to the conditions of Figs. 4a and 4b, were obtained as shown in Fig. 5. In Fig. 9, the heating rate $(\mathrm{d}T/\mathrm{d}t)_s$ is almost constant; in Fig. 8, the heating rate $(\mathrm{d}T/\mathrm{d}t)_s$ slightly decreases as the lead angle decreases. Therefore, the data measured with the 12.7-μm thermocouple for $r = 0.05$ mm/s are used in the following section to evaluate the temperature gradient near the surface.

Heat Loss from the Lead

The heat loss from the leads can be estimated by the following equations:

$$\Delta T_{smax} = T_{smax0} - T_{smax} \tag{4}$$

$$\Delta T_{smin} = T_{smin0} - T_{smin} \tag{5}$$

where suffix 0 indicates the temperature without heat loss. Using Fig. 6, T_{smin0} and T_{smax0} are estimated to be 420°C and 510°C for a 50-μm thermocouple with $r = 0.05$ mm/s. The heat losses ΔT_{smin} and ΔT_{smax} are shown in Fig. 10. The scatter of the temperature

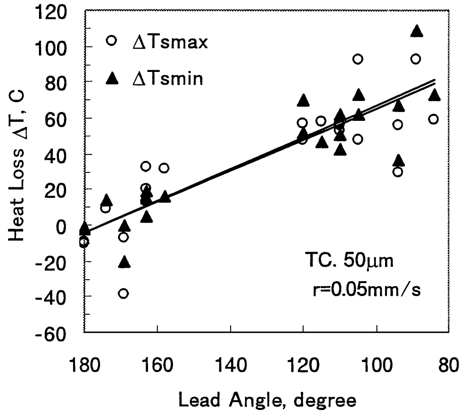


Fig. 10 Heat loss from leads.

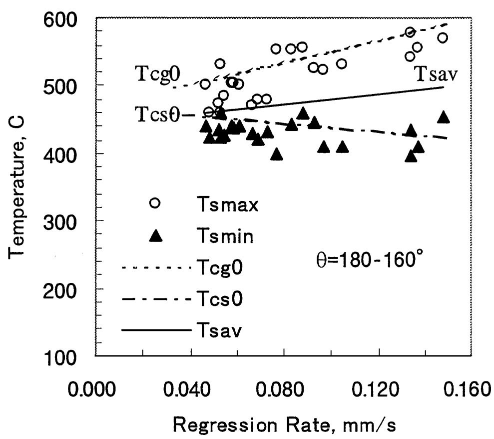


Fig. 11 Effect of the regression rate ($\theta = 180$–160 deg, 50-μm diam).

measurements is approximately 50°C in Fig. 6. Therefore, for the measurement using the 50-μm thermocouple in Fig. 10, one sees that the lead angle should be set to an angle of $\theta > 120$ deg to minimize the heat loss and thus keep the heat loss from exceeding the experimental scatter.

Effect of Regression Rate

The relationship between the measured temperature using 50-μm thermocouple wire and the regression rate is shown in Figs. 11 and 12. The figures show that the temperature difference between $T_{\rm smin}$ and $T_{\rm smax}$ increases as the regression rate increases. The average temperature $T_{\rm sav}$ is shown as a solid line in the figures. Even for $\theta = 180$ deg, the average temperature $T_{\rm sav}$ slightly increases as the regression rate increases. Thus, a U-shaped thermocouple with a larger bead and a higher regression rate does not show the actual burning surface temperature.

The temperature in the center of the bead is estimated by the following equations:

$$T_{\rm cs0} = T_s - \left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{s-} \cdot d_B/2 \tag{6}$$

$$T_{\rm cg0} = T_s + \left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{s+} \cdot d_B/2 \tag{7}$$

where $T_{\rm cs0}$ and $T_{\rm cg0}$ are the temperatures in the center of the thermocouple bead as shown in Fig. 13, and d_B is the diameter of the thermocouple bead, which was assumed to be 2.5 times larger than the wire diameter used in the experiment. $(\mathrm{d}T/\mathrm{d}x)_{s-}$ is the temperature gradient on the solid phase side of the burning surface. $(\mathrm{d}T/\mathrm{d}x)_{s+}$ is that on the gas phase side. Assuming that the thermal properties and the heat of decomposition near the surface are independent of the regression rate, the temperature gradients $(\mathrm{d}T/\mathrm{d}x)_{s-}$

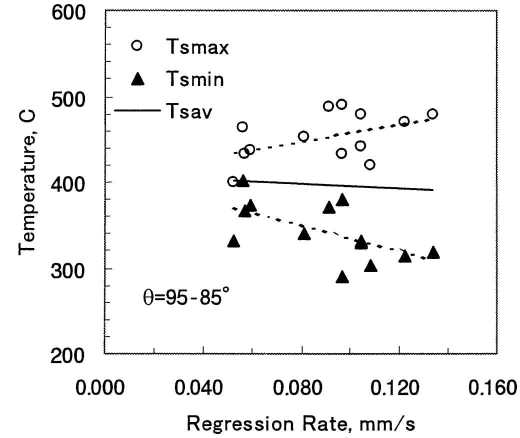


Fig. 12 Effect of the regression rate ($\theta = 95$–85 deg, 50-μm diam).

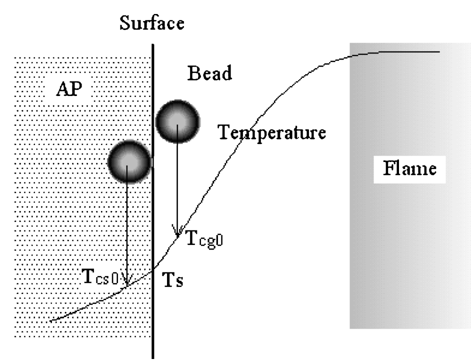


Fig. 13 Schematic of the bead near the surface.

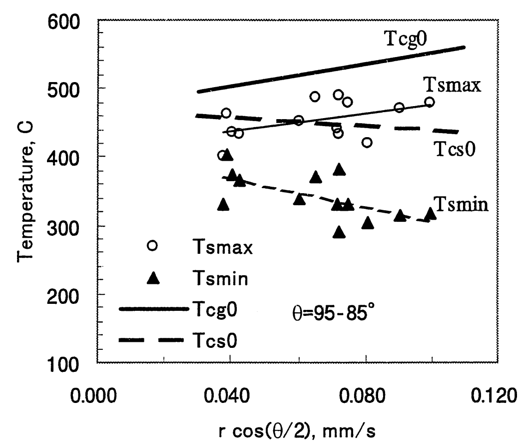


Fig. 14 Relationship between the temperature and effective regression rate (50-μm diam).

and $(\mathrm{d}T/\mathrm{d}x)_{s+}$ can be estimated by the following equations:

$$\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{s-} = \left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{\rm smin0}\left(\frac{r}{r_0}\right) \tag{8}$$

$$\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{s+} = \left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{\rm smax0}\left(\frac{r}{r_0}\right) \tag{9}$$

where r_0 is the regression rate 0.05 mm/s and $(\mathrm{d}T/\mathrm{d}x)_{\rm smin0}$ and $(\mathrm{d}T/\mathrm{d}x)_{\rm smax0}$ are the temperature gradients without heat loss, which are estimated using Fig. 9 and Eqs. (3), (8), and (9).

The results of Eqs. (6) and (7) are plotted in Fig. 11 using dashed lines. They show that the predicted temperatures $T_{\rm cs0}$ and $T_{\rm cg0}$ agree with $T_{\rm smin}$ and $T_{\rm smax}$. Therefore, the temperatures without heat loss, $T_{\rm smin0}$ and $T_{\rm smax0}$, can be estimated using $T_{\rm cs0}$ and $T_{\rm cg0}$ as shown in

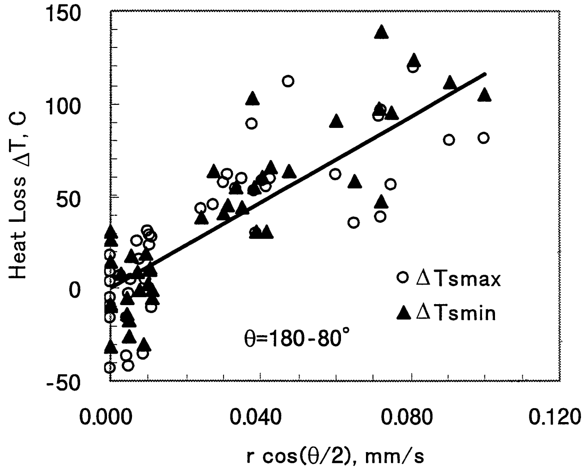


Fig. 15 Relationship between the heat loss and effective regression rate (50-μm diam).

Fig. 11. The lines for T_{cs0} and T_{cg0} in Fig. 11 and the data of Fig. 12 are plotted in Fig. 14 as a function of $r \cdot \cos(\theta/2)$. The ordinate $r \cdot \cos(\theta/2)$ is used because it is the component of the regression rate along the lead and can be considered to be related to heat loss from the leads. Therefore, heat loss ΔT_{smax} can be estimated from the difference between the solid lines T_{smax} and T_{cg0} in Fig. 14. Heat loss ΔT_{smin} can be estimated from the difference between the dashed lines T_{smin} and T_{cs0} in Fig. 14.

Finally, all of the 50-μm thermocouple data were plotted in Fig. 15 to estimate the heat loss from the thermocouple leads. The figure shows that the heat loss of a 50-μm thermocouple is obtained from the following equation:

$$\Delta T_s = 1200 \cdot r \cdot \cos(\theta/2) \tag{10}$$

Using this equation allows one to assess the error in the heat loss in the measurement of the burning surface temperature.

Conclusions

An inverted V-shaped thermocouple, which was used in the measurement of the burning surface temperature of a propellant, has errors due to heat conduction through the leads. In this study, these errors were evaluated using ammonium perchlorate.

In the case of the inverted V-shaped 50-μm thermocouple, the heat loss from the leads was obtained by a simple expression. As a result of the experiment, the burning surface temperature of AP at 0.1 MPa is estimated to be in the range of 460–470°C.

For a 50-μm thermocouple, the results indicate that the lead angle must be greater than 120 deg to keep the heat loss from exceeding the experimental scatter.

Acknowledgments

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