Experimental study on thermomechanical behaviour of polyurea under dynamic compressive loading

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Abstract. Polyurea is one kind of protective materials, which has been extensively used to enhance the survivability of structures under blast loading. To study the thermomechanical behavior of polyurea, compressive tests are conducted using a split Hopkinson pressure bar (SHPB) apparatus at high strain rates. An infrared thermograph is employed to observe the temperature rise. The experimental results show that the compressive stress strain response of polyurea presents a sensitivity of strain rate and strain. In addition, the deformation energy can transform to heating resulting in temperature increases under dynamic loading. Thus, the thermal softening decreases the mechanical behavior of polyurea, corresponding to temperature rise. The strain rate and length of strike bar can remarkably influence the variation about temperature rise.

1. Introduction

Owing to exhibit excellent properties such as high specific strength, chemical stability and low cost, polymeric materials have been widely used in aerospace, automobile, marine industries and buildings [1-4]. Polyurea as one of elastomeric polymers are sprayed at structures to reduce the damage subjected to blast or impact [5-8]. It is well known that polymers are dissipated as heat can have a strong effect on the mechanical response under high strain rates [9]. Therefore, the effects of the thermal transitions have been reported in the literature.

In order to obtain the temperature change of polymers at the process of deformation, some thermal measurement techniques have been conducted like infrared and embedded thermocouples. Chou et al [10], have measured the temperature rise of polymers related to PMMA, cellulose acetate butyrate (CAB), polypropylene (PP), and nylon 6-6 during deformation at various strain rates by utilizing the embedded thermocouples. Walley et al. [11] conducted two methods to test temperature rise of iron and copper via thermocouples and an infrared (IR) temperature measurement system during high rate loading. Arruda et al. [12] studied the temperature rise which occurs in PMMA deformed at low to moderate rates using an IR method. This technique has also been used in polymeric materials on the adiabatic heating. Rabin and Rittel [13] have developed a sophisticated analysis of the time response of solid-embedded thermocouples and investigated the temperature rise.

Li and Lambros [14] have investigated the heat generation of two common polymers of polymethyl methacrylate (PMMA) and polycarbonate (PC) during dynamic deformation. Temperature change was monitored using a focused high speed infrared detector array. It was found that thermal softening can
prevent the strain hardening and result in the slope of strain hardening drop. Regev and Rittel [15] conducted an additional temperature measurement study on PC material both IR and embedded thermocouple techniques at high strain rates. The results indicated that there were no differences between the two techniques at strain rates from 3000/s to 8000/s. Michael et al. [16] conducted the temperature rise that occurs in specimens on two amorphous polymers of PVC and PMMA undergoing rapid deformation by using two new thermocouple design methods. Fan et al. [17] performed the temperature rise tests of a soft polymer material by an infrared radiation (IR) camera to investigate the transformation of strain energy at various strain rates. They found that temperature rise shown the same rate dependency as the total deformation energy and temperature rise could improve the fracture toughness of CF 75 polymer material. Pan et al. [18, 19] investigated the heat generation of a solid polyurethane by high-speed optical and infrared imaging systems under the process of dynamic compression. To determine how the strain energy distributed of polyurea under the deformation process at strain rates from 0.025/s to 400/s, Mott et al. [20] carried out high speed thermography to measurement instantaneous temperature changes.

The aim of this work to investigate the heat generation and temperature distribution of polyurea material under various high strain rates. Dynamic compression loading was performed by using a split Hopkinson pressure bar (SHPB) set up. During the dynamic testing, an infrared thermograph was used to measure the temperature rise. Then, the temperature rise experienced of various strain rates and strike bar were analyzed. In addition, the relationship between temperature rise and strain energy were also analyzed. This study will be helpful to evaluate the temperature rise for the transformation of strain energy and predict the distribution of heat on the effects of themomechanical behavior of polyurea.

2. Experimental set up

2.1. Materials
The material used in this study was polyurea supplied from SanheSheng Polymer Technology Co., Ltd. This material is a type of elastomer derived from the reaction of isocyanate and amine [21, 22]. The specimens of test were cylindrical with around 4.7mm length and around 9.4mm diameter, which can be obtained using mechanical processing method.

2.2. Experimental tests
A SHPB apparatus was used to provide the condition of dynamic compression loading, and is illustrated in figure 1. All the dynamic compression tests were conducted at room temperature. The bars were made of aluminum alloy with elastic modulus of 75 GPa and a density of 2700 kg/m3. All the bars had the same diameter of 15mm. Both incident bar and transmitter bar were 1300mm in length. The length of striker bar had two types of 400mm (long striker bar) and 100mm (short striker bar). When strain rates below 1400/s and 2800/s, the long striker bar was able to use during dynamic loading. However, when the strain rate reached to 6000/s for experiment, the short striker bar was appropriate to avoid the deformation of incident bar and transmitter bar.
Figure 1. Mechanical properties and thermal testing under dynamic compressive loading: (a) Photograph of testing system, (b) enlarged image of infrared thermograph and (c) schematic drawing of SHPB set up and infrared thermograph.

For dynamic test, pulse shaper technology was used to achieve dynamic stress equilibrium and minimize the high frequency oscillations of stress waves. A thin layer of grease is applied between the sides of specimen and the end faces of bars to reduce the friction. A strike bar was propelled via gas gun with high pressure nitrogen gas, then the strike bar impacted the end of the incident bar, the elastic compressive wave reached the end surface between incident bar and specimen, part of the wave was reflected and part was transmitted through the sample into transmitter bar [17]. Based on the one-dimensional stress wave assumption and uniformity assumption, the engineering stress and strain can be determined from the following equations [21]:

\[
\sigma_E(t) = \frac{S_0}{S_0} \sigma_T(t) \\
\varepsilon_E(t) = -\frac{2c_0}{L_s} \varepsilon_R(t) \\
\varepsilon_E(t) = -\frac{2c_0}{L_s} \int_0^t \varepsilon_R(t) dt
\]
Where, $\sigma_E(t)$ is the engineering stress, $\varepsilon_E(t)$ is the engineering strain, $\dot{\varepsilon}_E(t)$ is the strain rate, $\varepsilon_R(t)$ and $\varepsilon_T(t)$ are the incident strain and transmitted strain, $E$ is the Young’s modulus of aluminum alloy, $C_0$ is the wave velocity in the bars, $S_0$ is the cross sectional area of the bars, $L_s$ and $S_s$ are the initial length and the initial cross sectional area of the specimen, respectively.

The relationship between engineering strain rate and time under strain rates ranging from 1300/s to 6000/s and the length of strike bar (400mm and 100mm) are shown in figure 2. As observed in figure 2, it can be found that the pulse width of reflected signals under strain rate of 1300/s is basically in accordance with that of strain rate under 2800/s as the length of strike bar is 400mm. When the length of strike bar at 100mm, both the pulse width of strain rate at 2800/s and strain rate at 6000/s is nearly the same. The lasting time of strain rate is related to the length of strike bar. Moreover, the magnitude of longitudinal axis increases with the increased strain rate.

![Figure 2. Engineering strain rates vs. time curves of compression experiment.](image)

The temperature rise measurement was carried out by using an infrared thermograph under impact compression. This temperature test set up is shown in figure 1 (b). The framing rate used was 500 Hz. Although the duration of dynamic loading was short, the temperature rise was able to obtain using infrared thermography due to viscoelasticity of polyurea. The thermal change of polyurea could be lasted a longer time during compressive loading. In dynamic compressive loading test, the infrared thermograph was held in front of the specimen and focused on surface of specimen. All the surface temperature of specimen on thermal results was recorded in computer through measurement software.

3. Results and discussion

3.1. Mechanical response under dynamic compressive loading

![Figure 3. The engineering stress-strain curves under various strain rates and strike bars.](image)
The dynamic compressive engineering stress-strain curves for polyurea under various strain rates and strike bars are shown in figure 3. As observed in figure 3, the engineering stress increase from 38MPa to 77MPa and engineering strain enhance ranging from 0.17 to 0.38 when strain rate range from 1300/s to 2800/s and strike bar at 400mm. In addition, for strain rates at a range of 2800/s – 6000/s, the engineering stress and engineering strain according to the maximum stress increase from 35MPa to 53MPa and from 0.065 to 0.17, respectively. At the same strain rate for 2800/s, the engineering stress-strain curves of shorter striker bar basically coincide with initial part curve of longer bar. It can be noted that the engineering stress-strain of polyurea is related with strain rate and strain during dynamic loading. When the stress reaches up to its maximum value, a sustaining softening is observed resulting in the stress decrease. Transient heat generation is associated with heating softening behavior during the deformation of polyurea. In dynamic tests, no obvious damage or cracking is observed. The final drop of engineering stress in figure 3 is specimen unloading, and not failure of polyurea. On the basis on the literature reported, thermal softening caused by high strain rate loading leads to the slope of strain hardening drop [14].

3.2. Temperature rise of dynamic loading

In dynamic experiments, a part of deformation energy is transferred into energy, which can make the temperature of experimental material rose. Temperature rise is considered to be have a significant influence on the mechanical properties of the material. The tests are regarded as adiabatic due to the short duration of impact compression.

The initial temperature of specimen was around 22℃ at room temperature. It is essential for infrared thermograph to calibrate the emissivity before tests. Compared to the initial specimen temperature, the emissivity of specimen was able to obtain by testing the surface temperature of specimen. It could be confirmed that emissivity of the specimens close to 1. It can be observed that heat generation in specimen is uniform from three frames images. The yellow bright spot of the small black frame represents the test specimen in these images. The first image shows the initial temperature of the specimen at the same loading condition.

Figure 4. shows the infrared images of polyurea compressed at the strain rate of 1300/s, 2800/s and 6000/s. From figure 4 (a) and figure 4 (b), these thermograms show temperature rise increases with the increase of strain rate at the same length of strike bar, which may be due to more deformation energy generated at higher strain rate. At a strain rate of 1300/s, the maximum temperature in specimen is around 30℃. The maximum temperature of specimen at a higher rate of 2800/s is around 35℃. When the strain rate increased to 6000/s, the maximum temperature of specimen is 30.3℃ due to the shorter length of strike bar. At the same strain rate, the longer of strike bar, the temperature rise become higher because of larger strain. The temperature rise increase from 25℃ at strike bar of 100mm to 35℃ at strike bar of 400mm.
Figure 4. Infrared images of polyurea under dynamic compression: (a) strike bar at 400mm and (b) strike bar at 100mm.

It should be pointed out that the temperature rise of specimens can be influenced in relation to strain rate and strain. Figure 5 shows temperature rise in the polyurea specimen under impact compression including various strain rate and strike bar. Figure 5 (a) depicts the relationship between temperature rise and strain rate with the strike bar length of 400mm. In figure 5 (a), the average maximum temperature rise of polyurea are 7.8 °C and 12.7 °C, corresponding to the strain rates of 1400/s and 2800/s respectively. The results indicated that the length of strike bar have a great influence on temperature change due to the extent of deformation. The strain rate effect on the temperature rise can be given by a power-law relation for polymeric material[17]. Then, the relationship of temperature rise and strain rate for specimen can be given as: $\Delta T = 0.08\varepsilon^{0.64}$ by fitting the experimental results. Figure 5 (b) depicts the relationship between temperature rise and strain rate with the strike bar length of 100mm. As observed in figure 5 (b), the temperature in specimen increase with strain rate from 2800/s to 6000/s, the temperature rise are 2.7 °C and 7.7 °C, respectively. Curve fitting indicate that the temperature rise of specimen have a significant tendency with the strain rate. Based on these experimental data, temperature rise can be expressed as: $\Delta T = 2.38 \times 10^{-5}\varepsilon^{1.47}$. It can describe the dependency of strain rate of polyurea at a range from 2800/s to 6000/s. At the strain rate of 2800/s, the strain of specimen with long bar and short bar are 0.065 and 0.38, as shown in figure 5(c). The temperature at the strain of 0.065 increased 2.7 °C and 12.7 °C at the strain of 0.38, respectively. The function of temperature rise and strain still accord with the form of power-law. Therefore, fitting these tested data, the dependency of temperature rise with strain can be written as: $\Delta T = 48.7\varepsilon^{1.36}$. It can be inferred from figure 5 that the specimen has a great temperature rise at strain rate of 6000/s when a longer strike bar used. However, a shorter strike bar is used in the tests avoid the deformation of SHPB.
Figure 5. Temperature rise of specimen under impact compression: (a) the length of strike bar at 400mm; (b) the length of strike bar at 100mm; (c) the max strain of two strike bars at the same strain rate of 2800/s.
In dynamic loading, the process is considered as adiabatic condition because of the heat dissipates at a much slower rate than temperature rise generated. An average temperature rise of specimen can be calculated based on plastic work of deformation of polymeric materials, using the following formula [18]:

$$\Delta T = \frac{\beta}{\rho C_v} \int_0^\varepsilon \sigma d\varepsilon$$

(4)

Here, $\beta$ is the fraction of plastic work rate converted into heat of the specimen, $\rho$ is the material density, $\rho = 1010$ kg/m$^3$, $C_v$ is the specific heat capacity, $C_v$ and $\int_0^\varepsilon \sigma d\varepsilon$ can be determined by integrating the stress-strain curve at a certain strain region. In this study, the value of $\beta$ is 0.95 and $C_v$ is 1840 J/(kg.K) on the basis of the literatures reported [22, 23].

The results of temperature rise values calculated are 3.1°C, 2.0°C, 11.2°C and 6.4°C at the strain rate of 1300/s, 2800/s (100mm bar), 2800/s (400mm bar) and 6000/s, respectively. Compared to experimental results, it can be found that these temperature rise values calculated are much lower than the experimental results using infrared thermograph. It is due to the results calculated is average values, but the results tested is maximum values. No matter which methods the temperature rise obtained, the two kinds of methods have the trends of temperature rise with the increase of strain rates. For instance, the temperature rise calculated of specimen is 2.0°C at strain rate of 2800/s using a longer bar at 400mm, the heat rising is decrease of 1.5°C compared to the experimental result of 12.7°C. In addition, at strain rate of 6000/s, the temperature rise calculated of specimen is 6.4°C, which is 1.3°C lower than experimental value of 7.7°C. As mentioned above, the results indicated that the temperature rise show strain rate sensitivity and strain sensitivity on polyurea under dynamic loading. Especially, the temperature rise leads to more distinct heat softening under high strain rate and larger strain.

4. Conclusions
We investigated the compressive mechanical response and temperature rise of polyurea under dynamic loading based on the SHPB set up and infrared thermograph. The following conclusions can be drawn:

The compressive engineering stress-strain response of polyurea is found to be dependent on both the strain rate and the length of strike bar. The flow stress of material increases with increasing strain rate and length of strike bar.

Temperature rise of polyurea were observed subjected to the compressive loading at a wide range of strain rate. It is found that the strain rate and deformation of material greatly affect the temperature rise change. Temperature rise can be enhanced as increasing the strain rate and the length of strike bar. The average temperature rise value calculated are lower than the experimental data. The relationship of temperature rise and strain rate for polyurea can be expressed as power-law relation.

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