Transient heat generation and thermo-mechanical response of epoxy resin under adiabatic impact compressions

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Abstract

This investigation examines transient heat generation and the thermal-mechanical response of epoxy resin subjected to quasi-static and dynamic compression. High-speed optical and infrared imaging systems are used to obtain visual and thermo-graphic images during dynamic tests. It is found that the post-yield response of epoxy resin depends on whether the loading is quasi-static or dynamic. Results from quasi-static compression show that yield is followed by post-yield softening, plastic flow and final hardening. An obvious difference for high-rate compression is that post-yield softening persists without a final hardening phase. From the high-speed infrared images, localizations of adiabatic heating and temperature distribution were identified morphologically in high strain rate compressions. Dynamic mechanical analysis (DMA) and quasi-static data for elevated temperatures confirm the temperature sensitivity of epoxy resin. By calculating the different pixel numbers in infrared images at the different temperature values, the inelastic heat fraction is estimated to be about 0.45 for the epoxy. A simple constitutive relationship that describes the mechanical behavior of the polymer, such as elasticity-plasticity, post-yield softening and final strain hardening for quasi-static loading, as well as adiabatic-heating softening for dynamic loading, is proposed.

Keywords: A. thermomechanical processes; B. polymeric material; C. Kolsky bar.

1. Introduction

Polymeric materials are extensively used in engineering applications, especially as matrix material in high-performance fiber-reinforced composites or nano-particle reinforced composites. Polymer composites are becoming increasingly important in aerospace, transportation, sports and civil engineering components. Epoxy resin is the most common used polymer for the polymer composites manufacturing. Unlike thermoplastic polymers such as polyethylene, polycarbonate and polypropylene, cured epoxy resins are thermosetting polymers. Their highly cross-linked molecular structure results in a relatively high modulus, high strength, low creep and thermal stability. Since the mechanical properties of composites are affected by the properties of the matrix, the role of epoxy resins in polymer composites is critical. The nonlinear relationship between mechanical properties and strain rate, temperature, pressure and time for polymers, is also present in epoxy resins. Such behavior has been extensively studied both experimentally and via constitutive modeling. The mechanical behavior of some similar epoxy resins may differ because differences in curing agents or curing processes affect their mechanical properties. Nevertheless, many studies [1-8] on epoxy resins subjected to different loading conditions, have revealed stress-strain curves that display a common trend - an initial nonlinear increase in stress until a peak is reached, followed by post-yield softening, plastic flow and a final hardening phase.

In aerospace, transportation, sports and civil engineering applications, epoxy resin composite components are likely to experience shock and impact loads during usage. Therefore, it is useful to identify the impact and high-strain-rate properties of epoxy resins. The split Hopkinson bar testing technique [9-11] provided an important approach for impact dynamics of materials under strain rates usually from 10^2 to 10^4 s^{-1} . For epoxy resins, much progress focus on the impact properties has been made, such as impact-induced voltage generation [12], three-point-bending impact fracture toughness [13], strain-rate sensitivity at small strain [14], multiaxial loading at high/low temperatures [15], adiabatic temperature measurement [16], thermomechanical behavior [17], high-strain-rate tensile properties [6, 18], high-strain-rate shear properties [6, 18, 19], high-strain-rate compression properties [6, 20], radial constraint effect [21], high-strain-rate molecular dynamics simulations [22] et al.

For the phenomena of post-yield softening, many analytical models have been established for various materials. For example, damage-induced strain softening model [23] by an approach of decomposition of material behaviors into typical, average and stress relieved behavior for geologic materials such as concrete and rock; rate-dependent continuous damage model [24] to describe strain softening in laminated

composites; a three-parameter nonlinear constitutive model [25] to describe the strain-rate dependent stress-strain curve with typical post-yield softening feature in tungsten heavy alloy; a modified Mulliken-Boyce model [5] to capture the compressive behaviors including strain softening over a range of strain rates for epoxy resin; a simplified piecewise-linear model [7] to fit the trend of post-yield softening in epoxy resin; and a modified EGP-model [26] with temperature and rate dependence to enable an description of the response of solid polymers. The exact physical origin is still not very clear [27, 28] for the post-yield softening in polymers, several existed mechanism explanations proposed, for example, shear stress-induced plastic deformation [29-31], localized shear bands and expanded shear region (observed using polarized light) [32-34]. Some results based on the time-temperature equivalence model [35, 36] confirm that stress degradation is caused by thermal softening in adiabatic conditions.

However, with respect to impact loading, it is important to study post-yield behavior with adiabatic temperature rise. Although it is commonly accepted that adiabatic responses are inevitable in high-rate deformation of polymers, there do not appear to be many reports on the morphological characteristics of impact-induced adiabatic heating in epoxy resins. Morphologically, there has been classical study [37] on the feature of plastic deformation and heat-affected zones produced by a hammer blow in metal. Other typical studies [38, 39] have shown characteristics of shear bands with strain softening phenomena in polymeric materials. In present work, the notion of ‘morphological characteristics of impact-induced adiabatic heating’ means the feature of temperature distribution in epoxy specimens under high strain rate compression. These features could be shown by localized bands/regions. The localized bands/regions herein means the localizations of adiabatic heating and temperature rise observed from infrared camera.

The objectives for this study are to compare the mechanical behavior difference of the epoxy resin between quasi-static and dynamic compression from capturing the adiabatic heating and temperature distribution in material under dynamic compression. The inelastic heat fraction will be obtained and a new phenomenological model to predict the post-yield softening response will be established based on the inelastic heating under adiabatic condition. It is envisaged that this work will provide insights to aid the utilization of epoxy resins and their composites in transient heating and shock-proof applications.

2. Experimental details

2.1 Material preparation

As listed in **Table 1**, an epoxy resin compound consisting of 53.33% bisphenol A, 45.33% modified

anhydride and 1.33% serotonin was fabricated and cured at 90 °C for 2 hours, 110 °C for 1 hour, 135 °C for 4 hours, followed by slow cooling to 23 °C over 8 hours. The specimens were subsequently cut into 6 mm cube specimens.

2.2 Experimental tests

An Instron-8874 universal testing machine was used to apply quasi-static compression to the specimens, and **Fig.1(a)** shows images of the deformation at a strain rate of 0.001 s^{-1} , recorded by a video camera. The stress-strain curves can be related to the video images to identify various phases of loading - initial stress increase (1-2), yield (3), post-yield softening (3-5), lower yield point (5), plastic flow (5-6), hardening (6-9), damage evolution (10-11) and final failure (11-12).

Split Hopkinson pressure bar (SHPB) apparatus is used to obtain the dynamic response of specimens, and is illustrated in **Fig.2**. The bars were made of steel with the density $\rho=7.8 \text{ g/cm}^3$ and Young's modulus $E=191.88 \text{ GPa}$. Length of the striker bar, incident bar and transmission bar is 500 mm, 1800 mm and 1200 mm, respectively. All the bars had the same diameter of 12.7 mm. When high pressure nitrogen gas is released from a chamber, it propels the striker through a barrel to impact the incident bar. This generates an elastic stress wave ($C_0 = \sqrt{\frac{E}{\rho}} = 4947 \text{ m/s}$) with a length equal to twice that of the striker. When the elastic compressive wave reaches the specimen-incident bar interface, part of it reflects back as an elastic tensile wave into the incident bar, while the rest of the compressive wave transmits through specimen into the transmission bar. To measure the incident, reflected and transmitted pulses, strain gauges are mounted on the incident and transmission bars. The strain rate ($\dot{\varepsilon}$), strain (ε), and stress (σ) in the specimen are given by:

$$\dot{\varepsilon}(t) = \frac{2C_0}{L_s} [\varepsilon_i(t) - \varepsilon_t(t)] \quad (1)$$

$$\varepsilon(t) = \frac{2C_0}{L_s} \int_0^t [\varepsilon_i(t) - \varepsilon_t(t)] dt \quad (2)$$

$$\sigma(t) = E \frac{A_b}{A_s} \varepsilon_i(t) \quad (3)$$

where $\varepsilon_i(t)$ and $\varepsilon_t(t)$ are respectively, the strain signals associated with the incident and transmitted pulses, L_s is the specimen length, and A_b and A_s are the respective cross-sectional areas of the

incident/transmission bars and specimen. Typical signals corresponding to three different strain rates are shown in **Fig.3**. Using Equation(1)-(3), the stress-strain curves for epoxy resin at strain rates ranging from 300 s^{-1} to 2500 s^{-1} are calculated and shown in **Fig.4**.

Fig.2 shows the high-speed optical camera and flash illumination system connected to the output of the oscilloscope linked to the split Hopkinson pressure bar set-up. When the input bar signal is detected by the oscilloscope, the flash is activated to illuminate the specimen and image capture by the high-speed camera begins. The framing rate used was 75,000 Hz. High-speed infrared imaging cannot be done simultaneously with high-speed optical imaging, because the flash illumination for optical imaging will affect the infrared imaging. **Fig.5** shows a schematic diagram of the high-speed infrared camera incorporated into the SHPB set-up. The triggering principle is similar to that for high-speed optical imaging. The framing rate applied was 2,762 Hz, corresponding to $362 \mu\text{s}$ between frames.

A PerkinElmer DMA-8000 tester was used to identify the thermo-mechanical behavior of the epoxy resin. A temperature sweep test of the resin was conducted using a single cantilever bending model at a ramp rate of $3.0 \text{ }^{\circ}\text{C}/\text{min}$. The resin specimen dimensions were $15.80 \text{ mm} \times 5.50 \text{ mm} \times 2.80 \text{ mm}$ (length $\times$ width $\times$ thickness).

3. Results and discussion

3.1 Quasi-static and high-rate compression response

The stress-strain responses show that the modulus and strength for high-rate loading is larger than that for quasi-static loading. However, the ultimate failure strain for high-rate loading is smaller than that for quasi-static loading. Furthermore, the post-yield response of the epoxy resin tested can be divided into two types: for quasi-static compression at 0.001 s^{-1} , as shown in **Fig.4**, the initial nonlinear increase in stress to the yield point is followed by strain softening and plastic flow until a hardening stage is reached. The maximum stress attained occurs towards the end of the stress-strain curve. However, for high-rate compression, the post-yield stress decreases with plastic flow and dominates the entire post-yield response.

It is important to determine whether the sustained decrease in stress at post-yield stage for dynamic compression is dominated by progressive failure or not. **Fig.1(a)(b)** shows ductile deformation characteristics for both quasi-static and dynamic loading. **Fig.1(a)** is the stress-strain behavior for quasi-static compression. It is the strain hardening instead of strain softening occurred during progressive

failure stage from the positions of 9 to 11 in Fig.1 (a). The specimen is still under ductile state without any visible damage observed from high-speed images in **Fig.1(b)**. There were no micro voids in the tested specimen. If the damage (including any micro-damage) was from the softening under dynamic compression, there should also be continued softening happened during quasi-static compression. As it is well known, the specimen is under adiabatic state during high-speed deformation. It is the reason that the continued decrease in stress for dynamic compression is linked to thermal softening. And high-speed infrared imaging technology should be a good method to reveal the temperature rise for the specimen under impact compression.

3.2 Localization of adiabatic heating and temperature distribution

With the naked eye, the color of epoxy resin is in faint yellow. However, the color of the epoxy specimen in infrared images before loading is close to black. It is because that the infrared camera had already been calibrated for this material before tests. This calibration ensured an emissivity of the specimen close to 1. In regard to the reason why the background had some bright colors and the steel bar has bright lines, it was caused by the reflection indoor light because the background was a white wall and the steel bar had its special metal luster. However, there was no problem to detect the temperature of the specimen. Because specimen was the only object cared about and it had already been calibrated to be treated as black body under the experimental conditions.

Fig.6 depicts sequential infrared images of specimens compressed at different strain rates. For deformation at 300s^{-1} , **Fig.6(a)** shows that specimen in the second frame is only slightly brighter than in the first one, indicating a very small temperature rise. Since the deformation speed and dynamic intensity are very low, the compression of the specimen is very small. The corresponding stress-strain curve (300s^{-1}) in **Fig.3** indicates that the initial yield stress has not been reached and the specimen is likely still in its elastic state. For compression at 570s^{-1} , **Fig.6(b)** shows that the adiabatic heating at corners and edges of the specimen is higher than the other regions. This may be due to stress concentration. The third and fourth frames of **Fig.6(b)** show an inclined band of adiabatic heating developing in the specimen. However, there is insufficient contrast for this to be clearly distinguished. For loading at 1090s^{-1} and 1430s^{-1} , as shown in **Fig.6(c)** and **Fig.6(d)** respectively, inclined bands and the triangular region between them are obvious. When dynamic loading is sufficiently intense at strain rates from 1560s^{-1} to 2500s^{-1} , as shown in **Fig.6(e)** to **Fig.6(i)**, localization of adiabatic heating and temperature distribution is clearly distinguishable.

Localization of adiabatic heating is assumed to be the primary cause of post-yield softening for high-rate compression. **Fig.7** schematically illustrates the localization characteristics of adiabatic heating from the side and cross-sectional views of the specimen. Lines **a** are localized bands through the specimen. Lines **b** are at specimen-bar interfaces, and are caused by stress concentration at these boundaries. The circular region (**A**) at the center of the specimen is formed by the intersection of the localized bands, while the triangular region (**B**) is enclosed by the bands and the specimen-bar interfaces. Lines **a**, **b**, region (**A**), and region (**B**) define the areas with the greatest temperature rise, while the triangular region (**C**) has the smallest temperature changes.

Fig.8 and **Fig.9** show that the stiffness, strength and ductility of the epoxy resin are strongly temperature-dependent, confirming increased softening at higher temperatures. From the DMA result in **Fig.8**, it is found that the storage modulus of the epoxy resin experiences an obvious decrease even from 25°C to 60°C. From the isothermal tests under quasi-static compression in **Fig.9**, it is found that yield strength experiences an obvious decrease from 23°C to 50°C. Therefore, it is confirmed that even 50°C or 60°C could lead to softening in the resin. Such temperatures persist mainly within localized bands and regions in the specimen during high-rate loading. As a result, post-yield softening is maintained as deformation increases.

3.3 Adiabatic temperature rise and inelastic heat fraction

It is instructive to analyze the temperature rise; however, multiple reflections of stress waves can occur in the incident bar. Correspondingly, the specimen experiences several phases of loading during an SHPB test. The second or even third loading can generate additional deformation and further temperature increases. Hence, it is important to identify infrared images which correspond to the first compression. **Fig.10** shows how this is done with the aid of high-speed optical images and a Lagrange diagram. When the incident stress wave reaches the strain gauge on the incident bar, it will trigger activation of the high-speed optical camera system. It takes about 283μs for the wave to reach the specimen. After reflections from the incident bar-specimen interface and the impacted end of the incident bar, a second compression of the specimen will commence at about 1013μs. Since the time interval between infrared image frames is about 362μs, four infrared frames can be examined. Although the specimen shown in the third or fourth frame may not be loaded, the temperature of the specimen continues to increase from the first to the fourth frame. This is because heat from the core of the specimen propagates to the surface.

Consider the specimen compressed at 2190 s⁻¹ as an example; **Fig.11** depicts the approach to obtain

the statistics of the temperature distribution as well as the average temperature of specimen. The white outline in the four frames defines the boundary of the specimen. Within this boundary, the constituent temperatures can be determined from the number of pixels associated with their respective temperature values. This is based on the fact that the color of every pixel indicates its temperature value. By the weighted average of all the pixels corresponding to different temperature values within the boundary, the Average Temperature of the whole specimen can be obtained. For example, in **Fig.11**, the temperature of the environment is 22.13°C, and the lowest temperature in the specimen (blue) is about 28°C, while the highest temperature in localized region (pink) is 52°C. **Fig.12** shows the variation of the average temperature with time, while **Fig.13** depicts the corresponding trend for the highest temperature in localized regions. It is found that both the average temperature of the whole specimen and the highest temperature in localized regions increase with time from the Frame 1 to Frame 4. But such increasing slows down from the Frame 3 to Frame 4.

The parameter determining the proportion of plastic work converted into heat is the inelastic heat fraction coefficient, commonly denoted by β . There have been some studies measuring the temperature associated with the deformation of polymeric materials [40-47]. In this study, the epoxy resin is an isotropic homogeneous material, and the relationship between heat generation and mechanical loading during dynamic deformation can be incorporated into the heat energy equation as follows:

$$k\nabla^2 T - \alpha(3\lambda + 2\mu)T\dot{\epsilon}^{el} + \beta\sigma : \dot{\epsilon}^{pl} = \rho C\dot{T} \quad (4)$$

where k is the thermal conductivity, T the absolute temperature, C the specific heat capacity, α the coefficient of thermal expansion, λ and μ the Lamé elastic constants, ρ the density, σ the stress tensor, and $\dot{\epsilon}^{el}$ and $\dot{\epsilon}^{pl}$ are respectively the elastic and plastic strain tensor; β is the inelastic heat fraction. In the case of high-rate loading, the thermal conduction term ($k\nabla^2 T$) becomes negligible, and the thermoelastic term ($\alpha(3\lambda + 2\mu)T\dot{\epsilon}^{el}$) is also neglected, since it is usually small compared to the thermoplastic term. Equation (4) can thus be reduced to

$$\beta\sigma : \dot{\epsilon}^{pl} = \rho C\dot{T} \quad (5)$$

which relates the temperature rise in the material and to the dissipative processes that generates heat during dynamic deformation. This expression enables the inelastic heat fraction to be estimated from:

$$\beta = \frac{\Delta T \rho C}{\int_0^\varepsilon \sigma d\varepsilon} \quad (6)$$

where ΔT (unit, K) is the average temperature increase of the specimen. The inelastic work $\int_0^\varepsilon \sigma d\varepsilon$ is the area under the stress-strain curve, ρ ($1.13 \times 10^3 \text{ kg/m}^3$) is the density, and C ($1.35 \text{ kJ/kg}\cdot\text{K}$) is the specific heat capacity. Inelastic heat fraction values calculated at different strain rates are listed in **Table.2**, and the average values are shown in **Fig.14**. In comparison with the results reported in [45], $\beta=0.25$. The inelastic heat fraction obtained from this study ($\beta=0.45$) is larger. It is due to the variety of epoxy as well as their curing agent and process.

3.4 Simple constitutive description of rate-dependence and adiabatic-softening

For application in numerical analysis or to model the response of components made of epoxy, an empirical constitutive relationship that describes the mechanical behavior is required. As an elastic-plastic material exhibiting post-yield softening and final strain hardening, selection of appropriate relationships that capture these characteristics is essential. **Fig.15** shows three basic functions selected as basis to establish the mechanical response observed. A function of the form $y = A \arctan(Ax)$ is able to describe the elastic-plastic response. The function $y = B[(Cx) \exp(-Dx)]^M$ can encompass elastic and post-yield softening response. Final hardening can be defined by a function of the form $y = Ex^N$. By combining these, a simple constitutive description of the elastic-plastic, post-yield softening and final hardening (EPSH) material response takes following form

$$\sigma_0(\varepsilon) = A \arctan(A\varepsilon) + B(C\varepsilon \cdot e^{-D\varepsilon})^M + E\varepsilon^N \quad (7)$$

where $A=50$, $B=18$, $C=37.5$, $D=12.5$, $E=49$, $M=6$ and $N=2$ are constants determined by fitting the reference stress-strain curve corresponding to a strain rate of 0.001 s^{-1} , using a numerical calculation software Matlab®. For quasi-static loading, the EPSH equation function is envisaged to be suitable for a variety of polymers, such as polymethyl methacrylate (PMMA), polycarbonate (PC), isotactic polypropylene (iPP) and polystyrene (PS), which display mechanical behavior characterized by post-yield softening, plastic flow and final strain hardening. Taking strain-rate into consideration, Equation (7) is modified to

$$\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_0(\varepsilon) \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^m \quad (8)$$

where

$$r(\dot{\varepsilon}) = a\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^b + c \quad (9)$$

and $r(\dot{\varepsilon})$ is the rate-effect term. The yield stress at $\dot{\varepsilon}_0 = 0.001 \text{ s}^{-1}$ is taken to be the reference value. The yield stresses at strain rates of 600 s^{-1} , 1850 s^{-1} and 2500 s^{-1} are then normalized with respect to this, resulting in values of 1.618, 1.685 and 1.805 respectively. As shown in **Fig.16**, the parameter values, $a=0.07$, $b=0.17$, $c=0.93$ are determined by curve fitting. **Fig.17** shows that the proposed relationship $\sigma(\dot{\varepsilon}, \varepsilon) = \sigma_0(\varepsilon)r(\dot{\varepsilon})$ fits well at small strains ($\varepsilon < 0.1$) but fails to satisfy the stress decrease at large strains. Therefore, taking strain-rate and adiabatic-softening effects into consideration, the relationship is expressed as follows:

$$\sigma(\varepsilon, \dot{\varepsilon}, \Delta T) = \sigma_0(\varepsilon)r(\dot{\varepsilon})g(\Delta T) \quad (10)$$

where the adiabatic-softening effect $g(\Delta T)$ is defined by

$$g(\Delta T) = \alpha \cdot e^{\lambda \Delta T} + \delta \quad (11)$$

To determine $g(\Delta T)$, isothermal quasi-static compression tests at elevated temperatures were conducted at a strain rate of 0.001 s^{-1} ; the responses are shown in **Fig.18(a)**, and the response for room-temperature is taken as the reference. A ‘stress reduction coefficient’ is defined to incorporate the effect of softening by dividing the stress at elevated temperatures by the stress at room temperature, for strains of 0.15, 0.30 and 0.45 respectively – see **Fig.18(a)**. The adiabatic-softening effect $g(\Delta T)$ in Equation(11) is actually an expression for the ‘stress reduction coefficient’ as a function of the temperature increase ΔT in **Fig.18(b)**. For high-rate loading, the heat generated can be calculated by $\beta \int_{\varepsilon_y}^{\varepsilon} \sigma d\varepsilon$, enabling the temperature increase ΔT to be estimated. The difficulty is that the stress and temperature are implicitly coupled. Hence, a strain increment method can be used to calculate the temperature-dependent stress as follows:

$$\sigma_{new}(\varepsilon + \Delta\varepsilon, \dot{\varepsilon}) = \sigma_{old}(\varepsilon, \dot{\varepsilon})g(\Delta T) \quad (12)$$

where

$$\Delta T = \frac{\beta}{\rho C} \sigma_{old}(\varepsilon, \dot{\varepsilon}) \Delta\varepsilon \quad (13)$$

Fig.19(a)-(f) shows the verification of the proposed mechanical prediction which considers both

strain-rate and temperature-softening effect. The proposed model matches the experimental data well, supporting the proposition that post-yield softening of the epoxy is dominated by adiabatic heating during dynamic compression.

In summary, we should clarify that the damages in epoxy specimen have never been neglected during this modeling. The quasi-static curve in **Fig.1 (a)** is a full-range mechanical response including elastic, plastic, softening and hardening stage. From experimental observation, damage occurred visibly when $\epsilon > 0.75$. The modeling begins with the fitting of the quasi-static curve in **Fig.1 (a)**. The fitting equation (Equation 7) agrees the quasi-static curve well. It has already included the visible damage process from the marked number 9 to 11 and possible micro-damage process before the marked number 9. Therefore, because Equation (8), (10) and (12) are all derived from Equation (7) multiplied with the strain rate and thermal softening effects. This implies the damages have already been included in our analytical modeling.

4. Conclusions

The mechanical and thermal responses of epoxy resin subjected to quasi-static and dynamic compression at room temperature are investigated. The post-yield response of the epoxy can be divided into two categories. Quasi-static compression gives rise to yield followed by post-yield softening, plastic flow and final hardening. The maximum stress is attained towards the end of the compression. However, for high-rate compression, there is obviously persistent post-yield softening and no final hardening. By using a high-speed infrared camera, morphologically, localization of adiabatic heating and temperature distribution are indentified. The stiffness, strength and ductility of the epoxy resin are strongly temperature-dependent. A decrease in stress at elevated temperatures is also observed. In a specimen, higher temperatures are associated with localized bands and their surrounding regions. Post-yield stress reduction at high strain rates is dominated by the adiabatic-heating softening behavior. The proposed simple constitutive relationship is able to capture the material behavior comprising an elastic-plastic response, post-yield softening and strain hardening (for quasi-static loading) / adiabatic-softening (for impact loading).

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(a) quasi-static compression testing at the strain rate of 0.001/s. (Visible damage begins from $\epsilon=0.75$ during strain-hardening stage)

(b) dynamic compression at the strain rate of 2190/s. (Persistent decrease in stress during the post-yield response without any obvious damage. There is no strain-hardening stage)

Fig.1 Typical quasi-static and high-rate behavior of the epoxy resin.

Fig.2 Schematic diagram of split Hopkinson pressure bar apparatus (with high-speed optical camera)

(a) 570/s

(b) 1090/s

(c) 2190/s

Fig.3 Typical strain signal of incident/transmission bar for compression at three different strain rates.

Fig.4 Stress-strain curves of epoxy resin for quasi-static (0.001/s) and dynamic compression (300 /s to 2500 /s).

Fig.5 Schematic diagram of split Hopkinson pressure bar system (with high-speed infrared camera).

(a) 300 /s

(b) 570 /s

(c) 1090 /s

(d) 1430 /s

(e) 1560 /s

(f) 1850 /s

(g) 2190 /s

(h) 2340 /s

(i) 2500 /s

Fig.6 Infrared image sequences illustrating localization of temperature increase for compression at 300 /s to 2500 /s.

Fig.7 Schematic diagram of the distribution of adiabatic heating in specimen under dynamic compression.

Fig.8 Dynamic Mechanical Analysis (DMA) of the epoxy resin

Fig.9 Thermal sensitivity of mechanical behavior

Fig.10 Identification of 1st phase of dynamic compression

Fig.11 Temperature distribution in a specimen.

Fig.12 Trend for the Average Temperature of the specimen from Frame 1 to 4

Fig.13 Trend for the Highest Temperature in the localized region of the specimen from Frame 1 to 4

Fig.14 Inelastic heat fraction β of the epoxy resin

Fig.15 Three component functions to capture mechanical properties of epoxy resin, which exhibit an elastic-plastic response, post-yield softening and strain hardening

Fig.16 Curve fit to determine the parameters in $r(\dot{\epsilon})$

Fig.17 Fits for stress-strain response, incorporating strain-rate effects

(a) Quasi-static compression tests at elevated temperatures

Note: stresses at strains of 0.15, 0.30 and 0.45 are used to calculate the 'stress reduction coefficient' in Fig18(b)

(b) fitting of the stress reduction coefficient as a function of ΔT

Fig.18 The adiabatic temperature-softening term $g(\Delta T)$ defines the variation of the stress reduction coefficient with temperature increase ΔT

(a)

(b)

(c)

(d)

(e)

(f)

Fig.19 Verification of the proposed stress-strain relationship in capturing both rate-sensitivity and adiabatic-softening, for strain rates from 1090/s to 2500/s

Table.1 Chemical components and curing process for epoxy resin

Mark	component	Viscosity at room temperature (MPa·s)	Epoxy equivalent value (eq/100g)	Mixing ratio	Curing process
JC-02A	bisphenol A epoxy resin	1000-3000	0.50-0.53		90°C 2hours,
JC-02B	modified anhydride	30-50	/	100:85:2.5	110°C 1hour,
JC-02C	serotonin	1-5	/		135°C 4hours.

Table.2 Calculation of the Inelastic Heat Fraction (β) based on the IR data and Stress-Strain curves

Strain rate (/s)	Initial temperature (°C)	Average temperature of the whole specimen after the 1 st impact (°C)	Temperature increase (K)	Inelastic work from S-S curve (10 ⁵ kJ/m ³)	β
300	23.25	24.01	0.76	2.50	0.46
570	22.13	24.19	2.06	7.57	0.42
600	22.23	24.66	2.43	8.57	0.43
620	22.23	24.76	2.53	8.78	0.44
1090	23.31	30.32	7.01	26.55	0.40
1130	23.15	30.46	7.31	26.99	0.41
1400	23.02	33.66	10.64	38.08	0.43
1430	22.47	32.49	10.02	39.24	0.39
1450	23.15	35.49	12.34	41.56	0.45
1560	22.55	36.32	13.77	45.41	0.46
1850	22.11	38.29	16.18	59.36	0.42
1960	22.75	42.25	19.5	61.69	0.48
2050	22.75	43.44	20.69	65.13	0.48

2180	22.13	44.09	21.96	72.61	0.46
2190	22.13	44.79	22.66	72.87	0.47
2340	23.43	47.54	24.11	79.04	0.47
2340	22.68	47.97	25.29	78.25	0.49
2500	23.43	49.96	26.53	85.53	0.47