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

Zhongxiang Pan [a], Baozhong Sun [a], Victor P.W. Shim [b], Bohong Gu [a,*]

[a] College of Textiles, Donghua University, Shanghai 201620, China
[b] Impact Mechanics Laboratory, Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117571, Singapore

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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.

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 $10^4\ \mathrm{s}^{-1}$. 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.

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* Corresponding author. Tel.: +86 21 67792661; fax: +86 21 67792627.
E-mail address: gubh@dhu.edu.cn (B. Gu).

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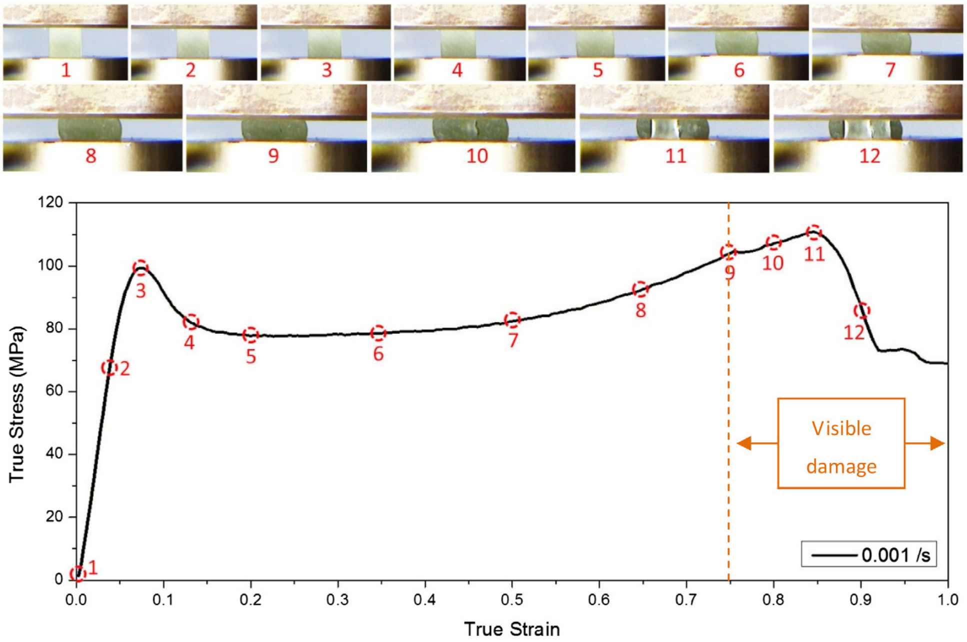
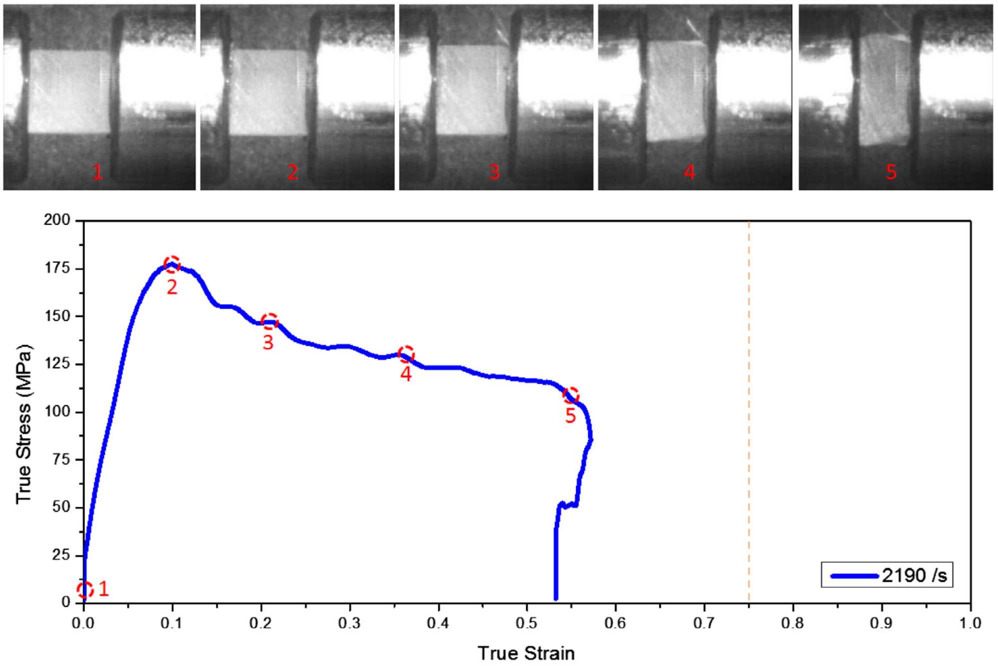
Table 1
Chemical components and curing process for epoxy resin.

Mark	Component	Viscosity at room temperature (MPa s)	Epoxy equivalent value (eq/100 g)	Mixing ratio	Curing process
JC-02A	Bisphenol A epoxy resin	1000–3000	0.50–0.53	100:85:2.5	90 °C 2 h, 110 °C 1 h, 135 °C 4 h
JC-02B	Modified anhydride	30–50	/		
JC-02C	Serotonin	1–5	/		



(a) quasi-static compression testing at the strain rate of 0.001/s. (Visible damage begins from ε=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.