

Effect of Strain Rate on Compression Behavior of Vinyl Ester Resin Casting

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Abstract: Quasi-static and high strain rate compressive experiments on vinyl ester casting were carried out by means of MTS (Material Test System) and Hopkinson bar. The behaviors of the compressed unstable and fracture of the resin casting at different strain rates were investigated. The results indicate that the response behavior of the resin casting is controlled by different mechanisms at different strain rate, and some mechanical properties of vinyl ester casting are rate-dependent: the casting are destroyed in toughness model under strain rate $3.3 \times 10^{-4} \sim 6.6 \times 10^{-3} / \text{s}$, while the casting are destroyed in brittleness model under strain rate 950~5800/s. The yield stress, yield strain energy density are all increased with the increasing strain rates at quasi-static as well as at high strain rates. What is interesting is that the yield strain decreased with the strain rates increasing at quasi-static while increased at high strain rates. It is considered that the casting occurred forcing high elastic deformation at high strain rates. The damage of the specimens is mainly controlled by axial stress before unstable deformation, while mainly controlled by shear stress after unstable deformation, and then developed to fracture finally. This progress is rate-dependent: the development of the cracks inside the castings increased with the strain rate increasing.

Key words: vinyl ester resin; quasi-static; high strain rate; strain rate response and crack development

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Vinyl ester resin (VE) is of low density and corrosion resistant, and the process performance is well. Because unsaturated double cross bonds lie on the two ending of molecular chain, the whole molecular chain will elongate and absorb mechanical energy under forcing, and then possesses good ability of impact and crack resistant. The hydroxyls in the molecular chain make VE infiltrate glass fiber, aramid fiber and UHMPE fiber *etc.* very well^[1], so VE is another widely used and studied resin followed epoxy resin. In the recent years, it has been reported that the VE resin had been used as matrix of ballistic resistant composites. Gama B. A. and Gillespie J. W. *et al*^[2,3] have studied the ballistic resistant performance of S2-glass fiber/VE composite, and the results showed that the composite has a good ballistic resistant property as the inside lining of armor composites. The properties of the resin matrix affect the properties of

the composite to a great extent.

In the past, resins were studied by looking at fibre-matrix interactions and the overall performance of the composite in terms of impact resistance and mechanical properties^[4-10]. An alternative approach is to study the properties of the individual resins (neat resins). Mechanical properties of neat resins are fundamentally important and need to be studied as matrix of ballistic resistant composites. The reason is the initial damage inside composite is controlled by matrix cracking, which in turn depends on the mechanical properties of the matrix material. As to examine the corresponding characters of VE under high strain rate loading, the compressed properties of VE resin was studied, meanwhile, the destroy status of the specimens at different stages were examined and the destroy mechanism were analyzed in this paper.

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1 Experimental

1.1 Experimental Materials and Manufacturing Methods

Standard Bis-A VE resin was made by ShangHai FuChen chemical Co. Ltd., the viscosity is $0.45 \text{ Pa} \cdot \text{s}$ at 25°C . The initiator was cyclohexanone peroxide and accelerator was cobalt naphthenate. Samples were made by casting resin into cylindrical moulds which were 5cm in length and 12mm in diameter, cured at 100°C in an oven for 1~2 h, and set at room temperature for 24h. The density of the specimens is 1140.9 kg/m^3 .

1.2 Experimental Apparatus and Procedure

The objective of the present was to investigate the VE casting mechanical properties at three quasi-static loadings (strain rate: 3.3×10^{-4} , 3.3×10^{-3} , 6.6

$\times 10^{-3}/\text{s}$) and five high strain rate loadings (strain rate: 950, 1500, 2300, 3700, 5800/s). The results are the average values of three effective tests from more than 5 repeated tests in every group. The environmental temperature of the test was 16°C .

The quasi-static tests were carried out by Electric Strength Tester as shown in Fig. 1. The high strain-rate tests were carried out by Split Hopkinson Pressure Bar setup as shown in Fig. 2. SEM investigated the fracture morphological character.

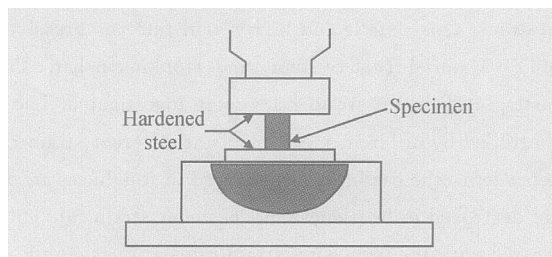


Fig. 1 The schematic diagram of the quasi-static testing

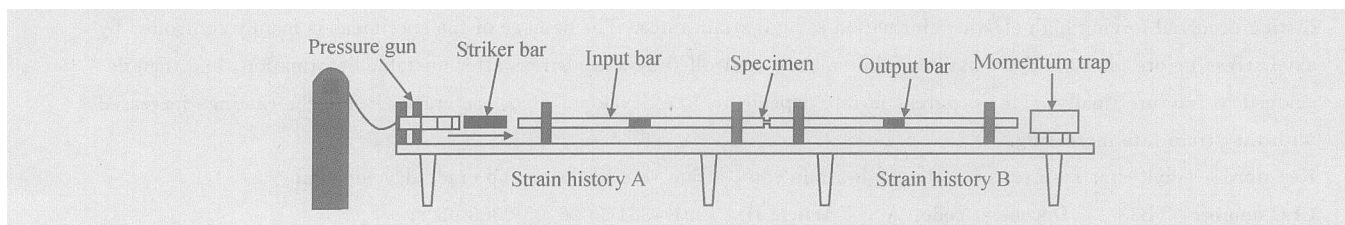


Fig. 2 The schematic diagram Split Hopkinson Pressure Bar

2 Results and discussion

Fig. 3 shows the compressed stress-strain curves at different strain rates. It is clear that the initial modulus and fracture stress under dynamic compression were greater than under quasi-static and they increased with the increasing of strain rates. The typical stress-strain curve in Fig. 4a suggests that, there is a stress plateau and the modulus approaches to zero when the strain is over to 20% under quasi-static. Comparing Fig. 4a with Fig. 4b, it is obvious that there is an unstable stage and an enhanced stage followed under quasi-static compression. It is also clear that the unstable stress is smaller than break stress under quasi-static compression: $\sigma_y < \sigma_b$, and the specimens are destroyed in toughness fracture model as shown in Fig. 5; while under dynamic compression: $\sigma_y > \sigma_b$, and the specimens are destroyed in brittle fracture model^[11, 12], as shown in Fig. 6. So it suggests that the strain rate affects the compression perform-

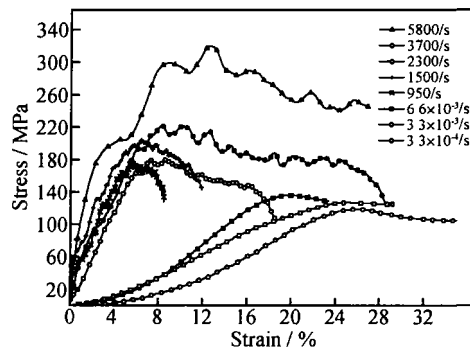


Fig. 3 Compressed stress-strain curves of VE at different strain rates

ance of the VE casts. The transformation of ductile model into brittle model goes forward with the increasing of strain rate. Fig. 5 shows the progress of unstable and breakage specimens under quasi-static compressed test. There is a short phase of elastic deformation under initial compressed force. In this phase, the stress-strain curve is straight, and the specimens are deformed as a drum. After this phase, the stress plateau come out as shown in Fig 4a. There are no cracks at this stage and this is because

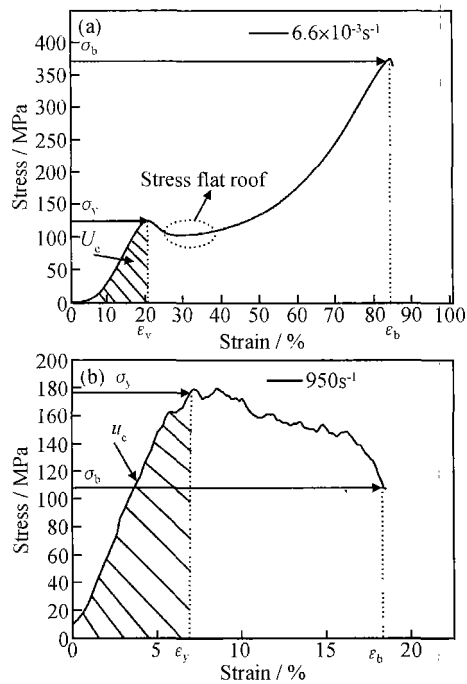


Fig. 4 The integrated stress-strain curves

in quasi-static and dynamic compressed testing

(a) strain rate is 6×10^{-3} s/s; (b) strain rate is 950/s

the specimen is mainly under axial stress as shown in Fig. 5b. The responses by compression within micro molecular chains include^[13]: random coils shrinking along stress direction; semi-stretched molecular chains curling completely and bearing elastic com-

pressive stress. After this phase, the cracks become to emerge due to the shear stress as shown in Fig. 5c. From microscopic view, parts of molecular chains become to slip or flow due to the damage of the secondary valence bonds between the molecular chains. The crystallite exists, chemical cross linkage or physical entanglement make some molecular chains can't move freely inside the specimens, and these molecular chains will be under high stress, which causes broken firstly. This broken will lead the sample to even more asymmetric stress distribution, and this accelerates the broken of molecular chains which developed into micro-cracks. The micro-cracks merge into big cracks or form to defect under continued shear stress loading, as shown in Fig. 5d. Macro damage causes inside the sample when the cracks develop into the whole body, as shown in Fig. 5e, and the specimens are spalled at fracture point ϵ_b . While under dynamic loading the specimens fracture due to cracks developing fast with severe deformation in axial direction, as shown in Fig. 6. A possible explanation for this is that the random coils and semi-stretched molecular chains have no time to shrink and adjust in large degree under high strain rate loading, *i. e.* the unstable strain under high strain rate is more smaller than that under quasi-static.

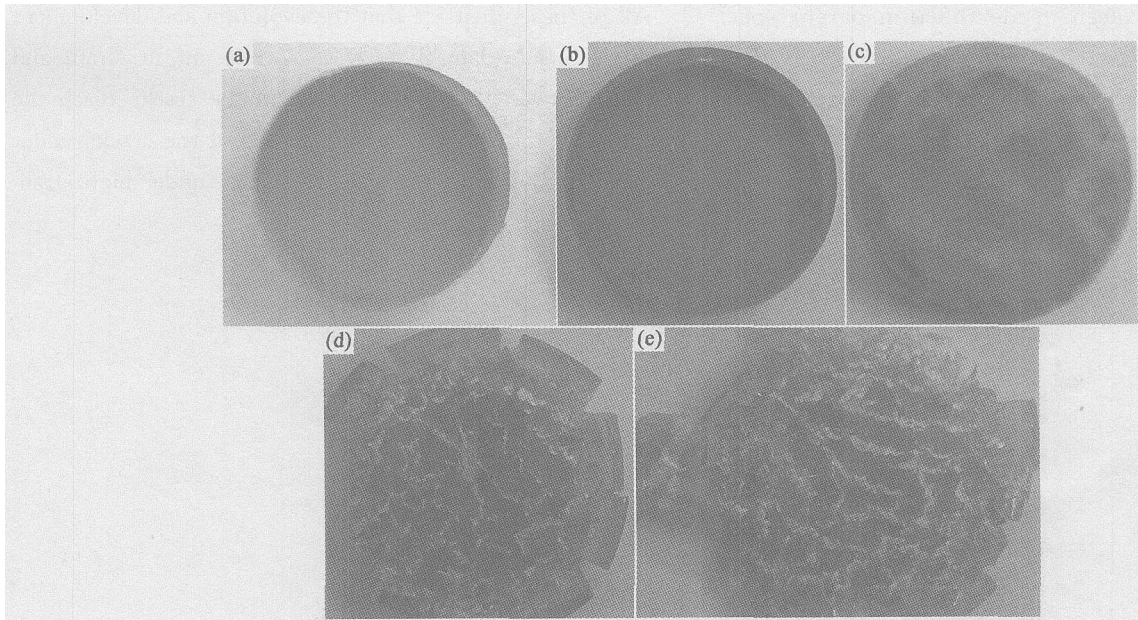


Fig. 5 The pictures of unstable and breakage specimens at quasi-static compressed testing

(a) original specimen; (b) drum specimen; (c) damage specimen at strain rate 3.3×10^{-4} s/s; (d) fracture specimen at strain rate 3.3×10^{-3} s/s; (e) fracture specimen at strain rate 6.6×10^{-3} s/s

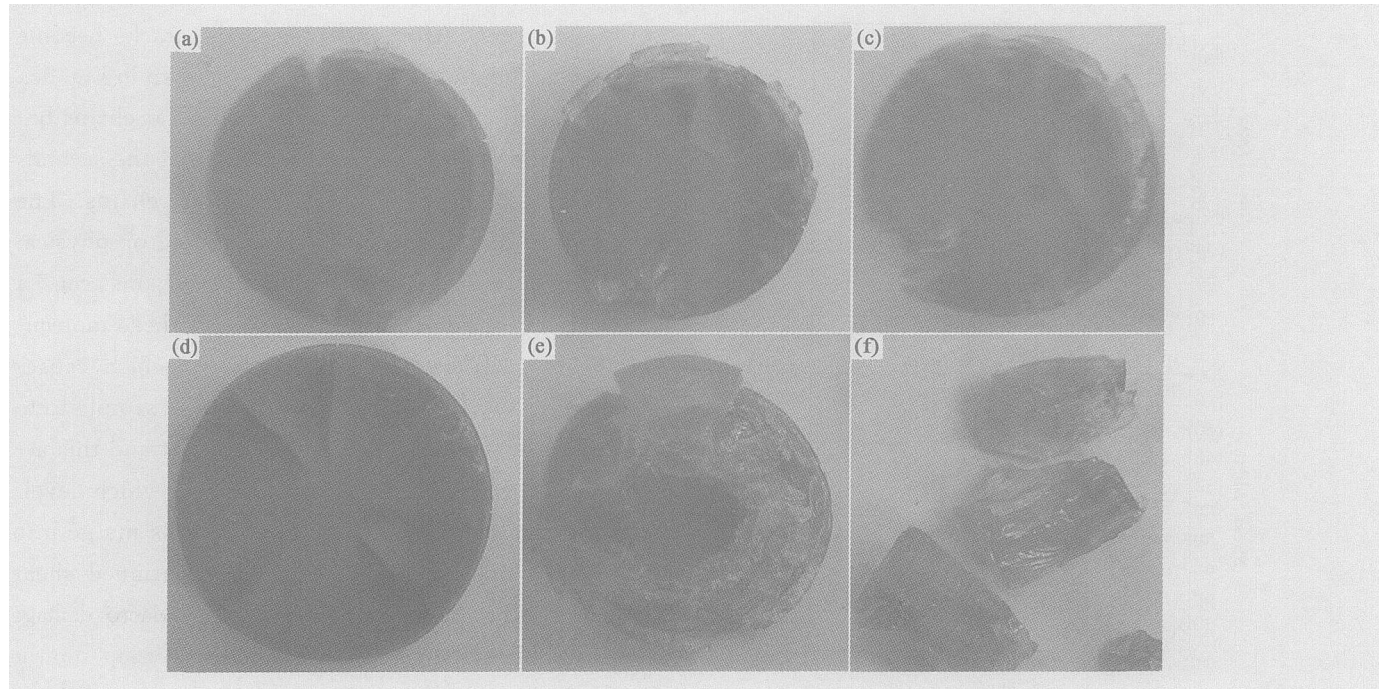


Fig. 6 The crack specimens at high strain rates compressed testing
(a) 950/ s; (b) 1500/ s; (c) 2300/ s; (d) 3700/ s; (e) 5800/ s; (f) 5800/ s fragment

As can be seen in Table 1, the specimens won't be destroyed until the compressed deformation are up to 20%~ 30% under quasi-static compression, while they are almost destroyed at deformation below 10%, *i. e.* causing impact embrittlement under high strain rate compression. In fact, the micro crack damage is always seen inside the transparent specimens before fracture. This illustrates that the damage proceed by the formation and development of the micro cracks under high strain rates loading.

With further study of quasi-static compression, it can be found that the cracks increased with the in-

creasing of strain ϵ under given strain rate $\dot{\epsilon}$ as shown in Fig. 5a, b, c. According to Fig. 5c, d, e, the cracks of the specimens at destroy strain point are increased with the increasing of strain rate $\dot{\epsilon}$. Under high strain rates, the micro-cracks are also increased with the increasing of strain rate as shown in Fig. 6. All of these illustrate that the evolution and development of the inside damage of VE are relevant to strain and strain rate at the same time. And the cracks reach the center of the specimens gradually, and the cracks under quasi-static loading are more than that under high strain rate loading as shown in Fig. 7.

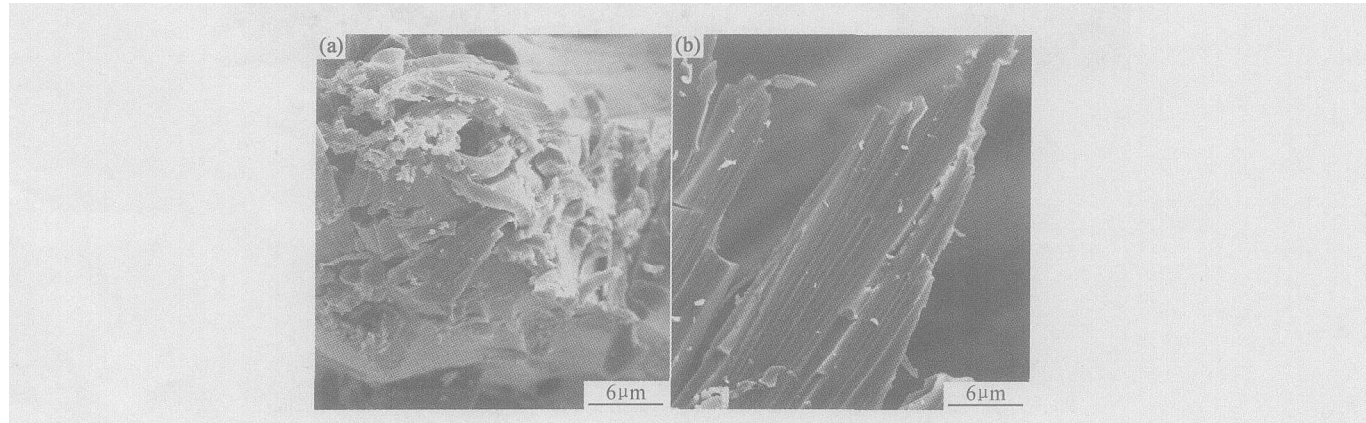


Fig. 7 SEM micrographs of sample section (a) at quasi-static; (b) at high strain rates

As shown in Table 1, under quasi-static loading, the unstable stress σ_y increase with the increasing of the

strain rate, while the unstable strain ϵ decrease with the increasing of the strain rate. Also the unstable stress σ increase with the increasing of strain rate under high strain rate loading. It is interesting that the unstable strain also increase with the increasing of strain rate under high strain rate loading. It is considered that the cast-

ing occurred forcing high elastic deformation at high strain rates. The essence of this phenomenon is that the molecular segment, which shrink are forced to move and deform to a great degree just as under high elastic stress. These indicate that the unstable stress and unstable strain are all sensitive to strain rates.

Table 1 Mechanical properties of VE at different strain rates

Strain rate/ s^{-1}	Unstable stress/MPa	Unstable strain(ϵ_y)/%	Unstable strain energy density (U_c)/MPa	Specific unstable strain energy density(u_c)/($10^3m^2s^{-2}$)
3.3×10^{-4}	117.9	26.3	12.59	11.0
3.3×10^{-3}	127.6	24.7	14.07	12.3
6.6×10^{-3}	132.3	21.6	15.49	13.5
950	175.3	5.7	9.56	8.3
1500	203.6	6.4	9.81	8.5
2300	178.8	7.2	7.28	6.38
3700	220.7	8.2	11.4	10
5800	302.6	11.7	25.8	22.6

Under both quasi-static and high strain rate loading, the unstable strain energy densities are all increased with the increasing of strain rate and achieve to the largest value $22.6 \times 10^3m^2s^{-2}$ at the strain rate of $5800s^{-1}$. So VE is a good kind of resin matrix for ballistic resistant composites.

3 Conclusions

(1) The casting are destroyed in toughness model in strain rate $3.3 \times 10^{-4} \sim 6.6 \times 10^{-3}/s$, while destroyed in brittleness model in strain rate $950 \sim 5800/s$. The unstable stress and strain energy density all increase with the increasing of strain rates under quasi-static loadings as well as under high strain rate loadings. It is interesting that the unstable strain decreases with the strain rates increasing under quasi-static loadings, while increases under high strain rate loadings. This is considered that the castings are forcing high elastic deformation under high strain rate dynamic loadings.

(2) The fracture of the specimens is mainly controlled by axial stress before unstable deformation, while mainly controlled by shear stress after unstable deformation. The scatches inside the casting are also rate-dependent: the development of the cracks inside the castings increase with the strain rates.

(3) VE resin has high unstable strain energy density, which increases with the increasing of strain rates. It is a good kind of resin matrix for ballistic resistant.

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