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Effects of Punch Test Conditions on the Mechanical Response of Polyethylene Materials

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***Abstract**: Polyethylene (PE) materials have been widely used in industrial and living fields such as natural gas pipelines, drainage pipes, sewage pipes. Punch test is an interesting tool for studying the mechanical properties of materials. However, the deformation behavior involved in punch test is complicated, it is, therefore, essential to investigate the influence of punch test conditions on the mechanical properties of PE materials. Punch tests have been carried out on PE specimens with different punching speed (0.01, 0.1, 1, 10 and 100mm/min) and different punch head diameters (4, 6, 8 and 10mm). The experimental results show that the maximum load from the load-displacement curve increases with the increase of the punch head diameter under the same punch speed. When the punch speed is slow, the force-displacement curve of PE specimens contains four typical stages, namely, elastic stage, yield stage, strain softening stage and strain hardening stage. However, the PE specimen breaks before reaching the strain hardening stage when the punch speed is fast. Similarly, the maximum load increases with the increase of punch speed when the same punch head diameters are used. Furthermore, a three-dimensional finite element (FE) model of PE specimens subjected to punch load has been established to further analyze the deformation and failure behavior. A good agreement between the simulation results and the punch test data is achieved.*

***Keywords:** polyethylene, punch test, FE simulation, mechanical properties*

1. Introduction

Polyethylene (PE) is a polymeric material that is extremely sensitive to environmental stress cracking (ESC) in practical applications. Serious losses will be caused once the engineering products are made of PE crack. Therefore, it is an important issue to predict the failure time of polymer materials under external force to ensure the safety of polymer products. Environment stress cracking resistance (ESCR) is an important problem to be considered in the cracking resistance of many polymers under load. Within a wide range of stress and fracture time, there exists not only the crazing fracture in the plastic field but also the yield shear band caused by the slip between molecular chains [1, 2]. An opportunity for the active reagents to permeate the interior was provided by the microcracks formed by the deformation non-uniformity of HDPE. It makes the HDPE plasticize, so that the surface energy is decreased, and slippage and separation of molecular chains in the stress concentrated are favored [3-5].

Several methods have been proposed for characterizing ESCR of PE materials [6-12]. At present, the most commonly used ESCR test method is the bent strip method, which belongs to the constant strain method. The notches are first introduced to the specimens and the specimens with notches are then bended. The bended specimens are immersed in a chemical solvent and the time to failure is recorded when a crack occurs in the specimens. However, the variability for the experimental data is relatively large due to the non-uniform notch depth and shape introduced by different testers [9]. Additionally, the strain level used during the tests needs to be strictly controlled because high strain leads to too fast crack to be observed, while low strain leads to too long an experiment time. On the other hand, the notched

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constant tensile load test (NCTL) formulated in ASTM D5397 is another method for the ESCR evaluation of polyolefin materials. The advantage of this method is that the testing duration can be shortened so that the efficiency and reliability of the test can be improved. The full-notch creep test (FNCT) is also widely applied to characterize the ESCR of PE in harsh environment. The specimen preparation and experimental operation are relatively simple in FNCT method, but the temperature needs to be strictly controlled. The testing time of FNCT method is too long for materials with good ESCR performance. Moreover, blow-molded container method is often used to evaluate the ESCR of blow-molded PE containers in three different stress modes. The main disadvantages of the ESCR testing methods mentioned above include poor repeatability of testing results and prolonged testing time. Therefore, a new test method based on punch test for the characterization of ESCR of PE has been developed using notch-free specimens [13, 14]. However, the deformation and fracture behavior involved in the punch test is complicated, it is of great importance to fully understand the dependence of the mechanical behavior of PE materials on the punch testing conditions.

2. Materials and methods

All specimens used in this study were prepared from HDPE and their dimensions are 40mm× 40mm× 3mm. A novel punch test device, which includes punch head, fix cup and universal testing machine has been developed for investigating the mechanical properties of PE materials.The experimental equipment and PE specimen with crack after the punch test is shown in Figure 1.The punch head and fix cup are fixed to the top and bottom of the universal testing machine, respectively. The specimens are fixed to the fixed cup using six nuts. The punch head is controlled to move down at constant speed and the variation of the punch load with the displacement of the punch head is recorded using the computer software. To study the influence of punch head diameter and punch speed on the mechanical behavior of PE, five punch speeds (0.01, 0.1, 1, 10 and 100mm/min) and four punch head diameters (4, 6, 8 and 10mm) were used in this study.

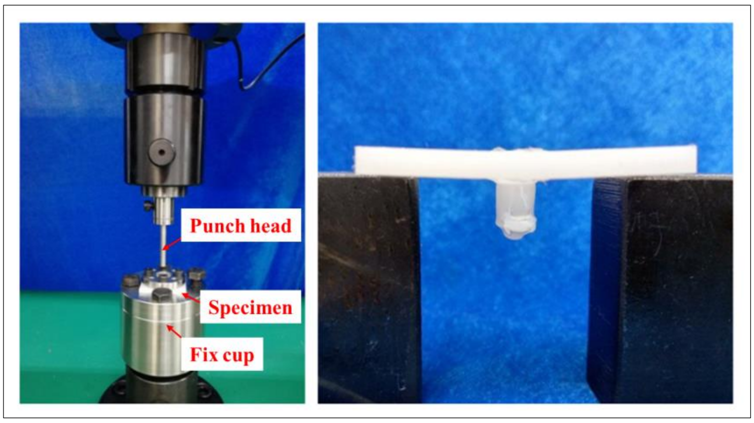

Figure 1. Experimental equipment and PE specimen

3.1. FE Simulation

A three-dimensional FE model was established using ABAQUS to study the mechanical properties of FE subjected to punch load at different punch speeds and punch head diameters. The model was composed of punch head, PE specimen and fix cup, as shown in Figure 2. Punch heads with diameters of 4mm, 6mm, 8mm, and 10mm were used in FE simulation to investigate the effects of punch head on the mechanical properties of PE materials. Note that the chamfer radius of the punch head is 1mm to prevent experimental errors due to stress concentration. The dimensions of the specimens are the same as those used in the experiment, which is 40mm×40mm×3mm.

Boundary conditions are the same as those used in the experimental testing, that is, the fixed cup and the specimen are completely fixed through four cylindrical holes, and a z-axis displacement is applied to the punch head. It is worth noting that the punch head and the fixed cup are modeled as discrete rigid bodies in the simulation, and reference points are included in the rigid bodies. The tangential friction coefficient used in the simulation was set as 0.08, and the normal contact was set as hard contact. The upper surface of the specimen was set in contact with the surface of the pressing head, and the lower surface of the specimen was set in contact with the upper surface of the platform and the surface of the inner diameter hole.

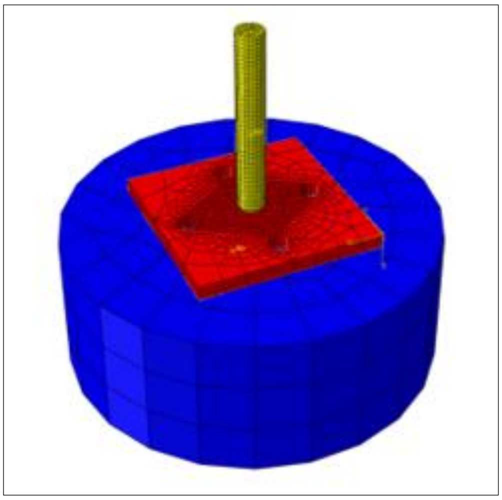

Figure 2. FE model for the PE specimen under punch load

The constitutive model adopted in this paper is divided into four stages: (a) linear elastic stage, (b) nonlinear elastic stage, (c) necking stage and (d) stress hardening stage [15].

$$\sigma(\varepsilon)=\begin{cases}\dfrac{E}{2(1+\nu)}\varepsilon & \varepsilon\le\varepsilon_y \quad (a)\\ d\left\{\left[a(\varepsilon+b)\right]^{(c-1)}-\left[a(\varepsilon+b)\right]^{(-c)}\right\}+e & \varepsilon_y\le\varepsilon\le\varepsilon_n \quad (b)\\ \alpha k\varepsilon^{N} & \varepsilon_n\le\varepsilon\le\varepsilon_t \quad (c)\\ ke^{M\varepsilon^{\beta}} & \varepsilon\ge\varepsilon_t \quad (d)\end{cases} \tag{1}$$

where σ is the equivalent stress in unit of MPa, ε is the equivalent strain, ε_y is the critical strain change from linear deformation to nonlinear deformation, ε_n is the critical strain for the one-set necking, ε_t is the strain at the beginning of stress hardening stage. Other parameters ($a,b,c,d,e,\alpha k,N,M,\beta,A,n,m$) are user-defined constant values. These constant values and strain ranges are modified until the punch load-displacement curves obtained from the experiment can be reproduced by the FE simulation.

3.Results and discussions

3.1. Experimental results

Figure 3 presents the load-displacement curves of PE specimens subjected to punch load under same crosshead speed using different punch head diameters. It can be observed that the force and the displacement at fracture increase with the increase of punch head diameter at the same punch speed.

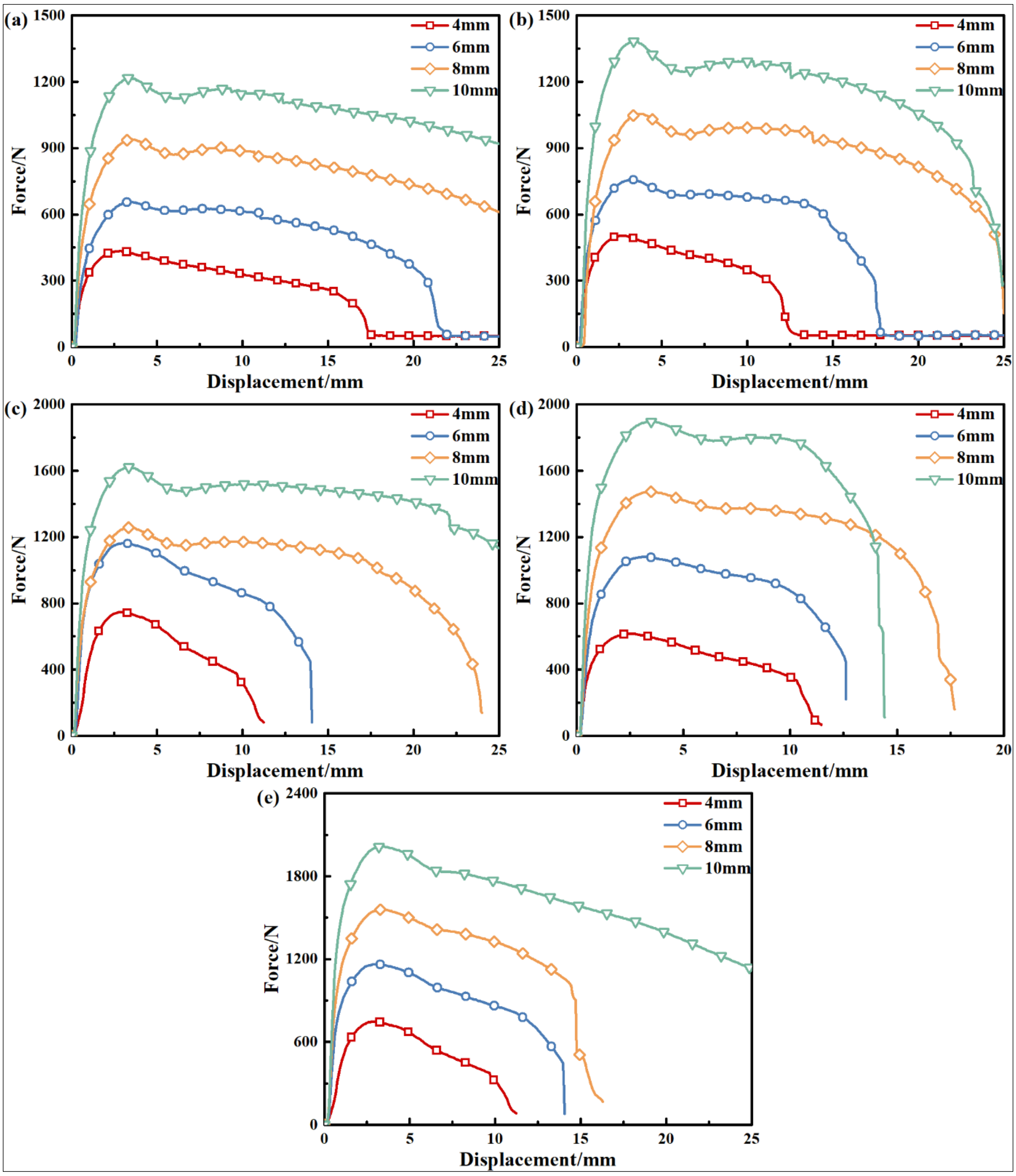

Figure 3. Load-displacement curves for PE specimens deformed using different punch head diameters at constant punch speeds of (a) 0.01mm/min, (b) 0.1mm/min, (c) 1mm/min, (d) 10mm/min, and (e) 100mm/min

The load-displacement curves of PE specimens punched at different speeds using the same punch head diameter are summarized in Figure 4. The results show that the force increases with the increasing punch speed when the punch head diameter is the same. The displacement at the peak load is not dependent on the punch speed. In addition, the displacement at fracture decreases with the increase of the punch speed suggesting that the fracture of PE specimen is changed from ductile to brittle when the punch speed is increased.

There is a jump on the curve (for example, when the punch head diameter is 6mm and the punch speed is 0.01mm/min, the curve suddenly drops when the displacement is about 11mm, but the overall trend of the curve is not affected), indicating that some slight cracks have appeared locally during the deformation process, but at this time the specimen has not been completely broken.

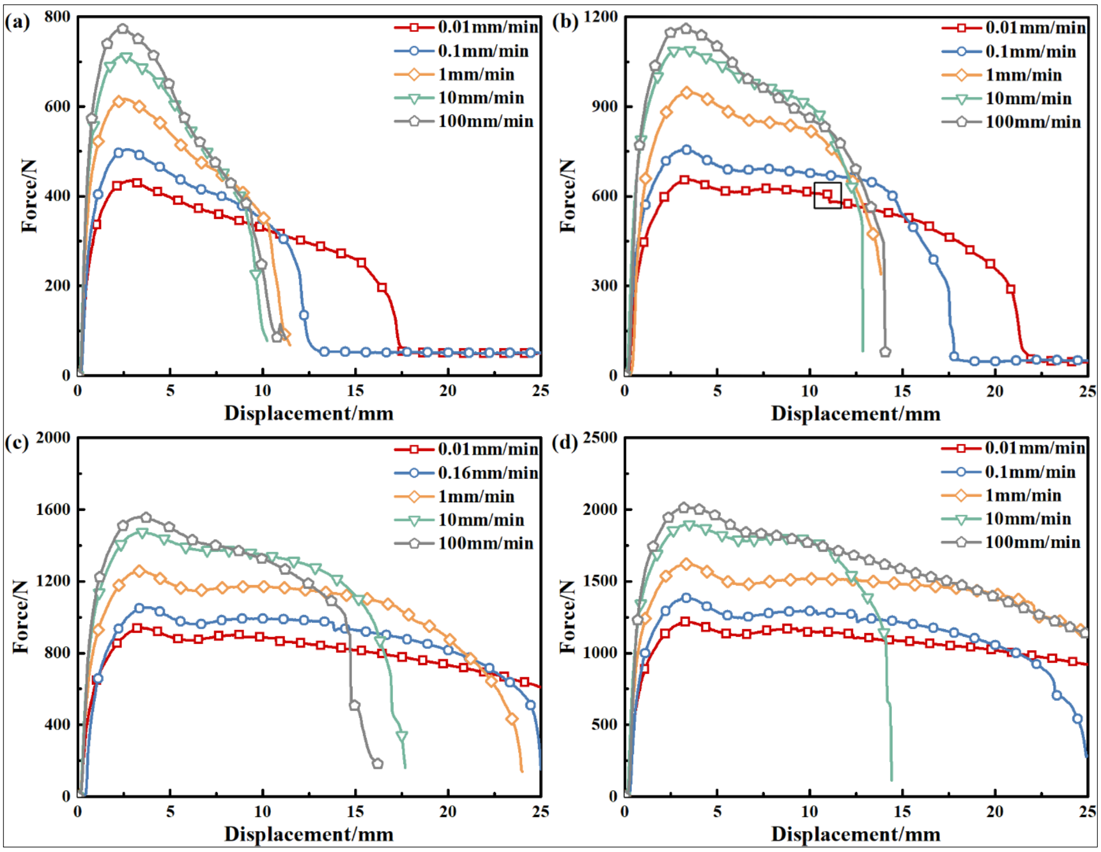

Figure 4. Load-displacement curves of PE specimens punched at different speeds using the punch head with the same diameters (a) 4mm, (b) 6mm, (c) 8mm and (d) 10mm

3.2. Simulation results

The comparison between the experimental results and the simulation results is depicted in Figures 5-9. The strain ranges and parameter values in equation (1) are listed in Table 1 and Table 3 respectively, and the creep parameter values are listed in Table 2. By analyzing the results obtained from experimental testing and simulation, it can be concluded that the FE simulation results are in good agreement with the punch test data. Especially, in the elastic stage, the results of experiment and simulation are well matched. At the yield stage, the numerical simulation results are slightly different from the experimental results. There is obvious yield phenomenon appeared in the numerical simulation results, while specimens deformed in the punch experiment had no yielding phenomenon. However, in the strengthening stage, the specimen in FE simulation had no obvious strengthening phenomenon, while obvious strengthening phenomenon appeared in experiment. Noted that the FE model does not simulate the fracture phenomenon of the specimen, but only the deformation process before fracture.

Table 1. Strain ranges in equation (1) determined from the FE simulation

Crosshead speed	**0.01mm/min**	**0.1mm/min**	**1mm/min**	**10mm/min**	**100mm/min**
Linear elastic stage	0-0.005	0-0.005	0-0.005	0-0.005	0-0.005
Nonlinear elastic stage	0.005-0.01	0.005-0.01	0.005-0.01	0.005-0.01	0.005-0.01
Necking stage	0.01-0.4	0.01-0.4	0.01-0.4	0.01-0.4	0.01-0.4
Stress hardening stage	0.4-0.6	0.4-0.6	0.4-0.6	0.4-0.6	0.4-0.6
	0.6-1	0.6-1	0.6-1	0.6-1	0.6-1
	1-1.2	1-1.2	1-1.2	1-1.2	1-1.2
	1.2-1.8	1.2-1.8	1.2-1.8	1.2-1.8	1.2-1.8
	1.8-2.8	1.8-2.8	1.8-2.8	1.8-2.8	1.8-2.8
Creep stage	0-2.8	0-2.8	0-2.8	0-2.8	0-2.8

Table 2. Values for parameters in equation (1) determined from the FE simulation

Crosshead speed			0.01mm/min	0.1mm/min	1mm/min	10mm/min	100mm/min
Linear elastic stage		E	880	900	900	900	900
		ν	0.4	0.4	0.4	0.4	0.4
Nonlinear elastic stage		a	5.6	3.7	3.1	3.1	3.1
		b	0.0877	0.0889	0.0889	0.0889	0.0895
		c	0.06	0.06	0.06	0.06	0.06
		d	-120	-120	-120	-120	-120
		e	100.16	200.16	270.16	270.16	270.16
Necking stage		$\alpha\kappa$	24.45	28.65	34.8	35.8	38.8
		N	0.06	0.06	0.018	0.018	0.018
Stress hardening stage	Section 1	κ_1	22.28	25.28	31.58	35.58	35.58
		M_1	0.4	0.4	0.42	0.42	0.42
		β_1	1.8	1.8	1.8	1.8	1.8
	Section 2	κ_2	24.2	27.2	34.35	38.35	38.8
		M_2	0.3	0.3	0.21	0.21	0.23
		β_2	1.8	1.8	1.8	1.8	1.8
	Section 3	κ_3	27.12	30.12	42.2	48.2	48.2
		M_3	0.3	0.3	0.09	0.09	0.094
		β_3	1.8	1.8	1.8	1.8	1.8
	Section 4	κ_4	24.47	26.97	31.1	33.1	34.1
		M_4	0.39	0.38	0.39	0.39	0.34
		β_4	1.8	1.8	1.8	1.8	1.8
	Section 5	κ_5	35	33.8	31.54	31.54	31.54
		M_5	0.26	0.3	0.35	0.37	0.36
		β_5	1.8	1.8	1.8	1.8	1.8

Table 3. Strain ranges inequation (1) determined from the FE simulation

A	n	T
6.60×10^{-15}	10	-0.61

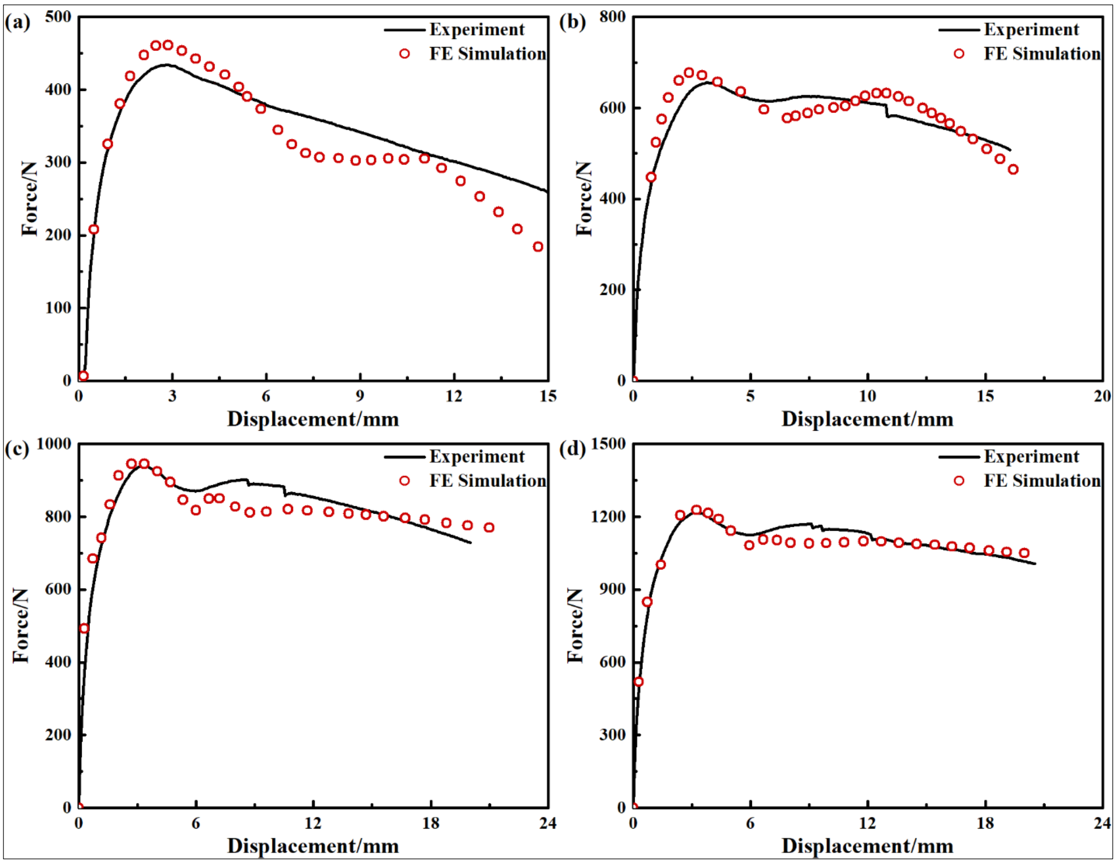

Figure 5. Comparison between the experimental testing and the FE results at a constant punch speed of 0.01mm/min using punch heads with diameters of (a) 4mm, (b) 6mm, (c) 8mm, and (d) 10mm

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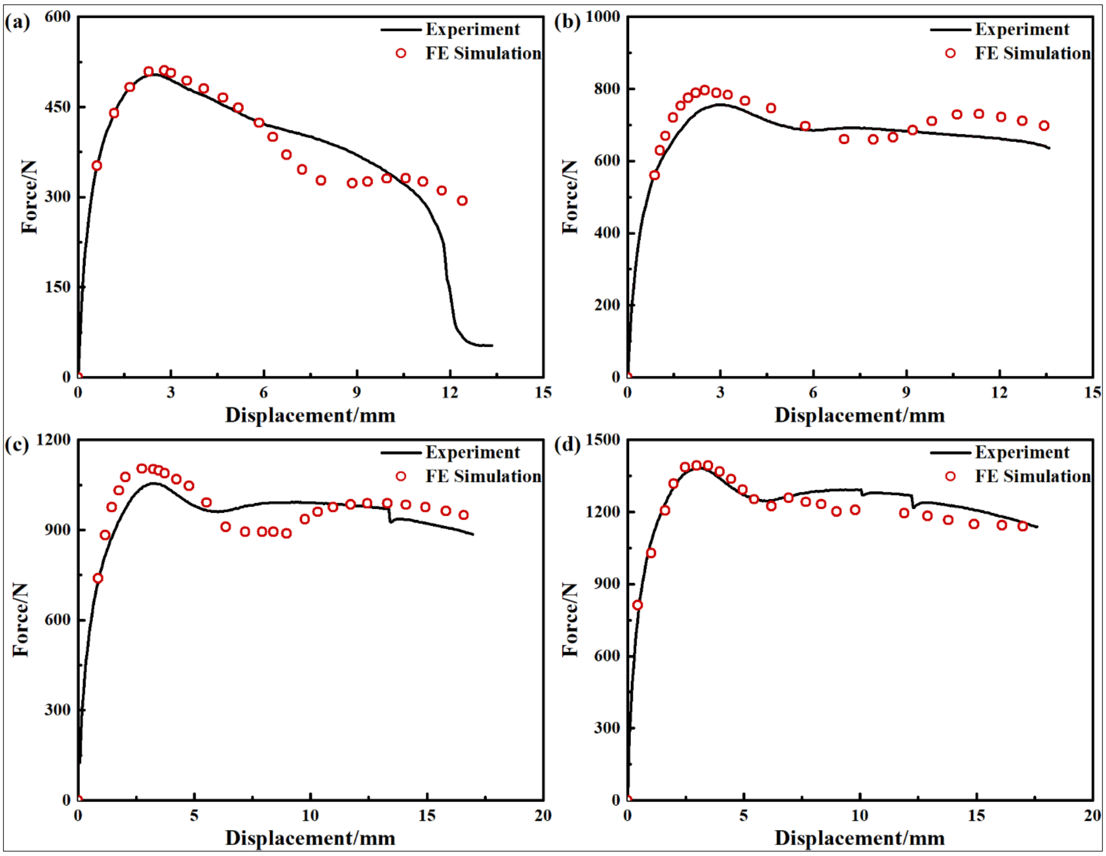

Figure 6. Comparison between the experimental testing and the FE results at a constant punch speed of 0.1mm/min using punch heads with diameters of (a) 4mm, (b) 6mm, (c) 8mm, and (d) 10mm

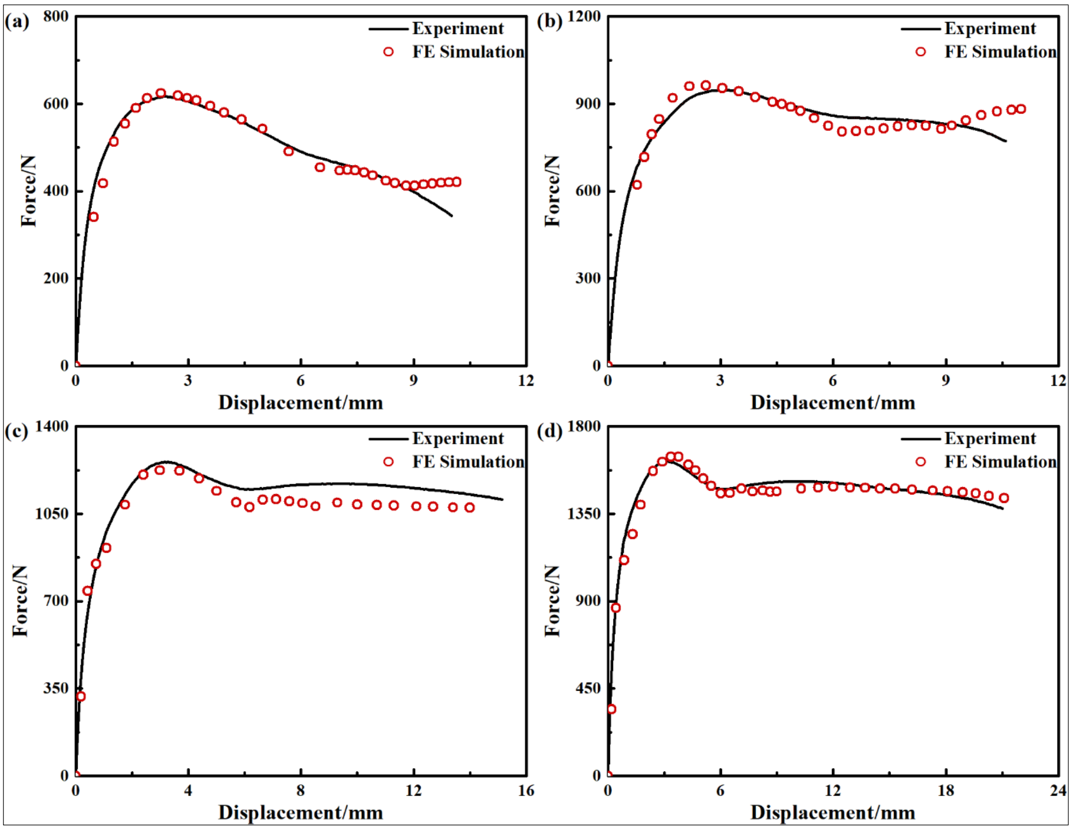

Figure 7. Comparison between the experimental testing and the FE results at a constant punch speed of 1mm/min using punch heads with diameters of (a) 4mm, (b) 6mm, (c) 8mm, and (d) 10mm

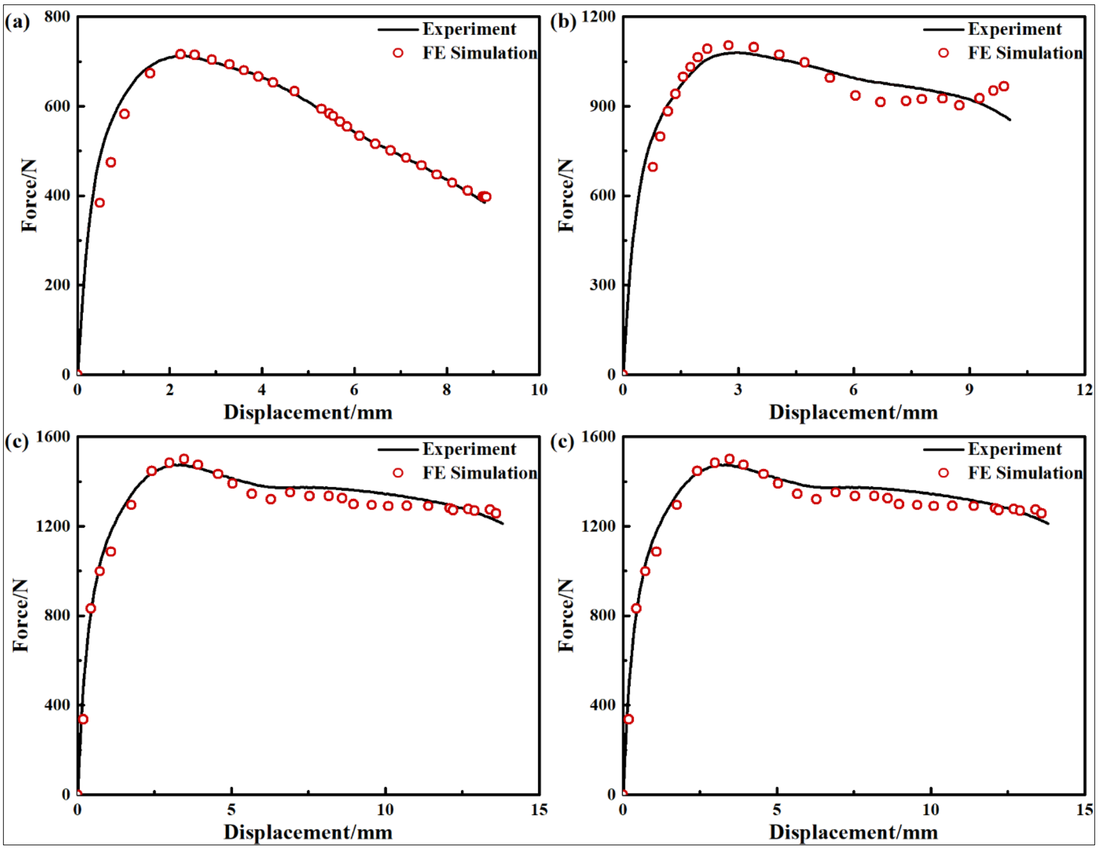

Figure 8. Comparison between the experimental testing and the FE results at a constant punch speed of 10mm/min using punch heads with diameters of (a) 4mm, (b) 6mm, (c) 8mm, and (d) 10mm

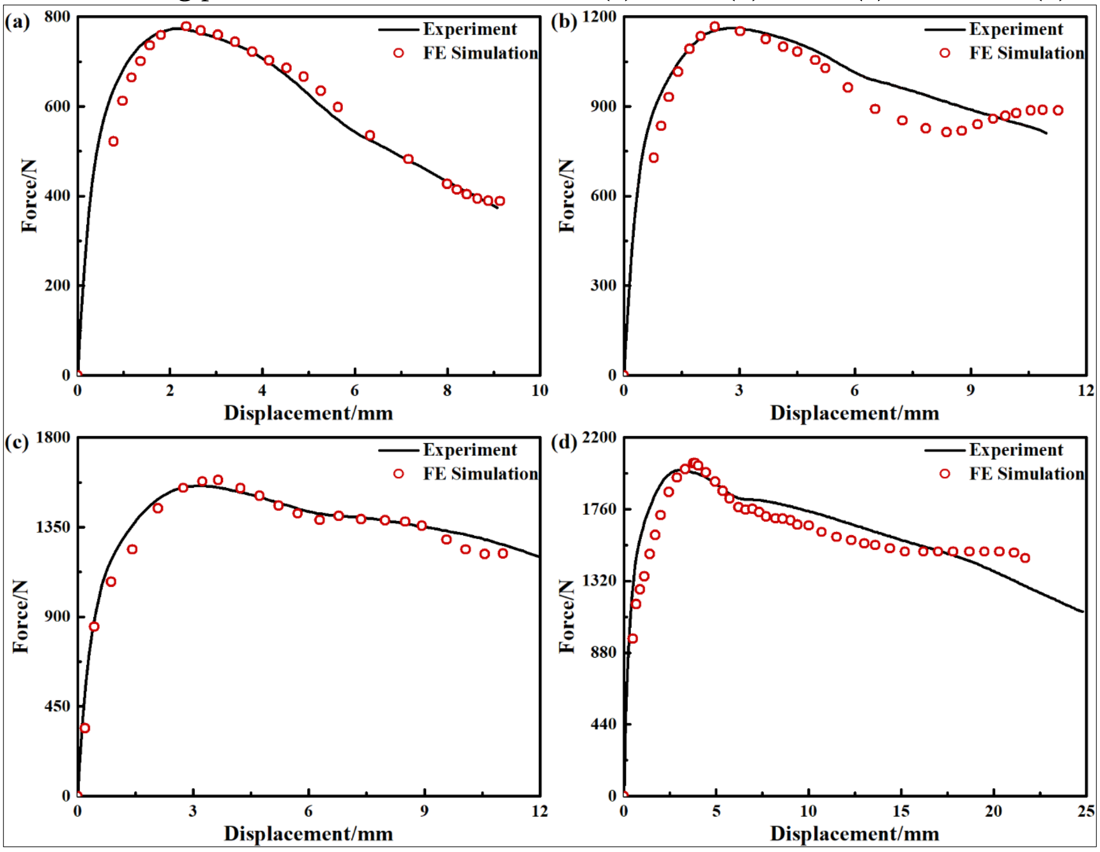

Figure 9. Comparison between the experimental testing and the FE results at a constant punch speed of 100mm/min using punch heads with diameters of (a) 4mm, (b) 6mm, (c) 8mm, and (d) 10mm

Figure 10 presents the stress distributions of PE specimens punched at 1mm/min using punch head diameters of 4, 6, 8 and 10mm. The results suggest that the stress distribution in the specimen is not uniform and the maximum Mises stress occurs at the corner of the specimen, which is consistent with the experimental results that the fracture in the specimen occurs at the same position.

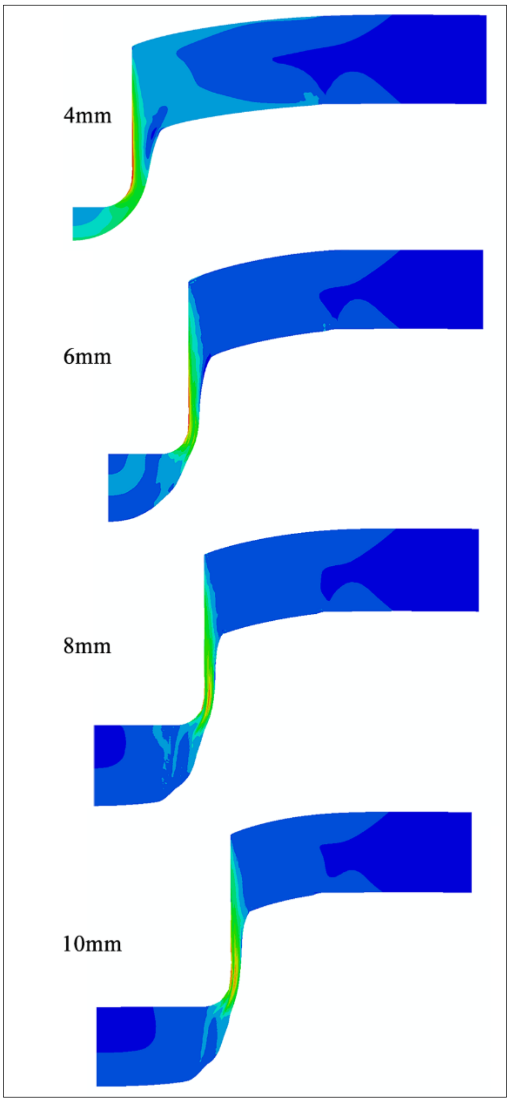

Figure 10. Stress distributions in PE specimens punched at a constant speed of 1mm/min using punch heads with diameters of 4mm, 6mm, 8mm, and 10mm

4. Conclusions

A method combining punch test and FE simulation has been proposed to investigate the effects of experimental conditions on the mechanical response of PE materials. The punch load-displacement curves under different loading conditions (different punch head diameters and different punch speeds) have been obtained from punch tests. The obtained curves are further compared and analyzed to analyze the deformation process and forced variation of PE specimens under different experimental conditions. The maximum punch load and the displacement at fracture for PE specimen increase with the increase of the punch head diameter at the same punch speed. When the diameter of the punch head is the same, with the increase of the punch speed, the maximum punch load gradually increases, while the displacement at the peak force is not affected. The FE model has been established to simulate the deformation process of PE specimens subjected to punch load. The load-displacement curves obtained by FE simulation are in good agreement with the experimental results, indicating the proposed FE model can successfully simulate the deformation process of PE materials involved in the punch test.

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