Finite element analysis of the high strain rate testing of polymeric materials

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Abstract. Advanced polymer materials are finding an increasing range of industrial and defence applications. Ultra-high molecular weight polymers (UHMWPE) are already used in lightweight body armour because of their good impact resistance with light weight. However, a broader use of such materials is limited by the complexity of the manufacturing processes and the lack of experimental data on their behaviour and failure evolution under high-strain rate loading conditions. The current study deals with an investigation of the internal heat generation during tensile of UHMWPE. A 3D finite element (FE) model of the tensile test is developed and validated with experimental work. An elastic-plastic material model is used with adiabatic heat generation. The temperature and stresses obtained with FE analysis are found to be in a good agreement with the experimental results. The model can be used as a simple and cost effective tool to predict the thermo-mechanical behaviour of UHMWPE part under various loading conditions.

1. Introduction

Advanced polymeric materials are of interest to researchers, owing to their versatile applications in aerospace, defence, medical sectors as well as the limited current understanding of these materials in terms of manufacturing processes and the complex behaviour of these materials at different loading and temperature conditions [1]. One of the important applications of polymeric materials in the defence sector is as a ‘liner’ for armour material. The need for efficient, light-weight armour is necessary because of the increase in military personnel and civilians being placed in life threatening situations. Typical armour consists of a bullet proof metal or ceramic front plate, backed by a liner material, such as polymer [2]. A liner is necessary to reduce the risk of shock impact behind the bullet proof layer.

Impact response is strongly dependent on the strain hardening, strain rate sensitivity and temperature sensitivity of a material. In high speed impact, high temperature levels can be induced in polymeric materials, which lead to thermal softening and degradation of their mechanical properties [3]. This is a result of irreversible thermodynamic processes which convert the plastic energy into heat. Adiabatic temperature increase is a precursor of plastic instabilities and consequent failure of a material. In this work, UHWMPE samples are tensile tested, to investigate the temperature effects at high strain rate and obtain experimental results to be used as a reference for the development of a
suitable numerical modeling method. A high resolution thermal camera was used to record the temperature increase in sample during the test and an elastic-plastic material model with adiabatic conditions was used to develop a finite element model of the experimental test.

2. Materials and preparation

Nascent ultra-high molecular weight polyethylene (UHMWPE) powders (Sarbic®UHMWPE3548) were purchased from SABIC with an average molecular weight of $3 \times 10^6$ mol/g. Compression moulding was used to mould the material using a square mould (10 X 10 X 1.65 mm) heated to 190 ºC, which is higher than the melting point of the UHMWPE (approximately 135 ºC). Various pressures (154, 232, 309, and 386 MPa) were investigated to optimise the properties of the material, such as hardness and crystallinity [4]. Various holding times at maximum pressure (10, 15 and 30 minutes) were also used to identify the most appropriate moulding parameters. The mould was cooled to room temperature using water. All specimens and testing methods were prepared according to ASTM D638 (2010).

3. Mechanical testing and characterisation

Tensile tests were carried out using an Instron 3366 tensile testing machine at room temperature (-22 ºC). Three crosshead speeds were applied, 0.2, 1 and 5 mm/s and at least 5 samples were tested at each condition. The specimen dimensions are shown in figure 1. During tensile testing, a thermal camera (FLIR SC3000) was used to measure the internal heat changing in the sample, with a temperature range from -20 to +150 ºC and accuracy of ± 1 ºC. ‘FLIR ResearchIR’ software was used for temperature analysis. This was used to create point, line and area profiles combined with histogram charts for the temperature – time changes. Figure 2 shows example of thermal contour plot at different times in the testing of a UHMWPE sample.

![Figure 1. Specimen dimensions (in mm)](image)

![Figure 2. Thermal images show temperature contours (a side view of the test section) during the tensile testing of UHMWPE at 5 mm/s crosshead speed a) 620 % strain and b) failure](image)
4. Experimental results and discussion

In order to demonstrate the influence of internal heat generation on the stress-strain behaviour of UHMWPE, crosshead speeds of 1 mm/s and 5 mm/s were applied using uniaxial tensile testing machine and a thermal camera was used to measure the temperature changes. Figure 3 shows the plot of engineering strain vs. engineering stress and temperature change. A significant temperature increase in the sample can be seen with the 5 mm/s crosshead speed, with the temperature increasing after the yield point. The results indicate that the heat generated during the plastic deformation is strongly dependent on the crosshead speed. This heat can be generated due to the high friction during the rearrangement and mobility of UHMWPE chains. High heat generation cause material softening as appears in the strain hardening region for the specimen tested at 5 mm/s crosshead speed, and this reduces the tensile strength. It appears from the figure 3 that approximately 50°C can be considered as a critical temperature to significantly affect UHMWPE mechanical behaviour. At 1 mm/s crosshead speed, the temperature is 40% less than the critical temperature value, and hence there is little thermo-mechanical effect at this crosshead speed.

![Figure 3. Effect of temperature on the tensile behaviour of UHMWPE at high strain rate.](image)

5. Finite element modeling

A numerical analysis was carried out to study the details of the underlying mechanics during the deformation process in the tensile test experiment. The finite element model was used to simulate the plastic deformation and heat generation in the UHMWPE and its effect on test sample.

5.1 Methodology and Numerical simulation

The simulation was performed using the ABAQUS explicit finite element code. The first approach was to assume an elastic-plastic material model with adiabatic conditions, i.e. no heat lost to the environment and all energy released in plastic deformation converted into internal heat generation. The elastic-plastic material model is a simple and effective way to investigate the effect of internal heat generation during plastic deformation [6]. The numerical model uses an inelastic heat fraction
parameter, $\eta$, to define heat generation caused by mechanical dissipation associated with plastic straining. The model assumes that plastic straining gives rise to a heat flux. The heat flux $r^{pl}$ is written as,

$$ r^{pl} = \eta \sigma \dot{\varepsilon}^{pl} $$

where $\sigma$ is the stress and $\dot{\varepsilon}^{pl}$ is the rate of plastic straining. The plastic strain increment is written from the flow potential as $\dot{\varepsilon}^{pl} = \dot{\varepsilon}^{pl} n$, where $n$ is the flow direction. We assume $n = n(\sigma, \dot{\varepsilon}^{pl}, \theta)$ where $\theta$ is the temperature.

### 5.2 Parameters of model

The finite element model is modelled with the same dimensions as shown in figure 1. Table 1 shows that mechanical and thermal properties of the material model used in the finite element model [7]. The model is meshed with element C3D8RT, an 8 node thermo-mechanical brick, element with reduced integration. A displacement rate of 5 mm/s was applied to one end of the test sample and the other end was fixed in all directions. An initial temperature of 26°C was applied.

#### Table 1. Mechanical and thermal properties of UHWMPE

| Material   | Elastic Modulus (MPa) | Poisson’s Ratio | Coefficient of expansion ($/\degree$C) | Thermal conductivity (W/m-c) | Specific heat (J/Kg-c) | Inelastic fraction | Density Kg/m$^3$ |
|------------|-----------------------|-----------------|---------------------------------------|----------------------------|-----------------------|--------------------|------------------|
| UHMWPE     | 450                   | 0.45            | 0.0002                                | 0.51                       | 1900                  | 0.9                | 934              |

### 5.3 Simulation results

The figure 4 shows a comparison of experimental and simulation results for the tensile test. The value of inelastic heat fraction used was 1, which represents as 100% of the plastic strain energy used to increase the internal temperature of test specimen. In this case an elastic-plastic material model overestimates the thermo-mechanical response of the UHMWPE.

![Figure 4. Experimental and simulation stress and temperature plot (inelastic heat fraction = 1)](image-url)
The value of inelastic heat fraction was reduced to 0.7 in finite element model to optimise the overestimated temperature. The figure 5 shows a comparison of experimental and simulation results for the tensile test. The value of inelastic heat fraction used was 0.7, which represents 70% of the plastic strain energy used to increase the internal temperature of test specimen. Figure 5 shows that an elastic-plastic material model can predict the thermo-mechanical response of the UHMWPE in a good agreement with experimental results. The material model used has limitation to predict the accurate stress values after the curve reaches the stress value of 25 MPa as shown in figure 5.

Figure 5. Experimental and simulation stress and temperature plot (inelastic heat fraction = 0.7)

The figure 6 shows a comparison of temperature contour for experimental and simulation at approximate 84% and 309% strain. The predicted FEA temperature contour plot shows approximately same temperature profile in necking area of the sample as observed in the experimental test by thermal camera.

Figure 6 Comparison of (a) simulation and (b) experimental temperature contour at approximate 85% and 309 % strain
6. Conclusion

The finite element model of the tensile test for UHMWPE has been developed and validated with experimental work. A good agreement was observed between experimental results and optimised FEA results. The tensile experimental results show that cross head speed parameter has influence on the rate of temperature increase and strength of UHMWPE. The proposed material model can be used as a simple cost and time effective tool to predict the thermo-mechanical effects in UHMWPE at high strain rates. Further experimental and simulation work is in process for other polymer blends and polymer nanocomposites material to understand their mechanical and thermal behaviour under high strain rate.

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