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Material properties

Morphology and strain rate effects on heat generation during the plastic deformation of polyethylene/carbon black nanocomposites

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ABSTRACT

The phenomenon of internal heat generation during the plastic deformation of polyethylene/carbon black nanocomposites at high strain rates was investigated using a high resolution thermal camera. Material morphology, strain rate and carbon black (CB) content were found to be critical factors that affected heat generation during tensile testing, and consequently changed the mechanical behaviour. Two processing methods (M1 and M2) were used to prepare the materials, with CB contents of 0.5, 1 and 3 wt.%. The results showed a significant increase in internal heat generation after yielding, with temperatures exceeding 70 °C for materials processed using M1 and 55 °C for materials processed using M2. The temperature increase was dependent on the processing method, the CB content and the strain rate. The increase in temperature due to plastic heat generation affected the properties of the material, reducing the plastic hardening and reducing the tensile strength at high strain rates. This is of significance when considering the use of these materials in applications involving high strain rates, such as impact protection.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a high performance thermoplastic with outstanding mechanical properties, such as high wear strength, chemical resistance and high toughness, which provide not only practical benefits but also scientific interest [1–3]. However, it's extremely high molecular weight, and subsequent high viscosity, raises difficulties in processing using standard techniques, such as twin screw extrusion and compression moulding. Reducing the viscosity of UHMWPE is an effective method of avoiding these processing difficulties. Blending UHMWPE with other polymers that have lower viscosity, such as high density polyethylene (HDPE) can, therefore, be used to improve processability. HDPE has a similar structure to UHMWPE but with lower molecular chain length, however, it exhibits lower wear resistance, yield strength and toughness than UHMWPE [1]. This reduction in performance on adding HDPE to UHMWPE can potentially be mitigated, whilst retaining the improved processability, by the addition of nano-reinforcement, which has been shown to improve the mechanical performance of polyethylene [4–11].

It is known that plastic work at high strain rates can be transformed partly into heat, which can lead to a significant temperature increase. Therefore, the behaviour of many materials can be affected by thermal softening when testing at high strain rates [12–19]. In a uniaxial tension test, heterogeneous deformation in the necking region can result in the localized generation of heat [17]. The necking mechanism in polymers is extremely complicated and the existence of nanofiller reinforcement increases this complexity. The effect of heat generation on polymer properties can be affected by several factors, such as the

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polymer matrix (glassy or rubbery), molecular weight, interfacial strength for filled polymer, filler type or shape and strain rate. Conflicting results have been reported on the dependence of heat generation on strain rate in glassy polymer nanocomposites. McNally et al. [18] investigated heat generation during the uniaxial tensile testing of polyamide-12 and a polyamide-12/MAE synthetic clay nanocomposite. They found that the measured temperature was independent of strain rate in the range tested but highly dependent on the presence of the nanofiller. The presence of the synthetic clay in the polymer was seen to increase the temperature at failure and elongation at break by 47 °C and 500% respectively. It was proposed that this was because the temperature increased above the glass transition temperature (T_g) in the polyamide-12/MAE (30 °C), hence changing the behaviour from glassy polymer to elastomeric. However, Shen et al. [19], found that strain rate had some influence on the strain hardening behaviour of a PET (polyethylene terephthalate)-clay nanocomposite, which is a glassy polymer with T_g around 70 °C. This was attributed to a possible increase in temperature at higher strain rates. However, the dependence of heat generation on strain rate has not been investigated to date for rubbery polymer nanocomposites. This could potentially provide clear relationships between heat generation, strain rate and nanofiller due to the large strains to failure in these materials. The aim of this paper is to investigate the effect of material morphology, carbon black nanofiller content and the strain rate on temperature changes during the tensile testing of PE nanocomposites. This is important when evaluating the use of such materials in applications involving high strain rates, such as impact protection equipment. A high sensitivity thermal camera was used and the spatial and temporal temperature variations were recorded along with the stress-strain behaviour.

2. Experimental methods

2.1. Materials

The materials tested in this study were UHMWPE/HDPE blended polymers with carbon black nanofiller. Nascent UHMWPE powder (Sabic®UHMWPE3548) which had an average molecular weight of (3×10^6 mol/g) was purchased from SABIC [20]. HDPE powder (ExxonMobil™ HDPE HMA014) was purchased from ICO Ltd. [21]. Carbon black powder (black pearls® 4040 BP4040) with 28 nm average particle diameter was provided by the Cabot Corporation [22]. Butylated hydroxytoluene and Tris (nonylphenyl) phosphate, supplied by Sigma-Aldrich [23], were used as primary and secondary antioxidants, to maintain the long term thermal stability and melt processing stability, respectively.

2.2. Processing

An in-house pre-mix methodology was used to incorporate the CB into the UHMWPE and HDPE powders. A twin-screw extruder was used to blend the 75 wt.% UHMWPE and 25 wt.% HDPE powders pre-mixed with CB, to form nano-filled UHMWPE/HDPE blends with various CB nanoparticle contents, (0.5, 1 and 3 wt.%). Two processing methods (M1 and M2) were used and the mixing temperature was controlled using five zones from feeding port to die; the processing parameters are shown in Table 1. A blend of 75 wt.% UHMWPE and 25 wt.% HDPE, abbreviated to U75H25, was used as the hybrid PE matrix to accommodate the nanofillers. Compression moulding was used to mould the nanocomposite materials. The raw material was placed into a square mould (100 × 100 × 1.65 mm), and then heated to 190 °C, which is higher than the melting point of the composite (approximately 135 °C). Various mould pressures (154, 232, 309, and 386 MPa) were investigated to optimise the properties of the material such as hardness and crystallinity. Various holding times at maximum pressure (10, 15 and 30 min) were also used to identify the most appropriate moulding parameters. The optimal moulding pressure and holding time were found to be 309 MPa and 15 min respectively, which resulted in the highest measured values of hardness and crystallinity. After compression moulding, the mould was cooled to room temperature using water. Then, the specimens were cut from the plaques into a dumbbell shape using a die punch cutter with the following dimensions: 75 mm overall length, 25 mm length of narrow parallel-sided portion, 12.5 mm width at the ends, 4 mm width of narrow portion and 1.65 mm thickness.

2.3. Material testing and characterisation

In order to characterise the CB dispersion and the microstructure of the nanocomposites, several experimental techniques were used. These included Depth Sensing Indentation (also called nanoindentation), Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). A high sensitivity thermal camera was used to record the temperature variations during the tensile testing at different strain rates.

Depth sensing indentation (DSI) experiments were performed on (10 x 10 × 1.65 mm) specimens at controlled machine chamber temperature, (24.8 ± 0.6 °C) using a NanoTest 600 from Micro Materials Ltd (Wrexham, UK). A Berkovich indenter, with face angle of 65.3°, was used to make a grid of 10 × 10 indents using 40 mN maximum load, 600 s dwell period and 2 mN/s loading and unloading rates. The results were analysed using the Oliver and Pharr method [24], and then plotted using Matlab software from MathWorks (Cambridge, UK). In this method, the initial portion of the unloading curve is described by the power low relation:

$$P = \alpha(h - h_r)^m \quad (1)$$

Table 1
Processing method parameters.

Processing method	Extruder speed (rpm)	Processing temperature (°C)					
		Zone 1	Zone 2	Zone 3	Zone 4	Die	Cooling
M1	400	180	190	200	210	220	Water
M2	190	220	250	260	270	280	Water