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Material behaviour

Nanoparticle type effects on heat generation during the plastic deformation of polyethylene nanocomposites

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ABSTRACT

The correlation between nanoparticle type and internal heat generation during the plastic deformation of polyethylene nanocomposites is investigated. The effects of three different types of nanoparticle (carbon nanotube (CNT), carbon black (CB) and inorganic nanoclay) were evaluated using infrared thermography, simultaneously with tensile tests. The results showed a significant influence of nanoparticle type, content, dispersion and interaction on the temperature increase measured at different strain rates. The addition of all the nanoparticles increased the rate of heat generation, which resulted in thermal softening in the strain hardening region, and reduced the tensile strength. At low volume fractions, CNT nanofiller resulted in higher temperatures than seen with CB. The addition of nanoclay resulted in only a small temperature increase, and straining was companied by the formation of microcracks.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a high performance thermoplastic with outstanding mechanical properties, such as high wear resistance, chemical resistance and high toughness, which provide not only practical benefits but also is of scientific interest [1–3]. However, its 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. UHMWPE/HDPE blends are of current interest owing to the improvement in the processability and creep resistance compared with UHMWPE [4,5]. 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 [6–14].

In the polymer matrix, the nanoparticle structure can be classified as one-dimensional (1D, e.g. nanotubes), two dimensional (2D, e.g. nanoclay platelet) and three-dimensional (3D, e.g, carbon black nanoparticle) [15]. Various studies have been carried out to investigate the effect of such nanoparticle structure, content, dispersion, interfacial strength, strain rate and processing on the mechanical performance of polyethylene nanocomposites for different applications [4–14]. However, in some applications that involve plastic deformation and high strain rate, such as impact, nanoparticle filler can potentially affect internal heat generation, and this has not been investigated to date. It is known that plastic work at high strain rates can be transformed partly into heat, which can lead to a significant

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temperature increase. Therefore, the behaviour of many materials can be affected by thermal softening when testing at high strain rates [16–23]. In a uniaxial tension test, heterogeneous deformation in the necking region can result in localized generation of heat [21]. 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 polymer matrix (glassy or rubbery), molecular weight, interfacial strength for filled polymers, filler type or shape and strain rate. To date, no work has been reported on the effect of nanoparticle structure on the heat generation during plastic deformation of polyethylene nanocomposites, and the effect of this heat generation on the mechanical properties. In this work, three different types of nanoparticle (carbon nanotube, carbon black and inorganic clay platelet) were embedded separately in a UHMWPE/HDPE blend to form nanocomposites using an in-house processing method. The effect of nanoparticle structure on the heat generation during plastic deformation was then investigated using a high sensitivity thermal camera applied simultaneously with tensile tests. The correlation between nanoparticle content, dispersion, interaction, tensile strength and heat generation were also investigated.

2. Experimental methods

2.1. Materials

The materials tested in this study were UHMWPE/HDPE blended polymers with various nanofillers. Nascent UHMWPE powder (Sabic®UHMWPE3548) was purchased from SABIC [24], and had an average molecular weight of 3×10^6 mol/g. HDPE powder (ExxonMobil™ HDPE HMA014) was purchased from ICO Ltd [25]. Carbon black (CB) powder with the commercial product name, black pearls® 4040 (BP4040) and average particle diameter of 28 nm were provided by the Cabot Corporation [26]. Natural hectorite nanoclay was supplied by Elementis specialties [27]. Multi-wall Nanotubes (MWNT) with diameters in the range of 5 nm to 50 nm were provided by Nanocyl [28]. Butylated hydroxytoluene and tris (nonylphenyl) phosphate, supplied by Sigma-Aldrich [29], 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 technology was used to incorporate the nanofillers into the UHMWPE and HDPE powders. A twin-screw extruder was then used to blend the UHMWPE and HDPE powders pre-mixed with CB, carbon nanotubes (CNT) or nanoclay to form nano-filled UHMWPE/HDPE blends with various nanoparticle contents, as 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. During processing, the mixing temperature was controlled using five zones from feeding port to die; the processing parameters are shown in Table 2. Compression moulding was used to produce test pieces of the nanocomposite materials. The raw material was placed into a square mould ($100 \times 100 \times 1.65$ 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 309 MPa and 15 min respectively, which resulted in the highest 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.

Table 1
Nanofiller content.

Base material	Filler	Filler content wt.%
U75H25	CB	0, 0.5, 1, 3
U75H25	CNT	0, 0.5, 1, 3
U75H25	Clay	0, 0.5, 1, 2

Table 2
Processing method parameters.

Extruder speed (rpm)	Processing temperature (°C)					
	Zone 1	Zone 2	Zone 3	Zone 4	Die	Cooling
190	220	250	260	270	280	Water

2.3. Material testing and characterisation

In order to characterise the nanofiller dispersion and the microstructure of the U75H25 nanocomposites, several experimental techniques were used. These included Differential Scanning Calorimetry (DSC), X-ray Diffraction (XRD), 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. The details of these techniques are given below.

Differential Scanning Calorimetry (DSC), (TA instruments, Shimadzu DSC60) was used to analyse the effect of different compression moulding parameters and nanofiller content on the crystallinity of the blend and nanocomposites. The specimens, with average mass of 5 ± 0.2 mg, were sealed in aluminium pans and heated from 20 to 180 °C at a rate of 10 °C per minute. The mass fraction degree of crystallinity was then determined by comparing the heat of fusion with that for fully crystalline polyethylene at the equilibrium melting point (290 kJ/kg) [30]. X-ray Diffraction (XRD) patterns were obtained by using a Philips X'Pert X-ray diffractometer (anode 40 kV, filament current 35 mA) with Nickel-filtered Cu-Kα_1 ($\lambda = 0.1542$ nm) radiation at a scan speed of 1°/min from