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Scratch behavior of low density polyethylene film: Effects of pre-stretch and aging

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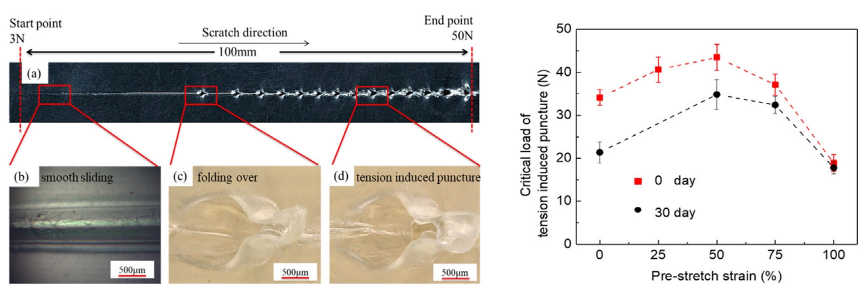
HIGHLIGHTS

- Three typical scratch damage modes: smoothing sliding, folding over and tension induced puncture are identified for LDPE film.
- When scratched parallel to the pre-stretch direction, the scratch performance of LDPE film improves with increasing pre-stretch level.
- Scratch resistance declines with the increase of residual stress when the pre-stretch direction is perpendicular to scratch.
- Thermal aging causes poor scratch resistance, as well as diminishes the anisotropy.
- A good correlation exists between the onset of tension induced puncture and the elongation at break of LDPE film.

GRAPHICAL ABSTRACT



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ABSTRACT

To investigate the influences of pre-stretch and aging on the scratch behavior of low density polyethylene (LDPE) film, the scratch tests were conducted with the linearly increasing normal load. The scratch process was recorded using a high-speed camera and the scratched surface morphology was microscopically investigated. Three typical film scratch deformation/damage modes, i.e., smooth sliding, folding over and tension induced puncture were identified. Their mechanisms and evolution processes were analyzed. It was found that the pre-stretch could improve the scratch performance of LDPE film in the same direction while the scratch resistance perpendicular to the pre-stretch direction declines. While the thermal aging tends to diminish this anisotropic scratch performance, a long thermal aging time causes poor scratch resistance. A good correlation was found between the critical load of tension induced puncture and the elongation at break of LDPE film. Thus, the elongation at break can be one of the good indexes to evaluate the scratch resistance. Those findings provide a fundamental insight for material scientists to design LDPE film with better scratch performance and longer service lifetime.

1. Introduction

Low density polyethylene (LDPE) film is widely used in many applications such as packaging, medical ware, mobile electronic equipment and household appliances because of its excellent barrier properties,

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good transparency and low cost [1]. For the storage and transportation of products, packaging is an essential process in which LDPE film plays an important role in containing and protecting the packed goods. However, due to its inherent relatively weak mechanical properties, LDPE film can be easily scratched by hard and sharp objects and lose its protective function.

In the past decades, many researchers have studied the mechanical properties [2–4], antimicrobial activity [5–7] of plastic films. The crystal orientation parallel to the machine direction (MD), as well as the extrusion thickness, shows a significant effect on the mechanical properties and fracture toughness of LDPE film [8, 9]. The tensile strength in MD of LDPE films is found to be higher than that in the transverse direction (TD). In addition to the anisotropy induced by the manufacturing process, LDPE film is always pre-stretched to wrap the products. The pre-stretched LDPE film suffers residual tensile stress which was found experimentally to have an adverse effect on the mechanical performance [10]. Meanwhile, exposure of LDPE film to weathering could cause degradation of their mechanical properties. Film's tensile strength and fracture strain drop with a long aging time [11, 12]. The comprehensive understanding of the effect of aging on long term integrity of LDPE film is important for designing the packaging with better performance and longer service lifetime.

Many research efforts have been made to explore the correlation between scratch performance and material properties of bulk polymer and film. Proposed an inverse relationship between brittleness and the elongation at break, Brostow et al. [13–15] found that the larger elongation at break, i.e., the better ductility, could mean the better scratch resistance of bulk polymeric materials. Hamdi et al. [16] demonstrated that the scratch resistance of polypropylene (PP) films improved with lower ethylene content. Hare et al. [17] conducted the scratch test of LDPE film to study the influence of the hardness of backing materials. They found that rubber backing shows better result than aluminum one. This finding somewhat agrees with the experiment and FEM results of polymer coating scratch from Jiang et al. [18]. Moghbelli et al. [19] showed that with larger molecular weight, as well as higher crystallinity due to thermal treatment, the scratch performance of PP thin sheets can be improved. Gao et al. [20] simulated the scratching process of talc-filled polypropylene panels. However, little open literature can be found to investigate the effects of pre-stretch and aging on the scratch behavior of LDPE film.

In this work, the scratch tests with a linear progressive increasing normal load were carried out to identify the typical scratch deformation/damage modes of the LDPE film under different levels of pre-stretch strain. Then, the critical loads of various scratch damage modes were measured. The scratch performance of LPDE film evolving with aging time was also investigated. After the correlation between the critical scratch load and material properties was evaluated, possible approaches to improve the scratch resistance of LDPE film for packaging application were also discussed.

2. Experimental

2.1. Material and specimens

The model material in this work is commercially available LDPE (2426H, BASF-YPC Co., Ltd.). It was manufactured in the form of film with a nominal thickness of 0.2 mm, provided by Sichuan Province XingDa Plastic Co., Ltd. The LDPE film was cut, along the MD and TD directions respectively, as 150 mm by 25 mm rectangular strips of 0.2 mm thickness. The gauge length was 100 mm.

The specimens were thermally aged at 80 °C with different time periods (0, 7, 14 and 30 days respectively) in an environment chamber (WG03, INBORN). After reaching the prescribed time, the specimens were air cooled to the ambient temperature.

The indentation tests were carried out using a commercial nano-indentation instrument (Keysight, G200) with a Berkovich indenter tip. A 10-s hold at maximum load was used to minimize the influence of creep on the unloading curve. The indentation modulus and hardness of LDPE film with different aging time were obtained from the unloading curve (at maximum load) using the Oliver–Pharr method [21].

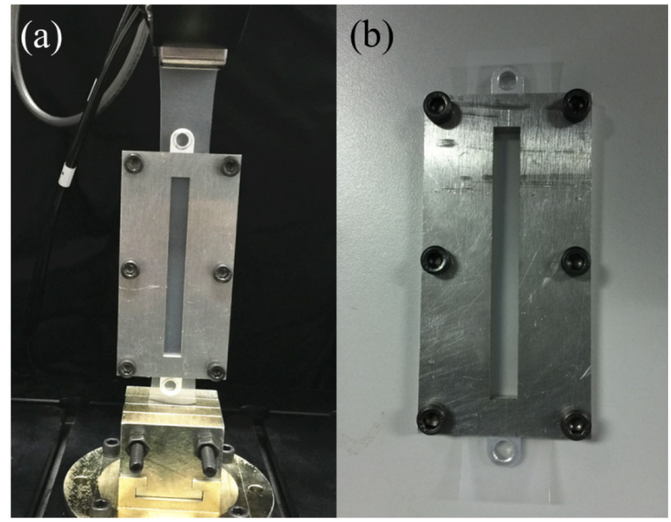

Fig. 1. Pre-stretch of LDPE film: (a) the aluminum clamping frame to keep constant strain; (b) pre-stretched specimen ready to be relaxed.

An electrodynamic material test machine (MTS Acumen) was utilized to pre-stretch the LDPE film specimens in a rate of 100 mm/min at the room temperature. The specimens were pre-stretched, in either the MD or TD direction, to a prescribed strain level of 25% and 50%, respectively. Clamped with a custom designed aluminum holder (shown in Fig. 1(a)) to withhold the elongation, the pre-stretched film was removed from the test machine (Fig. 1(b)).

To estimate the residual stress level of pre-stretched LDPE film specimens, the relaxation tests were carried out under the same condition as pre-stretch. The film was first loaded to the corresponding strain level (25%, 50%), and then held for more than 80 min until the time-stress curve became stable, as presented in Fig. 2. The residual stresses were then taken as 7.3 MPa and 11.2 MPa for 25% and 50% pre-stretched strain correspondingly.

2.2. Scratch test

The LDPE film samples, clamped on the backing material, were scratched using a home-made scratch device [21] at the room

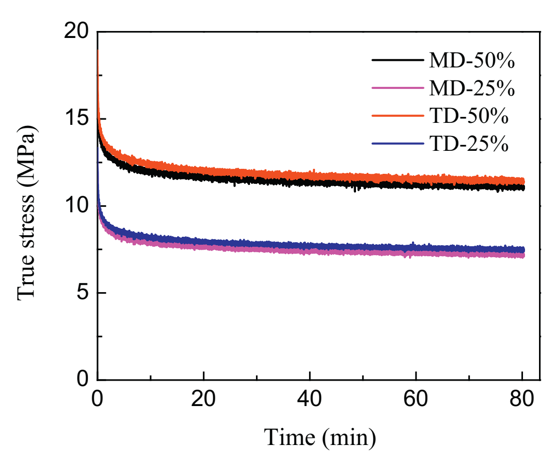

Fig. 2. The stress relaxation of LDPE film.