Materials and Design 91 (2016) 1–10

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Research on deformation behavior of isotactic polypropylene in uniaxial geogrid manufacture

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ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form 18 November 2015
Accepted 20 November 2015
Available online 21 November 2015

Keywords:
Geogrid
Tensile behavior
Mechanical property
Finite element method
Aperture

ABSTRACT

The present work investigates the deformation behavior of isotactic polypropylene in uniaxial geogrid manufacture experimentally and numerically. The extruded sheet with different geometric features of circular holes was stretched at elevated temperature and then tensile properties of geogrids at room temperature were evaluated. A numerical model based on the finite element method was established to analyze the strain distribution and predict the final shapes of products. It was found that the transverse distance played important roles on temperature deformation of the rib and the fracture behavior of geogrids, while the formation of apertures and failure locations were highly dependent on the longitudinal distance. The failure location was not sensitive to the hole diameter. It was proved that good predictions of the final shapes of the geogrid products were obtained using the proposed numerical model. The numerical results show that as the transverse distance varied, temperature deformation always focused on the rib. However, both dimensions and strain distributions at the junction exhibited different features when the longitudinal distance changed. The comparison of strain distributions with different geometric features of holes was discussed.

1. Introduction

The development of methods of preparing high-performance polymeric materials by stretching raises the possibility of using such materials in the reinforcement of soils for walls, foundations, steep slopes and roadway bases [1]. One successful application is the geogrid which represents a rapidly growing component within the geosynthetics. Rather than being a woven or knitted geotextile, geogrids are plastics formed into a grid-like configuration. The marked characteristic of all geogrids is apertures, which is the openings between the adjacent transverse and longitudinal ribs. The aperture should be large enough to allow interlocking with surrounding soil, rock, earth and other geotechnical materials for soil stabilization. The ribs of geogrids are quite stiff to endure the load from soils. Because of its structural features, the geogrid exhibits a significant mutual effect with the surrounding geotechnical materials [2].

Geogrids can be made with three main manufacturing processes, that is, extruded and punched-stretched, knitting, and welding [3]. The extruded and punched-stretched process will be investigated in the present work. In this process, the geogrid is formed through being stretched in one, two or three directions. The process begins with the flat extruded sheet of the appropriate polymer (mostly polypropylene or high-density polyethylene). Typical thicknesses are 4 to 6 mm. Under the action of punching dies, holes are punched into the sheet on a regular pattern. It is then stretched along the longitudinal direction at controlled temperature and strain rates by running over a series of rollers rotating at different speeds. At this stage the holes increase in size and a network can be obtained as a result. Consequently, a uniaxial geogrid has been produced. Based upon the formed uniaxial geogrid, the biaxial geogrid can be manufactured by subsequent stretching along the transverse direction. With the deformation of polymers, the molecular chains can flow into an elongated condition, especially in the rib. Therefore, aside from a significant increase in modulus and strength, the creep sensitivity of the elongated rib is also greatly reduced by the stretching process. The uniaxial geogrid is used in walls and slopes where the principal stress direction has been known, while the biaxial geogrid is employed to carry tensile forces in two directions along ribs.

The use of uniaxial or biaxial geogrids is an important issue in geotechnics and has been widely investigated by many researchers. It has been found that geogrids have played active roles in base and ballast reinforcement in both laboratory investigations and field studies [4–6]. On account of the fact that the deformation characteristics of geogrids are important for their engineering applications, the tensile behavior [7,8] as well as creep behavior [9,10] has been studied by experiments. Moreover, there are a number of significant researches on behaviors of geogrid-reinforced earth structures such as flexural behavior [11,12], shear behavior [11,13], fatigue behavior [14] and interface behavior [15], and many achievements were obtained. However, limited data

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http://dx.doi.org/10.1016/j.matdes.2015.11.075

related to the manufacturing process of geogrids have been published so far. The key stage in the geogrid manufacturing process is the stretching of materials at elevated temperature. In this stage, the final shape can be formed depending upon the material properties, the geometric characteristics of punched holes, and the stretching parameters such as temperature, strain rate and draw ratio. Thus, control of the stretching process meets significant challenges but is crucial for successful geogrid manufacture. Caton-Rose et al. [16] proposed an elastic model of large solid polymer deformations to predict the stretched shapes of polyethylene geogrids. Good predictions of the final shapes can be obtained even with the draw ratio of up to 8. Since the physical properties of stretched polypropylene are strongly dependent on molecular orientation, the orientation of the crystalline phase during the process has been thoroughly studied. Rizzo et al. [17] have reported the crystalline phase orientation in biaxially stretched isotactic polypropylene by X-ray diffraction patterns. The peculiar bimodal–axial orientation was formed in two-step biaxially stretched polypropylene, and it was believed that the presence of the bimodality of orientation was beneficial to the balance of mechanical properties along different directions in the sheet plane. In this way, enhanced stiffness and toughness can be achieved as a consequence of molecular orientation. The study carried out by Bao et al. [18] investigated the effect of draw temperature on the deformation-induced morphology evolution of isotactic polypropylene during uniaxial stretching. The crystal orientation, the degree of crystallinity and the deformation behavior at the crystal lattice scale were characterized. They showed that the morphology evolution was strongly temperature dependent and different deformation mechanisms operated at varied temperatures. Although the researches have revealed the evolution of material properties during the stretching process, the effect of geometric characteristics of punched holes on tensile deformation and mechanical performance of geogrids has not been fully understood.

In the stretching process, because of the requirement for heating, the sheet with punched holes is drawn in an enclosed space, so it is difficult to observe the deformation behavior and ensure the forming quality. The broad application of the finite element method can provide detailed deformation information and enables the manufacturers to deeply understand the process. A theory specifically for the modeling of large deformations of polymers considering necking instabilities has been demonstrated by Sweeney et al. [19]. Although the theory was elastic in nature, it included the necking phenomenon as an inherent property. A finite element analysis scheme was established and successfully applied to polypropylene sheets at 150 °C for both uniaxial and biaxial drawing. Based on a hyperelastic constitutive model, Caton-Rose et al. [16] proposed finite element simulation of geogrid manufacture in both two and three dimensions. The geogrid shapes in terms of the width and thickness at selected points showed reasonable agreement between the numerical and experimental results. Mimaroglu et al. [20] have reported the numerical study of geometric and material instability in uniaxial drawn polymers. They employed the finite element technique to model uniaxial drawing behavior of polymers and obtained the relationship between the neck profile, neck propagation and uniaxial stress–strain behavior of polymers. Dong et al. [3] adopted the finite element method to investigate the response of geogrids with rectangular and triangular apertures subjected to a uniaxial tensile load. Effects of the aperture shape of geogrids, elastic modulus and cross-section area of ribs on the tensile stiffness of geogrids were evaluated. Therefore, because of the possibility of the elimination of expensive experimental work, the finite element method has been a valuable product development tool in the geogrid manufacturing process.

This body of work investigated the deformation behavior of isotactic polypropylene in uniaxial geogrid manufacture experimentally and numerically. The extruded and punched sheet of isotactic polypropylene was stretched at elevated temperature under process conditions, and then the tensile property of geogrids at room temperature was further studied. A numerical model based on the finite element method was established to evaluate the strain distribution and predict the final shape of products after the stretching process. Specifically, effects of geometric characteristics of circular holes on tensile deformation and mechanical performance of geogrids were systematically analyzed.

2. Experiment

2.1. Analysis procedure

To examine the deformation behavior of isotactic polypropylene in uniaxial stretching and evaluate the mechanical property of geogrids at room temperature, experiments were carried out in two steps. Firstly, sheets of isotactic polypropylene were prepared through extrusion. Then the sheets were punched with a pattern of circular holes, stretched at elevated temperature, and finally cooled to ambient temperature. The purpose of the high temperature stretching test is to investigate the deformation characteristics of polymeric materials with a given arrangement of circular holes. Secondly, the mechanical property of formed geogrids such as tensile strength and elongation was tested using a universal testing machine. To investigate the effect of geometric characteristics of circular holes on deformation behavior and mechanical performance of geogrids, different transverse and longitudinal distances between holes as well as hole diameters were designed and a series of experiments were conducted.

2.2. Experimental equipment

Extrusion was realized by a SJ65/30 single screw extruder with a screw diameter of 65 mm, and the extruded sheet was then flattened through a SSGJ400 three-roll calendar. Because the diameter of circular holes in the present study was in a range of 2 to 10 mm, laser cutting was adopted to fabricate holes with the advantages of high accuracy, rapidity and flexibility. With this process, sheets with circular holes of various transverse and longitudinal distances between holes as well as hole diameters were manufactured. All sheets were cut into small specimens and stretched using a MTS CMT4104 testing machine incorporating a GDX70/350 high temperature oven at constant speeds. The maximum tensile force of the machine was 10 kN and the maximum

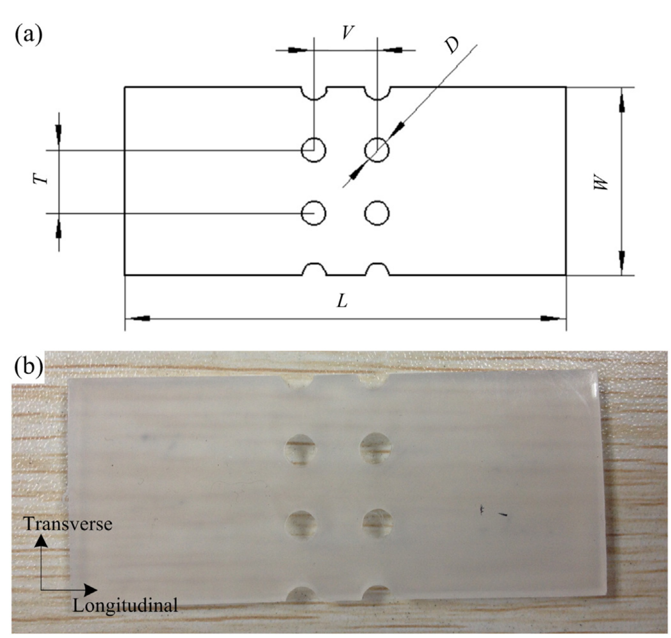

Fig. 1. Tensile specimen: (a) schematical diagram, and (b) product photograph.