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Effects of shearing parameters on cutting characteristics of polycarbonate sheet subjected to straight punch/die shearing☆

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ABSTRACT

Owning to the lack of understanding of the polycarbonate sheet's shearing behavior, this research work focused on revealing the unstable cutting characteristics of a 0.5 mm thickness polycarbonate worksheet subjected to a straight punch/die shearing. Mechanical conditions (such as the tool clearance and feed velocity) of the shearing process were varied and investigated. Through the experimental results, it was revealed that: (i) an overlapping (negative) punch/die clearance was not suitable for burrless cutting of the worksheet. (ii) When using a positive 2–20% clearance, two primary cracks were initiated in the vicinity of the cutting tool corners, where only one of the two cracks was largely propagated into the bulk of the worksheet. This deviated propagation strongly deteriorated the quality of the sheared profile of the polycarbonate worksheet. (iii) The deviated propagation of the crack seemed to be affected by an in-plane/lateral unbalanced stress state in the worksheet. (iv) As the shearing velocity varied ranging from 0.05 to 1.0 mm s^{-1}, the characteristics of the cutting load resistance were slightly variant, while the velocity seemed to have almost no effect on the pattern of crack initiation and its propagation. Moreover, the shearing problem was numerically studied based on a two-dimensional finite element analysis method by varying the constitutive equation of the worksheet. In order to discuss about the crack propagation, a state of two dimensional stresses in the worksheet was simulated.

1. Introduction

A polycarbonate (PC) resin sheet shows several unique properties such as high transparency to the visible light, excellent toughness, high electrical and heat resistance, etc. Due to these mentioned properties, the PC sheet is often employed for many applications e.g. transparent panels, electrical devices, architecture and so on (Crawford, 1999). There are a number of methods used for converting/cutting the PC sheet into net or near net shape products. Caiazzo et al. (2005) studied the cutting process of a PC sheet using a laser beam. Using this process, the PC worksheet undergoes three main states: fusion, vaporization and chemical degradation. Getu et al. (2008) studied the cut of a PC worksheet by an abrasive water jet cutting process. Owning to the needs of environmentally-friendly manufacturing, the cleaner and more effective cutting technologies are becoming important, and they seem to be continuously developed. Furthermore, Engelmeier et al. (2012) applied a carbon dioxide gas jet for cutting off a 1.2 mm thickness PC worksheet. An inspection result showed that the worksheet could be completely penetrated by the jet. Also, Mitsomwang et al. (2012) studied the cut of a polycarbonate sheet stacked on a flexible underlay by using a wedge blade indentation.

Apart from the processes mentioned above, punch/die shearing seems to also be one of the most attractive mechanical methods for cutting off the PC worksheet. Usually, it provides many advantages such as a high stability, high productivity and low operation cost. Notwithstanding, it seems to have only a few research works investigating the punch/die shearing of resin sheet materials. Jacobs et al. (2002, 2003) developed an apparatus for the shear cutting test, subjected various kinds of thermoplastic foil such as polypropylene, polyvinyl chloride and polyethylene terephthalate to the developed testing system, and then investigated the shearing characteristics of the foil. Experimental results revealed that the shearing force was significantly controlled by the sharpness of the cutting tool and the punch/die clearance rather than the foil temperature varied about ±10 K around the usual processing temperature of the foil. These research results seem to be helpful to minimize the cutting force and tool wear. However, there were not any investigations and discussions concerning the final features of sheared edges with respect to mechanical conditions of the shearing process.

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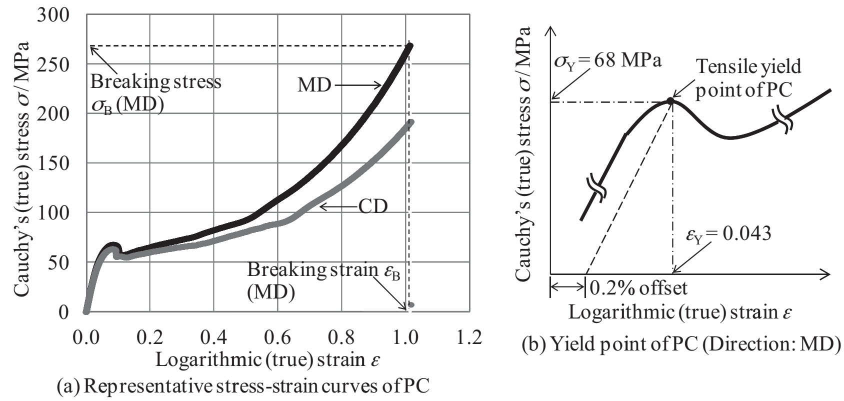

Fig. 1. Tensile test results of PC sheet (a) stress–strain curves and (b) yield point of PC sheet (cross head speed = 0.05 mm s^{-1}).

Several researchers have paid enormous attention to the shearing processability of ductile metallic sheet. Hatanaka et al. (2003) experimentally and numerically investigated the shearing process of mild steel. They illustrated that its sheared edge consisted of roll-over, burnished, fracture and burr zones. Through their investigation results, the features of these zones were confirmed to be determined by the punch/die clearance and the blank holder force. Hirota et al. (2009) investigated the shearing process of aluminum alloys under a negative punch/die clearance configuration. This clearance contributed to reduce the roll-over zone and suppressed the formation of a rough fracture surface. Mori et al. (2012) studied the shearing process of a high strength steel sheet. In that work, they applied an electrical resistance heater to increase the temperature of the sheet in the shearing zone. As the flow stress decreased in the material due to the rise of temperature, the maximum punching force decreased, while a shiny burnished surface was increased. The effect of an applied lateral pre-load to steel sheets on the sheared profiles was investigated by Neugebauer et al. (2013). In that work, a critical level of applied compressive stress, which caused the burnished zone to increase, was revealed. From this literature survey, the cutting characteristics of metallic sheet materials and the features of their sheared edges were understood to be strongly affected by several processing conditions. However, since the deformation and fracture mechanisms of the PC worksheet are largely different from the ones of those of ductile metals, the cutting characteristics of those metals seem to be insufficient to explain and predict the shearing characteristics of the PC worksheet.

Until now, the cutting characteristics of a PC worksheet subjected to punch/die shearing are not sufficiently revealed neither discussed to the high level required for promoting such a cutting technique to the sheet converting industry. Therefore, in this research work, a 0.5 mm thickness PC resin worksheet was chosen and subjected to a punch/die tool shearing. Mechanical conditions, such as punch/die clearance and shearing velocity were varied to investigate the load response and sheared profiles of the worksheet. Moreover, an finite element method (FEM) analysis of the PC worksheet shearing problem was conducted based on a two dimensional (plane-strain) model in order to further discuss about the primary crack propagation during shearing.

2. Experimental investigation of PC worksheet shearing

2.1. Specimen, tool and experimental condition

In the experiment, a PC worksheet which had a thickness t_S = 0.5 mm was used. Its mechanical property was evaluated by an in-plane uni-axial tensile testing based on the JIS (Japan Industrial Standard) K7127. Fig. 1 shows the stress–strain relationships

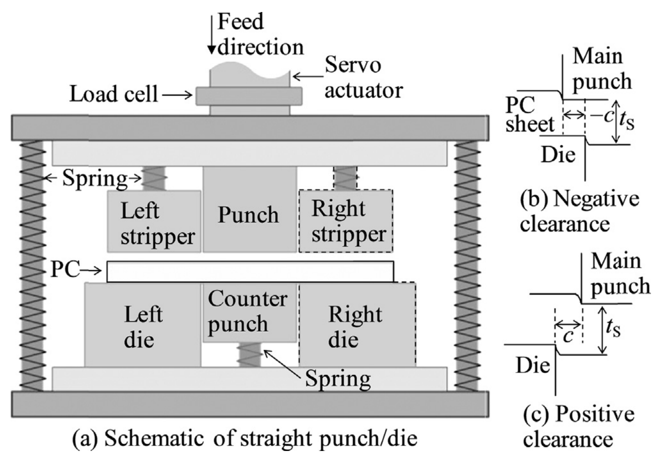

Fig. 2. Schematics of (a) experimental set-up in case of one line shearing (w/o right stripper and right die) and in case of two line shearing (with right stripper and right die), (b) negative clearance and (c) positive clearance.

of the PC worksheet in its machine direction (MD), cross-machine direction (CD) and the yield point of the PC worksheet. The shearing specimens had a square shape with a width w_S of 20 mm and a length l_S of 70 mm. All the specimens were appropriately washed water and dried. After being well dried, the specimens were kept in a room with a temperature of 296 ± 1 K and a room humidity of 50 ± 1%RH for 24 h before the shearing experiment.

As illustrated in Fig. 2(a), to cut off the specimens, the main punch of a shearing apparatus was pushed downward by a servo actuator. The main punch and dies were made of cold-work tool steel which had a hardness of 58–60 HRC. In this process, the displacements of the upper strippers and lower counter punch were determined by their attached backing springs. The spring constants for the stripper and the counter punch were 5.0 and 4.5 N mm^{-1}, respectively. A load cell (maximum capacity = 20 kN) and a high speed camera were installed in this shearing system to record the cutting load resistance F and the side-view deformation of the worksheet.

Concerning the mechanical conditions, the negative and positive punch/die clearances were chosen as c/t_S = −0.05, 0.02, 0.1 and 0.2. The definitions of the negative and the positive clearances are illustrated in Fig. 2(b) and (c). Also, the feed velocity of the main punch V was varied ranging from 0.05 to 1.0 mm s^{-1}. For the investigation of the punch/die clearance and feed velocity effects, an one line shearing was considered, namely the right stripper and the right die indicated by the dashed lines in Fig. 2(a) were removed from the shearing apparatus. However, these two parts are necessary for a symmetry shearing (two line cutting) test which is also discussed in