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A Review on Plastic Behavior of Polymer Sheets and Forming Process

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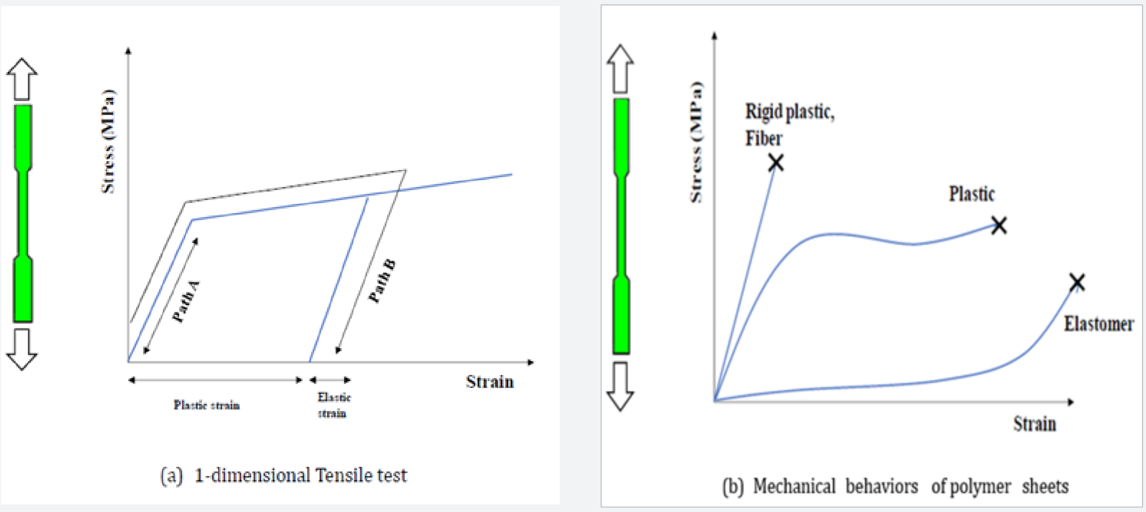
Abstract

This paper presents a mini review about plastic behaviour of polymer sheets. The fundamental of plasticity and concept of constitutive modeling are introduced. As an application of the plastic behaviour, studies on forming process of polymer sheets are presents. Finally, the future woks are also discussed in the conclusion section.

Keywords: Polymer; Plastic behaviour; Forming; Target temperature; Lightweight; Metal flow

Introduction



Figur 1: Plastic behavior of polymer sheets.

Polymer is one of widely used material due to the great availability and low cost. For mass production, moulding and extrusion technologies have been widely employed for polymer processing in industries [1]. Recently, automotive industries are trying to reduce the weight of the vehicles for improving the fuel efficiency [2]. For the reason, they have an interest in polymer materials, and many researchers have studied mechanical behavior of polymer materials. Figure 1(a) shows an example of 1-dimensional tensile test which is the most widely used material testingmethods to obtain the material's behavior. When a material is getting deformed, the material has aproportional relation between stress and strain within a range of strain and this proportional relation iscalled elastic modulus. This strain rage is called elastic range and the stress is called yield stress. In theelastic range, the deformed material can recover the original shape, as shown in the path A. However, if thestrain level is over the elastic limit, a permanent deformation remains on the material even though thematerial slightly recovers the strain [3,4]. This recovered strain is called elastic strain, and the permanentdeformation is called plastic strain, as shown in path

B of Figure 1(a). Figure 1(b) shows general behaviors ofpolymer materials. The elastic behavior is almost the same for all the materials. However, right after theelastic limit, rigid plastic easily leads to a material failure while other materials have more margin to bedeformed. For the reason, rigid plastic material does not show plastic behavior. This break point determinesthe elongation, the ration between the deformed length and the original length until the break point. Table 1 shows a summary of the mechanical property of polymer materials [5].

Table 1: Mechanical property of polymer materials [5].

Polymer Type	Ultimate Tensile Strength (Mpa)	Elongation (%)	Elastic Modulus (GPa)
ABS	40	30	2.3
Acetal Copolymer	60	45	2.7
Acrylic	70	5	3.2
Nylon 6	70	90	1.8
Polyimide	85	7	2.5
Polycarbonate	70	100	2.6
Polyethylene Terephthalate (PET)	55	125	2.7
Polypropylene	40	100	1.9
Polystyrene	40	7	3

During the plastic deformation, the stress-strain relation is given as below [6,7]:

$$d\sigma = D d\varepsilon^{e} d\varepsilon \text{ where } d\varepsilon^{e} = d\varepsilon - d\varepsilon^{p} , \quad (1)$$

then the increment of the plastic strain is given with the flow rule,

$$d\varepsilon^{p} = \frac{\partial q}{\partial \sigma} d\bar{\varepsilon}^{p} \quad (2)$$

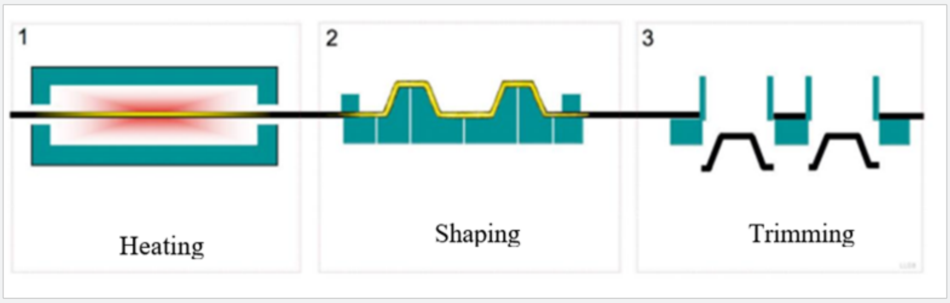
$d\sigma$ is the increment of stress, D is the elastic modulus matrix, $d\varepsilon$ is the increment of total strain. $d\varepsilon^{e}$ represents the increment of elastic strain, $d\varepsilon^{p}$ is the increment of the plastic strain. q is the plastic potential function, and $d\bar{\varepsilon}^{p}$ is the equivalent plastic strain. In order to obtain the $d\varepsilon^{p}$, below three conditions should be employed,

$$\bar{\sigma}(\sigma) = \rho\left(\bar{\varepsilon}^{p}\right) \quad (3\text{-}1)$$

$$\sigma_{n+1} = \sigma_{n} = d\sigma_{n+1} \quad (3\text{-}2)$$

$$\rho_{n+1}\left(\bar{\varepsilon}^{p}\right) = \rho_{n}\left(\bar{\varepsilon}^{p}\right) + H d\bar{\varepsilon}^{p} \quad (3\text{-}3)$$

$\bar{\sigma}$ is equivalent stress, ρ is flow stress model, and H is the slope of stress-strain curve. Equation (3-1) is the yielding condition, (3-2) is about the return mapping stress, and (3-3) is the hardening behavior. Solving the equations from (3-1) to (3-3) provides the increment of the plastic strain and stress. Then the strain and stress are used in numerical analysis of the plastic behavior.



Figur 2: Thermoforming process [8].

As an application of the plastic behavior, some researchers have developed forming technologies for polymer materials. Thermoforming is one of the most popular forming processes for polymer sheets. As shown in Figure 2 [8], the thermoforming process consists of three steps; heating, shaping and trimming. Withthe thermoforming, a polymer sheet is heated to a target temperature, then formed to a specific shape in a mold. The formed sheet is trimmed to make a product. The vacuum forming is very similar to the thermoforming. In the vacuum forming, a polymer sheet is heated to a target temperature, then stretched onto a mold, and forced against the mold with a vacuum condition to reach the target shape.

The thermoforming and vacuum forming requires a mold to form a polymer sheet to the target shape. The investment cost of the mold is expensive. In addition, a mold cannot be used for

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another shape. To reduce the cost, some researchers started studying incremental forming for polymers [9,10]. Figure 3 shows the concept of the incremental forming. A polymer sheet is locally deformed by a forming tool which moves on the surface of the polymer sheet. Since the moving tool is following a defined path in 3-dimensional space, this forming process is flexible to be applied to arbitrary shapes.

Some researchers have tried to build lightweight structures with polymers sheets. Figure 4(b) shows a pyramidal kagome structure made of a polypropylene sheet. Since the polymer sheet was not able to be deformed to reach the target shape in room temperature, a heated die set was employed to increase the formability of the polymer sheet, as shown in Figure 4(a). This study showed a possibility to make a complex shape by a polymer sheet forming process. Polymer sheets can be employed as a medium material to help metal flow in sheet metal forming processes. Figure 5 shows a viscous pressure bulge (VPB) test under biaxial state of stress. Since the viscous medium help the flow of the sheet metal, the VPB forming process was able to reach large strain state. As shown in above examples, forming process of polymer sheets has many chances to be employed in industrial applications.

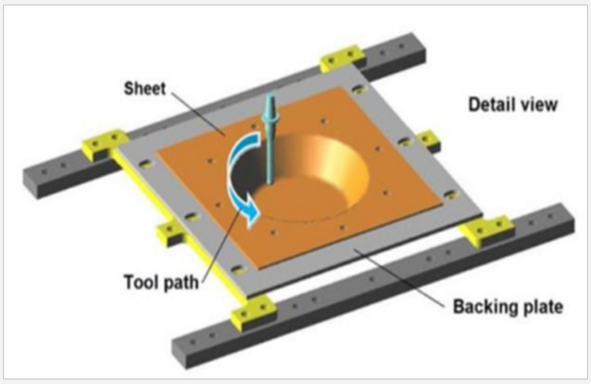
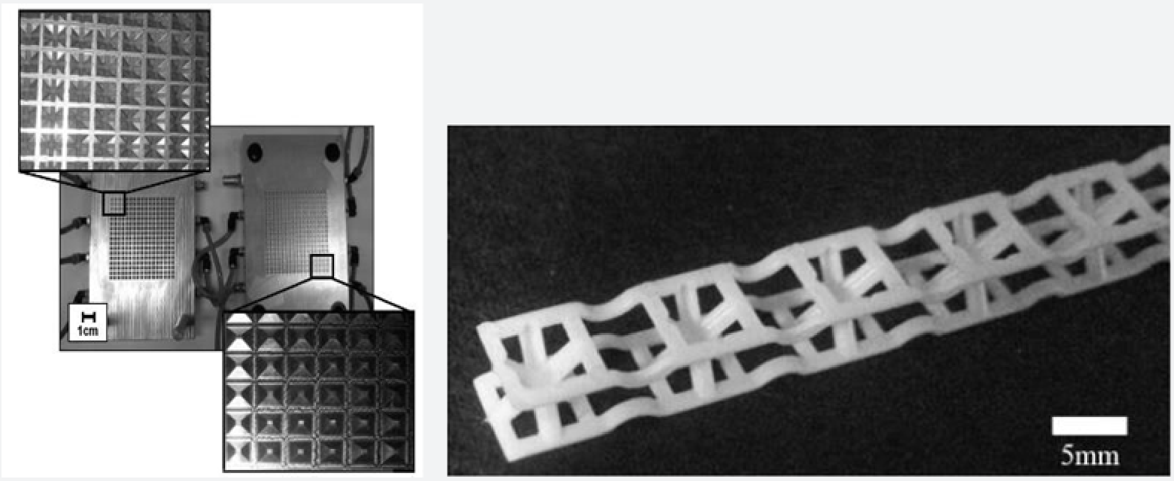


Figure 3: Concept of increment forming [1].



(a) Forming tools

(b) Polymer structure

Figur 4: Pyramidal kagome structure [11].

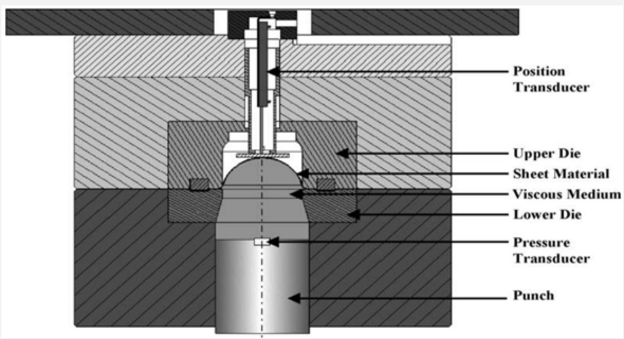


Figure 5: Viscous medium for bulge test [12].

Conclusion

This paper briefly reviews the plastic behavior of polymer materials and forming technologies as an application. To make more application of the plastic behavior, forming limit [13] and joining technologies [14] should be accounted. Because of the low cost and great availability, the demand of polymer is getting growing, and both fundamental and practical studies are required [15].

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