Materials and Design 98 (2016) 20–30

Contents lists available at ScienceDirect

Materials and Design

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

Influence of processing conditions on manufacturing polyamide parts by ultrasonic molding

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ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form 25 February 2016
Accepted 27 February 2016
Available online 3 March 2016

Keywords:
Ultrasound
Molding
Biomedical
Tensile test
Ultrasonic molding

ABSTRACT

Ultrasonic molding is a new manufacturing process for producing small and micro polymeric components where the material is plasticized using vibration energy. In small parts manufacturing, replicability is usually demanded. Downscaled tensile specimens were manufactured using ultrasonic molding on polyamide pellets not only to obtain specimens, but also to investigate the influence of the processing conditions on process performance and material characterization. A modeling approach is proposed to assess the energy flow involved in the process. It was observed that 300 mg of polyamide could be plasticized and injected in less than 3 s and the results showed a relationship between the processing conditions and the final product, i.e. the higher the values of applied pressure, ultrasonic time and vibration amplitude, the more accurate and more homogeneous parts were. Moreover, the material did not suffer chemical degradation, but light variation on the molecular weight and different chain alignment along the specimen were detected. The mechanical properties measured were slightly influenced by the processing conditions and were in accordance with what would be expected for that particular material when being processed using conventional injection molding.

1. Introduction

Product miniaturization is, nowadays, a consistent trend in industrial sectors where devices are becoming smaller and have more complex geometries. Some sectors experiencing an increase in this demand for micro products are information technology (IT) sector, the biomedical sector, the automotive industry, telecommunications and aerospace [1]. In some cases, these components have to be manufactured using sophisticated materials, which not only increases production costs, but also complicates the manufacturing process (e.g. reinforced materials or medical devices), resulting in cost per unit increases, especially if small series of these products are demanded.

Micro-injection molding (μIM) is a key technology for the mass-production of polymeric parts with micro-features [2,3]. Replicability, repeatability and high precision are guaranteed in this process. However, other processes such as hot embossing, reaction injection molding, injection compression molding, thermoforming or extrusion are also used to produce thermoplastic micro parts [4]. Now, a new technology called ultrasonic molding has appeared.

Ultrasonic molding is an innovative manufacturing process, which produces polymeric micro parts where the material is melted by the energy applied by ultrasonic vibration. This energy produces the polymer plasticization mainly via two mechanisms [5]: (i) the internal friction of the material, which is a factor related to material damping properties and (ii) the friction caused by the relative movement between the pellets. This combination increases the local temperature until the polymer melts.

The material is firstly placed in the plasticization chamber in the mold in solid pellet form. Then, the process starts and the sonotrode, which is the element that delivers the ultrasonic vibration to the material [6], starts to move until it reaches the material (Fig. 1a). At this point, it begins to vibrate as it continues its movement, causing the material to melt. Here, the sonotrode also acts as a plunger and forces the molten material to flow through the runners and fill the mold cavity. At the same time as the material melts, it is introduced into the mold cavity by the downward movement of the sonotrode. When the ultrasonic vibration stops, the sonotrode continues applying pressure to the material in order to pack it during the cooling stage (Fig. 1b). Finally, the sonotrode returns to its initial position, and the mold can be opened to extract the final part. Depending on the diameter of the sonotrode, the dimensions of the plasticization chamber and the power of the ultrasonic equipment, the amount of material that can be processed varies.

Ultrasound has been successfully used in the welding and riveting of polymeric components to produce neat bonding in a short time [7]. Ultrasonic energy is rapidly dissipated within the polymer causing local melting in the contact area. Taking advantage of this phenomenon,

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http://dx.doi.org/10.1016/j.matdes.2016.02.122
0264-1275/

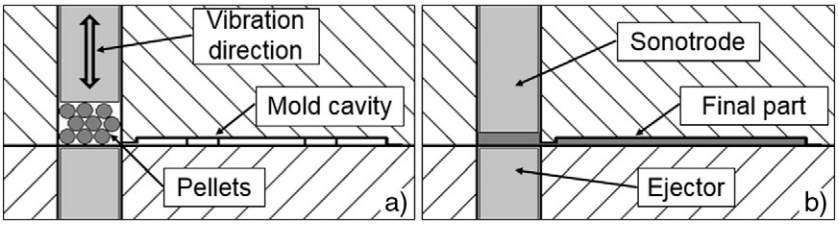

Fig. 1. Ultrasonic molding process representation: a) Start of the cycle, b) End of the cycle.

Michaeli et al. [7] proposed the use of ultrasonic energy to improve the plasticizing efficiency in micro injection molding processes. A very small amount of material was plasticized in an ultrasonic prototype set, thus obtaining a homogeneous material structure. Later, Michaeli and Opfermann [8] adapted the acoustic unit and the mold cavity of a conventional ultrasonic welding press to study the potential of ultrasonic plasticization. From preliminary experiments, they found that less than 3 s were needed to melt 500 mg of polyoxymethylene (POM) and obtain a homogeneous structure. Moreover, they found a relationship between vibration amplitude and plasticizing time, which would avoid polymer degradation. Next, instead of pellets they used disc shapes taken from a plastic sheet as rough material and the melt generated during the plasticizing process was pushed by the sonotrode into a mold cavity of micro-disc shapes. The part quality was poor due to the low injection pressure and the missing holding pressure in the set-up developed. Afterwards, Michaeli and Kamps [9] analyzed the effect of vibration amplitude and ultrasonic time on the amount of energy applied to the polymer. They recorded a temperature distribution along the lateral surface of a 2 mm solid polycarbonate (PC) cylinder in order to avoid the effect of pellet friction. They found that by using higher amplitudes, higher heating rates were achieved, and they were able to reach maximum values of 800 °C/s of material heating. Later on, Michaeli et al. [5] studied the ability of ultrasonic energy to process micro parts using different materials (polypropylene (PP) and POM), and the effect of the process parameters on the weight and the morphology of the resulting parts. They found that the vibration amplitude and compression force had little effect on the weight of the part, whereas the amplitude did affect the molten material. This was established with microscope images that revealed the presence of non-molten parts when lower energy was applied. Flow lines were observed in PP specimens, probably caused by a melting temperature being reached that was too low. Jiang et al. [10] studied the effect of ultrasonic voltage and pressure on the plasticization speed of the polymer and observed that for higher values of those parameters, higher plasticization speed was obtained. The ultrasonic voltage determines the amount of energy supplied to the material, resulting in higher plasticization speed. However, pressure influence was weak due to the reduction of ultrasonic cavitation effect, reducing the amount of bubbles formed in the liquid, caused by pressure variations, which then collapses and releases heat energy. Recently, in 2014, Sacristán et al. [11] used ultrasonic energy to produce polylactide (PLA) samples. Varying vibration amplitude and applied pressure, they found that higher levels of both parameters lead to material degradation, while samples presented material inhomogeneity when lower values were set. A relationship between the processing parameters was required to obtain homogeneous specimens. Planellas et al. [12] produced PLA and polybutylene succinate (PBS) micro parts by means of ultrasonic molding, and they found that there was no significant molecular degradation when the process parameters (ultrasonic time, amplitude and injection force) were optimized. Negre et al. [13] presented a study of the effect of the melting velocity and vibration time over part weight and dimensions. They found that three seconds of vibration energy were necessary to melt and inject 0.3 g of PP. A variation of porosity and homogeneity along the specimen were detected.

In reality, little research has been carried out on this technology, and most of it provides general views about the effect of the main process parameters, such as pressure or amplitude, on the plasticizing process and polymer temperature. However, as an emerging technology, ultrasonic molding faces many challenges such as difficulties in microcavity filling, dimensional accuracy, mechanical properties characterization, and microstructure analysis of micro products. The aim of this paper is to provide a preliminary study of the influence of the process parameters of ultrasonic molding on the part filling, dimensional accuracy and mechanical properties, not yet researched in the literature. Moreover, the homogeneity of the parts obtained and the polymer degradation were evaluated using different techniques. Finally, an energy balance, which considers the theoretical dissipated energy, the energy provided by the process, and the energy required to melt the material, is proposed. The biomedical material, polyamide (PA12), was used in this study.

2. Mathematical modeling of the ultrasonic energy balance

The mathematical modeling approach proposed in this investigation is based on the fundamentals of acoustic/ultrasound energy. In terms of the process, it is considered the dissipated energy resulting from oscillation movement and the movement of the sonotrode. Whereas, in terms of the material, the theoretical melting energy required is also included.

According to Rienstra and Hirschberg [14], the equation that describes the acoustic energy of a homentropic flow is given as:

$$\frac{\partial}{\partial t}\left(\rho e+\frac{1}{2}\rho v^2\right)+\nabla\cdot\left(\mathbf{v}\left\{\rho e+\frac{1}{2}\rho v^2+p\right\}\right) = -\nabla\cdot\mathbf{q}+\nabla\cdot(\boldsymbol{\tau}\cdot\mathbf{v})+\mathbf{f}\cdot\mathbf{v}, \tag{1}$$

where ρ is the density of material, e is the internal energy per unit mass, $\mathbf{q}$ is the heat flux resulting from the heat conduction, $\boldsymbol{v}$ is the material's flow velocity, $\mathbf{f}$ is the external force density, p is the pressure, $\boldsymbol{\tau}$ is the viscous stress tensor, and ∇ is the symbol representing the gradient operator. The $\mathbf{q}$ flux comes from the viscous effects of the material and becomes important because the pulsation of the applied sonotrode load is related to the resistance entanglement molecular forces [15,16] and has physical and chemical effects on the polymer melt that influence the apparent polymer viscosity and the melt molecular weight, respectively [17]. Furthermore, applying acoustic energy to a polymeric material produces a melt that is considered a non-Newtonian fluid [18] and then the density fluctuations in the material are assumed to be small [14]. Thus, the total polymeric melt energy density is given as:

$$E_{tot}=\rho e+\frac{1}{2}\rho v^2. \tag{2}$$

When the ultrasonic energy propagates in the fluid thorough oscillatory waves, the vibration energy per unit area is known as the fluid energy flux intensity, which is given as:

$$\mathbf{I}_{tot}=\mathbf{v}\left(\rho e+\frac{1}{2}\rho v^2+p\right). \tag{3}$$