Journal of Materials Processing Technology 229 (2016) 687–696

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Assessing a stepped sonotrode in ultrasonic molding technology

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ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form
24 September 2015
Accepted 19 October 2015
Available online 26 October 2015

Keywords:
Sonotrode design
Ultrasonic molding
Wear
Modal analysis
Microinjection

ABSTRACT

Ultrasonic molding is a new technology used to process polymeric micro-molded parts. An ultrasonic horn, or sonotrode, transmits ultrasonic energy which melts the material and pushes it into a mold cavity to configure a shape. Sonotrode design – and any transformations to the dimensions or shape caused by tool wear – strongly affects efficient operation. The sonotrode may go beyond the generator operating frequency range, thus affecting process performance. This paper assesses two issues involving a stepped sonotrode employed in ultrasonic molding: (i) a design procedure that can predict the sonotode's behavior during the molding process and (ii) a method for creating a sonotrode operating frequencies map which will facilitate the design of new sonotrodes and be able to determine the extent to which they can be re-machined after a certain period of wear. Numerical simulations carried out by finite element methods were compared to experimental measurements performed to capture the sonotrode frequency vibrational modes. A frequency map provides the dimensional range within which the sonotrode can be re-machined in order to eliminate tool wear and allow the sonotrode to work properly again, thus extending the lifecycle of the tool.

1. Introduction

Ultrasonic energy is currently being used to manufacture various components (Sackmann et al., 2015) with processes such as ultrasonic welding (Rani and Rudramoorthy, 2013) and ultrasonic machining (Singh and Khamba, 2006). It is also used to assist during the manufacturing process such as, for example, in ultrasonic-assisted EDM (Liew et al., 2014), ultrasonic-assisted machining (Tabatabaei et al., 2013) and ultrasonic assisted injection molding (Yang et al., 2014). According to Michaeli and Opfermann (2006), technologies based on ultrasound are also becoming an attractive alternative that can improve the micro injection process for obtaining micro parts weighing less than 10 mg.

Ultrasonic molding is a new technology for processing polymeric materials, using ultrasonic vibration energy to melt the material and fill the mold cavity. In this process the plastic pellets are introduced directly inside the plasticization chamber and the material melts due to the ultrasonic energy applied by the sonotrode. The sonotrode also acts as a plunger, pushing the molten material inside the mold cavity. This process is divided into four stages, as illustrated in Fig. 1. First, the pellets are introduced into the plasticization chamber (Fig. 1(a)). Then, the sonotrode is introduced until the tip reaches the pellets (Fig. 1(b)). Next, the sonotrode starts to vibrate and move down applying compression force to the pellets (Fig. 1(c)). According to Michaeli et al. (2011), the pellets melt because the sonotrode vibrational energy increases their internal heat and the friction between them. The molten material starts to flow through the runners inside the mold cavity. When the mold cavity is filled up, the sonotrode remains in its final position to maintain the pressure during the material cooling stage (Fig. 1(d)). Finally, the sonotrode returns to its initial position and the mold is opened to extract the molded part.

Michaeli et al. (2002) carried out pioneering tests using ultrasonic energy rather than common heat energy to increase the efficiency when plasticizing small amounts of polymeric materials. They subsequently showed the feasibility of ultrasonic plasticizing of polymeric materials in different micro parts of Polypropylene (PP) and Polyoxymethylene (POM) using a conical sonotrode working at 20,000 Hz (Michaeli and Opfermann, 2006). The results

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http://dx.doi.org/10.1016/j.jmatprotec.2015.10.023
0924-0136/

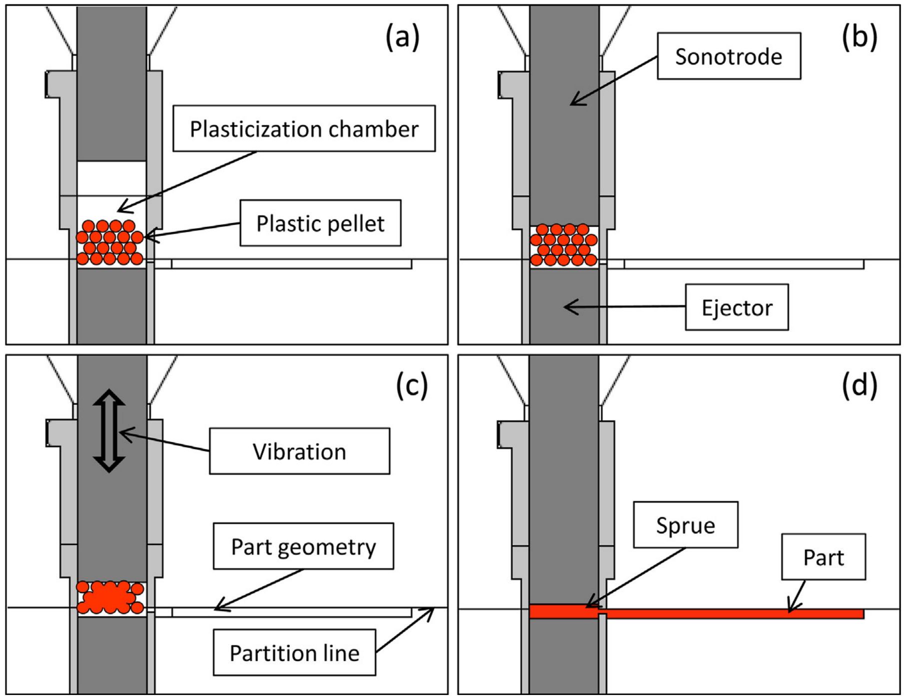

Fig. 1. Phases of the ultrasonic molding process: (a) feeding, (b) vibration initiation, (c) plasticization and cavity filling and (d) packing and cooling.

presented showed the potential use of ultrasonic energy as an alternative to conventional processes.

Ultrasonic energy is also used to assist injection molding process during the filling and packing stages. In that case, a conventional machine is used to inject the molten material into a mold cavity and next a sonotrode included in this cavity provides ultrasonic vibration to the final part before the molten material is solidified to improve the part properties. Yang et al. (2014) used a 45 mm diameter horn, vibrating at 20,000 Hz with and 15 microns of amplitude to investigate the influence of the vibration energy when processing polycarbonate flat specimens. Results showed an improvement of the filling efficiency, because the melt temperature could be maintained higher than in conventional injection molding during the filling stage. Sato et al. (2009) used a 19,000 Hz and 11 microns of amplitude acoustic equipment to process polycarbonate parts. They found that ultrasonic vibration enhanced the replication capabilities of the process, in particular, the weight was increased and surface roughness was improved.

In ultrasonic molding technology, the ultrasonic energy melts the entire material and, at the same time, the sonotrode pushes it into the mold cavity (Fig. 1(c) and (d)), which differs completely of assisted injection molding process. Ultrasion S.L. (Sirera et al., 2012) implemented this technology industrially with a machine called Sonorus 1G, obtaining successful results on process efficiency and reduced energy consumption compared to conventional processes of micropart production. Thus far, stepped sonotrodes have been used in Sonous 1G. Recently, Sacristán et al. (2014) and Planellas et al. (2014) studied the effects of ultrasonic vibration on the material properties of micro-parts processed by an ultrasonic molding machine. In both cases, a 1000 W and 30,000 Hz ultrasonic generator coupled with a titanium alloy stepped sonotrode was used to melt the polymer pellets. They found that part morphology was highly dependent on processing conditions, as well as on the combination of process parameters required for Polylactide (PLA) and Polybutylene Succinate (PBS) material.

In this ultrasonic molding machine configuration (Sonorus 1G), the sonotrode has to be designed to vibrate in longitudinal mode (at a frequency determined by the generator). Otherwise, the sonotrode may collide with the plasticization chamber producing undesirable effects, such as deformation or cracks. Moreover it acts as a plunger and must be able to support all the forces and the heat generated during the melting process. The friction and the high temperatures can damage the sonotrode, wearing it down and altering the material properties; this can lead to the sonotrode frequency moving beyond the generator's vibration frequency range. This paper focuses on two issues concerning the sonotrode: (a) a design procedure to meet all the machine requirements, and (b) an analysis of the sonotrode life cycle from the point of view of wear.

The most commonly-used shapes in the design of sonotrodes are: cylindrical, tapered, stepped, exponential, conical and catenoidal. The German Electrical Manufacturers Association (1980) provides some theoretical and empirical equations to design and calculate preliminary dimensions of stepped and conical sonotrodes according to the required operating frequency and the material used. Nanu et al. (2011) presented a theoretical approach to design and simulate a stepped sonotrode used for ultrasonic assisted EDM with a copper electrode on the tip. They used simplified equations based exclusively on the material properties to calculate the sonotrode dimensions to vibrate at 20,000 Hz and then performed a FEM (finite element methods) analysis to determine the variation of sonotrode frequency regarding theoretical geometric variations. Their results showed that the frequency increases when the sonotrode mass decreases. Nad (2010) analyzed several sonotrode shapes (cylindrical, tapered, exponential and stepped) for ultrasonic machining technologies and characterized them by FEM to determine the resonance frequency and the transformation ratio. He found that the value of resonance frequency and the transformation ratio of a sonotrode are essential parameters for selecting suitable shapes which, in turn, are strongly related to the technological process under consideration. Wang et al. (2011) designed a new sonotrode to optimize the displacement amplification based on a cubic Bézier profile. They used a multi-objective optimization algorithm and a FEM analysis procedure to design it. Furthermore, they manufactured cylindrical Bézier sonotrode prototypes and compared their proposed design to experimental results using photonic sensors. The results were also compared to a catenoidal shape