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Incremental forming of polycarbonate sheets

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ABSTRACT

The influence of the contact conditions at the tool-workpiece interface and the toolpath strategy on the quality of incremental formed parts made by polycarbonate sheets is investigated. To this end, different experimental tests were conducted involving different tool types (with fixed and rotating end) and toolpaths (unidirectional and alternate), to determine their influence on the material formability, twisting, elastic springback, forming forces, sheet thinning and surface roughness. The alternate toolpath enabled achieving the highest formability and minimum twisting, as compared to that observed when the unidirectional toolpath was used. On the other hand, the adoption of the tool with fixed end enabled reducing the springback, while the tool type showed negligible influence on the other quality parameters.

1. Introduction

Incremental Sheet Forming (ISF) is a technology applied to obtain small batches and customized functional parts or prototypes, either of full or scale size, for which specialized tooling and dies are not required (Lozano-Sánchez et al., 2017). Indeed, the process is based on the interaction of a tool, with a simple geometry (generally hemispherical tools are adopted) and small dimensions as compared to the geometry to produce, with the surface of the sheet with the edges clamped to a fixed frame.

A non deterministic intelligent ISF process can be performed by indicating the designed shape, the dimensional tolerance, etc. to a CNC controller, in order to manufacture the correct workpiece within the given constraints. This digitalization in manufacturing is in keeping with one of the main goals expressed by Industry 4.0 and which consists in connecting multiple devices, machines, sensors and people to perform process monitoring, adaptation as well as optimization. The concept of Industry 4.0 is connected with smart industries and particularly with the flexibility of the manufacturing cell, where the integration of sensors for the on-line monitoring of, among other things, the forces as well as the current geometry (for plastic deformation) or the tool wear can allow the automatic correction of the input parameters during the process.

A wide application of ISF for production of metal parts can be found in automotive, aeronautic but also in fields that require a technology capable of producing highly customized unique parts in a short time (Duflou et al., 2013) and at a reasonable cost, like in biomedical field (Araújo et al., 2013). In addition, ISF has been extended to polymeric materials where ISF is attracting a growing interest (Martins et al., 2009). Nevertheless, polymers show a different behaviour as compared to metals; thus, much larger amount of work is still required to fully understand the behaviour of these materials during ISF and the influence of the most common process parameters on quality of formed parts. Three mechanisms of failure were observed (Franzen et al., 2009) in polymer sheets processed by ISF:

- Mode 1 – Sheet fracture by ductile tearing along the circumferential direction, at the transition region between the wall and the corner radius of formed parts;
- Mode 2 – Wrinkling of the sheet along the wall of the part;
- Mode 3 – Tearing of the sheet in the radial direction, along the wall of the part.

In addition, the formability is limited by the development of wrinkles along the inclined wall of ISF parts. The wrinkles are twisted about the axis of revolution in the direction of tool rotation and are triggered in the region of the inclined wall close to the corner radius.

Besides these failure modes, twisting may also affect the quality of polymer parts made by ISF. This phenomenon is due to an uncontrolled pivoting of the workpiece around the support structure as a result of tangential forces exerted by the tool, which induces in-plane shear into the workpiece. Twisting has been also observed when dealing with metallic sheets; for example, twist angles of 5.6° were measured for axisymmetric components obtained by single point incremental forming (SPIF) of AA5052H19 sheets (Formisano et al., 2017a). Accumulating twist could be prevented by alternating the toolpath direction

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(Jeswiet et al., 2005).

In a conventional polymer sheet manufacturing process such as compression moulding, relatively high temperatures are required for sheet forming, in order to avoid the concentration of strain determining the fracture of the sheet. On the other hand, a localized deformation enables the forming of polymeric sheets under room temperature during ISF with significant reduction of the energy absorbed during the process. This was highlighted for the SPIF of different commercial thermoplastics, with structures varying from high-crystalline (polyethylene terephthalate) to amorphous (polycarbonate), (Marques et al., 2012). However, the local heating, due to the simple friction developed in the contact between the sheet and the tool, could favourite the formability and the reduction of the forming forces and springback, as reported in (Xu et al., 2013). Nevertheless, the temperature control is very difficult because it is influenced by many parameters: sheet thickness, vertical step, tool diameter, spindle speed, feed rate and wall angle (Wang et al., 2016). Moreover, the increase in temperature results in higher surface roughness for polymeric sheets (Bagudanch et al., 2014), leading to lower product quality.

Previous studies on the incremental forming of polymeric sheets were mainly focused on determining the effect of the process parameters on a limited number of aspects. On the contrary, this work is aimed at investigating more comprehensively the influence of the tool type and the toolpath strategy on several quality factors including: formability, forming forces, twisting, springback, sheet thinning and surface roughness as well as the forming forces. To this end, an experimental investigation of incremental forming process of polycarbonate thin sheets (less than 2 mm in thickness), under room temperature was conducted.

2. Materials and methods

Thin PC sheets, 1.90 mm thick supplied by Bayer, were used in this study. PC is characterized by high heat distortion temperature, good electrical insulation characteristics, excellent transparency, high toughness (with an elongation at rupture higher than 100%) and a relatively high tensile strength; this material is mainly used for optical/lighting, glass replacement, medical packaging, electrical products, automotive engineering, household products and safety applications (Kyriacos, 2017).

The main quasi-static mechanical properties of the material, which were determined in a previous study (Lambiase et al., 2015), are: Yield stress $\sigma_s = 60$ MPa, Young's modulus $E = 2.3$ GPa and maximum elongation $\varepsilon_{MAX} = 110\%$.

SPIF tests were conducted at room temperature by means of C.B. Ferrari high speed four-axis vertical machining centre. Although Davarpanah et al. (2016) highlighted the advantages of double sided incremental forming over SPIF in terms of formability and geometrical accuracy, SPIF was chosen as this technique combines a rather simple mechanical setup with a low-cost experimental apparatus. A square clamping frame with a free edge of 100 mm was used and all the tests were conducted with a constant feed rate of 3000 mm/min. Three replicates were conducted for each forming condition. A three-axis Kistler 9257A piezoelectric transducer was used to measure the vertical and one horizontal component of the forces acting on the tool during the SPIF processes; the data were acquired at 2000 Hz and subsequently filtered by means of a NI 9239 input module and the VBA 1.0 B software.

Two different tools, mounted on the mandrel of the CNC machine, were used to determine the influence of the friction developing at the tool-workpiece interface: a punch with a spherical fixed end (Fig. 1a) and a punch with a rotating end (a ball, Fig. 1b), both made of steel and with 10 mm in diameter. In addition, when the fixed tool was used, the workpiece was initially immersed in oil, in order to reduce friction and sticking effect at the tool-workpiece interface and, consequently, the risk of failure.

The effect of the toolpath strategy was also investigated; to this end, both unidirectional (UTP, described in anticlockwise direction) and alternate spiral toolpaths (ATP, with alternating the spirals in anticlockwise and clockwise directions), as schematized in Fig. 1c–e, were analyzed. The experimental setup of a SPIF process is shown in Fig. 2.

The formability of the PC sheets was investigated with varying wall angle conical frusta (VWACF) according to the study performed in (Hussain et al., 2007) and pyramid frusta (VWAPF) tests, as represented schematically in Fig. 3a–c. Although both shapes are widely employed for such a purpose, the VWAPF test introduces a geometrical singularity that could further stress the material formability. Each test was stopped as soon as the workpiece failed, and the corresponding angle was determined.

Beyond the formability issue, the influence of the tool type and the toolpath strategy on the forming forces, roughness, elastic springback, sheet thinning and twisting was assessed by forming pyramid frusta with a constant wall angle of 60° (Fig. 3d–e).

The twist angle was evaluated by measuring the rotation of the bottom flat surface of the pyramid with respect to the original position. To this end, the sheets were marked by cross lines (orthogonal to the clamping edges) before each test. On the other hand, the elastic springback was measured at the end of the SPIF process by moving up the tool with steps of 0.05 mm until the vertical force measurement zeroed. Thus, the springback was determined for the last portion of the sheet in contact with the tool and calculated as the difference between the two vertical coordinates of the tool.

An angular step of 1° and a vertical step of 1 mm were chosen for the varying wall angle geometries and the pyramids with constant wall angle, respectively.

The roughness was examined to control the quality of the contact between the tool and the workpiece and to verify the validity of the process with absence of deep groove. Surface analysis was conducted through the evaluation of the mean roughness (R_a), measured along the cross section of the workpiece by means of a Rugosimeter Surftest SJ-301 with differential inductance used as the detecting method and with Gaussian filter. The measurements were performed according to ISO 4288-1996 standard relatively to the recommended cut-off values; ten measurements were recorded for each case, divided equally over two contiguous internal faces of the pyramid frusta to avoid casual errors produced by any anisotropic behaviour in terms of sheet roughness.

Cross sections of the final geometries of the workpieces were made by means of a lubricated abrasive cutting machine and then polished with abrasive paper up to 1200 grit, to investigate the influence of the selected process parameters on the final geometry and wall thickness of the workpiece. The cross sections were acquired by means of optical microscopes model DMI5000M by LEICA and stereoscope model STEMI DV4 by Zeiss equipped with a DSLR camera model D5200 by Nikon. Ten measurements of thickness were recorded for each case, corresponding to equidistant locations along the whole length of the wall (about 45 mm).

3. Results and discussion

3.1. Formability

The macrographs of the workpieces after the formability tests are reported in Fig. 4. Unlike ISF of metal sheets, for which the failure develops along a circumference going on the toolpath for the cones and affects only the edges for the pyramids (Capece Minutolo et al., 2007), after the onset of a fracture on the PC sheet, the crack immediately propagates in the direction opposite to the tool displacement, typical of the failure mode 3. This behaviour was observed on all the specimens regardless the tool type and toolpath strategy.

The values of formability angles from the two different tests are reported in Fig. 5. According to the achieved results, ATP enables reaching high formability angles (up to 87.5°) for the components