A numerical approach to optimize the toolpath strategy for polymers forming

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Abstract. Incremental sheet forming is a relatively new technology with a deformation strategy that resembles the layered manufacturing principle of rapid prototyping; thanks to this, it can represent a viable way to form metal and polymer sheets, guaranteeing high customization and cost-effectiveness. On the other hand, and particularly when considering thermoplastic sheets, the components obtained by this process suffer from peculiar defects like, for example, twisting and wrinkling. A way of reducing the risk of such defects is to optimize the toolpath strategy to lower in-plane forming forces. To pursue this aim, the present work follows a numerical approach; a commercial FE code was used to simulate the incremental forming of polycarbonate sheets by varying the toolpath strategy. The investigation of some features like the forming forces and the deformation states was carried out, with the goal of determining an optimized toolpath strategy for the reduction of the incremental forming forces and the consequent expectation of reduced risk of failures and defects for incremental formed polymer sheets.

Introduction

The interest in the incremental sheet forming (ISF) of thermoplastic polymers has been experiencing a significant increase over the past few years since these important materials can be engineered to reach high specific strength and stiffness values, and the ISF technology guarantees high customization. The products manufactured with this process can cover many fields of application; for example, they are largely considered for aerospace and unmanned aerial vehicles, so as for racing and commercial cars [1], and several applications have been also found in the biomedical sector [2].

When formed by ISF, the polymer sheets (but not only) can suffer from failures and undesired deformation phenomena like, for example, twisting and wrinkling. The first one occurs as the effect of an uncontrolled twist of the sheets with respect to the clamping frame and it is caused by the in-plane shear that, in turn, is generated by the tangential component of the forming forces. The authors, in previous works, observed and quantified this phenomenon both for metal [3] and polycarbonate sheets [4], and the last ones, in the case of axisymmetric components obtained by a unidirectional toolpath, showed very high twisting angles (about 22°) if compared to the corresponding ones on metal sheets (less than 6°). On the other hand, they also observed a dramatic reduction of the twisting angle when adopting an alternate toolpath. All the same, severe forming conditions in terms of sliding forces on thin sheets of not particularly resistant materials like thermoplastics can determine the occurrence of wrinkling [5].

However, the attempt to reduce the sliding forces between the tool and the sheet can also be made for further different aims like, for example, to limit the global forming forces, to reduce the risk of failures of the forming tool and of the sheets, and to improve the surface quality of the incrementally formed parts; in addition, it could be possible to reduce the use of lubricants employed to lower friction and sticking of material to the tool.

Considering the above, this work aims to follow a numerical approach for the optimization of the toolpath strategy applied to the incremental forming of polycarbonate sheets, to reduce the forming forces and, with it, reduce the risk of failures and defects. To do this, the manufacture of cone frusta with fixed wall angle by varying the toolpath strategy was simulated by a commercial FE code; from the results of the simulations, some outputs were investigated, like the forming forces and the stress-strain states.

Materials and Methods

The manufacture of cone frusta with a fixed wall angle was simulated by means of the FE commercial code LS DYNA; the goodness-of-fit of the numerical model was evaluated in a previous authors' work [6] on the occurrence of wrinkling when thin polycarbonate sheets were worked by incremental forming.

Polycarbonate sheets with a thickness of 1.5 mm were considered; besides, the forming tool had a hemispherical head, 10 mm in diameter. The main geometrical features of the cone frusta are highlighted in Fig. 1; in particular, α represents the wall angle, h the height and R the radius of the major base.

The sheet and the tool (only its hemispherical head) were modeled, whereas the effects of the blank holder were simulated by setting fixed constraints to the nodes of the sheet periphery (a square of 100 mm × 100 mm in dimensions).

The elements of the sheet are fully integrated shells with five integration points through the thickness and a mean dimension of 1.41 mm. The material model was the MAT PLASTICITY POLYMER. For the tool head, Belytschko-Tsay shell elements with two integration points through the thickness and a mean dimension of 0.2 mm were used, while the MAT RIGID model was chosen, setting typical properties of the steel.

The main materials' properties are summarized in Table 1.

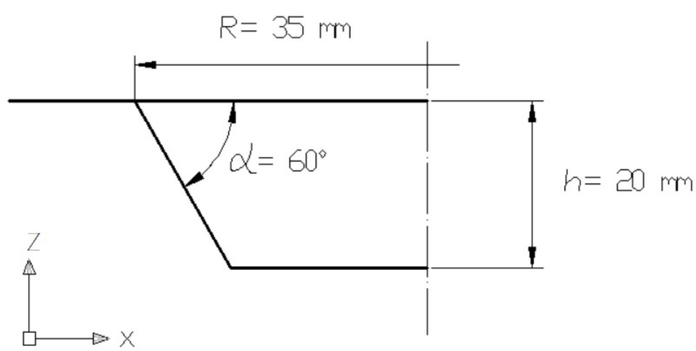

Fig. 1. Geometrical features of the cone frusta.

Table 1. Main materials' properties.

Material	Density [g/cm^3]	Young's modulus [GPa]	Poisson's ratio [-]	Yield stress [MPa]	Ultimate elongation [%]
Polycarbonate (sheet)	1.2	2.3	0.3	60	110
Steel (tool)	7.85	210	0.3	-	-

The SURFACE TO SURFACE contact card was selected for the tool/sheet interaction (consider that for this kind of test the sheets can be lubricated with mineral oil for cold forming to reduce friction and sticking of material to the tool and then, to avoid the risk of damages) and x, y, and z displacement laws were set in the BOUNDARY PRESCRIBED MOTION card to impose the tool movement (feed rate of the forming tool V_f=1000 mm/min).

Finally, the run time of the simulations was notably decreased, using mass scaling [3].

Different paths of the forming tool were considered to impress the deformation to the sheet with which comes in contact on points of a spiral path; in particular, the points were equally spaced around θ=6° from each other and the vertical step (*vs*, the vertical distance between two consecutive spirals) was equal to 1 mm (see Fig. 2; five exemplary consecutive points, from A to E, are reported).

Three solutions, reported in a not-to-scale schematization in Fig. 3, were chosen to cover the distance between two consecutive points: in particular, describing:

- one segment;
- a horizontal and a vertical segment;
- an upward (where H_r represents the ramp height) and a vertical segment.

These three typologies are labeled std_tp (standard toolpath), Hr0_tp and Hr1_tp, respectively.

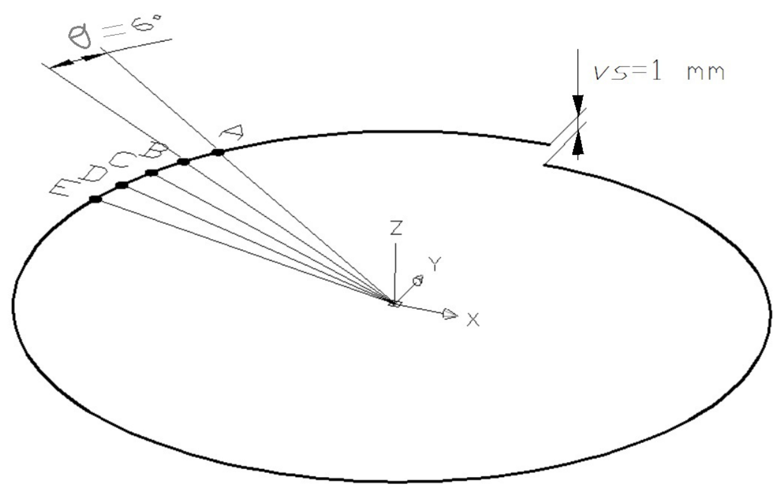

Fig. 2. Details of the spiral path.

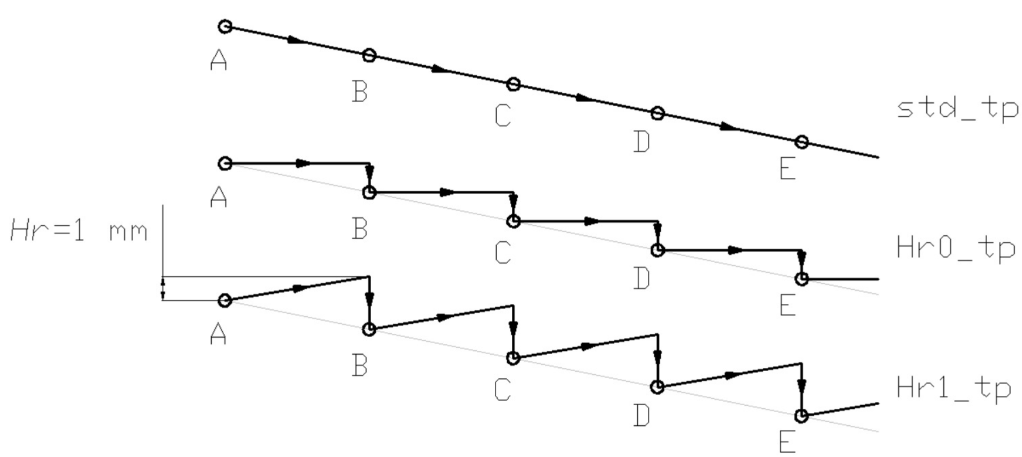

Fig. 3. Toolpath strategies.

Results

Fig. 4 shows an example of FE simulation of the ISF process for the Hr1_tp strategy; in particular, it is possible to observe the deformed sheet and the tool head for a z displacement of about 15 mm.

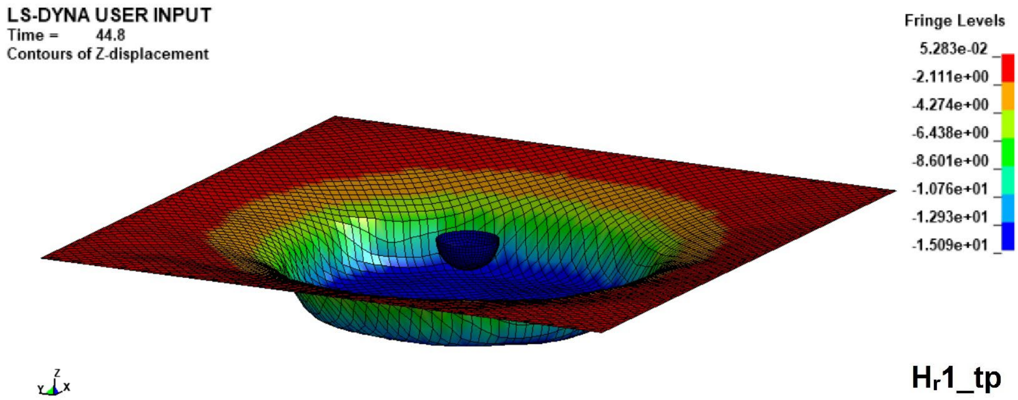

Fig. 4. FE simulation of the ISF process for the Hr1_tp strategy.

Fig. 5 reports the trend of the vertical (F_Z) and of one only horizontal force (F_X) for the different toolpath strategies. It is possible to note that the forces for the first two strategies show the typical trend for the manufacture of cone frusta by ISF with a spiral toolpath [5,7].

Moreover, they are similar, with very slightly lower values for the Hr0_tp compared to the std_tp; in detail, the maximum values of F_Z and F_X (in absolute terms) are of about 400 N and 300 N. This behaviour is an effect of the elastic springback that, despite being lower for the second toolpath, determines a significant tool/sheet contact and, consequently, high forming forces [8].

The third strategy allows a very significant reduction of both the components of the forming forces; F_Z lies below 200 N, while the absolute value of F_X does not exceed 50 N

In addition, the reduced regularity of the forces trend is representative of a noncontinuous contact between the tool and the sheet. On the other hand, the forming time for this last strategy increases, passing from about 40 s of the first two strategies to about 55 s, due to the increase of the length of the toolpath.

Moreover, Fig. 6 reports the max shear strain for three consecutive forming steps related to the std_tp and the Hr1_tp strategy. The figure highlights that the std_tp strategy determines strain accumulation on a large area of the sheet and in an asymmetric way, following the tool movement; this is not so true for the Hr1_tp strategy, which shows a more localized deformation and reduced shells distortion.

By considering the results on the forming forces from Fig. 5 and that the twisting is caused by the combination of continued strain accumulation and asymmetric stress levels [9,10], it can be assumed that the twisting can be reduced with the Hr1_tp strategy.

Finally, despite not being capable of predicting accurately wrinkling (the numerical model does not include wrinkle instability criteria), the results of the simulations let suppose that the occurrence of this defect is less likely for the Hr1_tp strategy.

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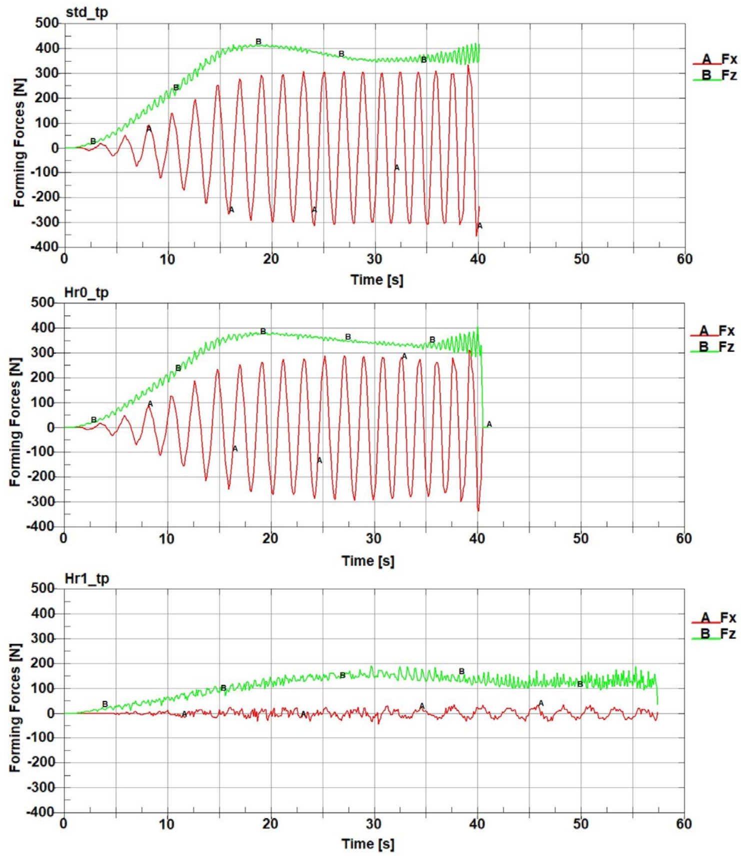

Fig. 5. Trend of the forming forces by varying the toolpath strategy.

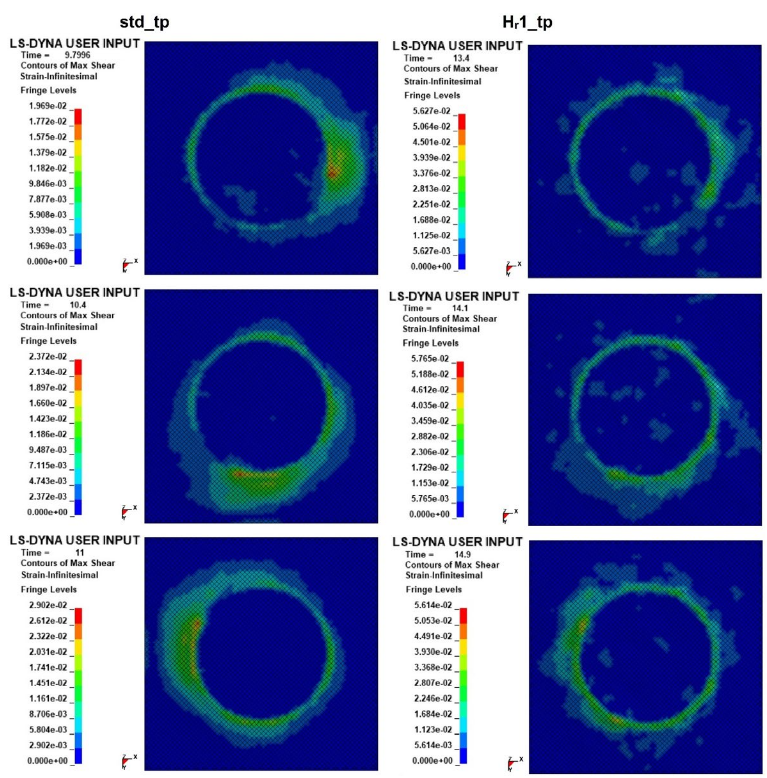

Fig. 6. Max shear strain distribution for std_tp and H_r1_tp strategy.

Summary

In the present work, a commercial FE code was used for the simulation of the incremental sheet forming of polycarbonate, with the aim of investigating different toolpath strategies. From the analysis of the results in terms of forces and strain states, it can be concluded that a stepped path, constituted by a sequence of upward and vertical segments, while showing higher forming times, can reduce drastically both the vertical and the in-plane forming forces, as well as the severity of the deformation states. Consequently, this may involve reduced risk of failures and defects like twisting and wrinkling.

Future works can focus on extending the numerical investigation by considering, for example, different forming tool shapes, and carrying out an experimental campaign for estimating what expected from the numerical analyses, in particular the reduction of the forming forces and of the twisting defect.

References

[1] M. Hassan, G. Hussain, H. Wei, A. Qadeer, M. Alkahtani, Progress on Single-Point Incremental Forming of Polymers, Int. J. Adv. Manuf. Technol. 114 (2021) 1-26. https://doi.org/10.1007/S00170-021-06620-7

[2] G. Centeno, I. Bagudanch, D. Morales-Palma, M.L. García-Romeu, B. Gonzalez-Perez-Somarriba, A.J. Martinez-Donaire, L.M. Gonzalez-Perez, C. Vallellano, Recent Approaches for the Manufacturing of Polymeric Cranial Prostheses by Incremental Sheet Forming, Procedia Eng. 183 (2017) 180-187. https://doi.org/10.1016/J.PROENG.2017.04.059

[3] A. Formisano, L. Boccarusso, F. Capece Minutolo, L. Carrino, M Durante, A. Langella, Negative and Positive Incremental Forming: Comparison by Geometrical, Experimental and FEM Considerations, Mater. Manuf. Process. 32 (2017) 530-536. https://doi.org/10.1080/10426914.2016.1232810

[4] M. Durante, A. Formisano, F. Lambiase, Incremental Forming of Polycarbonate Sheets, J. Mater. Process. Technol. 253 (2018) 57-63. http://doi.org/10.1016/j.jmatprotec.2017.11.005

[5] M. Durante, A. Formisano, F. Lambiase, Formability of Polycarbonate Sheets in Single-Point Incremental Forming, Int. J. Adv. Manuf. Technol. 102 (2019) 2049-2062. https://doi.org/10.1007/s00170-019-03298-w

[6] A. Formisano, M. Durante, A Numerical-Experimental Investigation on the Wrinkling Defect in Incremental Forming of Thin Polycarbonate Sheets, Int. Rev. Model. Simul. 12 (2019) 206-211. https://doi.org/10.15866/iremos.v12i4.17614

[7] N. Rosca, T. Trzepieciński, V. Oleksik, Minimizing the Forces in the Single Point Incremental Forming Process of Polymeric Materials Using Taguchi Design of Experiments and Analysis of Variance, Materials 15 (2022) 6453. https://doi.org/10.3390/ma15186453

[8] H. Wei, L. Zhou, B. Heidarshenas, I.K. Ashraf, C. Han, Investigation on the Influence of Springback on Precision of Symmetric-Cone-Like Parts in Sheet Metal Incremental Forming Process, Int. J. Light. Mater. Manuf. 2 (2019) 140-145. https://doi.org/10.1016/j.ijlmm.2019.05.002

[9] Z. Chang, J. Chen, Mechanism of the Twisting in Incremental Sheet Forming Process, J. Mater. Process. Technol. 276 (2020) 116396. https://doi.org/10.1016/j.jmatprotec.2019.116396

[10] J.R. Duflou, H. Vanhove, J. Verbert, J. Gu, I. Vasilakos, P. Eyckens, Twist Revisited: Twist Phenomena in Single Point Incremental Forming, CIRP Ann. Manuf. Technol. 59 (2010) 307-310. https://doi.org/10.1016/j.cirp.2010.03.018