Material Forming - ESAFORM 2024 Materials Research Forum LLC
Materials Research Proceedings 41 (2024) 2383-2389 https://doi.org/10.21741/9781644903131-262

Experimental evidence on the twisting of incrementally formed polymer sheets by varying the toolpath strategy

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Keywords: Incremental Forming, Polycarbonate, Toolpath Strategy, Forming Forces

Abstract. In recent years, polymer sheets have been formed by a relatively innovative technology, born for metals and in line with the layered manufacturing principle of rapid prototyping, the incremental sheet forming. This process guarantees high customization and cost-effectiveness but, at the same time, activates some peculiar defects like the twisting phenomenon. To reduce the risk of twisting and the occurrence of failures, it is preferable to reduce the forming forces and one of the solutions is the choice of opportune toolpath strategies. Concerning this, the present experimental research is along the same lines as recent numerical works of the authors; thermoplastic sheets were worked by incremental forming by varying the toolpath strategy. Following the realization of cone frusta, the forming forces and the deformation of the sheets were monitored, to investigate a toolpath strategy capable of reducing the risk of failures and defects for incrementally formed polymer sheets.

Introduction

Incremental sheet forming represents a viable way for customized production in a brief time and at a low cost, starting from sheets of pure metals, alloys, polymers, and composites [1]. Among them, the interest in the processing of thermoplastic polymers with this technique has been increasing over the past few years, starting from the studies of Franzen et al. on polyvinylchloride sheets [2] and going on with other commercial polymers [3], since it can represent a valid alternative to conventional technologies, based on heating-shaping-cooling manufacturing routes [4].

One of the main attractive features of this forming process is the achieving of high materials' formability with low-forming forces; on the other hand, incremental formed parts suffer from peculiar defects like twisting and wrinkling, and this is particularly true when using thermoplastic sheets [5].

A way to reduce the risk of the above-mentioned defects, as well as the occurrence of failures and the worsening of formed surfaces' quality, is to act on the toolpath strategy; consider, for example, that the twisting was significantly reduced by using an alternating toolpath in anticlockwise and clockwise directions [6,7]. Moreover, another solution is the reduction of the forming forces, particularly the ones acting in the sheet plane. Concerning the twisting phenomenon, its occurrence is more probable in the case of higher and more regular plane forces, which determine a combination of continued strain accumulation and asymmetric strain levels [8,9].

According to the considerations reported above and in line with previous authors' work aiming to optimize the forming process through a numerical approach [10], cone frusta with fixed wall angle were manufactured starting from thin polycarbonate sheets by the most common variant of the process under exam, named single-point incremental forming (involving the use of a simple tool and a clamping frame, and the absence of dies, for the superimposition of local deformations in the sheets), by setting typical process parameters [7] and by varying the toolpath strategy.

Some features from the experimental work were analysed, like the forming forces and the geometrical features connected to the occurrence of twisting, to individuate a toolpath strategy capable of reducing both and, also, the risk of failures and other defects on incrementally formed components.

Materials and methods

Cone frusta with fixed wall angle *α*, height *h,* and radius of the major base *R* (geometrical features and corresponding values reported in Fig. 1) were manufactured starting from 1.5 mm thick polycarbonate sheets. Polycarbonate is also known as a "transparency metal" because of its relevant mechanical and physiochemical properties [11] that make it strongly used in several applications in the fields of communication, transport, medical apparatus, aerospace environment, and so on [12].

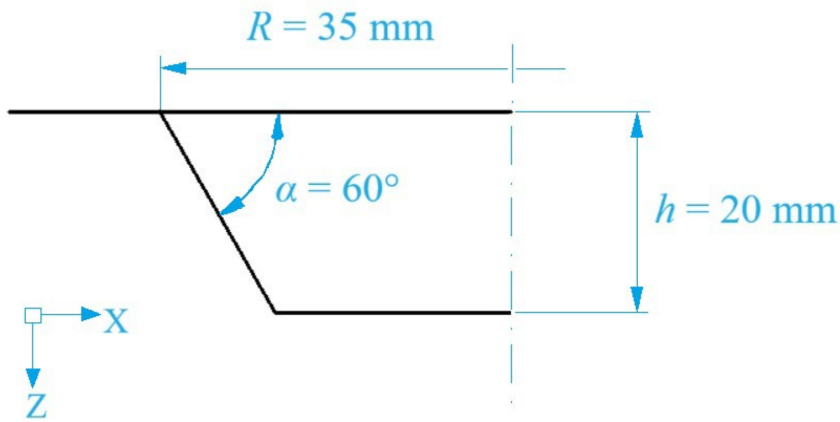

Fig. 1. Geometrical features of the cone frusta

The sheets were formed by using a C.B. Ferrari high-speed four-axis vertical machining centre, a clamping frame with an internal square area having a side of 100 mm and a 10 mm diameter hemispherical head stainless steel forming non-rotating tool. Fig. 2 reports the experimental setup during an incremental forming test, while the main properties of the sheet are the following: density of 1.2 g/cm^3, Young's modulus of 2.3 GPa, Poisson's ratio of 0.3, yield stress of 60 MPa and ultimate elongation of 110%. The surfaces of the sheets in contact with the tool were lubricated with a thin layer of mineral oil for cold forming to reduce the risks of damage because of the tool/sheet interaction.

Three different paths of the forming tool, described with a feed rate of 1000 mm/min, were considered to deform the sheets; concerning this, see the not-to-scale schematization in Fig. 3. In all the cases, the tool covered points of a spiral path, equally spaced around an angle *β* from each other; the vertical distance between two consecutive spirals was *vs* (see Fig. 3a, in which five exemplary consecutive points, from A to E, are reported, as well as the values of the geometrical features).

The three different toolpaths differed in the way they covered the distance between two consecutive points: in the first case, by describing a segment (reference toolpath, ref_tp, see Fig. 3b); in the other two cases, by alternating an upward and a vertical segment (hr0.5_tp and hr1.5_tp, where *hr* is the ramp height, see Fig. 3c).

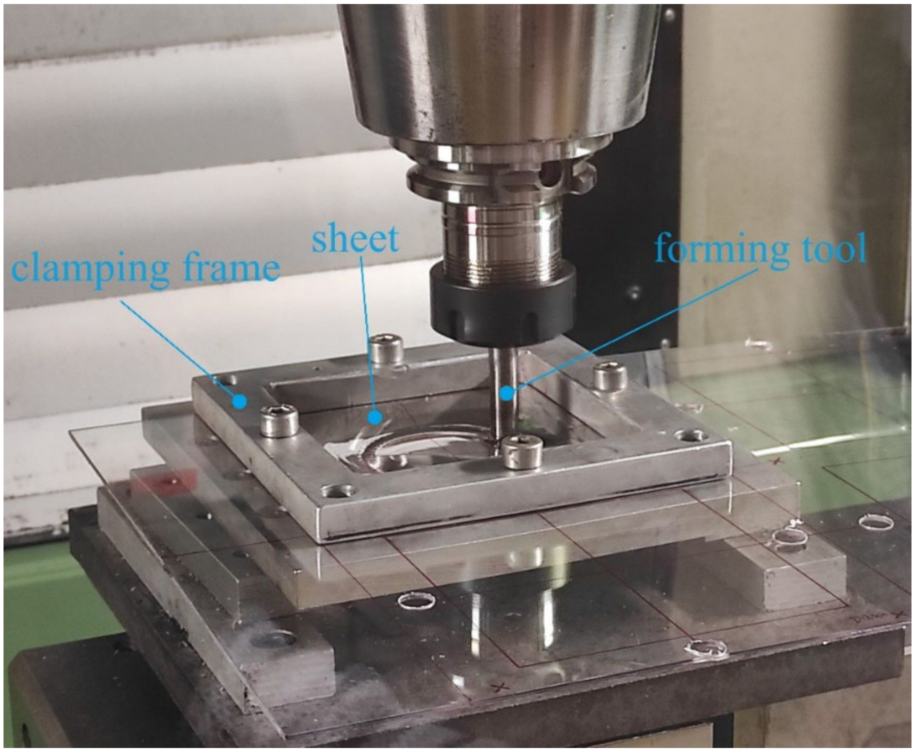

Fig. 2. Experimental setup during an incremental forming test

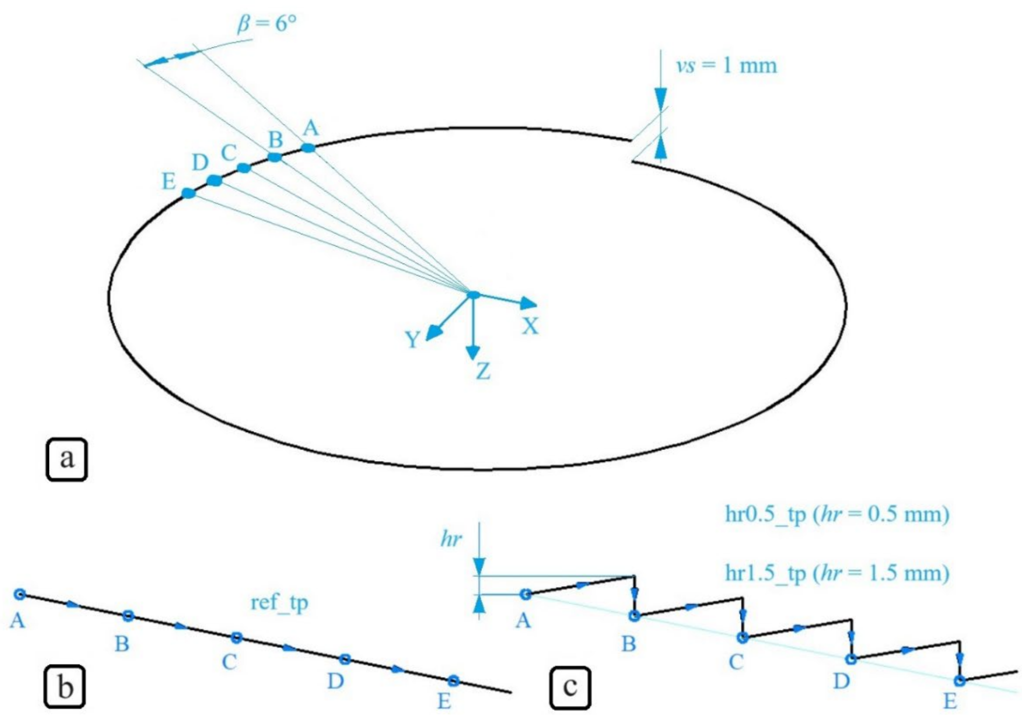

Fig. 3. Details of the toolpath (a) and toolpath strategies (b-c)

Two components of the forming force, F_Z and F_X (see the reference axes in Fig. 1), were acquired through a Kistler 9257A piezoelectric transducer; the data were collected at 2000 Hz and subsequently filtered using a NI 9239 input module and the VBA 1.0 B software.

Moreover, from the tests also the twisting magnitude was evaluated [13]; the twist angle θ was measured by CAD in terms of the rotation of a cross, marked on the bottom flat surface of the cone frusta, to their original position (see Fig. 4).

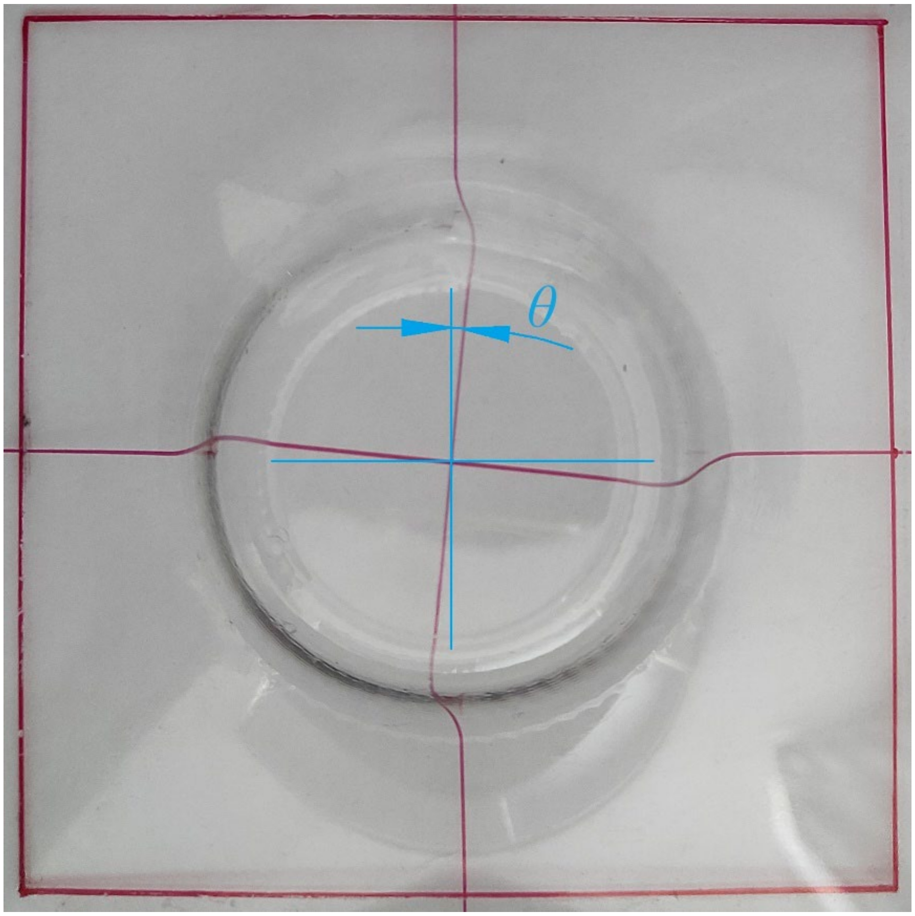

Fig. 4. Evaluation of the twist angle

Results and discussion

Before showing the results in terms of forces and twisting, it is worth highlighting that all the tests were conducted without incurring failures; then, all the toolpath strategies guaranteed the correct execution of the incremental forming process.

Fig. 5a and Fig. 5b report a particular of the vertical and the horizontal components of the forming force for the different toolpaths. Note that the time on the abscissa axis is expressed in percentage terms, for the processing time of each case, to simply compare the forces, because of the different lengths of the toolpaths by varying the strategy; moreover, the two-time windows are different to better understand the force trends (longer for the horizontal forces, to cover two entire spirals of the toolpath).

Fig. 5a highlights that the ref_tp strategy determines a continuous and constant tool/sheet contact condition (vertical force of about 450 N), because of a continuous vertical down movement of the tool. For the non-reference strategies, the trend is less regular and F_Z fluctuates (reaching a minimum value of about 200 N for the hr1.5_tp strategy) due to a partial elastic recovery [14]. For a comparison of the vertical forces, the mean values in the time window of Fig. 5a were evaluated. It is possible to affirm that the mean value of F_Z decreases from 443 (ref_tp) to 335 N (hr1.5_tp), passing from 375 N for the hr0.5_tp strategy.

The effects of the upward segments are also visible in terms of horizontal force (Fig. 5b), which shows the typical sinusoidal trend but partially irregular when using hr0.5_tp and hr1.5_tp strategies.

Fig. 6 reports the twist angle for the different toolpath strategies. From the histogram, it is possible to note that ref_tp determines the most severe contact conditions and the twisting phenomenon can be mitigated through the choice of the non-reference toolpath strategies, as supposed in [15].

Despite this, it can be affirmed that the toolpath can be further optimized; in fact, one can think of different solutions to reduce the sliding forces and point the twist angle towards zero.

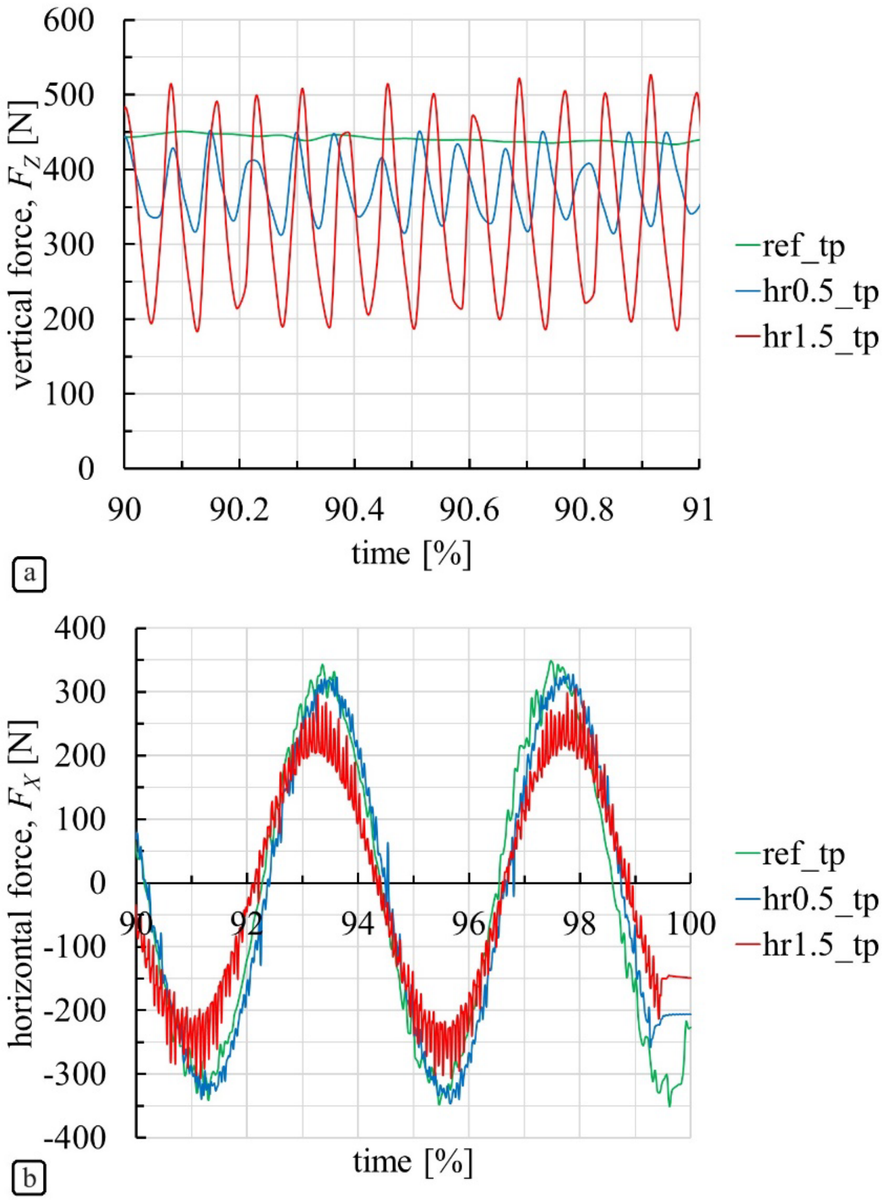

Fig. 5. Particular of the vertical (a) and the horizontal component of the forming force (b)

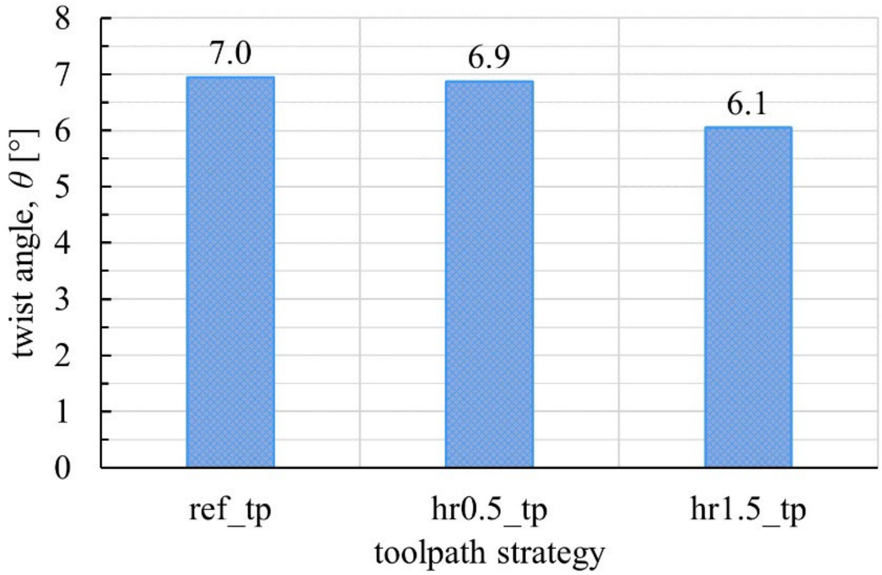

Fig. 6. Twist angle by varying the toolpath strategy

Conclusions

The present work presents the results of an experimental work involving the manufacture of fixed wall angle cone frusta by varying the toolpath strategy, intending to reduce the forming forces and the magnitude of the twisting phenomenon.

The tests highlight that, in comparison with a reference toolpath, it is possible to reduce the forming forces by adopting toolpaths with an alternation of diagonal up and vertical down steps, because of a partial elastic recovery during the process; most likely, this could imply a positive impact on the environment, in terms of energy consumption. At the same time, a slight reduction of the twist angle occurs.

Future works could aim to extend the research, both numerically and experimentally. For example, new variants of toolpath could be considered. In so doing, a further decrease of the twisting could be expected; moreover, the influence of the toolpath on the surface roughness could be investigated.

Acknowledgements

This work was supported by the "Programma per il Finanziamento della Ricerca di Ateneo (FRA) 2022" of the University of Naples Federico II.

References

[1] L. Bertini, A. Kubit, R. Al-Sabur, A. Gradzik, K. Ochał, J. Slota, M. Korzeniowski, Investigating Residual Stresses in Metal-Plastic Composites Stiffening Ribs Formed Using the Single Point Incremental Forming Method, Materials 15 (2022) 8252. https://doi.org/10.3390/MA15228252

[2] V. Franzen, L. Kwiatkowski, P.A.F. Martins, A.E. Tekkaya, Single Point Incremental Forming of PVC, J. Mater. Process. Technol. 209 (2009), 462-469. https://doi:10.1016/j.jmatprotec.2008.02.013

[3] P.A.F. Martins, L. Kwiatkowski, V. Franzen, A.E. Tekkaya, M. Kleiner, Single Point Incremental Forming of Polymers, CIRP Ann. 58 (2009), 229-232. https://doi:10.1016/J.CIRP.2009.03.095

[4] A. Rosa-Sainz, G. Centeno, M.B. Silva, J. Andrés López-Fernández, A. Jesus Martínez-Donaire, C. Vallellano, On the determination of forming limits in polycarbonate sheets, Materials 13 (2020) 928. https://doi.org/10.3390/ma13040928

[5] H. Zhu, H. Ou, A. Popov, Incremental Sheet Forming of Thermoplastics: A Review, Int. J. Adv. Manuf. Technol. 111 (2020) 565-587. https://doi.org/10.1007/s00170-020-06056-5

[6] J. Jeswiet, F. Micari, G. Hirt, A. Bramley, J. Duflou, J. Allwood, Asymmetric Single Point Incremental Forming of Sheet Metal, CIRP Ann. 54 (2005), 88-114. https://doi:10.1016/S0007-8506(07)60021-3

[7] M. Durante, A. Formisano, F. Lambiase, Incremental forming of polycarbonate sheets, J. Mater. Process. Technol. 253 (2018) 57-63. https://doi.org/10.1016/j.jmatprotec.2017.11.005

[8] 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

[9] J.R. Duflou, H. Vanhove, J. Verbert, J. Gu, I. Vasilakos, P. Eyckens, Twist revisited: Twist phenomena in single point incremental forming, CIRP Ann. 59 (2010) 307-310. https://doi.org/10.1016/J.CIRP.2010.03.018

[10] A. Formisano, M. Durante, L. Boccarusso, F. Memola Capece, A numerical approach to optimize the toolpath strategy for polymers forming, Mater. Res. Proc. 28 (2023) 1697-1702. https://doi.org/10.21741/9781644902479-183

[11] Z.X. Hou, J. Wu, Z.R. Wang, A Study of the Bulge-Forming of Polycarbonate (PC) Sheet, J. Mater. Process. Technol. 151 (2004) 312-315. https://doi.org/10.1016/j.jmatprotec.2004.04.080

[12] I. Beşliu, I. Tamaşag, L. Slătineanu, An Experimental Study on Incremental Forming Process of Polycarbonate Sheets, Macromol. Symp. 395 (2021) 2000282. https://doi.org/10.1002/masy.202000282

[13] 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

[14] 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

[15] A. Formisano, L. Boccarusso, M. Durante, Optimization of single-point incremental forming of polymer sheets through FEM, Materials 16 (2023) 451. https://doi.org/10.3390/ma16010451