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Experimental Evidence on Incremental Formed Polymer Sheets Using a Stair Toolpath Strategy

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Abstract: Incremental sheet forming represents a relatively recent technology, similar to the layered manufacturing principle of the rapid prototype approach; it is very suitable for small series production and guarantees cost-effectiveness because it does not require dedicated equipment. Research has initially shown that this process is effective in metal materials capable of withstanding plastic deformation but, in recent years, the interest in this technique has been increasing for the manufacture of complex polymer sheet components as an alternative to the conventional technologies, based on heating–shaping–cooling manufacturing routes. Conversely, incrementally formed polymer sheets can suffer from some peculiar defects, like, for example, twisting. To reduce the risk of this phenomenon, the occurrence of failures and poor surface quality, a viable way is to choose toolpath strategies that make the tool/sheet contact conditions less severe; this represents one of the main goals of the present research. Polycarbonate sheets were worked using incremental forming; in detail, cone frusta with a fixed-wall angle were manufactured with different toolpaths based on a reference and a stair strategy, in lubricated and dry conditions. The forming forces, the forming time, the twist angle, and the mean roughness were monitored. The analysis of the results highlighted that a stair toolpath involving an alternation of diagonal up and vertical down steps represents a useful strategy to mitigate the occurrence of the twisting phenomenon in incremental formed thermoplastic sheets and a viable way of improving the process towards a green manufacturing process.

Keywords: incremental forming; polycarbonate; toolpath strategy; forming forces; twisting; surface quality

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1. Introduction

Polymer materials show good properties like a light weight, strength, corrosion resistance, price, etc., which make them widely used in the manufacturing industry [1]. Typical parts made of thermoplastics are manufactured with repetitive operations of heating, shaping, and cooling [2]; usually, these operations are oriented to mass production both for energy costs and investments in equipment and tools. Moreover, the procedures usually used in sheet metal forming are frequently employed for the manufacture of polymer sheet parts of different shapes [3]; in these cases, the forming processes strongly depend on the material properties and the forming temperature, as was highlighted in [4].

During the last decade, the interest in developing procedures with a higher level of flexibility has increased progressively, due to the significant advances in the use of computers applied to manufacturing. For example, consider the additive manufacturing technologies [5] or incremental sheet forming (ISF) that can guarantee production without dedicated dies, in a brief time and at a low cost, starting from sheets of pure metals, alloys, polymers, and composites [6,7].

ISF represents a viable alternative to conventional technologies based on heating–shaping–cooling manufacturing routes, guaranteeing high levels of the materials' formability and being able to be carried out at room temperature; a clamped sheet is progressively deformed by a forming tool that, when controlled using a CNC machine, describes a path to manufacture the final part [8]. Due to its characteristics, it is strongly oriented towards the production of batches with small and medium sizes in a variety of fields; for example, aircraft canopies or medical prostheses can be obtained from polymer sheets formed using ISF [9]. Furthermore, recent studies have highlighted that ISF for polymer parts allows a reduction in energy consumption compared to conventional processes [10].

The first studies on the incremental forming of polymer sheets were conducted by Franzen et al. [11] and focused on the feasibility of ISF for polyvinylchloride (PVC) sheets, while Martins et al. [12] demonstrated its extendibility to other commercial polymers.

Significant analyses on the influence of the main process parameters were conducted on polypropylene (PP) sheets in [13] as well as on polyamide (PA), polycarbonate (PC), polyethene terephthalate (PET) and PVC [14–16] to determine their formability limits. Other studies were aimed at finding new methods to better investigate the formability limits [2,17].

Moreover, the behaviour of new materials like the biocompatible polycaprolactone (PCL) when incrementally formed was analysed [4], as well as the efficiency of new solutions to improve the quality of the ISF polymer parts; consider, for example, some previous authors' works that investigated a prior cold-rolling process of the sheets [18] or their self-heating as the effect of the feed rate and the spindle [19].

Another relevant field of investigation, strictly linked to formability, was related to the failure and defect modes. As reported by [11], a ductile fracture at the transition region between the wall and the corner radius or tearing along the walls, and/or defects like wrinkling and twisting, can affect the polymer sheets processed by ISF. The occurrence of these defects, although not representing sheet fractures, limits the formability of the ISF parts. Moreover, they are strictly connected; in particular, the wrinkles can be twisted around the axis of revolution in the direction of tool rotation. Then, the twisting can worsen the quality of polymer parts made by ISF; it is a phenomenon due to an uncontrolled pivoting of the formed parts around an axis orthogonal to the clamping frame and is caused by the tangential forces (with the consequent in-plane shear) that the forming tool exerts on the sheet.

The twisting phenomenon is observed in all materials, like metals [20], but it is particularly perceived in thermoplastic sheets [21] due to their softer nature. A viable way to prevent it is to act on the toolpath strategy; for example, it can be significantly reduced by using an alternating toolpath in anticlockwise and clockwise directions, so as shown by [8] and, for PC parts, by [22]. Even this solution, under severe forming conditions in terms of sliding forces on soft materials like thermoplastic sheets, can avoid instabilities and consequent wrinkling on the formed parts [23]. Another method is to reduce the forming forces that act on the sheet plane; note that the occurrence of the phenomenon is more probable for higher and more regular plane forces because they determine a combination of continued strain accumulation and asymmetric strain levels [24,25].

According to what is reported above and following previous authors' work aiming to optimise the forming process through a numerical approach [26], the main aim of this paper is, but not limited to, to investigate how to reduce the twisting phenomenon and, with it, the occurrence of failures, through the choice of toolpath strategies that make the tool/sheet contact conditions less severe. Cone frusta with a fixed-wall angle were produced using thin PC sheets, using the single-point incremental forming (SPIF) through setting typical process parameters [22] and different toolpath strategies.

The material used in this study is an amorphous thermoplastic polymer also known as a "transparency metal" due to its relevant mechanical and physiochemical properties; significant toughness, stiffness, strength, heat and flame resistance, and dimensional stability, among others [27], make it strongly used in several applications in the fields of communication, transport, medical apparatus, aerospace environment, and so on [28].

Some features from the experiment were analysed, i.e., the forming forces, the forming time, the twisting angle and the surface roughness, to investigate the pros and cons and to show the potential of the non-reference toolpath strategy for reducing the risk of failures and other defects on incrementally formed polymer parts.

2. Materials and Methods

The experiment on Makrolon PC sheets (supplied by Bayer) with a thickness t = 1.5 mm was conducted by carrying out SPIF tests at room temperature; SPIF represents the simplest variant of ISF and involves the use of a simple tool, a clamping frame, and the absence of dies. A C.B. Ferrari high-speed four-axis vertical machining centre drove the forming tool, a non-rotating hemispherical head stainless steel stylus with a diameter D = 10 mm; this tool setup provided very good results when performing the SPIF of PC thin sheets [22]. The main properties of the sheets and the forming tool are reported in Table 1 [29]; note that the plastic properties of the tool are not reported since it, compared to the sheet, can be considered infinitely rigid.

Table 1. Main properties of tool and sheet [29].

Properties	Tool	Sheet
Material	Stainless steel	Polycarbonate
Density [g/cm^3]	7.85	1.2
Young's modulus [GPa]	210	2.3
Poisson's ratio [-]	0.3	0.3
Yield stress [MPa]	-	60
Ultimate elongation [%]	-	110

The tests provided the manufacture of cone frusta with a fixed-wall angle; these components were characterised by a height h = 20 mm, a radius of the major base R = 35 mm, a wall angle α = 60° and a square flange with a side L = 100 mm. A clamping frame constituted the blocking system of the sheet. The geometrical features of the components and the forming tool with their values are reported in Figure 1, while the experimental setup during a SPIF test is shown in Figure 2.

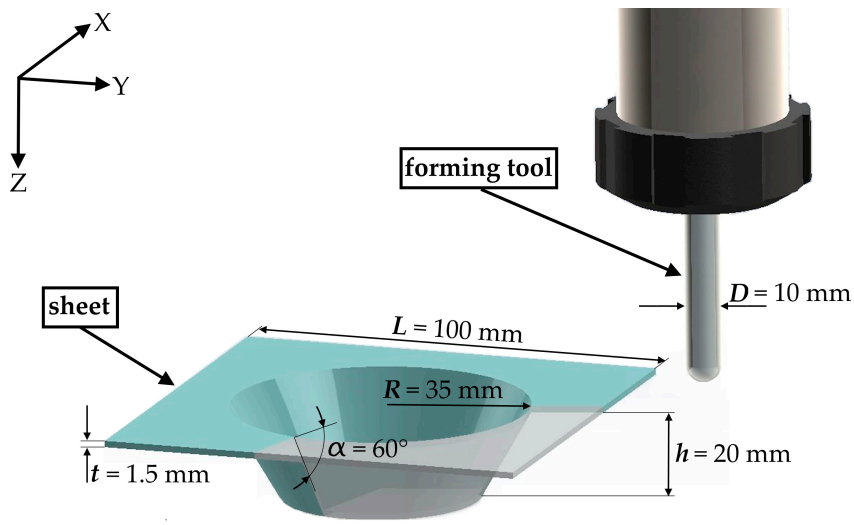


Figure 1. Geometrical features of the fixed-wall angle cone frusta and of the forming tool.

The forming process under exam involved a localised and incremental deformation of the sheet as the effect of its interaction with the forming tool; the risks of failing tests due to the tool/sheet interaction were reduced by lubricating the sheets with mineral oil for cold forming [30].

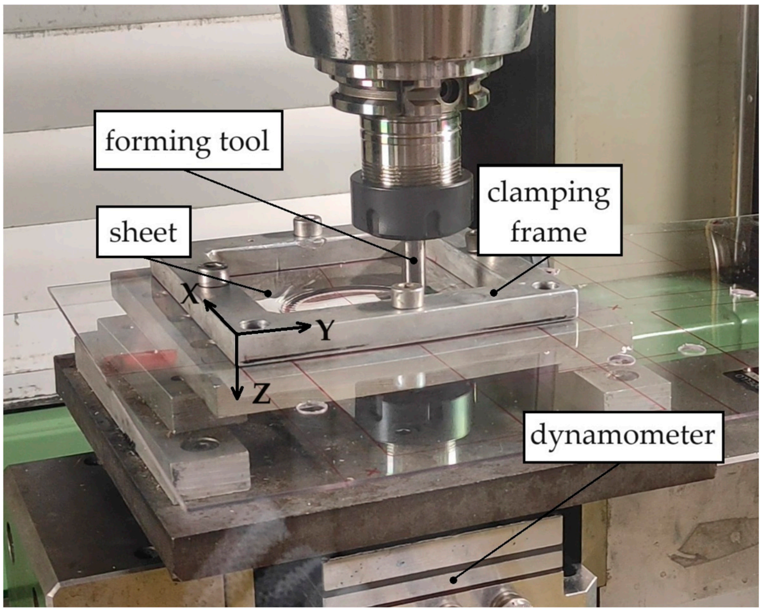


Figure 2. Experimental setup during an incremental forming test.

Two different toolpath strategies (of which a not-to-scale schematisation is reported in Figure 3) were considered, for a total of four toolpath types; for all the cases, a feed rate of 1000 mm/min was set. The two strategies required that the tool covered 60 equally spaced points for each complete turn of a conical helix, while the vertical distance between two consecutive turns was equal to vs. = 1 mm (see, in Figures 3a and 3b, respectively, for the three-dimensional representation of some turns of the helix and a complete turn in the XY-plane view, common for the two toolpath strategies).

With the first strategy, the distance between two consecutive points was covered by a segment; it can be considered as a reference toolpath (*ref_tp*) strategy. The second strategy (*hr_tp*) provided an alternation of an upward and a vertical down segment between two consecutive points of the helix; for this strategy, three different values of the height of the ramp (*hr*) of the upward segment were tested. They were equal to *hr* = 0.5 mm (*hr0.5_tp*), *hr* = 1.0 mm (*hr1.0_tp*) and *hr* = 1.5 mm (*hr1.5_tp*); for the last one, tests without lubrication (*hr1.5_tp_dry*) were also carried out to evaluate the influence of the lubrication conditions for the toolpath, which is expected to guarantee less severe contact conditions [26]. The differences between these strategies can be observed in the representation of a half-turn in the YZ-plane view of Figure 3c. Note that the arrows in Figure 3 indicate the toolpath direction.

To control the process, two components of the forming forces were monitored and acquired; in detail, the vertical (F_Z) and one horizontal component (F_X) were acquired through a Kistler 9257A piezoelectric dynamometer at 2000 Hz and subsequently filtered using a NI 9239 input module and the VBA 1.0 B software (see the reference axes for the forces and the position of the dynamometer in Figure 2). At the same time, the forming time was measured.

Moreover, the twist angle θ was evaluated as a measure of the twisting magnitude; to do this, the bottom of the undeformed sheets (which did not come in contact with the forming tool) was marked with a cross and its rotation at the end of the test, compared to its original position, was measured [23]. Figure 4 reports a CAD representation of this evaluation.

Finally, and according to [31] for the recommended cut-off (equal to 0.8 mm), the mean roughness (R_a) of the worked surfaces was measured using a Mitutoyo Surftest SJ-301 tester (Berg Engineering & Sales Company, Inc., Rolling Meadows, IL, USA), with differential inductance used as the detecting method and with Gaussian filter (ten measures for each case, along the meridional direction of the walls).

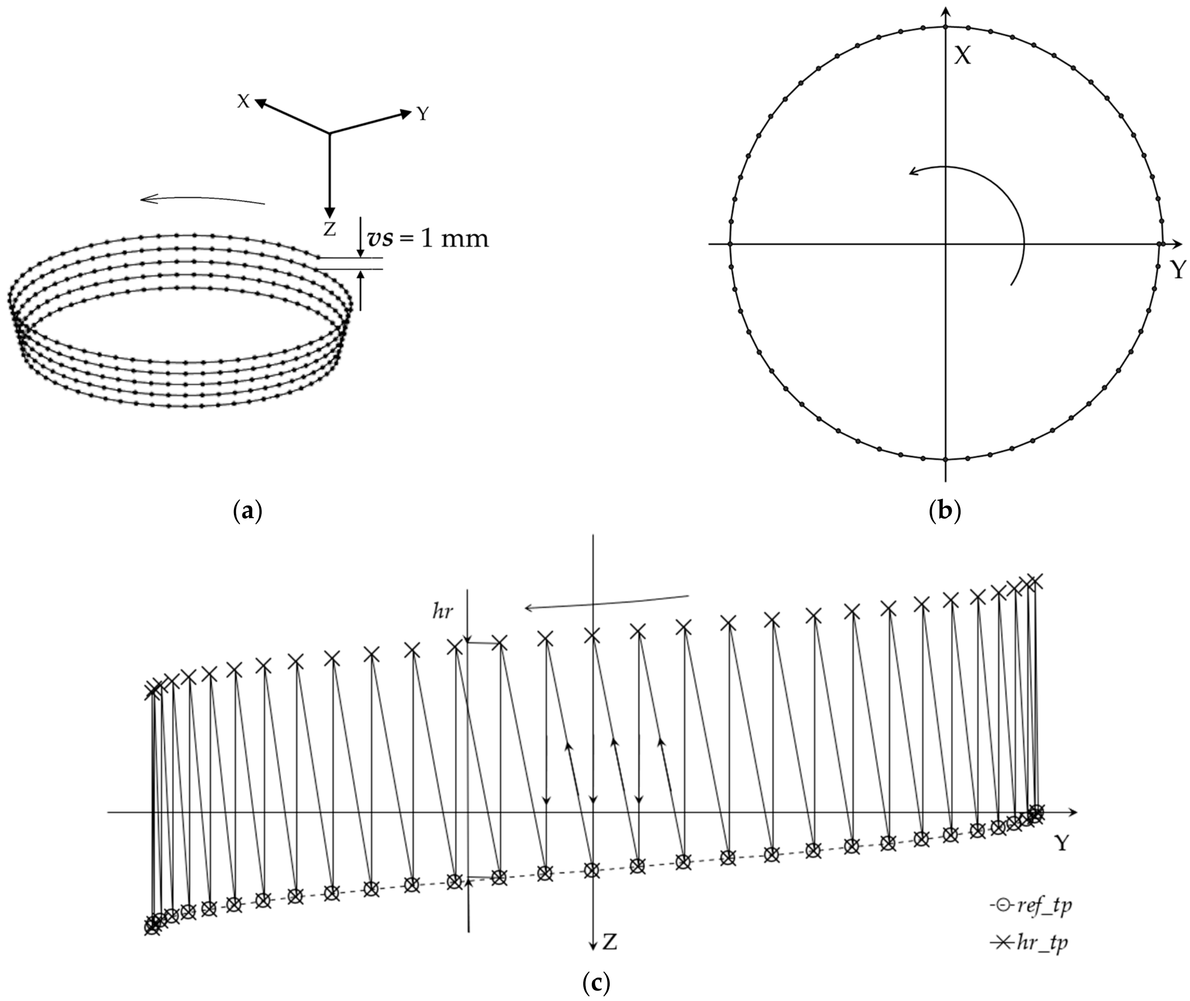


Figure 3. Not-to-scale schematisation of the toolpath strategies: (**a**) conical helix; (**b**) XY-plane and (**c**) YZ-plane views of the toolpaths.

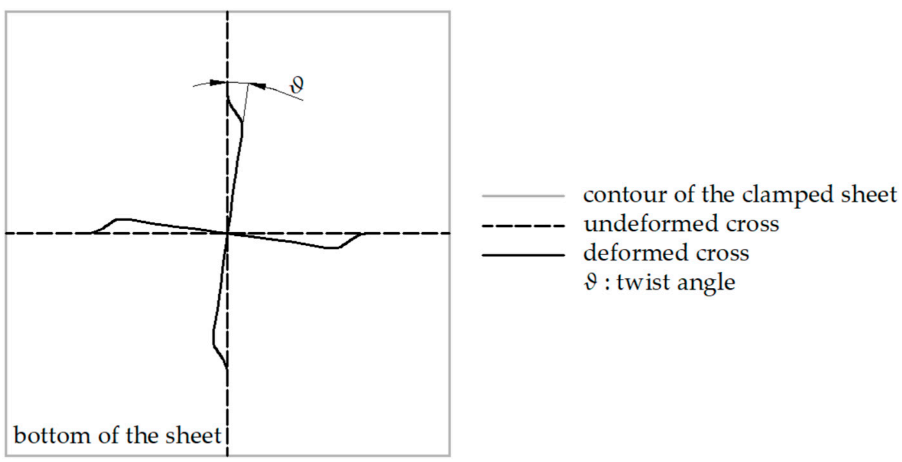


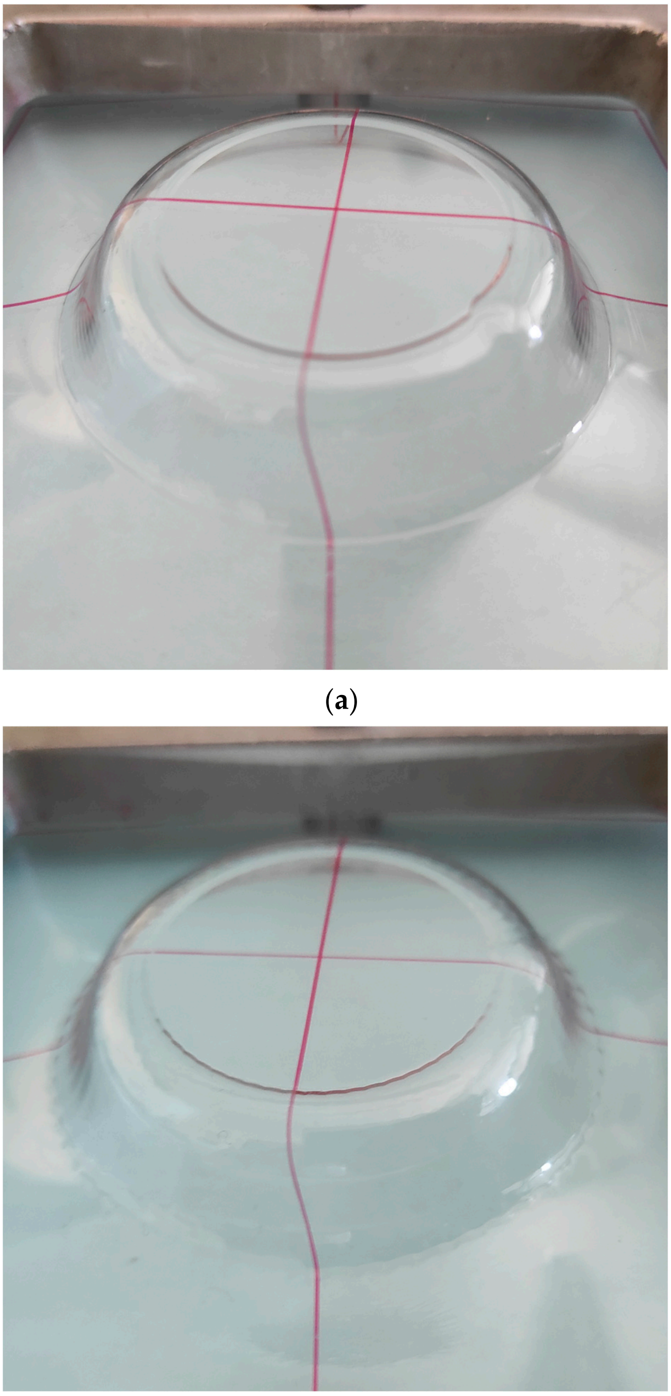
Figure 4. CAD representation of the evaluation of the twist angle.

3. Results

This section summarises the main results from the experimental tests (two repetitions for each case). Due to the very good repeatability of the experimental results, for the sake of conciseness and brevity, only the representative curves and average values of the features investigated are reported.

3.1. Defectiveness

All the tests were carried out without the occurrence of failures and wrinkles; at the same time, they all showed twisting. Concerning this, you can see in Figure 5 the bottom surface of a sound component created by the *ref_tp* (Figure 5a) and one by the *hr1.5_tp* (Figure 5b); these toolpaths represent the limit cases in terms of the severity of the contact conditions.



(**a**)

(**b**)

Figure 5. Cone frustum manufactured using: (**a**) the *ref_tp*; (**b**) the *hr1.5_tp*.

3.2. Forming Forces and Times

The complete trend of the two components of the forming forces for the above-mentioned toolpaths is reported in Figure 6; a better qualitative interpretation of them is possible by observing the 70 ÷ 80 percent time range (see Figure 7). See this for a simpler comparison of the trends; the processing time on the abscissa axis is reported in percent terms, because it is not the same for the different toolpaths, due to their different lengths. In this regard, Table 2 reports the forming time depending on the toolpath.

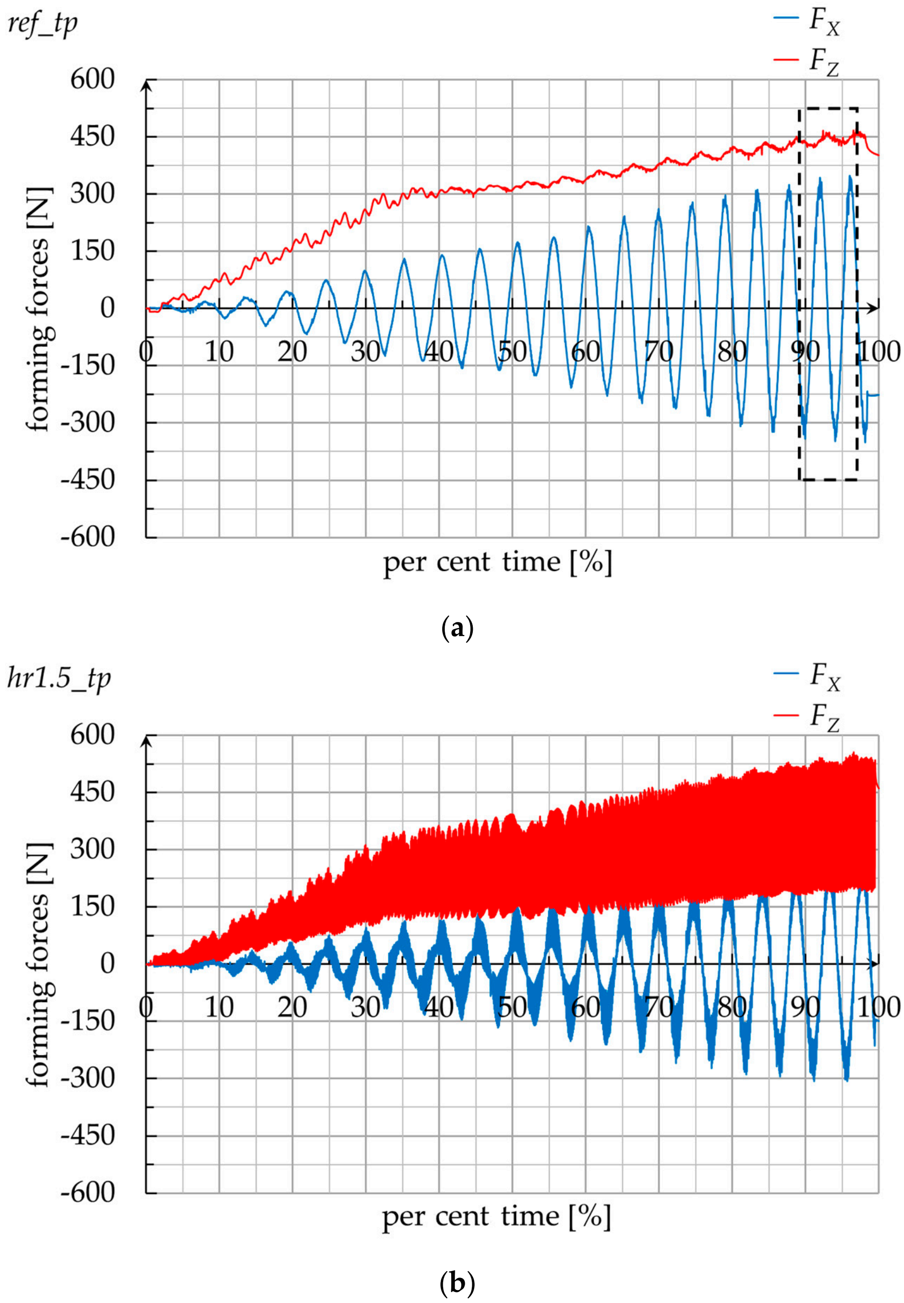
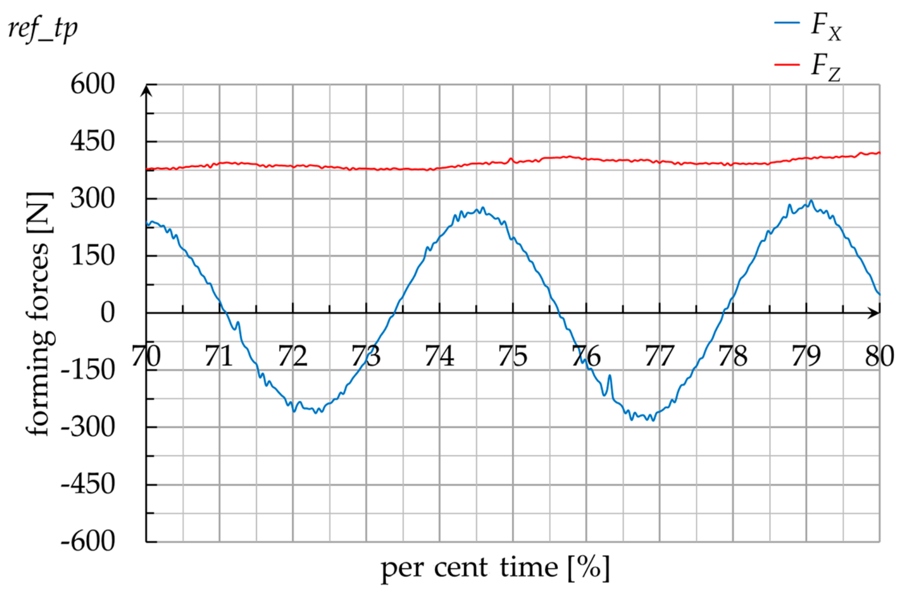
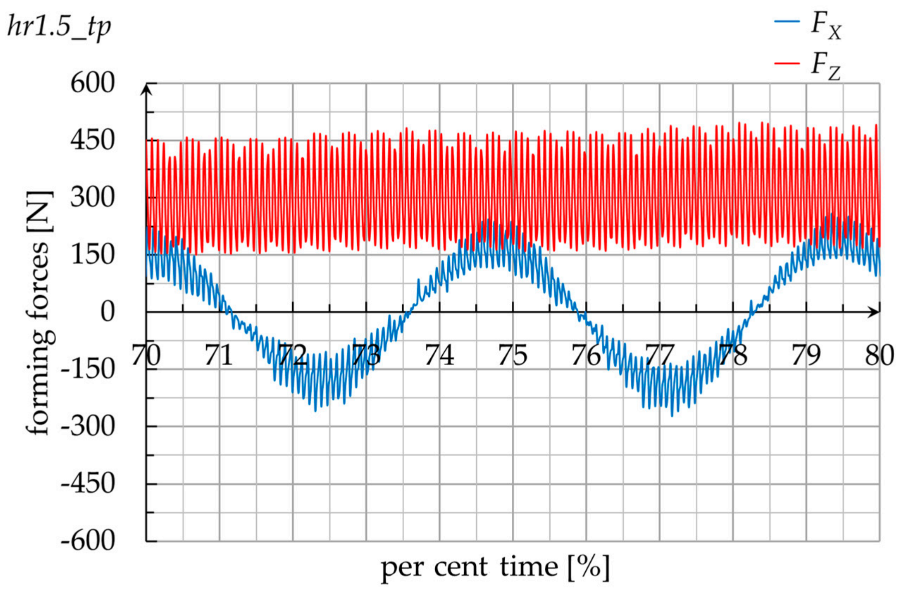


Figure 6. Complete trend of the forming forces using: (**a**) the *ref_tp*; (**b**) the *hr1.5_tp*.



(a)



(b)

Figure 7. Graph of 70 ÷ 80 percent time range trend of the forming forces using: (**a**) the *ref_tp*; (**b**) the *hr1.5_tp*.

Table 2. Forming time for the different toolpaths.

Toolpath	Forming Time [s]
ref_tp	200.5
hr0.5_tp	241
hr1.0_tp	286.5
hr1.5_tp	337.5

To compare quantitatively the forming forces for the different toolpaths, some relevant information was collected from the data of the two last complete turns (see the part of the trend in the rectangular box in Figure 6a). From this data set, a boxplot of the vertical component of the forming forces is generated, reporting five relevant values (see Figure 8a): minimum, first quartile, second quartile (median), third quartile and maximum. Moreover,

Figure 8b reports the average of F_Z and of the absolute values of F_X, labelled as $F_{Z,m}$ and $|F_X|_m$, respectively.

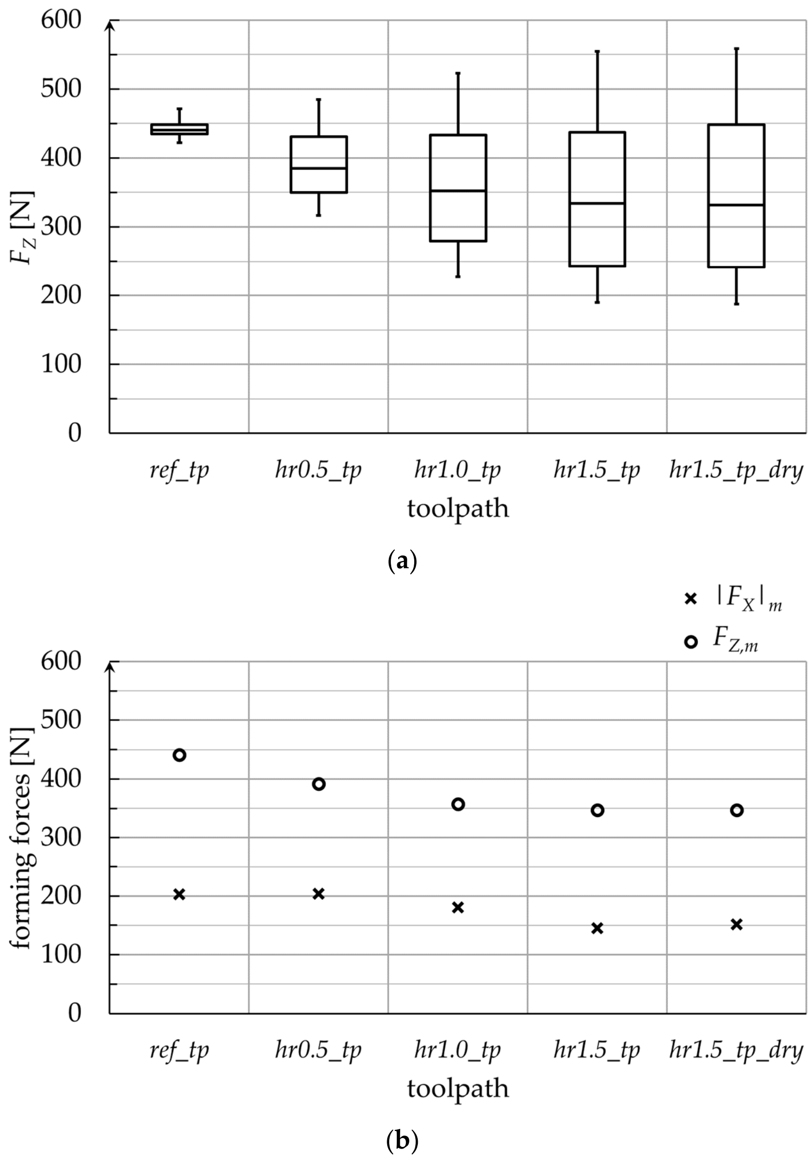


Figure 8. Forming force data analyses from the last two complete turns of the different toolpaths: (**a**) boxplot for the vertical component; (**b**) the average of the vertical component and of the absolute values of the horizontal component.

3.3. Twist Angles

Table 3 reports the twist angle for the different toolpaths (for the *hr1.5_tp*, this is both in lubricated and dry conditions).

Table 3. Twist angle for the different toolpaths.

Toolpath	Twist Angle, θ [°]
ref_tp	7.0
hr0.5_tp	6.9
hr1.0_tp	6.6
hr1.5_tp	6.1
hr1.5_tp_dry	6.2

3.4. Roughness

Finally, Table 4 reports the mean roughness for the different toolpaths (for the *hr1.5_tp*, both in lubricated and dry conditions).

Table 4. Mean roughness for the different toolpaths.

Toolpath	Mean Roughness, R_a [µm]
ref_tp	0.59
hr0.5_tp	0.83
hr1.0_tp	0.78
hr1.5_tp	0.66
hr1.5_tp_dry	0.77

4. Discussion

Following the first sentence of the results, all the tests were carried out without incurring failures (see Figure 5). Then, all the toolpaths guarantee the correct execution of the SPIF process. This is in line with what was expected, in light of the results in terms of formability from varying wall angle cone frusta tests carried out by the authors and presented in a previous work [22], which highlighted a maximum wall angle in similar conditions of about 80° (significantly higher than the one chosen for the fixed-wall angle of the cone frusta manufactured in this experiment).

Considering the analysis of the forming forces, from Figures 6a and 7a, it should be noted that the reference strategy shows a trend that is typical for the SPIF of cone frusta when using a conical helix toolpath [32], as a result of the continuous vertical down movement of the forming tool that involves a continuous and constant tool/sheet contact condition. The vertical component follows the tensile trend of the material, first with a significant and then second a more gradual increase with the forming time. Little oscillations are due to a little variability in the sheet stiffness because the distance of the tool (describing circular turns) from the frame (with a square shape) is not constant. The horizontal component shows a typical sinusoidal trend with an increasing amplitude, as does the vertical one. The stair path strategy (see Figures 6b and 7b for the *hr1.5_tp*) also presents typical SPIF trends, but with a fluctuation that follows the diagonal up and vertical down parts of the toolpath as a consequence of a partial elastic recovery [33].

As anticipated, the fluctuation of the forces increases from the reference to the stair path strategy and, for the last one, with the *hr* (see Figure 8a); conversely, the mean value of both the force components decreases (see Figure 8b), even if loading and unloading determine higher force peaks (see the maximum values in Figure 8a). Despite this, not even for the limit case (*hr1.5_tp*) do the forces go to zero (see the minimum values in Figure 8a); the selected toolpaths do not determine the no-contact conditions between the tool and the sheet at any time of the process. Furthermore, it should be noted that for the toolpath guaranteeing the less severe contact conditions, the lubrication results are irrelevant; this is evident by observing the corresponding force values in Figure 8b.

From Table 2, the stair paths present higher lengths and then higher forming times (increasingly so as *hr* grows); the reference strategy represents the shortest one, covering a helix with discrete points, while the other ones gradually diverge from this condition. This translates into a reduced productivity, compared to *ref_tp*.

The considerations on the forming forces, particularly the ones summarised in Figure 8b, translate into similar conclusions for the twisting phenomenon, with its reduction for the stair path strategy and with the increase in *hr* (lubrication conditions irrelevant for the limit case) as highlighted by the data in Table 3. Despite the reduction in twisting not being relevant, it is to be expected that it could be significant under more severe forming conditions (like, for example, on components with higher heights and lower thicknesses).

The R_a values, reported in Table 4, are slightly lower for *ref_tp*, and the influence of *hr* is not particularly relevant for the stair paths. For *hr1.5_tp*, the lubrication conditions are quite irrelevant, due to the non-continuous tool/sheet contact that makes the wear action of the tool in dry conditions less severe. However, in all the cases, the components show high surface quality: the roughness values are typical of burnished surfaces and the worked surfaces preserve their transparency.

Finally, despite the reduced productivity due to the higher forming times, the *hr1.5_tp* can represent a viable way of improving ISF towards a more efficient and green manufacturing process [34]. This is because of the reduction in the average of the forming forces, the irrelevance of the lubrication conditions (there is no need to clean or dry the parts before further production steps such as coating or joining processes) and the FEM prediction of reduced energy consumption [26]. Concerning the last point, the simulations portend a reduced total energy linked to reduced sliding energy and an increase in work performed in permanent deformation, as well as a different way of sheet deforming (from predominant distortion to compression), passing from a reference to a stair toolpath strategy.

5. Conclusions

An experiment, based on manufacturing using the single-point incremental forming of a fixed-wall angle cone frusta from polycarbonate sheets, 1.5 mm in thickness, was presented in the current paper. The aim was to investigate the influence of the toolpath strategy on features like the forming forces, the forming time, the twist angle, and the mean roughness of the worked surfaces.

The tests highlighted that, compared to a reference toolpath, a stair path strategy that alternates diagonal up and vertical down steps allows for the reduction in the average forming forces, due to a partial elastic recovery during the process, and the twist angle, albeit slight; the quality of the worked surfaces is very high, regardless of the toolpath type.

Furthermore, a comparison between the tests in lubricated and dry conditions when using this strategy with a ramp height of 1.5 mm highlights the irrelevancy of the lubrication conditions. This result, together with previous authors' FEM analyses, predicts reduced energy consumption and implies a positive impact on the environment, despite a reduced productivity connected to higher working times.

Future works could aim to extend the experimental research and to use numerical methods for the more effective optimisation of the incremental forming of polymer sheets; different toolpath strategies could be considered to further reduce the defectiveness, as well as to improve the dimensional accuracy and the surface quality of the incrementally formed components.

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