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Stainless steel deep drawing with polymer punches produced with fused filament fabrication technology: effect of tool orientation on the printing plate

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Abstract. In this research the potential of using polymer punches in a deep drawing process to realize stainless steel cups having diameter equal to 40 mm and drawing depth equal to 18 mm was investigated. Punches have been Additive Manufacturing printed following two different orientations (horizontal and vertical) and two different wire orientations with respect to the drawing direction (45° and 90°). Cups and punches radii, heights, roundness tolerances and linear profiles have been acquired to compare process performances. Results highlight benefits and problems of all tested punches.

Introduction

Nowadays manufacturing paradigm is changing into a production-oriented model to meet consumer expectations for a huge variety of products and allows the achievement of ad hoc product characteristics (mass customization) [1]. Highly customized production offers unique and very low-production-volume products; however, this causes an excessive increase of costs for the tooling, consequently customization it is not yet a competitive market.

In this scenario, the additive manufacturing (AM) process could be a good solution for producing tools for prototypes, small batches, or customized production. This technology includes a group of manufacturing techniques in which the shape of the physical part is generated by adding the material layer by layer [2]. AM technologies are characterized by short setup times, a wide range of printable materials for both plastics and metals, and a higher design complexity. Currently, there is a great demand for AM technologies to support product development of tooling or tooling inserts in different industrial applications such as casting [3, 4], injection moulding [5, 6] or forming [7, 8].

For deep drawing process a specific AM technology, the Fused Filament Fabrication (FFF), was tested to produce tools with polylactic acid (PLA) polymer and to deform cold-rolled steel sheets such as DC01 or DC04 with a thickness of 0.7–1 mm [9-12]. Results showed that PLA can be used to form steels sheets, but the process loads caused the punch flattening so affecting the cups drawing radius and height. The main limit is that all tested geometries have been produced with punch axis printed parallel to z axis that could be not the best solution for parts that must withstand to compression forces.

The present study focuses on the use of polymers reinforced with short carbon fiber to produce tooling for deep drawing applications with FFF technology; in particular the authors tested the influence of punches orientation on the print plate and measured punches performance in terms of quality of the produced cups and permanent deformation of the punches due to production process. An experimental campaign was designed, and a statistical approach has been followed to analyse the results.

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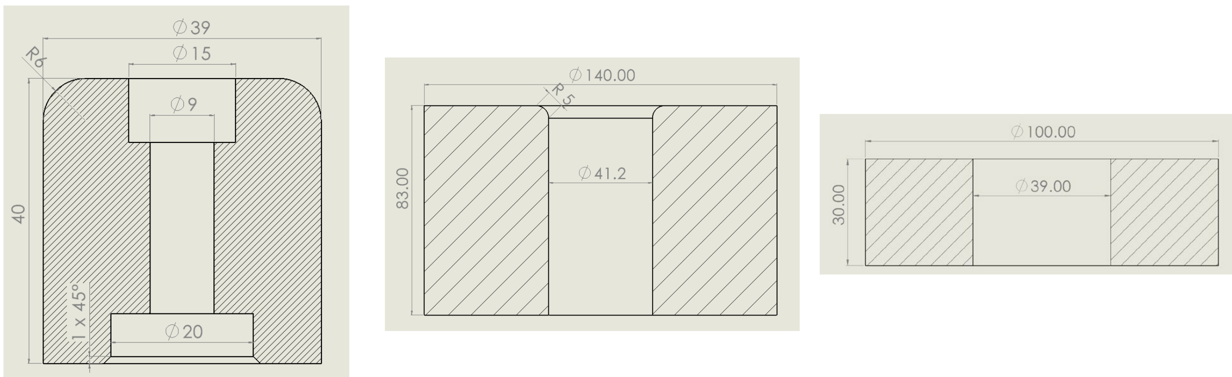
Materials and Methods

The investigated case study was the deep drawing of a circular blank (*Φ* 86, 1 mm thick) to produce cups with height equal to 18 mm; stainless steel alloy (AISI 304) was used as sheet material. Punches have a hollow cylindrical geometry with a central hole designed as a housing for the screw needed for the assembly on the press (Fig. 1a). Forming die and blankholder have hollow cylindrical geometries too (fig.1b). 45 NiCrMo 16 was selected as material for the forming die and blank holder.



(a) (b) (c)

Fig. 1 Geometry of punch (a), forming die (b) and blank holder (c)

Punches were produced using an FFF printer Mark Two (Markforged, Watertown, MA, USA). A solid filling strategy with two wall layers was adopted, the layer height was set to 0.125 mm. Onyx, which is nylon reinforced with carbon microfibers, was used as material and printed at 245 °C; the other process parameters as nozzle feed or offset distance between layer are blocked and it is not possible to change them from the machine governing software. Under these conditions three different punches have been designed as a function of the orientation on the printing plate and of the wire orientation inside the parts. In particular:

- Geometry H45: punch with axis parallel to the printing plate; wire oriented at 45° and 135° to the drawing direction; fillet radius average roughness equal to 7.2 µm.
- Geometry H90: punch with axis parallel to the printing plate; layer with wire oriented at 0° and 90° to the drawing direction; fillet radius average roughness equal to 8.1 µm.
- Geometry V: punch with axis orthogonal to the print plate; layer orthogonal to the drawing direction; fillet radius average roughness equal to 12.8 µm.

Tab.1 lists the mechanical properties of the involved materials. Fig. 2 shows the wires orientation in the cross section and punches position on the printing plate.

Tab.1 Mechanical properties of involved materials

	Onyx [13]	45 NiCrMo 16	AISI 304
Young Modulus [GPa]	2.4	284	193
Tensile Stress at Yield [MPa]	37	696	190
Tensile Stress at Break [MPa]	40	950	500-700
Tensile Strain at Break [%]	25	11	40
Density [g/cm^3]	1.2	7.84	8

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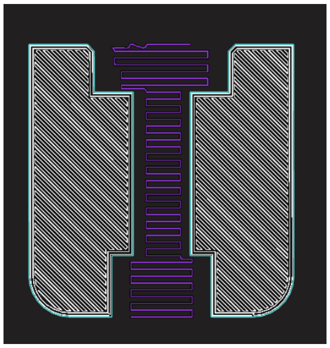
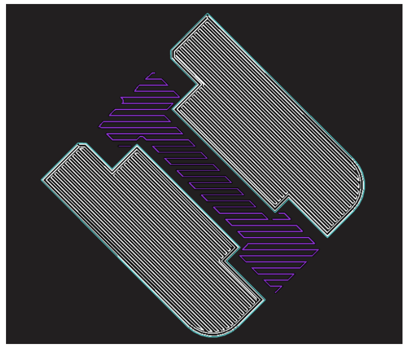
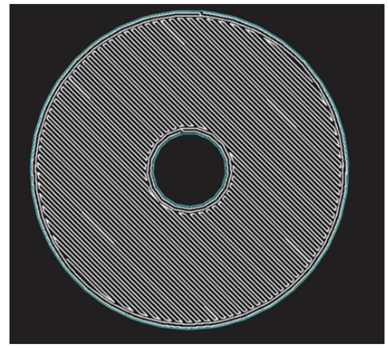


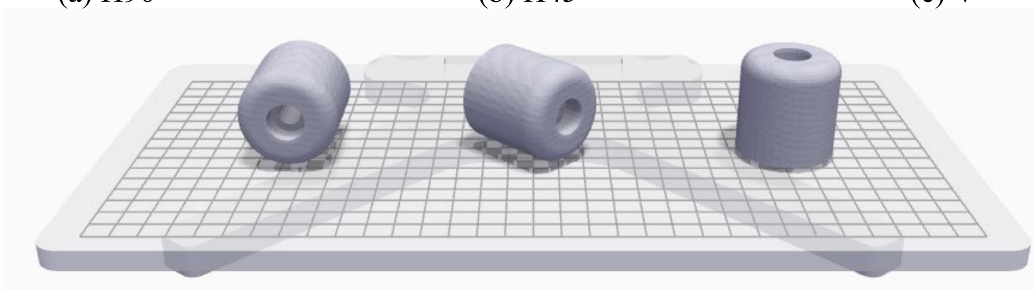
(a) H90



(b) H45



(c) V



(d) left H90, center H45, right V

Fig. 2 Cross section of polymer punches and orientation on the printing plate. (white for part, purple for support, cyan for wall layer)

The press utilized for the experiments was an EVL/400-A (Galdabini, Varese, Italy) with a power of 400 tons, the punch speed was set constant and equal to 10 mm/s and the maximum press load was equal to 180 kN. The blank-holder load was set to 1 kN (recommended value from the industrial practice), the blanks had a thickness of 1 mm and the punch-die clearance distance was set to 1.1 mm. The blanks were manually lubricated with mineral oil. Tab.2 reports the most significand process parameters.

Tab.2 Deep drawing process parameters

Punch diameter [mm]	39
Punch fillet radius [mm]	6
Forming die internal diameter	41.2
Forming die fillet radius [mm]	5
Clearance distance [mm]	0.1
Drawing ratio	2.2
Blank diameter [mm]	85
Blank thickness [mm]	1
Blank material	AISI 304
Drawing depth [mm]	18
Replicas	3

After production two different measures have been done both on cups and punches:

- A linear profile analysis (LP) to acquire the internal shape of the cups, the measures of the effective drawing height (h_d) and of the cup fillet radius. On the punches the LP was executed to identify possible plastic deformations of the fillet radius due to the drawing process and evaluate the punch height (h_p) after the cups production.

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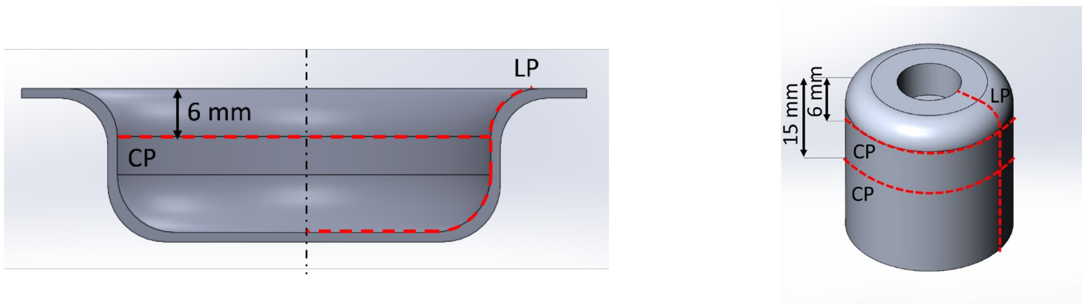
- A circular profile analysis (CP) to acquire the internal circumference of the cups at 6 mm from the top; these data were used to estimate the average cup radius (R_{med}) and cups roundness tolerances $r_t = R_{max} - R_{min}$. The same method was followed for punches CP analysis but with two acquisitions: a first one in the forming zone (6 mm from the punch top) and a second one 15 mm from the top to investigate if the forming process affect punches radius and roundness.

Data points were acquired using Cyclone Series 2 equipped with the probe SP620 (Renishaw, Wotton-under-Edge, UK). Results have been compared with statistics methods as ANOVA and Tukey range test. Fig.3 shows a scheme of the LP and CP measuring points.



(a) cup cross section (b) punch

Fig.3 Graphical representation of linear and circumferential profiles acquired

Results

In this section the most significant results have been reported; the analyses have been divided in two subsections referring to the cups and punches, respectively.

Cups analysis. The main results of the measures executed on the cups produced with H45, H90 and V punches are reported in Fig. 4. Specifically, fig.4a shows the LP of cups produced with additive punches, as can be observed similar trend was achieved by test H90 and V, on the contrary cups produced by test H45 are characterised by higher fillet radius. Fig. 4b shows a focus on the cup fillet radius. The ANOVA test evaluated on the drawing height shows a significative effect of punch orientation (p-value < 0.001) and Tukey range test highlights that test V produces cups with lower drawing height (Fig. 4c). The ANOVA test of cup radius present a p-value equal to 0.021 so that punch orientation is significative; Tukey range test identified three different cup radius levels with a maximum in test H90 and a minimum in test V (Fig. 4d). Tab.3 presents the average cup radius and the related standard deviation, drawing height and the roundness tolerances; about r_t it is possible to observed that is maximum in test H90 and minimum in V. Moreover, test H90 and H45 have higher cup radius standard deviation (0.150 and 0.148) with respect to test V (0.131).

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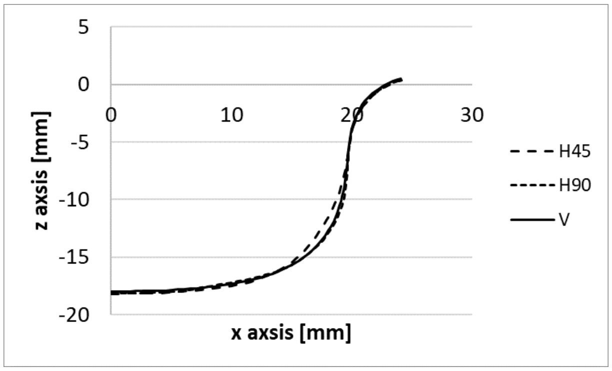
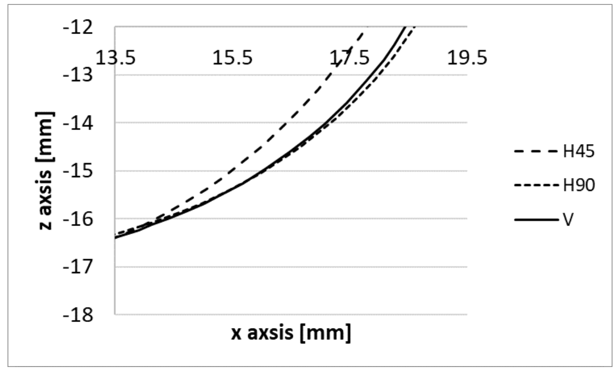
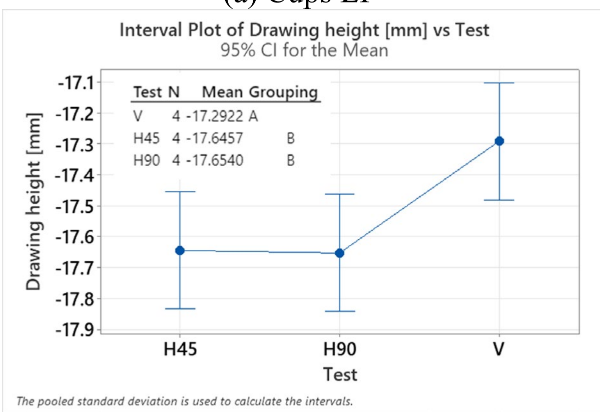


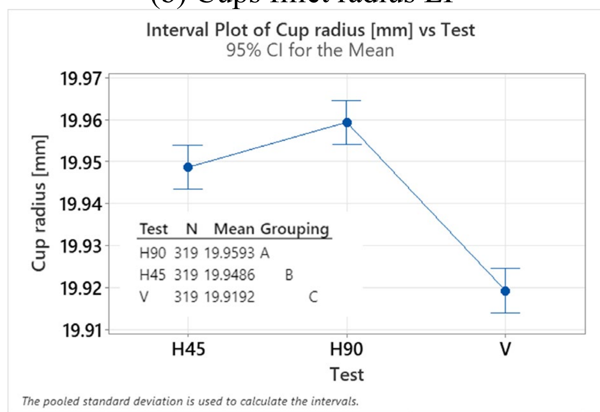
(a) Cups LP



(b) Cups fillet radius LP



(c) Drawing height Tukey results



(d) Cup radius Tukey results

Fig. 4 Main results of cups analysis

Tab.3: average cup radius, standard deviation, roundness tolerances, drawing height

Test	R_{med} [mm]	σ [mm]	r_t [mm]	h_d [mm]
H90	19.96	0.053	0.150	17.65
H45	19.95	0.048	0.148	17.65
V	19.92	0.041	0.131	17.29

Punch Analysis after deep drawing process. Results obtained from the punches analysis after drawing highlight that the process affects tools dimensions. Fig. 5a shows how both distance from top and test configuration are significant for the punch radius; as reported in Fig. 5b punch radius far from the forming zone (distance 15 mm) is quite similar for all tested geometries, on the contrary close to the fillet radius (distance 6 mm) the radius reaches lower values for the horizontal tests (H90). The loss of accuracy of horizontal punches is confirmed by Fig. 5c where a magnification of ¼ CP is plotted. These results are also reported in Tab. 4: test H90 has lower punches radius equal to 18.93 ± 0.49 mm at a distance of 6 mm from the top, moreover it has the higher roundness error (1.50 mm at 6 mm for top and 1.14 mm at 15 mm). Punches produced with axis parallel to z (V) are characterised by lower radius reduction on the fillet radius (19.3 ± 0.1) and lower roundness tolerances (0.4 mm for distance equal to 6). The LP analysis presents a better behaviour for vertical punches with respect to the horizontal ones. Fig. 5d shows a magnification of LP with a focus on the punch fillet radius: in this zone a similar trend could be registered for test V and H45 while test H90 has a higher fillet radius and lower punch height. This trend is confirmed by the values reported in Tab.4.

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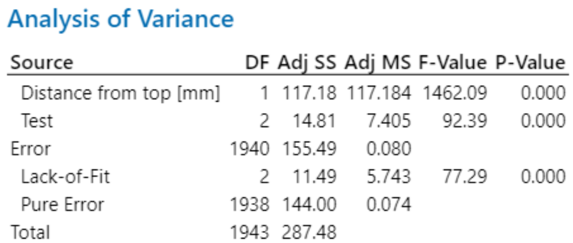
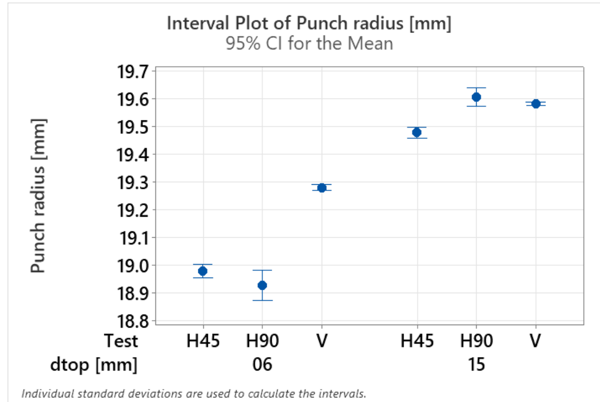


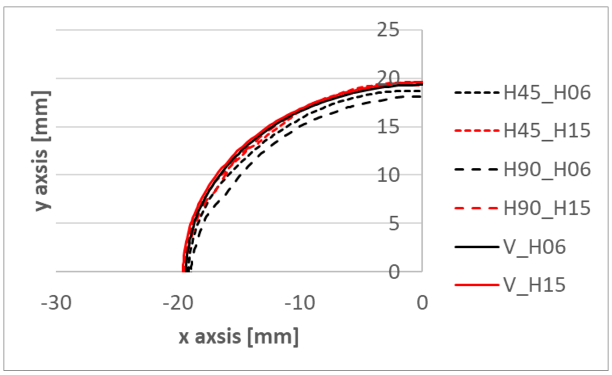
Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Distance from top [mm]	1	117.18	117.184	1462.09	0.000
Test	2	14.81	7.405	92.39	0.000
Error	1940	155.49	0.080		
Lack-of-Fit	2	11.49	5.743	77.29	0.000
Pure Error	1938	144.00	0.074		
Total	1943	287.48			

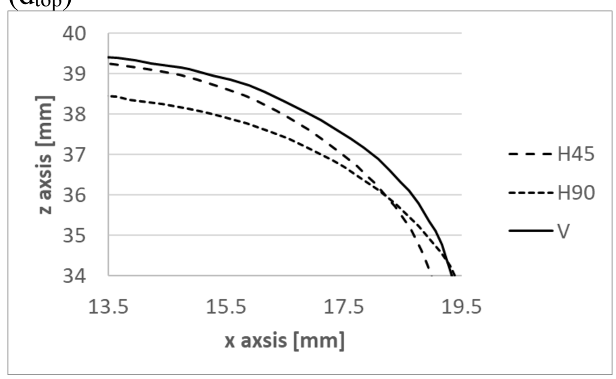
(a) punches radius ANOVA



(b) comparison between measured punches radius at different distance from the punch top (d_{top})



(c) quarter CP of punches



(d) LP of punches fillet radius

Fig. 5 Main results of punches analysis

Tab.4 Average punch radius with standard deviation, roundness tolerances, height

Test	Distance from top [mm]	R_{med} [mm]	σ [mm]	r_t [mm]	h_p [mm]
H45	6.0	18.98	0.230	0.980	39.8
H45	15.0	19.48	0.185	0.762	
H90	6.0	18.93	0.495	1.502	39.3
H90	15.0	19.60	0.294	1.140	
V	6.0	19.28	0.100	0.402	39.7
V	15.0	19.58	0.057	0.256	

Conclusion

In this research the authors investigated the influence of punch orientation on the printing plate produced by FFF technology. The results showed different trends for the tested geometries, in particular:

- Punches produced with axis parallel to z axis (test V) realise cups with lower drawing height, cup radius and cup roundness tolerances; the compression induced by the drawing process reduces punch height and generates a moderate diameter increase (punch radius is 19.5 mm while cup radius is 19.92 mm). This result is confirmed by the punch analysis that identify test V as the best in terms of minimum variation of punch radius acquired at different distances from the top, minimum punch roundness tolerances and higher punch height.
- Punches with horizontal axis and wire orientation at 45° and 135° with respect to the drawing direction (test H45) produced cups having higher heights, linear profile equal to

test V but higher cup radius and roundness tolerances. Punch analysis highlights a permanent deformation that increases fillet radius as it can be observed by the linear profile even if the punch height is coherent with test V (fig.5d). A significant difference can be found observing the radius measured at 6 and 15 mm from the top as shown in fig.5b with a roundness tolerance that reaches 0.98 and 0.76 mm, respectively.

- Punches with horizontal axis and wire orientation at 0° and 90° with respect to the drawing direction (test H90) realise higher cup drawing height but larger cup radius, cup roundness tolerances and from their linear profile it is possible to observe an increase of cup fillet radius compared to test H45 and V. Punch analysis shows results similar to test H45 but with higher punch roundness tolerance (1.5 mm).

Summarising all the results it is possible to assert that the punch orientation on the printing plate affects punch performance during deep drawing; horizontal punches guarantee higher drawing height but less accuracy in terms of cup radius and permanent punch deformation. On the contrary vertical punches guarantee closer roundness tolerances, more accurate profiles but lower drawing height. Future researches are ongoing to evaluate the punches behaviour when the number of produced cups increases.

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