Polymer Shaped Punches Produces with Fused Filament Fabrication to Improve Cup Accuracy in Sheet Metal Forming

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Abstract: Rapid tooling has become an effective solution for reducing time and costs in tool production. In sheet metal forming, polymer tools produced via additive manufacturing offer performance comparable to traditional tools. However, a key challenge in this area is compensating for the radial expansion of polymer tools during the forming process, which leads to reduced accuracy in the produced parts and limits the achievable forming depth. To address this issue, the authors of this study proposed a novel punch design aimed at containing radial expansion, thereby enabling greater drawing depth and improved part accuracy. Different punch geometries were designed with a re-entrant angle varying between 150° and 180°. Numerical simulations were conducted to evaluate the optimal geometry, identifying the 160° angle as the best option to compensate for radial expansion and reduce punch load. Experimental tests were then performed to verify the numerical results, demonstrating the potential of this new design producing cups with higher drawing depth and best radial accuracy.

Keywords: Rapid tooling, polymer, additive manufacturing, sheet metal forming.

1. INTRODUCTION

The substitution of metal parts with polymers in manufacturing has gained widespread popularity across numerous industries, thanks to advancements in polymer technology [1,2]. This transition is influenced by several factors, such as the need for weight reduction; polymers are substantially lighter than metals, making them ideal for applications where minimizing weight is critical, particularly in the automotive and aerospace sectors. Lighter materials help enhance fuel efficiency and performance. In terms of cost-effectiveness, polymers are typically more economical to produce and process than metals. They often require less energy during manufacturing, and their lower density can result in material cost savings. Furthermore, unlike metals, polymers are naturally resistant to corrosion and chemical damage, eliminating the need for protective coatings or treatments. This makes them well-suited for demanding environments [3,4]. Another key benefit is design versatility. Polymers provide greater design freedom compared to metals, enabling the production of intricate shapes and complex designs using methods like injection molding. This versatility allows manufacturers to combine several metal components into a single polymer part, reducing both assembly time and costs [5,6].

Common polymers used as metal substitutes include Polyamide (Nylon), Polycarbonate, Polyetheretherketone (PEEK), Polypropylene, Acrylonitrile Butadiene Styrene (ABS), and Thermoplastic Elastomers (TPE). Nowadays, polymers have found diverse applications across several industries. In the automotive sector, they are utilized in the production of bumpers, dashboards, fuel tanks, and engine covers, leading to reduced vehicle weight and enhanced fuel efficiency [7]. In the aerospace industry, lightweight polymers are used in interior components, structural elements, and insulation materials, contributing to fuel savings and lower emissions. Within the electronics sector, polymers provide excellent electrical insulation and are employed in circuit boards, connectors, and casings for electronic devices [8]. In the medical field, biocompatible polymers are used in implants, prosthetics, and medical devices, offering lightweight, corrosion-resistant solutions [9-11].

In the manufacturing of goods, polymer-based materials are increasingly used to create tooling [12,13], such as molds, dies, and fixtures, in a quick and efficient manner, particularly for prototyping and short production runs. Polymer tooling is generally more cost-effective compared to traditional metal tooling, making it ideal for prototypes and low-volume production, where the high expense of metal tooling cannot be justified [14-16]. Additionally, using polymer materials allows for faster production times, significantly reducing the lead time from design to the finished tool. Polymers are easier to shape and modify than metals, enabling the creation of complex geometries and intricate designs with greater ease [17,18].

To promote the use of polymer tools for rapid tooling application in this research the authors tested it in the production of steel cups by deep drawing process. In literature the tools were already tested demonstrating their advantages in the production of steel and aluminum cups [19,20]; in these researches the authors achieve geometrical accuracy higher than 95% and measured higher improvement when work piece size increase. Bergweiler *et al*. tested the performance of various reinforced polymers but did not

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find an optimal solution when using carbon fiber-reinforced Nylon in the production of DC04 cups obtaining maximum deviation from the desired value equal to 1.5 mm [21]. Athale *et al*. demonstrated that GF-PC polymer additive manufacturing (AM) tools can be used to stamp HSS 590 steel sheets, with accuracy in a range of 1mm, suitable for automotive prototyping volumes (100 formed parts) [22]. Park *et al*. developed and validated a method for predicting the failure mode of a cylindrical cup drawing die made from polyurethane, used for producing AISI 304 and Al 1100 cups. They confirmed that plastic deformation primarily occurs due to wrinkles in the sheet metal when no blank holder is applied, and that the drawing die fails when the maximum principal stress surpasses the die material's flexural strength [23]. Schuh *et al*. conducted a cupping test confirming that Polylactic Acid (PLA) tools provide enough stability for forming sheet metals, yielding results comparable to metallic tools in terms of formability (a deformation of + 0.5 mm) [24]. Additionally, Frohn-Sörensen *et al*. compared PLA and Nylon, showing that PLA offered superior cup accuracy (maximum deviation from CAD equal to 0.8 mm) while Nylon tooling experienced significant degradation after producing just 30 pieces, which further impacted cup precision [25].

In addition to the positive outcomes achieved, one advantage of producing these tools with additive manufacturing is the ability to implement an infill strategy that maintains the external geometry of the tool while reducing the material usage and production time [26,27]. The concept of "light weighting" in tool design involves reducing the tool's weight without compromising performance, durability, or usability. Various infill strategies can be applied, adjusting pattern and density to modify the mechanical properties of polymers [28,29].

Beyond the benefits, the state of the art has highlighted that the loss of accuracy measured in produced objects mainly depends on the plastic and elastic deformations to which the tools are subjected during processing. The primary effect of these deformations is a variation in the drawing depth of the produced cups, and as a secondary effect, there is a change in their width. The compression of the punches induces an expansion in the direction orthogonal to the advancement, resulting in the widening of the produced parts. This defect not only affects the geometric accuracy of the components but is also critical for the effectiveness of the process itself. In fact, the widening reduces the clearance between the punch and the forming die, causing stretching of the sheet during deformation and, in some cases, its rupture, thereby limiting the applicable drawing ratios.

The goal of this work is to address the issue of punch widening during the deep drawing process, ensuring it does not become critical. To achieve this, the authors propose a new punch design with a re-entrant angle, which modifies the punch's outer surface to prevent excessive radial expansion, a key factor in cup production failures. However, selecting the correct re-entrant angle is crucial, as its value affects the punch's volume and, importantly, its weight. A punch that is too light may not withstand the stresses of the steel drawing process, potentially leading to large deformations and instability. Therefore, careful selection of the angle and a thorough analysis of its effect on the process are essential. Initial analyses were carried out using process simulations to determine the optimal angle, followed by an experimental campaign to validate the simulation results

2. MATERIALS AND METHODS

The research activity was divided into the following steps: first, the geometries of the traditional punch and the design logic for shaped tools were defined, followed by the geometry of the forming die and the blank holder. The second step involved simulating the deep drawing process with the different punch designs to identify the most effective geometry. Finally, experimental testing was conducted to compare the performance of the selected punch with the traditional one. The various steps of the research process are summarized in Figure **1**.

In step 1, different shaped punches were designed with forms specifically created to compensate for the radial deformation typical of plastic punches when subjected to compression during the deep drawing process. The punch in its original geometry and its shaped geometry are shown in Figure **2a** and Figure **2b**, respectively. As can be seen, the shaped punch is characterized by two design parameters: the re-entrant angle α and the minimum distance d between the outer surface and the punch axis. In this work, three punches

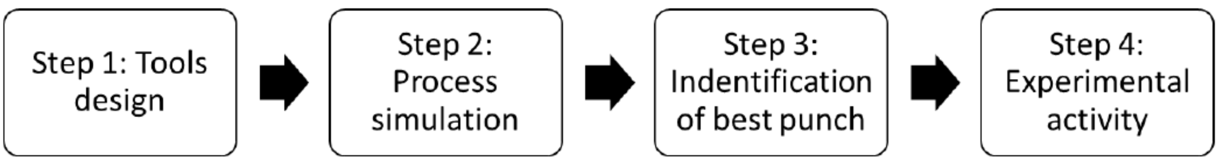


Figure 1: Scheme of research activity.

were designed with α values of 170°, 160°and 150°. It is important to note that the traditional punch corresponds to a shaped punch with an angle of 180°, while values smaller than 150° posed the risk of creating interpenetrating geometries. Table **1** summarizes the design data for the shaped punches. Additionally, Figure **1** shows the main dimensions of the die (Figure **2c**) and the blank holder (Figure **2d**).

For the deep drawing process simulation, the same settings used by the authors in a previous study focused on evaluating the performance of traditional punches were applied [19]. In summary, the simulation involved producing a 20 mm deep cup and 19.5 mm internal radius from an AISI 304 steel sheet with a radius of 42.5 mm and a thickness of 1 mm. The drawing ratio for this process was 2.2.

A finite element analysis (FEM) was conducted using Deform 3D software (SFTC, Columbus, OH, USA). Figure **3** illustrates the simulation setup, showing all components modelled for the process: the punches and blanks were treated as plastic bodies and meshed using tetrahedral elements, while the press, forming die along with the blank holder, were modelled as rigid. To determine the best balance between element size and computational efficiency, the minimum element length was set equal to1.5 mm for all simulations. This resulted in approximately 15000 elements for the blank and 50000 for the punch. The mechanical properties of AISI 304 were sourced from the software's database, while for punches, coherent with the experimental activity, Nylon filled with short carbon fiber was set; composite properties were added into software database from the literature [30,31]. The press speed was fixed at 10 mm/s, and the blank holder load was set to 1 kN. A shear friction factor of 0.1 was used to simulate lubrication in the contact areas between punch, blank, forming die, and blank holder [32]. The simulation employed a step increment of 0.01 seconds, totalling200 steps. The mechanical joints connecting the punch to the upper press was recreated by fixing the contact nodes together. The process was simulated using a LaGrange incremental method.

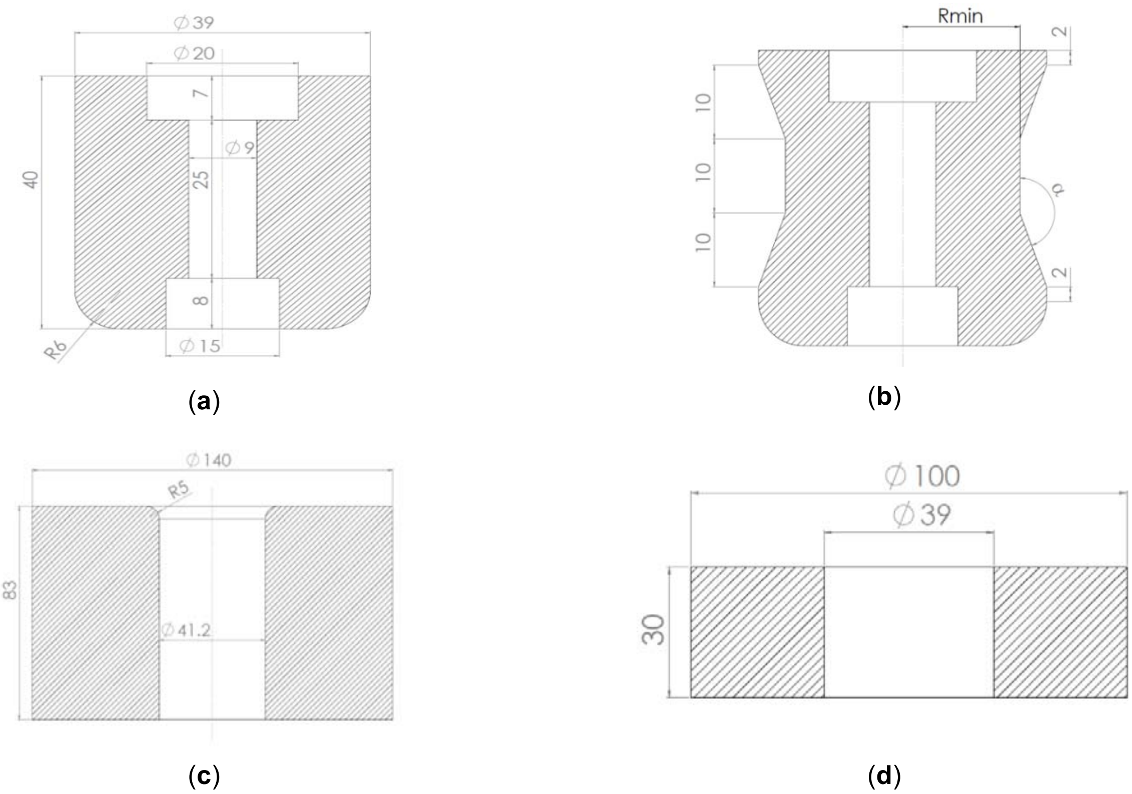


Figure 2: Main dimension of Traditional punch (**a**); Shaped punch (**b**); Forming die (**c**); Blankholder (**d**).

Table 1: Shape Inclination (A) and Minimum Distance from Axis (D) of the Designed Punches

Punch name	α [grad]	R_{min} [mm]
Traditional (T)	180	19.50
Light Shaped (S_170)	170	17.74
Medium Shaped (S_160)	160	15.86
Strong Shaped (S_150)	150	13.73

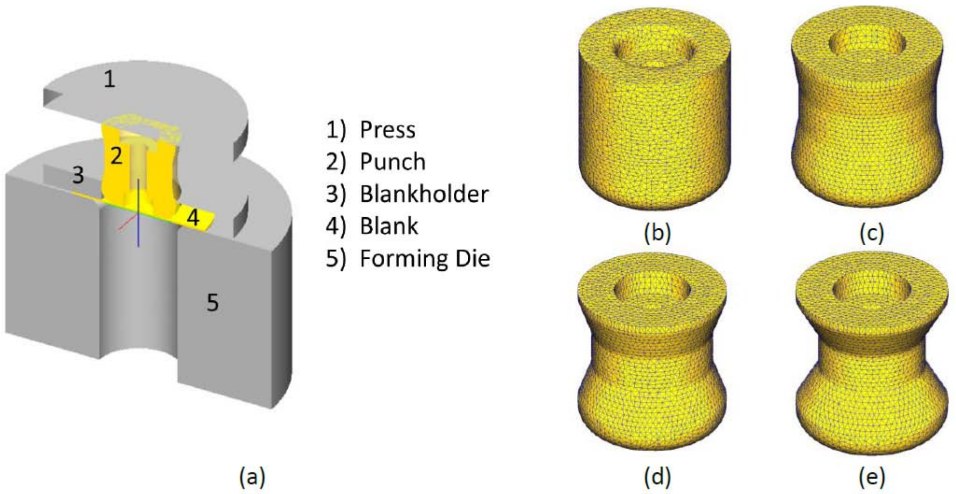


Figure 3: Set up of the simulation (**a**); traditional punch (**b**), S_170 (**c**), S_160 (**d**), S_150 (**e**).

At the conclusion of the simulations aimed at determining the optimal punch geometry, the forces and energies exerted by the punches were recorded to assess any potential energy differences. Additionally, the axial and radial displacements were measured to evaluate the deformation experienced by the punches, and the stress applied to the sheets to form the cups was also analyzed.

Once the optimal punch was selected, it was fabricated along with the traditional punch. The parts were produced using a Mark 2 machine (Markforged, Watertown, MA, USA), which operates with Fused Filament Fabrication technology. The commercial material used was Onyx, supplied by Markforged. For the punch fabrication, a full infill strategy was chosen with a layer thickness of 0.1 mm. The punches were printed with their axis aligned parallel to the z-axis of the machine.

The experimental tests were conducted using the EVL/400-A press (Galdabini, Varese, Italy), which has a capacity of 400 tonnes. The press was operated with a maximum load of 180 kN, and the punch speed was maintained at 10 mm/s. The thickness of the AISI 304 blanks was 1 mm, with a punch-die clearance of 1.1 mm, and the blank-holder load was set to 1 kN, in accordance with industrial standards. A mineral oil served as the lubricant during the tests. Two cups for experiments were produced to test process precision.

To assess the accuracy of the produced cups, two different measurements were taken: a cross-sectional measurement to calculate the drawing depth, and a circumferential measurement at a distance of 10 mm from the bottom to evaluate the circularity and average radius of the cups. The measurements were obtained using a Cyclone Series 2 coordinate measuring machine (Renishaw, Wotton-under-Edge, UK). Figure 4 illustrates the method followed for data acquisition.

3. RESULTS

This paragraph presents the main results of the numerical simulations that led to the selection of the punch with the best performance. Following this, the results of the experimental activity are discussed, where the selected punch was compared with the traditional punch in the production of the studied cups

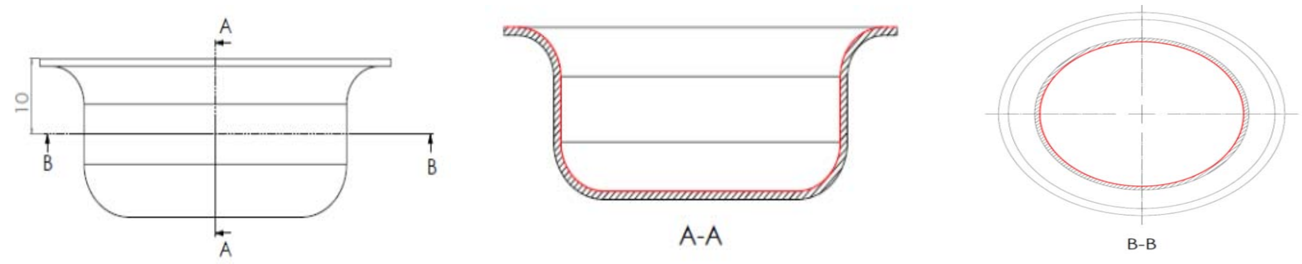
3.1. FEM Results

Figure **5** shows the graphs of force and energy evaluated for the different punches used over time. By analyzing the forces, it is possible to observe a linear increasing trend for all the simulations conducted. It is also evident that an increase in the inclination angle α is directly proportional to the increase in the slope of the line, resulting in a higher maximum value (it is important to note that the traditional punch T is simply a shaped punch with an inclination of 180°). A similar trend was measured for the energy, with the difference that in this case, the trend is no longer linear but can be approximated by a second-degree polynomial.

The comparison, both in absolute terms and as a percentage relative to the traditional punch T, of the maximum forces and energies is shown in Table **2**. Analyzing the values, it can be observed that the inclined punches, being effectively lighter, use up to 12% less force and 10% less energy compared to the traditional punch.

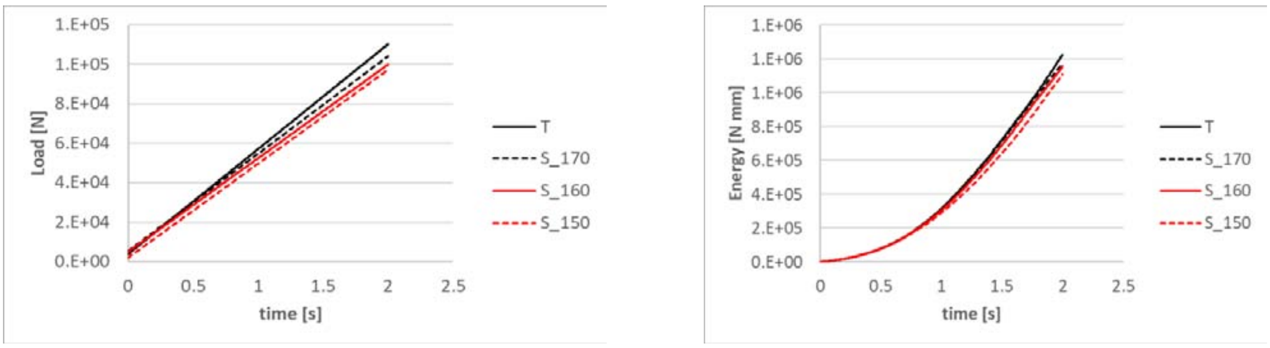
In order to assess any deformations experienced by the punch during the deep drawing process, false color maps related to depth and radial displacement were plotted, shown in Figure **6a** and Figure **6b**, respectively.

To better understand the graphs, it is important to specify that in the graph in Figure **6a**, for a rigid and non-deformable punch, the displacement should be uniform across the entire punch and equal to 20 mm.



(**a**) (**b**) (**c**)

Figure 4: Cup draft with cross section selected (**a**); side linear profile (**b**), circumference profile (**c**).

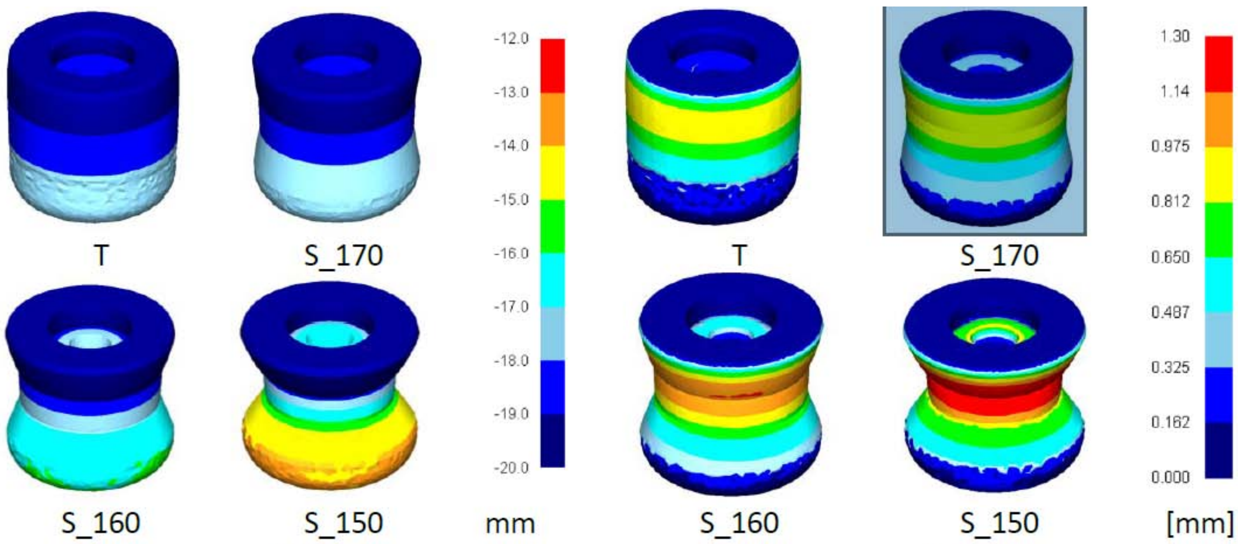


(**a**) (**b**)

Figure 5: Punch Load (**a**) and Energy (**b**) as a function of time.

Table 2: Maximum Load and Energy Acquired with the Related Percentage Difference with the Traditional Punch

	F_{max} [N]	%	E_{max} [N mm]	%
T	1.10E+05		1.23E+06	
S_170	1.04E+05	6%	1.18E+06	4%
S_160	1.00E+05	9%	1.16E+06	6%
S_150	9.73E+04	12%	1.11E+06	10%



(a) (b)

Figure 6: False colour map of Punches height (**a**) and radial displacement (**b**) with relative scale bar achieved at the end of simulations.

On the contrary, if the punch undergoes deformation due to compression, the reported displacement value decreases. A logical consequence of the decrease in displacement is the production of cups with less depth.

Based on this premise, it is possible to observe that all the punches analyzed experience a reduction in height due to the compressive forces developed during the process. Specifically, it can be seen that the minimum displacement value is located in the area of the punch in contact with the cup, gradually increasing up to 20 mm in the area in contact with the press. A quantitative analysis of the data shows that the traditional punch already experiences a loss of about 1.5 mm, and this value increases as α increases in a non-linear manner, resulting in a loss of approximately 2 mm for the S_170 punch, 3.5 mm for the S_160 punch, and nearly 6 mm for the S_150 punch.

Regarding the radial expansion experienced by the punches during the process, the value shown on the false color map in Figure **6b** refers to how much the punch has widened compared to its original dimension. Here, too, larger deviations are observed for greater inclinations. However, unlike the depth displacement, these deviations are located above the median section of the punch, with the minimum recorded in the area in contact with the press and in the radius transition area of the punch. Consistent with the physics of the process, it is reasonable to assume that radial expansion would produce cups with a larger diameter than estimated. Furthermore, this radial expansion tends to reduce or even eliminate the clearance distance between the punch and the forming die, thus preventing the sheet from sliding and leading to potential fracture. However, in order to correctly evaluate the results, it is necessary to consider that the inclined punches do not have a constant radius and are therefore able to deform radially while still ensuring defect-free cup production. If we examine the simulation performed with the S_150 punch, Figure **6b** shows a radial expansion of about 1.6 mm. However, observing Table **1**, it is clear that the minimum radius is 13.73 mm, meaning that despite the radial expansion, the punch radius is still far from the cup wall, which ideally measures 19.5 mm. To better analyze these results, Figure **7** presents a detailed view of the radial displacement, including the cup and the forming die.

From the analysis of the image, it can be inferred that, from a radial expansion perspective, the S_160 and S_150 solutions are the most advantageous, as contact with the sheet metal is present only in the

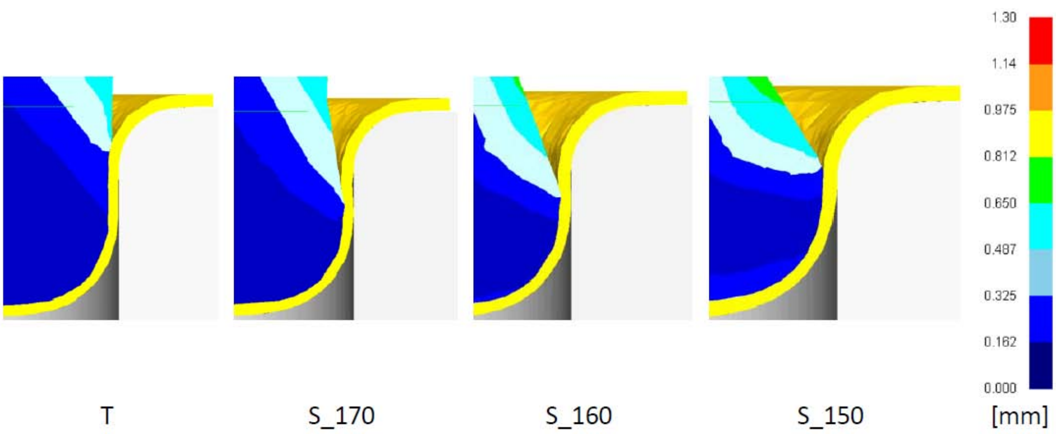


Figure 7: Detailed view of Punches radial displacement together with cup and forming die at the end of simulation.

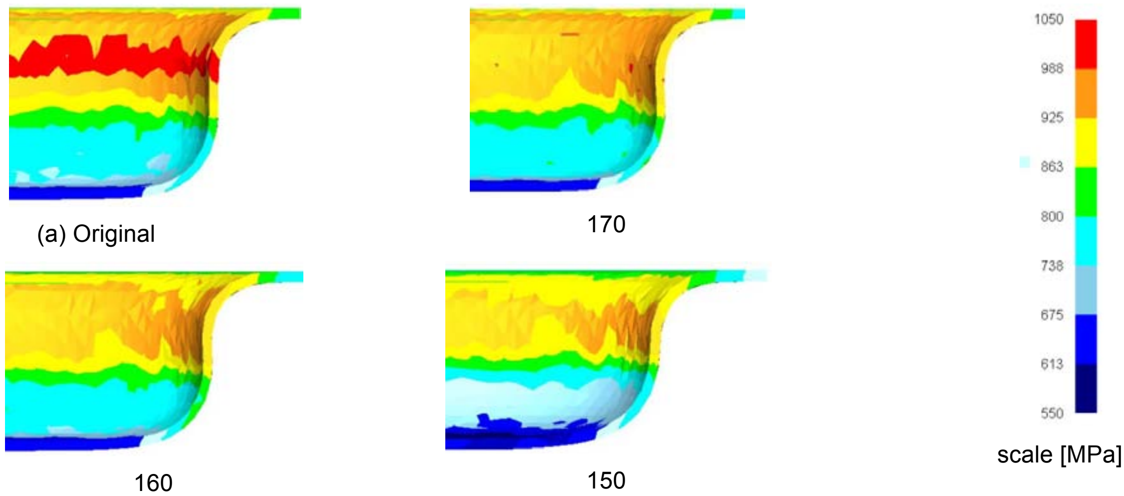
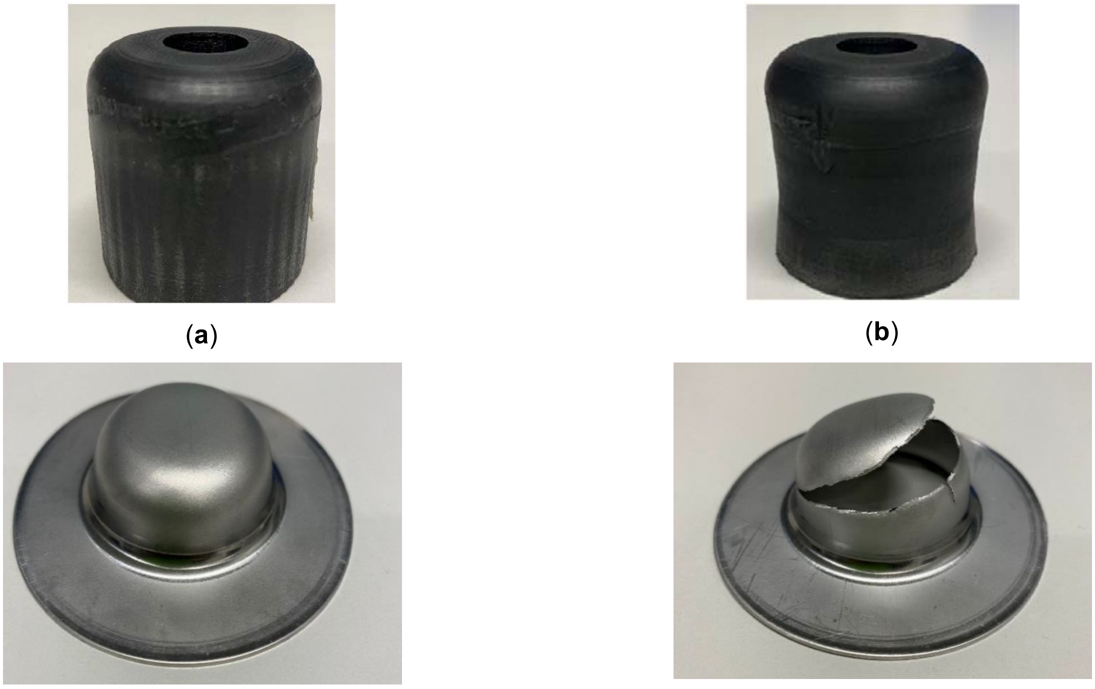


Figure 8: False colour map of cups stress effective achieved at the end of simulation as a function of the different punches tested.



(**a**) (**b**) (**c**) (**d**)

Figure 9: Photo of traditional (**a**) and S_160 (**b**) punch after cups production. Example of cup correctly produced (**c**) and with fracture defect (**d**).

punch's radius area. The final comparative analysis for the selection of the optimal punch was the evaluation of the stress experienced by the sheets during the deep drawing process. Figure **8** shows the false color map of the effective stress accumulated by the cups at the end of the simulation.

Analyzing the figure, it can be seen that the stress on the cups is lower in the bottom area, ranging between 550 and 600 MPa for all simulations, and increases along the cup wall, reaching its maximum near the forming die fillet. Comparing the results, the traditional punch generates higher stress on the cup, both in terms of maximum value (around 1000 MPa) and the extent of the area with stresses above 900 MPa. The varying stresses on the cups are consistent with the different values of maximum force and energy reached during the simulations.

Resuming all the simulations results, it is clear that increasing the re-entrant angle α offers advantages in terms of reducing maximum force and energy, as well as decreasing radial expansion, meaning less widening of the cup due to the radial expansion of the punch, and producing cups that are generally less stressed. On the other hand, the simulations revealed a reduction in punch height due to compressive forces typical of the process, which can result in a compression of around 6 mm in the case of the S_150 punch.

Based on these results, the authors identified the S_160 punch as a good compromise between the advantages listed above and a loss of deep drawing accuracy of around 3.5 mm.

3.2. Experimental Results

Following the simulations, the S_160 geometry was chosen as the optimal one to be compared with the traditional geometry; once produced, the punches were used for experimental activities, setting strokes of 20 and 25 mm. Two cups per punch type and stroke were produced. The 25 mm stroke was tested because, based on the numerical analysis of punch height displacement, it is reasonable to expect cups with a depth smaller than the stroke set on the punch. Furthermore, to evaluate the actual improvement in radial displacement and the possibility of setting larger strokes to obtain deeper cups, two different strokes were set: 20 and 25 mm. The cups were correctly produced without visible defects. Figure **9a** and Figure **9b** shows the traditional punch and the S_160 after their use in the experimental activity, respectively. Observing Figure **9a**, it is evident that the lateral surface of the punch shows striations due to forced sliding with the sheet, while, on the contrary, the S_160 punch (Figure **9b**) does not have such defects, although it shows a final height of XX, indicating some compression during the process. Regarding the production of the cups, both punches were able to produce those with a depth of 20 mm; Figure **9c** shows an example (S_160 punch) of a correctly produced cup. Conversely, for the cups produced with a 25 mm stroke, only the S_160 punch was able to manufacture them,

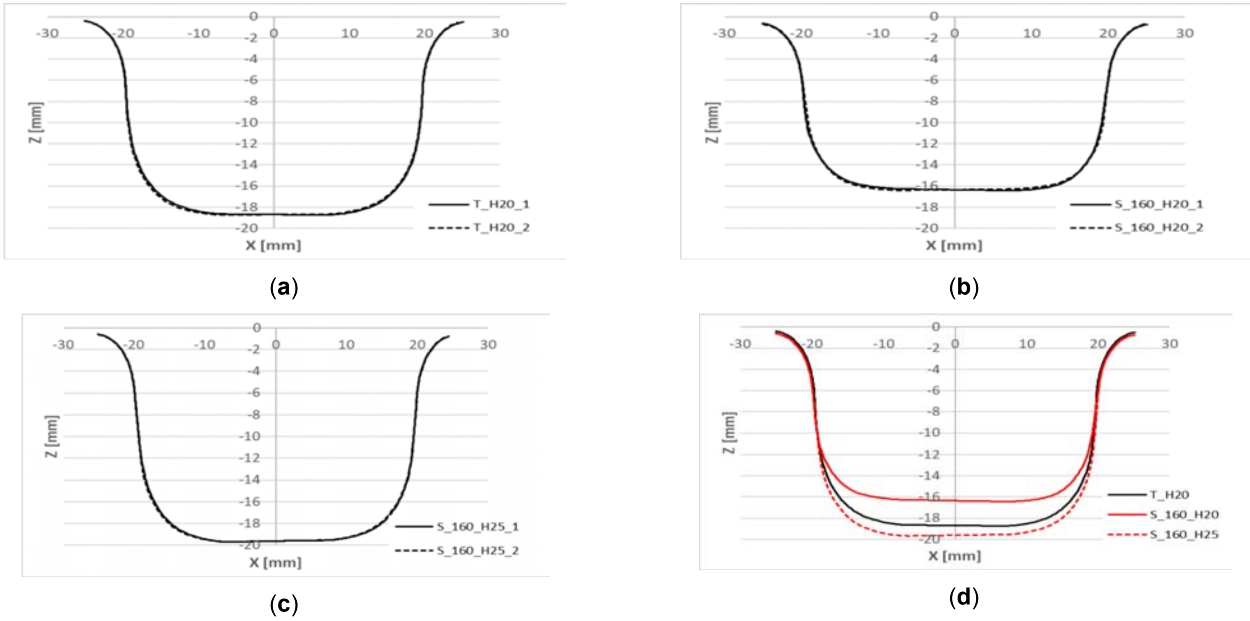


Figure 10: Side linear profile measured for cups produced with Traditional T punch and drawing depth equal to 20 mm (**a**); S_160 and drawing depth 20 mm (**b**) and 25 mm (**c**); comparison of all profile measured (**d**).

Figure 11: Circular profile measured for all experiment executed (**a**); histogram plot of average radius measured with standard deviation bars (**b**).

Figure 12: comparison between cups produced with S_160 and drawing depth 20 mm (left); T 20 mm (middle); S_160 depth 25 mm (right).

while the cup made with the traditional punch experienced a fracture, as shown in Figure **9d**.

In Figure **10**, the graphs of the measurements acquired with the CMM related to the lateral profile of the cups produced with the different punches and different strokes (H) are shown. Observing the graphs 10a, 10b, and 10c individually, it can be seen that the process is highly repeatable, in terms of cups profile, for each of the tested punches. As expected, the S_160 punch undergoes significant compression during the process, resulting in a cup with a depth of about 16 mm, which is 80% of the expected measurement. On the contrary, with the traditional punch, a depth of about 18.5 mm (92.5%) was measured. Observing the lateral profile of the cup obtained with the S_160 punch, but increasing the stroke to 25 mm, it is possible to observe an improvement in the dimensional accuracy of the drawing depth, obtaining a cup of 19.5 mm (97.5%). To better highlight the differences between the different profiles obtained, the graph in Figure **10d** is shown.

Analyzing the circumferential profiles shown in Figure **11a**, it can be observed that these profiles overlap. Meanwhile, looking at the histograms in Figure **11b**, the added value of the inclination becomes evident, allowing for cups with a radius closer to the CAD compared to those obtained with the traditional punch. Specifically, the average radius values measured for the cups drawn with a 20 mm punch stroke are 19.73 mm for the traditional punch and 19.63 mm for the S_160 punch. Cups produced with a 25 mm stroke using the S_160 punch further improve the average radius, bringing it closer to the CAD value (19.54 mm).

In conclusion, it was measured that the inclined S_160 punch is able to produce more precise cups compared to the traditional punch, both in terms of drawing depth and average radius. However, achieving these performances is ensured by increasing the stroke of the punch itself. Figure **12** shows images of the cups produced during the experimental activity.

4. DISCUSSION

The results obtained highlighted how the proposed geometry increased the drawing depth and improved radial accuracy. As already noted in the literature for similar works [21,22,25], the punches undergo deformations in the order of millimeters, which implies a loss of precision in the production of the cups. However, with traditional punches, as also observed in [19], increasing the punch stroke to improve the drawing depth is not an effective solution, as the increase in punch radius nullifies the clearance distance, crushing the cup between the punch and die, resulting in breakage. FEM simulations have shown that creating a re-entrant angle does not reduce its radial expansion; rather, it increases it. However, not only not affect the cup radius but it prevents the punch from pressing the cup along the die, allowing for higher punch strokes without the risk of breakage. This advantage, as demonstrated by experimental tests, can be useful because it allows for an increase in punch stroke to achieve cups with a depth close to the desired value.

CONCLUSION

In this study, a new polymeric punch geometry featuring a re-entrant angle was proposed to compensate for radial deformations experienced during the deep drawing process of steel sheets. Three punches with re-entrant angles of 170°, 160°, and 150° were designed. A numerical analysis was conducted to examine the behaviour of these punches and compare them to the traditional cylindrical geometry. The case study involved deep drawing an AISI 304 blank with a diameter of 42.5 mm and a thickness of 2 mm to produce a cup with an internal diameter of 19.5 mm and a depth of 20 mm. The numerical analysis identified an optimal inclination angle of 160°, which reduced forces and energy consumption while preventing contact between the punch and the cup wall during formation. However, simulations revealed significant compression along the punch's drawing axis due to its reduced weight, limiting the achievable drawing depth. To compensate for this limitation, the experimental campaign aimed at validating FEM results increased the depth by 25%, resulting in cups with more accurate dimensions in terms of depth and average radius compared to the traditional punch, achieving a depth of 19.5 mm and an internal radius of 19.54 mm.

Future work will focus on evaluating the performance of this new geometry in medium- to large-scale production and developing a model capable of predicting punch stroke as a function of cup depth.

ACKNOWLEDGEMENT

The authors are grateful to R. Pinti of Pinti Inox S.p.a. – Sarezzo (Brescia) for the experimental campaign and the CMM analysis.

FUNDING

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript."

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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Received on 19-08-2024 Accepted on 16-09-2024 Published on 17-10-2024

https://doi.org/10.6000/1929-5995.2024.13.18