INFLUENCE OF POLYMER TYPE ON TOLERANCE IN ADDITIVELY MANUFACTURED BENDING DIES

Cristian Giolu [1], Cătălin Gheorghe Amza[2] and Constantin Alex Sumanariu[3]

[1] National University of Science and Technology Politehnica Bucharest, Faculty of Industrial Engineering and Robotics, cristian.giolu@gmail.com

[2] National University of Science and Technology Politehnica Bucharest, Faculty of Industrial Engineering and Robotics, catalin.amza@upb.ro

[3] National University of Science and Technology Politehnica Bucharest, Faculty of Industrial Engineering and Robotics, sumanariuc@yahoo.com

ABSTRACT: This research paper explores the influence of different polymer materials on the tolerance and performance of additively manufactured bending dies used in sheet metal forming. Traditional bending dies, commonly made from high-strength metals like steel, are both time-consuming and costly to produce, especially for small-batch or custom parts. Additive manufacturing (AM), specifically 3D printing, offers a cost-effective alternative by utilising polymers for the dies. The study employs Finite Element Analysis (FEA) using ANSYS software to compare the performance of polymer-based dies against conventional metal dies. It examines various parameters, including sheet thickness, material elasticity, and deformation behaviour during the bending process. The results highlight that while polymer dies show greater elastic deformation and springback compared to metal dies, certain materials like PLA and PET provide superior performance in terms of dimensional accuracy and durability.

KEYWORDS: Additive manufacturing, Bending die, Sheet metal, 3D printing,

1. INTRODUCTION

Sheet metal bending is a critical process in various industries, including automotive, aerospace, and construction, where precise and durable components are essential. This process involves the plastic deformation of metal sheets into desired shapes, using bending dies, which are traditionally manufactured from high-strength materials like steel. However, the production of these metal dies is both time-consuming and costly, especially for small batch production or custom parts. This has driven the search for more cost-effective and flexible alternatives.

In recent years, the advent of AM, commonly known as 3D printing, has opened up new possibilities for producing functional parts, including bending dies, from polymers. These polymer-based dies are not only faster to produce but also significantly cheaper compared to their metal counterparts. The reduced cost and production time make researchers in the industry increasingly study this concept, particularly due to its potential for implementation in small-scale manufacturing and rapid prototyping applications.

Grigoraș et al. [1] explore the potential of using AM for creating stretch-forming dies. The study focuses on using polylactic acid (PLA) as the material for 3D printed dies, evaluating its performance in the stretch forming of aluminium 2024-T0, commonly used in the aviation industry for aircraft skin. The research investigates the impact of various process parameters, including punch radius, material thickness, and deformation speed, on the dimensional accuracy and mechanical properties of the formed parts.

The findings reveal that smaller punch radii result in higher punch forces and increased deviations from circularity, correlating with a more pronounced springback effect. Despite the relatively high deformation forces, the 3D printed dies maintained their structural integrity, showing no significant damage or dimensional deformations during the stretch-forming process. This demonstrates the feasibility of using 3D printed PLA dies for low-volume production and prototyping, offering a cost-effective alternative to traditional metal dies.

Further studies by Tondini et al. [2] evaluate the performance of 3D printed polymer tools in sheet metal forming processes, focusing on V-bending and groove pressing of 1 mm aluminium sheets. The study explores the use of Fused Filament Fabrication (FFF) and Vat Photopolymerization Additive Manufacturing (VPAM) to produce these tools, assessing their geometrical accuracy, wear resistance, and overall suitability for forming applications.

The research finds that FFF-printed tools, despite being less accurate than those produced by VPAM, offer sufficient precision for prototyping and small-batch production. The study demonstrates that the tools undergo surface changes during the initial strokes, reaching a steady state after approximately five strokes, with minimal further wear. In V-bending, the elastic deflection of the tools significantly influences the final geometry of the formed parts, particularly in terms of springback and bend radius. The study also highlights the importance of the punch nose radius relative to the shell thickness of the printed tools, noting that deviations in the formed components can be attributed to the accuracy of the printed tools themselves.

This study explores the feasibility of using 3D-printed polymer dies for sheet metal bending. By investigating the mechanical properties and performance of these novel dies, the research aims to establish whether they can meet the functional requirements of industrial bending processes. If successful, this approach could revolutionise the way bending dies are manufactured, offering a more efficient and economical alternative to traditional methods.

In a related study, Strano et al. [3] investigate the use of 3D printing, specifically extrusion-based additive manufacturing (EAM), for producing polymeric tools for sheet metal applications, focusing on V-die air bending of aluminium and mild steel sheets. The study utilises PLA as the material for the dies, with various parameters such as die opening size and raster orientation being analysed through simulations to optimise the mechanical behaviour of the PLA tools.

The research demonstrates that a raster orientation of 45–0–45 and a die opening size between 8 and 12 mm yield the best strength for the PLA-based V-die. Under real-life testing conditions, the 3D printed PLA die showed comparable springback behaviour to traditional metal tooling and maintained its structural integrity over more than 100 repeated bends without significant deterioration.

However, the study found that the PLA tools were not capable of bending 2-mm thick sheets, indicating that these tools are more suitable for short-run production and thinner materials.

Additionally, Nakamura et al. [4] investigate the applicability of plastic tools, specifically those manufactured using fused deposition modelling (FDM), for sheet metal forming processes such as V-bending and deep drawing.

The study examines the mechanical limitations of plastic tools, including lower stiffness and yield stress compared to traditional steel tools, which result in reduced dimensional accuracy of the formed parts. To address these challenges, the authors explore methods to enhance tool performance, such as reinforcing the plastic tools with steel bars and modifying the tool shapes to correct for elastic deformation and springback.

The research demonstrates that while plastic tools exhibit lower initial accuracy, their performance can be significantly improved with structural reinforcements. For instance, the reinforced plastic tools showed improved dimensional accuracy in V-bending, approaching that of steel tools.

Additionally, the study finds that plastic tools are particularly effective in preventing scratches on the metal surface during forming, an advantage over steel tools in certain applications.

Although studies have shown that the process is feasible under certain circumstances, there remain issues related to the precision of this concept, as highlighted in the research [2, 3, 4].

This paper aims to address these issues by investigating the influence of polymers on the accuracy of the workpieces.

2. MATERIALS AND METHODS

The process consists in analysing the V-bending process of a part by means of FEA using different parameters regarding the sheet thickness and materials used to manufacture the device. Subsequently, the materials that had the best behaviour in relation to the bending of the part and the deformations occurred in the device after the process, will be analysed regarding their influence on the dimensional deviations of the resulting parts. At the same time, the performances of devices made of polymers will be compared with those of a conventional device made of metal to complete the picture of the capacity of this novelty.

2.1 Workpiece Design

The workpiece selected for this study is a V-shaped component with side lengths measuring 75 mm and an inner radius of 4.5 mm. To comprehensively evaluate the performance of the AM-produced die, tests will be conducted on sheet metals of varying thicknesses, specifically 0.5 mm, 1 mm, 1.5 mm, and 2 mm (illustrated in Figure 1). This variation in thickness will provide insights into the die's adaptability and the mechanical behaviour across different material gauges, allowing for a deeper understanding of potential deformation patterns, stress distribution, and the overall precision of the process under different conditions.

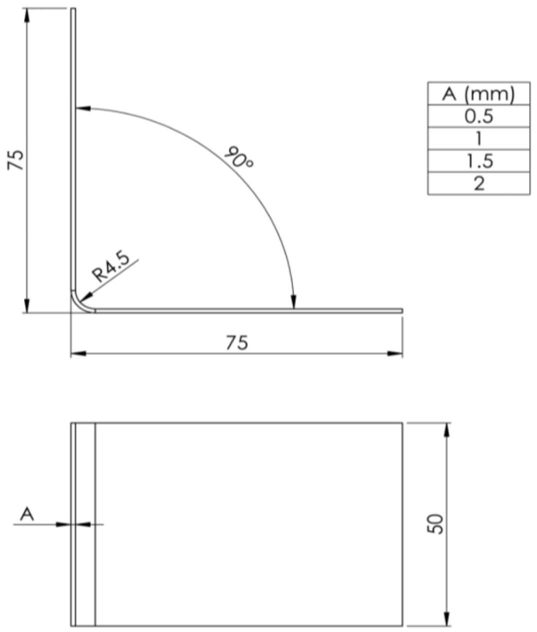

Figure 1. Bending part dimensions

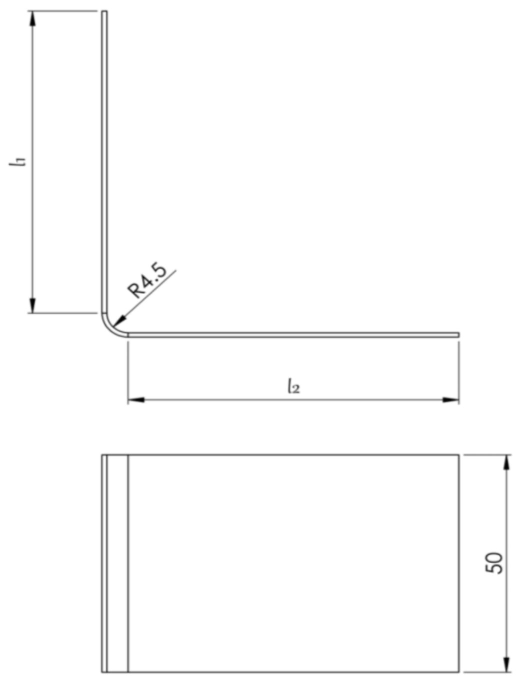

Figure 2. Bending part segments

In order to start the design process of the device, it is important to determine the dimensions of the unfolded part (Fig. 2), using the equation:

$$L = l1 + l2 + 2(r + xS) \tag{1}$$

where:

L—length of the flat portion;

r—inner radius of the bend;

x—coefficient with which the position of the neutral layer is determined;

S—thickness of the sheet metal.

Table 1 gives the values of the coefficient x (verified in practice) for the 90° bending of wide steel blanks. The values of the coefficient x refer to the case when bending occurs without stretching the bent strips, as well as without their thinning or stiffening between the die and the punch [5].

Table 1. Values of the coefficient x for bending at 90°

$\frac{r}{S}$	0.1	0.2	0.25	0.3	0.4	0.5	0.6	0.8
x	0.3	0.33	0.35	0.36	0.37	0.38	0.385	0.405
$\frac{r}{S}$	1	1.5	1.8	2	2.5	3	4	5
x	0.42	0.44	0.45	0.455	0.46	0.47	0.475	0.48

Lastly, in order to be able to determine the length of the unbent part, it is chosen to calculate for the case when its thickness is 1mm

$$l1 = l2 = 69.5\ mm$$

r=4.5 mm
x=4.5
S=1 mm

thus, the formula becomes:

$$L = 69.5 + 69.5 + 2(4.5 + 4.51)$$

$$L = 153.1\ mm.$$

With the dimensions of the blank determined, the designing process of the bending die can start.

2.2 Tool design

The development of the device model for analysis using FEA is limited to the modelling of the active components of the die, the other parts not presenting a significant influence on the analysis data. Thus, the punch and the bending plate will be designed using the conventions specific to conventionally manufactured devices.

2.2.1 Punch

The punch is a key component of the bending device, applying pressure to the workpiece and imparting the desired shape to it. In the design process, the inner shape of the bent area is used to determine its form. Thus, the punch is represented by a prism responsible for forming sheet metal parts and a base equipped with features for accommodating assembly components, ensuring its attachment to the upper plate (Fig. 3).

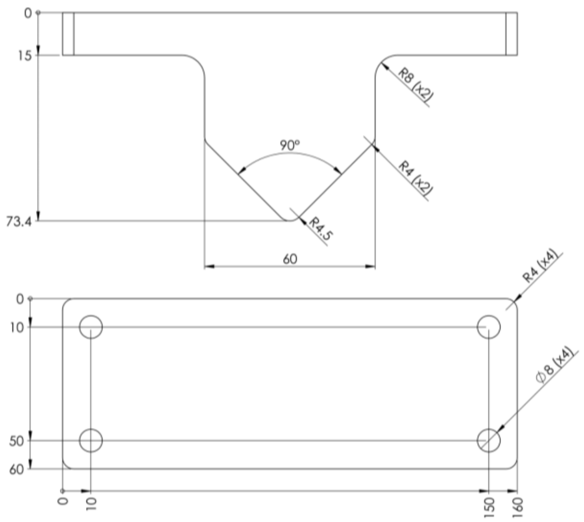

Figure 3. Punch dimensions

2.2.2 Bending plate

The forming (bending) plate (Fig. 4) serves the purpose of providing the mechanical support necessary for the deformation of the sheet metal part, acting as the negative die (in contrast to the punch, which is considered the positive die) for forming. It also includes structures for accommodating assembly components, enabling its attachment to the mounting bracket using ISO 4762 M10 cylindrical head screws with hexagonal sockets.

Its shape and dimensions are determined by the characteristics of the processed sheet metal that it must accommodate, resulting in a parallelepiped with a V-shaped material cutout. Additionally, the bending plate is designed with a concavity intended to accommodate all sizes of workpieces, eliminating the need for designing and manufacturing multiple bending plates.

Since most of the bending forces within the device will be concentrated on the bending plate, its height is specifically chosen to be greater to increase its resistance to mechanical stress. Consequently, it is designed to be equivalent to its counterpart made from conventional materials (as such, a height of 60 mm has been assigned), with the possibility of modifying this dimension later if required.

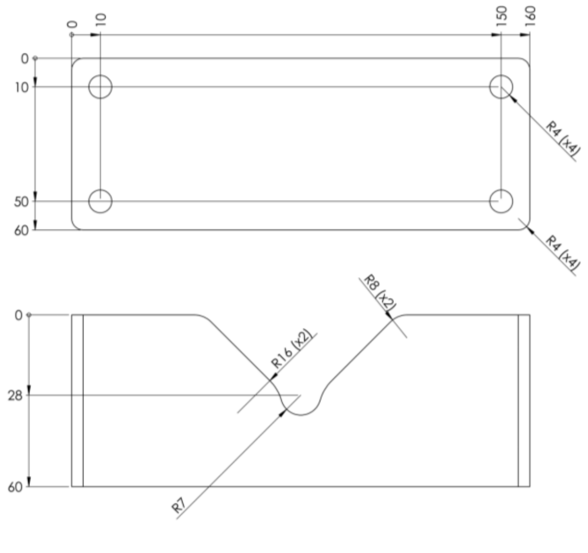

Figure 4. Bending plate dimensions

The model thus designed exhibits the characteristics that will allow it to be subsequently manufactured using MEX technology and assembled alongside the other components that will define the entire die assembly.

The next step involves conducting finite element analysis on the designed components to study their behaviour and thereby obtain theoretical confirmation of the experiment.

2.3 F.E.A.

Ansys is a comprehensive engineering simulation software platform used to model, simulate, and analyse the behaviour of physical systems in a virtual environment. It uses FEA to predict how products or systems will respond to different forces, stresses, temperatures, and other physical factors [6].

For this stage, the decision was made to use Ansys software, where a simulation will be conducted on a conventionally manufactured steel device, with the results being compared to a series of similar devices made from polymers. The process will involve model preparation, performance measurement, and strength analysis. The version used is 2022 R1.

2.3.1 Model simplification

SpaceClaim is a 3D modelling software designed for engineers and simulation specialists to quickly create, edit, and prepare geometry for simulation, manufacturing, or 3D printing. It is part of the Ansys suite and is known for its ease of use, flexibility, and speed in handling complex geometries without the need for specialised CAD knowledge [7].

To simplify the model, SpaceClaim was used, where features such as screw holes and fillet radii (where not necessary) were removed to enable faster solution calculation. The Fill function was employed to fill gaps in selected regions or to remove specific elements, such as the mounting holes along with some fillet radii.

2.3.2 Materials

For the simulation of a conventionally manufactured device, D2 steel was assigned as the material for the active components of the die, as it is frequently used in industry due to its high wear resistance. For the metal sheet, DIN 1.1121 steel was selected, given its processing reliability, which makes it suitable for cold forming processes.

2.3.3 Connections

For the contacts between parts, the Frictional method was selected, with a friction coefficient of 0.03 [8], to simulate a process where lubrication is used at the contact points between the active components and the workpiece [4,9]. These contacts are found at the punch-workpiece and bending plate-workpiece interfaces. To simulate the stamping process, the bending plate was fixed at the bottom, similar to its attachment to a base plate.

2.3.4 Mesh generation

Given the general parallelepipedal geometry of the parts, cuboid-shaped mesh elements were assigned to ensure a regular and uniform element distribution. This approach allows for a more efficient computation, reducing both the time required for analysis and the likelihood of errors during the solving process.

After evaluating the results from multiple iterations where different element sizes were tested, it was determined that a 2 mm element size provided the optimal balance between computational accuracy and efficiency. Consequently, the Hex-dominant meshing method was selected with a 2 mm element size, achieving a uniform element distribution of cuboid shape.

In regions characterised by complex geometries or high stress gradients—such as the connection radii of the forming plate—additional meshing techniques were applied. Local mesh generation strategies and mesh control tools were employed to ensure a high-quality, uniform mesh. These measures were crucial in accurately capturing both the stress gradients and fine geometric features in critical areas.

2.3.5 Displacement

Given that the kinematics of the die are entirely vertical, the punch movement can be characterised as pure translational motion, without the presence of any rotational joints.

Accordingly, the punch displacement was modelled using a Joint - Displacement configuration, specifying a linear translation over a total distance of 47 mm. The motion was divided into six equal steps, with each step lasting 1 second. As a result, the punch completes a full stroke with a constant velocity of 7.8 mm/s.

3. RESULTS

Multiple simulations were conducted for a series of four sheet thicknesses and five types of material associated with the bending device. A total of 20 simulations were performed, and the results were compiled and subsequently compared.

3.1 Total Deformation - Workpiece

Using the results from the *Total Deformation* solution, the resulting part dimension can be determined.

The measurements of the bending angle of the parts were made on the resulting .STL files, where the workpiece already went through the rebound effect. The angle values thus established were compared with the table of General Tolerances from ISO DIN 2768-mk [10] to determine the influence of the material of the device on the tolerance of the bending angle.

ISO DIN 2768-mk refers to a standard that specifies general tolerances for linear dimensions, angular dimensions, and geometrical characteristics such as straightness, flatness, and perpendicularity in manufacturing processes. They are typically used when tolerances are not individually specified on technical drawings.

The tolerance grades are f (fine), m (medium), c (coarse), v (very coarse) and they define how tight or loose the tolerances are for the manufactured part (Table 2).

Table 2. Angular dimensions grade

Angular dimensions (°)	f (fine)	m (medium)	c (coarse)	v (very coarse)
Over 50 up to 120	±0°20’	±0°20’	±0°30’	±1°

Ideally, the angular dimension of the part is as close as possible to a right angle (90°), and any increase in this dimension indicates reduced resistance of the bending device to the compression forces involved during the deformation process.

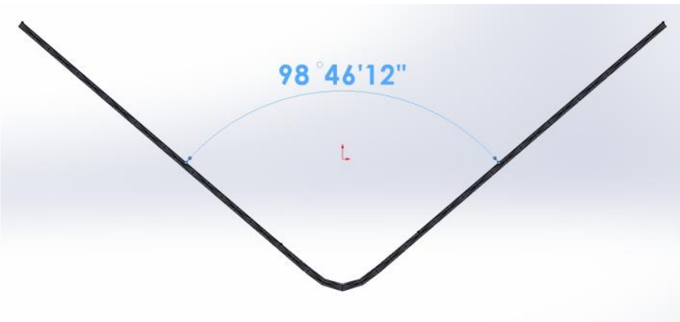

Figure 5. Sample of angular dimension measurement

Table 3. Resulted angular dimensions for workpiece

Material	0.5 mm	1 mm	1.5 mm	2 mm
D2 steel	94°12’	97°21’	101°45’	104°37’
ABS	95°30’	98°46’	102°38’	106°11’
PLA	95°12	98°22’	102°05’	105°6’
PET	95°15’	98°23’	102°12’	105°7’
Nylon	95°22’	98°35’	102°25’	105°47’

The elastic springback process is captured by these simulations (Fig. 5, Table 3), being more pronounced in workpieces produced using devices manufactured from ABS and Nylon. The best results were observed for devices made from PLA and PET, which exhibited similar behaviour to each other.

Since these elastic springbacks are relatively easy to anticipate, this process can be mitigated during the design phase, where the device is assigned a deviation (from the desired angle of the workpiece) in the profile of the active components.

Thus, since the process can be easily controlled, the comparison of the ability to maintain the desired shape of the resulting part, produced by different polymer dies, will be made using the material with the best properties as a benchmark.

For this reason, PLA is chosen as the reference material, and the other materials will be compared against it in terms of the precision imparted on the workpiece by the other materials.

Table 4. Differences between angular dimensions for workpieces

Material	0.5 mm	1 mm	1.5 mm	2 mm
ABS	0°18’	0°24’	0°33’	1°5’
PLA	-	-	-	-
PET	0°3’	0°1’	0°7’	0°1’
Nylon	0°10’	0°13’	0°20’	0°41’

In Table 4, the colour code was assigned as follows: Green for f (fine) and m (medium), orange for c (coarse), and red for v (very coarse).

3.2 Total Deformations - Bending Plate

Using the results of Total Deformations, the extent of deformations imposed on the devices during the bending process can be observed (Fig. 6, Table 5).

An essential aspect of mass production is the device's capacity to consistently produce parts within the established tolerances over its operational lifespan. Therefore, an analysis of the device’s ability to return to its original shape after undergoing the mechanical bending process will be conducted.

This examination is critical for understanding the resilience of the AM-produced parts and their ability to maintain dimensional stability over repeated cycles, which directly impacts the quality and uniformity of the stamped parts.

The deformations imposed on a device by the forces applied over its operational lifespan dictate the precision of the workpieces.

Therefore, the residual deformation values are extracted during the final step of the simulation, when it is assumed that no forces are acting on the forming plate.

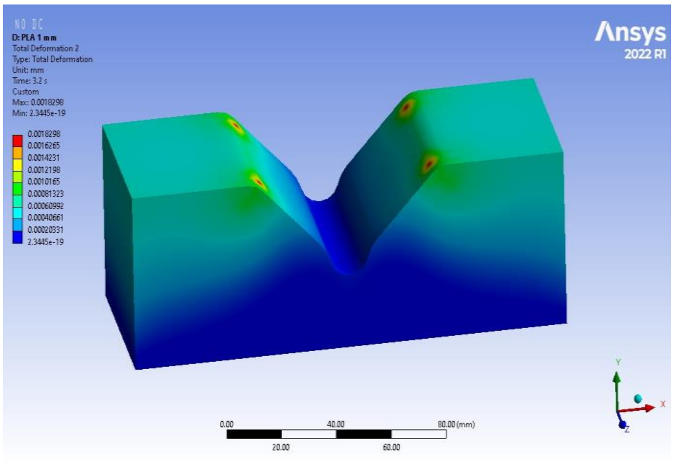

Figure 6. Total deformations of the forming plate that persist after the bending process, as viewed through Ansys Workbench window.

Table 5. Total deformations of the forming plate that persist after the bending process (mm)

Material	0.5 mm	1 mm	1.5 mm	2 mm
D2 steel	0	0	0	0.001
ABS	0	0.001	0.008	0.1
PLA	0	0.001	0.012	0.14
PET	0	0.001	0.012	0.13
Nylon	0	0.001	0.016	0.18

During the analysis, it was observed that the punch did not undergo significant deformations relevant to the process, and was thus excluded from the results, with the analysis focusing on the forming plate of the device.

A generally acceptable behaviour was observed across all devices, with particularly good recovery to the initial shape seen in devices made from ABS, likely attributed to their higher elasticity compared to the other materials.

3.3 Equivalent Stress

Using *Equivalent Stress*, information is obtained regarding the stress values acting on the device during the metal sheet bending process.

These values will be used to detect critical areas of the assembly and assess their behaviour, with the aim of validating their structural integrity (Fig. 7, Table 7).

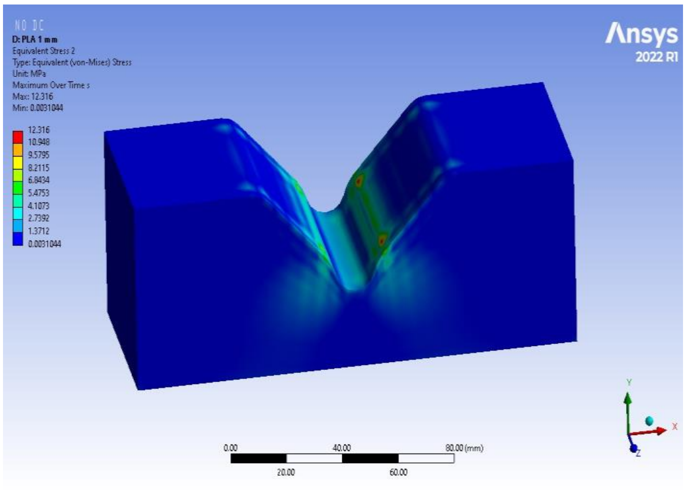

Figure 7. Maximum equivalent stress incurred in forming plate, as viewed through Ansys Workbench window.

Details regarding the mechanical properties of the materials were extracted from the Ansys Workbench library (Table 6). These properties were then used to compare with the stresses obtained during the process, allowing for the validation of the materials ability to withstand various scenarios within the process.

Table 6. Tensile yield strength and tensile ultimate strength for studied materials. (MPa).

Material	Tensile Yield Strength	Tensile Ultimate Strength
D2 steel	2066	2292
ABS	36.13	38.73
PLA	52.44	62.93
PET	52.44	57.45
Nylon	38.86	49.77

Table 7. Maximum equivalent (von Mises) stress achieved during the bending process (MPa)

Material	0.5 mm	1 mm	1.5 mm	2 mm
D2 steel	7.67	15.2	18.31	21.26
ABS	5.43	8.97	12.21	15.4
PLA	7.32	12.31	13.6	17.18
PET	7.14	11.99	13.82	17.64
Nylon	6.92	10.4	14.65	18.2

It can be observed that the specific elasticity of ABS plays a crucial role in dissipating the forces within the active part of the die, resulting in the smallest forces being generated there. Overall, it can be concluded that all materials passed the metal bending test, with no candidates exhibiting irreversible structural deformations or material fractures.

4. CONCLUSIONS

These results highlight the effectiveness and potential of polymeric dies in metal sheet bending applications. The test results for devices made from PLA and PET indicate that these materials demonstrate superior wear resistance and minimal deformation, which can be attributed to their higher tensile strength and impact resistance compared to ABS and Nylon. Notably, the workpieces produced using devices manufactured from PLA and PET exhibited acceptable deviations in part production compared to other materials, particularly for thinner sheets. However, this deviation can be corrected during the design phase, where the dimensions of the device can be adjusted, taking into account material springback and die deformations during the bending process.

As for the residual deformations within the devices, they can be considered negligible, and, according to Nakamura et al. [4] and Gunter et al. [9], these deformations are larger after the first processing cycle, with subsequent processes having an insignificant effect on the dimensions of the devices.

Additionally, devices made from Nylon and ABS also successfully handled metal sheet bending processes, though they tend to offer lower precision in the processed part due to their higher elasticity compared to the other polymers.

In conclusion, while polymeric materials show promising potential for bending applications, providing a balance between strength and manufacturability, further optimisation research is necessary to improve their dimensional accuracy and expand their application range. This study underscores the need for continued investigation into material properties and their practical implications in die manufacturing, in order to fully harness their potential in industrial applications.

5. REFERENCES

1. Grigoraș G., Chiriță B., Brabie G., Additive manufacturing of a stretch forming die using 3D printing technology, IOP Conf. Serv., (2019). Additive manufacturing of a stretch forming die using 3D printing technology - IOPscience
2. Tondini, F.; Basso, A.; Arinbjarnar, U.; Nielsen, C.V. The Performance of 3D Printed Polymer Tools in Sheet Metal Forming. Metals (2021), 11, 1256. https://doi.org/10.3390/met11081256
3. Strano, M., Rane, K., Farid, M.A. *et al.* Extrusion-based additive manufacturing of forming and molding tools. *Int J Adv Manuf Technol* 117, 2059–2071 (2021). https://doi.org/10.1007/s00170-021-07162-8
4. Nakamura, N., Mori, Ki. & Abe, Y. Applicability of plastic tools additively manufactured by fused deposition modelling for sheet metal forming. *Int J Adv Manuf Technol* 108, 975–985 (2020). https://doi.org/10.1007/s00170-019-04590-5
5. Romanovski, V.P. *Ștanțarea și Matrițarea la Rece*, 4th ed.; Editura Tehnică: București, Romania, 1970.
6. Wikipedia. Available online: Ansys - Wikipedia (accessed on 15 Sep 2024).
7. Wikipedia. Available online: SpaceClaim - Wikipedia (accessed on 15 Sep 2024).
8. Coefficient of Friction Equation and Table Chart, Engineers Edge. Available online: Coefficient of Friction Equation and Table Chart (accessed on 15 Sep 2024).
9. Schuh, G.; Bergweiler, G.; Bickendorf, P.; Fiedler, F.; Colag, C. Sheet Metal Forming Using Additively Manufactured Polymer Tools. *Procedia CIRP* 2020, *93*, 20–25. https://doi.org/10.1016/j.procir.2020.04.013
10. *ISO 2768-1:1989*; General Tolerances Part 1: Tolerances for Linear and Angular Dimensions without Individual Tolerance Indications. Available online: ISO 2768-1:1989 - General tolerances — Part 1: Tolerances for linear and angular dimensions without individual tolerance indications (accessed on 15 Sep 2024).