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EFFECT OF INFILL PERCENTAGE FOR 3D PRINTED DIES ON SPRING BACK FOR ALUMINUM SHEETS

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Abstract- 3D printing is considered an effective modern manufacturing technology to fabricate forming tools. In this paper, Polylactic Acid (PLA) filaments were used to print 3D punches and die to perform V-Bending for sheets of aluminum. Three variables, each of which has three levels were studied. Plate thickness (0.7, 1, 2mm), Punch and die material (steel, PLA 20% infill, PLA 50% infill). Taguchi method was utilized to analyze the experimental results. With the (design of experiment) technique, the combination of factors and their levels were determined and an L9 orthogonal array was prepared. Signal-to-Noise ratios and ANOVA techniques were used to find out the optimum values for the variables and the contribution of each variable in the bending process. The results showed that the plate thickness has the largest influence on spring back by 72.16%, then die infill by 12.24%, and punch infill by 1.35%. To obtain the optimum spring back angle, it is advisable to use a 50% infill punch with a 50% infill die to bend a plate with a thickness of 2mm.

Keywords: Sheet metal forming, V-Bending, Spring back, 3D Printed tools, Taguchi, ANOVA.

1. INTRODUCTION

Metal forming is an industrial process where the geometry of thin plate material is modified to the required shape by an applied force without removing material from it. Sheet metal forming is widely used in many industrial applications like automobile body parts, airplane wings, household appliances, trains and engine cuppers, building roofs, and many others. Bending is a famous metal forming operation used to form parts like flanges, folds, seams, … etc. When bending a thin plate, its stiffness, moment of inertia, and resistance to vibration increase. On the other hand, the final product has lightweight with cheap operating costs. V-bending is one of the simplest bending operations where a V-shaped punch and die are used to bend the sheet metal to the required angle. When sheet metal is bent, it is subjected to a combination of bending and stretch forming, and many parameters influence the operation like plate thickness, width, bending angle, punch nose radius, plate material, and others.

When bending a sheet metal, spring back happens due to the relaxation of the stresses after removing the applied forming force. Many parameters may influence the spring back like punch angle, using a small punch angle will create a small plastic zone which results in a high spring back. Plate thickness is another important parameter to consider, increasing plate thickness decreases the spring back. Punch nose radius, grain direction, punch travel, blank holder force, prebend conditions, and tooling-blank interface friction are additional process parameters that effects spring back behavior [1-6].

The dimensions of the plate size will change due to the spring back; therefore, it is desired to predict and reduce spring back so that the final part dimensions can be controlled as much as possible. In V-Bending, spring back angle value indicates the resulting accuracy of the product, therefore, to get the exact product size, and shape prediction of spring-back angle helps in determining the amount of over-bend required so that the exact V bend angle can be obtained in the component.

3D printing is a modern technology that can be used in a wide range from fast prototypes of final parts to industrial-scale products. One of the attractive aspects of 3D printing is its ability to control the material density within the printed part, thus controls its hardness and improves its mechanical properties. Recently, researchers tried to form sheet metals with plastic tools manufactured by 3D printing technology. The printed tools can be considered as as prototype tools which make sheet metal bending efficient for small production volumes because it reduces the production time and cost of the tools. During bending, the dimensions of the plastic punch and die may change due to the elastic deformation that arises from the bending force, this, in turn, may affect the dimensional accuracy of the final part. Therefore, if the effective stress in the 3D printed plastic tool did not exceed the elastic limit for this tool, the last can be used effectively in metal forming [7-15]. Different materials can be used to print the bending tools; among them are Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), reinforced carbon fiber [16-18].

This work aims to investigate the possibility of using 3D printed plastic dies to conduct V-bending process for thin sheet aluminum and compare them with metal die to produce minimum spring back. Taguchi method was utilized to optimize the process and find out the contribution of different parameters on spring back values.

2. MATERIALS AND METHODS

Wire filament made of PLA was used with a 3D printing machine; the wire was fed into heated extruder and deposited through multiple layers to produce a three-dimensional punch and dies.

2.1. Materials

Strips of AL 1100 with different thickness (0.7, 1, and 2 mm) were used to investigate the variation of spring back with sheet thickness. Punch and dies were manufactured from AISI 1010 Steel with the main parameters (Bending angle 90 degrees, Punch nose radius 5mm, and die corner radius 2.5mm). Plastic punch and die shown in Figure 1 were printed using Polylactic Acid (PLA) Plastic, their main dimensions were same as that for the steel, and two inside filling strategies were adopted (50% and 20%). Other printing parameters were (Printing temperature = 200^{o}C, Nozzle diameter = 0.4mm, Layer height = 0.2mm, Number of layers = 10). The mechanical properties of Aluminum, steel and PLA plastic are listed in Table 1.

Figure 1. 3D printed punch and die

Table 1. Mechanical properties of materials used in work

	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (MPa)	Poisson's ratio
AL 1100	56	112	69000	0.33
1010 Steel	305	365	190000	0.33
PLA Plastic	70	73	1280	0.36

2.2. Taguchi Methodology

Taguchi method uses three major tools to analyze the experimental results statistically. These tools are the orthogonal array, signal-to-noise ratio (S/N), and analysis of variance technique (ANOVA). The orthogonal array is a set of all processing parameters and their levels with a minimum number of required experiments. S/N ratios and ANOVA are used to find out the optimum variable values and the contribution of each variable in the process [19]. In this work, three parameters were studied (Workpiece thickness, punch material, and die material), each of these parameters contains three values as listed in Table 2.

Table 2. Variable parameters and their levels

Variables	levels		
	1	2	3
Thickness (mm)	0.7	1	2
Punch	steel	PLA 50%	PLA 20%
Die	steel	PLA 50%	PLA 20%

2.3. Bending Process

To study how the different parameters affect spring back, the bending process was conducted using three cases. In case 1, steel punch was used with three different dies (steel, Plastic 50% infill, and plastic 20% infill). In case 2 and case 3, Plastic 50% infill punch and Plastic 20% infill punch respectively were used with different dies. All these punch-die combinations were used to bend aluminum strips with different thickness as shown in Figure 2. Image processing technique with the aid of Solidworks software was adopted to calculate the spring back angles for the resulting specimens.

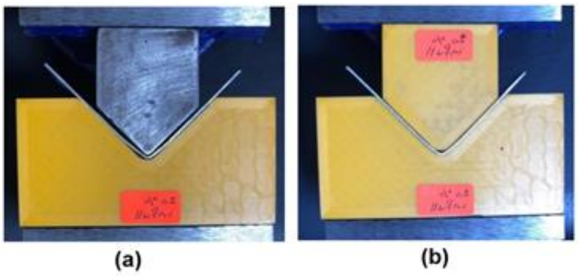

Figure 2. Punch-die combinations
(a) Steel-50% infill, (b) 50%-50% infill

3. RESULTS AND DISCUSSION

The spring back resulting from the different Punch-Die combinations for different strip thickness was measured and will be discussed below.

3.1. Punch (Steel) - Die (Different Materials)

It was noted that increasing plate thickness decreases the spring back as shown in Figure 3**.** Increasing plate thickness increases the bending moment during bending and in turn increases the mechanical deformation which affects the spring back angle significantly. A comparison between the different die materials shows that for small plate thickness (i.e., 0.7mm) using punch and die made of steel (steel-steel combination) gives the minimum spring back value and a big gap in spring back value between the steel-steel combination and the steel-plastic combinations was observed. For 1mm and 2mm plate thickness, the gab decreases significantly and results for steel - 50% infill combination shows spring back angle better than steel-steel.

3.2. Punch (50% Infill) - Die (Different Materials)

For this case, lower values for spring back angle were observed for both plastic-plastic combinations in comparison with plastic-steel combination as shown in Figure 4. For 0.7mm plate thickness, the spring back angle for 50%-20% and 50%-50% infill is almost the same (6.36 and 6.34 degrees respectively), while for 50%-St combination it was (9.96 degrees). For 1mm plate thickness, the spring back angle was (2.31, 3.22, and 7.46 degrees) for 50%-50%, 50%-20%, 50%-Steel, respectively. For the range 1 to 2mm plate thickness, the spring back angle for both plastic-plastic combinations is almost constant. The 50%-50% infill combination results in the minimum spring back angle, which means that we can use the plastic-plastic combination effectively.

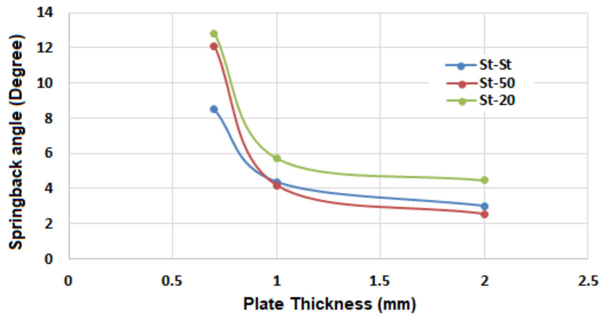

Figure 3. Spring back variation with plate thickness, steel punch and different dies

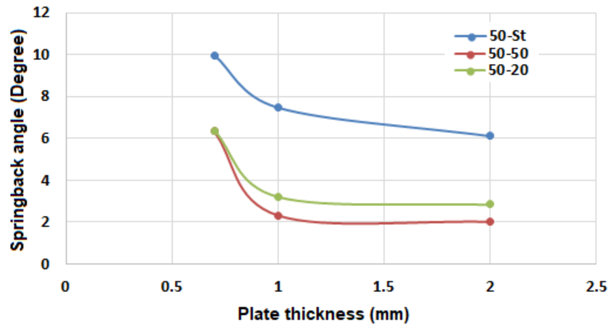

Figure 4. Variation of spring back with plate thickness, 50% infill punch and different dies

3.3. Punch (20% Infill) - Die (Different Materials)

For this case, again lower spring back angle was observed for both plastic-plastic combinations in comparison with plastic-steel combination for 0.7mm plate thickness as shown in Figure 5. For 1mm thickness, the minimum spring back angle is observed with the 20%-St combination followed by the 50%-50% combination. For 2mm plate thickness, 20%-steel combination still results in the minimum spring back angle and the difference in spring back angle is small (about 0.27 degree between 20%-St and 20%-50%) which indicates the ability of replacing plastic-steel combination with plastic-plastic combination.

It can be noted from the previous results that for plate thickness 0.7mm, using any combination of steel-plastic or plastic-steel results in higher values for spring back angle. Also, it can be noted that increasing the plate thickness decreases the gap between spring back values. For plate thickness 0.7 mm, the spring back angle for both plastic-plastic combination is less than steel-steel combination, while for plate thickness within the range (1 to 2mm), using 50%-50% combination can give spring back results better than that for St-St combination as shown in Figure 6.

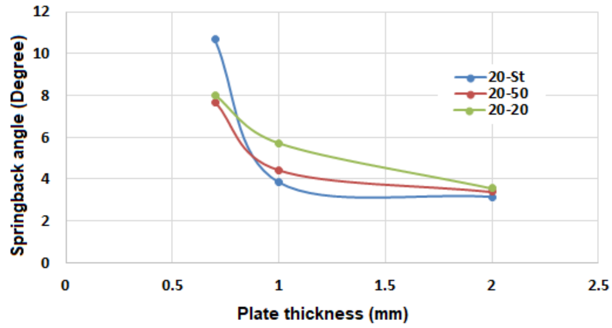

Figure 5. Spring back variation with plate thickness, 20% infill punch and different dies

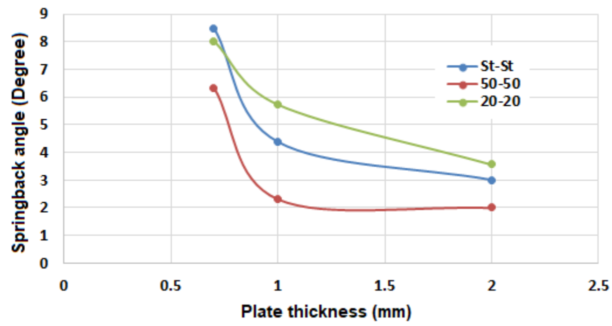

Figure 6. Spring back for plastic and steel combinations

3.4. Economic Considarations

Using 3D printed dies offers some economic advantages. It was noted that there were surface scratches at the outer surface of the bent strip when using steel-steel or steel-plastic combination. These surface scratches were less when using plastic-plastic combinations. Six hours and forty-one minutes was required to print the 50% infill density PLA plastic punch and die, while this time was two hours and seven minutes when printing the 20% infill density punch and die. On the other hand, steel dies are heavier than plastic dies. The total weight of 50% infill density punch and die was (128 grams) and that for 20% infill density was only (89 grams). Plastic dies don't need experienced worker to manufacture them as they depend on 3D-printer while steel dies need a skilled worker to manufacture them; therefore plastic dies are less expensive than steel dies. Taking the economic cost in consideration, it can be concluded that a (50%-50%) combination can be used effectively to replace the (St-St) combination in V-Bending.

3.5. Analyzing Spring Back Variations

Minitab 19 software was used to obtain the signal to noise ratio for plate thickness, punch material, and die material in each of the nine tests to see the effect of these parameters on the spring back value. Table 3 shows the design of experiment.

The "Smaller the Better" equation was selected to calculate the S/N ratio, since the lowest spring back value was the desired outcome for the bending process. Table 4 lists the mean (S/N ratio) for spring back at each level for the different parameters. The graphical illustrations of the S/N ratios are presented in Figures 7-9. As can be noted that all variables have significant influences on the spring back, but their significance degrees vary. The sheet thicknesses are the most significant than the punch and die infill percentage.

Table 3. Design of experiment

Test No.	Punch infill (%)	Die infill (%)	Thickness (mm)	Spring back (Degree)
1	100	100	0.7	8.49
2	100	50	1	4.16
3	100	20	2	4.45
4	50	100	1	7.46
5	50	50	2	2.00
6	50	20	0.7	6.36
7	20	100	2	3.14
8	20	50	0.7	7.68
9	20	20	1	5.73

Table 4. Mean Signal-to-Noise ratio for spring back

Level	Punch	Die	Thickness
1	-14.270	-14.733	-17.452
2	-13.182	-12.037	-15.000
3	-14.642	-15.324	-9.642
Delta	1.461	3.287	7.809
Rank	3	2	1

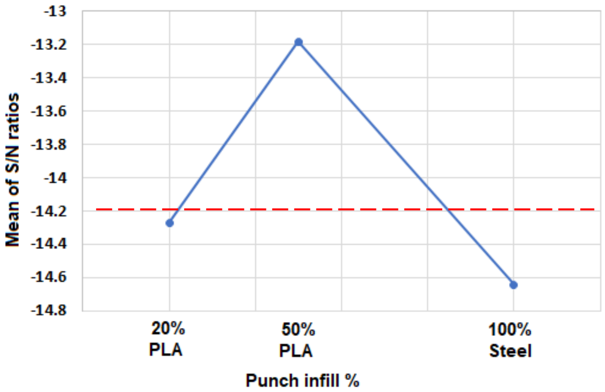

Figure 7. Effect of punch infill % on spring back

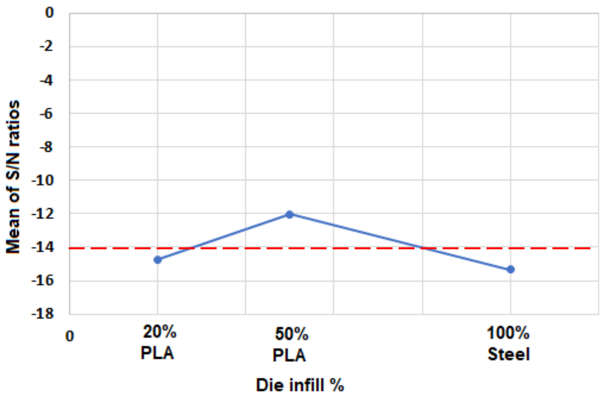

Figure 8. Effect of Die infill % on spring back

The infill density is an important parameter. Increasing the infill density increases the amount of material for the punch or die and this increases the bonding areas between layers. When increasing the bonding area between the layers this in turn reduces the tendency for layers delamination and part fracture.

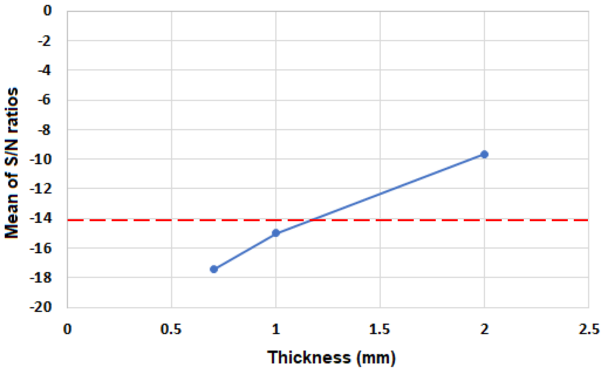

Figure 9. Effect of plate thickness on spring back

3.6. ANOVA for Spring Back

Analysis of variance (ANOVA) was performed to find out the contribution of the punch, die infill and plate thickness. Table 5 lists the spring back ANOVA results for the V-bending operations.

Table 5. Analysis of variance for Spring back

Source	DF	Seq SS	Contribution	F-Value	P-Value
Punch	2	0.02721	1.35%	0.09	0.913
Die	2	0.24605	12.24%	0.86	0.538
Thickness	2	1.45050	72.16%	5.06	0.165
Error	2	0.28647	14.25%		
Total	8	2.01023	100.00%		

The smallest P-Value is (0.165) which means that the plate thickness has the greatest influence on the spring back with the highest contribution of (72.16%), followed by the Die infill contribution of (12.24%), and the lowest contribution (1.35%) is referred to the punch infill%. In addition, we can see in the response table for means table 6 the same contribution, first rank is plate thickness second is die infill% followed by punch infill%.

Table 6. Spring back for means

Level	Punch	Die	Thickness
1	5.517	5.513	7.510
2	5.273	4.613	5.783
3	5.700	6.363	3.197
Delta	0.427	1.750	4.313
Rank	3	2	1

The main effects plot for means is shown in figure 10, it shows that if we use a 50% infill punch with 50% infill die to bend a plate with thickness 2mm, we will have the most optimum spring back angle. With the infill density of 50% configuration, we obtain a good balance between printing time, material content, and punch/die strength.

4. CONCLUSIONS

This work investigates the effect of infilling percentage for 3D printed bending tools on spring back when bending aluminum sheets having different thickness. Taguchi method was used to analyze and find the optimum levels for infilling percentages and thickness parameters to find their effect on spring back. The following conclusions can be remarked:

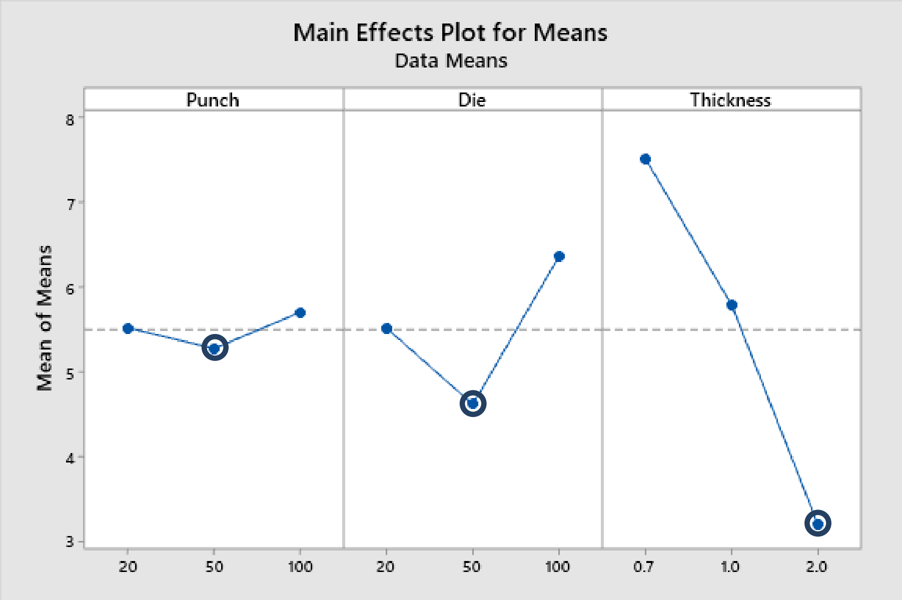

Figure 10. Effect of plate thickness on spring back

1. 3D printed plastic tool can be used effectively in tool-making, specifically in V-bending of sheet metal for single and small batch production.
2. 3D printed plastic tool are economical tools, the printing process did not need the presence of operator because it is fully automated, and therefore it can be performed continually 24 hours a day.
3. Using plastic tools with 50% infill is more economical than steel dies for limited production rates and can results in less spring back.
4. When using plastic tools with different infill density, printed PLA tools with 50% infill had less minimum spring back than printed PLA tools with 20% infill.
5. Infill percentage affects the spring back significantly and the optimum levels of processing parameters were found to be at 50% infill punch with 50% infill die to bend a plate with thickness 2mm.
6. The contribution of the different parameters on spring back was found to be (72.16%) for plate thickness, (12.24%), and (1.35%) for die infill % and punch infill%, respectively.

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