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BENDING AND SPRINGBACK ANALYSIS ON SHEET METAL MATERIAL DISCONTINUITY

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ABSTRACT
Origami concept came up as an emerging technique for sheet metal bending or folding and is called as Origami-based sheet metal (OSM) folding. This process fits right in criteria of effectiveness, efficiency, and sustainable manufacturing due to minimal resources required to make the fold or bend. In this process, the line was created on which the bend was supposed to perform. Traditionally the intermittent material was removed from that line with a through cut. Then the bend was performed. During bending the force required was very less and thus it can also be called as easy bend operation. Because the material and removed all the way through the thickness of the metal, these part after bending cannot be used to contain particles smaller than the cut width or liquid solution due to leakage issue. To overcome this issue, this paper investigates the material discontinuities with a blind cut, where the material through the thickness was not completely removed. For this 4 sample types were created. Three additional variables were added in placing the sample during bend operation. Experiments were performed and bending deformation and springback were analyzed. After analyzing the results, it was found that significant thickness difference regions in the sample, smaller clearance, smaller width or cut, and width of cut facing punch are the best variable to have a better bending and less springback.

INTRODUCTION
Decades of knowledge in metal forming and the new advancement brings more effective, efficient and cheaper parts. Due to which the infrastructure has seen an enormous growth that demanded more parts. Due to billions of parts manufactured every day, these parts take part in our daily life. Most of the parts are for the automotive and aerospace industry. In the United States every household owns 2-3 three of these automotive vehicles. In addition, the transport has been seen an increase in level. Because of the continuous running part, the fuel prices have gone up. On the other hand, the emissions have stricter regulation due to environmental impact and greener initiatives has been started. To follow the green initiative the companies are pushed to produce the lighter part to increase the fuel efficiency. However, while producing the lighter parts the crashworthiness standards should be in consideration and should not be compromised [1]. The pollution level increases due to higher consumption of gasoline. The heavier vehicles need a lot of power to drive and thus the consumption of gasoline is higher which increases the emissions. Two approaches are generally can be followed to reduce the vehicle weight, first by using the lower dense vehicle, however, low dense materials are either expensive or lack in strength. Another approach is to process the high strength affordable material by improving the manufacturing technique to get the best out of the material [2]. Generally to reduce the machine tonnage, either lower density material to be chosen or a lower gage material is used. But think if some modification could be made to the material geometry, so the less effort would be needed to manufacture the part. On such technique to make the change in the sheet metal geometry is the Origami Sheet Metal (OSM) folding or bending. The focus of this paper is to learn the parameters used in OSM and how to improve the bending process so less force would be needed to bend the part.

The concept of OSM came from the Origami shapes for decoration. To create the origami shape the colorful sheet paper is used, in which the bend lines are created on which the bending of a sheet is performed. The similar technique is used but by removing the material on the bend line [3-4] as shown in Figure 1. Due to material removal, the section is having a discontinuity in the material and thus is called as material discontinuity.

Variety of material discontinuity designs and bending process were previously studied to understand the bending and the springback [5-7]. Springback is deformed as the material

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geometry distortion after the load is been released. This is also considered as a defect in manufacturing as the part cannot fit in the assembly due to geometry distortion. It was found that less bending force was required to bend the pieces. The bending force decreases with material removal but found to be not proportional. The shape and geometry of material discontinuities influence the bending of the pieces and the springback due to stress concentration due to material discontinuities. It was also listed that springback reduce with all material discontinuities. In all cases of material discontinuities, it was found that the material was removed thoroughly, i.e., the light can pass through those sections. This means none of the manufactured parts from OSM can be used to store any liquid material. None of the literature was found on blind material discontinuities. To cover this gap, this paper focuses on creating the material discontinuities blind in the material. The bending operation was performed on the blanks with material discontinuities. Process parameters were varied to analyze the results. The bending force, material deformation at bend and springback was analyzed to conclude the results.

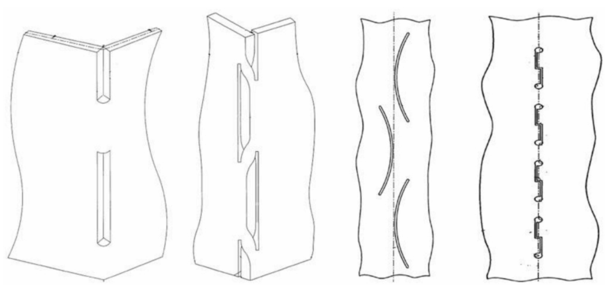

FIGURE 1. Various through cut material discontinuity designs on bend line [5]

MATERIAL AND METHODOLOGY

TENSILE TEST

The material used for this work is the low carbon steel with a thickness of 2 mm and a width of 12.7 mm. The tensile samples, dimensions as shown in Figure 2a, were used for the mechanical tensile test. The tensile tests were performed on an MTS 810 servo-hydraulic machine (Figure 2b). Reflective tape was placed at both ends of the gage length. A laser extensometer was used to measure the displacement of the sample during the tensile test. The specimens were pulled at a rate of 5 mm/min. The force-displacement data was captured and converted to a stress-strain curve.

BENDING SAMPLE

Figure 3 shows the sample for a bend test. The sample was cut with an overall length as required for that particular sample as detailed in Table 1. The width of the sample (i.e., in or out of paper width) was 12.7mm. Once the overall length was cut from the steel bar, one edge was marked X and other as Y as shown in Figure 3. From edge X the distance to the start of the width of cut "w" was always constant as 25.4 mm. The distance from the end of the width of cut "w" to edge Y was always constant as 38.1 mm. Now based on the width of cut the sample overall length can be changed. Two widths of cuts "w" were chosen 12.7, and 6.35 mm. The sample thickness was 2mm. Thus two thickness of cut in the region of the width of cut were chosen i.e., 1, and 0.5 mm. That is with 0.5 thickness cut the sample thickness at bend region will be thicker than with 1mm thickness cut. The material was removed using a CNC milling machine. The diameter of the mill tool was 2.5 mm. With that, overall 4 types of samples were made i.e, A, B, C, and D as listed in Table 1.

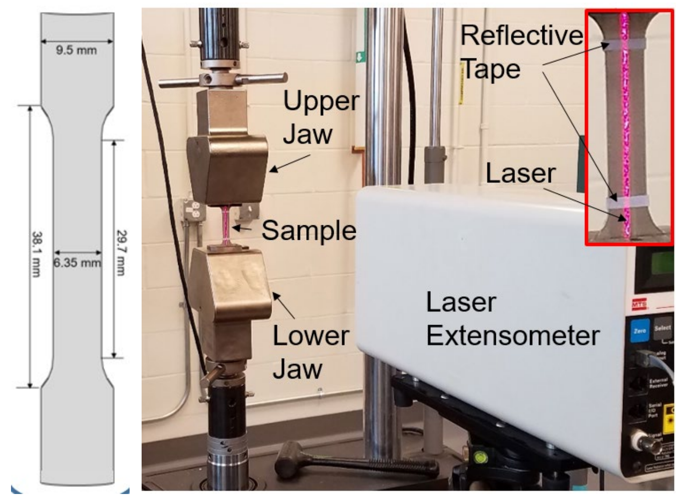

FIGURE 2. Tensile test: sample from tube specimen (left), and tensile test set-up on mts servo hydraulic machine with laser extensometer (right)

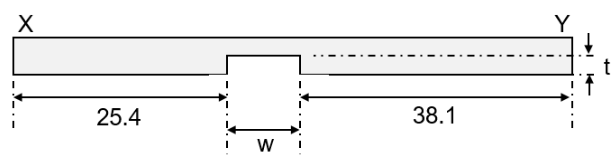

FIGURE 3. Bending sample with material discontinuity (Units – mm)

TABLE 1. Bending sample dimensions

Sample	Width of cut "w" (mm)	Thickness of cut "t" (mm)	Overall Length of sample (mm)
A	12.7	1	76.2
B	12.7	0.5	76.2
C	6.35	1	69.85
D	6.35	0.5	69.85

BEND TEST AND SAMPLE PLACEMENT

Figure 4 provides the schematic illustration of a 90^{o} bend test. To perform the bend, the sample was placed between the die and the blankholder and tightened by the bolt so no sliding of material should take place during the test. As there was no change in the sample width (i.e, in and out of the paper width),

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the test was considered as the plane strain bending. Due to the variation of width or cut where the material was taken out by milling operation from the sample, the placement of the sample is important for this study. For this, some variables are shown in Figure 4. Again just for recap the edge X was always placed towards punch side and edge Y was placed towards die side. "c" is the clearance between the punch and die. As the sample thickness was 2mm, this was one of the considered value for clearance "c". "d" is the distance between the width or cut start from edge Y to the die surface and called as Offset distance". Two "d" values were chosen for this study i.e., 0 mm and 12.7 mm as listed in Table 2. In addition to this one, more variable was added in the study i.e., the width of cut facing die or punch (Table 2). It is worth to explain few sample placement for clear understanding.

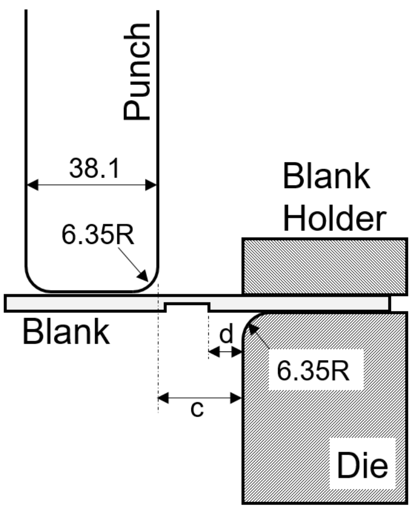

FIGURE 4. 90° bend test set-up

Sample A-Die: A-Die means sample A width of cut was facing the die (as shown in Figure 4). Here the clearance "c" is 2mm and Offset distance "d" is 0 mm, it means width of cut start line from edge Y was inline with die surface and the distance between die and punch was 2mm, i.e, same as sample thickness. In this case, when the punch was taking its final stroke, there was no gap between the punch, blank and die and the image will be like blank was sandwich between the punch and die.

Sample D-12.7 Punch: D-12.7 Punch means sample D width of cut was facing the punch and offset distance "d" was set with 12.7mm. The sample was placed such that the width of cut start line from edge Y was 12.7 mm away from the die surface. Then the punch was placed 12.7 mm plus width of cut (6.35 mm in sample D case) i.e., 19.05 mm apart from the die surface. All sample placement conditions are provided in Table 2. On each condition, 3 tests were performed to check repeatability. At least 2 repeated tests out of 3 of a set were considered as a good test. Thus the overall 51 tests were performed.

After the sample was bent and the punch was retracted, the specimen would like to recover elastically. This is called as springback. Any deviation from the desired part would be the springback. The sample was placed on the quarter inch grid paper and then the angle was measured. Further, the deviation was calculated as shown in Figure 5.

TABLE 2. Bending sample placement in a bend test experimental set-up

Sample	Punch-Die Clearance "c" (mm)	Offset distance "d" (mm)	Cut facing on	Number of tests performed
Baseline	2	NA	NA	3
A-Die	2	0	Die-Side	3
A-Punch	2	0	Punch-Side	3
A-12.7 Die	25.4	12.7	Die-Side	3
A-12.7 Punch	25.4	12.7	Punch-Side	3
B-Die	2	0	Die-Side	3
B-Punch	2	0	Punch-Side	3
B-12.7 Die	25.4	12.7	Die-Side	3
B-12.7 Punch	25.4	12.7	Punch-Side	3
C-Die	2	0	Die-Side	3
C-Punch	2	0	Punch-Side	3
C-12.7 Die	19.05	12.7	Die-Side	3
C-12.7 Punch	19.05	12.7	Punch-Side	3
D-Die	2	0	Die-Side	3
D-Punch	2	0	Punch-Side	3
D-12.7 Die	19.05	12.7	Die-Side	3
D-12.7 Punch	19.05	12.7	Punch-Side	3

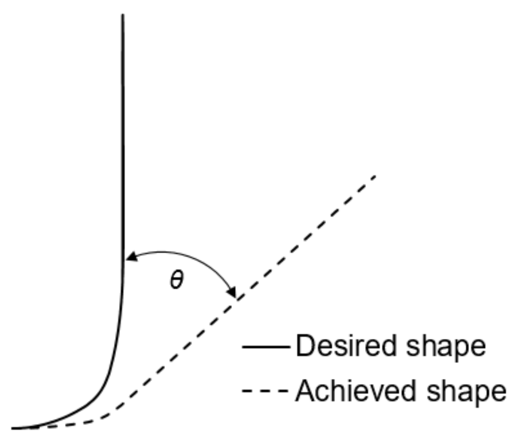

FIGURE 5. Springback Measurement [8]

RESULTS AND DISCUSSION

The force-displacement data was normalized to Engineering stress-strain data and is shown in Figure 6. It can be seen that the material doesn't have any strain hardening. The yield and tensile strength of the material are very near. The mechanical properties of the material are detailed in Table 3. Due to no

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strain hardening, the material springback would be lower with an increase in strain.

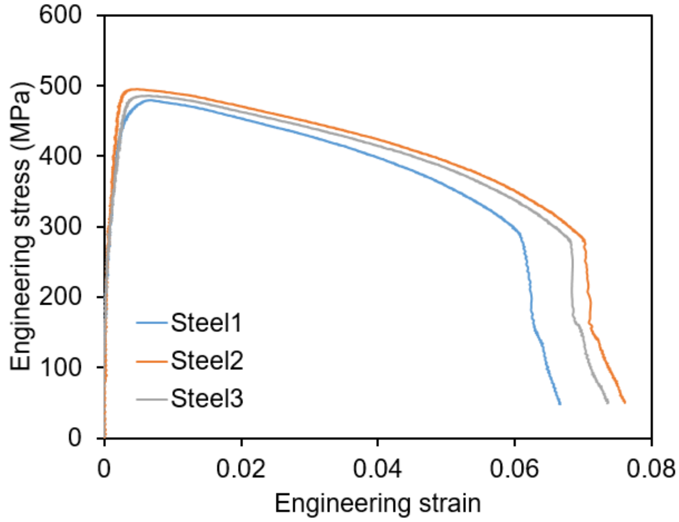

FIGURE 6. Engineering stress strain curve for low carbon steel

TABLE 3. Mechanical properties of low carbon steel

Yield Strength, MPa	Tensile Strength, MPa	%Elongation	Necking strain
470	486	7.3%	6.7%

FIGURE 7. Bent specimens of Baseline

Figure 7 provides the bend test on as-received sample i.e., no cut was made in the sample. The 3 bend test sample shows consistency in the bending and springback.

Figure 8 provides the bend images for sample A. From bottom to top the samples are showing as follows: A-Die, A-punch, A-12.7 Die, and A-12.7 Punch. It can be observed that when the clearance between die and punch was 2 mm and zero offset distance the, the sample bends very near to 90°. Based on the achieved shape, as compared to A-Die, A-Punch performed better as the cut was facing towards punch and was bending in the opposite direction of the width of cut and the radius between the cut was not influencing the bend and thus very close to 90° could have been achieved. However, with A-Die the radius between the cut was opposing to bend and thus the results was not very close to 90°. When the offset distance of 12.7 mm and clearance of 25.4 mm were considered, the samples are bending at the width or cut line near to the die and not to the punch. Also, no bend around the die radius was noticed. This is because more thickness material was removed in sample A cases i.e., 1mm, so remained material was 1mm. The 2 mm thickness region in the sample A acts like stiffener and do not want to bend even around the die radius and only bent at the start of the width of cut.

FIGURE 8. Bent specimens of sample A

FIGURE 9. Bent specimens of sample B

Figure 9 shows the bend images for sample B. Again sample B are similar as sample A with the only difference is the material removal through thickness i.e., 0.5 mm material was removed during milling and thus remaining thickness in the material was 1.5 mm. As this is the significant material as compared to the 2 mm, not much stiffening effect was seen and

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even 2 mm thickness region was contributing to bending. Again bottom to top is the B-Die, B-punch, B-12.7 Die, and B-12.7 Punch. When the clearance between the die and punch was 2 mm and offset distance was zero, the bend did not happen directly at the start of the width of cut, but even the 2 mm thickness region was taking the shape of die radius and contributing in the overall bend of the sample. Similar behavior was observed with B-12.7 Die and B-12.7 Punch. It was noticed that the 0.5 mm thickness material removal was not enough to create a bend line like in origami sheets.

Figure 10 shows the bend samples of sample C. Again from bottom to top are sample C-Die, C-Punch, C-12.7 Die, and C-12.7 Punch. Here the overall behavior of these samples is very similar to sample A as the material thickness removal was the same as 1 mm. Due to which the significant thickness difference regions were created which brought the stiffening effect. The only difference in these samples as compared to sample A was the width of the cut i.e., 6.35 mm instead of 12.7 mm. Nevertheless, changing the width did not have much influence on the bending of the sample.

FIGURE 10. Bent specimens of sample C

The bend samples for specimen D are shown in Figure 11. From bottom to top the samples are as follows: D-Die, D-Punch, D-12.7 Die, and D-12.7 Punch. The deformation behavior of these samples are very close to sample B. Again only difference between these samples and sample B was the width of cut i.e., 6.35 mm instead of 12.7 mm. Due to an insignificant difference between the thickness regions the whole specimen as contributing in the bending deformation.

Figure 12 shows the force-displacement curve for all 3 samples tested for baseline bending. It can be seen that approximately 500 N force was required to bend the 2 mm thickness sample. Figure 13 shows the force-displacement curve for sample A-Die. Sample A-Die thickness at the width of cut was 1 mm, and thus can be seen that only half of the force required to bend the specimen i.e, 250 N. Similar force level was observed in sample A-Punch (Figure 14) with a jump of forces at ~22 mm displacement. In sample A-Punch the width of cut was facing the punch. During the punch stroke open width or the cut was rubbing the movable die and thus the spike of force was observed. As compared to A-Die and A-Punch, sample A-12.7 Die, and A-12.7 Punch showing the bend force level to very minimal i.e., ~70 N (Figure 15 and 16). This is due to the reason that the gap between the die and punch was significant as compared to only 2 mm in sample A-Die and A-Punch. Thus, easy bending was possible.

FIGURE 11. Bent specimens of sample D

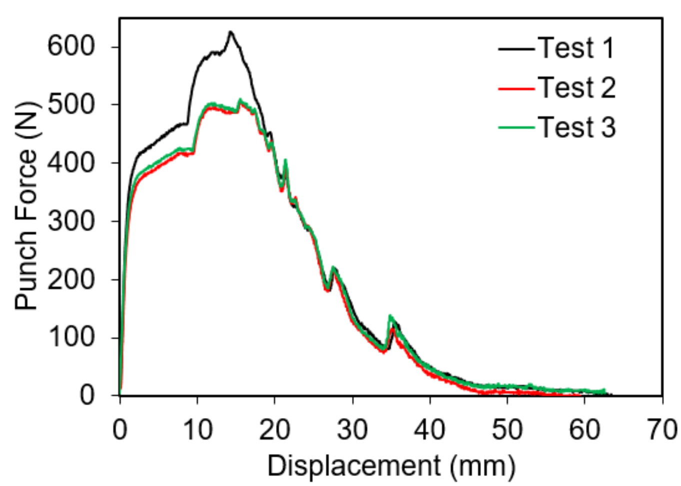

FIGURE 12. Force displacement curve for Baseline samples

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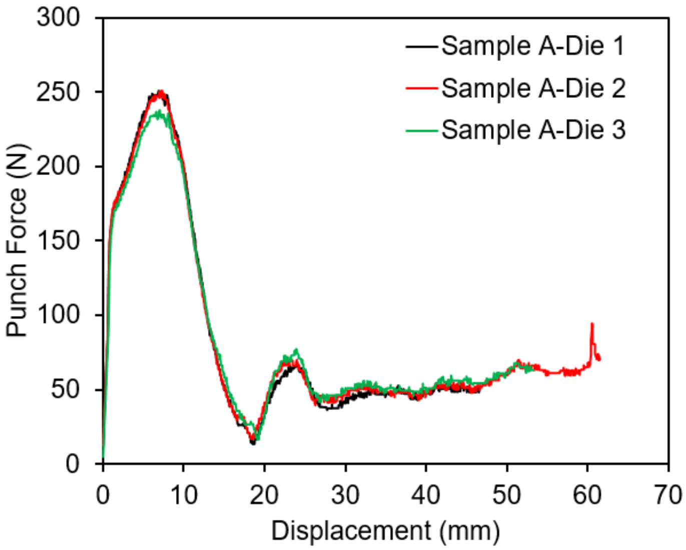

FIGURE 13. Force displacement curve for A-Die samples

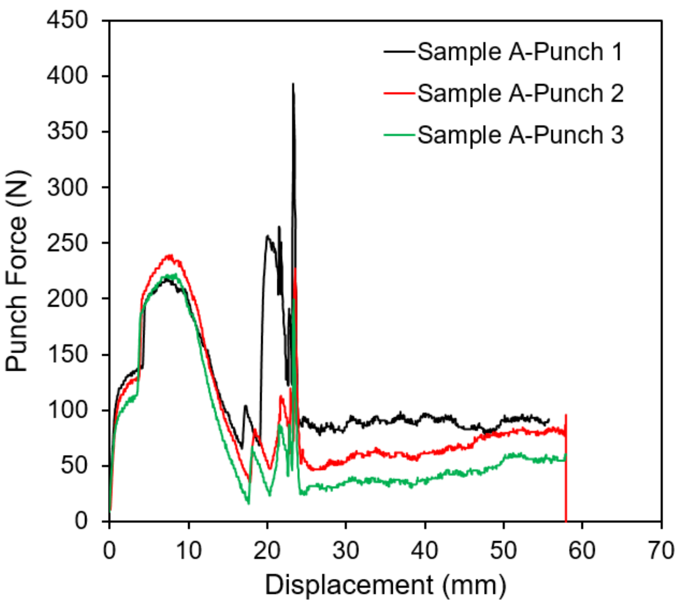

FIGURE 14. Force displacement curve for A-Punch samples

The angles were measured and the springback was calculated and is detailed in Table 2. It can be seen from the table that the highest springback is 32.35°. This springback is for sample B-12.7 Die. If closely observe the variable for this sample the thickness material removed was 0.5 mm i.e., remaining material was 1.5 mm which is insignificant different with 2 mm thickness region and this no stiffening effect was observed and the whole material was contributing the springback. Also, the radius between the cut was not helping the bend which resulted in the highest achieved bend in all samples. As compared to this sample with sample D-12.7 Die which got 26.6° as springback, sample D-12.7 Die had less clearance between the punch and die as compared to in sample B-12.7 Die. The lowest springback was found with sample C-Punch. To count the number of advantages with this sample they are 1) significant difference in thickness between region which helped in making the higher thickness material as stiffer and brought the stiffening effect, 2) width of cut was facing punch and thus radius of cut was helping in bending, 3) clearance between the die and punch was minimal i.e., 2 mm with no offset distance, and 4) width of cut was minimal when compared to sample A-Punch.

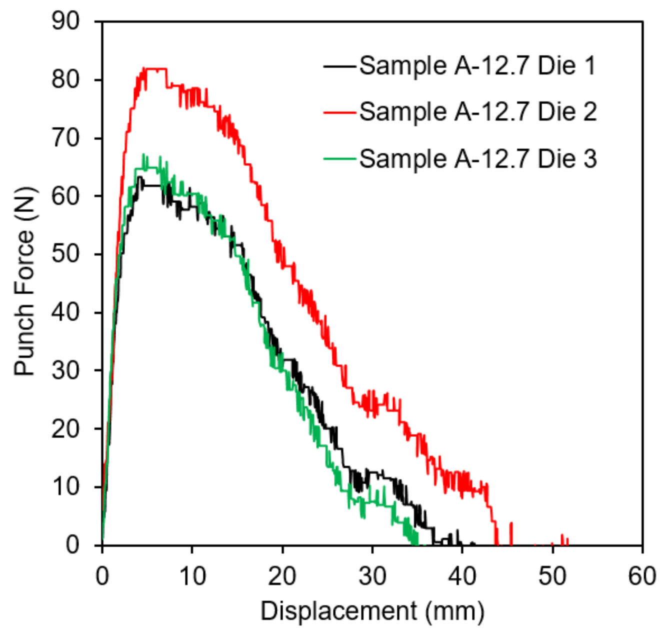

FIGURE 15. Force displacement curve for A-12.7 Die samples

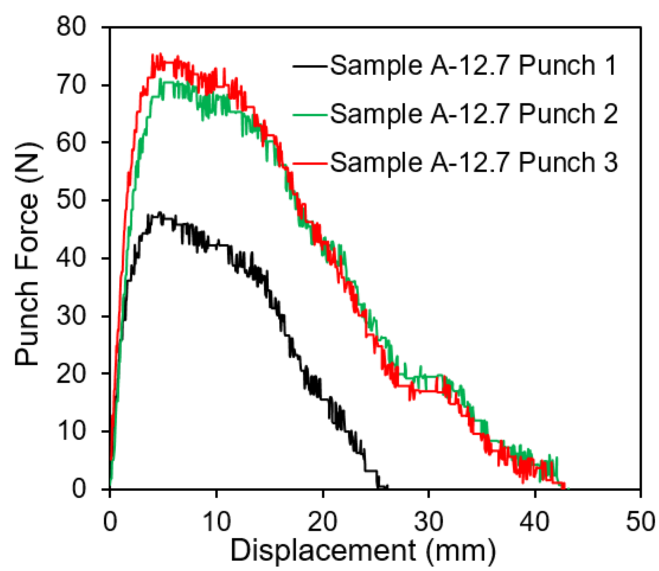

FIGURE 16. Force displacement curve for A-12.7 Punch samples

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TABLE 2: Springback results

Sample	Average Springback (°)
Baseline	8.5
A-Die	7.1
A-Punch	4.3
A-12.7 Die	25.02
A-12.7 Punch	26.6
B-Die	7.13
B-Punch	5.7
B-12.7 Die	32.35
B-12.7 Punch	31
C-Die	3.6
C-Punch	1.09
C-12.7 Die	14.9
C-12.7 Punch	16.7
D-Die	7.13
D-Punch	7.13
D-12.7 Die	26.6
D-12.7 Punch	26.6

CONCLUSION

In this paper, the bending and springback of the samples with material discontinuity were studied through the simple bend test. For this 4 types of samples were created by changing the width of the cut and the thickness of the cut. The variables like clearance between die and punch, and offset distance i.e., distance between the start of width of cut to the die surface were introduced. In addition to this one more variable of the width of cut facing to die or punch was introduced. On each condition, 3 tests were performed to check repeatability. Thus, a total of 51 tests were performed. Based on the gathered results it was found that origami approach of blind material discontinuity would be the better way rather than through cut, so the parts can be used for a variety of purpose. From the results, it was observed that four points need to learn while creating the material discontinuity specimen and placing the specimen for the bend. They are 1) significant difference in thickness between region which will help in making the higher thickness material as stiffer and bring the stiffening effect, 2) width of cut should be facing punch and thus radius of cut will help in bending, 3) clearance between the die and punch should be no or minimal offset distance, and 4) width of cut should be minimal i.e., a simple deep scratch would help.

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