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ORIGINAL ARTICLE

EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE COLLAR PRODUCTION ON THE PIERCED FLAT SHEET METAL USING LASER FORMING PROCESS

Rasoul Tarkesh Esfahani*, Sa'id Golabi
Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

ABSTRACT: In this paper the limitations in collar production around a hole on a flat sheet metal were studied. In previous work, the collar production technology was developed; however, no research has addressed the limitations of this process. In this research, the scan path sequences were studied according to the developed equivalent simulation first. Then, the amount of the increase in the internal diameter and height was studied and finally, the effective range of the scan radius for forming and the minimum amount of the hole diameter were investigated. It was shown that the best scan sequence was the one which starts from the farther scan radii from the hole toward the hole, and the maximum achieved amount of sheet metal deflection was three times the metal thickness. According to this investigation, the effective region for scan radius was found to be twice the internal hole radius, and the minimum ratio of sheet metal hole diameter to its thickness had to be more than 14.28. The simulation results were shown to have a good agreement with the experimental results performed to confirm this research.
KEYWORDS: laser forming, collar production, forming limit, circular scan path.

INTRODUCTION

The laser forming process is one of the advanced sheet metals forming processes which has widely employed for ship, automobile, microelectronics and airplane manufacturing. In this process, the sheet metal is formed using the non-uniform thermal stresses generated by laser scan. Comparing to the other common sheet metal forming processes, the laser forming has several advantages including the lower manufacturing costs, shorter production time and higher precision in small manufacturing volumes. Forming of the complex contours with curved profile and manufacturing of small work-pieces are also possible in this process. Furthermore, it is possible to form brittle materials such as titanium alloys, nickel alloys and ceramics (Shi *et al.*, 2006). Most of the researches in the laser forming field has been performed on the laser linear radiation path to achieve the forming results. To manufacture the complex profiles and specifically, those with the curved profiles (e.g. the dome shaped or double curvature parts), the laser radiation strategies are developed according to the curved radiation lines. If the curved profiles are employed instead of the straight lines in forming, three dimensional parts would be produced which have significant variations in the process mechanism, the forming process and the amount of forming.

Hennige, (2000) investigated the effect of various irradiation strategies for production of complex shapes. Furthermore, the experimental forming results for manufacturing of a spherical dome shape and some finite element simulations were also presented in his paper. The investigations on the effect of the different irradiation geometries on the bending angle produced on the circular and spiral profiles showed that an advanced understanding of the laser forming process was obtained just when the mechanisms of the produced effects were determined and analyzed precisely. To manufacture a three dimensional part using laser (e.g. a spherical dome), generally two different types of irradiation strategies could be employed. The first was the circular radiation paths which were irradiated with the temperature gradient mechanism parameters and the second one includes the radial irradiation paths which were irradiated with the laser parameters for the upsetting mechanism (UM).To avoid the disadvantages of these main strategies, a combined strategy has been developed in this research which employs the advantages of both these irradiation method.

Lin and Yao designed a method for laser forming using finite element (FE) technique which extended the method for relatively thick sheet metals by taking into account bending strain in addition to plane strain (Liu and Yao, 2005). In their work, the strain field was calculated using FE model of elastic and macro deformations. The scan paths were selected along the directions of the minimum main strains of both upper and

Corresponding Author: Rasoul Tarkesh Esfahani, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran. **E-mail:** tarkesh@grad.kashanu.ac.ir

middle planes. The ratio of plane strains tobending strains were calculated to determine the heating conditions and a research was also performed for two shapes i.e. a double curvature and dome shape. Finally the general structure was verified by experimental data. Nadeem, (2011) and Nadeem and Na, (2012) have studied the circular laser path of a 90 and 180 degree sections for pierced circular sheet metals. They found that because of the low thickness of the sheet metal, the effect of strain hardening and the thickening of the sheet metal was negligible and therefore its behavior could be assumed to be linear. They also showed that in small sections, the amount of bending was much less than that of large sections and ratiocinated that there was not enough material to resist the expansion. They also found that as the section angle increases, the amount of sheet metal bending increases as well, and the amount of deformations in the straight energy lines were more than that of circular profiles. They also showed that because of the asymmetry of the geometry, the bending hardness in the sheet metal was higher and therefore, less deformation was expected.

Shekhar Chakraborty *et al.*, (2012) studied the paths and parameters of laser scan for production of a dome shape. They found that the minimum beam diameter of laser radiation and maximum laser power in the lowest velocity of the laser head lead to the maximum deflection of work-piece. They found that the amount of the formed angle increases as the result of increase in the laser scan radius. They concluded that the combination of circular and radial scan paths leads to better forming results. Nadeem, (2013) studied the scan paths for production of a bowl shape form. They found that an unexpected phenomenon occurred in full circular parts and therefore, investigated other geometries such as open 360 degrees circle, and smaller circle pieces. They also found that the combination of two scan path sets had more effect on the amount of final form; however, lower unexpected form was observed in the radial scan paths. This group suggested the application of uniform thermal flux or using unequal radial scan paths as solutions for prevention of unexpected form in the future researches.

The technique of collar production on a hole edge was investigated by Golabi, (2013). They found that the circular scan paths buckle the sheet metal and it is necessary to conduct the buckling toward the desired shape by producing asymmetry. The collar production limitations were not studied in their research.

In this paper the limitations of the collar forming around a hole was investigated. The scan strategy sequence limitation was studied first, formability limit and final deflection limit were then investigated and finally, the effective scan zone and minimum deformable hole diameter were studied.

STUDY OF COLLAR TECHNIQUE CREATION ON A PIERCE FLAT SHEETS

In this research the limitations for producing a collar form, according to the research conducted by Golabi, (2013), was the matter of interest. They showed that the solution for preventing the production of double curvature form, i.e. the buckling, to achieve the desired form presented in Figure 1 is by application of an external force or initial defection around the hole. According to Golabi, (2013), radiation scanning strategy, analysis of the forming limit and the amount of deflection in the sheet metal, the minimum formable diameter and the effective scan radius for forming are necessary to achieve the required form.

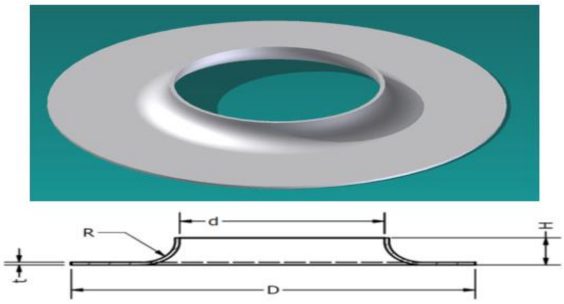

Figure 1: Schematic of Collar Form on flat plate

SETUP OF EXPERIMENTS

The sheet metal used for the experiments is AISI1010 with 0.7mm thickness (Figure 2). To enhance the specimens' laser absorption, graphite coating has been applied to the subjected surface. The specimens have been irradiated using a 300 W output power CO2-laser. A two-axis computer numerical control (CNC) table has been utilized to control laser head.

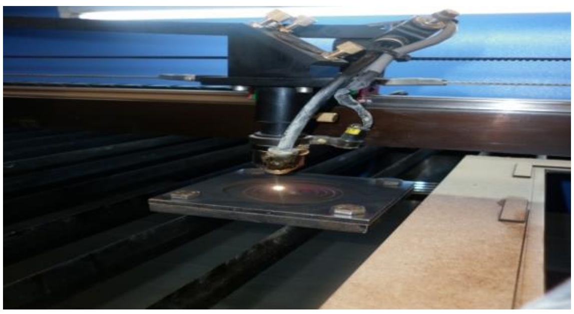

Figure 2: laser CNC

3.1. The effect of laser scans order and location on the final shape of collar

In this section, the effect of scan location and sequences on the amount of obtained deflection in the collar edge is discussed. The laser parameters and geometrical conditions of sheet metals for these studies are presented in Table 1. Two circular paths for single and multiple laser beam scan were selected with the Radii of R_1=6 mm and R_2=8 mm (Figure 4).

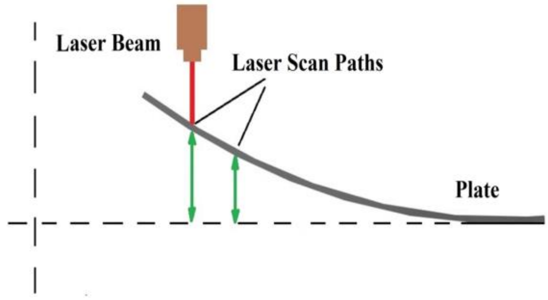

Figure 3: schematic of scan radius location on plate

Table 1: The geometric and process parameters of laser forming

Laser power (w)	Beam scan speed (mm/s)	Beam Diameter(mm)	Thickness (mm)	Inside Hole Diameter (mm)
200	2400	2.4	0.7	10

The results of collar deflection for various laser beam passes and separately for two different circular paths were presented in Figure 4. The laser beam is irradiated on two different circular paths and each path is tested on a distinct specimen. Note that all other geometrical and process parameters were kept constant. From Figure 4, it can be observed that the farther the circular laser scan path from the collar edge, the larger the produced deflection on the collar edge.

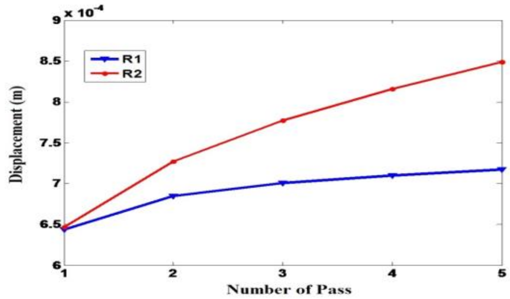

Figure 4: Collar deflection vs. the number of laser beam scanning passes in two separated test piece with different radii (R_1=6 mm(dot) and R_2=8 mm (triangles))

Figure 5 shows the variations of deflection for two different sequences of circular paths. The first path was scanned circularly and completely only by single pass firstly. Then the scan of the second path started and the scan procedure was repeated sequentially until the fifth pass. The blue curve (triangles) is the edge variations as a result of the first circular path scan. The red curve (dot) shows the variation of collar deflection after the end of second circular path scan. In other words, the red curve (dot) is the final collar deflection results. The effect of the second circular path scan on the amount of the deflection produced as a result of the first circular path scan is shown in this figure. As can be seen, the second scan has slightly less amount of deflection compared with the first one.

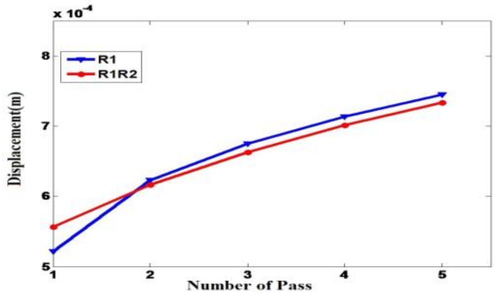

Figure 5: Various collar deflection vs. the number of laser beam scanning passes in one test piece Sequentially applied with different radii (R_1=6 mm(dot) and R_2=8 mm (triangles))

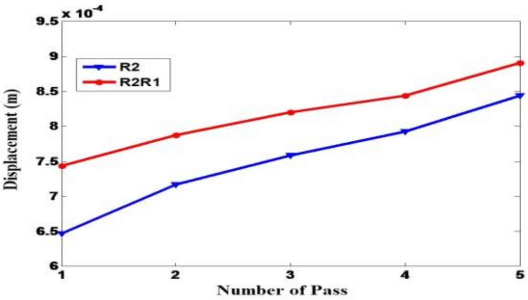

Figure 6: Collar deflection vs. the number of laser beam scanning passes in one test piece Sequentially applied with different radii (R_1=6 mm(dot) and R_2=8 mm (triangles))

Conditions considered in Figure 6 are similar to the previous one; however, the second path was scanned circularly and completely only in single scan first. Then, the first path was scanned and repeated sequentially up to five passes. The blue curve (triangles) is the edge deflection resulted from the second circular path scan. The red curve (dots) shows the variation of collar deflection after the first circular path scan ends.

In other words, the red curve (dots) is the final result of collar deflection variations. The effect of the first circular path scan on the amount of the deflection produced as a result of the second circular path scan is shown in this figure. Scanning the first path after the second one, unlike the previous condition, accumulates the deflection of the collar edge and does not have the previous destructive affects. Another suggested method for multiple scans is predefined circular path. For example, all five desired passes would be scanned in the first circular path and then, the next five passes would be scanned by the laser beam in the second circular path. The result of this method is presented in Figure 7.

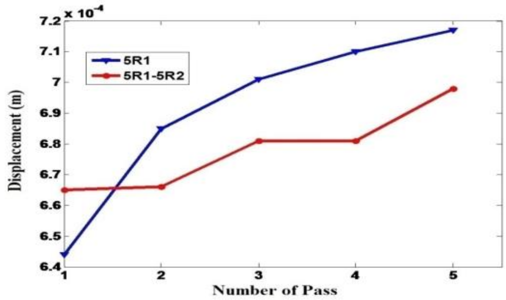

Figure 7: Collar deflection vs. the number of laser beam scanning passes in one test piece separately and sequentially applied with different radii (R_1=6 mm(dot) and R_2=8 mm (triangles))

The blue curve (triangles) shows the collar deflection variations versus the number of scan passes on the first circular path. The red curve (dots) also shows the collar deflection variations versus the number of scan passes on the second circular path. The resultant deflection from the first scan was reduced significantly by scanning of the second circular path. Figure 8 is exactly opposite the scan method shown in Figure 7. The five scans of the first circular path were after the fifth scan of the second circular path.

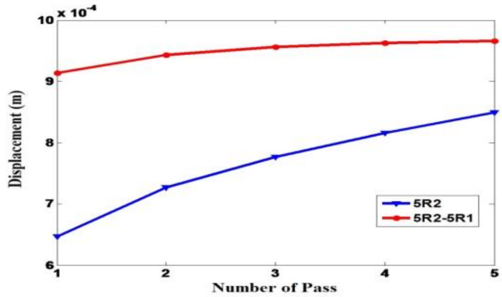

Figure 8: Deflection variations of collar edge depending on the number of laser beam scanning passes in one test piece separately and sequentially applied with different radii (R_1=6 mm(dot) and R_2=8 mm (triangles))

Unlike the scanning method of Figure 7, the deflection produced by the second circular path scan shown in a Figure 8 was not destroyed by the first circular path scan and similar to Figure 6, the accumulation of edge deflection was significant. From Table 2 could conclude that among the different types of scan sequences in multiple circular paths on pierced sheet metal, the one in which the scans were started from the larger diameter and proceed toward the center (Figure 6 and Figure 8) are more desirable. Finally this type of scan increases the deflection by accumulation of deflection from the former paths. In other words, the best scanning of the circle radii procedure was to start scanning from the external radius toward the internal radius, so that all the scans of each radius were performed first and then, the smaller radii scans were carried out. The results achieved from the best scanning procedure were in good agreement with the experimental results shown in Figure 9 (Table 1).

Figure 9: Experimental test components in accordance with Table 1 and according to the scanning order in Figure 8

The main reason for effectiveness of scanning from external radius to internal one was related to the nonlinear buckling effects. The buckling in larger radius reversely affects the buckling in smaller radii, while the buckling in smaller radii positively affects the total deflection. As a matter of fact, scanning the surface located between the scan radius and the hole, increase the temperature more than the surface surrounded by the scan radius and external diameter. Therefore while scanning from the smaller radius toward the larger one, the increase in temperature causes the material to reflaten soften the previously formed zone and hence, its previous deflection decreases. The results were confirmed by experiments. Accordingly, it is recommended to complete the scanning of each radius while starting the scans from the external radiuses.

Table 2: Compare the results of different scanning modes

		Deflection (mm)				
		Scan-1	Scan-2	Scan-3	Scan-4	Scan-5
1	R1	0.522	0.623	0.675	0.714	0.745
	R1R2	0.557	0.617	0.663	0.702	0.734
	Percentage of Difference	6.28	-0.97	-1.81	-1.71	-1.50
2	R2	0.647	0.717	0.759	0.793	0.844
	R2R1	0.744	0.788	0.820	0.844	0.891
	Percentage of Difference	13.04	9.01	7.44	6.04	5.27
3	R1	0.644	0.685	0.701	0.710	0.717
	5R1-5R2	0.665	0.666	0.681	0.681	0.698
	Percentage of Difference	3.16	-2.85	-2.94	-4.26	-2.72
4	R2	0.647	0.727	0.777	0.816	0.849
	5R2-5R1	0.914	0.943	0.956	0.963	0.966
	Percentage of Difference	29.21	22.91	18.72	15.26	12.11

3.2. Studying the maximum produced collar deflection using laser forming

In the mechanical process of producing a collar on a sheet metal, the maximum strain occurs around the edges of hole. While the applied deformation is increased in this process, the initial hole diameter is increased and the sheet metal thickness is decreased accordingly. The excessive deformation and elongation of the hole edge is the reason for its tearing. Production of the collar with a mechanical process is usually performed using a mechanical press with a punch similar to the final collar shape. The amount of the tensile strain around the internal edge of this formed collar can be calculated as follows (Equation 1)(Chakrabarty, 2006):

$$e = (D - d)/D \qquad \textbf{Eq.1}$$

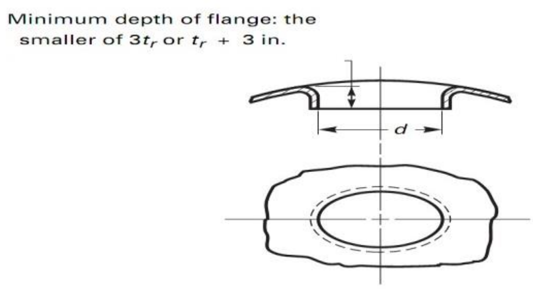

Figure 10: The Schematic of flange height (Vessels and Co, 2010).

This amount of strain has to be less than the permissible material tension. The *D/d* ratio limitation confines the material deformation because of the limitation of material elongation, which consequently, confines the produced collar height *h* (Figure 10).

The maximum common amounts of collar produced around the edges of a hole was three times the sheet thickness (Vessels and Co, 2010) which is a limitation need to be considered throughout this process. As a matter of fact, there are two limitations, namely the height and the increase in the diameter limitations, which could be studied.

Figure 11 shows the variations of edge deflection versus laser radiation time in laser forming of a hole with 4 laser beam scan paths. (In section 3 it was shown that if the number of circular scans is increased, starting the scans from the larger scan path radius and proceeding to the smaller ones accumulates the final collar deflection and each circular scan path affects the final deflection positively.) On each path the number of scan passes was selected adequately large (20 independent scans for each path). The first 20 passes were radiated on the larger radius and the next 20 passes were radiated on the smaller one and until the last scan path. The laser forming parameters along with the sheet metal and its hole geometrical conditions are presented in Table 3.

Table 3: The Geometric and Process Parameters of laser forming

Laser power(w)	Beam scan speed(mm/s)	Beam Diameter(mm)	Thickness(mm)	Material	Inside Hole Diameter(mm)
200	2400	2.4	0.7	AISI1010	20

For the first time in this research the result of a light normal load on the edges of a hole was investigated. As stated earlier increasing the number of scans will buckle the sheet metal around the hole and applying the normal load will conduct the deflection and obviates the buckling effects. The result of proposed scanning procedure which starts from the larger radiuses toward the center with 50N normal load is shown in Figure 11. The maximum deflection as a rule of thumb (2-3 times the thickness), was 2.4 mm. As shown in Figure 11, the maximum deflection is approaching to 1.8 mm. Increasing the force from 50 N to 100 N, increases the amount of deflection after cooling in the last scan to 2.5 mm. Note that in both 100N and 50N conditions, the maximum produced tensile strength have been below the amount of allowable tensile strength of steel AISI 1010. This condition, as expected, shows that there was a specific constraint for the deformations including the deflection and the final collar diameter produced by laser.

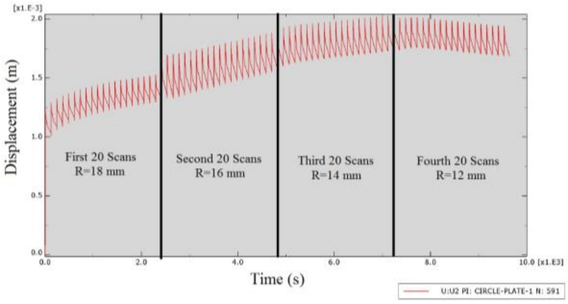

Figure 11: Variation of edge deflection versus time for 4 circular scan path with 20 scans for each radius and 50 N constant force.

Also according to the amount of allowable strain of steel AISI 1010 (0.2) and Equation 1 (Volume, 1990), it was predicted that the maximum produced collar diameter in laser forming would be 25 mm. the diameter achieved from the finite element simulation while applying the force 100 N was 24 mm. Therefore it can be concluded that the presented method for prediction of the maximum amount of the collar using the mechanical method is also applicable for laser forming and could be employed for estimation.

By increasing the force to 150 N, the deflection was also increased, but the maximum tensile stress produced in the hole edge, using finite element analysis, was reached to 368 Mpa. In another word, it could be claimed that the sheet metal edge was torn in this condition, and the calculated result was not acceptable. According to the current discussions and the experimental results it could be concluded that the maximum amount of the height was about 3 times the sheet thickness and the amount of the sheet metal internal hole diameter depends on the work-piece formability limit.

3.3. Determining the final limit of laser effective scan radius

Figure 14, Figure 15 and Figure 16 show the edge deflection variations versus the laser beam scan path diameter for 3 work-pieces with different internal hole diameter. The laser forming conditions for each of these three figures are presented in Table 4. According to the simulation results and the corresponding figures (Figure 14, Figure 15 and Figure 16), it was concluded that by increasing laser beam circular path diameter from a specific position, the amount of the produced deflection would be limited to less than 2%. In another word, it can be stated that application of the scan paths on a zone larger than 2 times the internal hole diameter was not efficient. Therefore by obtaining the specific area for circular paths (a range from 1.1 to 2 times the internal hole diameter) and the analysis of its accuracy using the results of performed simulation and experiments (Figure 12 to Figure 16), it can be certainly concluded that the laser radiation had a positive influence on the amount of collar deflection and the radiation of the beams which did not significantly affect the final shape and edge deflection must be prevented. The experimental results also show that, laser scan out of the area with more than 2 times the hole diameter, , would increase the maximum amount of deflection by about 2%. This experimental result was extracted from 2 holes with 20 and 30 mm diameter.

Table 4: Laser forming conditions for each of the three samples

picture	hole diameter (mm)	beam diameter(mm)	Speed (mm/s)	Power(watt)
Figure 14	10	3.5	50	300
Figure 15	20	2.4	60	300
Figure 16	30	2.8	40	300

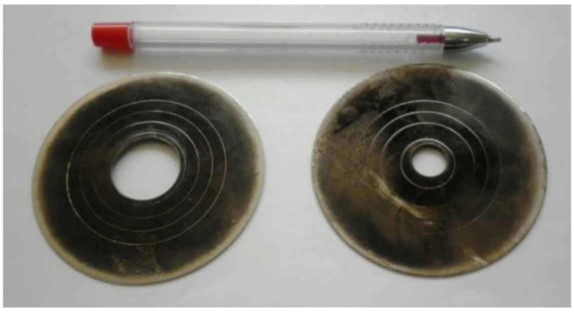

Figure 12: Experimental test samples for obtaining the limits of effective scan radius

Also since the deflection does not change in Figure 14, it was concluded that for a sheet with 0.7mm thickness the minimum usable hole diameter for collar is between 10 to 20mm.Similar results were achieved from experiments on a hole with 10mm diameter and 0.7mm thickness and other power conditions, beam diameters and scan speeds. To develop a general results a dimensionless parameter (d/t) was defined and its effect was studied by both simulation and experimental results. It was concluded that the amount of this diameter-to-thickness dimensionless parameter has to be more than 14.28 ($14.28 < d/t$). To compute a more precise amount for the presented dimensionless parameter, larger hole diameters between 10 to 20 mm were studied, tested and simulated with similar conditions mentioned in Table 4 and shown in Figure 13.

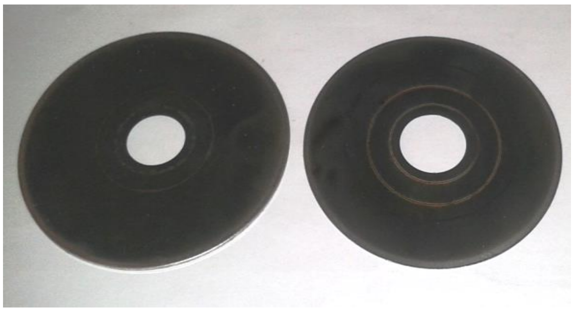

Figure 13: Experimental test samples for obtaining the minimum of effective hole diameter (with ID 15 mm and 18 mm)

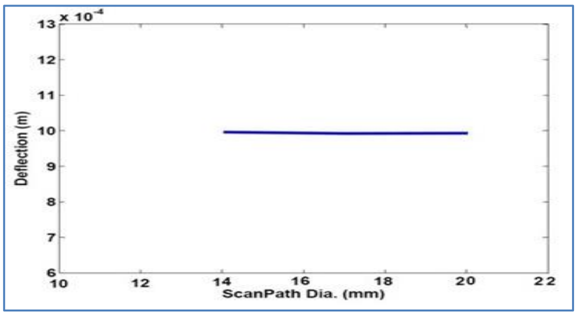

Figure 14: Scan path Diameter for test pieces with 10 mm inside Diameter

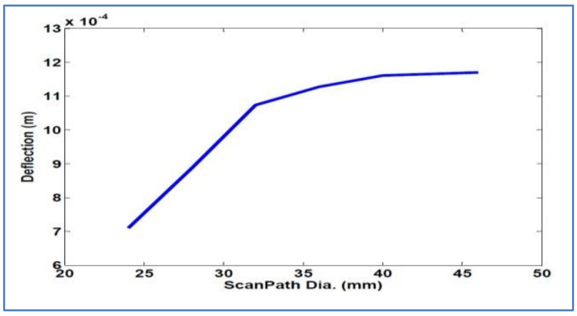

Figure 15: Scan path Diameter for test pieces with 20 mm inside Diameter

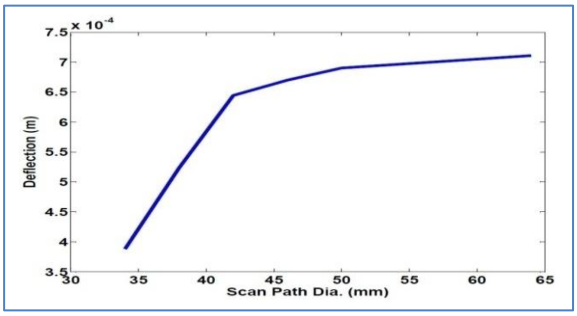

Figure 16: Scan path Diameter for test pieces with 30 mm inside Diameter

DISCUSSION AND CONCLUSION

The effect of laser scan for making collar around a hole was thoroughly studied by both finite element analysis and experiments in this research. According to the acquired finite element simulations it was concluded that the best scan order, i is the one started from the farther scan radius and proceeded toward the hole. It was also revealed that the maximum amount of sheet metal's deflection in collar production was 3 times the sheet thickness, and the amount of increase in hole internal diameter depends on the formability limit of the sheet metal. The effective scan limit radius was studied and it was concluded that the maximum effective scan radius was about 2 times the internal hole radius (r). It was also shown that increasing the scan limit to more than 2r may just increase the deflection by up to 2%. Furthermore, it was concluded that the minimum amount of hole diameter-to-thickness ratio for production of a collar in a plane was 14.28. It was shown that the maximum collar deflection may be increased by applying an external normal load around the hole edge.

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