LASER FORMING OF METALLIC DOME-SHAPED PARTS USING SPIRAL AND RADIAL-CIRCULAR SCAN PATHS

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ABSTRACT: Laser forming process is a new flexible forming process without any contact between rigid tools and sheet metal, in which the form of a sheet metal is changed permanently by high thermal stresses caused by laser. In general, laser forming of spatial shapes and laser forming of two dimensional simple shapes are different. On one hand, heating path and pattern of thermal stress are increasingly being used in a laser forming process, which are especially important in forming three dimensional complicated parts. In a laser forming technique, a desired final shape can be achieved by a control of the laser scan path and other process parameters such as laser irradiation pattern, laser power, speed of laser scan and laser beam diameter. A new application of the laser forming process is production of dome-shaped parts as a prototype. For the production of curved parts, especially for the dome -shaped ones, different strategies have been developed which are mostly based on curved irradiation paths. In this paper, a circular-radial strategy of scanning path to form dome shapes by using laser is investigated. Experiments have been carried out to validate the numerical results. As a result, a new scanning pattern is presented as a spiral strategy. It was shown that the stress distribution is more uniform in laser forming with the use of spiral scanning path. In addition, the deformed parts with spiral scanning path are more uniform compared to other scanning paths investigated. Furthermore, it was found that laser forming with radialcircular scan paths will result in buckling mechanism whereas spiral irradiation will lead to gradient mechanism. The study also shows that radial and circular irradiations lead to occurrence of low thermal gradient and buckling mechanism. Additionally, low thermal gradient and buckling mechanism is happened by spiral irradiation. Finally, thickness distribution and temperature gradient of the deformed parts caused by different laser paths have been investigated.

KEYWORDS: *Laser Forming, Finite Element, Dome Shaped, Spiral Path.*

1.0 INTRODUCTION

Laser Forming is an advanced technology that has been developed in order to shape metal parts. The process is obtained by thermal stress to steel sheet by controlled radiation from a focused laser beam. Laser forming is a combination of mechanical heat process in which heat is applied by a laser beam on one side of the sheet metal in a specific direction [1]. Stress-strain relation on the sheet is not only nonlinear, but also is temperature dependent. In the laser forming process, the shape and position of a bend are determined by radiation exposure rate, beam size, and the position of the laser beam, all of which are considered process variables. In traditional forming techniques such as bending, stretching and pressing, heavy-duty tools are required for the applied external forces to transform a flat piece of sheet metal by devices or the form in which the deformation process can be completed. The biggest advantage of the laser forming technique compared to the traditional method is production flexibility and cost reduction as well as production time. Various applications of the laser forming process have been identified to shape the macro aspects of rapid prototyping and proofing industries like automobile, aerospace and ship building. Aspects of laser forming of micro-industry microelectronic components to precisely adjust the shape of laser applications and several new methods of laser forming are under review and development. Features of this process include extremely high reliability, flexibility, production of complex shapes, capability of rapid prototyping, production of high-precision, low recalculation and access to the detailed form of the slight return spring. Types of mechanisms that are produced by laser are as follows:

- Thermal gradient process
- Buckling process
- Upsetting process

As the gradient heat process suggests, the process depends on the creation of high slope heat in sheet thickness and it is caused as a result of bending the sheet towards the laser beam. Process buckling is created when the slope of heat in sheet width is small and due to low thickness of sheets, the diameter of heated region is bigger than sheet thickness. The result of the process is sheet bending towards laser beam and away from the laser beam. In the upsetting process, the heating conditions are the same as the other two mechanisms, but due to geometrical constraints, it is not possible to do sheet bending and, for this reason, deformation leads to an increase in the thickness or the upsetting of the sheet. In the general states, because of high thickness of sheets, a diameter of heated region is equal to sheet thickness, a mechanism that causes reduction in the length of the sheet, but bending does not occur [2].

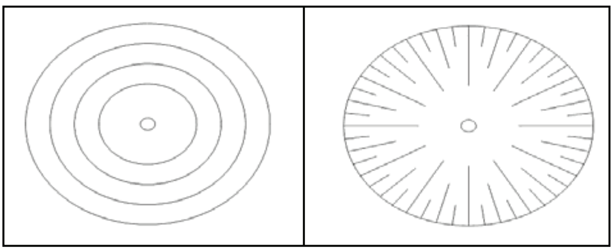
A new application of forming process using laser is called controlled irradiation as the specific pattern on the metal plates to create specific pieces for quick prototyping and production of small parts. Forming the circular plates as bowl-shaped or dome-shaped requires a contraction within a sheet and a bend outward of the sheet.

To manufacture complex curved space components (such as a domeshaped), somewhat different irradiation patterns on curved lines and curved radiation are to be discussed. In general, if curved lines of radiation are used instead of straight lines, collections of threedimensional laser forming will be created and thereby a significant change in the nature of the process and its dependence on the geometry of the components can be created [3-4].

Since 2000, Laser research group at the University of Liverpool has conducted extensive research in the field of laser forming alloys and composite materials used in aerospace industries, as well as forming a complex three-dimensional laser body and parts of the ship [5-8]. Edwardson offered radiation pattern to form a saddle-shaped surface and proposed an alternative model for the formation of a surface which is presented as a pillow [9]. Li and Yao presented a process based on the finite element method to determine the path of irradiation, irradiation step, exposure rate and exposure to form a curve in two dimensions [10]. On the other hand, Maggie and her colleagues studied concentric lines with upsetting mechanism in a laser forming of a domed surface [11]. Through experimentation on the circular ring segment of steel SAE1008 with 2-mm diameter, Hennige showed that the required amount of exposure of laser for circular plates and annular plates is lower in comparison with rectangular plate. Moreover, in the circular sections, aberration and distortion are more than that of ring sections [12-13]. Following the research done by Hennige et al, a radiation pattern consisting of radial radiations under upsetting mechanism and circular radiations under a temperature gradient mechanism for producing domeshaped surfaces are proposed. In the previous researches, two different irradiating schemes were used to produce double curvature shapes with laser beam. In the first irradiating scheme, circular paths were used. Also, in this irradiating scheme, thermal gradient mechanism was considered to be dominant. In the second irradiating scheme, the radial straight lines were used and the dominant mechanism was UM. Both of these irradiating schemes have their own advantages and disadvantages depending on the initial geometry of the sheets [14].

In the second irradiating scheme, if only radial lines are used, the successive positions of the radiation will be very important, because not only can a linear beam be radiated at each step, but the residual stress distribution asymmetry can also be created as a result of the asymmetric shape. Therefore, the symmetry of the piece must be provided with successive radiations. These patterns are shown in Figure 1 [15].

Due to the disadvantages mentioned about radial pattern and circular pattern, a new irradiating scheme was presented by Henning for production of a dome-shaped plate in 2000. This irradiating scheme was a combination of both radial and circular patterns and aforementioned disadvantages were eliminated using this scheme. In this pattern, concentric lines are used in order to stabilize the plate due to the open edges curved radial lines during the heating process.



(a) (b)

Figure 1: (a) Pattern of concentric circles (b) Pattern of radial lines

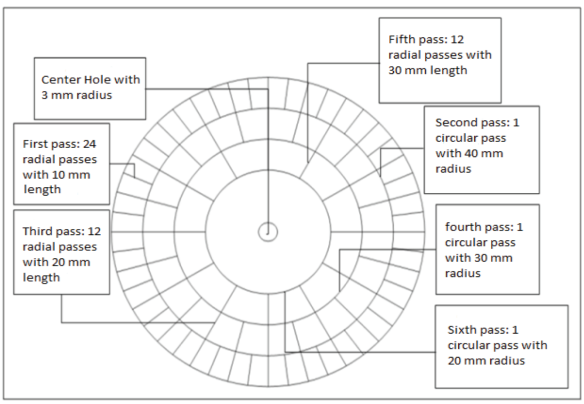


Figure 2: Radial - circular pattern [12]

In this paper, a new irradiating scheme is proposed for the production of a double curvature dome-shaped pattern from a circular blank. At first, one of the irradiating schemes that have been proposed by other researchers is used in the experimental and numerical works. In this stage, numerical simulations are verified with experimental observations. After this verification, numerical simulations of laser forming of a double curvature dome shape are performed along with spiral irradiating scheme. Finally, a comparison is made on the results of the produced dome-like shape with spiral irradiating scheme and the scheme contains circular paths. The results will be shown in terms of distribution of residual stresses, achievement of the domed-like shape, rate of edges symmetry and forming condition of edges. Spiral pattern is much better than the circular-radial pattern.

2.0 EMPIRICAL ANALYSIS

In this study, a source of carbon dioxide laser along with a power of 150 Watts was used. In order to move the samples to create necessary exposure pathways, a three-axis CNC workstation was used. A circular blank of 100 mm diameter and a- 1 mm and 2 mm thickness were cut from the as-received low carbon steel and were used as a specimen. In Figure 3, experimental setup of laser forming of circular blank is shown.

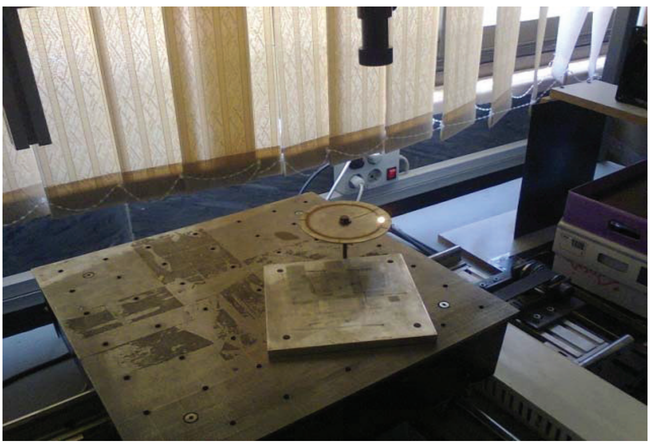


Figure 3: Configuration and installation of the work piece formed by radial - circular path with a thickness of 1 mm

In the following empirical analysis, a closer examination of the temperature distribution and the effect of intermittent and parallel exposure over time are examined. As indicated in Figure 4 in a straight line along the path of exposure, a third beam irradiation was investigated. Initially, the temperature begins to rise due to the convective effect of the temperature, but when focused beam of laser reaches to the edge of the plate, convection between the laboratory and the sheet metal reduces the surface temperature of the sheet.

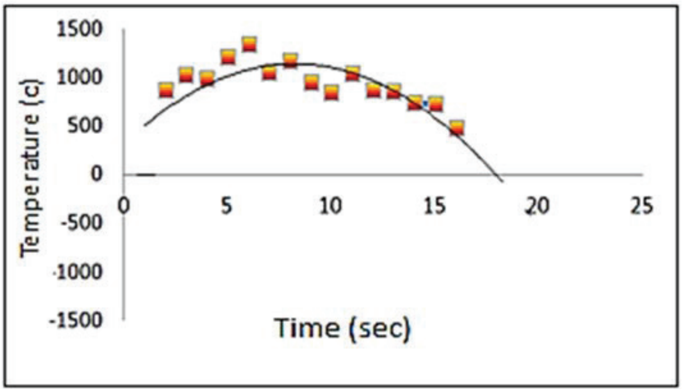


Figure 4: Plot of the variation of temperature during laser irradiation pitch 5 mm

3.0 FINITE ELEMENT ANALYSIS

In the finite element analysis of the forming process made by laser, ABAQUS software was used [16]. This analysis is also done implicitly. In the analysis related to simulations, mechanical calculations can be decoupled from the thermal ones. This is because of negligible energy dissipation from plastic deformation as compared with the high laser energy used in the process. In the decoupled solution, the thermal analysis is performed first to obtain the temperature field, and then the results of thermal calculations are used as the thermal loading for the mechanical analysis. During the process of formation used by laser and heat flux distribution on the sheet, the following equation is obtained:

$$q_{(r)} = \frac{2\eta P}{\pi R^2} \exp\left(-\frac{2r^2}{R^2}\right) \tag{1}$$

Here, the heat flux absorption coefficient, P, is the power of the laser beam, R acts as radius of the laser beam and r is the distance from the center of the plate to the center of the laser radiation source. After the metal plate is irradiated, the temperature of the radiation increases. Temperature rise is affected by convection and radiation heat transfer. Finite element model for the formation of a laser sheet is shown in figure 5. For the modeling, a circular plate with a radius of 50 mm and a thickness of 1 mm were modeled in ABAQUS software model.

In order to compare the numerical results with the experimental ones, this paper is attempting to provide identical conditions with the experimental and numerical results. Properties of the steel used in the simulation are as follows.

Table 1: Physical properties of the work- piece

Young's modulus Gpa	154
Density kg/m^3	7700
Yield stress Mpa	243
Specific heat $J/kg\ k$	550

In the simulation of the process, three dimensional solid elements of the type DC3D8 which has 8-node tri-linear displacement were used. To be precise, 2 layers of elements through the thickness were generated in the work-piece and the mesh of the work-piece contained 15120 elements. In addition, DFLUX subroutine has been used to apply the heat flux. The analysis is performed in two modes: the first analysis was thermal and then, the deformation analysis of the sheet metal was done by results of thermal analysis.

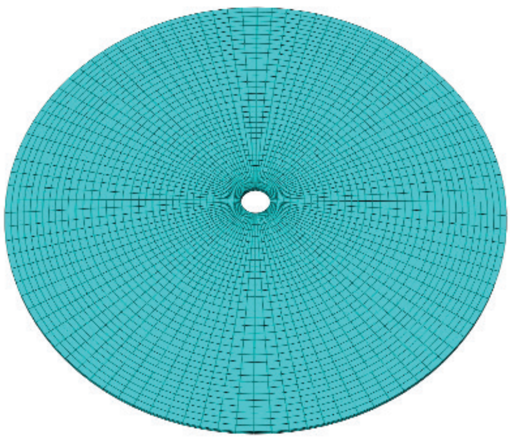


Figure 5: Finite element mesh of sheet

4.0 RESULTS AND DISCUSSION

4.1 Deformation by circular-radial radiation on the sheet

In Figure 6, the result of laser forming a circular blank with circular – radial irradiation paths is shown. As illustrated, the total deformation of the edge in the zero degree path is positive. On the other hand, in the 90- degree path the total deformation of the edge is negative. As such, the values of an edge dislocation in both paths were different and will be discussed below.

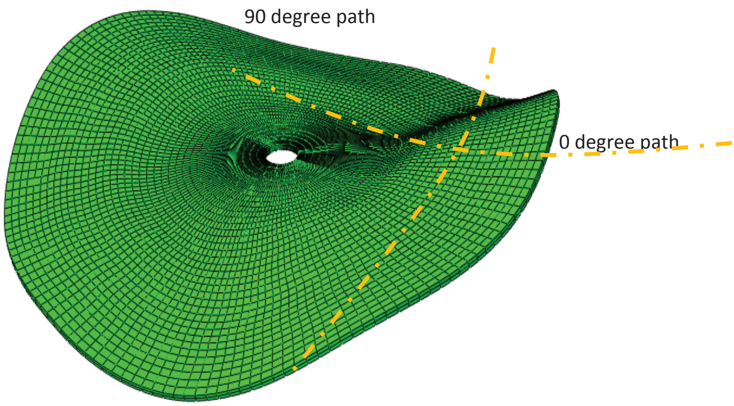


Figure 6: Status of sheet metal forming by circular-radial pattern radiation

4.2 Evaluation of removable edges of sheets forming in circular radial radiation

In Figure7, the status of the edge dislocation and profile of the dome with a circular- radial radiation are shown. As can be seen along both directions, the displacement along the edges in a zero degree direction is positive with the value of around 8 mm. Furthermore, the displacement of the edge along the 90- degree direction is negative and the value is nearly 8 mm.

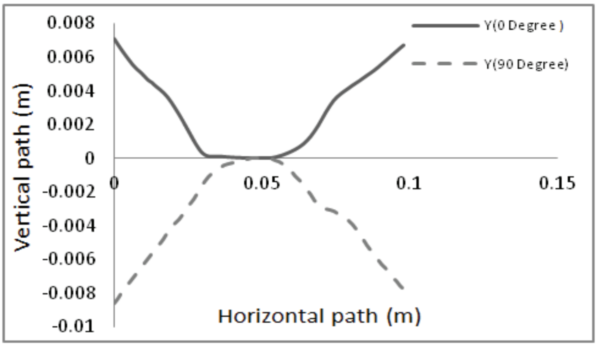


Figure 7: Diagram of the dome-shaped profile with a circular-radial pattern

4.3 Distribution of stress in the laser forming process by circular-radial radiation

Figure 8 shows the effect of von mises stresses and residual stress values on the final geometry of work piece. Residual stresses are those that remain in a solid material after the main causes of the stresses are removed. It is observed that the pattern of residual stresses is somewhat non-uniform and the areas of the plate that are affected by the stress are expanded. They are rooted in large number of radiation beams on the surface of the sheet, the immense variety of possible exposure and the other effective parameters.

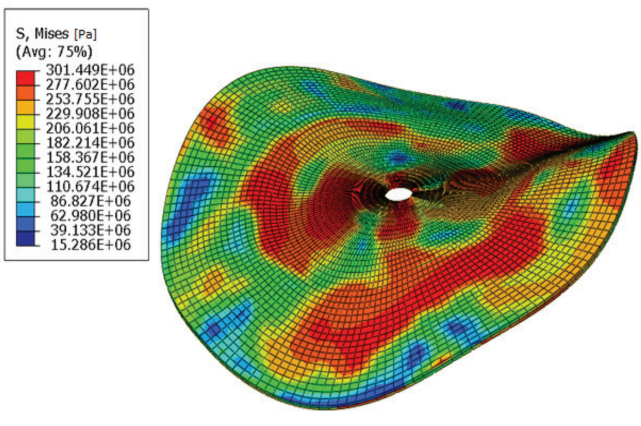


Figure 8: Residual stresses in circular-radial radiation pattern

4.4 Temperature distribution under circular-radial irradiation

In this section, the temperature distribution of the upper and lower surface of sheet metal under laser radiation of circular-radial path is investigated. Using this temperature profile, dominant mechanisms in the laser forming process are found. In figure 9, the temperature distribution has been studied under radial irradiation. The buckling mechanism has occurred due to the very low thermal gradient between layers of the upper and lower plate by the radial irradiation.

In figure 10, the temperature changes under circular irradiation have been studied. According to figure 10, a small thermal gradient between the upper and lower surfaces have occurred. Therefore, low thermal gradient leads to buckling mechanism in the work-piece.

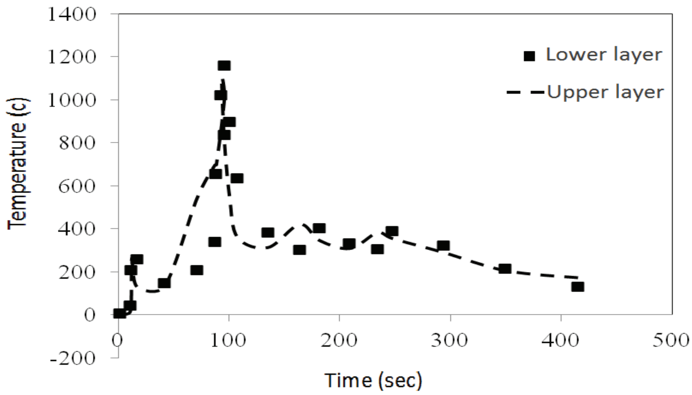


Figure 9: Temperature distribution in the exposure of the upper and lower layers of radial radiation

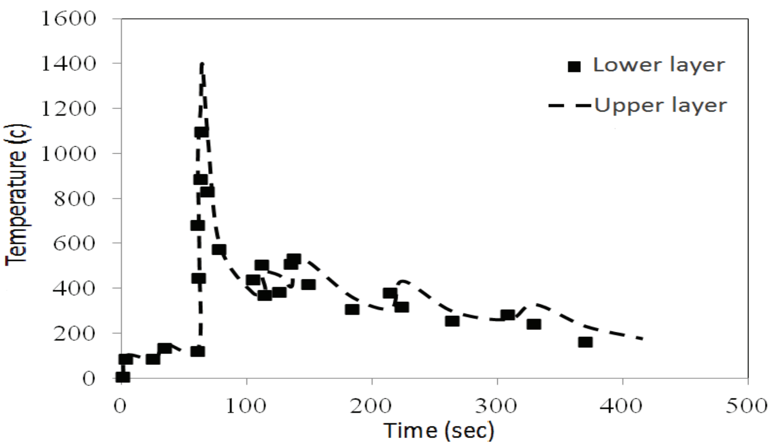


Figure 10: Temperature distribution in the exposure of the upper and lower layers of circular radiation

4.5 Distribution of thick sheet metal with circular-radial radiation

To investigate the formation of dome-shaped pattern by circularradial radiation pattern, increasing the thickness numerically at 9 points along the diameter direction at a zero degree angle is measured.

As it can be seen in Figure 11, value thickening terms are in micrometers. It should be noted that due to the fact that small thickness is increased, the amount of increase will have negligible effects on the nature of the sheet metal forming.

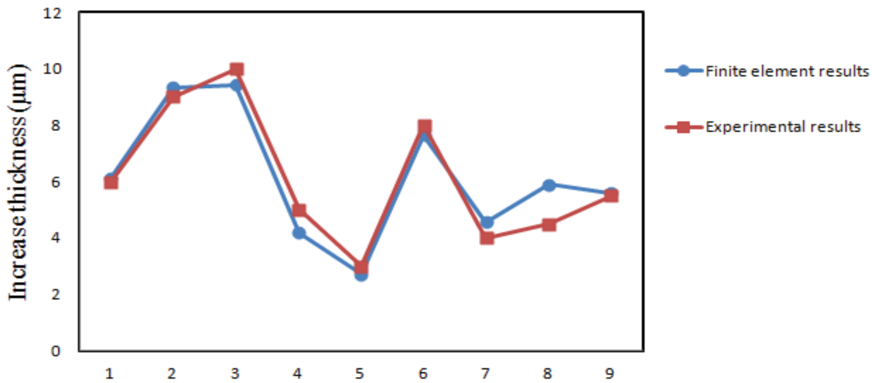


Figure 11: Thickness distribution by circular-radial irradiation

5.0 FORMING A BOWL SHAPE BY SPIRAL EXPOSURE

In continuation of the study about laser forming of bowl-shaped surface in this paper, a new path has been proposed. This path is radiated on sheet metal in terms of spiral pattern as shown in Figure 12. Hence, this path was investigated by the experimental and FEM analysis.

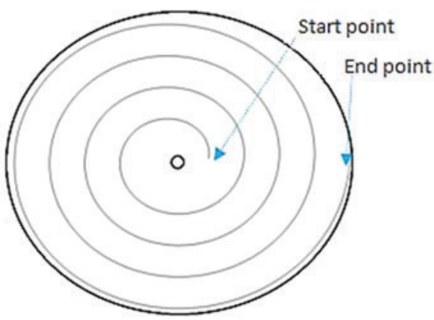


Figure 12: Spiral pattern observed in the study

Figure 13 shows the installation of sheet metal and laser irradiation in the laboratory under a spiral pattern.

Figure 13: Spiral exposure on sheet metal

5.1 Deformation caused by helix radiation on the sheet

Deformation caused by numerical analysis from the spiral pattern is specified in figure 14. Based on the illustration, the displacement of edge along the zero degree direction is positive. Also, displacement of edge along the 90 degree direction is better than the edge displacement by circular-radial pattern and it can be seen that spiral path results in domed-like shape. Of course, the values of edge displacement by circular-radial path and spiral path were different.

It can be noted that, the spiral pattern is better than the circular-radial one in achieving dome shaped forms.

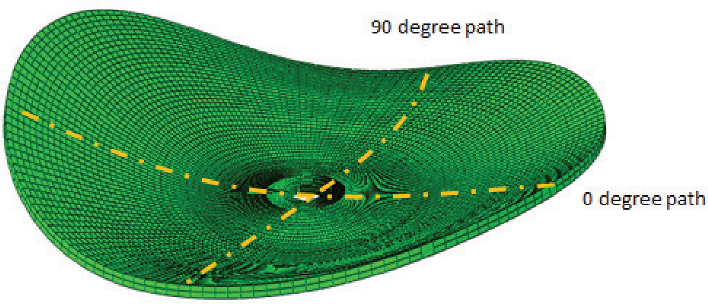


Figure 14: Status of sheet metal by forming a spiral pattern

5.2 The edge symmetry by spiral irradiation

In the following diagram, the status of the dome-shaped profile of edges is shown by spiral irradiation.

In addition, the symmetry of the dome-shaped surface that was formed by spiral pattern is also shown. As it can be seen from Figure 15 along the zero degree and 90 degree direction, the value of edge displacement along the direction of zero degree is positive and it is about 3 mm.

Likewise, the value of edge displacement along the direction of 90 degree is positive. In terms of edge symmetry, formation made by spiral pattern to achieve dome shape is appropriate. Furthermore, forming a bowl shape and motion of the positive edge by spiral radiation pattern is remarkably improved and is better than circular-radial pattern.

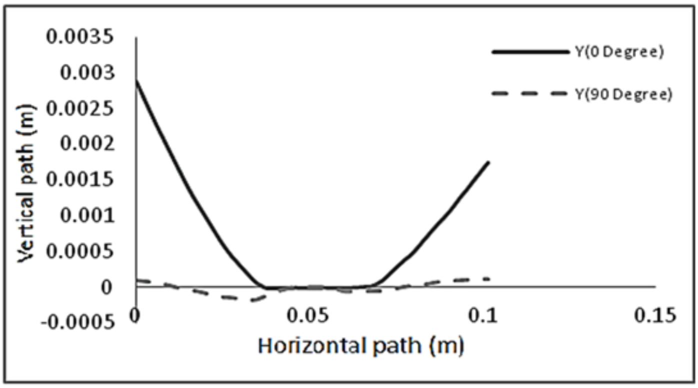


Figure 15: Diagram of the dome-shaped profile with a spiral pattern

5.3 Evaluation of the stress distribution in the forming process of laser in spiral irradiation

Figure 16 shows the effect of the von mises stress and the residual stress values on geometry of work piece. It is observed that the residual stresses are more uniform than the distribution of residual stresses on circular-radial pattern. The reasons are that, firstly, the spiral pattern is not complex compared to circular-radial pattern and secondly, starting points and ending points of spiral radiation patterns are much less than that of circular-radial radiation patterns.

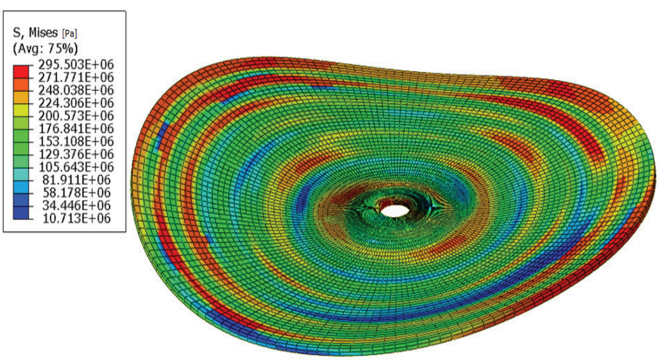


Figure 16: Residual stresses in circular spiral pattern

5.5 Examining the temperature distribution of the spiral beam path

Temperature distribution of the upper and lower surfaces of sheet metal under the spiral irradiation indicated how the process happened in the sheet.

In Figure 17, the status of temperature changes under spiral radiation is investigated. According to Figure 17, the less heat gradient has occurred between upper surface and lower surface showed that the buckling mechanism under spiral radiation has occurred.

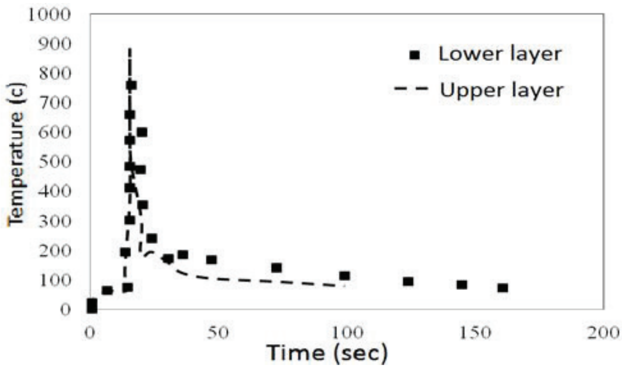


Figure 17: Temperature distribution in the exposure of the upper and lower layers of the spiral radiation

6.0 CONCLUSION

In this paper, the effects of circular-radial radiation to form domeshaped profile/pattern by laser were investigated experimentally and numerically.

In the laser forming process, domed steel parts produced by circularradial pattern have no axial symmetry and the final form produced by circular-radial irradiation pattern along an axis has positive displacement value while the other axis has negative displacement value. In other words, the final shape is saddled-like one.

In the final form, which is irradiated by circular-radial pattern, it does not lead to uniform displacement. Therefore, this irradiating pattern has not been industrially applied. Furthermore, the edges condition of the formed plate has no adequate quality as compared with the spiral pattern.

In a circular-radial radiation pattern, buckling mechanism under circular-radial radiation was created.

In terms of the distribution of residual stresses, due to an immense variety of the circular-radial irradiation and the exposure path parameters, the final form does not have any appropriate conditions. Precisely, residual stress is very high and it has bad effect on micro structure of work-piece.

For the proposed spiral radiation pattern, in terms of shaping sheet metal into a bowl, the symmetry boundary conditions are better than circular-radial radiation patterns.

In terms of the distribution of residual stresses, multiplicity and complexity of the spiral radiation pattern on the metal blank is simpler than circular-radial radiation. Likewise, because of the starting points and end points of laser radiation on work piece that result in an increase in stress on the blank, work piece under spiral irradiation has better forming condition than that under circularradial irradiation. Moreover, stress distribution in work piece under spiral pattern is more uniform than that of circular-radial pattern.

According to the influential parameters of buckling mechanism which rooted in low temperature gradient along the thickness, spiral radiation pattern contributes to thermal buckling mechanism.

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