Finite element analysis, experimental investigation and process parameter optimization of sheet metal bending by line heating method.

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Abstract

The present study concerned with finite element analysis and experimental investigation of sheet metal deforming by line heating method that incorporates the combined effect of traverse speed of the torch, thickness of the sheet metal and number of passes of the torch. For the numerical analysis of metal bending by line heating, the finite element method is employed and the design of an experiment with an orthogonal array L9 is used for the experimental investigation and parameter optimization. Mild steel of 300 x 200 mm is used for both the numerical and experimental investigation. The results from the two approach shows that thermal deformation of the sheet metal mainly depends on geometrical parameters like the thickness of the metal. From the result, a 2 mm thickness metal with a 5mm/s travel speed and single-pass line heating is the best optimum combinations for the maximum temperatures and deformations. The deformations generated from this case are 0.25 mm from the reference plane with a peak temperature gradient of 667.5℃. And also, for the required amount of deformation, the thickness has a significant effect than travel speed and number of passes with a percentage contribution of 93.48%, 5.69%, and 0.41% respectively. And also, for the two approaches, numerical modeling is well agreed with the experiments. Finally, it has been shown that the numerical modeling of the moving heat source developed for this purpose accurately predicts the real process in a mechanical workbench with a user interface.

Key-word: Line heating method, moving heat flux, double pass line heating.

1. Introduction

A study on plate bending by line heating have been reported in 1956 [1]. For the past 40 years, there has been a significant effort to formulate the line heating process and to automate the process such as to replace bending by cold work using a universal press, and efforts to translate human work into artificial technology, or development of a simulator to train skilled operators.

When a metal is formed by line heating, plastic deformation is generated by the applied thermal stresses produced during heating and subsequent cooling of the metal.

Generally, there are two mechanisms commonly used to form steel plates into curved structures, Mechanical forming and Thermal forming.

In mechanical forming, to generate the required shape and size of the plate, the load is applied through the hydraulic press or a set of rollers. But in the case of thermal forming, the required shape is produced through the thermal load. Many types of research and mathematical analysis can also be done on the mechanism of the line heating process to know the final shape of the metal plates when given the heating condition and mechanical properties of the material. But this method has a difficulty and some uncertain factors that are obstacles to the automation.

Not only this, the accurate determination of the heating parameters like travel speed, the gas torch power intensity, beam radius is not fully developed which is mostly a command-based analysis and assumption based analytical method which is an error sensitive and difficult to understand the algorithm.

Though many types of research were conducted in this area, there should be enough deterministic method to understand factors affecting the final shape of the metal during sheet metal bending by line heating.

[2] Oxy-acetylene flame assisted double pass line heating for varying plate thickness were investigated. [3] Investigate the material properties of a plate formed by the line heating method by changing the parameters like plate thickness and heating speed. [4] Discussed an overall literature review on a plate forming by line heating method.

[5] Propose a numerical method to predict the deformation of a real plate of large size. [6] Describes the effect of previous heating on inherent deformation for the case of two heating lines crossing each other. [1] Works extensively on the mechanism of the forming process using line heating and he develops a tool for efficient calculation and prediction of its behavior. [7] Develop the formulae that predict the thermal deformation of steel plate due to multiple line heating. [8] In this work, the effect on angular deformation under different operating parameters, such as energy, scanning speed, and a number of passes along with the thickness of the substrate material, was studied under straight-line scanning schemes. [9] In this study by considering the line heating process as an automatic, they studied the temperature distributions on the plate under heating. The temperature variations during the process with the changes of three variables were investigated. [10] Presented a semi-analytical simple thermo-mechanical model that predicts angular deformations of plates due to line heating.

The present work focuses on 3D finite element analysis and experimental investigation using manual line heating on sheet metals that will consider the combined effect of metal geometry and heating parameters which helps to contribute in the scientific knowledge in metal forming by line heating method.

1.1 Materials and methods

1.1.1 Parent material used for the investigation

All analysis is carried out on rectangular sheets as shown in figure (1) and the metal is 300 mm in length and 200 mm in width by varying the thickness as it is an influential factor during the bending process. The mechanical and thermal properties of this material are present in fig (4) and fig (5).

1.1.2 Method of analysis and measurement

For the numerical analysis of metal forming/bending by line heating, three-dimensional finite element method (FEM) is employed to simulate the process, since the nature of the process is time and temperature-dependent. Factors affecting the metal deformation such as the number of passes, traverse speed of the torch, thickness of the metal is analyzed with a new version of the moving heat flux.

The line heating experimental investigation involves heating of the sheet metal along a single path by considering those parameters which may affect the measurable deformation. Like the Finite element method is employed and heating is applied to the center of the sheet, the same heat, and material were employed during an experimental investigation. All experiments are done manually and the application of heat will be adjusted in such a way that the maximum temperature on the surface of the metal is 700 ℃ and the cooling process is also involved and the metal is heated along the center on the top surface. After the finite element, numerical analysis is completed and experimental investigations are carried out, finally, there is a way of validation of temperature gradient on the top surface and the deformations for both approaches. And the experimental investigation is carried out to evaluate the capability and effectiveness of the numerical approach. Two uncontrollable parameters were measured during the investigation, those are the Temperature distribution on the center top surface of the metal by infrared thermometer while the torch is moving and the deformation of the metal by keeping the deformed model on the reference table and measuring the two half of deformed metal by a digital Vernier caliper. The fig (1) shows the sheet metals used in experimental investigation and method of measurements used during the investigation. Both approaches are analyzed and followed based on the established design of experiments of Taguchi orthogonal array L9 with their level of investigation. So, nine runs for both numerical simulations and experimental investigation will be carried out. The parameters specification with their level is tabulated in table (1).

Figure 1: During the measurement of temperature and deformation

Table 1: parameter specification

Beam radius (mm)	*Traverse Speed (mm/s)*	*Thickness of material (mm)*	*Number of passes*
3	*5*	*2*	*Single*
3	*10*	*4*	*Double*
3	*15*	*5*	*Triple*

During the finite element numerical analysis, the thermal model of all the systems is considered including the thermal model of the moving heat source. Once the thermal model is completed, the structural model is followed to see the structural response of the metal. So, during the process, the thermal model results will be imported as a load for the structural analysis. So, the two processes outputs or results from the numerical analysis is the temperature distribution on the center of the metal and the total deformation of the two half of the metal for the peak temperature values.

It's also possible to express the deflection of the metal due to thermal deformation and it may be referred to as an angular deformation. So, the deformation of the metal after a thermal load, can be calculated by utilizing the mathematical geometry which describes the slope of the deformed shape under the applied load.

1.2 Modeling

Assumptions used in the analysis

- Heat flux from the gas torch is considered as a thermal load and the travel speed of the torch movement is considered to be very high.
- Since it is difficult to control the gas amount and keeping a constant distance between the gas torch tip and the metal which was done by the most experienced workers, a constant value of a stand of distance and flux density is used during manual application.
- Density is not affected due to thermal expansion.
- Linear Newtonian convection cooling is applied on all the surfaces.
- The phase change is not considered since the maximum temperature attained does not exceed 700 Oc [1].
- Since the deformations induced by line heating are very small, a small strain formulation has been generated [1].
- The sheet metal is considered as flat and free of residual stress, so this residual stress will not produce spring back.

1.2.1 Thermal Model

Boundary conditions

To understand the basic boundary conditions like Heat affected zone, the coordinate system and the heating directions Figure (2) is presented. The heating line by which the heat source is applied for the line heating is assumed as region R1 along the z-axis and all the rest surfaces except R1 region are considered as R_2.

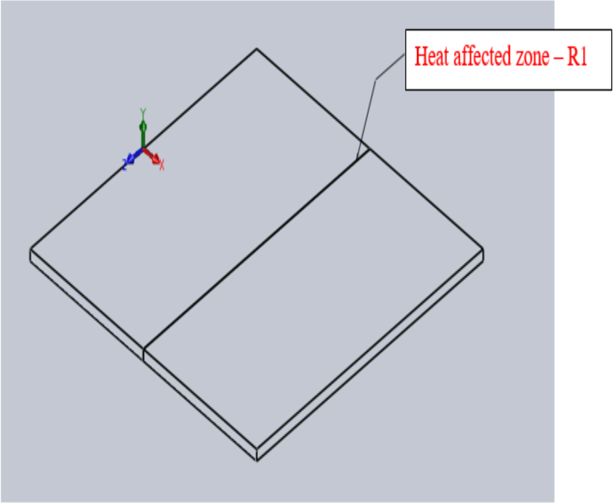

Figure 2: Sheet metal model that shows boundary condition and heating direction.

First boundary condition

The governing differential equation which considers heat conduction in a material is given as;

$$\left[\frac{\partial}{\partial x}\left[K\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[K\frac{\partial T}{\partial Y}\right]+\frac{\partial}{\partial z}\left[K\frac{\partial T}{\partial Z}\right]\right]=pc\frac{\partial T}{\partial y} \qquad (1)$$

A specific heat flow acting over heating zone R1 for $t > 0$, is given by

$$qn = -qsup$$

Second boundary condition

Newton's law of cooling states assumptions that considers heat loss due to convection over surface *R2* is described as,

$$qconvection = hf(T - T\infty) \qquad (2)$$

$where\ ,\ -K\frac{\partial T}{\partial n} = hf(T - T\infty)$, applied on all the surface

for t > 0

Third boundary conditions

Radiation from the sheet is also considered which was given by Stefan-Boltzmann's law.

$$QR = \left[\int_A^\infty E\delta(Ts - TB^4)dA\ \right] \qquad (3)$$

Where; A is an area, E is radiant emissivity and δ is the Stefan-Boltzmann constant.

1.2.2 Modeling of the Moving Heat Source

Numerical modeling of moving heat sources can be used to accurately simulate a variety of industrial processes including welding and forming. In the past, modeling this type of moving heat source was time-consuming and required creating custom MAPDL commands. Now, a free ANSYS ACT Extension developed for this purpose simplifies this greatly. This "Moving Heat Source Version facilitates the definition of a moving heat source in Mechanical Workbench with a user interface. The movement of the heat source in a predetermined path can easily be known, but the present study includes the straight-line path of the moving heat which can be governed by equation (4).

$$q = C2\ e^{-[(x-xo)2+(y-yo)2+(z-zo)2]/C1^2} \qquad (4)$$

1.2.3 Thermo-mechanical model

Boundary conditions

In this study, a simple fixed support has been considered at the bottom surface for the simulation of the metal deformation in the Y-axis (along with the thickness) and in Z-axis (along with the length / the heating direction) and degrees of freedom are constrained which means, the sheet is constrained at the center for free and equal deformation of the two halves. This constraint about the point of symmetry of the sheet has not hindered the free deformation as in the actual experiment.

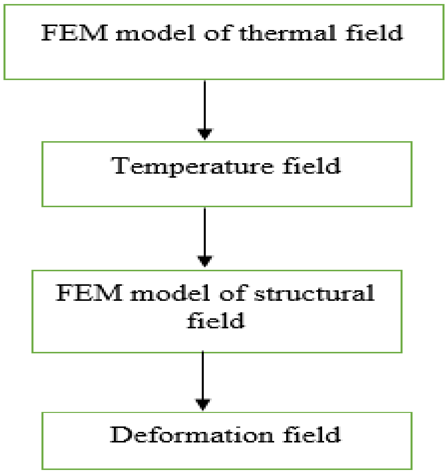

Figure 3: Thermo Mechanical analysis flow diagram

3. Material Properties of mild steel (C-MN steel)

As the size of the metal is described before, a 3-D finite element model based on the temperature-dependent material properties of mild steel for the transient heat transfer analysis and elastoplastic analysis is clearly defined in figure (4) and figure(5).

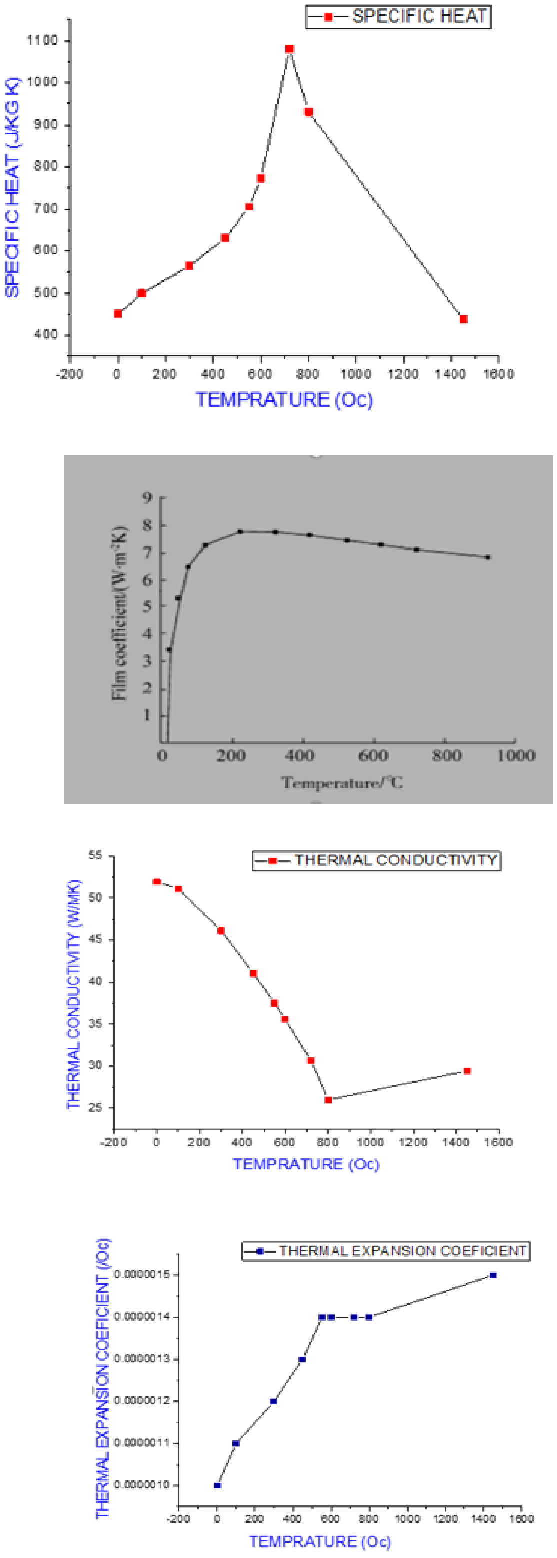

Figure 4: Thermal properties of the material [4].

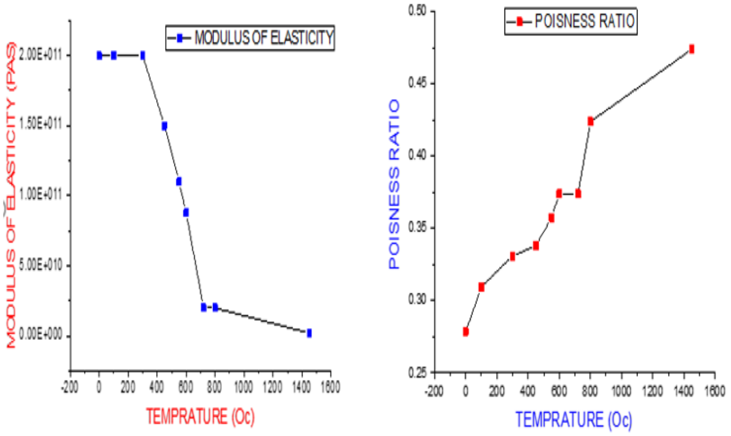

Figure 5: Mechanical properties of the material [4].

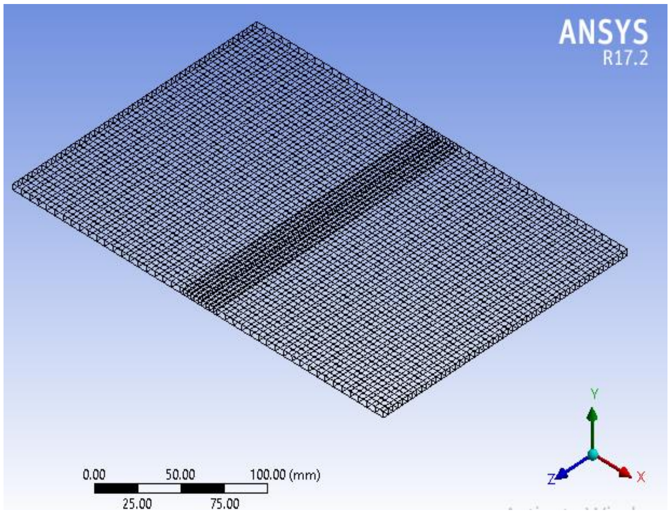

Figure 6: Mesh model of the work piece

Table 2: Chemical composition of C-MN steel [3].

C	SI	Mn	P	S	CR	NI	Mo	CU	Al
0.19	0.37	1.57	0.023	0.027	0.06	0.03	0.01	0.04	0.046

4.Meshing

It is recommended that a mesh with a few nodes and elements are possible to save computation time. To do this, a fine mesh near the heated region and the rest as a course is recommended on the surface where heat is applied, because higher temperature and strain gradients exist near the heated line and to improve the accuracy.

The element type of SOLID70 is used for the model in the simulation according to its special characteristics which have hexahedral elements with eight nodes and surface.

5. Result and discussion

Numerical simulation results of best selected runs

Simulation run 1

Even though nine runs are conducted for the present study, Only three simulation results are presented based upon the average signal to noise ratio that has the highest value of temperature gradient from the analysis. Simulation run 1 was conducted by considering the heating parameters which was established based on the design of experiment and the thickness of the metal is 2 mm and a single pass heating is considered. The time from start to end point on the surface is 40 sec and after the torch passed the surface, the metal is exposed to cooling for about 110 sec after heating. To simulate the thermal field generated by line heating, it is necessary to model the moving heat source. So, the loading conditions of the Moving heat flux for the first run is: velocity of the heat source = 5mm/s, start time = 2 sec, end time of the source = 40 sec, the beam diameter = 6mm and convection = tabular.

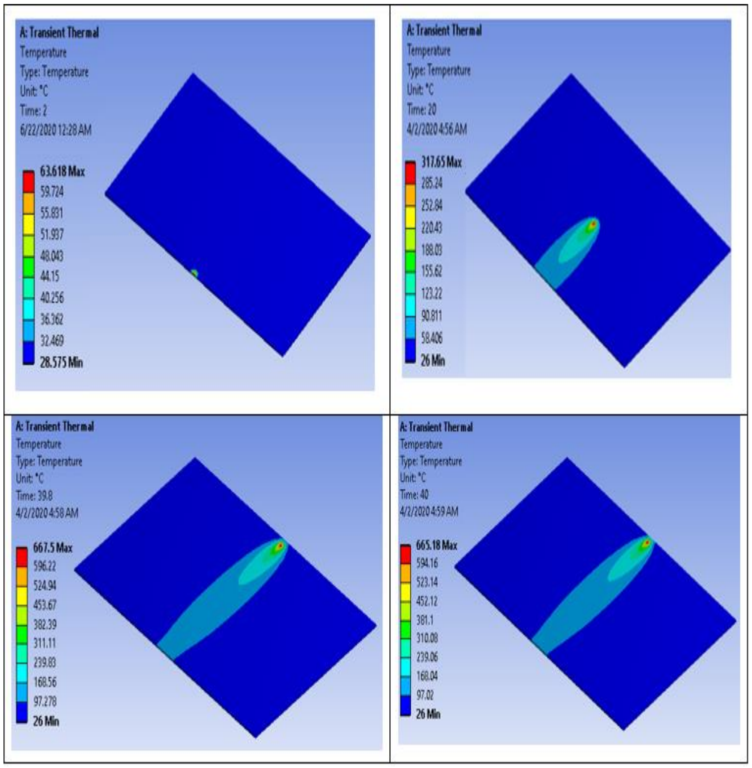

Figure 7: Temperature distribution for the first run

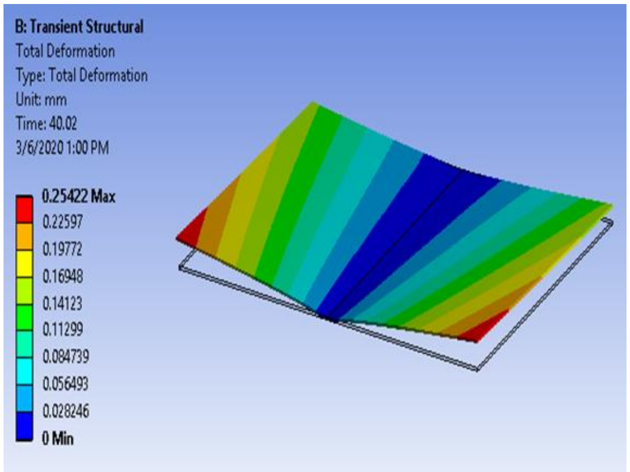

Figure 8: Structural response for the first run

Fig (7) shows the temperature histories on the center of the sheet metal and it can be seen that the temperature rises rapidly and reach a maximum of nearly 667.5°C and then subsequently drops smoothly when the torch passes away from the surface.

The deformation or bending on the center of the metal is shown in Fig (8) and the deformation of this sheet is investigated along a y-axis through the thickness direction.

Simulation run 4

In the simulation run 4, the sheet metal is 4 mm in thickness and was subjected to a double pass heating with a flux density and beam diameter as constant as the first two simulations. And also, the torch travel speed is 5mm/s and the sequence of heating is double on the same path which means that the torch travels two times to reach some maximum value and cools down. So, two temperature histories are recorded. As shown from Fig (9), the temperature reaches a maximum of 610.06 °C for a single pass and 632.58 °C for double pass line heating.

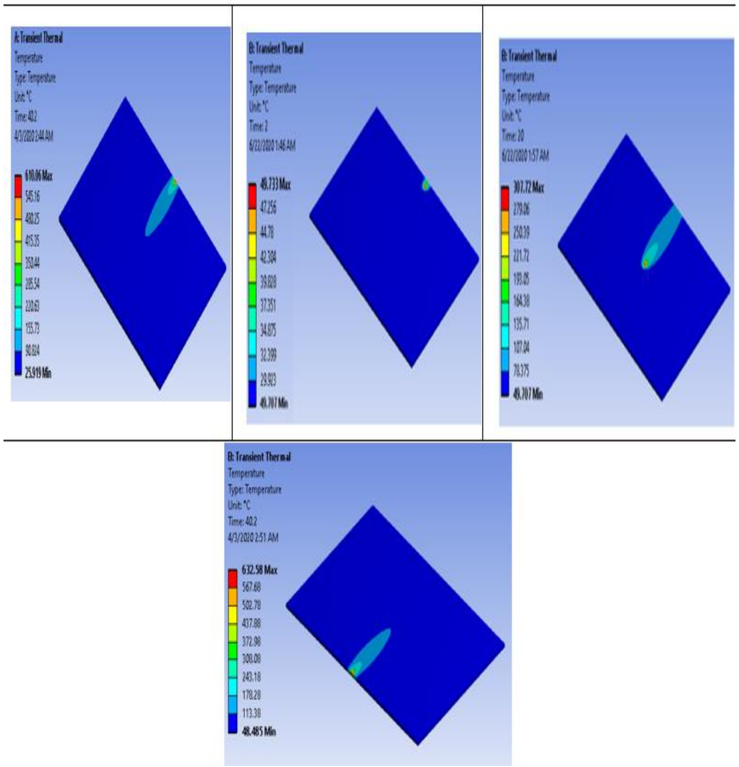

Figure 9: Temperature distribution for run 4

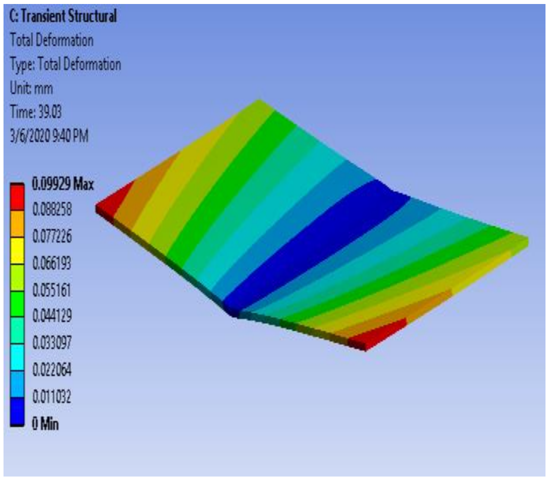

Figure 10: Structural response of simulation run 4

The total deformation generated during line heating of the sheet metal at the center of the metal surface for a simulation run 4 is shown in the Fig (10) and this is also investigated along the thickness direction.

Simulation run 7

Finite element modeling of line heating for 5 mm thickness which is used to predict temperature distribution with the triple pass of the torch and with 5mm/s of torch travel speed is presented as follows.

To get the maximum temperature for a triple pass of the torch, first, a single and double pass line heating should be investigated with the same amount of heating and torch travel speed to show the effect of a number of passes on the temperature distribution.

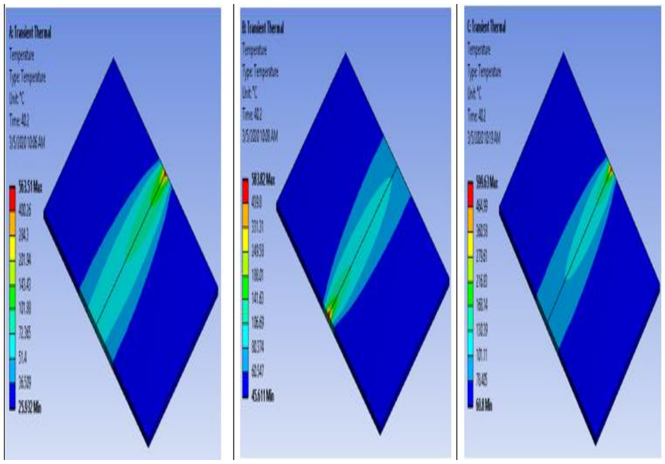

Figure 11: Temperature distribution for run 7

The deformation shape for 5mm thick metal undergone triple-pass line heating is shown in Fig (12)

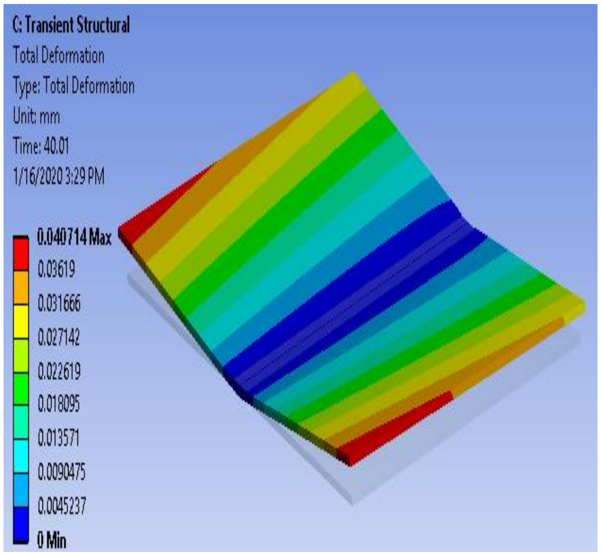

Figure 12: Structural response of simulation run 7

Effect of travel speed of the torch

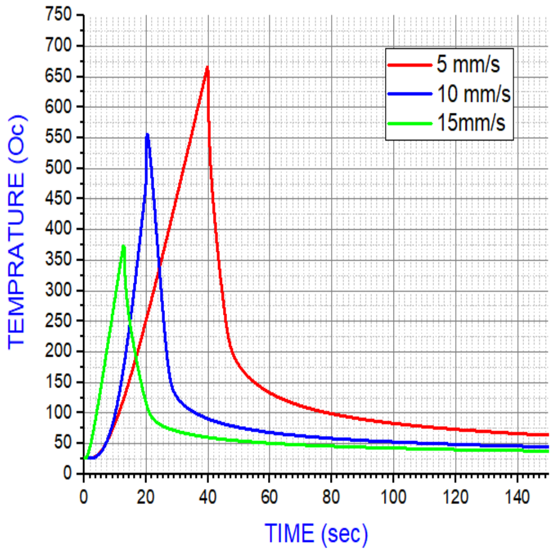

Figure 13: Temperature versus time graph for a variable Traverse speed on 2mm thick metal

According to Fig (13), the pattern of the temperature distribution indicates that a decrease in the traverse speed of the torch will increase the temperature of the metal until the metal reaches the phase change temperature. This is due to the higher amount of heat is transferred to the metal. So, a slow movement of the torch (5 mm/s), will result in a large amount of heat to be transferred to the metal and penetrate thought the thickness because a high surface temperature is being applied for a long period.

In other words, when the travel speed of the torch is fast (15mm/s), the thermal cycle is also short and the heating rates are very fast and the time to generate high-temperature gradient thought the thickness is very short. But a very high-temperature gradient is produced along the heating line.

Effect of thickness of the sheet metal

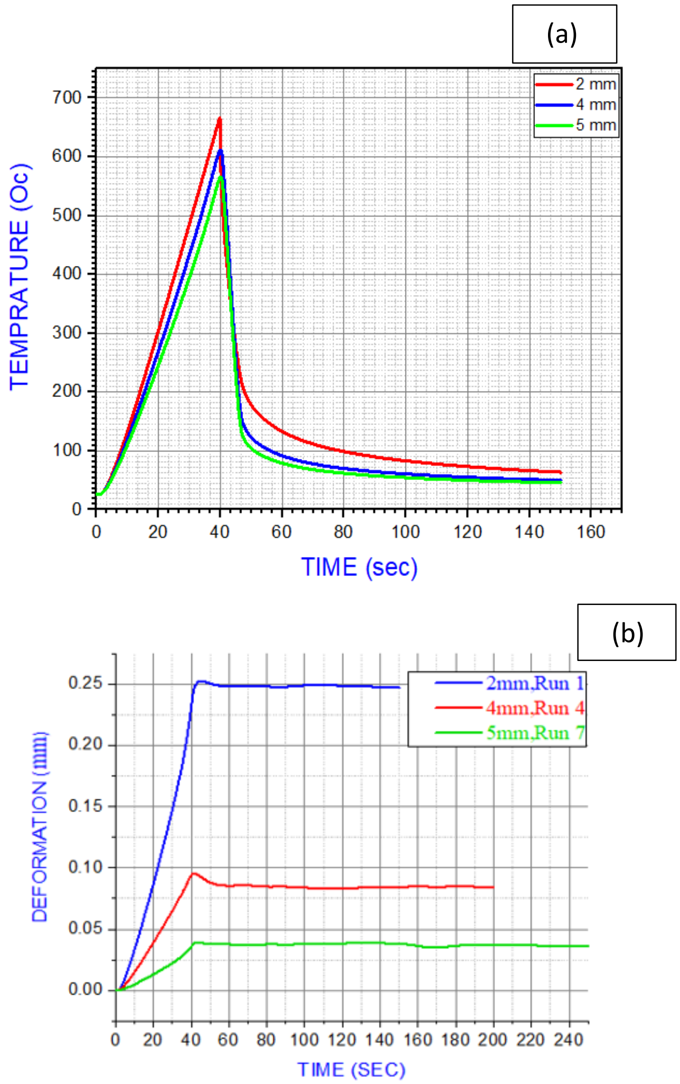

Figure 14: (a) Temperature versus time for a variable thickness of the metal for 5mm/s traverse speed with a single pass line heating (b) effect of thickness on total deformation.

The different metal thickness will result in a different amount of heat dissipation. Fig (14), (a) shows the nodal temperature distribution against time steps for different metal thickness. From the graph, it has been observed that the peak nodal temperature on 2 mm is the highest value compared to 4mm and 5mm metals.

This indicates that as the thickness of the metal increase, the value of peak temperatures attained will decrease. So, thicker metals can absorb more heat since they have a bigger volume compared to thinner metals, thus the rate of heat dissipations in thicker metal is high.

And also, the heat can easily be penetrating through thinner metals than the thicker as the thermal expansion coefficient on thinner metal is high. Small deformation by increased thickness is due to the need for high-temperature gradient for large cross-sectional areas so that a minimum temperature difference between the top and bottom surface can be created in minimum time as long as the bending or deformation is closely related to the temperature gradient.

So, as it can be seen from the pattern of the Fig 14 (b) is that, the thickness of the sheet metal has a significant effect on the total deformation than the temperature and due to this a very small temperature difference is observed in Fig 14 (a) but with a large difference in deformation value with the thickness is observed in Fig (b).

Effect of number of passes along the heating line

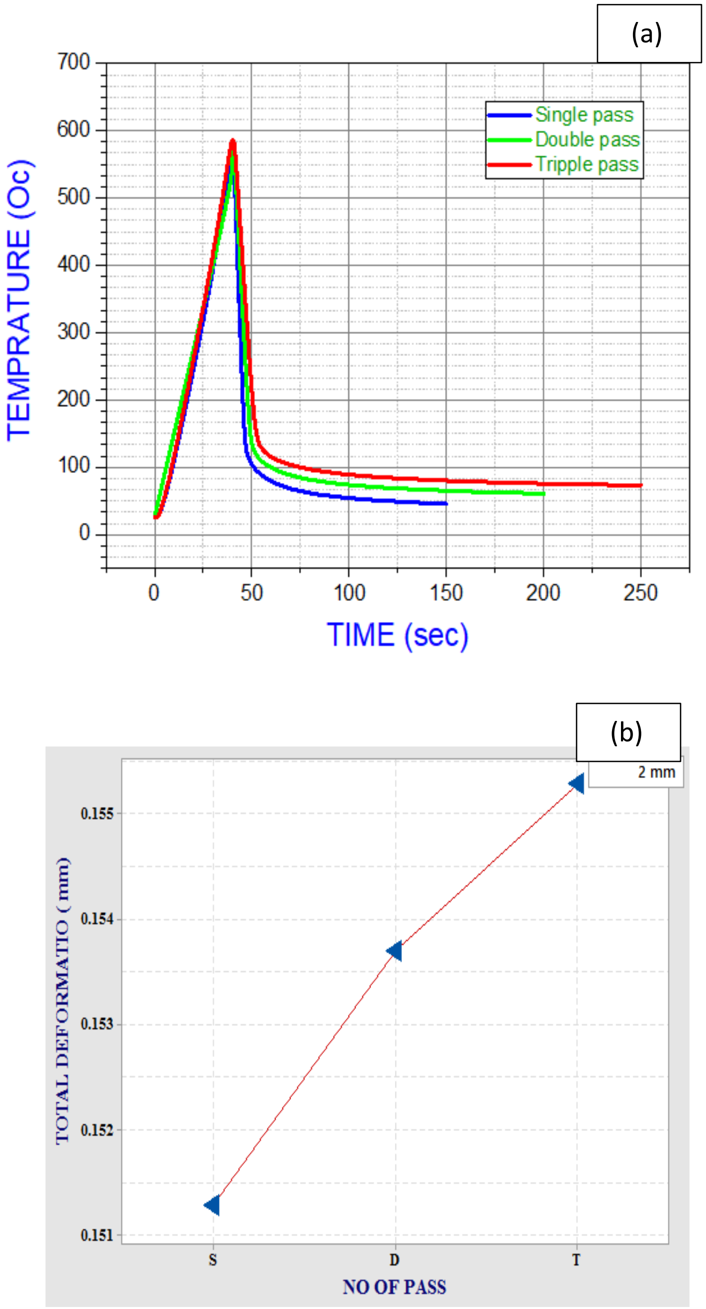

Figure 15: (a) Temperature versus time response for a variable number of passes on 5 mm thick metal and 5mm/s traverse speed (b), Effect of number of passes on total deformation with 15 mm/s travel speed.

From Fig (15), it has been shown that repeated heating increases the temperature gradient and deformation through the metals. So, the peak temperature generated from the second passes is larger than the first passes, and also the third passes generate higher peak temperature than the second.

During this time the first pass could serve for the additional heating for the next pass by reducing the temperature-dependent stress of the metal in such a way that hot metal is easier to deform than a colder one. So that the deformation increases with the number of passes. But the effect of these number of passes is very small as we observe from the Fig (15) (b), which means that the effect of a single pass from double and the effect of a double pass from triple passes are very small.

This is because small plastic stains are generated during the second passes and third passes than the first passes as this subsequent heating repeated the elastic-plastic loading and unloading with less new plastic strains.

So, during thermal deformation, the strain hardening generated inside the material will be incorporated to reduce the ductility of the metal during repeated heating.

From Fig (15) (b), large deformation is obtained on a metal with a triple pass line heating. In general, large deformation with fewer pass can be obtained by maintaining a constant temperature difference between the top and bottom surfaces. The rate of deformation decreases subsequently with an increase in the number of passes as the temperature difference between the top and bottom surfaces decreases.

Sample preparation and experimental setup.

In doing the experimental study of sheet metal bending using line heating, both the table which provides as a bed for the torch to travel along and fixtures where designed and manufactured in the workshop of mechanical engineering as shown in Fig (16)(a). After developing the set up for the investigation, the test samples are carefully positioned before applying the heating torch as shown in Fig (a). The position of the sheet is along the width to promote a suitable deformation**.** All analysis is carried out on rectangular sheets as shown in Fig (16) (b). The metal is 300 mm in length and 200 mm in width by varying the thickness. Like in numerical simulation, the heating is done on its center at equal distance from both ends as it has been explained in the procedure. Fig (17) shows how to make sure the condition is in ambient during the first step of the experiment and then the time-dependent temperature histories will progress from the initial time step.

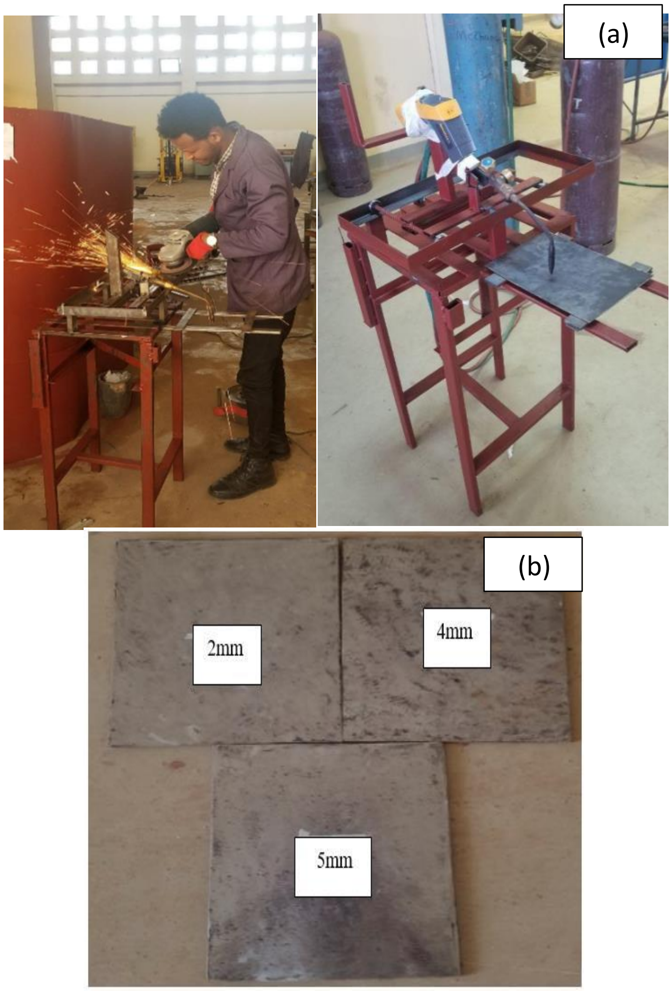

Figure 16: (a) Set up for the experimental investigation, (b) rectangular sheet metals

Figure 17: Initial set up for temperature measurement

7. Application of ANOVA

To investigate the degree of importance of the process parameters, the ANOVA technique is carried out. The ‘‘larger is better” (S/N) characteristics are considered for the sheet metal deformation and given by (Eq 5.). The ANOVA technique is also performed to establish the likely relationship that exists between those factors and the output values.

$$S/N = -10\,log\,1/\,n\,\Sigma\,1/y2 \tag{5}$$

The main effect of the parameters can also be used to conclude the critical factors on the deformation of the sheet metal. The figure (18) shows the main effect plot for S/N ratios for three process parameters, i.e. thickness, traverse speed, and a number of passes. The graphs obtained through the Taguchi technique show that the S/N ratio is highest for parameter thickness and traverse speed of the torch. It is also seen that S/N is lower for the parameter number of passes.

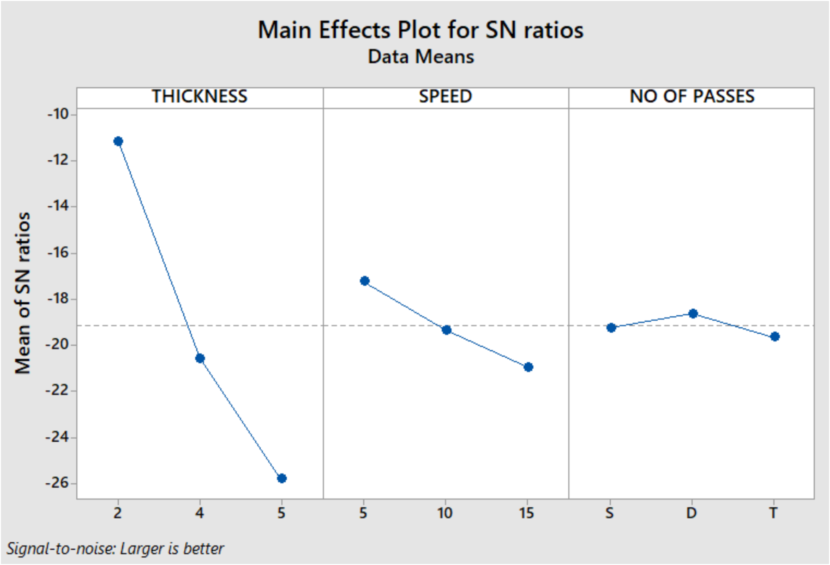

Figure 18: The main effect of S/N ratio

Table 3: The optimal factor setting

Factor	Code	Level	Optimum level
Thickness	A	1	2
Speed	B	1	5
Number of passes	C	1	S

The optimal condition is the optimal factor setting which yields the optimum performance. In this case, it is the factor setting which provides the highest total deformation at the highest peak temperature values.

So, the optimal condition is obtained by identifying the levels of significant control factors that yield the highest S/N ratio and maximum total deformation. Based on the larger is better characteristics of S/N, a larger value of this yields better results. Accordingly, the 2mm thickness of the sheet metal with the travel speed of 5 mm/s and a single pass line heating is the best optimum combinations of the parameters which yield the larger value of total deformation.

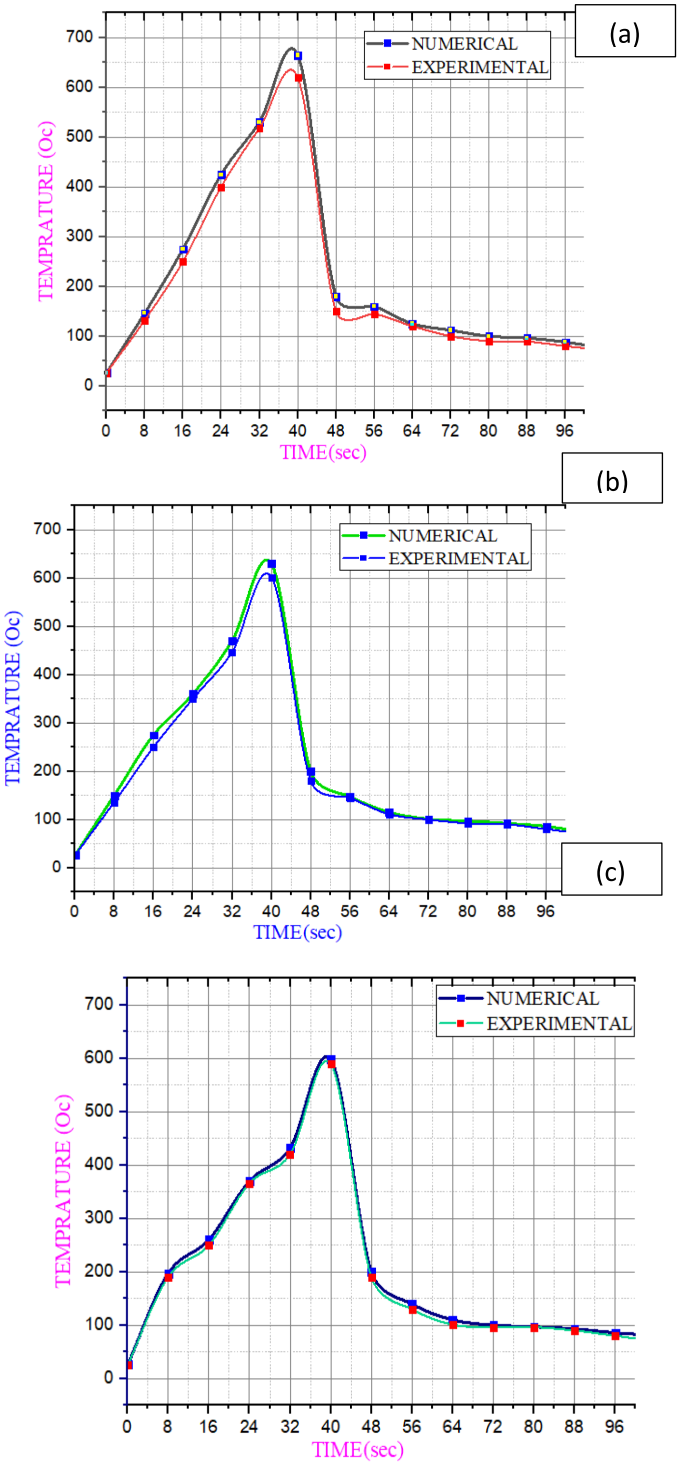

Figure 19: Validation of temperature distribution for (a) run 1 (b) run 4 and (c) run 7 for 2mm, 4mm, and 5 mm thick sheet metals respectively

Fig (19) shows the comparison between the temperature distribution on the top surface of the sheet metal for the three selected runs based upon the average signal to noise ratio that has the highest temperature gradient from both numerical and experimental analyses. The temperature on the top surface is enhanced by reducing the traverse speed of the torch with a smaller thickness of the metal and with an increasing sequence of a number of passes. But it is also observed from the three graphs is that the time required for heating the metal to reach the peak temperature gradient for the experimental line heating is smaller than the numerical one. So, the thermal cycle for the experimental line heating is smaller than the numerical. Even though the heating time and the temperature gradient for the two approaches are different, the cooling rate is acceptable.

Some errors were raised during the cooling process especially for an experimental run one within the range of 48 – 72 sec time intervals due to some external forces of atmospheric room temperature. Besides all this limitation, the graph also shows the numerical modeling is well agreed with the experimental investigation.

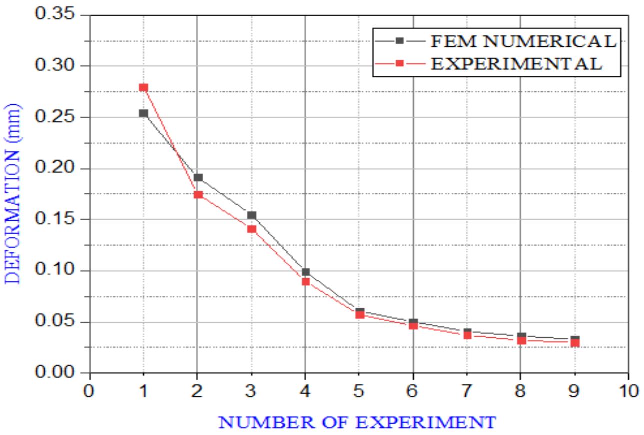

Figure 20: Comparison of total deformation

From Fig (20), the computed numerical results and the characteristic experimental results of the total deformation obtained during the sheet metal bending by using line heating are compared. The black line from figure (21) refers to the numerically computed total deformation derived for all numerical results and the red line shows the experimental one of total deformation with pre-defined parameters and with their respective magnitudes. The deformation of the metal which can be obtained in angle from the horizontal plane is also calculated using mathimatical geometry.

This comparison is also governed by the design of the experiment for all runs. From the figure, it can be shown that the total deformation of the metal decreased with an increased in traverse speed and increased in the thickness of the sheet metal but, with a decreased value of the number of passes. The graph also ensures the accuracy of the numerical results but, with an unexpected value of experimental results for the first run. As described so far, the experimental results are less expected than the numerical results as the numerical simulation results were calculated in the closed system and will compensate for some parameters which will raise an error during an experimental investigation. And also the graph shows that the finite element numerical modeling of line heating is well agreed with the experimental analysis for the deformation of the metal with a less amount of error.

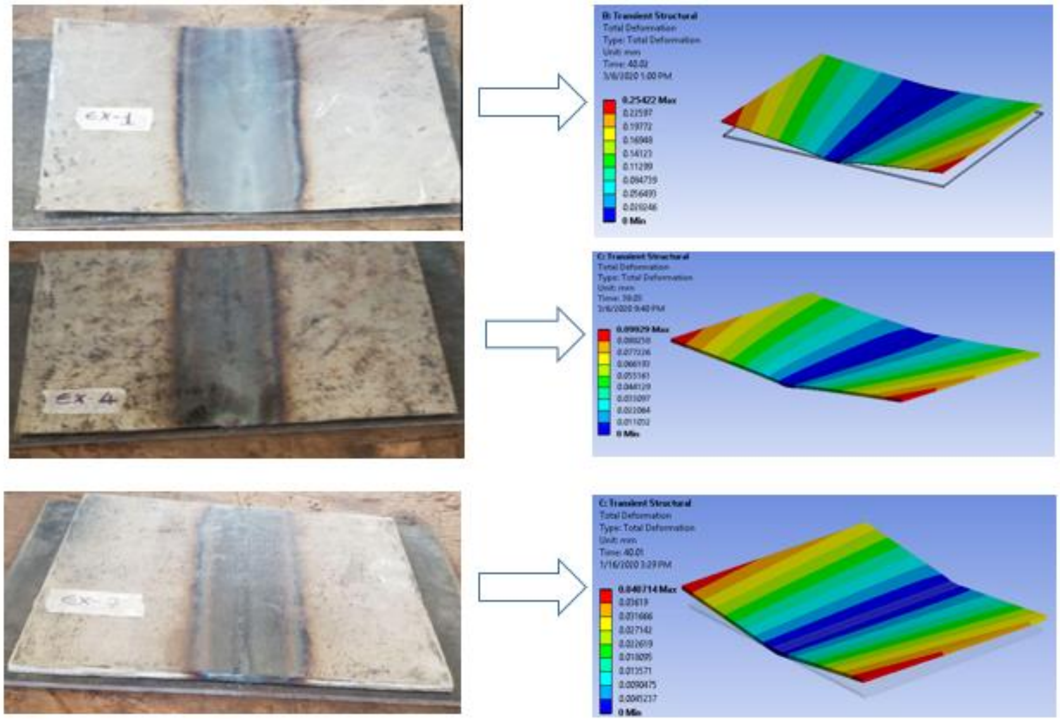

Figure 21: Comparison of the structural model for the two approaches

Conclusion

Generally, the following conclusions are drawn for both FEA and experimental investigation.

- The temperature generated in a metal maximum when slow torch travel speed with thinner metal is used. That means the thermal gradient along the thickness is high when the temperature on the top surface is maximum so, a maximum temperature gradient of 667.5℃ is recorded on 2mm metal thickness with 5 mm/s travel speed of the torch.
- Bending or deformation is reduced with an increase in torch travel speed and thickness of the sheet metal.
- Repeated heating will enhance both the temperature and total deformation of the sheet metal with a small amount of changes.
- The analysis based on the design of the experiment again predicted that the thickness of the metal is the most influential parameter in achieving the desired deformation followed by speed and number of passes with a percentage of contribution of 93.48%.
- Optimization of the parameters identified that a factor setting with a traverse speed of 5mm/s with a single pass line heating and a sheet metal thickness of 2 mm is an optimal combination that generate a deformation of 0.25 mm.
- Finally, for the deformation of the metal, the numerical method shows a good agreement with the experimental one with an average percentage error of 9.58 % for all runs.

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