Materials Today: Proceedings 56 (2022) 2398–2409

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Experimental investigation and process parameter optimization of sheet metal bending by line heating method

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ARTICLE INFO

Article history:
Available online 10 January 2022

Keywords:
Line heating method
Moving heat flux
Double pass heating

ABSTRACT

The present study is concerned with the 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 the 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 × 200 mm is used for both numerical and experimental investigation. The results from the two approaches show that the 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 5 mm/s travel speed and single-pass line heating are 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 °C. 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.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Applied Research and Engineering 2021.

1. Introduction

A study on plate bending by line heating have been reported in 1956 [1]. Clausen 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 [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 replacing bending with 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 difficulty and some uncertain factors that are obstacles to 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 algorithm.

Though many types of research were conducted in this area, there should be enough deterministic methods to understand factors affecting the final shape of the metal during sheet metal bending by line heating. Pankaj et al., Oxy-acetylene flame-assisted double pass line heating for varying plate thickness was investigated [2].

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https://doi.org/10.1016/j.matpr.2021.12.451
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the International Conference on Applied Research and Engineering 2021.

Hyung and Joo-Sung investigate the material properties of a plate formed by the line heating method by changing the parameters like plate thickness and heating speed [3]. Das and Biswas discussed an overall literature review on a plate forming by line heating method [4].

Vega et al., Propose a numerical method to predict the deformation of a real plate of large size [5]. Adan et al., describe the effect of previous heating on inherent deformation for the case of two heating lines crossing each other [6]. Lee et al., develop the formulae that predict the thermal deformation of steel plates due to multiple line heating [7]. In this work, the effect on angular deformation under different operating parameters, such as energy, scanning speed, and the number of passes along with the thickness of the substrate material, was studied under straight-line scanning schemes [8]. In this study by considering the line heating process as an automatic, they studied the temperature distributions on the plate under heating [9]. The temperature variations during the process with the changes of three variables were investigated. Yu et al., Presented a semi-analytical simple thermo-mechanical model that predicts angular deformations of plates due to line heating [10].

Bae et al., Develop a Simplified mathematical formula that predicts deformations of a plate during the forming process through line heating with an oxy-propane flame was proposed. The formulas are derived from a statistical approach using the finite element method (FEM). The results of the analyses and the predictions of the formulas are well compared with those of the experimental measurements [11]. Shin and Woo present an analysis of the heat transfer during line heating. A turbulent thermal flow analysis method is used to get the temperature distribution. Both experimental and numerical approaches are carried out that includes different parametric analysis. The study shows that the nozzle diameter and the tip clearance are the important factors of the heat flux [12]. Shin develops and describes engineering concepts of automated line heating process which is more advanced than the previous concepts where a control system and automated machines were developed separately. But this study makes these things work simultaneously to easily understand by technicians about information related to heating location, torch speed, heating sequence, and other related information. The developed system shows that it is very user-friendly and includes advanced engineering calculations for accurate work [13].

Heat source models are used to define the heat flux distribution in the domain. The optimal design finds out defects due to temperature distribution within the material. The numerical method is an important tool to solve many complicated mathematical problems since analytical solutions are available for simple problems [14].

Zhou develops an FEA model for line heating which verifies the feasibility of the multiple torches were studied. In this study, both numerical and experimental investigations were conducted to prove the validity of the model. The study shows that the numerical and experimental were in good agreement and it could be concluded that the multiple torch process of line heating is a feasible method and could greatly reduce processing time [15]. Kant and Joshi give a theoretical understanding of the sheet bending process. Their explanation mainly focuses on the laser bending process using temperature gradient mechanism, buckling mechanism, upsetting mechanism and also they had tried to explain the effect of process parameters on the bending of metals like power, scanning speed, a number of scans, cooling condition, and effect of material properties and their research show this process has some challenges like the development of efficient bending with a moving load and process design and control [16].

Teixeira specified the accuracy and limitation of different types of heat sources were, as the limitation of each model is not specified. All analysis is performed by ANSYS software. The result from the analysis shows that the Gaussian heat source model is a model in which heat is generated over a surface and therefore it may not be suitable to be applied to thick plates [17]. Zhu and Yang Proposed heating path generation and simulation for ship plate steel based on STL mode. In this method, simulation is performed by inserting the models of the heating equipment into the simulation system by using VC++ and OpenGL. The study of this research shows that the method can solve the inconvenience of manual heating and the whole heating process can be observed by the simulation [18]. Jang et al., Focuses on the simulation of triangle heating and for the analysis model of the elastoplastic procedure of triangle heating, a circular disk-spring model is proposed. The results from the simulation were compared with those of experiments and show a good agreement. And It is also shown that the models used in this study are effective and efficient for simulating triangle heating for the steel plate forming process [19].

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 to the scientific knowledge in the metal forming by line heating method.

2. Materials and methods

2.1. Parent material used for the investigation

All analysis is carried out on rectangular sheets as shown in Fig. 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 Figs. 4 and 5. The chemical composition of the selected material C-MN steel is given in Table 1 .

It's generally difficult to obtain data that mainly has a temperature-dependent material property [1]. The selection of material is based on the application area that can be used and almost all preliminary studies were conducted on this material. As the line heating method is majorly applied in ship building and automotive industry, where mild steel is an effective material for the construction of the body and some components.

- Mild steel changes with the properties according to the amount of carbon in it.
- Many automobile manufacturers used mild steel for making the body parts of the vehicles.

So, based on the amount of carbon content and the required mechanical properties the grade of Mild steel which C-MN steel was used.

2.2. Method of analysis and measurement

For the numerical analysis of metal forming/bending by line heating, the 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 are analyzed with a new version of the moving heat flux.

The line heating experimental investigation involves heating 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

Fig. 1. Measurement of sheet metal temperature & deformation.

Table 1
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

maximum temperature on the surface of the metal is 700 °C 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 validating 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 the deformed metal by a digital Vernier caliper. Fig. 1 shows the sheet metals used in the experimental investigation and the 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 2.

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 are the temperature distribution on the center of these 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.

Following Assumptions are used in the analysis [1]

- 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 keep 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 °C.
- Since the deformations induced by line heating are very small, a small strain formulation has been generated.
- The sheet metal is considered flat and free of residual stress, so this residual stress will not produce spring back.

Table 2
Parameter specification.

Factors	Levels		
	Level 1	Level 2	Level 3
Traverse Speed (mm/s) (A)	5	10	15
Thickness of material (mm) (B)	2	4	5
Number of passes (C)	Single	Double	Triple

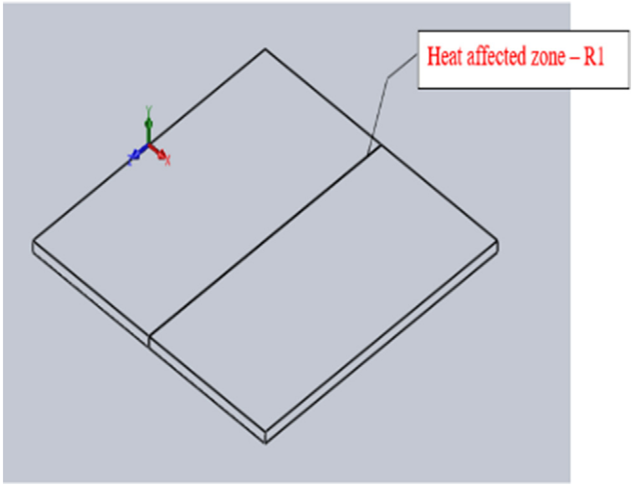

Fig. 2. Sheet metal model that shows boundary condition and heating direction.

2.3. Thermal model

To understand the basic boundary conditions like Heat affected zone, the coordinate system, and the heating directions, Fig. 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 the R1 region are considered as R2 (See Fig. 2). Flow Diagram for Thermo Mechanical analysis is shown in Fig. 3.

First boundary condition

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

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

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

$$qn=-qsup$$

Second boundary condition

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

$$qconvection = hf(T-T\infty \tag{2}$$

where, $-K\frac{\partial T}{\partial n}=hf(T-T\infty)$, applied on all the surfaces for t > 0

Third boundary conditions

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

$$QR=[\int_{A}^{\infty}E\delta(Ts-TB^{4})dA] \tag{3}$$

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

2.4. 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 Eq. (4).

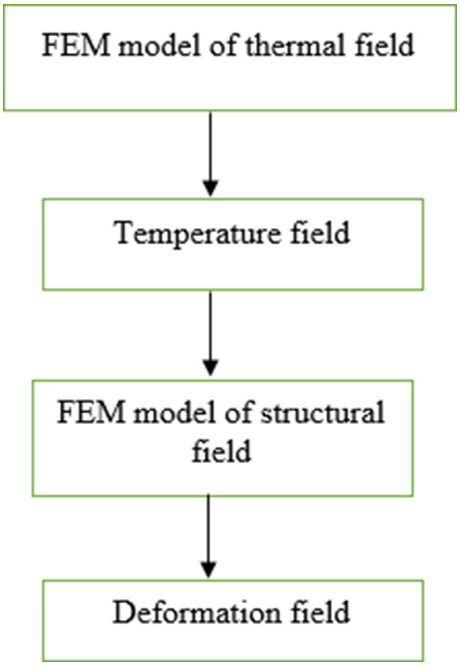

Fig. 3. Thermo Mechanical analysis flow diagram.

$$q=C2e^{-[(x-xo)2+(y-yo)2+(z-zo)2]/C1^{2}} \tag{4}$$

where, q is heat flux on the desired surface, C1 is Radius of the beam, C2 is Source power intensity, (Xo, Yo, Zo) is Instantaneous position of the center of the heat flux

2.5. Thermo-mechanical model

In this study, simply 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.

2.6. 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 Figs. 4 and 5.

2.7. Meshing

It is recommended that a mesh with a few nodes and elements is 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 a surface. Fig. 6 indicates the mesh model of the workpiece.

3. Result and discussion

3.1. Numerical simulation results of best-selected runs

Even though nine runs are conducted for the present study, Only three simulation results (Run 1, Run 2, Run 3) 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 were established based on the design of experiment orthogonal array L9 (coded values) which is given in Table.3 and the thickness of the metal is 2 mm and a single pass heating is considered. The time from start to endpoint on the surface is 40 s and after the torch passed the surface, the metal is exposed to cooling for about 110 s 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 are the velocity of the heat source = 5 mm/s, start time = 2 s,

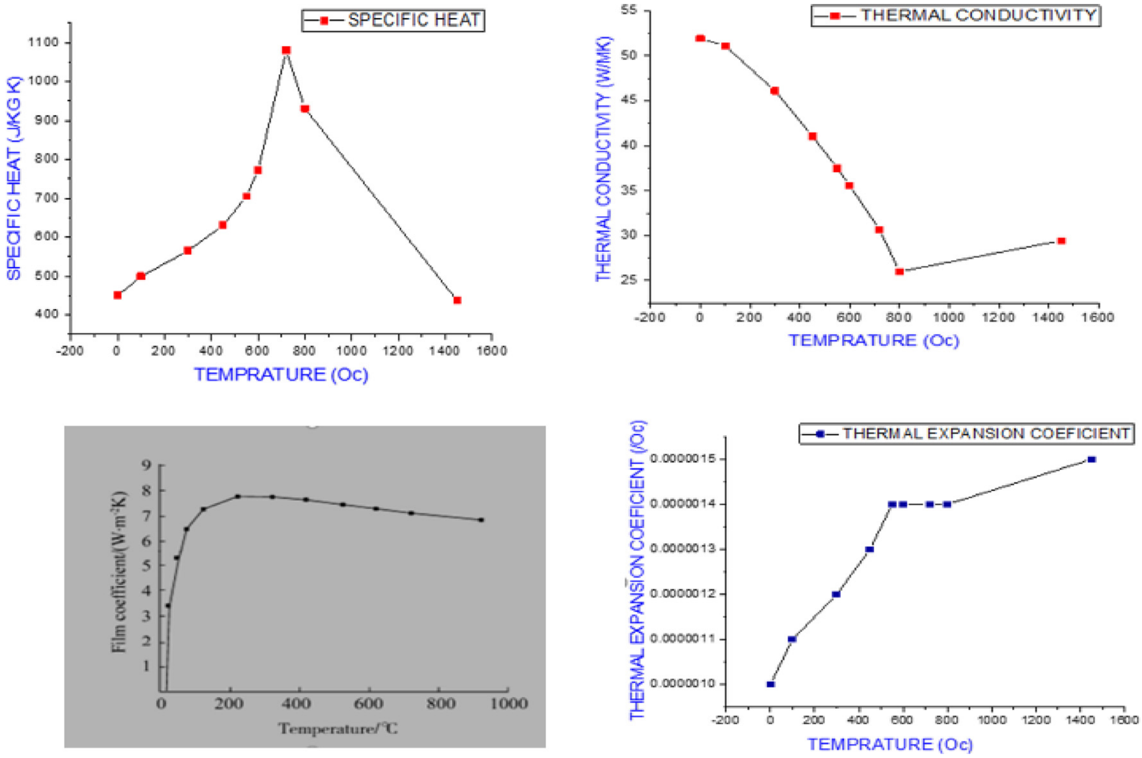

Fig. 4. Thermal properties of the material [4].

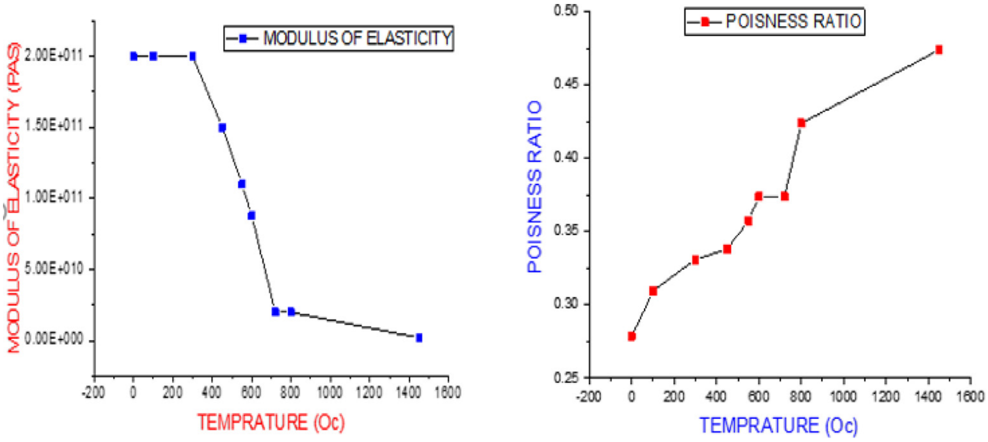

Fig. 5. Mechanical properties of the material [4].

end time of the source = 40 s, the beam diameter = 6 mm, and convection = tabular.

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 for this run is shown in Fig. 8 and the deformation of this sheet is investigated along a y-axis through the thickness direction.

In 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 5 mm/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.

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 Fig. 10 and this is also investigated along the thickness direction.

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 5 mm/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 the number of passes on the temperature distribution. Fig. 11 shows the peak temperature distribution for the triple-pass heating after both the first and second passes are done.

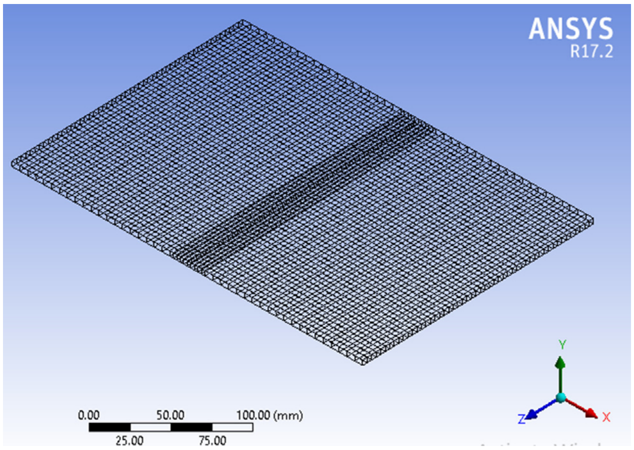

Fig. 6. Mesh model of the workpiece.

Table 3
Design matrix- L9 orthogonal array (coded values).

Run	Thickness (mm) (A)	Speed (mm/s) (B)	Number of Passes (C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

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

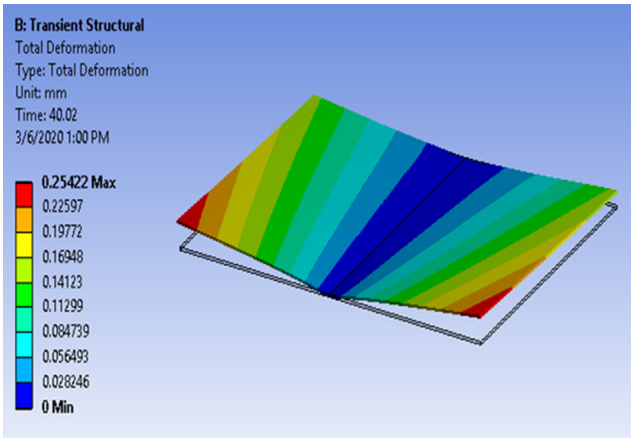

Fig. 8. Structural response for the first ru.

3.2. Effect of travel speed of the torch

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 penetrating through 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 (15 mm/s), the thermal cycle is also short and the heating rates are very fast, and the time to generate a high-temperature gradient though the thickness is very short. But a very high-temperature gradient is produced along the heating line.

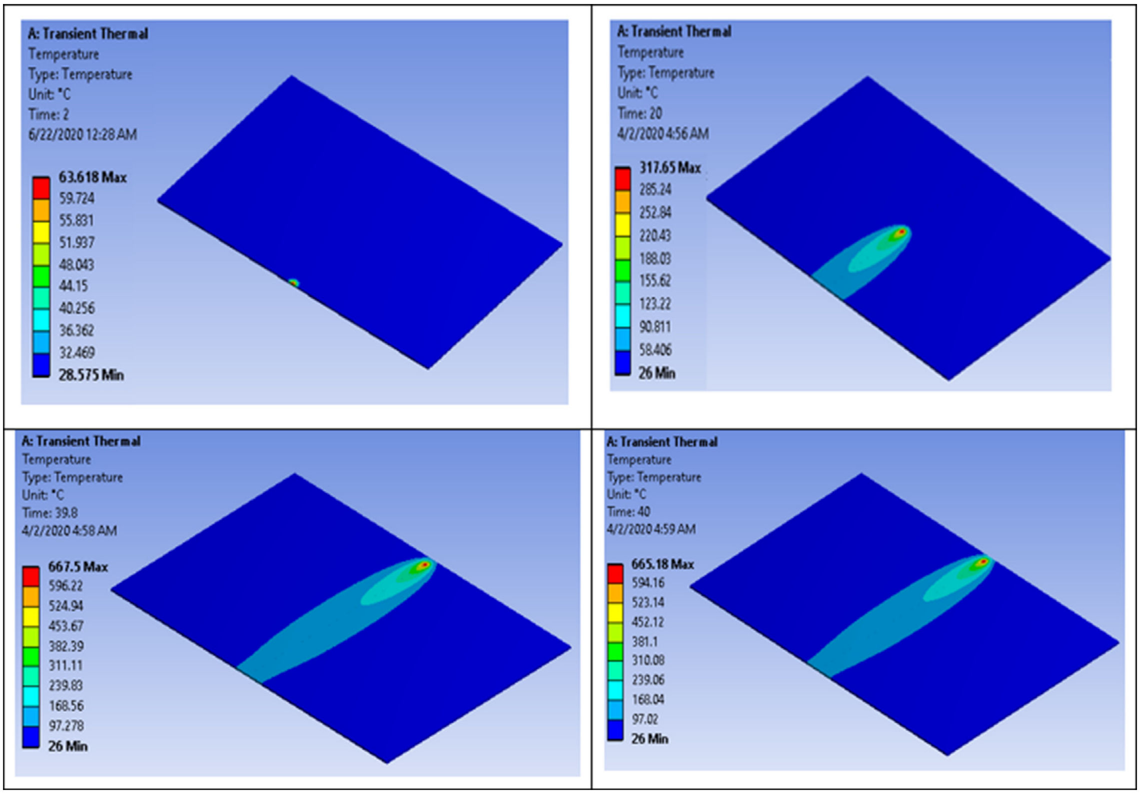

Fig. 7. Temperature distribution for the first run.

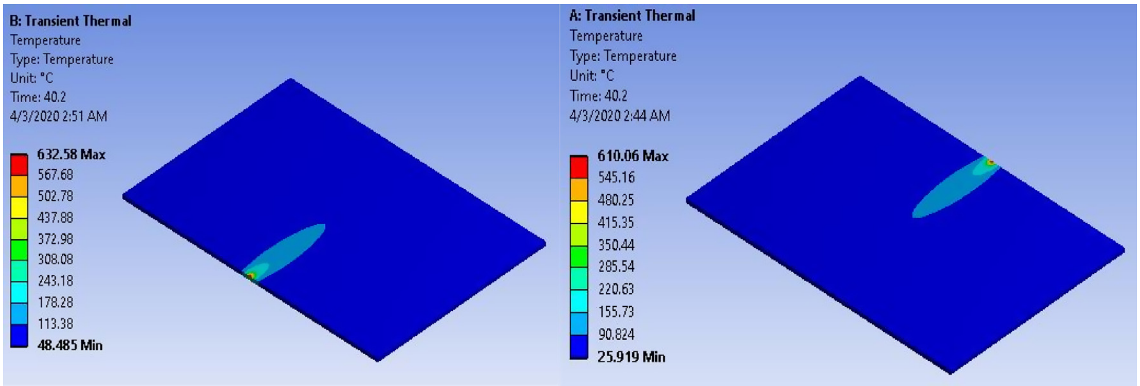

Fig. 9. Temperature distribution for run 4.

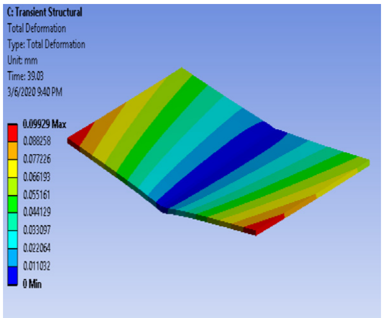

Fig. 10. Structural response of simulation run 4.

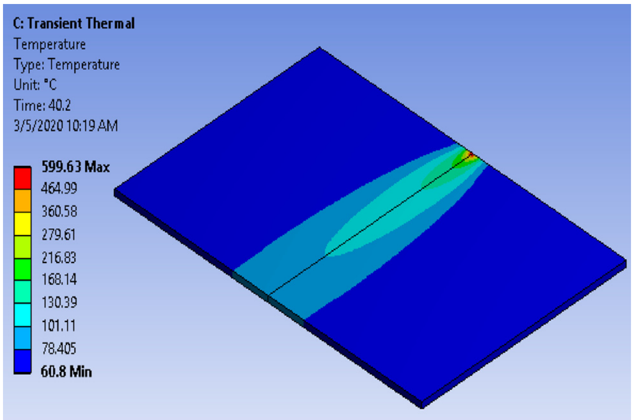

Fig. 11. Temperature distribution for run 7.

3.3. Effect of thickness of the sheet metal

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 of 2 mm is the highest value compared to 4 mm and 5 mm 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 ones as the thermal expansion coefficient on thinner metal is high. Small deformation by increased thickness is due to the need for a 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.

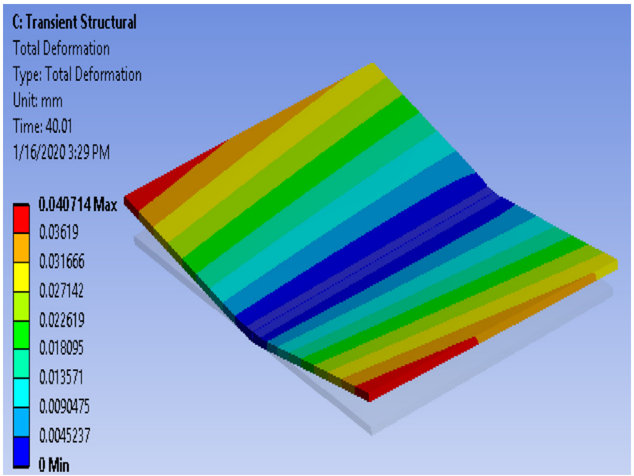

Fig. 12. Structural response of simulation run 7.

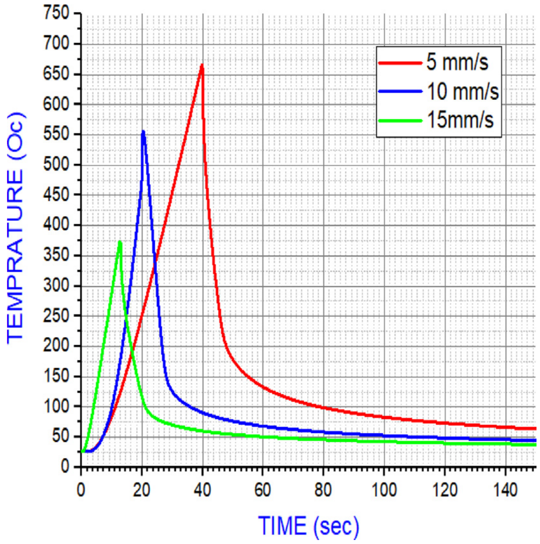

Fig. 13. Temperature versus time graph for a variable traverse speed on 2 mm thick metal.

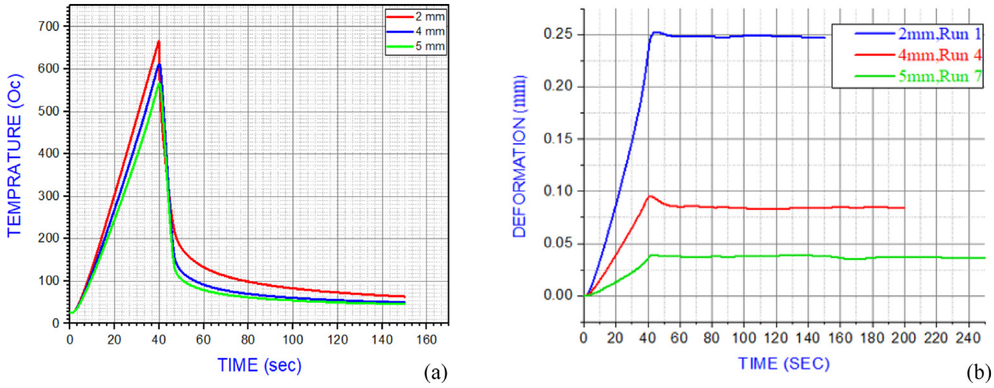

Fig. 14. (a) Temperature versus time for a variable thickness of the metal for 5 mm/s traverse speed with a single pass line heating (b) effect of thickness on total deformation.

So, as it can be seen from the pattern of 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. 14(b).

3.4. Effect of number of passes along the heating line

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 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 a fewer passes 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.

3.5. Sample preparation and experimental setup

In doing the experimental study of sheet metal bending using line heating, both the table which provides a bed for the torch to travel along, and fixtures were designed and manufactured in the workshop of mechanical engineering as shown in Fig. 16(a).

After developing the setup for the investigation, the test samples are carefully positioned before applying the heating torch as shown in Fig. 16(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 an equal distance from both ends as has been explained in the procedure. Fig. 17 shows how to make sure the condition is ambient during the first step of the experiment and then the time-dependent temperature histories will progress from the initial time step.

3.6. 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

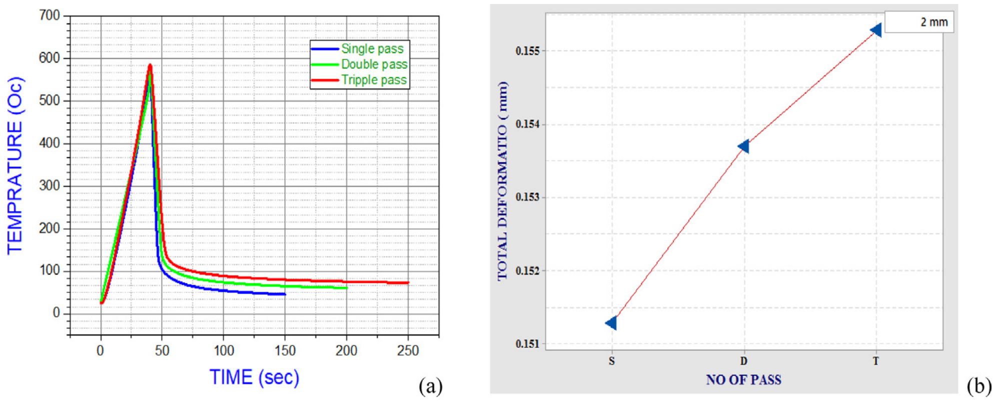

Fig. 15. (a) Temperature versus time response for a variable number of passes on 5 mm thick metal and 5 mm/s traverse speed (b), Effect of number of passes on total deformation with 15 mm/s travel speed.

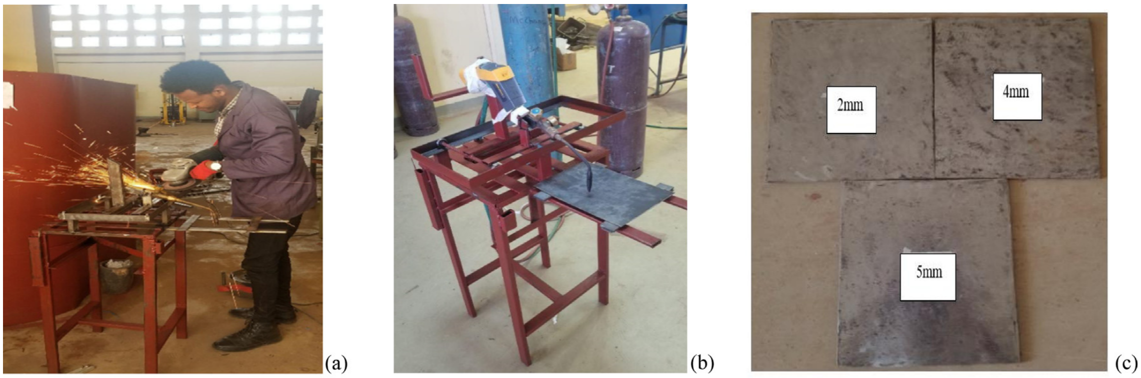

Fig. 16. (a) Set up for the experimental investigation, (b) position of the sheet metals; (c) sheet metal with different thickness.

Fig. 17. Initial set up for temperature measurement.

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. Fig. 18 shows the main effect plot for S/N ratios for three process parameters, i.e. thickness, traverse speed, and the 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.

The optimal condition is the optimal factor setting which is given in Table 4 yields the optimum performance. In this case, it is the factor setting that 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 2 mm thickness of the sheet metal with the travel speed of 5 mm/s and a single pass line heating is the best optimum combination of the parameters which yield the larger value of total deformation.

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 the 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 within the range of 48–72 s time intervals due to some external forces of atmospheric room temperature. Besides all these limitations, the graph also shows the numerical modeling is well agreed with the experimental investigation.

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 Fig. 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 predefined parameters and with their respective magnitudes. The deformation of the metal which can be obtained at an angle from the horizontal plane is also calculated using mathematical 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 increase 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. The comparison for all the three optimum structural models of the two approaches experimental and numerical models is also shown in Fig. 21.

4. Conclusion

The following conclusions are drawn for both FEA and experimental investigation.

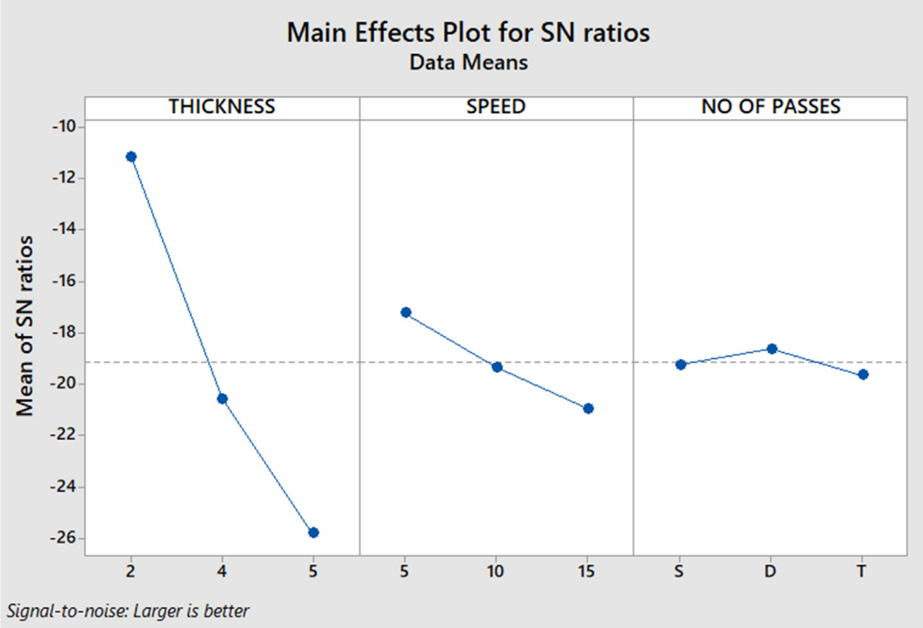

Fig. 18. The main effect of S/N ratio.

Table 4
The optimal factor setting.

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

- 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 °C is recorded on 2 mm 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 5 mm/s with a single pass line heating and a sheet metal thickness of 2 mm is an optimal combination that generates 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.

CRediT authorship contribution statement

Dawit Muluneh Yona: Investigation, Data curation, Conceptualization, Methodology, Resources, Writing – original draft. **A. Johnson Santhosh:** Software, Data curation, Formal analysis, Resources. **Eyuel Abate Lemma:** Software, Data curation, Formal analysis, Resources. **P. Murugan:** Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

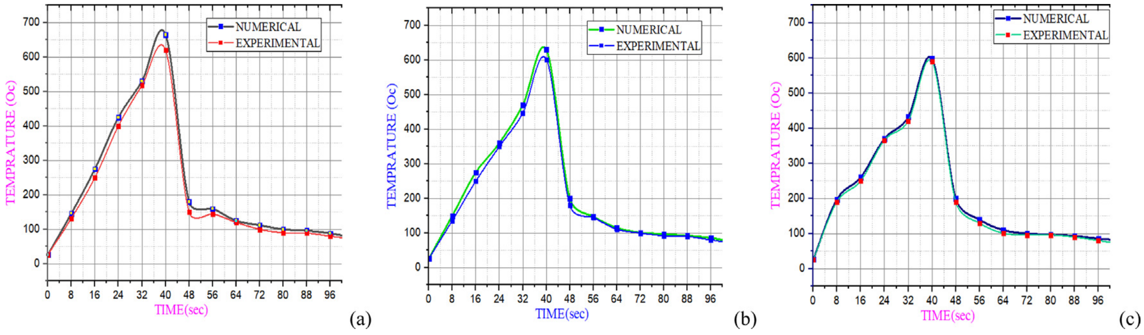

Fig. 19. (a) Validation of temperature distribution for run 1; (b) run 4 and (c) run 7 for 2 mm, 4 mm, and 5 mm thick sheet metals respectively.

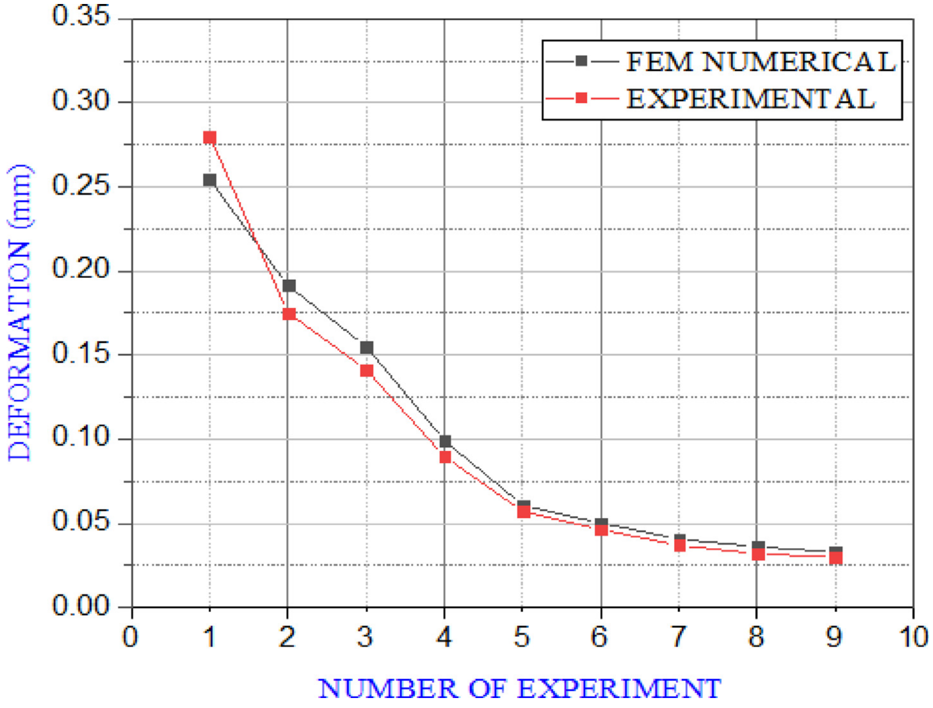

Fig. 20. Comparison of total deformation.

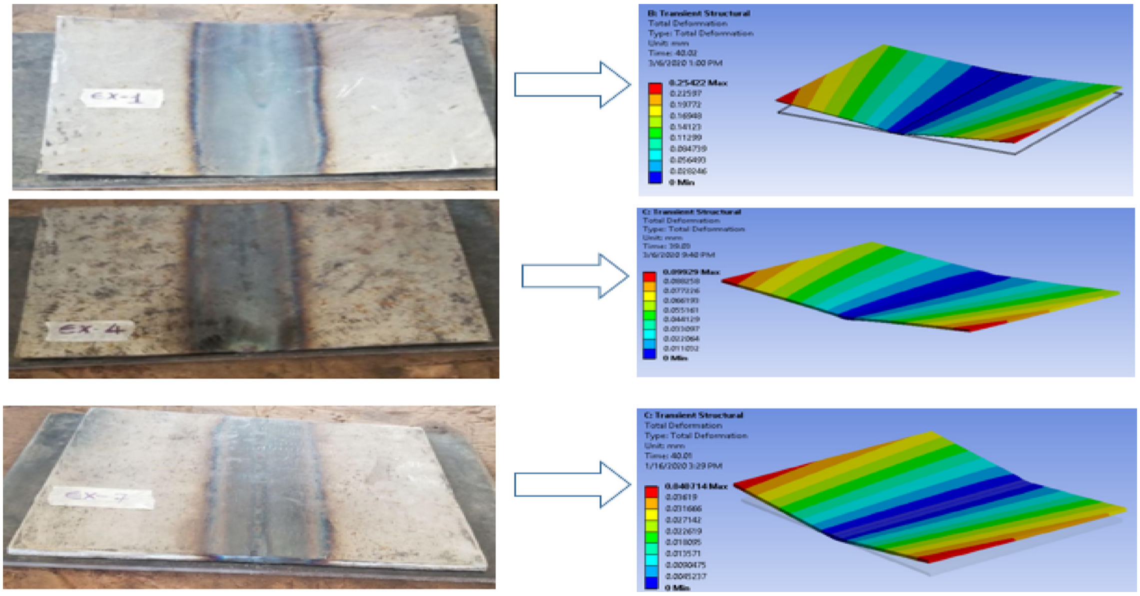

Fig. 21. Comparison of the structural model for the two approaches.

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