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FEM-based virtual manufacturing for deformation analysis of coupled welding-forming process

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ABSTRACT

This research presents the development of Virtuall Manufacturing (VM) procedure using Finite Element Method (FEM) for analysing the final deformation behaviour of coupled welding-forming process. The chained process simulation was executed by using FEM-based VM software Simufact.Welding and Simufact.Forming. The initial GMAW welding process is executed prior forming process and was modelled and simulated for of 2mm thickness butt joint made of DC04 low carbon steel material prior to forming process. In welding simulation, the weld bead is modelled using a simplified bead geometry without reinforcement and the heat source model is based on Goldak's double ellipsoid model. The result of welding simulation is transferred to Simufact.Forming under the consideration of additive isotropic hardening plasticity model based on von-mises yield criteria. In this VM procedure, temperature distribution for calibration purpose, material history transfer, damage criteria are put into consideration. As final outcome, it can

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be concluded that a proper VM procedure should be implemented to obtain desired results for industrial application. The result between VM simulation and experiment shows a good agreement in term of error percentage which falls within the range of 4.35%-33.1% in total deformation result.

Keywords: *Welding; Forming; Bending; FEM; Deformation.*

Introduction

In the engineering environment nowadays, manufacturing companies are pressured as demand of costumized and diversified products are rising as well as the urgent need of both quality improvement and delivery time. In order to tackle this issue, a manufacturing company has a need to develop a concept which enables a rapid product development, cost reduction as well as the fast response towards the demand of such a complicated products, this could lay in the change within the early development stage of product design which replaces the trial and error that involves a physical inventories into a digital conceptual design which also able to reduce the overall manufacturing cost [1].The emerging technology called Virtual Manufacturing (VM) enables to tackle the challenges above through their ability to provide capabilities in essence in order to develop the manufacturing in the virtual world of the computer. VM enables the corporation to manage the affordability and producibility of manufactured goods, manufacturing process concept with risk, impact to manufacturing abilities, cost and production capacity are taken into account in VMs operational routine [2]. VM is an essential realization of real manufacturing process within the computer world. VM mixes computer simulation and virtual reality on modelling the entire manufacturing process along with enhancing decision-making and control among all levels within the manufacturing process. Finite Element Method (FEM) is one of the simulation type within VM which has the most complex priority among the VM tools [3].

The process of joining of two materials in mechanical engineering environment is called Welding Process [4]. Gas Metal Arc Welding (GMAW) is one of the welding process which is belong to fusion welding which used commonly and known of its high range of productivity and flexibility on engineering process. An arc plasma is established between a filler metal electrode along with the workpiece and obscured by a shielding gas. Due to the heating effect of the arc, the electrode gradually melts, leading to formation of droplet at the electrode tip [5].

Forming process especially a sheet metal forming has been used in a modern manufacturing environment which mostly found in automotive sector. The Bending process involves a dies and workpiece, the process has a purpose to press the workpiece into a deformed state by a die [6]. In forming process, bending is divided by two state of process which are cold forming and hot forming process. Cold forming process is the selected bending method for this study of which a sheet metal is pressed by dies. Hydraulic press bending is chosen as type of press for this study which has an advantage on providing a full force of hydraulic on driving the upper die for the entire length of stroke [7].

Coupled Manufacturing process (CMP) or often called Multistage Manufacturing Processes (MMP) is a combined of two or more manufacturing process involved on creating a single product which propagate and accumulate while the manufacturing processes are in progress. Usually, CMP implemented for a more complex design [8]. One of the approach to evaluate the coupled manufacturing process is by means of inclusive FE Simulation. The usage of FE method could lead to the minimization of overall lead time caused by physical try outs, one of the examples is analysis of forming process chain [9].

One of the most well-known phenomena on forming process is spring back effect, the condition of which affects the accuracy of geometry on free from bending of hollow section within the specimen causing a more time-consuming setup [10]. Due to its sensitivity, VM using FEM method has been chosen as one of the most prominent method to challenge this complexity and make a bold prediction [11]. FE result would predict an improved result to the measured data which is why the research which involves spring back effect nowadays have involved FE method in order to simulate the spring back effect in an accurate manner [12].

In this research, a final deformation or springback of a coupled process welding to forming is going to be investigated by means of FEM-based Virtual Manufacturing and experiments. The final deformation means the final condition of the bended workpiece after undergone the whole coupled welding to forming processes.

Virtual Manufacturing Simulation of Coupled Process Welding-Forming using Simufact Software

Virtual Manufacturing for Welding Process using Simufact.Welding

For the geometry modelling, MSC Patran is utilized on designing the geometries that will be assigned in VM simulation. The butt joint weld specimen is developed within dimension of 70x140x2 (x,y,z) which shares the same dimension with the real butt joint specimen used in experimental process in order to ensure the similaritiy between VM simulation and experiment. 3D global mesh geometry is applied for all geometries which imported to Simufact.Welding. This welding simulation assigns simplified weld bead design without reinforcement as weld filler. Figure 1 displays the schematic illustration of FE model which assigned on Simufact.Welding, which displays the dimension of geometry along with weld sequence.

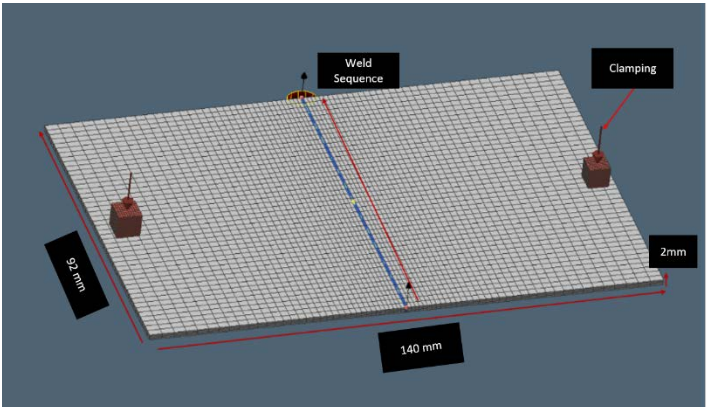

Figure 1: Details of butt-joint welding component displayed in Simufact.Welding.

DC04 material is assigned for this simulation which acts as both weld and filler materials. Junyan and Wahab [13] has stated that a more advanced numerical technique could become a comprehensive research on predicting low carbon steel's microstructure in welding. Thermomechanical properties and the flow curve of DC04 are exhibited on Figure 2 and 3 respectively.

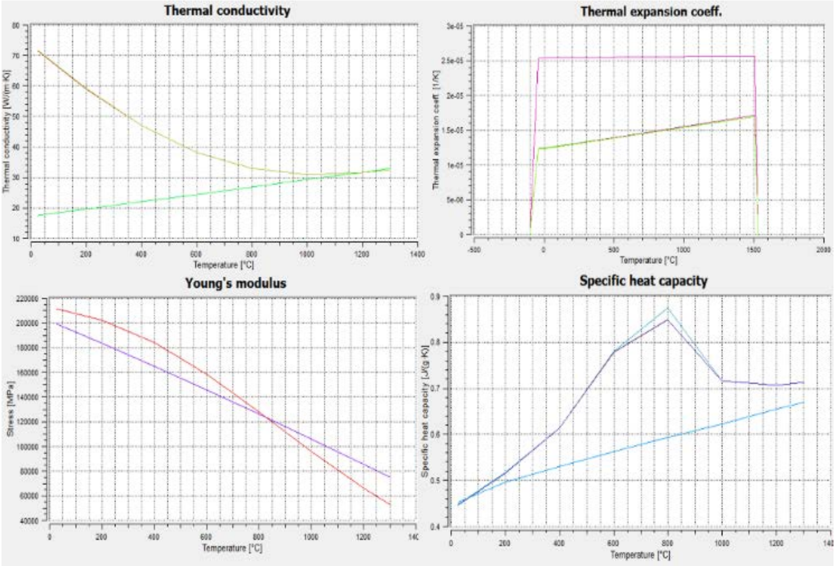

Figure 2: Temperature-dependant material properties of DC04.

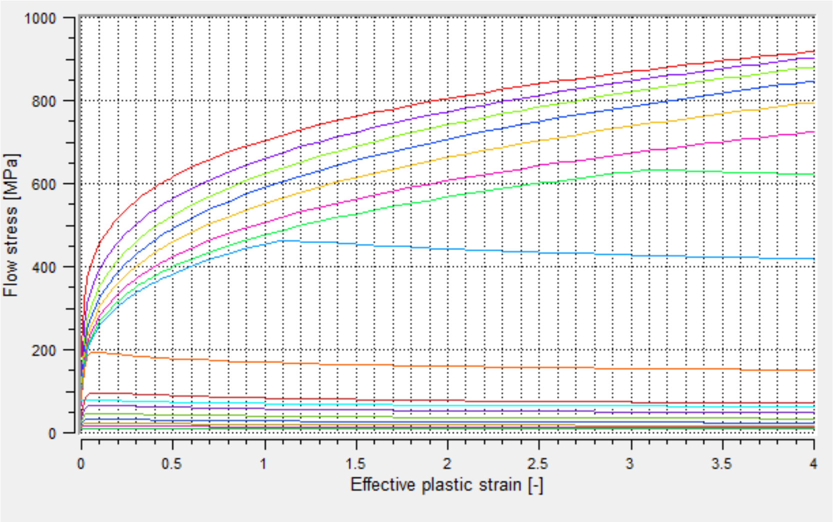

Figure 3: DC04 flow-curve.

The heat source model that utilized in this welding simulation is Goldak´s double ellipsoid model. Simufact.Welding provides a heat source option which allows user to input the heat source parameter based on selected heat source model. Table 1 displays the heat source model using Goldak´s Double Ellipsoid heat source model while Table 2 displays the welding parameters within Simufact.Welding.

Table 1: Heat source parameters of T-Joint and Butt joint welding simulation using Simufact.Welding

Heat source dimenstion	Value
Width (mm)	3.0
Depth (mm)	3.0
Rear Length (mm)	4.0
Front Length (mm)	4.0

Table 2: Welding simulation parameters assigned in Simufact.Welding

Parameters	Value
Current (A)	115
Voltage (V)	17
Efficiency (%)	80
Welding Speed (mm/s)	5.8

A Temperature measurement analysis also executed in experimental welding process by means of thermocouple investigation. The thermocouple is placed on the centre of the weld specimen with the approximate distance to weld filler is 5mm. The exact same location also serves as the measurement point in VM simulation using Simufact.welding which would be later compared to the thermocouple results as demonstrated in Figure 4 below.

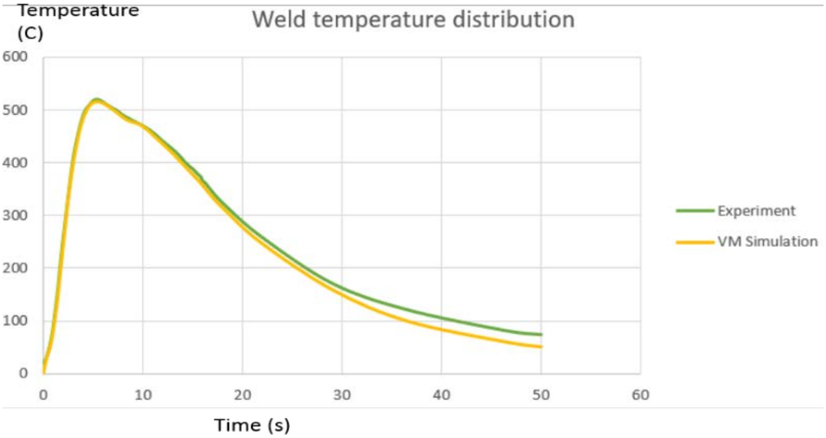

Figure 4: Comparison of temperature measurement between thermoucouple result by experiment and temperature measurement of Simufact.welding.

Virtual Manufacturing for Forming Process using Simufact.Forming

The FEM Simulation software which is used to simulate the forming process is Simufact.Forming, a specialized FEM software which has a tool designed to simulate the real life forming process faithfully. The type of forming used in this simulation is 3D Bending Simulation, which simulate the bending process using 3D models.

The result from Simufact.Welding is imported to Simufact.Forming by transferring the latest increment result produced by Simufact.Welding. The results which are transferred from Simufact.Welding are: Effective stress, strain, damage, temperature, microstructure and displacements. The whole coupled process welding to forming simulation is described in Figure 5 below.

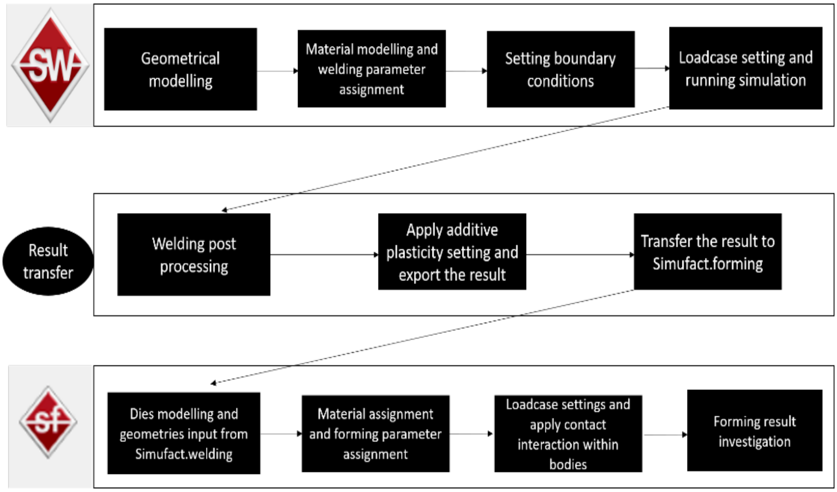

Figure 5: Process flowchart of coupled process welding-forming simulation using Simufact.Welding and Simufact.forming.

The transferred result generated by Simufact.Welding serves as the basic initial condition of the forming process. To ensure that the results has been transferred successfully, prior running the forming simulation the welded plate must shows the contour band display of deformation before undergoing the forming process. Figure 6 displays the successfully transferred stress from Simufact.Forming while Figure 7 shows the dimension of forming model and dies within forming simulation.

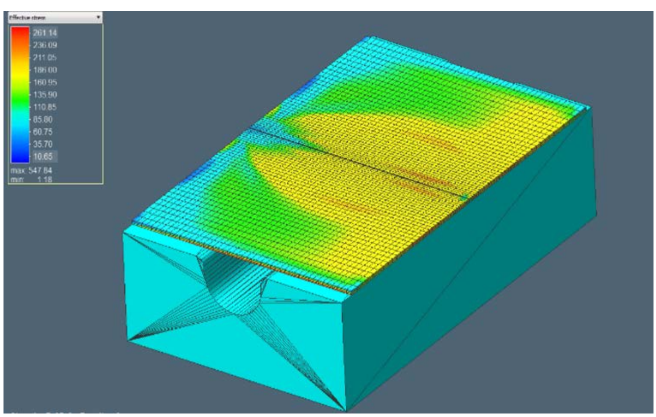

Figure 6: Transferred stress result from Simufact.Welding to Simufact.Forming.

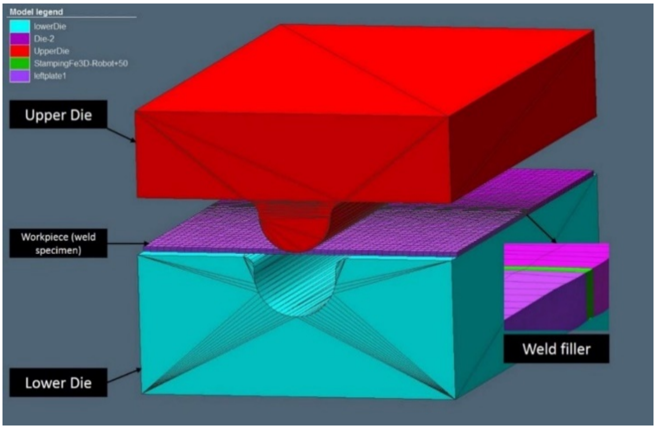

Figure 7: Details of forming components displayed in Simufact.Forming.

This study incorporates Hydraulic Press as the type of press used in bending simulation which also the same press used in experimental study. The bending simulation will only involves upper die as the moving object while keeping the lower die in constant position as bearing condition for the work piece. The pressure of hydraulic press can be defined by mathematic equation (1) as:

$$P = \frac{F1}{A1} \tag{1}$$

Where P is input pressure, F_1 input force and A_1 is the cylinder area. Equation (2) defines the calculation of output force in hydraulic press.

$$F2 = \frac{A2}{A1}\, F1 \tag{2}$$

Where A_2 is the cylinder area for output and F_2 is the output force. The forming parameters assigned within the simulation is displayed in Table 3 below.

Table 3: Forming simulation parameters assigned in Simufact.Forming

Forming Parameters	Values
Stroke (mm)	14
Type of Press	Hydraulic press
Press Velocity (mm/s)	4.0
Room Temperature (´c)	30

The damage criteria for this coupled process is based on Lemaitre damage criteria which is based on stress-strain diagram result of tensile test. In order to obtain the stress-strain diagram of DC04, a tensile test is conducted with three difference phases of DC04. Figure 8 displays the Illustration of Lemaitre damage criteria.

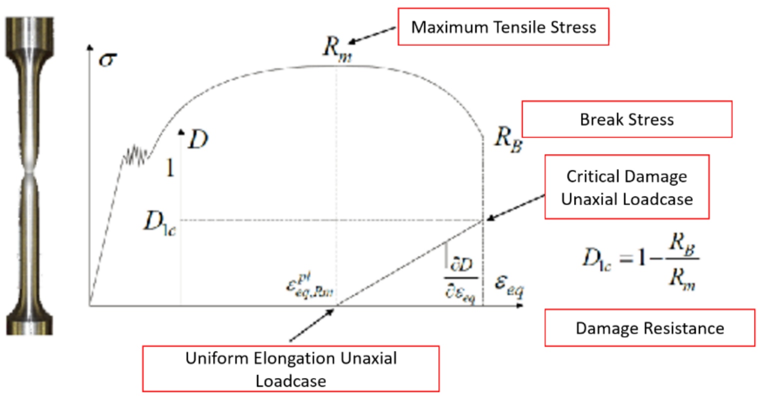

Figure 8: Lemaitre damage criteria based on stress-strain diagram. [14]

Experimental Setup and Procedures of Coupled Process Welding to Forming

Welding Experimental Setup and Procedure

A series of comprehensive welding and forming experimental was executed as a part of this research in order to obtain the experimental result that will be compared to simulation result. For Butt joint welding process, the robotic welding which executed the welding process is Comau Robotics SMART NS-16-1.65. Figure 9 displays the robotic welding machine utilized for welding experimental process.

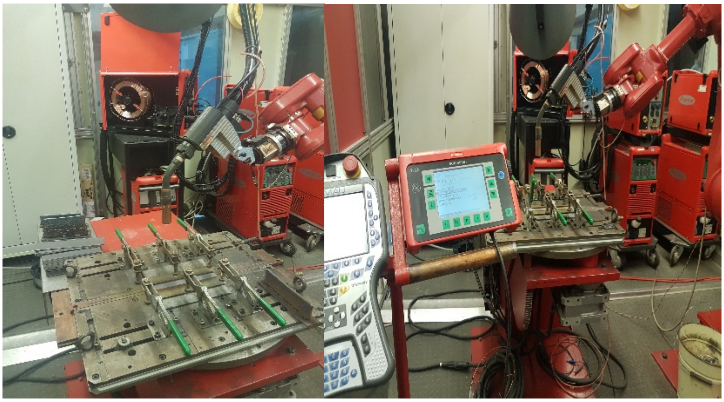

Figure 9: Robotic welding machine Comau Robotics SMART NS-16-1.65.

DC04 low carbon steel material is selected in the experimental process of which the chemical composition which is similar material assigned in VM simulation. The experimental parameter assigned for experimental process is similar to the parameters assigned within welding simulation process using Simufact.Welding in order to ensure a reliable comparison between simulation and experiment. The welding experimental parameters is described in Table 4.

Table 4: Welding experimental parameters

Welding Parameter	Value
Current, I (A)	90 -105
Voltage, V (V)	15.8
Travel Speed, v (mm/s)	5.8
Wire Feed Speed (mm/min)	8.3

Forming Experimental Setup and Procedure

A set of comprehensive experimental forming processes were conducted in order to verify the simulation FEM result of Forming Simulation. This bending machine is used to bend the Butt joint specimen which already undergone a welding process prior bended. The forming machine appointed in this forming experimental process which is exhibited on Figure 10 below.

Figure 10: Sheet metal bending machine VEB Werkzeug PYE 160S.

The deformation investigation is executed by means of comparing the final springback result from FE simulation to experimental result. In this study, a deformation measurement using coordinate measuring machine is chosen as validation method of VM simulation result. Mitutoyo 707 is the CMM machine used in Deformation measurement.

Results and Discussion

Prior to being moved to forming process, the specimen would undergo welding process first of which would be later moved to forming process. The result produced by Simufact.Welding was transferred to Simufact.Forming as the initial conditions, the results transferred includes displacements, effective stresses and phase changes resulted in welding process.

The transferred results is crucial to the coupled process simulation because it ensures that the data from previous manufacturing is taken into account prior conducting the follow-up manufacturing process. Forming force resulted by bending is occurred in the upper die used in sheet metal forming process of which in this study, it possesses a higher force due to the specimen has undergone welding process beforehand which explains that the hardness towards welded region. Forming force displayed in Simufact.Forming is shown in Figure 11 while Table 6 displays the comparison of VM simulation forming force and experimental coupled process.

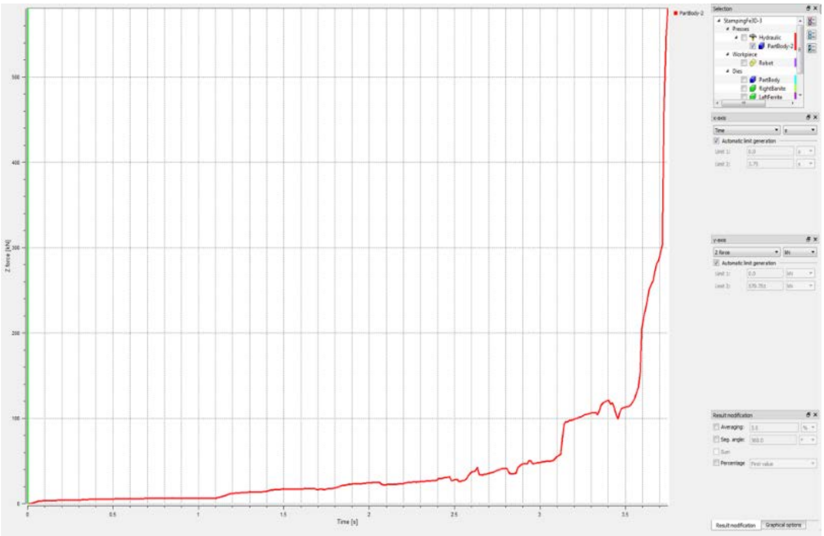

Figure 11: Forming force graph shown in Simufact.Forming.

Table 6: Comparison of forming forces between forming simulation and experimental

Forming Force		
Maximum simulation value (kN)	Maximum experimental value (kN)	Percentage difference (%)
57.9	61.14	5.70

Figure 12 displays the displacement towards vertical direction which becomes the base analysis of deformation analysis, the deformation analysis is conducted by investigating the displacement created after the specimen is being bended, thus the displacement in Z-axis is examined in various locations of the specimen. Figure 13 exhibits the deformation based on experimental results measured by using Coordinate Measuring Machine (CMM). Table 7 shows the comparative deformation results of FE simulation and experimental coupled process.

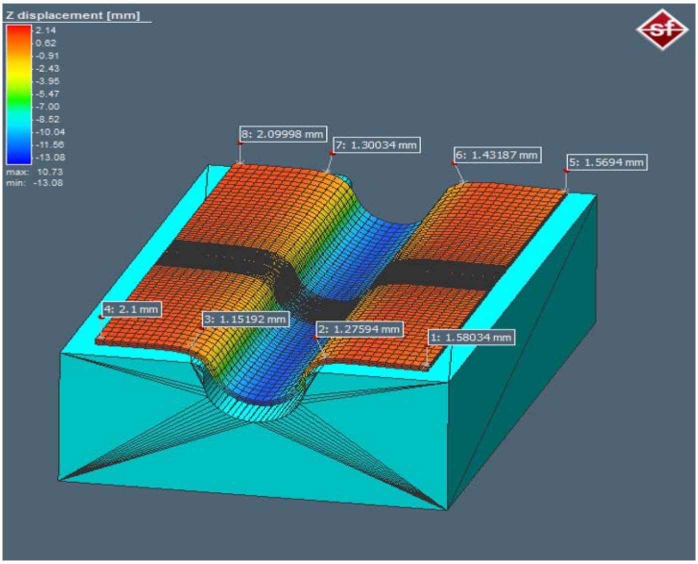

Figure 12: Virtual manufacturing simulation result of final deformation after coupled process welding-forming.

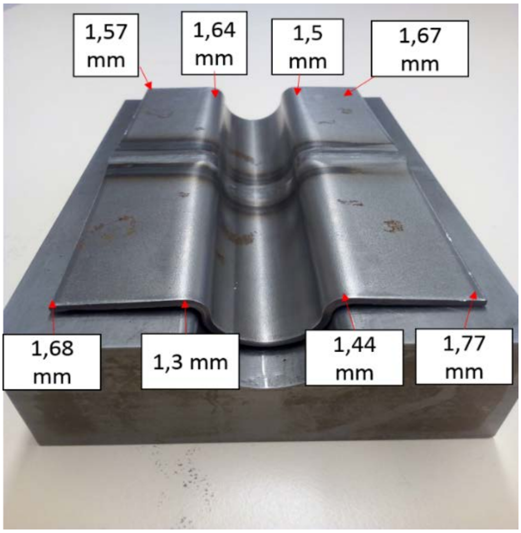

Figure 13: Experimental result of final deformation after coupled process welding-forming.

Table 7: Results and percentage error of deformation results of coupled process based on VM and experimental process

	Displacement (mm)							
Point	1	2	3	4	5	6	7	8
FE Simulation	1.58	1.279	1.15	2.1	1.57	1.438	1.30	2.09
Experiment	1.77	1.44	1.3	1.68	1.67	1.5	1.64	1.57
Error (%)	10.73	11.18	11.39	25	6.02	4.54	20.7	33.1

The deformation results shows the uniform range in eight location points of measurement. The displacement which are located within the far side of the workpiece can be seen to possesses a slightly higher deformation compared to the center part of the workpiece, of which the error percentage also higher when it compared to experimental deformation result.

This compliments the state of workpiece geometry after the workpiece has been bended and it shows the higher ratio of displacements within that region. From the result in table 7 above, the deformation result produced by Simufact.Forming has shown to be able to produce a reliable result as the FE results displays a good agreement towards the experimental result.

Conclusion

Through the Finite Element Method, a study of final deformation induced by coupled process Gas Metal Arc Welding (GMAW) and sheet metal bending process had been executed. The research covers both numerical and experimental analysis which was compared as final output of this research. The combination of FE software Simufact.Welding and Simufact.Forming are used for all numerical analysis. To conclude this research, there are some crucial points that will be explained by following statements:

1. The FEM analysis of Welding and forming model were executed successfully and the simulation procedure is clear as well as structured,
2. Forming process simulation can generate a reliable result regarding deformation effect on a specimen after undergone a welding process with simplified bead shape within a range 4 – 34% error when compared to experiment,
3. Simufact.Forming shows good agreement on forming force compared to the results of experiment (approx. 6%).
4. For this joint type, the simulation results show insignificant dependency on selection of element type,
5. The non-homogenous material, geometrical model including reinforcement, pre-condition of welding process and the fluctuating

parameters during experimental analysis, might cause the difference between simulation and experimental results.

From the knowledge point of view, important information through simulation could be obtained which can be used as a planning tool within the design phase or prior to actual welding process. This investigation could bring a contribution towards the further development of research in Virtual Manufacturing area such as by considering the reinforcement and material modelling.

Acknowledgement

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References

[1] M.C.F Souza, M. Sacco, V. Porto, “Virtual manufacturing as a way for the factory of the future,” Journal of Intelligent Manufacturing 17(6), pp. 725-735, 2006.

[2] R. Radharamanan., “Virtual manufacturing: an emerging technology, Proceedings of the 2002,” *American Society for Engineering Education Annual Confference and Exposition.* 2002.

[3] V.G Bharath, P. Rajashekar., “Virtual Manufacturing: A review,” *International Journal of Engineering Research and Technology*, *NCERAME-2015 Conference Proceedings*, 2015.

[4] M Trautman, M. Hertel, U. Fussel, „Numerical simulation of TIG weld pool dynamics using smoothed particle hydrodynamics,” *International Journal of Heat and Mass Transfer* 115 (B), pp. 842-853, 2017.

[5] Y. Zhao, Hyung Chung, “Numerical simulation of droplet transfer behavior in variable polarity gas metal arc welding,” *International Journal of Hear and Mass Transfer* 111, pp 1129-1141, 2017.

[6] S K. Gupta, “Sheet Metal Forming: Forming part families for generating shared press-brake setups,” *Journal of Manufacturing System* 21(5), pp 329-350, 2002.

[7] A. Ghiotti, E. Simonetto, S. Bruschi, P.F Bariani, “Springback measurement in three roll push bending process of hollow structural sections,” *CIRP Annals* 66(1), pp. 289-292, 2017.

[8] D. Djurdjanovic, Y. Jiao, M. Vidosav, “Multistage manufacturing process control robust to innacurate knowledge about process noise”, *CIRP Annals* 66(1), pp. 437–440, 2017.

[9] A. Govik, L. Nilsson, R. Moshfegh, “Finite element simulation of the manufacturing process chain of a sheet metal assembly,” *Journal of Material Processing Technology*, Volume 212, pp. 1453-1462, 2012.

[10] A. Ghiotti, Enrico Simonetto, Stefania Bruschi (1), Paolo F. Bariani (1). Springback measurement in three roll push bending process of hollow structural sections. (2014) R.E Gite, K.S Phad, D.S Bajaj, “Spring back effect analysis of bracket using finite element analysis,” *International Advanced Research Journal in Science, Engineering and Technology* 3(1), pp. 246-255, 2016.

[11] M.R. Jamli, A.K. Ariffin, D.A. Wahab, “Integration of feedforward neural network and finite element in the draw-bend spring back prediction,” *Expert System with Aplications* 41(8), pp. 3662-3670, 2014.

[12] H.U. Hassan, H. Traphöner, A. Güner a, A.E Tekkaya, “Accurate springback prediction in deep drawing using pre-stain based multiple cyclic stress-strain curve in finite element simulation,” *International Journal of Mechanical Sciences* 110(C), pp. 229-241, 2016.

[13] N. Junyan, M.A Wahab, “A numerical kinematic model of welding process for low carbon steels,” *Computers and Structures* 186, pp. 35-49, 2017.

[14] Simufact Engineering, GmbH. *Simufact.Forming Manual Books*.