Analysis of distortion of coupled process forming to welding using fem-based virtual manufacturing with experimental verification

D P Ishak¹, K P Prajadhiana², Y H P Manurung*,², M S Sulaiman² and M K A Saberi²

¹Faculty of Industrial Engineering, University of Indonesia, Jakarta, Indonesia.
²Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia.

*yupiter.manurung@uitm.edu.my

Abstract. In this paper, the numerical model of coupled process forming to welding by means of FEM is developed in order to analyse the displacement. Simufact.Forming and Simufact.Welding are utilized to execute a thermomechanical FEM analysis of forming to welding coupled process. Prior to welding process, a sheet metal bending process is performed in order to bend the 2mm plate into a U-shaped geometry. The material used for this process is S235 low carbon steel along with filler material ER70s. Goldak’s double ellipsoid model is chosen as the heat source model for GMAW simulation. A series of sheet metal bending and GMAW experiment is executed in order to verify the distortion result produced by FEM analysis. ABB IRB 2400/16 is the assigned robotic welding equipment used in GMAW process while sheet metal bending machine SUNFLUID 800/2007 is utilized for sheet metal bending process. For the calibration model, a forming force between FE simulation will be compared with the forming force of experimental bending process. The final results have shown that the distortion result of FEM analysis of coupled process forming to welding shows a good agreement with the experimental coupled process.

1. Introduction
In today environment, the competition within engineering environment has reached a whole new level where a global integration between industries becomes the main concern, of which Virtual Manufacturing becomes one of the component that would able to tackle said problem by improving the state of the company by means of production ability and cost efficiency [1]. Since the last few decades, Virtual Manufacturing (VM) which covers information technology and computer simulation has been used to model real world manufacturing processes for analysing and understanding the physical behaviour of the product during the process. VM is also suitable for cost optimization of the integrated product, process and resource design, while reducing the time of development cycle, improving the production efficiency, as well as product quality [2-3].

VM can be defined by several hierarchies within its usage [4], one of the utilizations of VM is by implementing the Finite Element Method (FEM) on simulating the real manufacturing process. Finite Element Method has a purpose on separating a one big element into several similar smaller elements in order to simplify the total element calculation, which is a common method utilizes in VM cases [5].
Two- or three-dimensional FEM analysis are the option that can be utilized in VM application of where the elements are divided into both planar and axial [6].

A forming process which aims to press the workpiece specimen into U or V shape geometry by utilizing punching die is called sheet metal bending process [7]. Bending Process, which is a part of forming process is divided by two methods of execution which are cold and hot forming process. In this study, cold forming process is selected which means the heat distribution within workpiece is static by means of maintaining the initial room condition while the workpiece is undergo a bending process. The usage of FEM on simulating the sheet metal bending process has been performed by engineers for the last several years. One of the examples is an engineering research performed by Panth et al [8] which utilizes FEM on spring-back prediction in a metal bending case.

Fusion welding is a process of joining metals by using adequate heat to produce coalescence in material to form a strong bonding. It is widely used in shipbuilding, construction, aviation and automotive industries. A stress phenomenon potentially leads to non-uniform expansion and contraction called distortion especially for materials that have low thermal conductivity. The most common distortion caused by heat is warping and buckling [9]. A type of fusion welding which utilizes a plasma arc that is enlisted the electrode and heat of a filler metal on top of workpiece while being covered by shielding gas is called Gas Metal Arc Welding (GMAW). The droplet that resulted by the arc heating would be transferred towards base material, thus embedding it with weld bead [10].

The welding process is often plagued with an unwanted deformation, of them is called Welding Distortion, which is created due to an unbalanced induced tress which often occurs within the region of the workpiece that unrestrained and often results in misalignment causing difficulties in assembly as well as poor appearance of the finished product or structure [11]. In welding process, distortion is caused by both local heating and cooling which affects the unstrained regions [12]. Several research over the past few years has investigated the distortion within welded components by means of Finite Element Method. An advanced engineering research performed by Andud et al [13] predicts distortion within the mild steel based GMAW process which shows that different material properties and pre-condition of welding affects the distortion value and its standard deviation in overall. The minimization of distortion of GMAW process by means of FE method utilizing Simufact.welding has performed by Vyas et al [14] with Voltage, current, travel speed, wire feed rate and gas flow rate as the welding parameters conditions which is similar to this study.

Multistage Manufacturing Process or also well known by the name Coupled Manufacturing Process is a combination between two or more manufacturing process which are utilized into creating an advanced product. Due to more complex product design arises in manufacturing environment today, a coupled manufacturing process has become a key on meeting the criteria of the demanded products. The CMP which concerns about the involvement of both forming and welding process, of which a FEM analysis also involved such as an analysis of CMP of forming and welding process by Zaeh et al [16], which talks about raw items being joined together by means of welding prior to be stamped during forming process. Bauer et al [17] has performed a study of forming to welding process of tube specimen by utilizing the two similar VM software. The material assigned for the mentioned research is mild steel DC04 which has less carbon compared to regular mild steel, which also offers better formability. The research explains the data management of transfer mechanism from Simufact.Forming to Simufact.Welding which covers the transition of result from the first manufacturing process towards the next one that includes displacements, temperature distribution as well as residual stresses. This study’s main objective is to investigate the final distortion induced by coupled process forming to welding by means of VM simulation and experimental study.

2. FEM Simulation of Coupled Process Forming-Welding using VM software Simufact.

2.1 FEM for Forming process using Simufact.Forming
The VM software which utilizes to simulate the sheet metal forming process in this study is Simufact.Forming, of which a VM software issued by Simufact Engineering GmBh which specialized on developing a numerical model for forming processes, one of them is metal bending process. In this research, a sheet-metal bending process is chosen as the forming process operated within
Simufact.Forming, which falls under the cold forming module. The process flowchart of forming simulation within Simufact.Forming can be seen in Figure 1.

![Figure 1. Forming simulation procedure using Simufact.Forming.](image)

The dies geometry is designed within software CATIA while the weld plate which acts as a workpiece for sheet metal forming simulation is designed within FE software MSC Patran. The dimension of the dies, both lower and upper die are 150x92x40 while the weld plate possesses a 70x92x2 dimension. For the forming simulation, two workpieces are going to be formed by means of sheet metal bending process execution. The detailed engineering drawing for the forming dies is exhibited in Figure 2, while the forming simulation of the plain low carbon steel plate is exhibited in Figure 3.

![Figure 2. Detailed engineering drawing of forming die design.](image)
Figure 3. Detailed setup on sheet metal bending simulation using Simufact.Forming.

For this research, a low carbon steel material S235 is chosen as the base plate material for the workpiece assigned in both Simufact.Forming and Simufact.Welding. This type of material has common usage in a manufacturing environment for decades especially in both welding and forming oriented researches due to its great formability and acceptable weldability. The temperature-dependent graph for S235 material is described within Figure 4 [18] which covers thermal conductivity, thermal expansion coefficient, young’s modulus and specific heat capacity.

Figure 4. Temperature-dependent properties of S235 material.

The forming simulation parameters assigned in Simufact.Forming for this research is displayed by means of Table 1. These parameters consist of Forming Forces, press velocity and room temperature along with the type of press assigned within VM simulation of sheet metal bending process.

Table 1. Parameter of forming process in Simufact.Forming

| Forming Parameters       | Values                    |
|--------------------------|---------------------------|
| Stroke (mm)              | 15                        |
| Type of Press            | Hydraulic press metal bending |
| Press Velocity (mm/s)    | 4.0                       |
| Room Temperature (°C)    | 25-35                     |
2.2 FEM for Welding process using Simufact.Welding

Simufact.Welding is the VM software utilized to develop a FEM model of welding simulation in this study for distortion investigation. This VM software also incorporates a comprehensive clamping conditions which could mimic the real-life clamping condition placed within the weld component in order to ensure the precision of the result prediction. Simufact.Welding has a user-friendly pre-processing procedure which is exhibited by Figure 5 below.

![Figure 5. Welding simulation procedure using Simufact.Welding](image)

The result of sheet metal bending simulation which was executed in Simufact.Forming would later undergo the proper transferring process to Simufact.Welding. The transferred forming results would bring the following results: Final displacement, heat input within the workpiece, final effective stress, material properties, and the bended shape of the workpiec. The two bended work pieces would be aligned within the same coordinate in order to ensure the similar starting position for easier weld trajectory assignment. The material assigned within this welding simulation is still the low carbon steel S235 due to the data of S235 already transferred from the sheet metal bending result. The welding simulation setup which includes the clamping conditions implemented in Simufact.Welding is exhibited in Figure 6.

![Figure 6. Details of welding simulation setup displayed in Simufact.Welding](image)
The Goldak’s double ellipsoid model is chosen as the heat source model involved within this welding simulation due to its capability to be implemented within GMAW process [18]. The Goldak’s double ellipsoid parameters are set within the welding simulation in order to determine the expansion of the heat affected zone which occurs during the course of welding.

Heat input parameters which covers current, voltage, welding speed and heat efficiency are set within the thermal boundary conditions section within Simufact.Welding which would later use again for verification purpose by means of experimental study. Table 2 and 3 displays the welding parameters and heat source dimension parameters respectively.

| Parameters                | Value |
|---------------------------|-------|
| Current (A)               | 100   |
| Voltage (V)               | 16.6  |
| Efficiency (%)            | 80    |
| Welding Speed (mm/s)      | 6.0   |

**Table 2. Parameter of welding process in Simufact.Welding**

| Heat source dimension    | Value |
|--------------------------|-------|
| Width (mm)               | 3.0   |
| Depth (mm)               | 3.0   |
| Rear Length (mm)         | 5.0   |
| Front Length (mm)        | 4.0   |

**Table 3. Heat source parameters of T-Joint and Butt joint welding simulation using Simufact.Welding**

3. **Experimental Setup and Procedures of Coupled Process Forming to Welding**

A series of comprehensive forming and welding experimental processes are conducted in order to verify the result of the FEM simulation performed in both Simufact software. The first chain of manufacturing process executed is the sheet metal bending process which aims to bend the workpiece into a U-shaped geometry prior undergo the welding process. The equipment used for experimental process is the sheet metal bending machine SUNFLUID 800/2007 which is located in Advanced Manufacturing Laboratory in Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. This forming machine incorporates the hydraulic fluid system on its mechanism. The sheet metal bending SUNFLUID 800/2007 is displayed in Figure 7.

**Figure 7. Sheet metal bending machine SUNFLUID 800/2007**
The forming parameters assigned for experimental metal bending process is within the similar range with the simulation of forming process in order to ensure the realistic comparison between experimental and simulation studies. For material assignment, a low carbon steel with code S235 is chosen as the workpiece material which is a similar material with the material assigned within forming simulation. The similarity of chemical composition between materials assigned in FE simulation and experiment has been verified by means of Ark Spark Spectrometer test. Table 4 displays the parameter of the experimental sheet metal bending process while Table 5 displays the chemical composition of the material used in experimental process for both forming and welding.

| Table 4. Forming parameter used in sheet metal bending process |
|---------------------------------------------------------------|
| Forming Parameter | Value           |
| Press velocity   | 3.5-4.5 mm/s    |
| Bending stroke   | 14-15           |
| Material used    | S235 Mild steel |

| Table 5. Chemical compositions of material assigned in simulation and experiment |
|-------------------------------------------------------------------------------|
| Alloying Elements (%) | C    | Si    | Mn    | S     | P     | Cr    | Ni    |
|-----------------------|------|-------|-------|-------|-------|-------|-------|
| S235 in Simufact      | 0.18 | 1.6   | 0.55  | 0.035 | 0.035 | 0      | 0      |
| Mild steel used in experiment | 0.186 | 0.146 | 0.011 | 0.001 | 0.001 | 0.035 | 0.032 |

For welding experimental process, robotic welding equipment ABB IRB 2400/600 together alongside its power source KEMPNI ProMig Evolution is utilized to make a joint between two bended plate. A shielding gas which consists of pure argon was activated during the course of welding process. The display of a robotic welding equipment is shown in Figure 8 while the configuration for the welding experimental which also displays the clamping condition is displayed by means of Figure 9. The parameters of experimental welding process are exhibited in Table 6.

**Figure 8. Robotic welding equipment ABB IRB 2400/60**
Table 6. Experimental parameter of welding process

| 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           |

The distortion is measured prior and after welding process by using Coordinate Measurement Machine (CMM). By utilizing the CMM machine, the amount of displacement occurred during the course of welding process can be examined within certain nodes that become the focus of distortion measurement. CMM Machine Mitutoyo Beyond 707 is used to measure the distortion for experimental study and is displayed in Figure 10.

Figure 9. Configuration for welding experimental process of a bended S235 plates

Figure 10. CMM Machine Mitutoyo Beyond 707

4. Results and Discussions
This section will cover the result presented by both simulation and experimental study of coupled process welding to forming, the first section will cover the displacement which causes the spring back effect within the specimen, thus serves as the initial condition for welding process later on. The spring back effect which was occurred within the work piece after sheet metal bending process is described in
Figure 11 below, which displays the value of workpiece radius. The spring back effect is calculated by involving both die radius and workpiece radius which is described in Table 7.

![Image of spring back effect](image)

**Figure 11.** Spring back effect occurred within bended workpiece

| Table 7. Spring back effect factor of metal bending process in Simufact.Forming |
|-----------------|-----------------|-----------------|
| Die Radius      | Workpiece Radius| Spring-back factor |
| 13mm            | 13.12mm         | 1.008           |

The displacement caused by spring-back effect would later be transferred to Simufact.Welding as the initial condition prior welding process was executed. The angular distortion which symbolizes the displacement towards the vertical direction is the main aim for this research, which occurred after two bended specimens are joined together by means of welding process. The distortion result displayed in this research are represented by utilizing the contour band displays option, of which the colour legends are applied in order to describe the level of displacements of the welded component. Figure 12 and 13 displays the distortion result of the FE simulation executed in Simufact.Welding by means of front view and aerial view respectively.

![Image of welding distortion](image)

**Figure 12.** Front view of welding distortion result in Simufact.Welding
The result of the distortion caused by the coupled process forming to welding will be compared with the experimental distortion result. The final distortion value of experimental coupled process forming to welding is measured by utilizing the CMM machine. Table 8 exhibits the distortion result comparison between FE simulation of coupled process welding to forming and experimental coupled process. The measurement point for distortion analysis is taken in three measurement points within the middle of the component, which where the displacement occurs due to regions being unclamped which are marked in Figure 1 above.

| Coupled Process | Point 1 (mm) | Point 2 (mm) | Point 3 (mm) |
|-----------------|-------------|-------------|-------------|
| Simulation      | 0.146       | 0.249       | 0.205       |
| Experiment      | 0.198       | 0.197       | 0.201       |
| Error percentage (%) | 26.2  | 26.3       | 2.5         |

From the comparison distortion result which was shown in Table 7, it can be concluded that the distortion result which was resulted from the coupled process forming to welding by both Simufact.Forming and Simufact.Welding has been proven on producing a reliable result as the FE results displays almost similar result when it compared towards the experimental result within the range of error of 2.5% until 26.3%.

5. Conclusion
A study of investigation of distortion induced by coupled process forming to welding by utilizing FEM based VM simulation and experimental study has been successfully executed. The research covers both numerical and experimental analysis which was compared as final output of this research. The combination of FE software Simufact.Forming and Simufact.Welding are used for all numerical analysis. Some important points that need to be addressed in order to conclude this research are:

1. A good agreement of result in term of range of error has been achieved by looking at the result of coupled manufacturing process Forming and Welding using both Simufact.Forming and Simufact.Welding
2. The final distortion result produced from coupled process simulation exhibits a similar result to the distortion of experimental process which possesses the error margin percentage for 26.2%, 26.3% and 2.5% for each measurement points,
3. The difference of the final result might be caused by pre-condition of manufacturing process as well as the non-homogeneous material assigned between simulation and experimental study.

As further recommendation, a more detailed metallurgical approach should be taken into account while assigning the material properties during VM simulation. Furthermore, the temperature-dependent properties of filler material should be created instead of using equivalent existing material.

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