UNIVERSITI TEKNIKAL MALAYSIA MELAKA

# Faculty of Manufacturing Engineering

## SIMULATION OF BOBBIN FRICTION STIR WELDING USING DEFORM-3D

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**Master of Manufacturing Engineering (Manufacturing Systems Engineering)**

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# SIMULATION OF BOBBIN FRICTION STIR WELDING USING DEFORM-3D

**FIRAS AHMED MOHAMMED ABDULGHAFFAR**

**A thesis submitted**
**in fulfillment of the requirements for the degree of Master of Manufacturing Engineering**

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**2018**

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# DECLARATION

I declare that this thesis entitled "Simulation of Bobbin Friction Stir Welding using DEFROM-3D" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ..........................................

Name : ..........................................

Date : ..........................................

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## APPROVAL

I hereby declare that I have read this report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Manufacturing Engineering (Manufacturing Systems Engineering).

Signature :……………......................................................

Supervisor Name :……………………….....................................

Date :…………………….........................................

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# DEDICATION

To my beloved mother and father

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# ABSTRACT

Bobbin Friction Stir Welding is a relatively new solid-state process and a variation of Friction Stir Welding (which was invented and patented by *The Welding Institute*) that distinguishes itself in terms of tool structure, characteristics and advantages. Despite the lack of sufficient understanding of this process, Bobbin Friction Stir Welding is known to surpass conventional welding because its double-sided feature contributes to low thermal distortion, reduces down force, eliminates root causes and produces better quality welds with strong mechanical structure. Bobbin Friction Stir Welding tool consists of two cylindrical shoulders connected by a pin, all of them contact the work-piece. The tool penetrates two joined metal plates at the joint-line, which heats the material. When plastic state is achieved, the softened material of the each plate is mixed with the other, forming a solid bond at the solid state. There is still a relative shortage of literature concerning the mechanism of this process. Therefore, the goal was to contribute to the existing research findings by investigating this welding process. The objective of this project was to analyze temperature behavior and flow of work-piece material during the welding process at different welding parameters, utilizing Finite Element Analysis and DEFORM-3D software for simulation, and validate the results by comparison with previous study. A three-dimensional, Finite Element Model of the bobbin friction stir welding tool and work-piece was developed and evaluated using DEFORM-3D software tool. Welding speeds were varied throughout the simulation, and the simulation results were compared with those obtained by previous researchers. Additionally, several past studies on the subject of both conventional and bobbin friction stir welding were analyzed for validation purposes. The findings of this analysis revealed that temperature profile was symmetric along the X-Y axis as the tool moves along the work-piece, while in the X-Z section it exhibited symmetry of wide distribution at the surfaces of the work-plates and narrow radius about the mid-thickness, forming a „waist shape‟. Furthermore, the findings also indicated that sufficient welding temperature was achieved slower when the welding speed increased in each simulation run. Finally, the plastic material was observed to form a tail as it flowed outward towards the rear of the work-piece. These observations were reinforced and validated by other similar studies.



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# *ABSTRAK*

*Bobbin Friction Stir Welding (BFSW) adalah proses keadaan pepejal yang agak baru dan variasi Friction Stir Welding (yang diciptakan dan dipatenkan oleh Institut Kimpalan) yang membezakan dirinya dari segi struktur alat, ciri dan kelebihannya. Walaupun kekurangan pemahaman yang mencukupi mengenai proses ini, Bobbin Friction Stir Welding melampaui kimpalan konvensional kerana ciri dua sisi menyumbang kepada herotan haba yang rendah, mengurangkan kekuatan, menghilangkan punca akar dan menghasilkan kimpalan yang lebih baik dengan struktur mekanik yang kuat. Alat Pengental Gunting Bobbin Alat kimpalan terdiri daripada dua bahu silinder yang disambungkan dengan pin, semuanya menghubungi bahan kerja. Alat ini menembusi dua plat logam bersambung pada garis sambungan, yang memanaskan bahan. Apabila keadaan plastik dicapai, bahan yang dilembutkan dari setiap plat dicampurkan dengan yang lain, membentuk ikatan padu pada keadaan pepejal. Sampai sekarang masih terdapat kekurangan literatur berkaitan mengenai mekanisme proses ini. Oleh itu, matlamatnya adalah menyumbang kepada penemuan penyelidikan yang sedia ada dengan menyiasat proses kimpalan ini. Objektif projek ini adalah untuk menganalisis tingkah laku suhu dan aliran bahan kerja semasa proses kimpalan pada parameter kimpalan yang berbeza, menggunakan Finite Element Analysis dan perisian DEFORM-3D untuk simulasi, dan mengesahkan hasilnya berbanding dengan kajian terdahulu. Finite Element model, 3-dimensi alat bobbin dan bahan kerja dibangunkan dan dinilai menggunakan alat perisian DEFORM-3D. Welding speed telah berubah-ubah di seluruh simulasi, dan keputusan simulasi dibandingkan dengan yang diperoleh oleh penyelidik terdahulu. Selain itu, beberapa kajian terdahulu tentang subjek kimpalan adunan konvensional dan bobbin dianalisis untuk tujuan pengesahan. Penemuan analisis ini mendedahkan bahawa profil suhu adalah simetrik sepanjang paksi X-Y apabila alat bergerak di sepanjang bahan kerja, manakala di bahagian X-Z ia mempamerkan simetri pengedaran luas di permukaan plat kerja dan radius sempit mengenai ketebalan pertengahan, membentuk 'bentuk pinggang'. Tambahan pula, penemuan juga menunjukkan bahawa suhu kimpalan yang mencukupi dicapai lebih perlahan apabila kelajuan kimpalan meningkat dalam setiap jangka simulasi. Akhirnya, bahan plastik diperhatikan membentuk ekor ketika ia mengalir keluar ke belakang bahan kerja. Pemerhatian ini diperkuat dan disahkan oleh kajian serupa yang lain.*



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## LIST OF SYMBOLS

| | | |
|---|---|---|
| AA-5052 | - | Aluminum Alloy 5052 |
| AS | - | Advancing Side |
| BFSW | - | Bobbin Friction Stir Welding |
| CFD | - | Computational Fluid Dynamics |
| CFSW | - | Conventional Friction Stir Welding |
| FE | - | Finite Element |
| FEA | - | Finite Element Analysis |
| FEM | - | Finite Element Model/Modelling |
| FSW | - | Friction Stir Welding |
| P | - | Pressure |
| Q` | - | Heat flux |
| R | - | Surface radius |
| RS | - | Retreating Side |
| T | - | Temperature |
| TWI | - | The Welding Institute |
| t | - | Time |
| q` | - | Heat generation |
| $q`_f$ | - | Heat generation due to friction |
| $q`_p$ | - | Heat generation due to plastic deformation |
| $\mu_f$ | - | Coefficient of shear friction |
| $\mu_0$ | - | Nominal coefficient of friction |



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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Friction Stir Welding (FSW) is a variation of friction welding, classified as a solid-state process used to join two objects together through the application of friction-generated heat. This method was invented and patented in the UK in 1991 by *Wayne Thomas* of *The Welding Institute (TWI)* and was consequently followed by a rise in related patents over the years. FSW differs from the conventional friction welding in many aspects. For instance, friction welding requires one or more parts to be rotated in order for friction to occur. Whereas a reciprocating tool travelling between two objects is what performs the joining action in FSW.

FSW involves the concept of frictional heat. A non-consumable rotating tool is plunged into the joint line between two parts that are butted together in a manner that prevents them from being forced apart (Essa *et al.*, 2016). The rotation generates frictional heat as the tool travels along the joint line such that when the heat is sufficient, the material around the pin heats up and softens to a plasticized state (Hilgert *et al.*, 2010) where it can be easily deformed (Rambabu *et al.*, 2015). The linear traveling of the tool causes the softened material to relocate to the back of the pin, forming a solid weld once the material solidifies.



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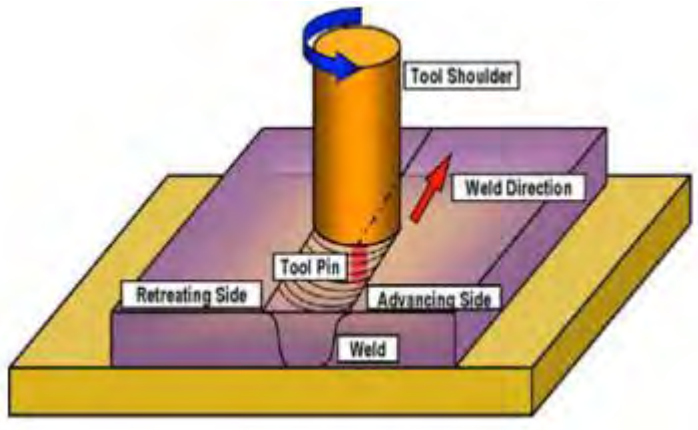


Figure 1.1: Diagram of Friction Stir Welding (Sharma and Bhushan, 2013)

**Advantages and limitations**

FSW technology is an environmentally-friendly process because it produces little to no pollutants and is preferred over conventional fusion methods due to ease of handling and high degree of repeatability. It improves weld strength and quality compared to other welding methods, although the weld strength may vary due to temperature difference between the weld region and the rest of work-piece material.

### 1.1.1 Types of Friction Stir Welding

FSW can be categorized into two types based on tool configuration: (1) Conventional FSW, and (2) Bobbin FSW (Chaudhary and Bhavsar, 2016; Chen *et al.*, 2015).

#### 1.1.1.1 Conventional Friction Stir Welding (CFSW)

As shown in Figure 1.2 below, conventional FSW involves a rotating tool with a profiled pin that is plunged into the joint area between two aluminum plates onto a backing plate (Mijajlovi *et al.*, 2012) until the tool shoulder is in contact with the work-piece.



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A particular advantage of conventional FSW is the ability to enhance the mechanical properties of the material and weld similar and dissimilar alloys. However, it is incapable of welding most of lightweight metals such as some aluminum and copper alloys (Taylor, 2010). Furthermore, this process requires specially designed machine to operate, which is expensive (Zapata *et al.*, 2013).

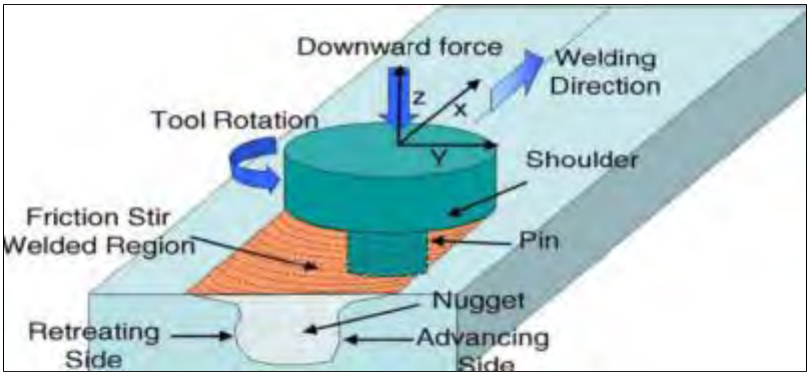


Figure 1.2: Conventional friction stir welding (Yisong et al., 2012)

#### 1.1.1.2 Bobbin Friction Stir Welding (BFSW)

Bobbin FSW – also referred to as self-reacting FSW (Sued, 2015; Scupin, 2015; Tamadon *et al.*, 2018; Singh, Biswas and Kore, 2016) – is another version of Friction Stir Welding. The main difference in comparison with the traditional method is that instead of one, BFSW utilizes a two-shoulder tool – the second shoulder is attached to the lower end of the pin (Hilgert *et al.*, 2010). As shown in Figure 1.3, this special tool configuration allows double-sided welding, reduces the down force and contains the reactive forces of the welded material (Sued, 2015).



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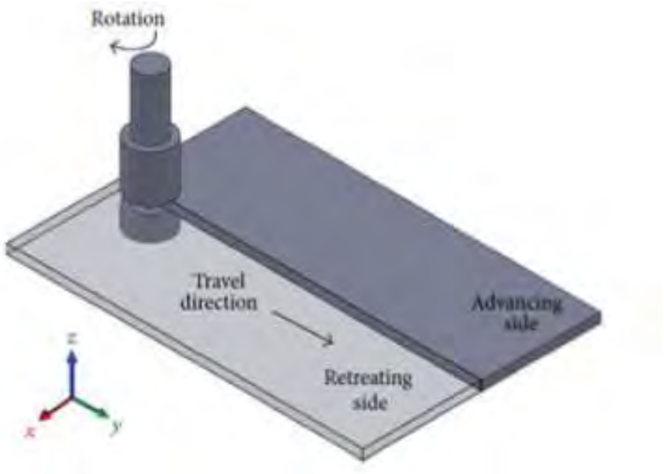


Figure 1.3: Illustration of FSW Bobbin tool (Sued and Pons, 2016)

Bobbin FSW surpasses conventional methods in many aspects. For instance, there tends to be a risk of root flaws in CFSW due to being a single-sided process, and since BFSW is a double-shouldered process, it essentially eliminates this problem (Threadgill *et al.*, 2010).

As stated by Sued (2015), there are different types of FSW bobbin tool configuration based on the gap between the shoulders as follows:

(i) Fixed bobbin: whereby the tool has a fixed gap between its shoulders;

(ii) Floating bobbin: the tool can adjust its position in the Z-axis relative to the component.

(iii) Adaptive bobbin tool: The gap between the two shoulders can be adjusted during the welding process.



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### 1.1.2 Friction Stir Welding Simulation

Throughout the years, significant efforts have been put into understanding the mechanism of FSW process and how to optimize results. Despite the difficulty and complexity of FSW modeling due to the multiphysics involved within the operation including heat flow, temperature variation, plastic deformation and microstructure evolution (Mimouni *et al.*, 2016), related literature is abundant with a wide range of mathematical and numerical studies, as much as it is with experimental work. Common examples of such analyses have used methods like Finite Element Analysis (FEA), Finite Different Analysis (FDA) and Arbitrary Lagrangian-Eulerian (ALE) technique (Khalkhali and Saranjam, 2015). The following is an overview of some notable numerical and mathematical modeling examples conducted on the topic of FSW:

#### 1.1.2.1 Conventional Friction Stir Welding (CFSW)

##### I. Numerical modeling

The following are samples of studies from past literature that employ FEA on FSW with the aid of different software tools.

##### a) FEA using DEFORM 3D

Khalkhali and Saranjam (2015) investigated the dynamic recrystallization to predict the nature of microstructure evolution and average grain size in FSW of aluminum alloy plates. Their approach involved developing a thermo-mechanical FEM model using DEFORM 3D software. The following equations have been used:



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**a. Constitutive equation**

The relationship between strain rate, flow stress and temperature can be described by the Arrhenius equation as:

$$\acute{\varepsilon} = A[\sinh(\alpha\sigma^{p})^{\pi}]\exp(\frac{Q}{RT}) \text{ ...............................(1)}$$

**b. Avrami equation**

The relationship between effective strain and dynamic recrystallization can be expressed with the Avrami equation as:

$$X_{DRX} = 1 - \exp[-\beta_d(\frac{\varepsilon - a_{10}\varepsilon_p}{\varepsilon_{0.5}})^{k_d}] \text{ ...............................(2)}$$

The results showed that the temperature was symmetrically distributed and it reached a maximum of 494 C, higher than the melting temperature of the work-piece material.

**b) FEA using ABAQUS**

Similarly, a Thermo-mechanical, FEM of FSW of AA6082-T6 Alloy was established by Iordache *et al.* (2016) based on Coupled Eulerian Lagrangian method, Johnson-Cook equation for the material deformation, and Coulomb"s law of friction using Abaqus/cae software. The objective was to measure temperature distribution of the welding process.

The Johnson-Cook model was used by Lordache and his team for material deformation. The model is described as follows:



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$$\bar{\sigma} = [A + B.(\bar{\varepsilon}^{pl})^n]\left[1 + C.\ln\left(\frac{\dot{\bar{\varepsilon}}_{pl}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right]\ [GPa]..(1)$$

Another formulation incorporated in their study was the Coulomb Law of friction to define the contact of different elements in the FE model:

$$\tau = \mu . \sigma_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

The results of the simulation revealed that first, the temperature distribution was not symmetric in the cross section of the model; and second, the temperatures recorded on the advancing side (AS) were higher than the retreating side (RS).

## II. Mathematical Modeling

### a) Mathematical modeling using Response Surface Method (RSM)

A mathematical model is developed by Shanmuga, Murugan and Suresh (2011) to examine the influence of four process parameters – namely, (1) tool rotation speed; (2) tool welding/traveling speed; (3) tool pin diameter and (4) axial plunging force of the tool on the tensile elongation (TE) of aluminum alloy AA5083-H321 produced by FSW.

Response Surface Methodology (RSM) was used as a tool to carry out three tasks: (1) develop a regression model; (2) Define the correlation between the parameters and tensile elongation and (3) Predict the effect of these parameters.



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The function that expresses tensile elongation, incorporating tool rotation speed (N), tool welding/traveling speed (S), pin diameter (D) and axial plunging force (F) is written as:

$$TE = f(N, S, D, F) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Then the second order polynomial regression equation was used to express the response surface (Y), which is given as:

$$Y = b_0 + \Sigma b_i\, x_i + \Sigma b_{ii}\, x^2{}_i + \Sigma b_{ij}\, x_i\, x_j \ldots\ldots\ldots\ldots\ldots(2)$$

The findings showed that first, the operating parameters had a direct effect on the process and second, tensile elongation of FSW joints was lower than the base metal regardless of the parameters incorporated in the process.

#### 1.1.2.2 Bobbin Friction Stir Welding (BFSW)

While previous researchers (Sued, 2015; Xu *et al.*, 2017; Hilgert *et al.*, 2010) have investigated aspects of BFSW such as the behavior of material flow and mechanical properties and quality of the weld, unlike FSW, there is still a lack of enough research material that deal with the BFSW modeling and numerical analysis that could offer in-depth understanding of the process and its mechanism. The following are a couple of studies highlighting the process of BFSW.



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**a) Thermo-mechanical model using COMSOL**

The aim of the study conducted by Singh, Biswas and Kore (2016) was to investigate the temperature distribution in the tool and work-piece as well as the material flow by developing a fully coupled thermo-mechanical model of BFSW using COMSOL software.

The researchers developed a three-dimensional fully coupled thermo-mechanical model using computational fluid dynamics (CFD) method and COMSOL software. The material was assumed to be a non-Newtonian fluid and the contact condition between the tool and the work-piece considered to be slip and stick. Therefore a slip factor was involved in the analysis, which was given in the following equation:

$$\delta = \frac{\sqrt{x^2+y^2}}{Rs} \qquad \text{...(1)}$$

The coefficient of friction was also incorporated into the study and was expressed as:

$$\mu = \mu 0 \ x \ e^{-\lambda \ x \ \delta \ x \ \omega \ x \ \sqrt{x^2+y\verb|^|2}} \qquad \text{...(2)}$$

According to the findings, there was no variation in temperature between the top and bottom surface of the work-piece. However, the temperature at the AS was higher than the AS. An hourglass-shaped temperature profile was formed due to the heat input from the two shoulders of the tool.



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#### b) Thermo-mechanical model using DEFORM-3D

Another attempt on Bobbin FSW simulation was undertaken by X.M. Liu *et al.* (2014) for the purpose of understanding the mechanism of the process.

The objective was to create a physical model to analyze the temperature field. The following formula is used for the analysis:

$$\rho c\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2}\right) + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}) + q` \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The results of this study supported those of the previous example, as the highest temperatures were recorded in the regions nearest to the tool and a waist or hour glass shape was created at the work-piece material.

## 1.2 Problem Statement

This study was motivated by the lack of research material concerning the field of Bobbin FSW (BFSW), contrary to its conventional counterpart. Based on literature surveying, what research there is on the field of BFSW typically focuses on the study of temperature profile and distribution, carried out through lab experimentations; only few analyses have attempted to numerical modeling. This creates an opportunity to investigate this area in hopes to further validate what previous researchers have concluded.

Conducting an actual experiment is both costly and time consuming; therefore numerical modeling and software simulation are used as an alternative for this project.. DEFORM-3D is a commercially available FE simulation software commonly used by designers to analyze solid-form processes such as forming, rolling and machining (Tamizharasan and Kumar Senthil, 2014) and it is known for its robustness, ease of use and



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