Development of Continuous Drive Friction Welding (CDFW) model in ABAQUS for AA 6061-T6 alloy to verify experimental results and to predict behavior of similar and dissimilar alloys AA 6061-5083

Muhammad Umar Elahi

00000273793

Supervisor

Dr. Shahid Ikram Ullah Butt

DESIGN AND MANUFACTURING ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

August, 2021

Development of Continuous Drive Friction Welding (CDFW) model in ABAQUS for AA 6061-T6 alloy to verify experimental results and to predict behavior of similar and dissimilar alloys AA 6061-5083

Author

Muhammad Umar Elahi

Registration Number

00000273793

A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

Thesis Supervisor:

Dr. Shahid Ikram Ullah Butt

Thesis Supervisor's Signature:

____

DESIGN AND MANUFACTURING ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,

ISLAMABAD

August, 2021

Thesis Acceptance Certificate

It is certified that the final copy of MS thesis written by **Muhammad Umar Elahi (Registration No. 273793)** of department of **Design and Manufacturing Engineering** has been verified by undersigned, found complete in all respect as per NUST statutes / regulations, is free from plagiarism, errors and mistakes and is accepted as a partial fulfilment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in this dissertation.

Signature: ________________________

Date: ____________________________

Dr. Shahid Ikram Ullah Butt (Supervisor)

Signature HOD: _____________________

Date: _____________________________

Principal: __________________________

Date: _____________________________

-

FORM TH-4

MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: **Muhammad Umar Elahi Reg. No: 00000273793**Titled: Development of Continuous Drive Friction Welding (CDFW) model in ABAQUS for AA 6061-T6 alloy to verify experimental results and to predict behavior of similar and dissimilar alloys AA 6061-5083 be accepted in partial fulfillment of the requirements for the award of **MS** degree and awarded grade ____.

Examination Committee Members

1. Name: Dr. Syed Hussain Imran Signature:________________

2. Name: Dr. Aamir Mubashir Signature:________________

3. Name: Dr. Najam Ul Qadir Signature:________________

Supervisor's name: Dr. Shahid Ikram Ullah Butt Signature: ________________

Date:____________________

Head of Department: __________________ Date:_____________________

COUNTERSIGNED

Date: _______________________ _________________

Dean and Principal

Declaration

I certify that this research work titled "*Development of Continuous Drive Friction Welding (CDFW) model in ABAQUS for AA 6061-T6 alloy to verify experimental results and to predict behavior of similar and dissimilar alloys AA 6061-5083"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

MUHAMMAD UMAR ELAHI

00000273793

Plagiarism Certificate (Turnitin Report)

This thesis has been checked for Plagiarism. Turnitin report endorsed by Supervisor is attached.

Signature of Student

MUHAMMAD UMAR ELAHI

Registration Number

00000273793

Signature of Supervisor

Copyright Statement

Acknowledgements

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor Dr. Shahid Ikram Ullah Butt for his help throughout my thesis and also for QRM and Computer integrated manufacturing courses which he has taught me. I can safely say that I haven't learned any other engineering subject in such depth than the ones which he has taught.

I would also like to pay special thanks to Dr. Aamir Mubashir, Dr. Syed Hussain Imran, Dr. Najam Ul Qadir and Dr. Bilal Ahmad for his tremendous support and cooperation. Each time I got stuck in something, they came up with the solution. Without their help I wouldn’t have been able to complete my thesis. I appreciate their patience and guidance throughout the whole thesis.

I would also like to thank Muhammad Muzamil, Muzamil Ahmad Shabbir, Zubair Hassan, M. Hassan Zafar, Danish Falak and Daniyal Anjum for being on my thesis guidance and express my special thanks to Dr. Najam Ul Qadir for his help. I am also thankful to Dr. Salman khan and Sir Zarak Khan for their support and cooperation.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

Contents

List of Figures

List of Equation

Abstract

Continues drive friction welding, a type of rotary friction welding, is a solid state welding process in which similar materials and dissimilar materials are welded together. During the process one part is rotated with a particular RPM and other part is moved with the help of axial force or pressure towards the rotating rod. First both surfaces of rod are rubbed to generate heat which should be below the melting point and then pressure or axial force is applied that moves the rod into the rotating rod and cause a weld. The temperature generated during fusion of rods, is the main parameter which is less than melting point of materials but greater than that at which crystallization of newly formed crystals during mixing of similar and dissimilar materials takes place. The fusion temperature is important for the weld strength. Experimentally temperature with respect to varying time, radius of rods, RPM can be measured using thermocouples. So in this research, a 3-D model is developed of Continues drive friction welding in ABAQUS environment to observe the change of temperature with respect to time and other parameters for similar AA 6061-T6 and dissimilar AA 1050 with AISI 304 Austenitic steel and AA 6061-T6 with AA 5083 H111. Experimental results and simulated results of temperature with respect to other parameters and material properties i-e Von Mises of simulated results are compared which are less than 10 percentage errors. Results obtained were better in ABAQUS environment as compared to COMSOL in which 2-D analysis was done.

1. Introduction

Welding is the process in which materials or plastics are joined together with and without help of filler material. The main principal of this process is that two materials are fused together which in results generate heat. Different methods are used to generate heat either using external source or material itself [1]. There are two methods to joint materials, i.e., fusion welding or solid state welding. In fusion welding the faces of both joining materials are melted while in solid state welding, joining faces are heated to red hot temperature and pressure or force on the other side of the joining face is applied to create weld.[2]

As advancement in technology is increasing day by day, heat generation for fusion can be done externally using electricity etc. in 1782, electric welding was used in Germany for welding purpose.

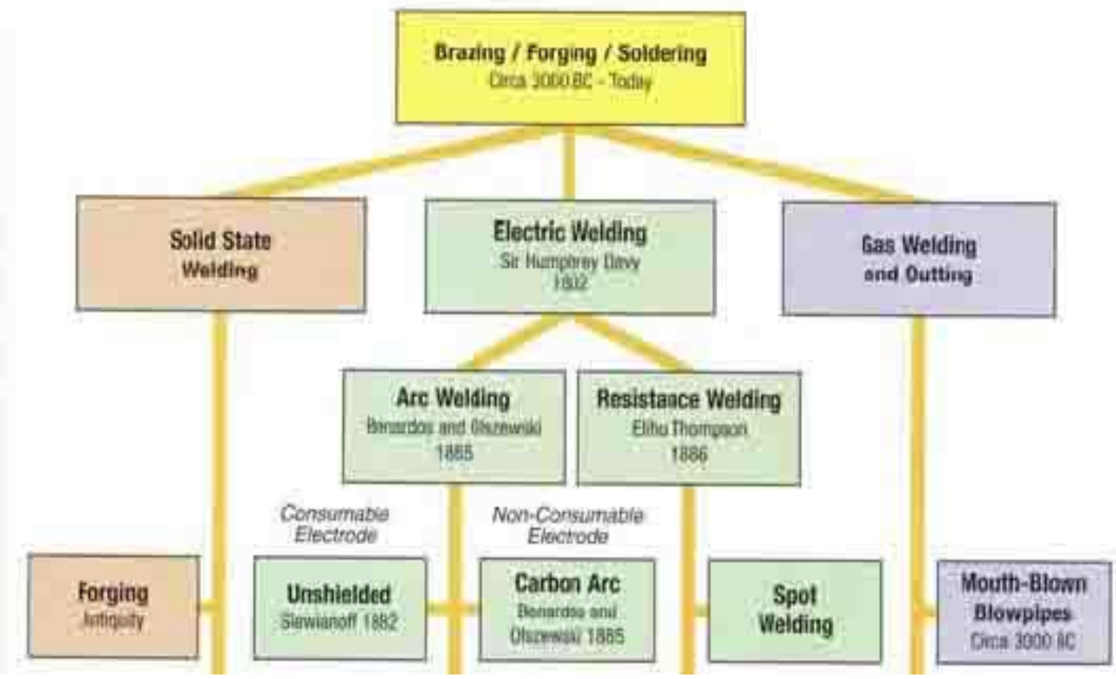


Figure 1 History of Welding

1.1 Types of welding

The welding process is mainly divided into three categories which are,

1.1.1 Heat welding

In this welding, heat is used to join the materials. Similar and dissimilar materials can join together using this process. This process is also using in many industries.

1.1.2 Pressure welding

In this welding, pressure is used to join the materials, as pressure is applied due to which material heated up and fused together to make a weld.

1.1.3 Friction welding

In this welding, the heat is generated by the friction of faces of the materials which than fuse together to make a weld. This is also used to join similar and dissimilar metals.

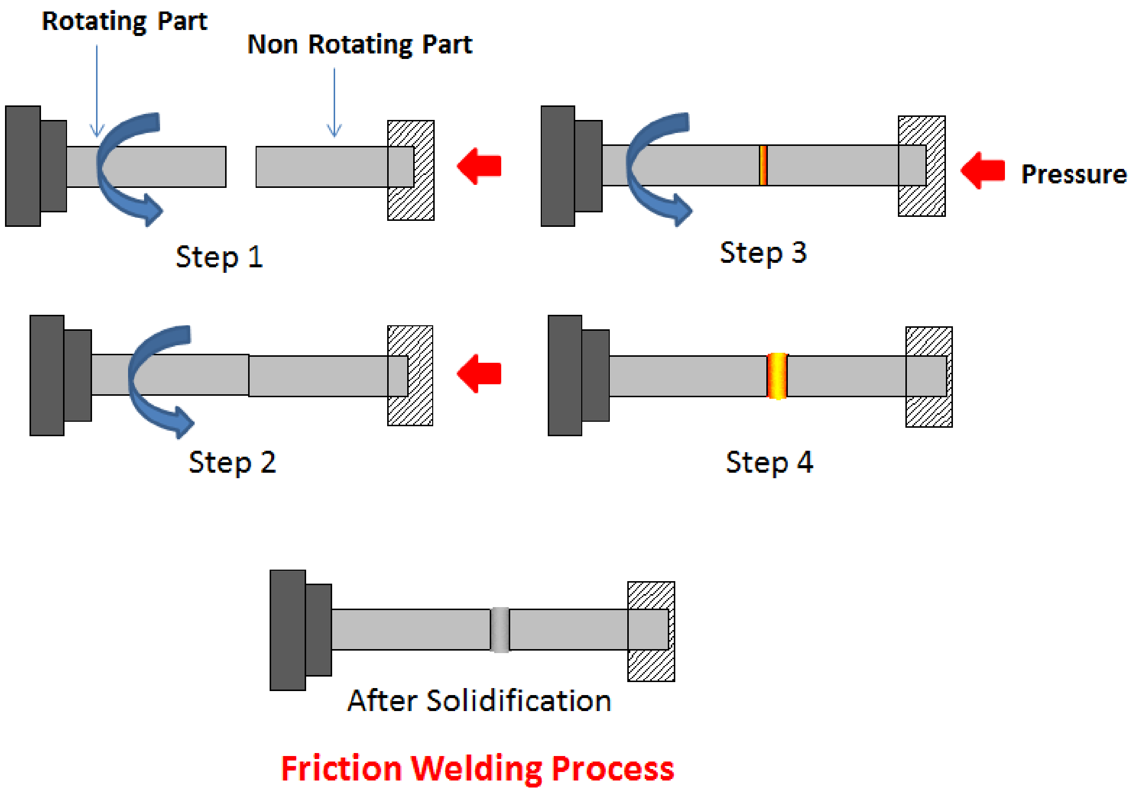


Figure 2 Friction Welding Process

1.2 Friction Welding

According to the definition of American welding society, Friction welding is[3]

'Friction welding is a solid state joining process in which materials are joined using the compressive force contact of joining parts which are rotating or moving relative to one another resulting generation of heat and plastically displaced material from the faying surfaces. In normal conditions surfaces do to weld. Advantage of this process is that filler metal and shielding gas are not required'.

Friction welding is type of solid state welding process in which efficient welds are produced for similar and dissimilar materials. In this process two materials are rubbed together which produce heat and then axial force or pressure is applied to fuse the material. One part is rotated with particular RPM and other part is other part is moved axially toward the rotating part to form a weld. The Heat generated by the friction of both faces at interface initiates the welding process. The pressure is applied to increase the temperature for fusion. When pre molten state is reached, then rotating part is stopped and other part is axially moved with high pressure toward the stopped rotation part which increase the strength of weld.

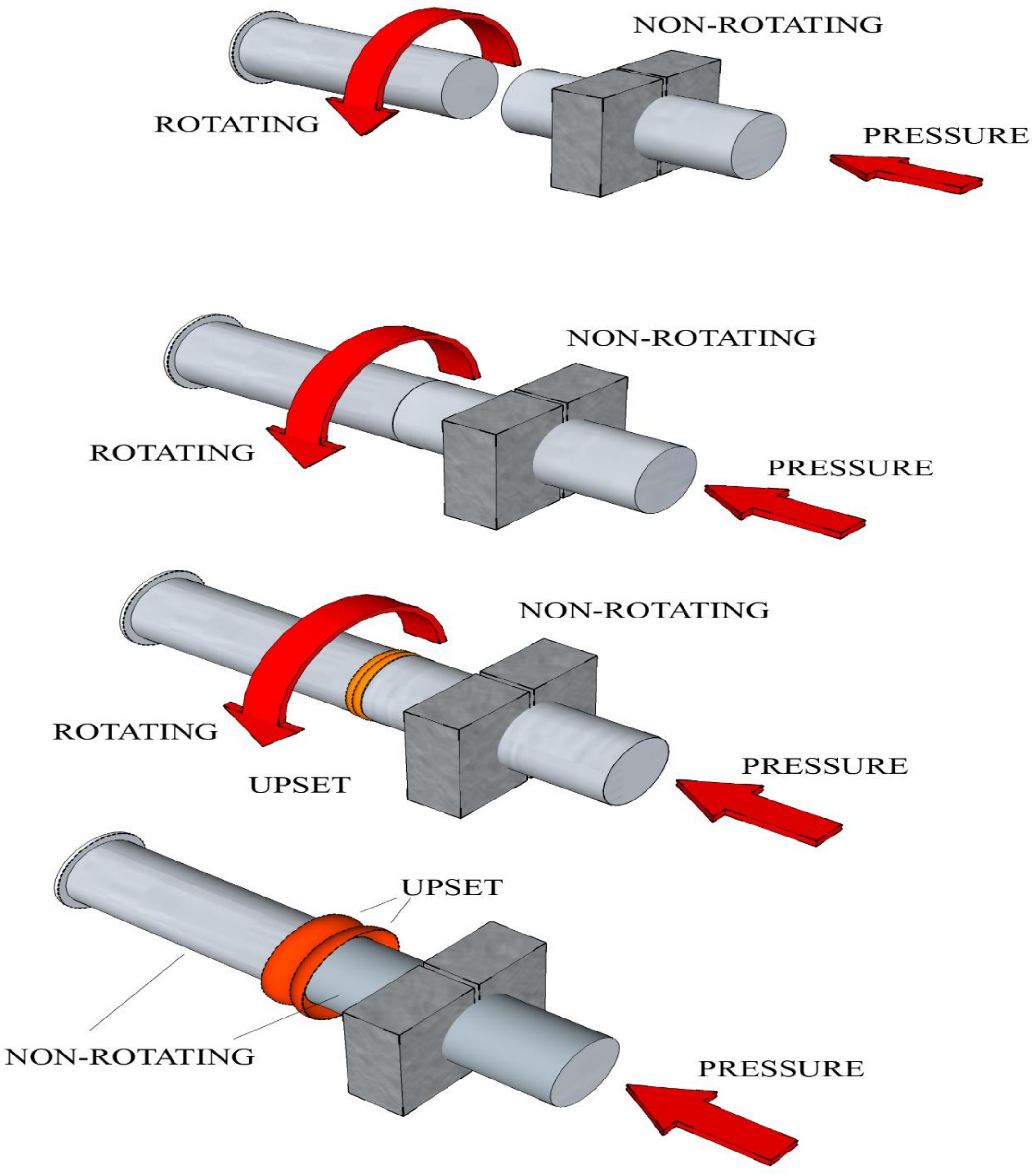


Figure 3 Stages of Rotary Friction Welding

1.2.1 Types of Friction Welding

There are three types of friction welding which are;

- Rotary Friction welding (RFW)
- Linear friction welding (LFW)
- Orbital friction welding (OFW)

These three types are widely used in industries but rotary friction welding is the oldest process and mostly used process due to simple setup needed for this weld.

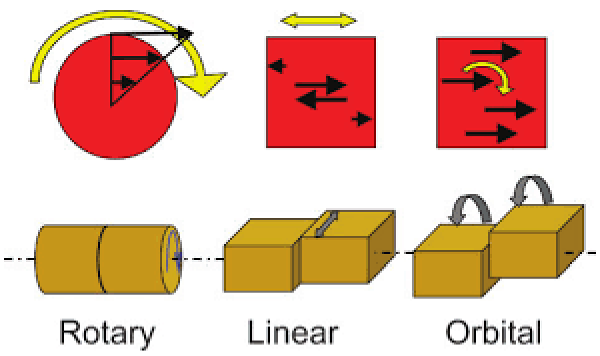


Figure 4 Types of Friction Welding

In linear welding process, work pieces move relative to each other under pressure and in parallel vibrational motion of small and fixed amplitude cause heat generation and pressure cause the fusion results a weld.

In orbital friction welding, both parts have an orbital motion around their longitudinal axis in a constant speed. [4]

The compassion of friction welding shows that rotary friction welding is simplest method of friction welding. But it has limitation that it cannot weld non circular cross section. The another disadvantage of this rotary friction welding(RFW) is non uniform thickness of heat affected zone (HAZ). Non uniform generation of heat leads to non-uniform thickness around the radius of the rod.

The rotary friction welding is further divided into two processes depending upon the source of rotating part.

- Inertia welding
- Continuous drive welding

Inertia drive welding is type of RFW in which rotating part is rotated with the help of flywheel in which kinetic energy is stored and then work piece is attached for rotation.

Continuous drive friction welding is type of welding in which rotating part is rotated continuously, rotation continuously cause heat generation.

1.2.2 Advantages of Friction welding

The main advantage of friction welding is that similar and dissimilar materials which cannot weld by other method can join by this method. It can join many combination of dissimilar metals and also similar material.[5]

In this process mechanical energy is directly converted into heat energy which results a large temperature gradient. This large temperature gradient produce small HAZ. The less HAZ region, the less distortion in joined metals.

The process is also very short in terms of time. The process is very energy efficient and short joining time, results in high production.

The defects regarding porosities or slag contamination is also not in this weld because this is solid state welding, because these defects produced when metals melts.

As higher weld strengths formed which is result of removal of slag contamination at the interface. The strength increases due to high forging pressure.

The joining of dissimilar metals is unique advantage of this process because it produces full joint strengths if process parameters are chosen correctly. The new material formed at the interface which have different properties and can be used for future use after fusion of two different metals.

The process didn’t not require and filler materials, shielding gas, flux which reduce the cost of overall process.

The process is environmentally friendly as it didn’t produce any toxic or harmful fumes or vapors. It is also worker friendly process in which human can operate the machine and handle the process easily.

The process has short cycle time which can be used for further automation of this process for mass production which can lead to reduce labor cost.

In this process, joint preparation is not required as commonly used joints are made by say cut work pieces. This is because rods for weld form plastic material at the interface which finish the need of joint preparation.

1.2.3 Application of Friction Welding

Friction welding is being widely used in every manufacturing industry in which automotive, aerospace, electrical industries, petroleum and pipe industry. The application of this welding included the joining of butt joints in shafts to engine valves in jet engine parts.

Figure 5 Applications of RFW

Figure 6 Application of RFW

1.2.4 Stages of friction welding process

There are three stages in friction welding process.

1. In the first stage, heat is generated below the melting point. This is also called heating up stage. In this stage two rods/metals are given relative motion and moved towards each other with the help of axial pressure. The temperature increase at interface and applied pressure decrease the flow of stress of the material.
2. In second stage the material cannot bear the applied pressure and temperature results plastic deformation due to which flash is produced. The flashes are important for the strength of weld joints as flashes removes the slag contamination and oxide layer from the interface.
3. In the third stage, rotation stops and both the welded pieces are kept under high compressive forces which results in high strength of weld joints.

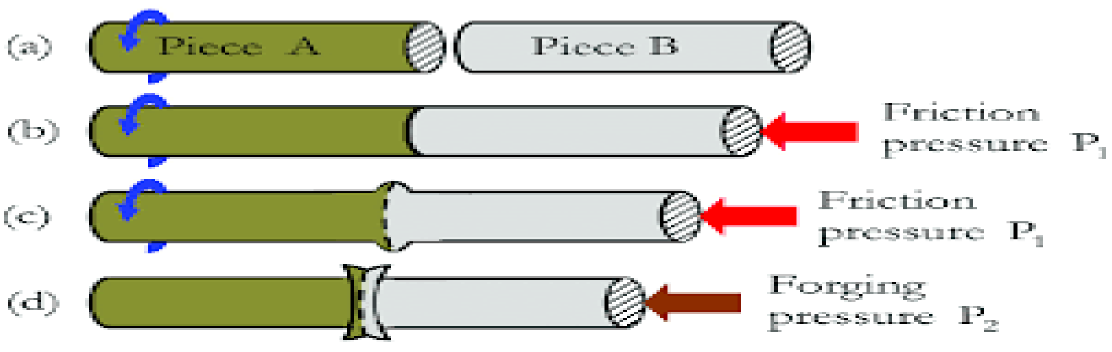


Figure 7 Different Stages of RFW

1.2.5 HAZ Structure and joining mechanism

The phenomena occurring in rotary friction welding is diffusion. It is concluded in research that diffusion play avital role as interface temperature and manually calculate results of temperatures were measured along with mechanical properties[6].

The diffusion layer exists between the interface of the two rods, when joining dissimilar metals [7]. It was also concluded that if the solubility of both metals increase than formation of joint for dissimilar metals will be easy. That will result in high strength of weld.

Instead of advantages of diffusion, there is also a disadvantage of diffusion in rotary friction welding. Although diffusion increases the quality of weld but not all time. It may affect the weld strength. The weld between carbon steel or medium plain carbon steel may become ductile due to decarburization of the weld joint. The brittle nature occurs in different metals due to formation of intermetallic layer or phases. E.g. weld between steel and aluminum, copper and titanium. When examination of these weld was done, the weld interface has thin layer in which missing of both dissimilar metals was found.

1.2.6 Zones in friction Welding

- Contact zone:

The edges where contact occurred is contact zone. The faces which rubbed together and friction is done in this zone. Rotational velocity is the key parameter in this zone. In this zone, severe plastic deformation, strain and the recrystallization of grain structure results in formation of good quality weld and highly fine grain structure.

- Fully Plasticized Zone:

  In this zone, material and crystals grains did not participate in friction welding, but some amount of plastic deformation is occurred in this zone due to high temperature. In this zone fine and regularly placed crystals also formed due to dynamic re crystallization.

- Partly deformed zone:

Moving away from the above zones, due to conduction and due to low temperature, partly deformed zone is formed which is quite low and strain rate is also less. These factors make poor re crystallization and microstructure become coarser.

- Un-deformed Zone:

In this phase, material is not deformed or change its phase which depends on maximum temperature. Although grains are formed in this region.

1.2.7 Parameters in Friction Welding

The welding between similar and dissimilar metals, parameters should have kept into consideration as, parameters effect the strength of weld. The parameters are:

- Rotating Speed (RPM)
- Friction Time
- Friction Pressure
- Torque
- Upset time
- Upset pressure
- Shortening

Basically in continuous drive friction welding process, one part is rotated with particular RPM and other part is moved towards the rotating part for face to face heat generation with the help of axial force or pressure until plastic deformation starts. Reaching a high temperature, the stationary part is than pushed more into the stopped rotating part to get more plunge area and it will create high quality weld.

The following graph will show the different parameters with respect to time.[8]

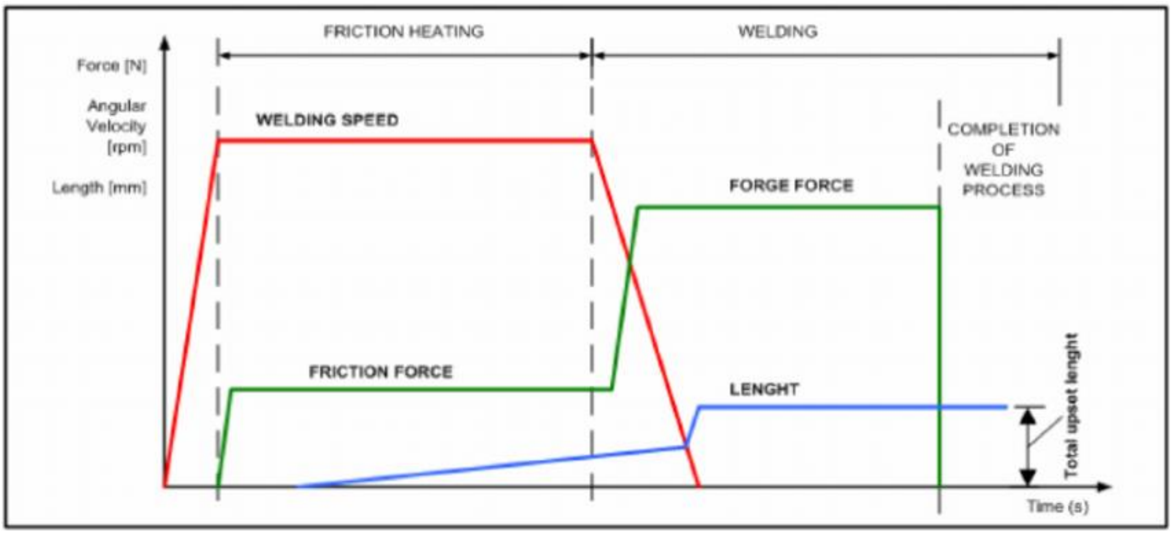


Figure 8 Parameters of RFW

From the graph, it is clear that quality weld and high strength of weld can be achieved by using rotational speed, axial force and welding time. These parameters give heat generation which should be kept into consideration because heat generation plays important role in this process. These parameters also determine the heat energy required for contact zone.

According to graph, the pressure increase rapidly as process is started and heat generation is required. It than decreases up to a constant value after some time. This rapid rise and decrease in pressure is due to formation and braking of interfering asperities and material soft in plastic zone. In second phase the friction torque is kept constant. In third phase, forging is started and rotation is stopped. The axial forces are increased in third phase due to forging. Increase of axial force, increase the friction torque and reached to maximum value and then become zero rapidly.[9]

2. Literature Review

In this research, experimental results and simulation results of a 3-D model have been compared. In this similar aluminum alloys AA6061-T6, dissimilar AA1050-AISI 304 austenitic steel and AA 6061-T6 with AA 5083 has been done in simulation.

For AA 1050-AISI 304, a 2-Dimentional model was developed in COMSOL environment in which effect of different parameters on temperature profiles were developed against total time of process, rotational speed, radius and pressure applied. Also phase transition is studied in COMSOL environment [2]. The experimentation of

AA 1050-AISI 304 was done and experimentally interface temperature was measured with the help of Thermocouple data logger which gather data in real time operation[10]. The welded parts were than examined and good results in term of mechanical properties were produced. The rotary friction welding is compared and concluded prodigious method to join dissimilar metals as compared to fusion welding [11]. The first model regarding dissimilar metals was performed in ABAQUS environment, Three Dimensional Alumina-Steel weld was examined. The main results were temperature profiles with respect to time, von mises and intermetallic layer depth were also measured. Also experimentally performed with same parameters and results were compared [12]. Experimentally, effect of friction time on mechanical and thermal properties were examined and tensile test was performed. In this experiment, forging is not required as it does not effect such in similar alloys AA 6061 and also decrease the process time[13]. For different types of friction weld, model was created in ABAQUS environment using ABAQUS explicit and ALE adaptive mesh controls were incorporated and compared with experimental results[14].

Cheng [9] designed the first model of the Friction Welding process by using Numerical Methods. He used measured power to define a hypothetical heat flux uniformly distributed on the friction interface and compared it to other welding process. Nguyen also used similar approach to establish the friction welding process[15]. Maalekian [16] carried out the comparative analysis of heat generation and temperature prediction for friction welding of steels. He studied temperature dependent properties from the database of DEFORM and verified his results by DEFORM. He compared the temperature profiles by adapting four different methods including constant friction coefficient method, slip-stick method, power method, and inverse method. The power method and the inverse method showed excellent results because they were based on the experimental results. As the temperature cannot be measured directly, inverse method proved significant to predict temperature on the friction interface. Ahmet [17] also established the dependence of temperature profiles on different work piece parameters. Subhavardhan [18] carried out several tests to study the effect of variation in pressure and time on the strength of joint of dissimilar metals. The effects on the strength of the joints were observed by tensile test in three ways, by keeping upset pressure and upset time constant, by increasing friction pressure and by increasing friction time. Moreover, the decrease in strength of the joint with the increased friction time was due to the formation of the inter-metallic impurities formed at the joint interface. The joint had considerable strength but this strength was less than the tensile strength of AA6082 used for this purpose[19]. The rotary friction welding of AA6061-T6 was conducted and the influence of rotation speed was investigated on friction behavior and on radially non-uniform mechanical properties of AA6061-T6 rotary friction welded joint. The results show that, as the rotation speed increases from 500 to 2100 rpm, the curves of friction time and friction work present like 'V- curve' with a minimum value at 900 rpm and the ratio of friction work in the first stage to that in the whole process increases and then decreases after reaching a maximum value at 900 rpm[20]. For similar joining, AISI 304 austenitic steel was joined by friction welding, and 95% efficiency of weld was obtained[21]. Temperature profiles are determined for similar AISI 1040 grade steel using COMSOL with respect to time and compared experimentally[22]. Experimental and numerical results of temperature profiles are compared using DEFORM finite element method. Temperature and deformation of 1045 carbon steel and AISI 304 austenitic steel was investigated[23]. A 2-D model was created in ABAQUS for CDFW of Mild steel. Different parameters, axial pressure, rotating speed and axial shortening was examined [24]. Rotary friction welding of similar and dissimilar materials of steel and aluminum were carried out experimentally at 900, 1250 and 1800 RPM.

3. Aim and objectives

The aim of this research is to develop a model for continuous drive friction welding for similar and dissimilar metals. For similar metals, AA 6061-T6 is selected because it is widely used in different industries and its properties are available in literature. The model has been validated and then for dissimilar metals, AA 1050- AISI 304 austenitic steel model has been created and temperature evolution with respect to time and von mises have been compared with experimental results. AA 6061-T6 with AA 5083-H111 has been selected because both combinations are used in aerospace industry and oil rigs respectively.

The objectives of this research are;

- Development of Continuous Drive Friction Welding (CDFW) model in ABAQUS for AA 6061-T6 alloy to verify experimental results and to predict behavior of similar and dissimilar alloys AA 6061-T6 5083.
- To develop a thermal model for similar and dissimilar metals using finite element method and to predict temperature distribution in similar metals AA 6061-T6 work pieces during CDFW. Also for dissimilar metals i-e. AA1050-AISI 304 austenitic steel and AA 6061-T6-AA5083.

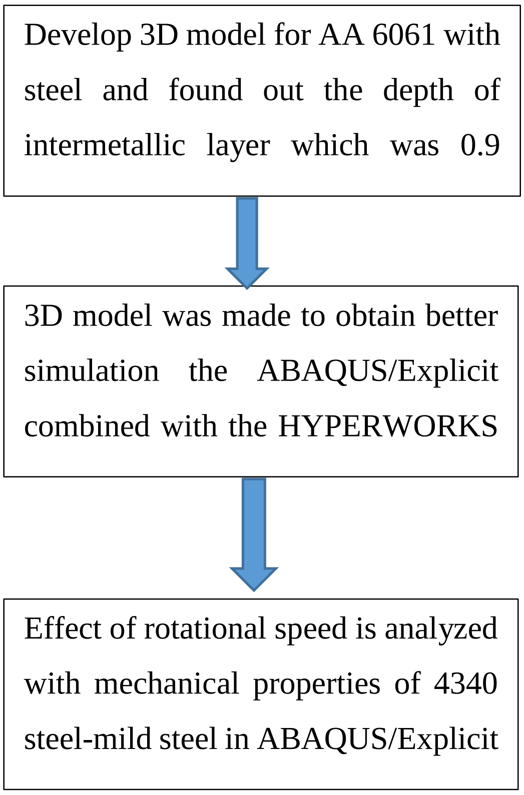
- Numerical modelling of CDFW in Abaqus will use to predict plunge depth, temperature evolution, stress and strain for the weld which will produce weld quality characterization.

4. Research methodology

In this research, FEM is done for a CDFW model made in ABAQUS/explicit. First parts are made and material properties are assigned to both rods. Section is assigned which is solid and homogenous. Then assembly is created in instances where coincident constraint is used. Each part is independent for mesh attributes. Then mesh is generated. When mesh size is coarse, time for simulation increase so nominal size of mesh is created so that time consumption should be less. As parts are meshed and assembly is created, interaction properties and interaction is defined. Interaction is general contact explicit and surface to surface Explicit is selected as both surfaces have to fuse into another. Than pressure is applied in Load. Boundary conditions are defined in which one part is ENCASTRE and other part is rotated with different RPM and linearly moved with a velocity. In predefined field temperature is set to be 29 ^{o}C as initial temperatures. Then Job is submitted for the FEA analysis. Results can be seen from Visualization.

First of all model for similar metals is validated. The AA 6061-T6 is made and temperature evolution at interface has been verified and compared with the experimental results. Than for dissimilar metals, AISI 304 and AA 1050, both with COMSOL and experimental temperature evolution has been verified and less than 5 % error was taken into account for further model verification. Than a model for AA 6061-T6 and AA 5083 has been proposed with the available literature review properties.

4.1 Flow chart from literature review



4.2 Selection of Parameter

The rotary friction weld is generated with the help of heat generated. As rotational speed is increased in first stage, the heat generation also increased. As weld quality depends upon the heat generated, so RPM should be in consideration and optimized for the welding parameters.[20]

As heat generated can be given by the equation:

$$q = \frac{\pi^2 p f n R^3}{20}$$

Equation 1 Heat Generation of RFW

Where q = heat power

p =unit pressure

f = friction coefficient

n = rotation speed

R = radius of rod

5. Modelling in ABAQUS

First parts were created in ABAQUS/explicit environment. For similar parts AA 6061-T6, the parts were solid (diameter=25mm) extruded to length 40mm. one part is named FIX part and other is named Rotatory part in experiment, length was 100 mm, which can cause increase in simulation time so, 40 mm was selected. Section is created which is solid and homogenous and assigned to both part. Material properties: General (density 2700 kg/m^3), in Mechanical properties elastic, plastic in which Johnson- Cook model values are used, expansion temperature dependent values, in thermal properties: conductivity, latent heat and specific heat are used for AA 6061-T6.

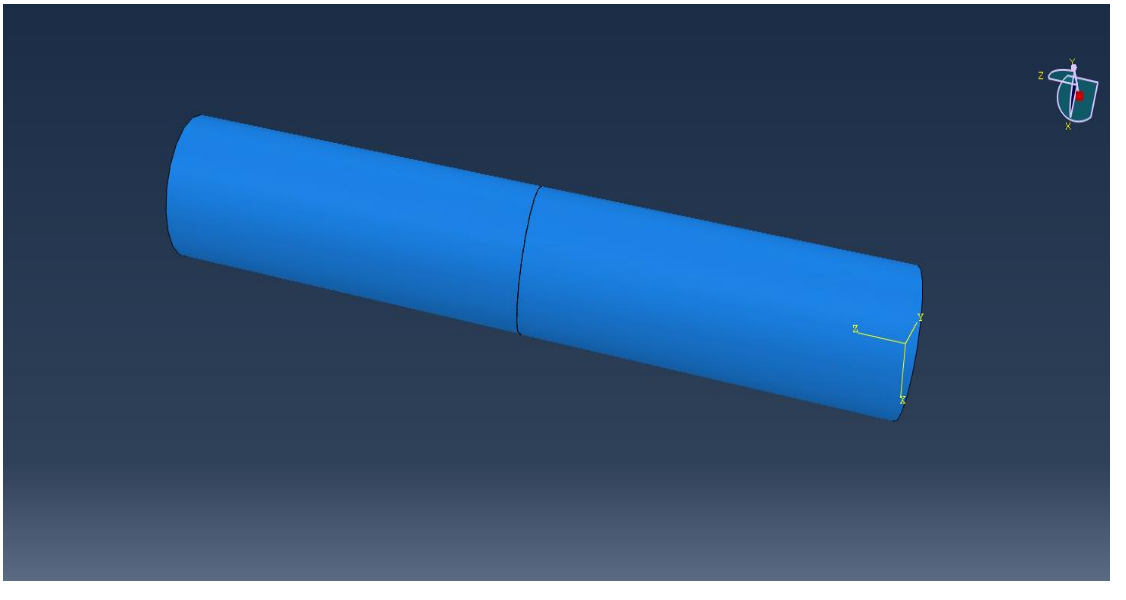


Figure 9 Initial Free Body Diagram for RFW

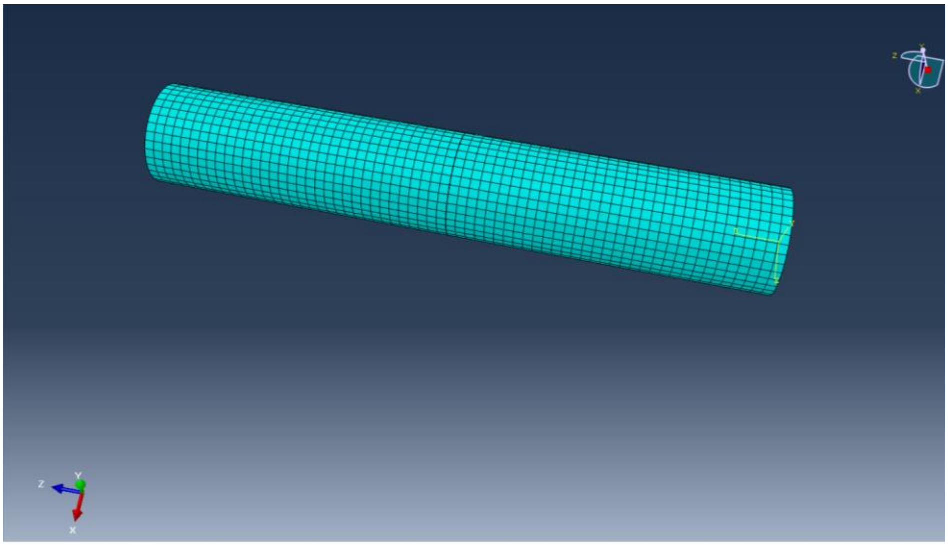


Figure 10 Mesh Free Body Diagram of RFW

Assembly is created in which part were moved together in instance and clearance of 0.0002 mm was created. This gap is quite higher in experimentation but in simulation higher gap will cause increase in simulation time so gap is less. Now step is created. So three steps were made, first for heat generation called rotating step in which step time was 4 sec. the second step is named plunge which depend upon the velocity which is 2m/sec so time for plunge of 0.9 mm was 0.0045 sec was taken. For cooling 2 sec step time was given for cooling. Field Output Request was for stress (stress, mises only), strain (PEEQ, PEEQMAX), forces/reaction, contact and thermal was selected. Interaction is surface to surface explicit is selected and material properties for interaction are defined in interaction properties. The properties are tangential behavior (Penalty, friction coefficient temperature dependent properties), heat generation (friction converted into heat 0.9 and heat distributed to slave surface is 0.85). 15% losses were taken into account for radiation and convection. Normal behavior: hard contact is selected. Thermal conduction is selected for different conduction for different clearance. Loads are applied in which pressure for first stage Load 1: P= 40 MPa on rotating part which helps to generate heat more as friction increases. Same pressure is created as load 2 for plunge step which create a forging action. Mesh is generated for both parts with global seed size value 0.2 mm and C3D8RT an 8-node thermally coupled brick, trilinear displacement and temperature, reduced integration, hourglass control is selected which reduce integration results and produce more refine result. The minimum size of mesh was 0.2 mm and maximum size was 1 mm which Boundary condition are BC1 Encastre: U1=U2=U3=UR1=UR2=UR3=0 for fixed part. BC2 for

Angular velocity and linear velocity in which RPM is given in VR3 and V3 as part motions were defined in Z-axis. At last predefined field, initial temperature was given to parts which is 29ºC. Than part is submitted for analysis and results were analyzed.

5.1 Model development for Similar Aluminum Alloys 6061-T6

Model develop in ABAQUS/EXPILICT environment, as to verify experimental results, we have to create the same as experimental values of Diameter and length is taken. The material properties used in ABAQUS are:

Table 1 Material Properties of AA 6061-T6

Material	Temperature (°C)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Heat capacity ($J.kg^{-1}.K^{-1}$)	Density ($kg.m^{-3}$)	Thermal expansion ($\times 10^{-6}$ K^{-1})	Young's modulus (GPa)	Yield stress (MPa)	Poisson's Ratio	Melting point (°C)
Aluminum alloy 6061-T6	0	162	917	2703	22.4	69.7	277.7	0.33	582-652
	98	177	978	2685	24.61	66.2	264.6		
	201	192	1028	2657	26.6	59.2	218.6		
	316	207	1078	2630	27.6	47.78	66.2		
	428	223	1133	2602	29.6	31.72	17.9		
	571	253	1230	2574	34.2	0	0		

Experimental parameters for AA 6061-T6 and results are are[20]:

Parameters	Value
RPM	500,800,900,1200,1400,1500,1800,2100
Diameter	25 mm
Length of rods	100 mm
Friction Pressure	40 MPa
Forging Pressure	40 MPa
Linear velocity Range	0.66 m/sec -2.73 m/sec

Table 2 Parameters for AA 6061-T6

Same parameters are included in simulation so that results have less error. Experimental temperature evolution is given by below graph against the RPM.

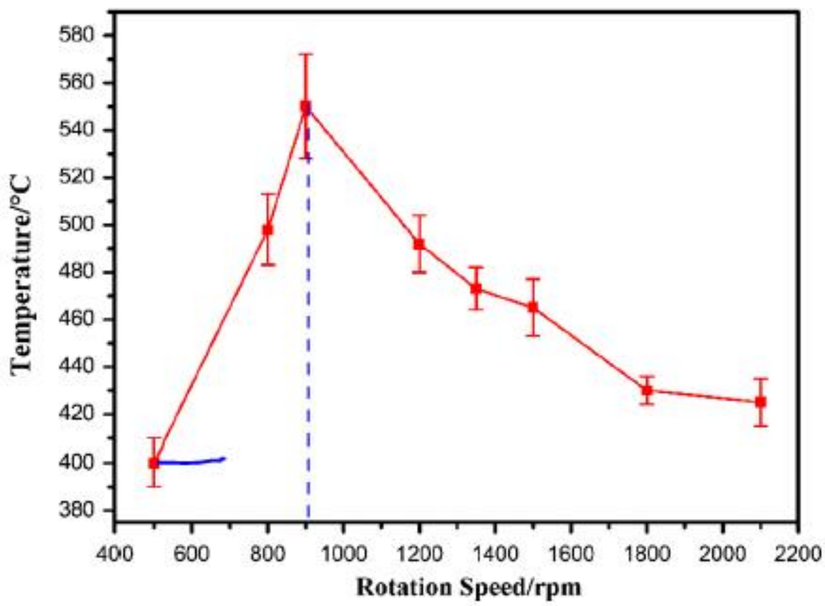


Figure 11 Experimental Results of AA 6061-T6

Three simulations have been done for the verification of temperature and then stress and strain i-e. Von-Mises was compared with allowable stress. Three RPM which were taken into account for simulation are 500(52.36 rad/sec), 900 RPM (94.25 rad/sec), 2100 (219.91 rad/sec). The temperature evolution regarding these RPMs are 400 ºC, 550 ºC and 420 ºC.

5.2 Model Development for AISI 304- AA 1050

So first for this model parameter are taken from previous literature review which are used in experimental determination of temperature. We have reduced the length of both the rods as there is no effect of heat along the long lengths of rod. In first step, the rod of aluminum is rotated and friction time is taken 15 secs to generate maximum heat. In this pressure called friction pressure is applied simultaneously with rotation which help to increase heat at the interface. In second step plunge is given 15 secs so that material intermixes properly and forging pressure is applied with a linear speed. 0.9 mm is depth of plunge and material is moved with linear velocity. Last step is cooling step which is 5 sec and material is set to cool down and for formation of new grain structure with applied forging pressure.

The Parameters are:

Name	Value	Description
T1	15	Friction time (Sec)
P1	2.10E+06	Friction Pressure
P2	1.4E+06	Forging Pressure
Length Aluminum/ Steel	40 mm	Lengths of rod
W	3200	RPM
Total Time	35	Total time

Table 3 Parameters for Dissimilar Alloys

Properties of 304 and AA 1050 [25]

Table 4 Properties of AISI 304 and AA 6061-T6

Material	Mechanical properties				
	Strenght σ (MPa)		Elongation ε (%)		Modulus of elasticity E (GPa)
	Yield	Maximum	Maximum	Fracture	
AA1050 aluminum	44.70	78.48	21	43	59.12
AISI 304 stainless steel	354.69	643.79	48	63	177.10

5.3 Model Development for AA 6061-T6 with AA 5083

The dissimilar model which is research interest. Both aluminum alloys are used in different oil field rigs and their combination can be used for further industrial purposes. Model was created with similar parameters for AISI 304 and AA 1050. The temperature evolution and von misses of material is gathered from the ABAQUS output model results.

Mechanical properties of the AA5083 aluminium alloy at initial state (undeformed).

Notation	Ultimate tensile strength UTS (MPa)	Yield strength YS (MPa)	Elongation to fracture ε_f (96)	Hardness HV10
AA5083	350	188	18	85

Johnson Cook model For AA 5083 ;[26]

A [MPa]	B [MPa]	C	m	n	T_m [K]	T_r [K]
137.9	216.7	0.02	0.4845	1.225	933	293

6. Simulation Results and Conclusions

The output which is considered for Simulation results is Nt11 (Nodal temperature in one axis active) to get maximum temperature evolution and von mises which should be less than allowable stress.

6.1 For AA 6061-T6

RPM(rad/sec)	Maximum temperature Result ºC	Simulation Result ºC	Error
500	400	395.6	1.11
900	550 ºC	532.6	3.26
2100	420 ºC	397.3	5.71

Table 5 Simulation Results for AA 6061-T6

The temperature evolution at 500 RPM with respect to time is shown in below graph.

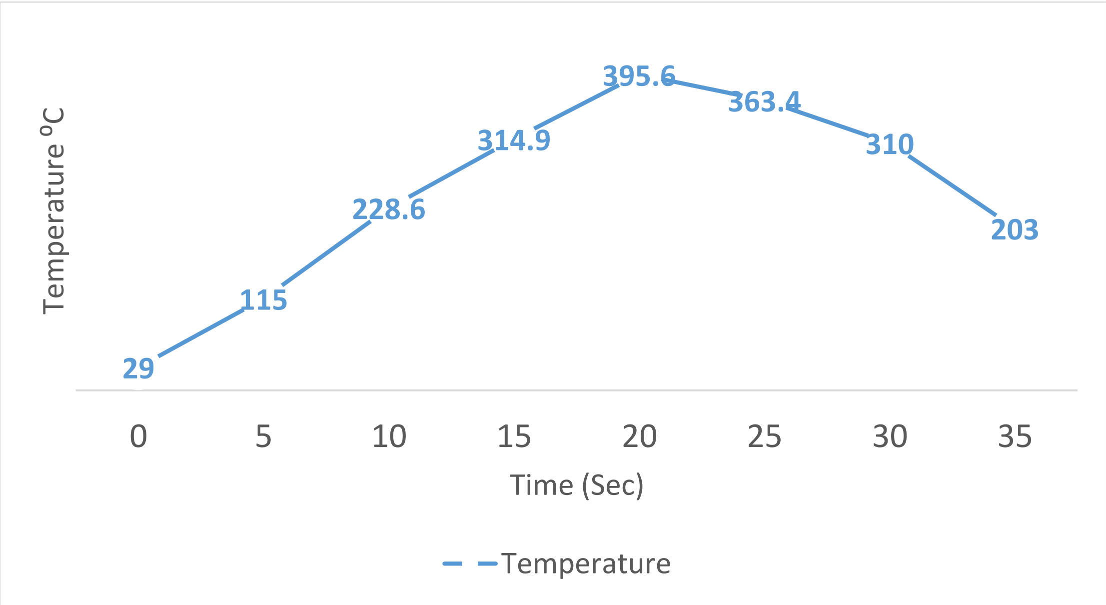


Figure 12 Temperature Vs Time

The maximum temperature increases till 18 secs and then drops when rotational speed is stopped. The cooling stage drops the temperature till 200 ^{0} C. The maximum temperature experimentally measured is 400 ⁰ C. Maximum von misses that reached in whole simulation is 38 MPa which is less than the allowable stress of the material.

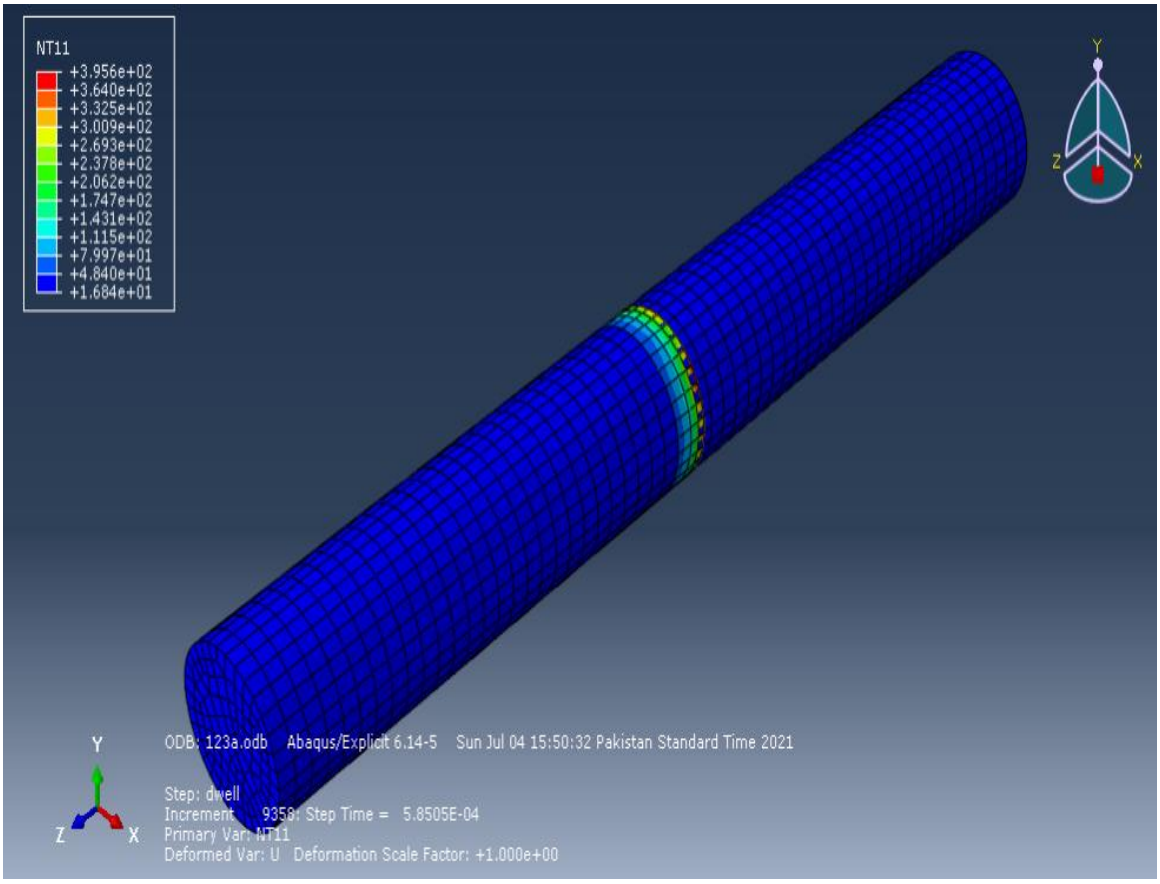


Figure 13 Model of AA 6061-T6 at 500 RPM

The temperature evolution for 900 RPM is 532.6 ⁰C while experimentally determined temperature is 550 ⁰ C, and percentage error is less than 1.2 %. The model validated and then dissimilar model is created and results are validated.

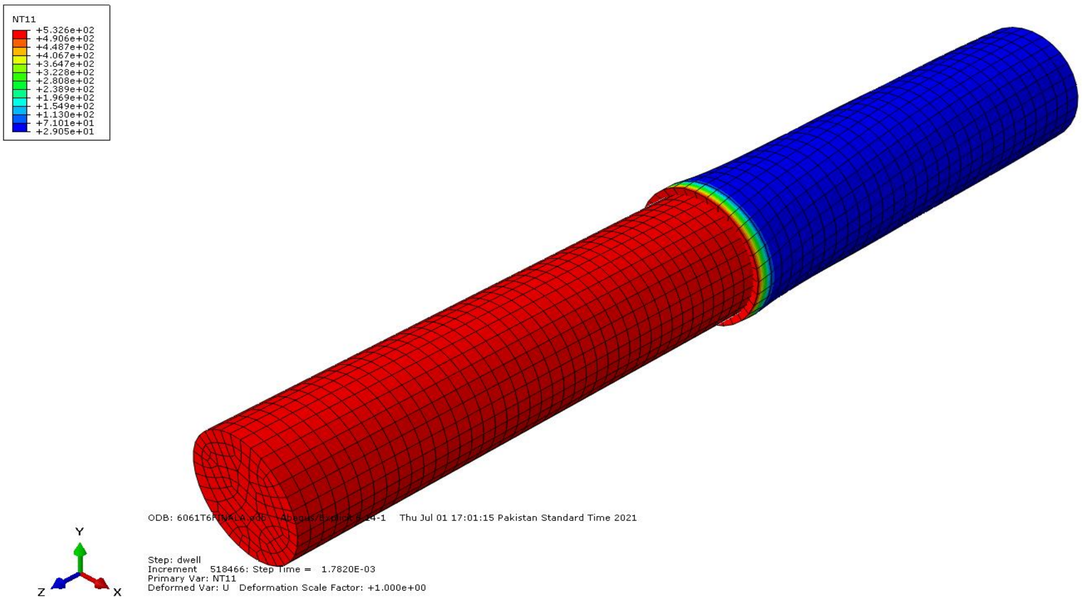


Figure 14 Simulated Result of AA 6061-T6 at 900 RPM

The temperature evolution for 2100 RPM is 397.3 ⁰C while experimentally determined temperature is 420 ⁰ C, and percentage error is less than 6 %.

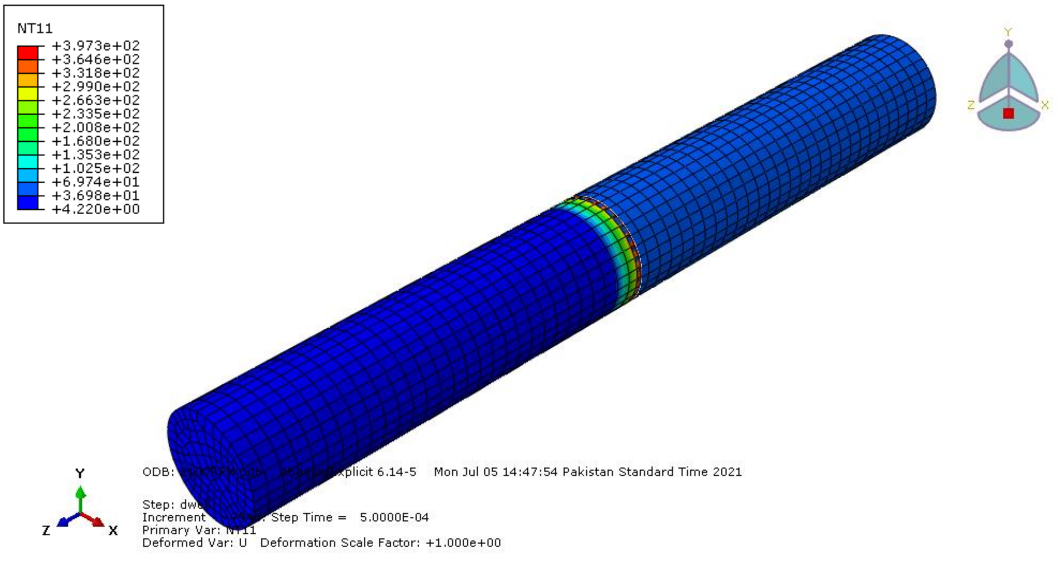


Figure 15 Simulated Result of AA 6061-T6 at 2100 RPM

6.2 Result for AA1050-AISI304

The simulated results are validated with the experimental results. The temperature reached maximum is almost 0.6 times the melting temperature of both materials. The error was less than 6 % and material mix with each other in plunge step without resistance. The material intermix region shows a deformed grained which are regular but radially aligned with each other. The higher RPM evolves maximum heat which is a good parameter for dissimilar alloys.

With comparison to COMSOL, a 2-D model was previously made and in this research a 3-D model is created which shows better results of temperature evolution. The least temperature evolution error with respect to experimental results is quite less in ABAQUS.

RPM	Maximum Temperature Result	Simulation Result	Error
3200	376 ºC	356.8 ºC	5.106 %
Material	Allowable Stress for AA 1050 and AISI 304 (MPa)	Simulation Von Mises (MPa)	Material deform or safe
AA 1050 AISI 304	44.7[10] 356.7	40.3	Safe

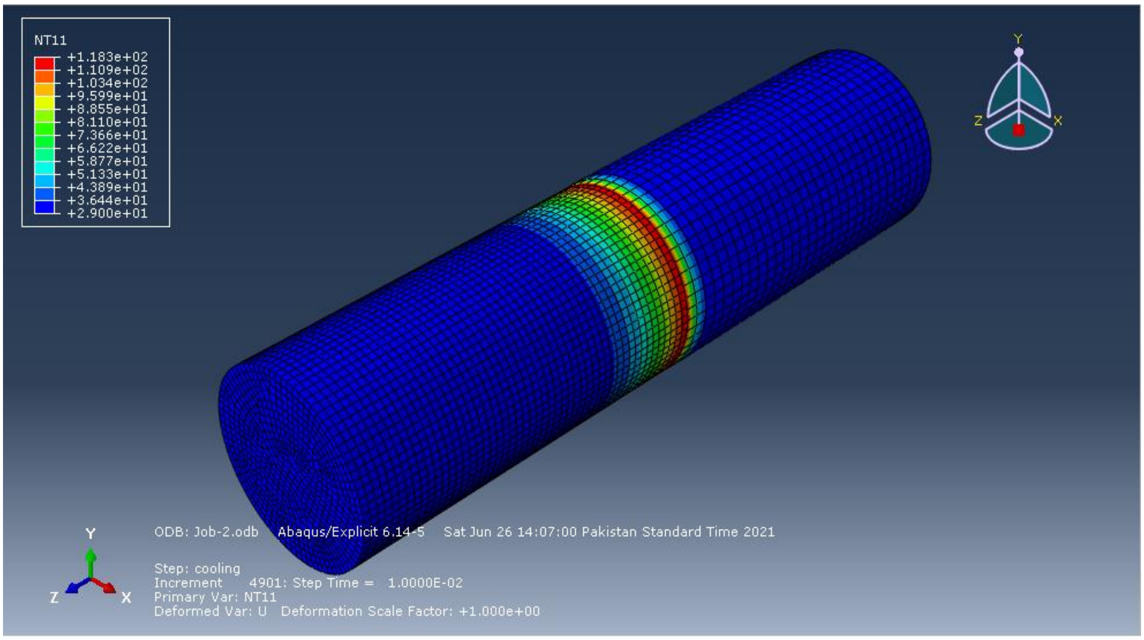


Figure 16 Simulation result of AISI 304 with AA 1050

The heat gathers at the edges and then material deform from center to external surface. Heat is seen that heat moves away from the center and origin of heat was center. The heat was not uniform along the radius of the rods.

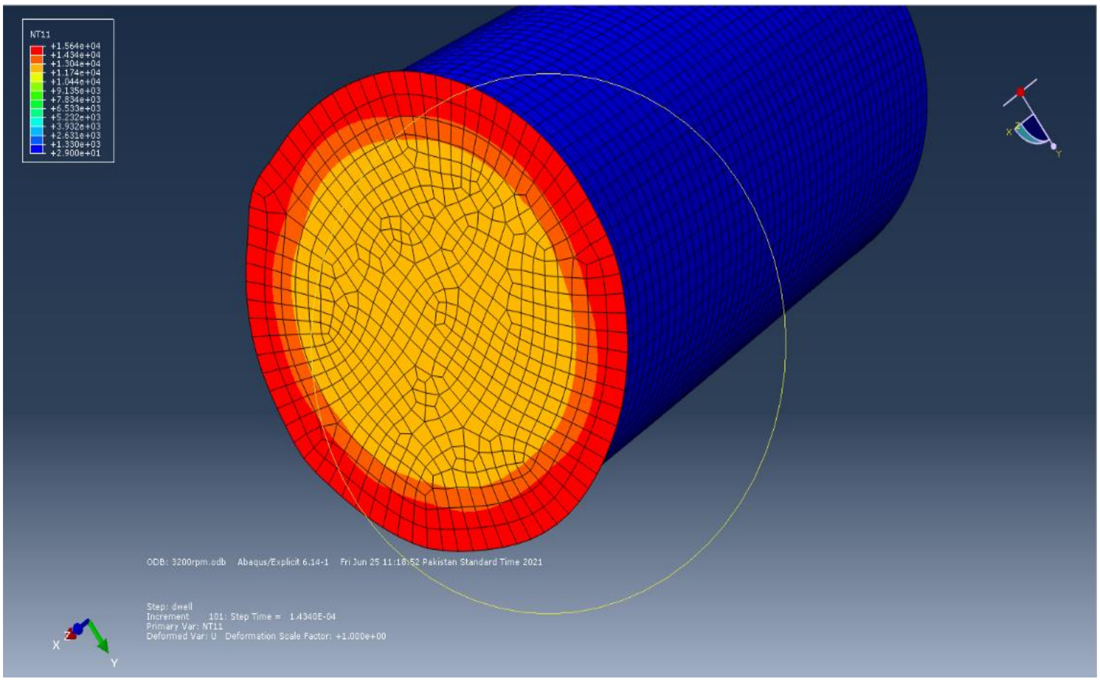


Figure 17 Heat Propagation during RFW

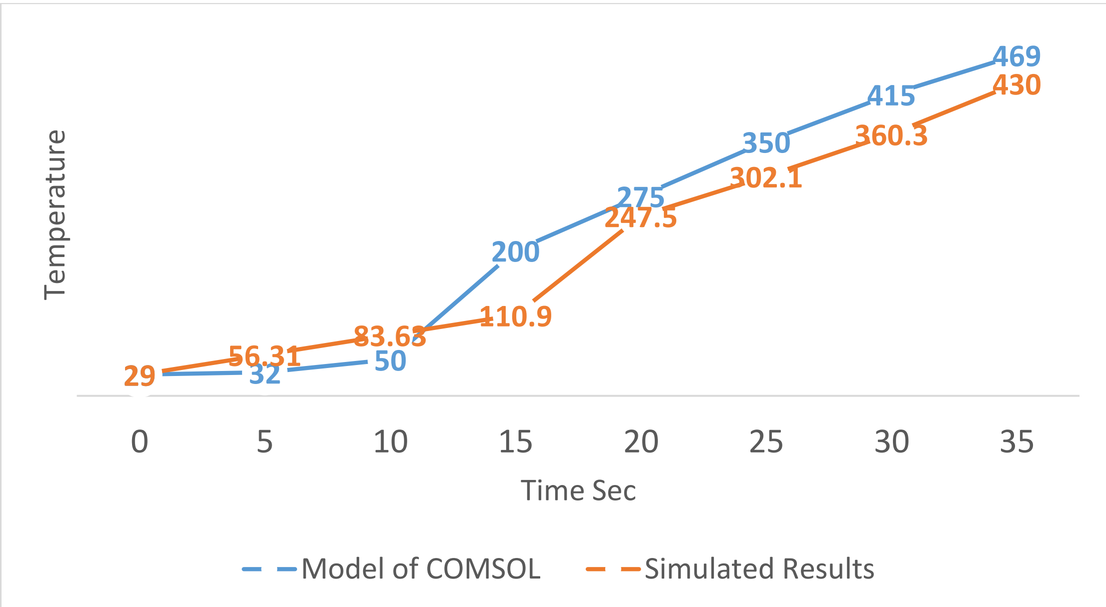


Figure 18 Comparison of Simulated Result of COMSOL and ABAQUS

6.3 Results of AA 6061-T6 with AA 5083

The weld between AA 6061-T6 and AA 5083 can be done while the evolution of temperature is about 500-550 ^{0} C. the evolution of temperature was at 19 secs which generate maximum heat. Then plunge is taken which can be shown in figure 18. Both material can experimentally have welded together at 20 sec friction time. Temperature that reached to the melting point ranges from 0.8-0.9 of the melting temperature of both materials. Material failure is also determined using von mises and stress is less than the allowable stress of both materials. Maximum Temperature Rise: 538.6 ^{0} C and Von Mises: 37.97GPa < 241 MPa (AA 6061-T6) < 228 MPa (AA 5083).

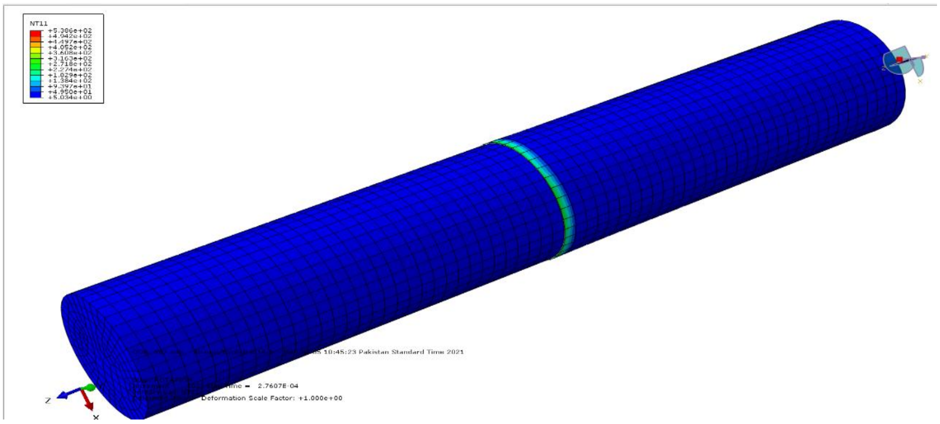


Figure 19 Temperature Result of AA6061-T6 with AA 5083

7. Future work

In future this model can be used for temperature evolution at particular time. This model is created in langragian approach used in ABAQUS. In this deformation cannot seen in this simulation. If deformation has to be consider in simulation, then Coupled Eulerian langragian Approach can be used in ABAQUS software. In this research rotational speed has been taken in to consideration, while other parameters effect can also be seen in this ABAQUS software. Output results that are taken in this research are Von misses and Temperature evolution with respect to time. Other output like, strain, maximum energy absorbed, linear strain, maximum deflection etc. can also be used for further results betterment.

References

[1] P. Rombaut, W. De Waele, and K. Faes, “Friction welding of steel to ceramic,” *Sustain. Constr. Des.*, vol. 2, no. 3, pp. 448–457, 2011.

[2] A. B. Dawood, S. I. Butt, G. Hussain, M. A. Siddiqui, A. Maqsood, and F. Zhang, “Thermal model of rotary friction welding for similar and dissimilar metals,” *Metals (Basel).*, vol. 7, no. 6, 2017, doi: 10.3390/met7060224.

[3] M. Maalekian, “Friction welding - Critical assessment of literature,” *Sci. Technol. Weld. Join.*, vol. 12, no. 8, pp. 738–759, 2007, doi: 10.1179/174329307X249333.

[4] U. Raab, S. Levin, L. Wagner, and C. Heinze, “Orbital friction welding as an alternative process for blisk manufacturing,” *J. Mater. Process. Technol.*, vol. 215, no. 1, pp. 189–192, 2015, doi: 10.1016/j.jmatprotec.2014.06.019.

[5] M. Sahin, “Joining of stainless-steel and aluminium materials by friction welding,” *Int. J. Adv. Manuf. Technol.*, vol. 41, no. 5–6, pp. 487–497, 2009, doi: 10.1007/s00170-008-1492-7.

[6] WANG KK and NAGAPPAN P, “Transient Temperature Distribution in Inertia Welding of Steels,” *Weld J*, vol. 49, no. 9, pp. 419–426, 1970.

[7] S. Fukumoto, H. Tsubakino, K. Okita, M. Aritoshi, and T. Tomita, “Friction welding process of 5052 aluminium alloy to 304 stainless steel,” *Mater. Sci. Technol.*, vol. 15, no. 9, pp. 1080–1086, 1999, doi: 10.1179/026708399101506805.

[8] M. Trancossi, A. Dumas, and R. Emilia, “Rotary Friction Welding Thermal Prediction Model,” no. January 2016, 2011, doi: 10.4271/2011-01-2723.

[9] M. KIMURA, H. INOUE, M. KUSAKA, K. KAIZU, and A. FUJI, “Analysis Method of Friction Torque and Weld Interface Temperature during Friction Process of Steel Friction Welding,” *J. Solid Mech. Mater. Eng.*, vol. 4, no. 3, pp. 401–413, 2010, doi: 10.1299/jmmp.4.401.

[10] E. P. Alves, F. P. Neto, C. Y. An, and E. C. da Silva, “Experimental determination of temperature during rotary friction welding of AA1050 aluminum with AISI 304 stainless steel,” *J. Aerosp. Technol. Manag.*, vol. 4, no. 1, pp. 61–68, 2012, doi: 10.5028/jatm.2012.04013211.

[11] E. P. Alves, F. P. Neto, and C. Y. An, “Welding of AA1050 aluminum with AISI 304 stainless steel by rotary friction welding process,” *J. Aerosp. Technol. Manag.*, vol. 2, no. 3, pp. 301–306, 2010, doi: 10.5028/jatm.2010.02037110.

[12] H. Seli, M. Awang, A. I. M. Ismail, E. Rachman, and Z. A. Ahmad, “Evaluation of properties and FEM model of the friction welded mild steel-Al6061-alumina,” *Mater. Res.*, vol. 16, no. 2, pp. 453–467, 2013, doi: 10.1590/S1516-14392012005000178.

[13] M. A. Tashkandi, “Effect of Friction Time on the Mechanical and Microstructural Properties of AA6061 Joints by Continuous Drive Friction Welding,” vol. 10, no. 3, pp. 5596–5602, 2020.

[14] W. Li, S. Shi, F. Wang, Z. Zhang, T. Ma, and J. Li, “Numerical simulation of friction welding processes based on ABAQUS environment,” *J. Eng. Sci. Technol. Rev.*, vol. 5, no. 3, pp. 10–19, 2012, doi: 10.25103/jestr.053.03.

[15] T. C. Nguyen and D. C. Weckman, “A thermal and microstructure evolution model of direct-drive friction welding of plain carbon steel,” *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.*, vol. 37, no. 2, pp. 275–292, 2006, doi: 10.1007/BF02693157.

[16] M. Maalekian, E. Kozeschnik, H. P. Brantner, and H. Cerjak, “Comparative analysis of heat generation in friction welding of steel bars,” *Acta Mater.*, vol. 56, no. 12, pp. 2843–2855, 2008, doi: 10.1016/j.actamat.2008.02.016.

[17] A. Can, M. Sahin, and M. Kucuk, “Modelling of Friction Welding,” *Unitech ’10*, pp. 135–142, 2010, [Online]. Available: http://www.singipedia.com/attachment.php?attachmentid=1872&d=1295634535.

[18] S. Rn and S. Surendran, “Friction Welding to Join Dissimilar Metals,” *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 7, pp. 200–210, 2012.

[19] Fitria, *済無No Title No Title*, vol. 53, no. 9. 2013.

[20] X. Li, J. Li, Z. Liao, F. Jin, J. Xiong, and F. Zhang, “Effect of rotation speed on friction behavior and radially non-uniform local mechanical properties of AA6061-T6 rotary friction welded joint,” *J. Adhes. Sci. Technol.*, vol. 32, no. 18, pp. 1987–2006, 2018, doi: 10.1080/01694243.2018.1458771.

[21] J. Strength, “Effect of Mechanical Properties and Microstructural Characteristics of Friction Welded Austenitic Stainless Steel Joints,” *Aust. J. Basic Appl. Sci.*, vol. 9, no. August, pp. 267–276, 2015.

[22] A. Łukaszewicz, “Nonlinear Numerical Model of Friction Heating during Rotary Friction Welding,” *J. Frict. Wear*, vol. 39, no. 6, pp. 476–482, 2018, doi: 10.3103/S1068366618060089.

[23] P. Geng, G. Qin, and J. Zhou, “Numerical and experimental investigation on friction welding of austenite stainless steel and middle carbon steel,” *J. Manuf. Process.*, vol. 47, no. July, pp. 83–97, 2019, doi: 10.1016/j.jmapro.2019.09.016.

[24] W. Li and F. Wang, “Modeling of continuous drive friction welding of mild steel,” *Mater. Sci. Eng. A*, vol. 528, no. 18, pp. 5921–5926, 2011, doi: 10.1016/j.msea.2011.04.001.

[25] K. Krishnaprasad, C. S. Sumesh, and A. Ramesh, “Numerical modeling and multi objective optimization of face milling of AISI 304 steel,” *J. Appl. Comput. Mech.*, vol. 5, no. 4, pp. 749–762, 2019, doi: 10.22055/JACM.2019.27528.1414.

[26] E. E. M. Kishta, F. H. Abed, and B. M. Darras, “Nonlinear Finite Element Simulation of Friction Stir Processing of Marine Grade 5083 Aluminum Alloy,” pp. 313–328, 2014.