COMSOL MODELING

OF

ROTARY FRICTION WELDING

FOR

SIMILAR AND DISSIMILAR METALS

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Dedicated to

My Parents

They have been a source of motivation for me.

Hoping to make them proud, one day.

Insha Allah

Acknowledgement

In the name of Allah, the Most Gracious, the Most Merciful.

Man gets whatever he strives for. And this path of intellect and research cannot be travelled alone. It requires a continuous struggle and support from teachers, friends and family. I'm lucky enough to have a lot of people supporting me throughout this struggle.

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Executive Summary

The process of welding is being extensively used in the industry and nowadays Friction welding is of great importance because it doesn't use filler materials and the joint obtained, has excellent properties.

Mathematical modeling of different processes has been always of great interest. And in case of Friction welding a number of scientists have worked on obtaining the temperature plot of the welding joint. Comparisons are made in between the experimental values and the model plots.

This research is about the use of a new property for the temperature estimation in modeling of Rotary Friction Welding Process. Previously the mathematical models that have been developed used the techniques of constant friction and slip-stick friction.

For the first time, a combined model for the similar and dissimilar materials has been presented, with an introduction of the effects of phase change property of the materials. The model was made on COMSOL and thermal, along with the structural modules were used to plot the temperature curve. The curve for welding of both similar and dissimilar metals was compared with that of practical curves already obtained and a significant improvement was seen.

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1. Introduction

Welding is the technique in fabrication that being used for joining of metals and plastics. The main principle of this technique is the fusion of material by using heat generated by different methods depending upon the type of welding being used[1].

Welding technique is known to humans since 1000 BC and it was a main thing to join metals for making weapons such as swords and shield.

With the advent of technology the process improved to the generation of heat by using electricity. This heat was then used to melt the metal for its fusion. Electric welding process is believed to be used in 1782 in Germany. However majority of the references point to late nineteenth century for the development of electric arc welding process.

A brief history of welding process is shown in the figure below.

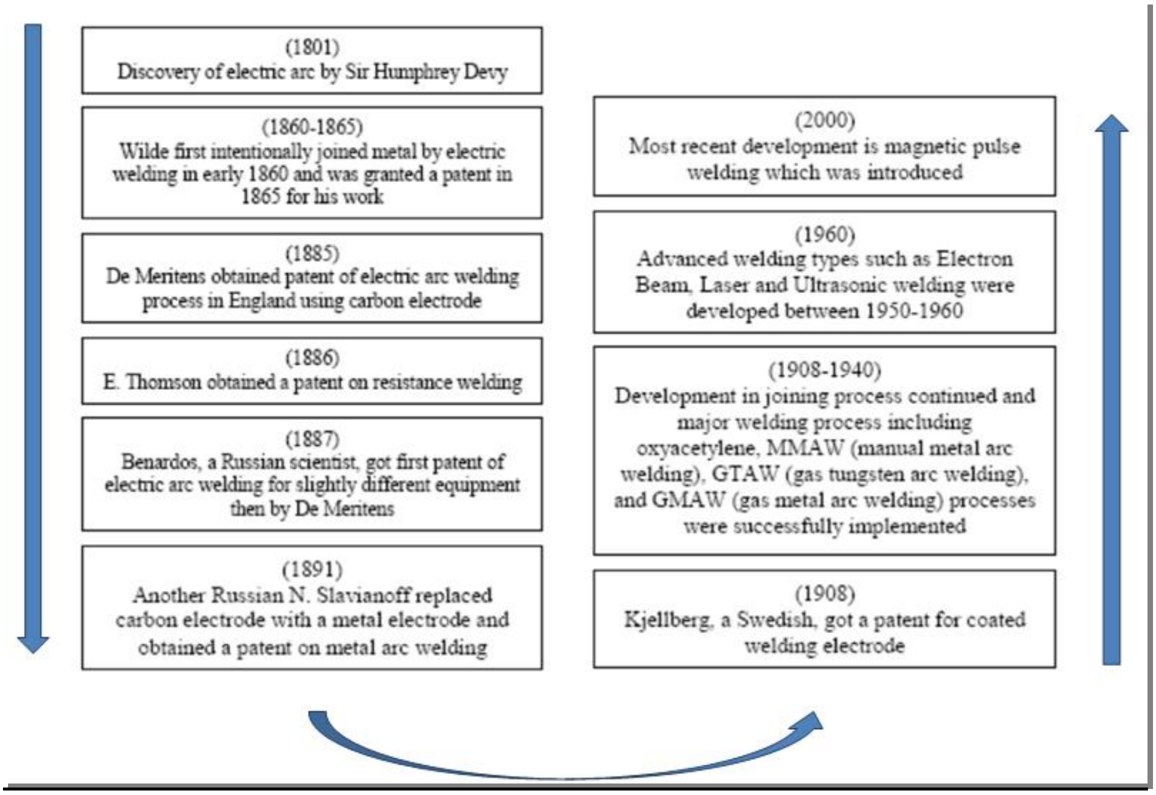


Figure 1: History of Welding

1.1 Types of Welding

The welding technology is mainly divided into two categories.

1.1.1 Heat Welding

Heat welding uses heat to weld two metals together. It is the most common technology being used in industry.

1.1.2 Pressure Welding

In Pressure Welding, pressure is applied to the weld two pieces or metals together.

1.1.3 Friction Welding

In Friction Welding, the heat generated by the force of friction is used by to weld to similar/dissimilar metals.

These three categories are further divided into subcategories.

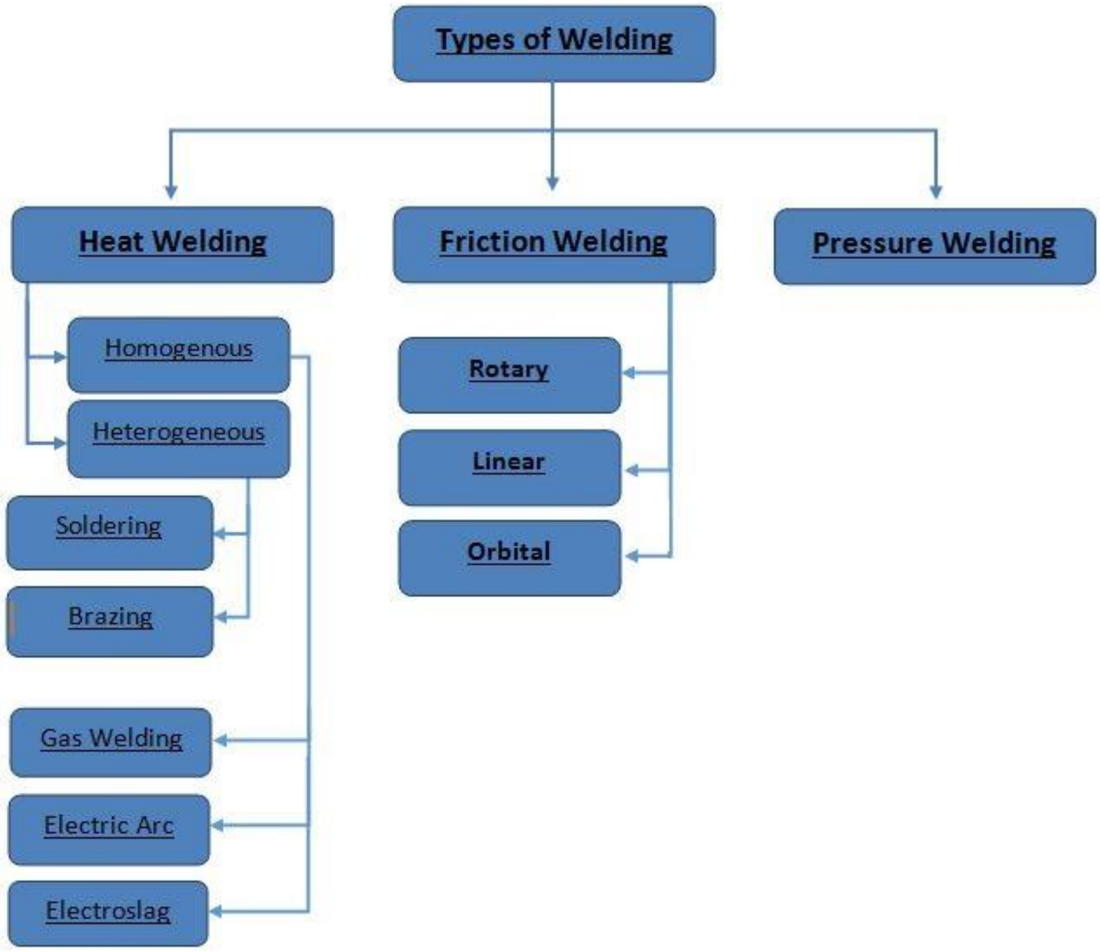


Figure 2: Types of Welding

1.2 Friction Welding

Friction welding definition in American Welding Society is as follow[2].

'Friction welding is a solid-state joining process that produces coalescence of materials under compressive force contact of work pieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. Under normal conditions, the faying surfaces do not melt. Filler metal, flux, and shielding gas are not required with this process'.

Friction Welding is categorized as solid state welding process characterizing high quality weld joints between similar and dissimilar metals. The weld is made by using heat, generated from friction by rubbing two metal pieces. The heat generated by these friction metal pieces on both sides of the interface and this molten metal initiates the welding procedure. The pressure on the static metal piece is increased to reach the fusing temperature. Once when enough temperature is reached the rotation of the piece is stopped and the static piece is forced with a high pressure to fuse and strengthen the weld.

The main apparatus needed for this type of welding is basically a machine (lathe type) that rotates one piece at certain speed and the other static piece with a hydraulic assembly is pushed against that rotating part to produce friction and create weld bond.

Fig 1 shows the illustration of whole friction welding process.

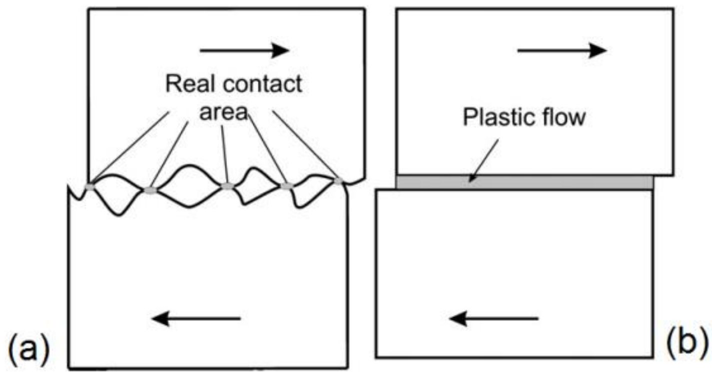


Figure 3: Illustration of interfacial conditions during friction welding (a) Dry Friction; (b) Plastic Flow

1.2.1 Types of Friction Welding

There are three process variants in Friction Welding and these are as under

- Rotary Friction Welding
- Linear Friction Welding
- Orbital Friction Welding

These three processes are shown in the figure 2 shown below. Among the three of the under mentioned processes, Rotary Friction Welding Process is the oldest and most used process because of the simplicity of the used apparatus.

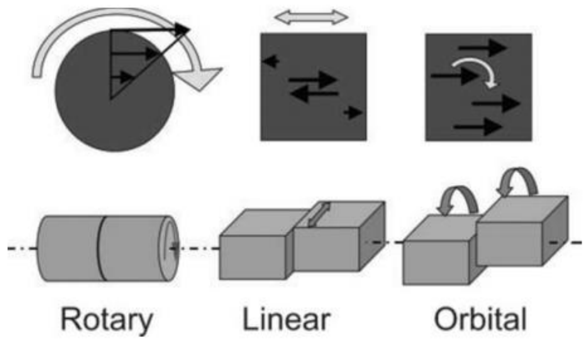


Figure 4: Three variants of friction welding

The linear process of friction welding uses the relative motion of the two work pieces under pressure in a vibratory motion through small and fixed amplitude in parallel to the joint of the welding.

The two parts to be joined make an orbital motion around their longitudinal axis in a constant speed in orbital friction welding.

If these three methods of friction welding are compared it is concluded that the rotary method of friction welding is the simplest one. But it has an inherent limitation, i-e it cannot be used for the welding of parts with non-circular cross section.

Another main disadvantage of Rotary friction welding is the non-uniform thickness of heat affected zone (HAZ). This disadvantage is because of the generation of non-uniform heat generation rate at the interface because of the linear change in rotational speed over the radial distance from the center.

The Rotational Friction welding is further divided into two main categories, depending upon the drive of the rotational part.

- Inertia Drive
- Continuous/Direct Drive

Inertia drive uses the stored kinetic energy in the flywheel to rotate one of the work pieces.

Continuous or Direct drive uses the continuous source of rotation to be converted into the heat.

1.2.2 Advantages of Friction Welding

A large variety of materials can be joined by using Friction welding. It can also be used to join many combinations of dissimilar metals in addition to similar metals[3].

Another advantage of Friction welding is that, in this process mechanical energy is directly converted into heat energy resulting in a large temperature gradient. This large temperature gradient results in a very small heat affected zone (HAZ). Due to minimized HAZ the distortion in the joined metals is very small.

The process is highly energy efficient and results in short joining times, due to which the process results in high productivity.

This welding process is defined as solid state welding process which mean that the defects associated with the other welding process i-e porosities and slag contamination in melting and solidification, are not observed in this process.

Another advantage in this process is that during burn off and then forging at high pressure, results in the removal of the slag contamination at the interface, resulting the higher weld strengths.

The joining of dissimilar metals is the main advantage of this process and it can result in to a full joint strength if right parameters are chosen for this process. This strength is the result of formation of an entirely new material at the joint interface comprising of the original two metals.

Friction welding produces an airtight weld with 100% interface. This eliminates the risks of defects associated with traditional welding processes eg. Cracks, leakages and porosity.

Friction Welding doesn’t require filler material, shielding gas or flux for it’s working. This results in a minimal cost of this process.

For this process, there is no need for joint preparation. Commonly used joints are made by saw cut work pieces. This is because, the formation of plastic material at the interface eliminates any need of joint preparation.

The process has short cycle times. This results in the possibility of automation of this process and hence reduction in the labor cost of the process.

The process doesn’t use any flux or shielding gases, and doesn’t produce any hazardous fumes or vapors. This makes the process environment friendly. This process is not at all dangerous to the operators as compared to the traditional welding process.

1.2.3 Applications of Friction Welding

Friction Welding is being used in wide range of industries including automotive, agriculture, petroleum, aerospace and electrical industries. It has a wide range of application from butt joints in shaft to engine valves and complicated jet engine parts.

Figure 5: Applications of Friction Welding

1.2.4 Stages of Friction Welding Process

There are 3 stages in Friction Welding process.

The first stage is also called heating up stage. In this stage two work pieces with a relative motion in between them are brought together under axial pressure. The temperature at the interface increases because of the friction and the applied pressure, this decreases the flow stress of the materials[4].

At next stage the material is unable to withstand the applied pressure and temperature, and it deforms plastically producing flashes. These flashes are important in the strength of the weld joints since these flashes remove slag contamination and oxides from the interface.

At the third or the forging state the rotation stops and the two work pieces are kept under high compressive force, this results in high strength weld joints.

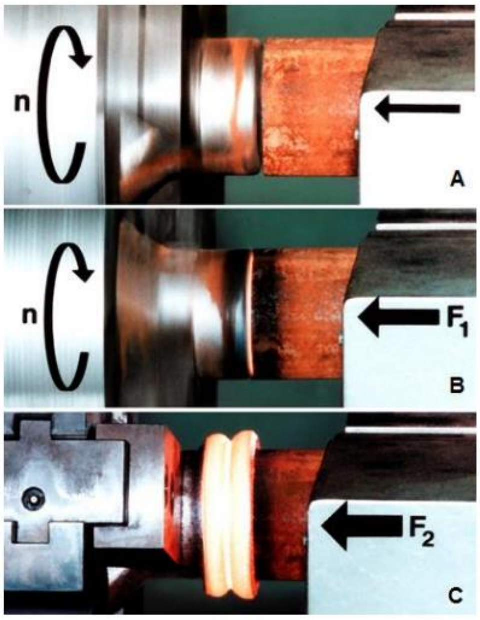


Figure 6: Three stages of Rotary Friction Welding Process

1.2.5 HAZ structure and joining mechanisms

It has been concluded that diffusion is the main phenomenon in friction welding, when the measured interface temperature and the extrapolated temperatures were measured along with metallographic studies[5].

Different researchers have demonstrated that the diffusion layer exist at the interface of the two work pieces, especially when joining dissimilar metals[6]. It has also been stated that the ease of formation of joints for dissimilar metals increases as the solubility of both the metals increases. As a consequence of this a high strength bond is made in between the dissimilar metals.

It's is an established fact that diffusion doesn't only increases the quality of the joint. It may deteriorate the joint as well. For example the joint in the joining of carbon steel or medium plain carbon steel, becomes ductile due to decarburization at the weld joint. Similarly while joining steel and aluminum, copper and titanium, the formation of inter metallic phases causes the joint to be brittle in nature. When the properties of this type of dissimilar joints were studied, it was found that the joint occurred by the mixing of the thin layer of the metal on the both sides of the weld interface.

1.2.6 Zones in Friction Welding

Contact zone:

The zone where the friction or rubbing occurs and metal fragments get transfer from surface to surface. In this zone the rotational velocity is the main parameter that controls the strain rate of the zone. This is the zone that undergoes severe plastic deformation, severe straining and the re-crystallization of the grain structures, this results in the formation of highly fine grain structure.

Fully Plasticized zone:

Grains or material in this zone doesn't participate in friction or rubbing of the material but it undergoes considerable amount of plastic deformation itself. The grains in this zone are quite fine and regularly placed due to dynamic re-crystallization and high temperature.

Partly deformed zone:

As we move away from the contact zone and the fully plasticized zone the temperature experienced by partly deformed zone is quite low and the strain rate as well. These factors result in poor re-crystallization and the microstructure becomes coarser.

Un-Deformed Zone:

The material in this phase doesn't undergo phase transformation, depending on the maximum temperature. This results in the formation of the grains in this region.

1.2.7 Friction Parameters

While joining dissimilar metals the most important thing is the selection of friction welding parameters[7].

In the process on part is held stationary and the other is rotated at certain speed while the stationary part is pushed axially with a specific force till the plastic deformation and then the rotation stops and the part is put under high pressure till the joint cools down.

The following graph shows the different parameters influencing the friction welding.

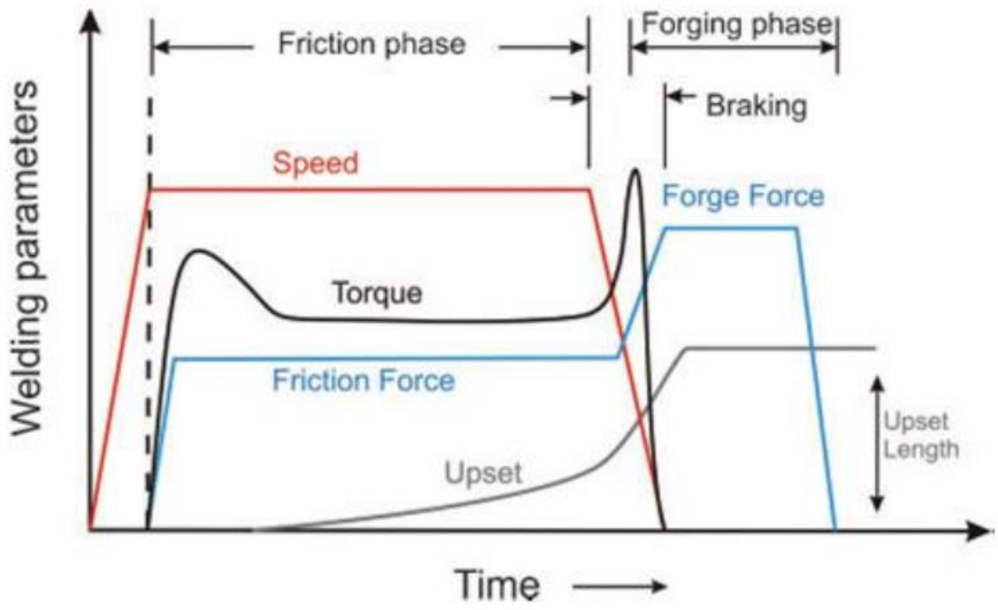


Figure 7: Variation of Welding parameters with time in direct drive friction welding

It is evident from the graph that the main parameters to be controlled in Rotary friction welding are rotational speed, axial forces and the welding time. These variables determine the heat energy that is introduced into the weld joint. This is shown in the graph above.

According to the above graph the process can be divided into 3 stages. Initially the pressure of increases rapidly to a high value as the process starts. It then decreases to the equilibrium value after some time. This rapid rise and then decrease in the pressure is due to the formation and then the breaking of interfering asperities and then the softening of the material in the plastic phase. During the second phase the friction torque somewhat remains constant. And the third phase is associated with the forging. The rotation stops. The axial forces are increased and this creates the forging effect. Due to increased axial forces the friction torque also increases and reaches a maximum value before it rapidly decreases to zero[8].

2. Literature Review

Mathematical model of a process offers insight and enables prediction of process attributes and its performance. Comparison between the mathematical model and experimental results obtained from the thermocouple has always been an area of interest.

When it comes to the modeling of the Friction Welding process, Cheng[9] made the first attempt to model this process by using Numerical Methods. In his work he used used measured power to define a hypothetical heat flux uniformly distributed on the friction interface and used this in his model, and then made a comparison. The similar approach has been used by NGUYEN[10]. Maalekian[2, 11] has presented the comparative analysis of heat generation and later on temperature prediction for friction welding of steels. He has used DEFORM for the verification of his results and has used the temperature dependent properties from the database of DEFORM. The comparison made was between, temperature profiles obtained by using 4 different methods: constant friction coefficient method, slip-stick methods, power method, and inverse method. The power method and the inverse method showed excellent results because they were based on the experimental results. Moreover, inverse method was important to predict temperature on the friction interface, because that temperature cannot be measured directly. Ahmet CAN[12] has also modeled this process and has established the dependence of temperature profiles on different work piece parameters.

A number of test were carried out to check the effect of varying pressure and time on the strength of joint of dissimilar metals by Subhavardhan[13].

The effects on the strength of the joints was observed by tensile test

- By keeping upset pressure and upset time constant
- By increasing friction pressure. Strength increased to a certain point and then decreased.
- By increasing friction time. Strength increased to a certain point and then decreased.

The decrease in strength of the joint with the increased friction time was because of the formation of the inter metallic impurities formation at the joint interface.

The joint had considerable strength but this strength was less than the tensile strength of AA6082 used for this purpose.

Vickers micro hardness test was performed to check the hardness and the hardness decreased as we propagated from steel to the aluminum side. Since Al was already work hardened absorbed heat from the process and became relatively soft.

Fatigue testing was also carried out for the joints of dissimilar metals and as a result of this test the material failed after repeated stresses. Hence it was established that these joints are not suitable for fatigue loading.

Charpy test was performed and it was established that the amount of energy increased with the increase of the pressure and then after reaching a certain point decreased.

SEM and EDX analysis showed the formation of inter metallic compounds at the joint interface. And these inter metallic compounds were responsible for degrading the quality and strength of the joint.

The limitation in the models presented by NGUYEN[10] was the use of average or constant values for the temperature dependent properties for example, density, thermal conductivity and specific heat. Maalekian[11] analyzed that the methods based on the experimental data produced exceptional results, but the profiles generated from the mathematical model were not reliable at all. In other words, he only established this fact, and nothing was done in improving the results from the mathematical model. Ahmet's work[12] was somehow restricted to work piece parameters for example, dependence of temperature on the radius of the work piece.

In this research, first of all the temperature profile was to be developed for the complete duration of the process, instead of its dependence on a particular parameter. Secondly, COMSOL material library helped us in using the temperature dependent properties of the materials used, this way we didn't have to use constant values for such properties. Thirdly, using 'heat transfer in solids' and 'mechanics structural' modules in COMSOL simultaneously, helped us in developing better temperature profiles, and this is explained later.

3. Theoretical Background

When the phase change occurs, the heat supplied to the metal, doesn't increase the temperature, but is used to change the molecular form[14, 15].

Friction welding being a multi-physics phenomenon cannot be just expressed as a model of a single physical process. For this purpose the modules of **Solid Mechanics** and **Heat transfer in solids** were used.

In Solid Mechanics the contact pair was defined as a frictional contact with a static frictional co-efficient of 0.61 between Aluminum and steel. [16]

Heat Transfer in Solids determines the Pair Thermal Contact uses the following equation as used by Ahmet Can[12] for the calculation of heat flux.

$$\dot{q} = \pi . \omega . P . r \qquad (W/m^2) \qquad (1)$$

In this equation **ω** is the rotational speed of the work piece, **P** is the pressure being applied, and **r** is the radius of the work piece.

The Heat Transfer Module in COMSOL uses **Apparent Heat Capacity Method**[17] for the modeling of phase change phenomenon. In this method an additional term is added to heat capacity i-e Latent Heat.

Heat transfer equation along with a convective term is as follow.

$$\rho C_p .\ \nabla T = \nabla.(k. \nabla T) \qquad (2)$$

This Apparent Heat Capacity Method uses a phase transition function **α(T)**, and while the implementation of phase change the interval $\Delta T_{1\to 2}$ is to be defined during which a smooth transition occurs. During this interval, the material has mixed properties of liquid and solid form.

The figure below shows an example of Phase Transition Function for phase change of iron.

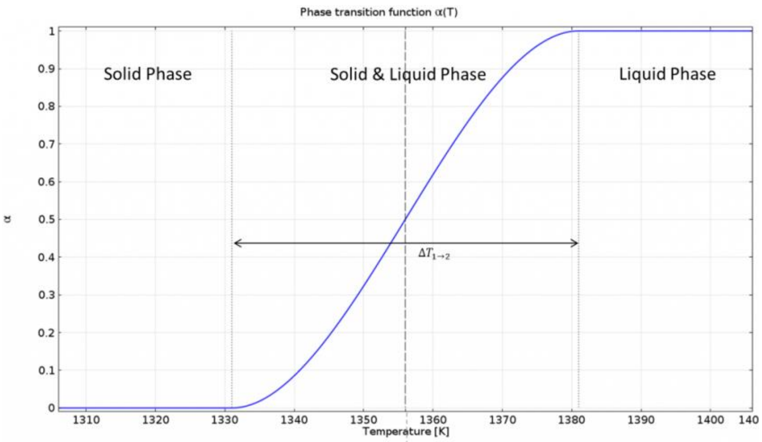


Figure 8 : Phase Transition Function

The transition function **α(T)** changes its value from 0 to 1 during this whole process of transition. **α(T)=0** for pure solid and for pure liquid **α(T)=1**. Although in COMSOL, the material properties for solid and liquid phases are defined separately. But during the phase change an equation depending on the transition function is used to find the combined properties for the transition phase[18]. For the phase change, Heat Capacity is as follow.

$$C_p = C_{p,\,solid} \,.\, (1-\alpha(T)) + C_{p,\,liquid} \,.\, \alpha(T) \qquad (3)$$

The same process is used for the finding other temperature dependent parameters like density and thermal conductivity. The equation caters the change of properties during the phase transition.

When Apparent Heat Capacity Method is used an additional term for Latent Heat is added to the above equation.

$$C_p = C_{p,\,solid} \,.\, (1-\alpha(T)) + C_{p,\,liquid} \,.\, \alpha(T) + L_{1\text{->}2}\frac{d\alpha}{dT} \qquad (4)$$

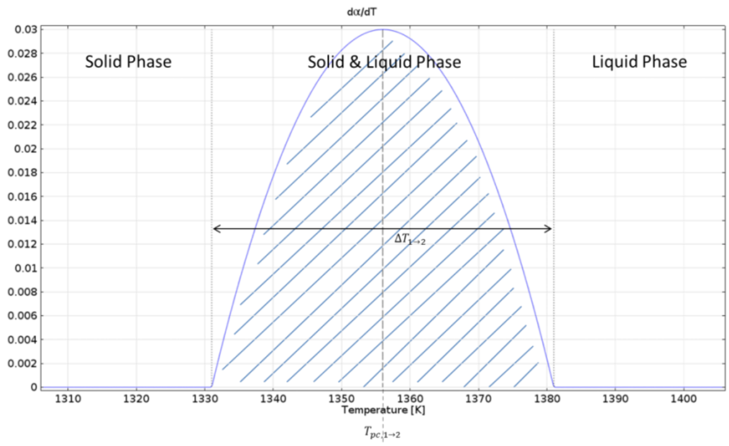


Figure 9: Plot Example for dα/dT

The integration of this function during the interval **$\Delta T_{1\text{->}2}$** gives us the total of 1, and when this function is multiplied to $L_{1\text{->}2}$ gives us the amount of Latent Heat that is released over **$\Delta T_{1\text{->}2}$.**

4. COMSOL Modeling

4.1 Finite Element Modeling:

First of all, the software for the modeling of rotary friction welding as multi-physics phenomenon was to be selected. For this purpose COMSOL, because of its user friendly interface and its diversity, was to be worked on.

Later on a 2D axisymmetric feature of COMSOL was used for the modeling because of large simulation time needed for 3D simulations.

The meshing in COMSOL was calibrated to be for General Physics and predefined finer mesh size was selected with the maximum element size of 0.0078m and minimum element size of 2.63E-5m. Since it is an axisymmetric problem, the element type selected was free triangular. The meshed geometry of both the rods is shown below.

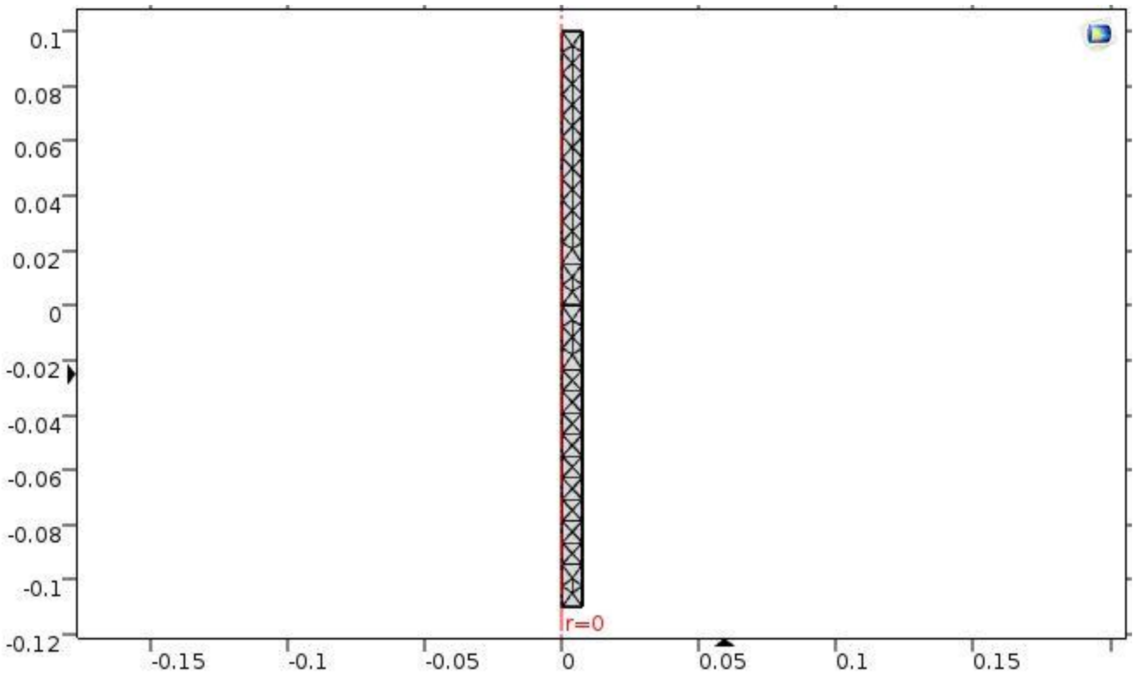


Figure 10: Geometry and its meshing

COMSOL provides a probe tool that facilitates the measurement of different parameters throughout the course of simulation. So for the measurement of temperature at the core of the interface of the two rods a probe was places at (0,0) for the simulation of similar metals i-e steels and at (0,0.0012) for dissimilar metals i-e steel and aluminum. As the simulation was run, the temperature probe started plotting the temperature with respect to time.

4.2 *For dissimilar metals*

- **Parameters**

  Parameters were to be defined as the first step of the modeling. And for this purpose the parameters defined for the experimental determination of temperature, for the rotary friction welding of the dissimilar metals as used by Alves et. al. [19] were used.

Name	Value	Description
t1	60	Friction Time
P1	2.10E+06	Friction Pressure
P2	1.40E+06	Forging Pressure
rad	7.4[mm]	Radius of the rods
length_Al	100[mm]	Length of Al rod
length_st	110[mm]	Length of Steel rod
w	3200	RPM
t_ap	10	Approach Time
t_total	120	Total Time

Table 1: Parameters defined for Dissimilar Metals Welding

The table and the graph below, shows how RPM during the whole process changes. A piecewise function shown below, was developed that used parameter of friction time to define the time period for which the RPM were to be kept 3200. It can be seen in the function and plot that as soon as the friction time ends i-e 60 seconds, the RPM decreases rapidly to zero.

Start	End	Function
0	t1	W
t1	t1+3	w-((t-t1)*(w/3))
t1+3	t2	0

Table 2: Piecewise function of Omega, for Dissimilar Metals Welding

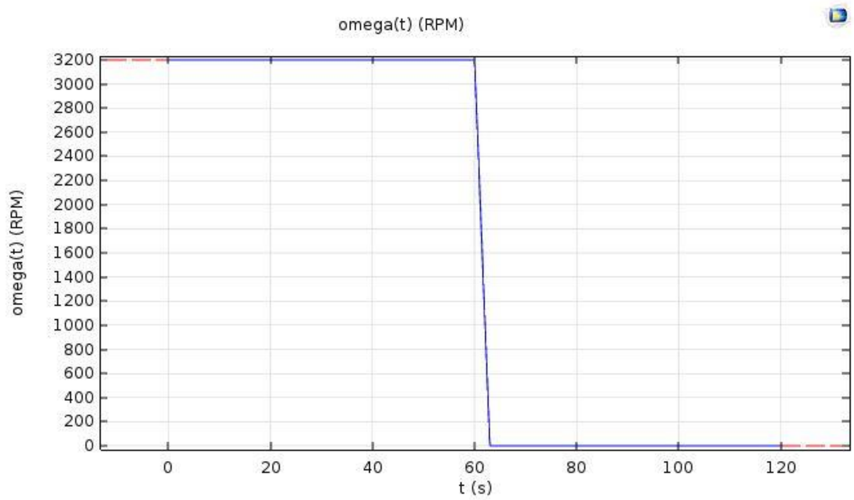


Figure 11: Omega for welding of dissimilar metals

This table and plot below shows how pressure acts on the two work pieces. Piecewise function was developed and is shown below. From **0** to **t_ap** is the approach time and after that the pressure rises when the two work pieces are in contact. Then a pressure **P1** i-e **2.1E6 Pa** is applied. This is the friction phase. When the friction phase is over the forging phase starts and the pressure drops from **P1** to **P2** i-e **1.4E6**.

Start	End	Function
0	t_ap	0
t_ap	t_ap+1	(t-t_ap)*P1
t_ap+1	t1	P1
t1	t1+1	P1-((t-t1)*(P1-P2))
t1+1	t_total	P2

Table 3: Piecewise function of Pressure for welding of dissimilar metals

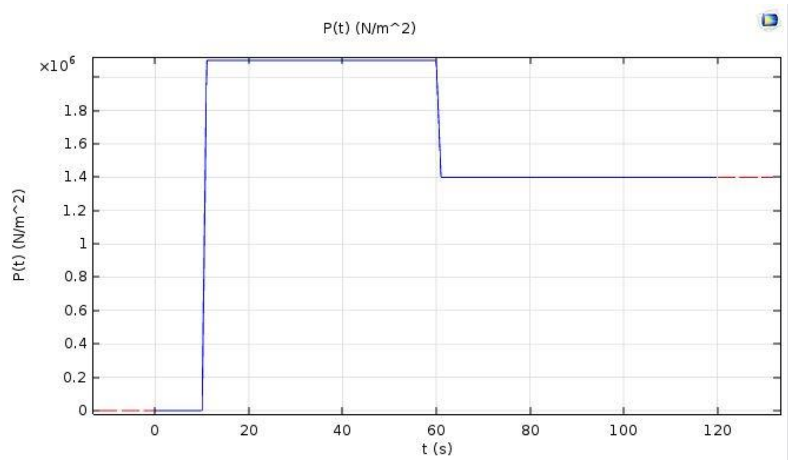


Figure 12: Pressure for the welding of dissimilar metals

All the parameters are in accordance with the experimental work carried out by Alves[19].

- **Geometry**
  Since the 2D axisymmetric feature is used, the geometry needed to be just the two rectangles with one side overlapping the axis. According to the dimensions mentioned, the diameter of the steel rods was taken to be 14.8mm and the length of steel and aluminum rods used was, 110 and 100 mm respectively.

- **Material**
  The materials were AA1050 aluminum alloy and AISI 304 austenitic steel. COMSOL material database provides the liberty of choosing a material and then all the properties of that particular material are used from the database. Our main concern was to use the temperature dependent properties such as thermal conductivity and the specific heat as these are important in temperature determination.

- **Results**

  The image below shows the temperature distribution at the instant of maximum temperature achieved. The figure clearly shows the two different materials, one with the expanded color bands is aluminum. This is because the thermal conductivity of Aluminum is far greater than that of steels. Theoretically the heat generated at the center of the rods is zero, and the maximum heat is generated at a distance 'r' from the center.

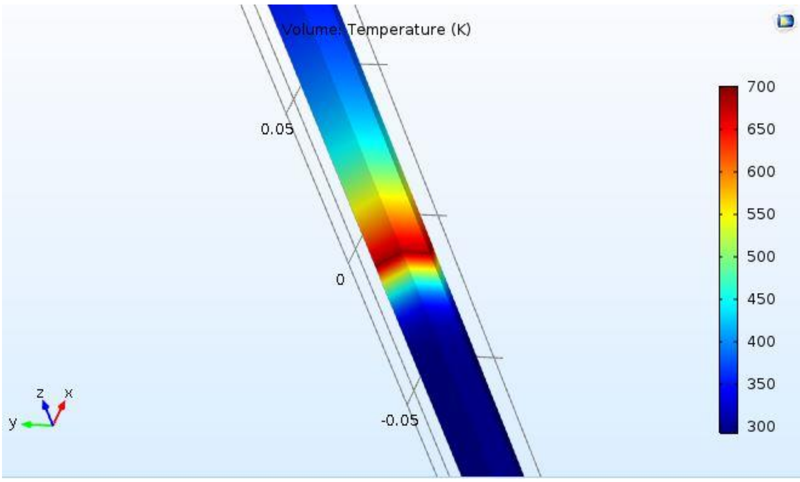


Figure 13: Temperature Distribution for Dissimilar Metals

The data extracted from the model was converted from Kelvin to Centigrade. The results of the temperature profile from mathematical model of the rotary friction welding of steel and aluminum alloy at a distance of 0.12mm from the contact surface are shown in the figure below.

The initial 10 seconds is the approach time. When the two work pieces are in contact the temperature at the interface rises abruptly. When the temperature reaches approximately 250 ◦C, the slope of the plot decreases. This is because the phase change temperature of the aluminum is taken from 0.5 to 0.6 of T_m. And during this phase the rate of change of temperature decreases. After that the temperature still rises because of the continuous application of the pressure and it reaches a maximum temperature of 460 ◦C. At this point the friction phase ends and the forging phase starts, in which the omega is reduced to zero and the pressure is changed to forging pressure. In this phase the temperature initially decreases rapidly because of the large temperature difference with the atmosphere and as the temperature of the work pieces decrease the rate of change of change of temperature also decreases.

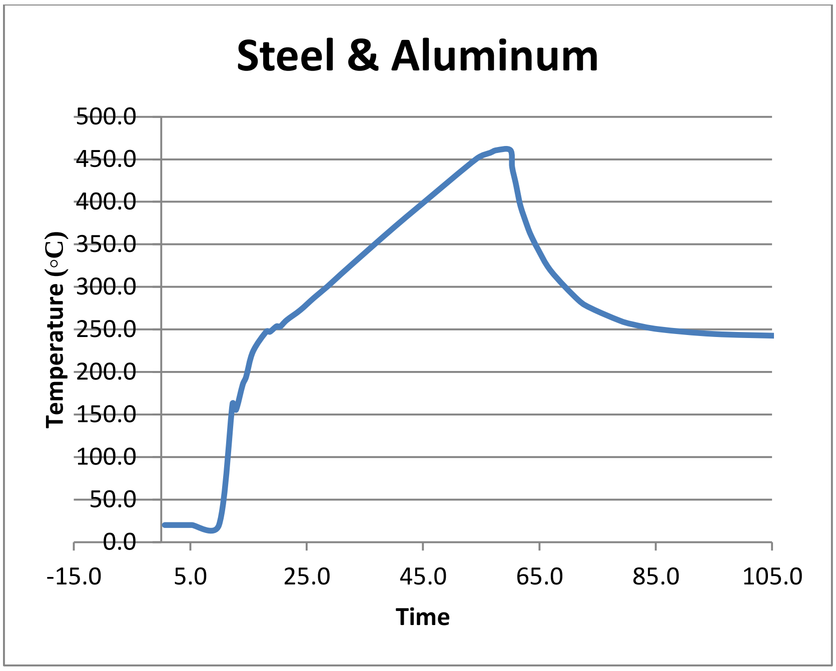


Figure 14: Temperature Profile for the Welding of Dissimilar Metals

4.3 *For Similar Metals (Steel)*

- **Parameters**
  The first step in modeling as similar to the previous model was to define parameters and the values of these parameters were to be set such as to verify the experimental result already present in literature.

Name	Value	Description
t1	3	Friction Time
P1	1.31E+07	Friction Pressure
P2	1.00E+08	Forging Pressure
Rad	7.4[mm]	Radius of the rods
length_Al	100[mm]	Length of Al rod
length_st	110[mm]	Length of Steel rod
W	1410	RPM
t_total	4	Total Time

Table 4: Parameters for the Welding of Similar Metals

The table 5 shows the Pressure changes during the whole process.

Start	End	Function
0	0.1	t*(P1/0.1)
0.1	t1	P1
t1	t1+0.1	P1+((t-t1)*(P1-P2))
t1+0.1	t_total	P2

Table 5: Piecewise function of Pressure for the Welding of Similar Metals

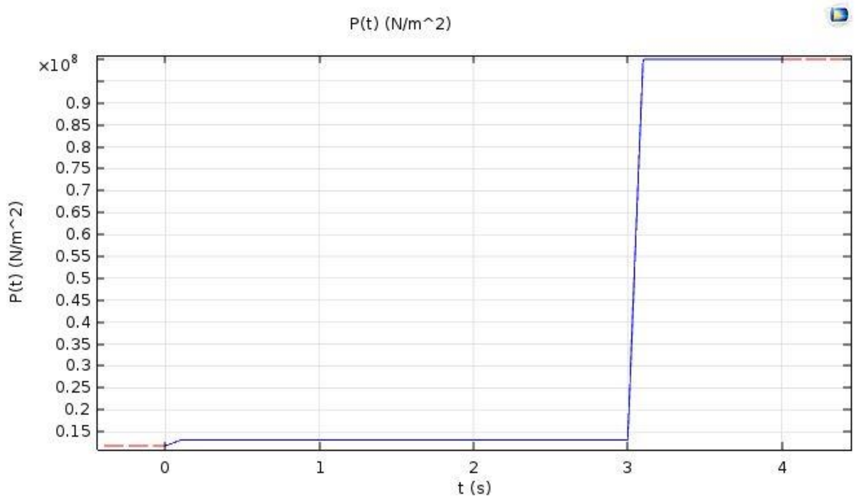


Figure 15: Pressure applied for the welding of Similar Metals

Table 6 shows the RPM of one work piece during the whole process.

Start	End	Function
0	t1	w
t1	t1+0.1	w-((t-t1)*(w/0.1))
t1+0.1	t_total	0

Table 6: Piecewise function of Omega for the welding of Similar Metals

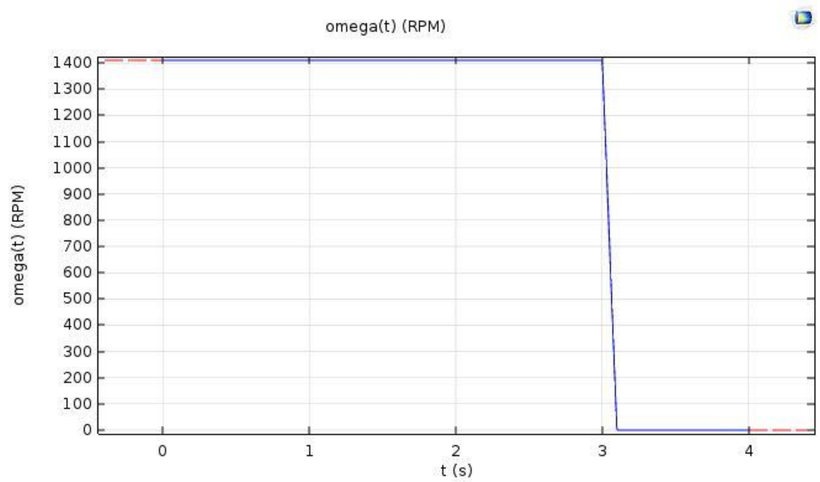


Figure 16: Omega applied for the welding of Similar Metals

- **Geometry**
  Since axisymmetric feature is used, the geometry needs to be the two rectangles with one side overlapping the axis. According to the dimensions mentioned, the diameter of the steel rods was taken to be 20mm and the length of 88mm.
- **Material**
  The material used for the modeling the friction welding process of steel is AISI 304 austenitic steel. The material was available in COMSOL materials database, and the main purpose of using this material from the database was to use the temperature dependent material properties of metals in the modeling of the process, as mentioned earlier.

- **Physics**
  The same modules have been used in the modeling of the process for steel, as they were used for dissimilar metals. The coefficient of static friction has been assigned a value of 0.7as suggested by James F. Sullivan[20]. The same equations were used for the heat flux, as used above in the dissimilar metals modeling.
- **Results**
  The following graph shows the temperature profile of the model at the interface of welding.
  As the process starts the temperature rises quickly and at about 550◦C the slopes decreases and the temperature somehow becomes constant. The phase change temperature for the steel was taken to be from 0.5 to 0.6 of T_m. At this moment the heat being generated is used to for the phase change or atomic restructuring. As the change of phase completes, the temperature rises again to a maximum value of about 1000◦C.
  At this point the friction phase end, and the pressure rises to forging pressure while the omega reduces to zero. The temperature then decreases rapidly but gradually the slope decreases.

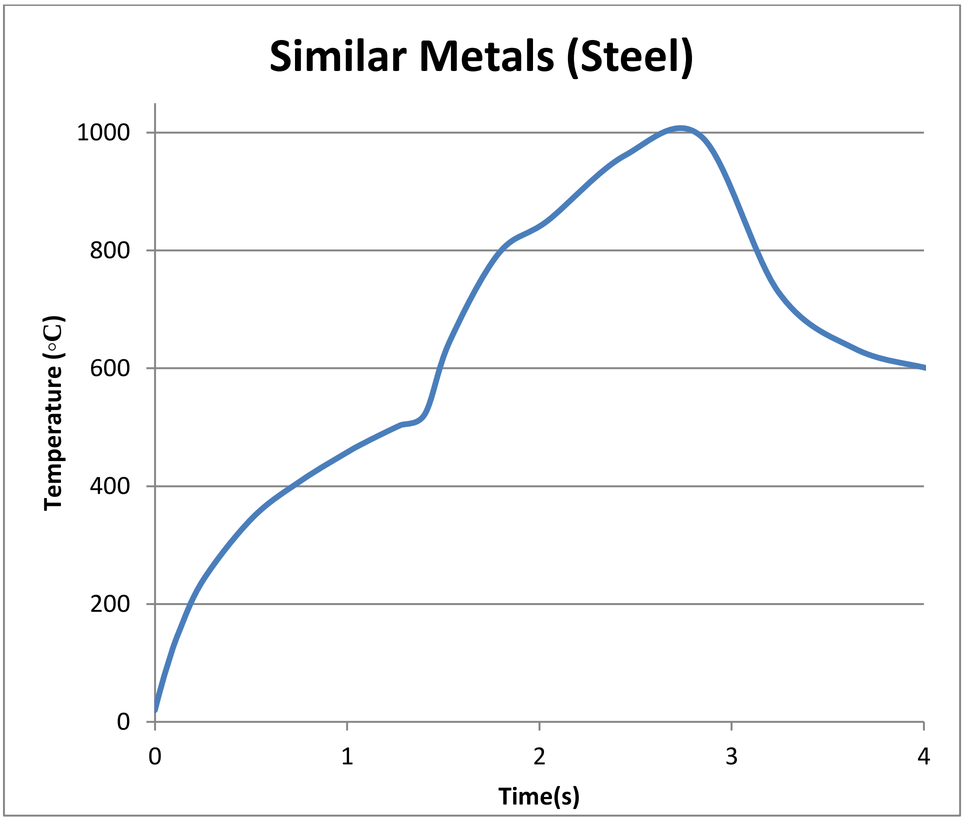


Figure 17: Temperature profile for the welding of Similar Metals

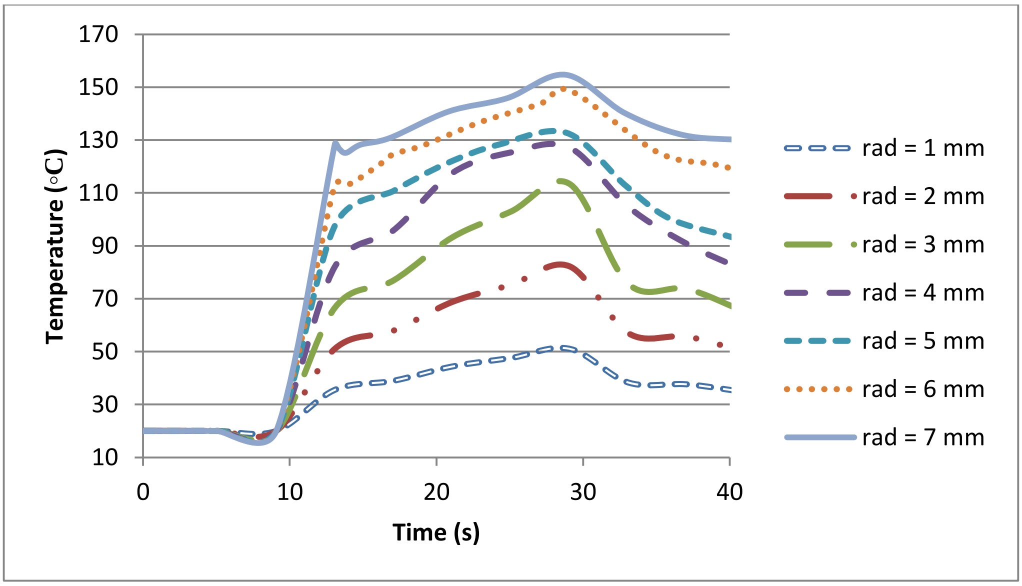
5. Temperature Profile Prediction

After the verification of the model for similar and dissimilar metals, the temperature profile for the rotary friction welding of copper rods was predicted. For this process, initially the basic parameters used were the same as that of used by alves[19]. To plot the dependence of temperature profile on radius the friction and the forging pressures were kept to be $2.1x10^6$ and $1.4x10^6$ Pa respectively. Omega used was 3200 and the radius used was varied from 1 to 7mm with an increment of 1mm.

The table 7 shows the parameters used and the prediction figure 1 shows the their corresponding profiles.

Friction Pressure(Pa)	Forging Pressure(Pa)	Omega(rpm)	Radius(mm)
$2.1x10^6$	$1.4x10^6$	3200	1
$2.1x10^6$	$1.4x10^6$	3200	2
$2.1x10^6$	$1.4x10^6$	3200	3
$2.1x10^6$	$1.4x10^6$	3200	4
$2.1x10^6$	$1.4x10^6$	3200	5
$2.1x10^6$	$1.4x10^6$	3200	6
$2.1x10^6$	$1.4x10^6$	3200	7

Table 7: Change of radius for temperature prediction

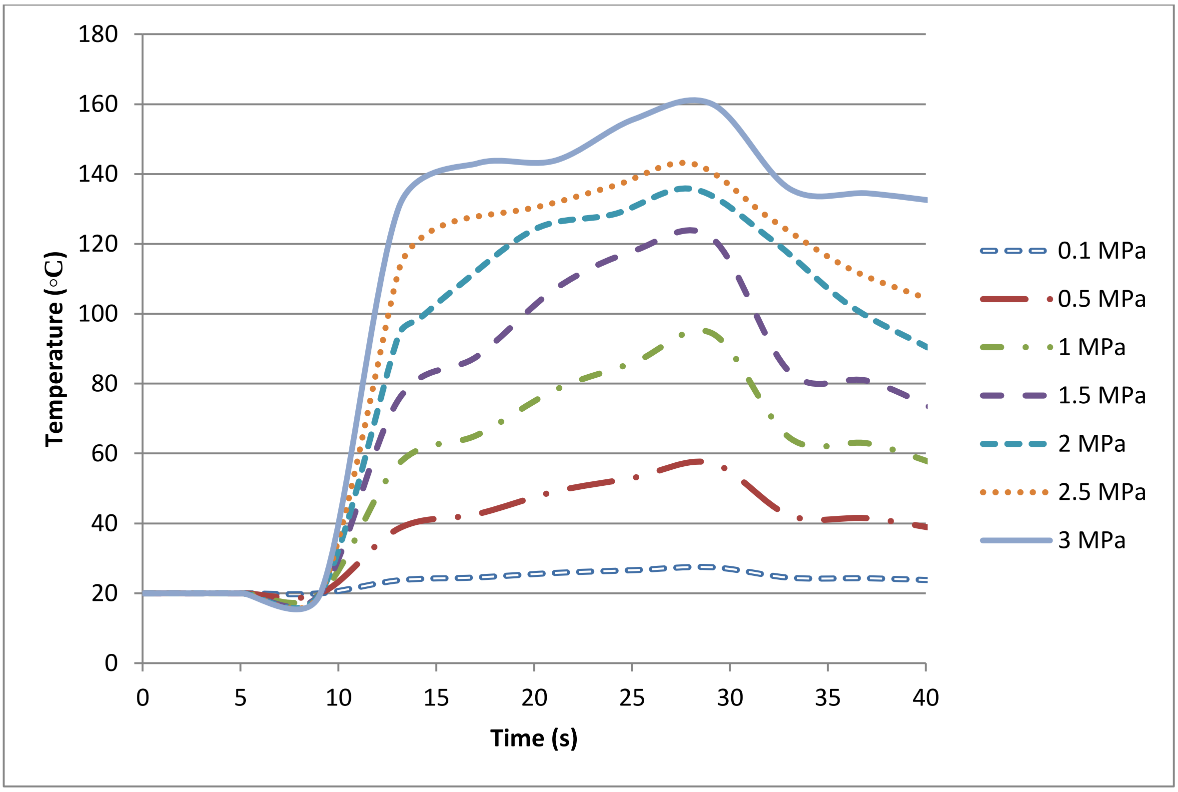


Prediction Figure 1: Temperature profiles generated by changing the radius

For studying the change of pressure on the temperature profiles, the radius and omega of the work piece was fixed to be 5mm and 3200rpm respectively. The friction pressure was changed from 0.1 MPa to 3 MPa, While the forging pressure was kept constant at $1.4x10^6$ Pa. The table 8 and the prediction figure2 show the change in pressure and its effect on the temperature profiles.

Friction Pressure(Pa)	Forging Pressure(Pa)	Omega(rpm)	Radius(mm)
$0.1x10^6$	$1.4x10^6$	3200	5
$0.5x10^6$	$1.4x10^6$	3200	5
$1x10^6$	$1.4x10^6$	3200	5
$1.5x10^6$	$1.4x10^6$	3200	5
$2x10^6$	$1.4x10^6$	3200	5
$2.5x10^6$	$1.4x10^6$	3200	5
$3x10^6$	$1.4x10^6$	3200	5

Table 8: Change of friction pressure for temperature prediction

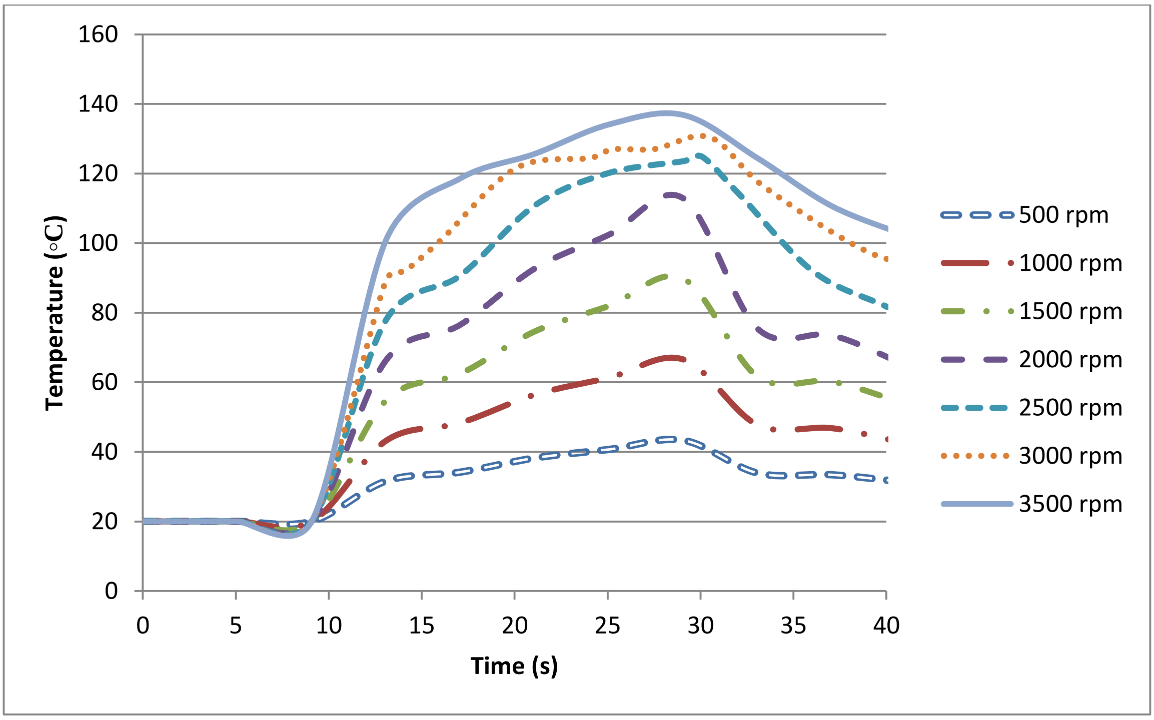


Prediction Figure 2: Temperature profiles generated by changing the friction pressure.

For studying the change of rotational speed on the temperature profile, the frictional pressure, radius and the forging pressure were kept to be 1MPa, 5mm and 1.4MPa respectively.

Friction Pressure(Pa)	Forging Pressure(Pa)	Omega(rpm)	Radius(mm)
$1x10^6$	$1.4x10^6$	500	5
$1x10^6$	$1.4x10^6$	1000	5
$1x10^6$	$1.4x10^6$	1500	5
$1x10^6$	$1.4x10^6$	2000	5
$1x10^6$	$1.4x10^6$	2500	5
$1x10^6$	$1.4x10^6$	3000	5
$1x10^6$	$1.4x10^6$	3500	5

Table 9: Change of rpm for temperature prediction



Prediction Figure 3: Temperature profiles generated by changing rpm

6. Analysis and Discussions

- **Dissimilar Metals**
  For the first time the modeling of Rotary Friction welding for dissimilar metals has been done, so there are no previous models with which the results can be compared, but with the experimental data.
  Although it's the model with phase change implementation but because of low latent heat of Aluminum, the decrease in temperature gradient is not very prominent as it was in case of steels.

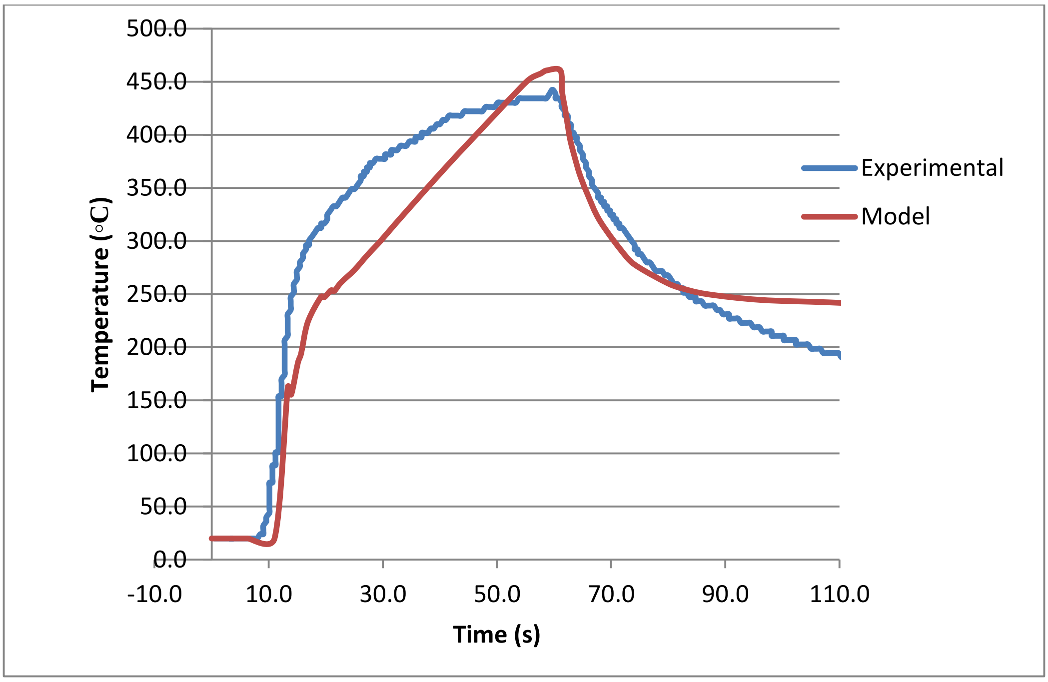


Figure 18: Comparison of the experimentally collected data with the COMSOL model generated data

The graph shows that the maximum difference of the two values i-e experimental and the model is found to be at 21.5 seconds. The values of temperature in Kelvin for both these profiles at 21.5 sec are 605.9 and 534.1 K respectively. And the error found at this point is the maximum error of **11.84%.** The peak temperature for both the profiles is at 57.7 seconds and the error calculated at this moment is found to be **3.72%.**

- **Similar Metals**

  The graph below shows three data sets, Constant friction, Power Method and Phase change model.

  The Constant friction model is the model that was previously used to approximate the temperature of the friction welding process.

  The Power Method is the method that is analyzed by Maalikian[11] in approximation of the temperature at the interface by using the experimentally measured power. In other words, it has been proved to be the most accurate method of predicting temperature at the interface.

  If the below graph is observed, the approximation is better than the constant friction method because of the phase change implementation and also the use of temperature dependent properties of material eg. Thermal conductivity and Specific Heat.

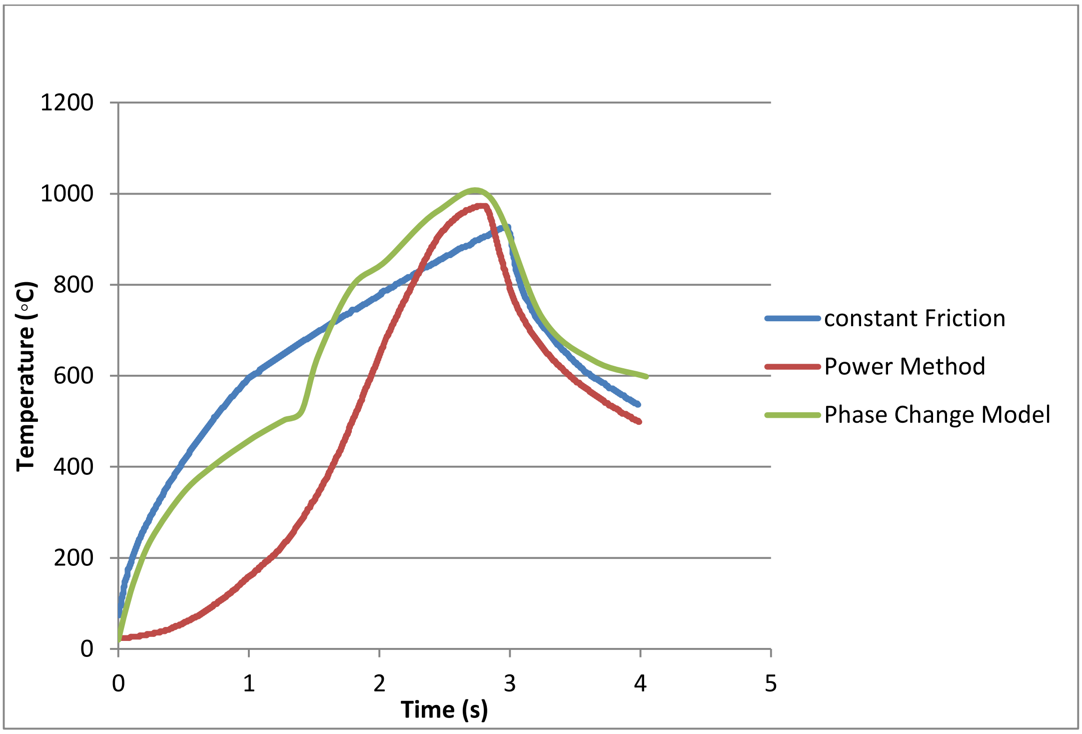


Figure 19: Comparison of the temperature profiles generated by Constant Friction Method, Power Method, and Phase Change Model

The error of the peak temperature calculated is found to be **3%** and the COMSOL profile follows the Power method profile in a much better way as compared to the constant friction method.

When the two profiles, Constant friction and Phase Change Model were compared the following plot was obtained. It shows the %age error in between the two models and plot obtained experimentally i-e by using power method.

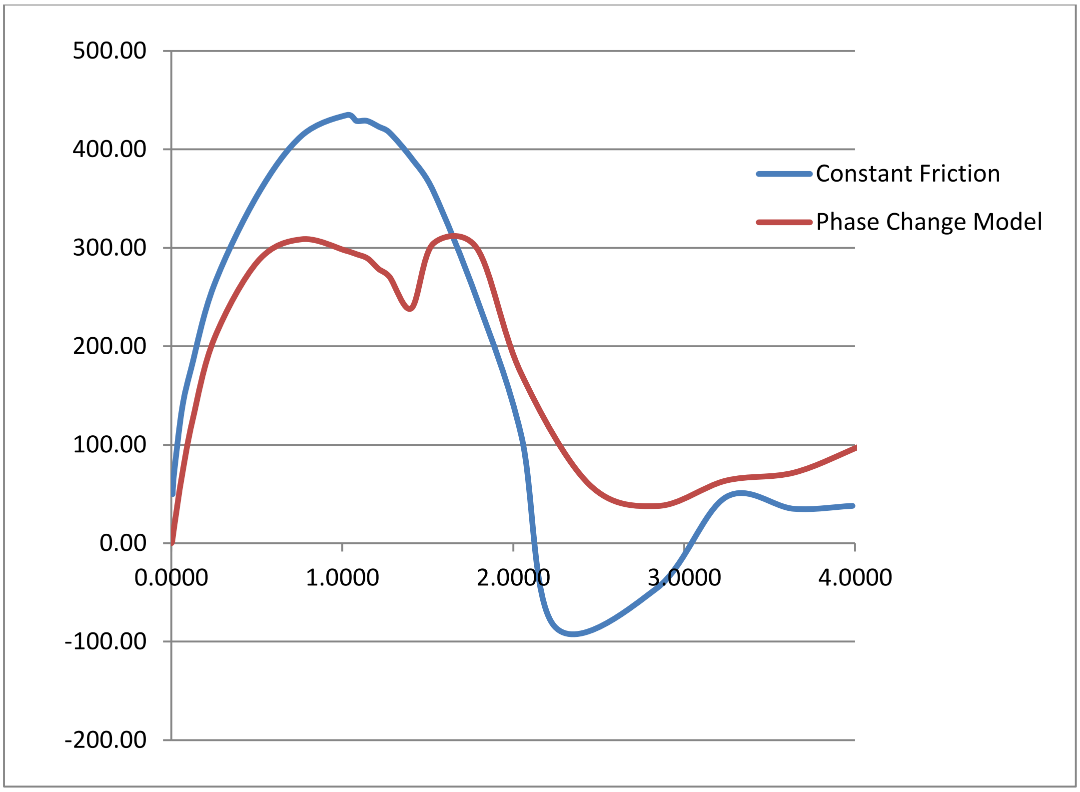


Figure 10: Error calculation for Constant Friction and Phase Change model

- **Temperature Prediction**

The temperature prediction figures show that if any of the parameter is increased then the peak temperature achieved also increases. Eq.1 shows the direct proportionality dependence of temperature on the radius, friction pressure and rotational speed. And all of these factors have shown an increase in the maximum temperature achieved. Hence the direct proportionality of these factors has been established by using phase change model and the future works may include the comparison and verification of these temperature profiles with the experimentally generated profiles.

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