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Thermal Model of Rotary Friction Welding for Similar and Dissimilar Metals

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Abstract: Friction welding is one of the foremost welding processes for similar and dissimilar metals. Previously, the process has been modeled utilizing the rudimentary techniques of constant friction and slip-stick friction. The motivation behind this article is to present a new characteristic for temperature profile estimation in modeling of the rotary friction welding process. For the first time, a unified model has been exhibited, with an implementation of the phase transformation of similar and dissimilar materials. The model was generated on COMSOL Multiphysics® and thermal and structural modules were used to plot the temperature curve. The curve for the welding of dissimilar metals using the model was generated, compared and analyzed with that of practical curves already acquired through experimentation available in the literature, and then the effect of varying the parameters on the welding of similar metals was also studied.

Keywords: rotary friction welding; COMSOL modeling; steel; aluminum; Cu; dissimilar metals

1. Introduction

Welding is a fabrication technique used extensively for joining metals and plastics. There are two main ways of integrating the components, i.e., fusion welding and solid state welding. In fusion welding, the joining edges are melted, while in solid state welding, these edges are heated to red-hot temperature and pressurized to create a joint. The former method has a disadvantage of substantial micro-structure and property changes. Conversely, the latter method does not evidently demonstrate such changes.

Friction welding is a solid state welding process. The American Welding Society defines friction welding to be a joining process, using compressive force, utilizing heat from frictional contact, resulting into a joint without employing filler material, flux or shielding gases.

Friction welding develops excellent quality weld joints between similar and dissimilar metals. The weld is developed using heat, generated from frictional force by rubbing two work-pieces. In the most unpretentious form of frictional welding, pressure on the rotating metal piece is escalated to reach an appropriate welding temperature. Once nominal temperature is achieved, the rotating work-piece is stopped and the stationary piece is forced with increased pressure to coalesce with the counter-piece. Figure 1 shows the illustration of three variants of the friction welding process.

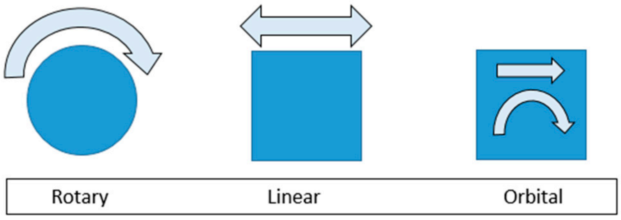

Figure 1. The three variants of the friction welding process [1].

The rotary method of friction welding is the simplest one, but it has an inherent limitation, i.e., it cannot be employed for the welding of parts with a non-circular cross-sectional area. Another main disadvantage of 'rotary friction welding' is the non-uniform thickness of the Heat Affected Zone (HAZ). This disadvantage is because of the generation of non-uniform heat at the interface resulting from the linear change in rotational speed of the work-piece over the radial distance from the center.

During this process, the foremost thing is the selection of the friction welding parameters [2]. In the process, one part is held stationary and the other is rotated at a certain speed, while the stationary part is pushed axially with a specific force until the plastic deformation is started. At that point, the rotation stops and the part is subjected to high pressure until the joint cools down. Figure 2 shows different parameters influencing the friction welding. The parameters being used for modulating the quality of the developed weld are time, pressure, and rotational speed.

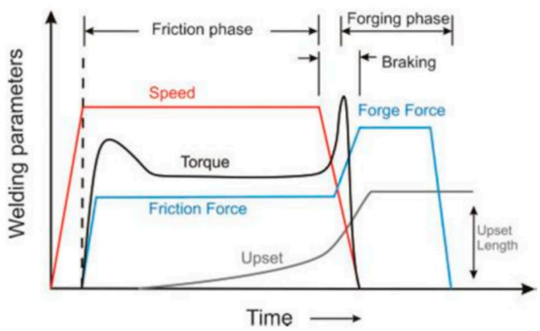

Figure 2. Variation of welding parameters with time in direct drive friction welding [1].

2. Literature Review

A mathematical model of a process offers apprehension and enables the prediction of process attributes, as well as its performance. Comparisons between mathematical models and experimental results obtained from the thermocouple has always been an area of interest. Cheng [3] used measured power to define a hypothetical heat flux uniformly distributed on the friction interface in his model, followed by a comparison. A similar approach has been used by Nguyen [4]. Maalekian [5,6] has presented the comparative analysis of heat generation, and later on temperature prediction, for friction welding of Steels. Maalekian used DEFORM™ for verification of his results and the temperature dependent properties. The comparison made was among temperature profiles obtained by using four different methods: the constant friction coefficient method, the slip-stick method, the power method and the inverse method. The power method and the inverse method showed excellent results because they were based on experimental results. Moreover, inverse method was important to predict temperature on the friction interface, because that temperature cannot be measured directly. Can et al. [7] have also modeled this process and has established the dependence of temperature profiles on different work-piece parameters.

The limitation in the models presented by Nguyen was the use of average or constant values for the temperature dependent properties, namely, density, thermal conductivity and specific heat.

Maalekian 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, Maalekian only established this fact, and nothing was done to improve the results obtained from the mathematical model. Can et al.'s [7] work was somehow restricted to work-piece parameters, for example, dependence of temperature on the radius of the work-piece.

In this research, firstly the temperature profile was developed for the complete duration of the process, instead of its dependence on a particular parameter. Secondly, COMSOL Mutliphysics® software material library was used in utilizing the temperature dependent properties of the materials used; thus not allowing for the use of constant values for such properties. Thirdly, using 'heat transfer in solids' and 'mechanics structural' modules in COMSOL software simultaneously, helped in developing better temperature profiles.

3. Proposed Approach for Modeling of RFW

When the phase change occurs, the heat supplied to the metal is used to change the molecular form instead of the increase in temperature [8]. 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 coefficient of 0.61 between Aluminum and Steel [9]. In heat transfer in solids, the process is to determine the 'pair thermal contact' and use the following equation, as used by Can et al. [7] for calculation of the heat flux $\dot{q}$.

$$\dot{q} = \pi \cdot \omega \cdot P \cdot r \left(\mathrm{W/m^2}\right), \tag{1}$$

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 the 'apparent heat capacity method' [10] for the modeling of phase change phenomenon. In this method, an additional term is added to heat capacity i.e., 'latent heat'. The heat transfer equation along with a convective term is as follows:

$$\rho \cdot C_\mathrm{p} \cdot \nabla\, T = \nabla \cdot (k \cdot \nabla \cdot T), \tag{2}$$

In this equation ρ is the density, C_p is the heat capacity, T is the temperature and k is the thermal conductivity.

This 'apparent heat capacity method' uses a phase transition function $\alpha(T)$. During the implementation of the phase change, the interval ($\Delta T_{1\to 2}$) is to be defined, through which a smooth transition occurs. The material has mixed properties of liquid and solid forms in this interval, with its density 'ρ' ($\mathrm{kg/m^3}$) and thermal conductivity 'k' (W/(m·K). Figure 3 shows an example of the phase transition function for the phase change of iron [11].

The transition function $\alpha(T)$ changes its value from 0 to 1 during this whole process of transition., namely $\alpha(T) = 0$ for pure solid and for pure liquid $\alpha(T) = 1$. 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. For the phase change, heat capacity 'C_p' is given in Equation (3); wherein, 'α' is the 'linear thermal expansion coefficient' ($^\circ\mathrm{K}^{-1}$) and 'T' is the 'temperature' in (°K) [12]:

$$C_\mathrm{p} = C_\mathrm{p,solid} \times (1 - \alpha(T)) + C_\mathrm{p,liquid} \times \alpha(T), \tag{3}$$

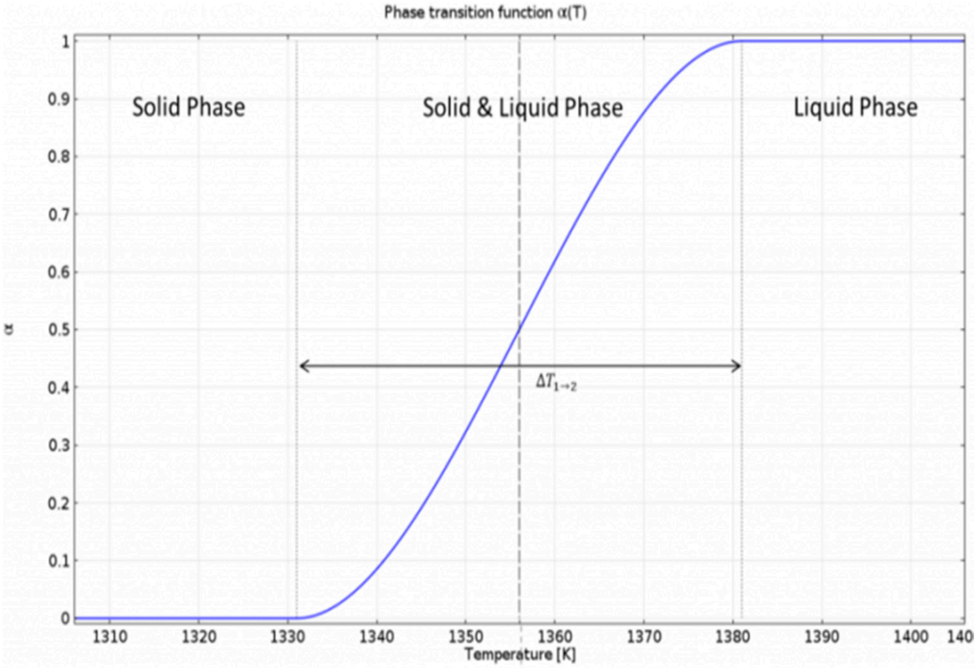

Figure 3. Phase transition function [11].

The same process is used for finding other temperature dependent parameters, such as density and thermal conductivity. The equation caters for 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 Equation (3).

$$C_{\mathrm{p}} = C_{\mathrm{p,solid}} \times (1 - \alpha(T)) + C_{\mathrm{p,liquid}} \times \alpha(T) + L_{1\to 2}\,\frac{d\alpha}{dT}, \quad (4)$$

In Equation (4), $L_{1\to 2}$ represents the latent heat from Phase 1 to Phase 2. The integration of this function during the interval $\Delta T_{1\to 2}$ gives the total value of 1, and its multiplication with $L_{1\to 2}$ gives the amount of 'latent heat', which is released over $\Delta T_{1\to 2}$ as shown in Figure 4 below.

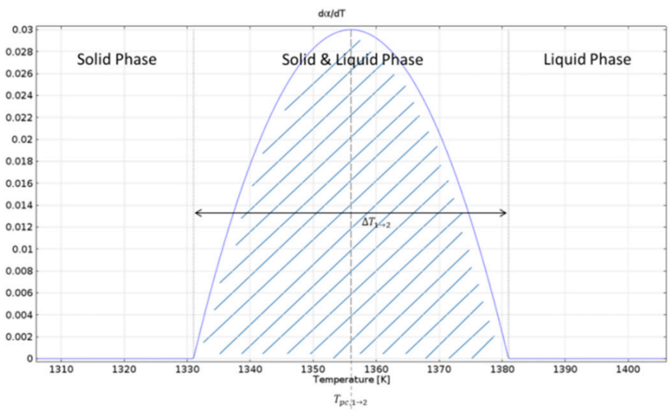

Figure 4. Plot example for $d\alpha/dT$—derivative of phase transition function [11].

4. Setup of Finite Element Model

First of all, the software for the modeling of rotary friction welding as a multi-physics phenomenon was selected. COMSOL, because of its user-friendly interface and diversity, was shortlisted.

Later, a 2D axisymmetric feature of COMSOL was used for the modeling because of the large simulation time required for 3D simulations. The meshing in COMSOL was calibrated for General Physics and a predefined finer mesh size was selected, with the maximum element size of 0.0078 m and minimum element size of 2.63×10^{-5} m. Since it is an axisymmetric problem, the element type selected was free triangular. The meshed geometry of both the rods is shown in Figure 5 below.

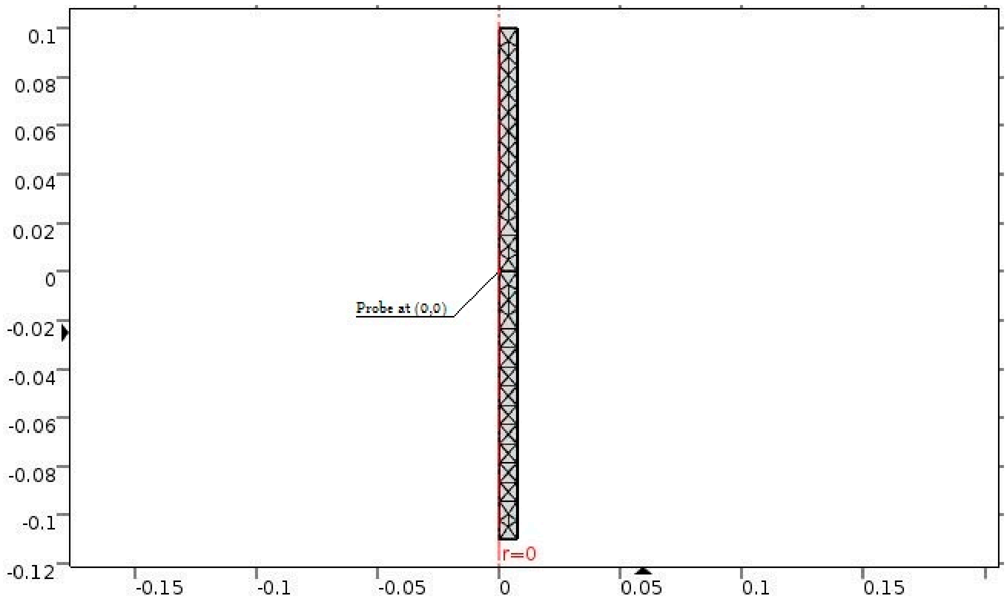

Figure 5. Geometry and its meshing.

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 placed at (0, 0) for the simulation of similar metals, i.e., Steel, and at (0, 0.012) m for dissimilar metals, i.e., Steel and Aluminum. As the simulation was run, the temperature probe started plotting the temperature with respect to time.

4.1. For Dissimilar Metals

4.1.1. Parameters

As a first step of the modeling process, parameters were defined for the experimental determination of temperature for the rotary friction welding of dissimilar metals. In this regard, parameters defined by Alves et al. [13] have been used for this research work. These parameters are given in Table 1 below.

Table 1. Parameters defined for dissimilar metals welding.

Name	Value	Description
t_1	60	Friction Time
P_1	2.10×10^6	Friction Pressure
P_2	1.40×10^6	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 2 and the graph in Figure 6 show how RPM is varied during the whole process. A piecewise function, shown in Table 2, was developed that used the parameter of friction time in order to define the time period for which the RPM was to be kept at 3200. It can be seen in the function and plot that as soon as the friction time ends, i.e., 60 s, the RPM decreases rapidly to zero.

Table 2. Piecewise function of Omega, for dissimilar metals welding.

Start	End	Function
0	t_1	W
t_1	$t_1 + 3$	$W - ((t - t_1) \times (w/3))$
$t_1 + 3$	t_2	0

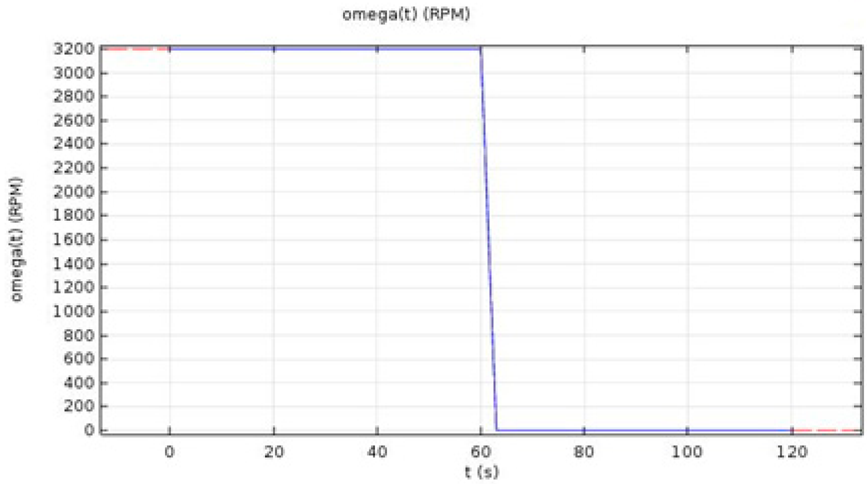

Figure 6. Omega for welding of dissimilar metals.

Table 3 and the plot in Figure 7 show pressure acting on the two work-pieces. A piecewise function was developed, as shown in Table 3. From *0* to *t_ap* is the 'approach time' and after that the pressure rises when the two work pieces come in contact. Then, a pressure P_1, i.e., 2.1×10^6 Pa is applied, which is the friction phase. When the friction phase is over, the forging phase starts and the pressure drops from P_1 to P_2, i.e., 1.4×10^6. All the parameters are in accordance with the experimental work carried out by Alves [13].

Table 3. Piecewise function of pressure for welding of dissimilar metals.

Start	End	Function
0	t_ap	0
t_ap	$t\_ap + 1$	$(t - t\_ap) \times P_1$
$t\_ap + 1$	t_1	P_1
t_1	$t_1 + 1$	$P_1 - ((t - t_1) \times (P_1 - P_2))$
$t_1 + 1$	$t_{\_total}$	P_2

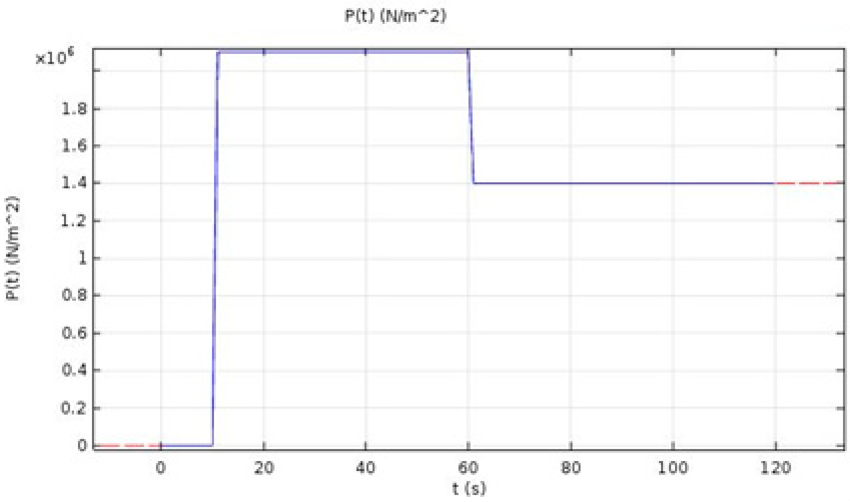

Figure 7. Pressure for the welding of dissimilar metals.

4.1.2. Geometry

Since a 2D axisymmetric feature is used, the geometry consists of only two rectangles, having their one side overlapping the axis. According to the dimensions mentioned, the diameter of Steel as well as Aluminum rods used for the experiment, were fixed at 14.8 mm, while the lengths of the Steel and Aluminum rods were kept at 110 mm and 100 mm, respectively.

4.1.3. Material

The materials chosen for the experiment were AA1050 Aluminum alloy and AISI 304 austenitic Steel. The COMSOL material database provides the liberty of choosing a material, and then all the properties of that particular material are used from the database. The main concern was to use the temperature dependent properties, such as thermal conductivity and the specific heat, as these are important in temperature determination.

4.1.4. Results

The image in Figure 8 shows the temperature distribution when maximum temperature is achieved. The figure clearly shows the two different materials; the one with the expanded color bands is Aluminum. This is because the thermal conductivity of Aluminum is far greater than that of Steel. 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. The data extracted from the model was converted from Kelvin to Centigrade. The results of the temperature profile from the mathematical model of the rotary friction welding of Steel and Aluminum alloy at a distance of 12 mm from the contact surface are shown in Figure 9.

It is evident from Figure 8 that the initial 10 s constitute the approach time. When the two work-pieces come into contact, the temperature at the interface rises suddenly. The slope of the plot decreases when the temperature reaches approximately 250 °C. This is because the phase change temperature of Aluminum is taken from 0.5 to 0.6 of the temperature of metal 'T_m' and during this phase, the rate of temperature change decreases. After that, the temperature still rises because of the continuous application of 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 (ω) 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 the conduction of heat away from the interface; as the temperature of the work pieces decreases, the rate of temperature change also decreases.

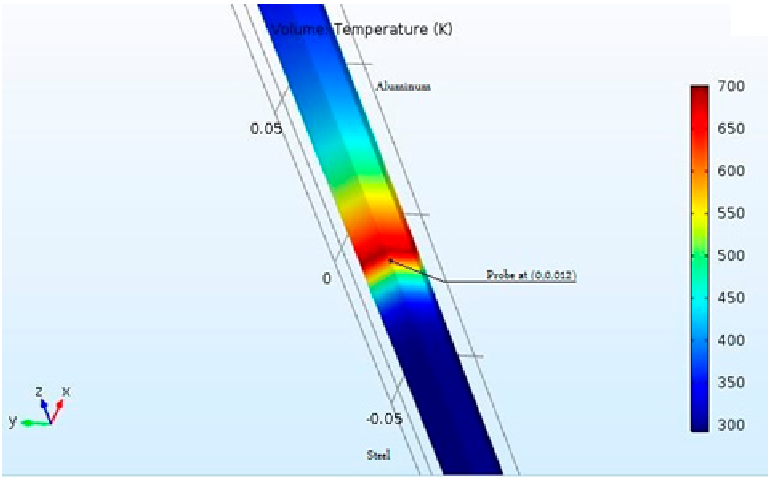

Figure 8. Temperature distribution for dissimilar metals.

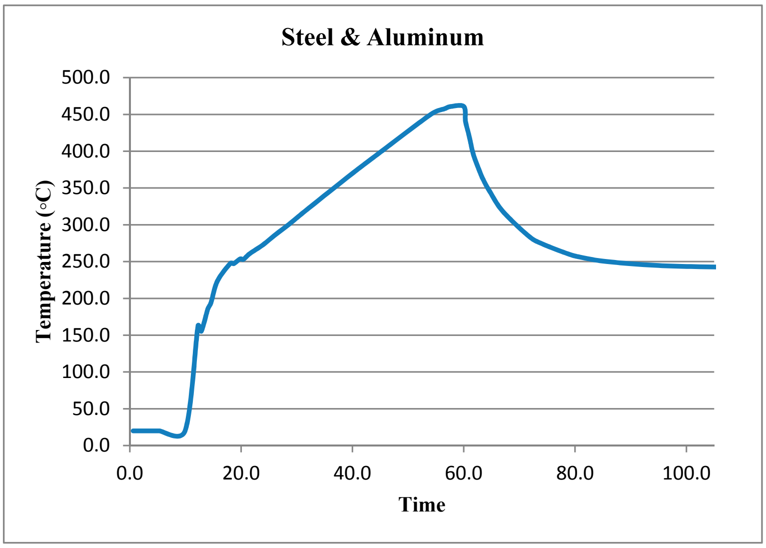

Figure 9. Temperature profile for the welding of dissimilar metals.

4.2. For Similar Metals

4.2.1. Parameters

The first step in modeling, similar to the previous model, was to define parameters, and the values of these parameters were to be set so as to validate the experimental results already present in the literature, as given in Table 4 below.

Table 4. Parameters for the welding of similar metals.

Name	Value	Description
t_1	3	Friction Time
P_1	1.31×10^7	Friction Pressure
P_2	1.00×10^8	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 5 shows the pressure changes during the whole process and the same is graphically represented in Figure 10.

Table 5. Piecewise function of pressure for the welding of similar metals.

Start	End	Function
0	0.1	$t \times (P_1/0.1)$
0.1	t_1	P_1
t_1	$t_1 + 0.1$	$P_1 + ((t - t_1) \times (P_1 - P_2))$
$t_1 + 0.1$	$t_{\_total}$	P_2

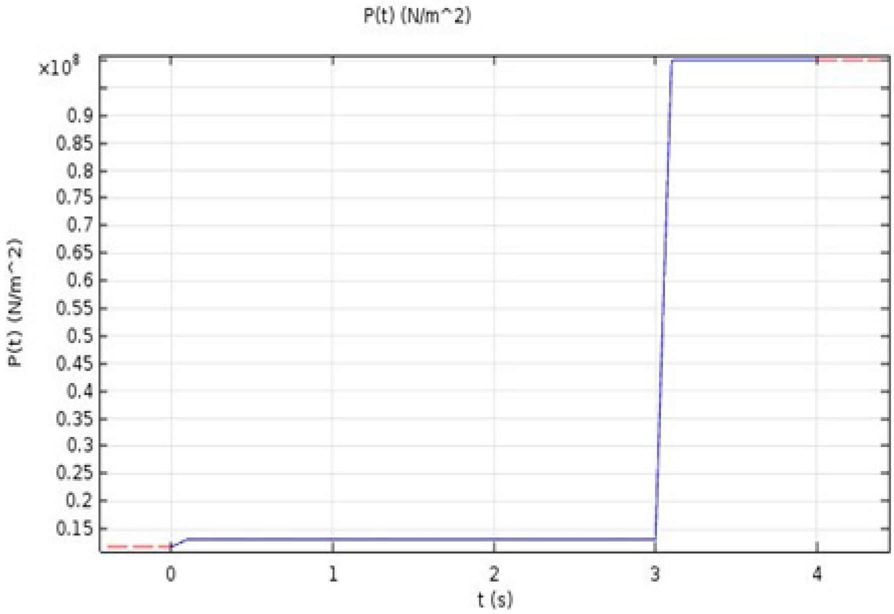

Figure 10. Pressure applied for the welding of similar metals.

Table 6 shows the RPM of one work-piece during the whole process and the same is graphically represented in Figure 11.

Table 6. Piecewise function of Omega for the welding of similar metals.

Start	End	Function
0	t_1	w
t_1	$t_1 + 0.1$	$W - ((t - t_1) \times (w/0.1))$
$t_1 + 0.1$	$t_{\_total}$	*0*

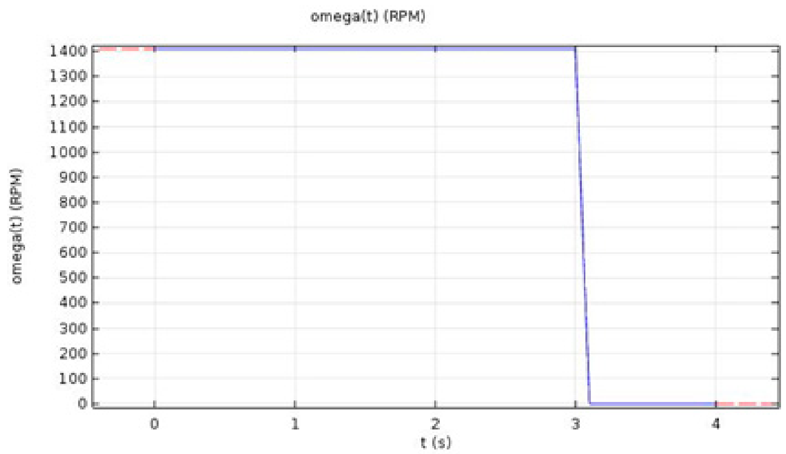

Figure 11. Omega applied for the welding of similar metals.

4.2.2. Material

The material used for modeling the friction welding process of Steel is AISI 304 austenitic Steel. The material was available in the COMSOL materials database, and the main purpose of using this information from the database, was to use the temperature dependent material properties of metals in the modeling of the process, as mentioned earlier.

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 0.7 as suggested by Sullivan [14]. The same equations were used for the heat flux, as those that were used above for dissimilar metals modeling.

4.2.3. Results

Figure 12 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 decrease and the temperature somehow becomes constant. The phase change temperature for Steel was taken to be from 0.5 to 0.6 of metal temperature 'T_m'. At this moment, the heat being generated is used for the phase change or atomic restructuring. As the change of phase is completed, the temperature rises again to a maximum value of about 1000 °C.

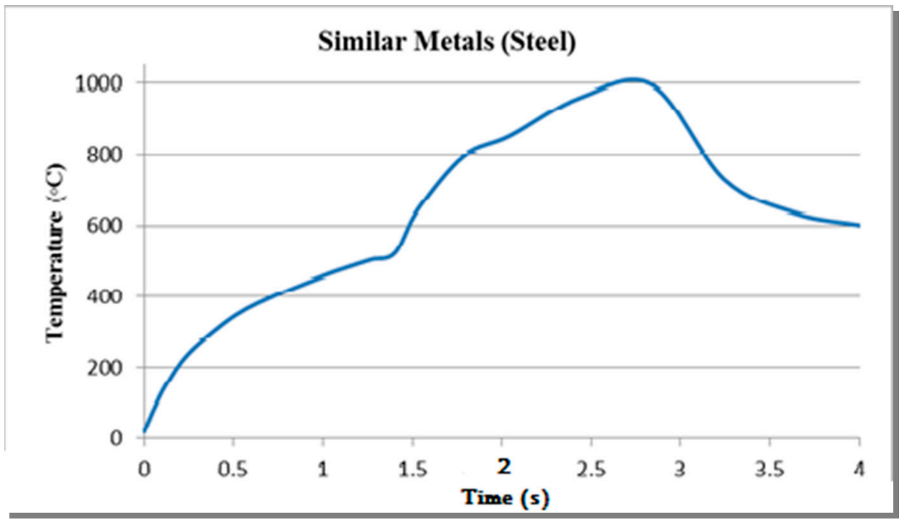

Figure 12. Temperature profile for the welding of similar metals.

At this point the friction phase ends, and the pressure rises to the forging pressure, while the omega reduces to zero. The temperature then decreases rapidly, but the slope decreases gradually.

5. Analysis

For the first time, the modeling of rotary friction welding for metals using the phase change property of metals has been done.

While this is a model with phase change implementation, because of the linearity of the phase change function during the solid and liquid phases, the temperature profile gets less steep at about 250 °C. Comparison of both of the profiles is shown in Figure 13 below.

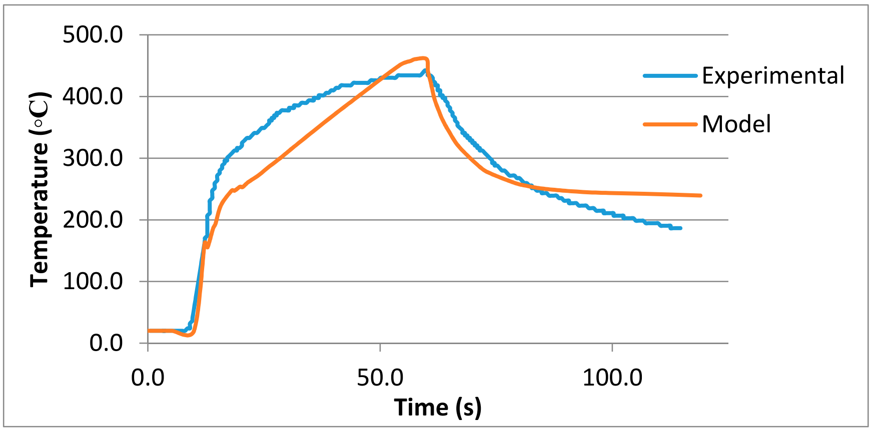

Figure 13. Comparison of experimental and model generated temperature profile for dissimilar metals.

Figure 13 shows that the maximum difference of the two values, i.e., experimental and the model, is found to be at 21.5 s. The values of temperature in Kelvin for both these profiles at 21.5 s are 605.9 K and 534.1 K, respectively, and the maximum error found at this point is 11.84%. The peak temperature for both the profiles is at 57.7 s and the error calculated at this moment is found to be 3.72%.

For welding of Steel, Figure 14 shows three data sets, i.e., constant friction, power method and phase change model. The constant friction model was previously used to approximate the temperature of friction welding process. The power method is analyzed by Maalikian [5] for 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 for predicting the temperature at the interface.

If Figure 14 is carefully analyzed, the approximation is better than the constant friction method, because of the phase change implementation and also the use of temperature dependent properties of the materials, e.g., thermal conductivity and specific heat. The error of the peak temperature calculated is found to be 3% and the COMSOL profile follows the power method profile, which is the experimental method curve used here for comparison purpose, in a much better way than in comparison to the constant friction method. The difference in the temperature profile could be due to surrounding temperature when the actual experiment was performed.

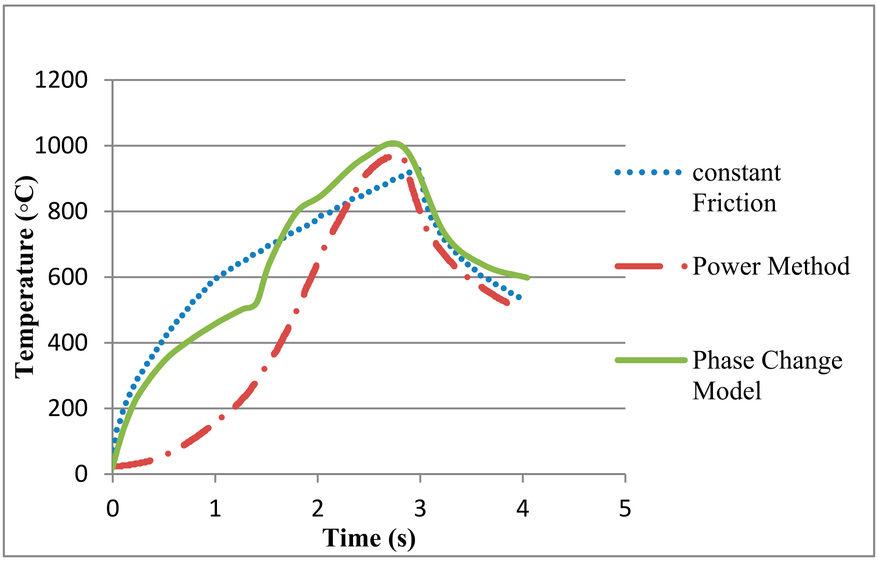

Figure 14. Comparison of the temperature profiles generated by constant friction method, power method, and phase change model.

6. Discussion

After the modeling and validation of the rotary friction COMSOL model, the model was then used to study the dependence of temperature profile on the three parameters discussed above, i.e., radius, pressure and omega, and the material selected for this study was Copper. The range of the parameters used for this study was kept the same as used by Alves [13].

It is quite clear from Equation (1) that the heat flux is directly proportional to the pressure, omega and radius. Initially, the effect of changing the radius was studied by keeping the pressure and omega constant. The values of the pressure and omega were taken to be 2.1×10^6 MPa and 3200 rpm, respectively. The radius of the work-pieces was changed from 1 mm to 7 mm, with 1 mm increment. Corresponding temperature profiles are shown in Figure 15.

To study the effects of the next parameter, i.e., pressure during the friction phase of the process, the radius and omega were kept constant at 5 mm and 3200 rpm, respectively, and the pressure was varied from 0.1 to 3 MPa, with an incremental step of 0.4 and then 0.5 MPa. A similar trend was observed, as before, while varying the pressure as shown in Figure 16.

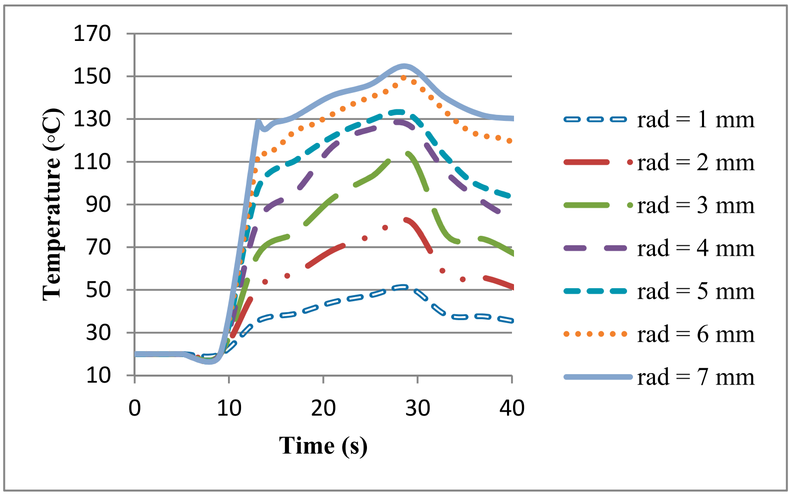

Figure 15. Temperature profiles generated by varying radius of the work-piece.

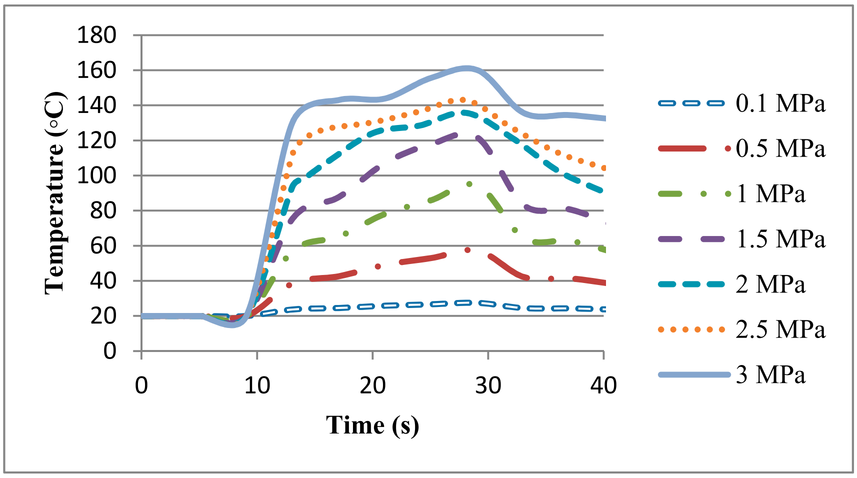

Figure 16. Temperature profiles generated by varying applied pressure.

The last parameter in Equation (1) to be varied is the omega, i.e., the rotating speed of one of the two work-pieces. Omega was varied from 500 to 3500 rpm, with an increment of 500 rpm. While the pressure and radius was kept constant at 1 MPa and 5 mm, respectively. The profiles generated are shown in the Figure 17 below.

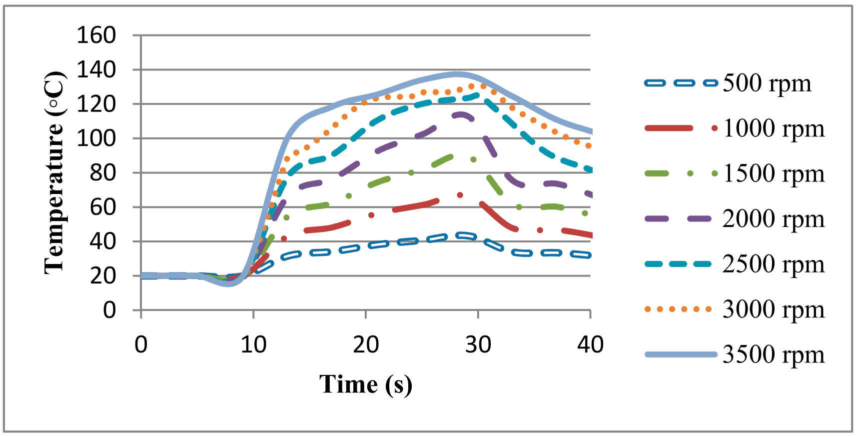

Figure 17. Temperature profiles generated by varying rotational speed.

7. Conclusions

Temperature profiles are generated by employing a new module of phase transformation in COMSOL and the 'apparent heat capacity method' has been used in this module. A model was initially developed for the welding of similar metals, i.e., Steel, as well as dissimilar metals, i.e., Steel and Aluminum, and later it was used to develop temperature profiles according to the parameters of experiments conducted by Alves [13]. Structural modules were introduced to accommodate contact conditions, while thermal modules were used to define heat flux and phase transformation of the metals. When both profiles were compared, an error of 3.72% was found in the peak values.

The same model was then used to generate the temperature profile for the welding of similar metals, i.e., copper, and the effect of varying different parameters, i.e., radius, pressure and omega on these profiles, was studied individually. It is pertinent to mention that when one of the three parameters was raised, the maximum temperature range also increased. Hence, the existence of direct proportionality of the peak temperature with these parameters has been established. Results presented by Serio et al. in their research also support the fact that the thermal behavior of joints is closely connected to the process parameters, which therefore, also strengthens the simulation model presented in the research [15,16].

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Author Contributions: Shahid Butt and Ghulam Hussain conceived and designed the experiments along with guidance during the research phase; Abu Bakar did the literature review, performed the Simulation model and verified the experimental results; Adnan Maqsood and Faping Zhang helped in performing Simulations and Analyzing the data; Mansoor Siddiqui formatted paper as well as corrected text and font etc.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsor NUST had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results except the authors.

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