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# Analysis of Heat Distribution in Friction Stir Welding: Role of Tool Design and Material Properties

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**Abstract:**

Friction Stir Welding (FSW) is a solid-state welding technique extensively used for joining materials, especially lightweight alloys like aluminum. This study focuses on the design and transient thermal analysis of the FSW process, comparing two different tool geometries: conical and cylindrical. The primary goal is to assess the impact of tool design on thermal behavior and joint performance when welding Aluminum 2024 and Aluminum 6061 alloys, both of which are commonly used in aerospace and structural applications due to their excellent strength-to-weight ratios To investigates the thermal effects in the nugget zone at three different operating temperatures: 250°C, 300°C, and 350°C. A transient thermal analysis is performed using Finite Element Modeling (FEM) to simulate heat generation, temperature distribution, and cooling rates during the FSW process. The analysis also compares the heat-affected zones (HAZ) and thermal gradients associated with each tool design. Results show significant variations in heat input and thermal profiles depending on the tool shape and temperature settings. The conical tool exhibited a more concentrated and deeper heat penetration, while the cylindrical tool offered more uniform heat distribution. These thermal differences directly impact the mechanical strength and microstructure quality of the welded joint. This study contributes to the optimization of tool design and process parameters for enhanced weld quality and thermal efficiency in friction stir welding applications.

**Keywords:** FSW, Al alloys, Transient thermal analysis

## 1.Introduction

Friction Stir Welding (FSW) is a solid-state welding process that utilizes mechanical stirring to join materials without the need for additional heat sources. In this process, a rotating tool moves along the joint line, generating heat through friction with the workpiece. The heat softens the material, causing it to become semi-solid. As the tool advances, the plasticized material in front of it is stirred and displaced behind the tool, layer by layer. Initially applied to alloys, fusion softening techniques have since been extended to various metals, particularly those that are difficult to melt. The heat generated by friction causes atomic diffusion, allowing the ends of the workpiece to bond together. The ideal weld formation depends on several factors, including rotational speed, welding speed, axial pressure, and tool profile, all of which must be balanced to achieve the right combination of heat and pressure for successful welding.

### Objectives

- To Study the FSW weld joints

- To weld joints design was done by using NX 12.0
- To validate the transient thermal analysis with various parameters (Temperature, heat flux thermal error) using different tools
- To analyze the temperature distribution in the workpiece during FSW using conical and cylindrical tools using ANSYS 2024 R1

## 2.Literature review

A review on the Design and Transient Thermal Analysis of Friction Stir Welding (FSW) Using Different Tools (Conical and Cylindrical Tools) would typically explore the key aspects of FSW, including its thermal behavior, tool design, and the differences in performance between conical and cylindrical tools. Bonifaz, E.A et al. [1] the optimum shoulder diameter design criterion was established that would allow for the most efficient use of input torque for traction. K.V. Jata et al. [2] FSW was carried out on T745-tempered aluminum alloy 7050 to investigate its influence on the material's microstructure and mechanical qualities. Grains in the original material are transformed into dynamically recrystallized grains using FSW. L.E. Svensson et al. [3] It investigated the impact of Friction Stir Welding on the microstructure and mechanical properties of welds made from the aluminum alloys AA 5083 and AA 6082. Fricke, S et al. [4] used a Ni foil interlayer to test laser penetration welding on steel and aluminum. Intermetallic compounds couldn't form because of the overlaps between the steel and aluminum in the fusing zone. Frigaard et al. [5] Creating a finite difference model of FSW heat flow in three dimensions. Nectarios Vidakis et al. [6] investigated the use of FSW on an increasing number of MEX 3D printed components. Plaques of poly (methyl methacrylate) (PMMA) were assembled into a factorial design experiment. It was determined how three FSW parameters affected the final weld product. Preety Rani, [7] The primary objective of this study is to review and thoroughly examine the majority of research done on friction stir welding of aluminum alloys. Weld reactions, material flow, and microstructure as they relate to the effects of process variables are being studiedAkshansh Mishra et al. [8] The FSW (friction stir welding) method and its settings were analyzed. Scientific research has shown that this method successfully welds together a wide variety of metals, including aluminum alloys, copper, magnesium, zinc, steels, and titanium, with no harmful byproducts or fillers required.Chintamani Mahananda et al. [9] The preferred approach for joining these materials is friction stir welding, a solid-state forge welding procedure that might solve problems typically encountered while welding them. All of the steps take place in a solid state via plastic deformation and mass transfer between the various components; therefore, there is no melting involved. C. Rajendran et al. [10] investigated the results of FSW on lap-joined AA2014-T6 aluminium alloy by adjusting the parameters.

## 3. Methodology

This study investigates the Friction Stir Welding (FSW) process for dissimilar aluminum alloys, specifically Aluminum 2024 (Plate 1) and Aluminum 6061 (Plate 2), using a conical tool geometry. Both alloys are widely utilized in aerospace and automotive industries due to their excellent mechanical properties, making their successful joining critical for advanced manufacturing applications. The conical tool proved effective in enhancing heat distribution and material mixing across the weld interface steps

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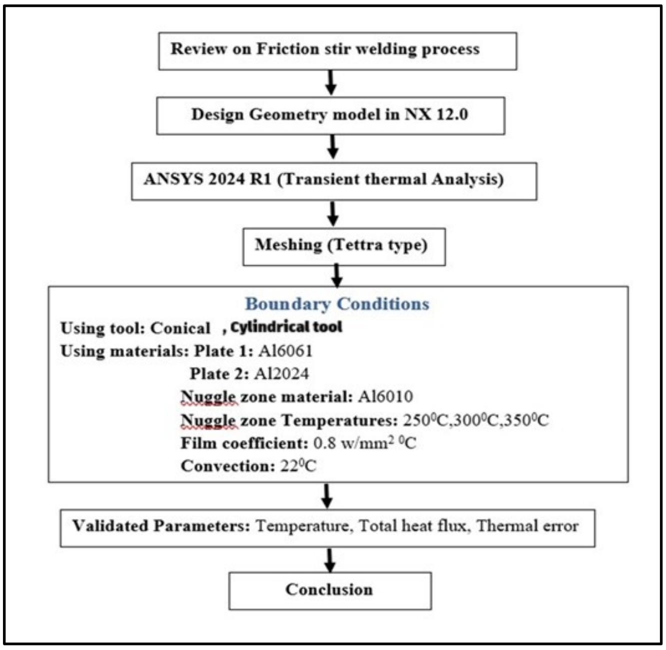


**Figure 1:** Design flow chart

**Using Friction Stir Welding Materials:**

The FSW process is versatile and can be used with a wide range of materials. The process involves a rotating tool that generates frictional heat to plastically deform and join materials without melting. The tool geometry, materials being welded, and process parameters play a crucial role in determining the quality of the weld. Some of the most commonly used materials include.

| Al6061 | Al 2024 |
|---|---|
| Density: 2.70 g/cm³ | Density: 2.78 g/cm³ (2,780 kg/m³) |
| Melting Point: ~582–652°C | Melting Point: 502–638°C |
| Tensile Strength: ~310 MPa | Thermal Conductivity: 121 W/m·K |
| Yield Strength: ~276 MPa | Poisson’s Ratio: 0.33 |
| Thermal Conductivity: 166 W/m·K | Modulus of Elasticity: ~73 GPa |

**Design of FSW WELD Joint:**

The NX software supports the full product development and manufacturing process, from the initial idea through the completed product being packaged.

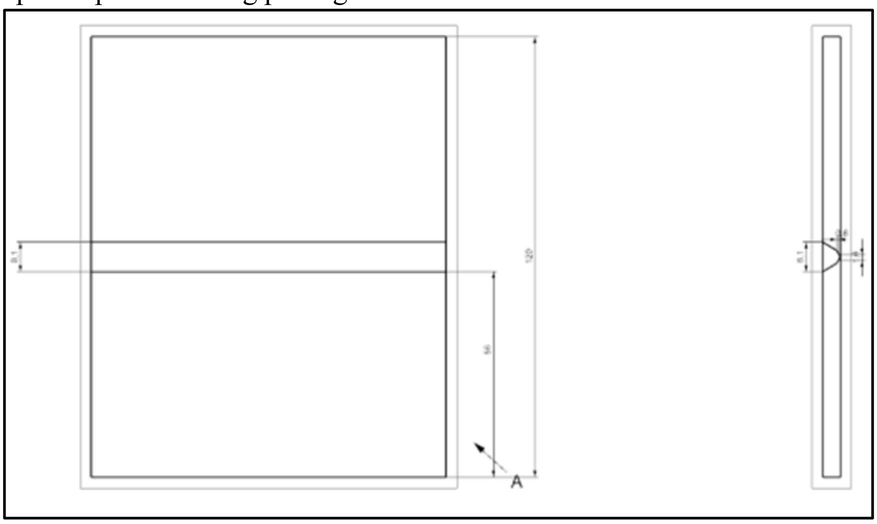

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**Figure 2:** Geometry Model Conical tool

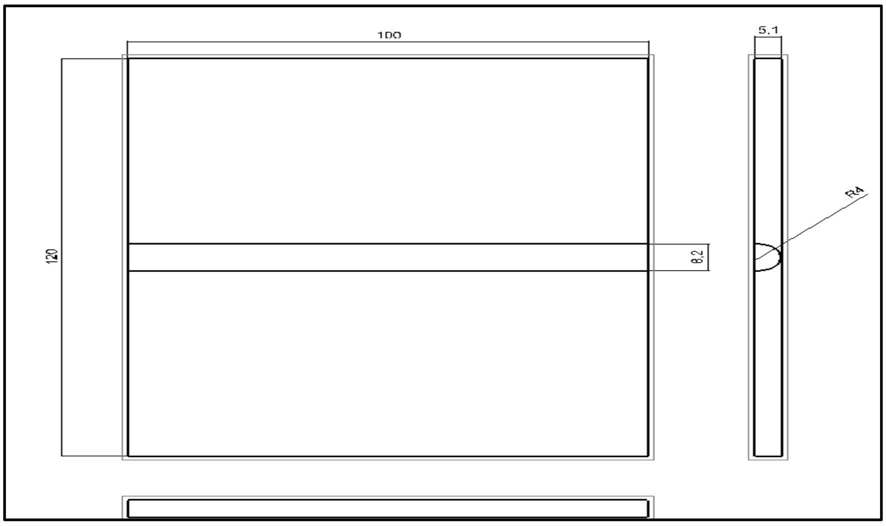


**Figure 3:** Geometry Model Cylindrical tool

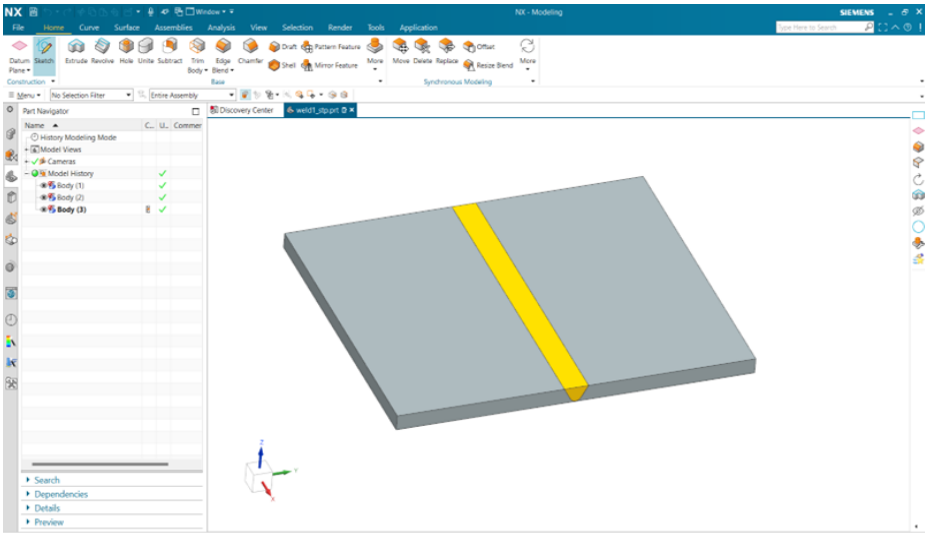

**Figure 4:** Design File Using NX 12.0

The following figures show the transient thermal analysis of FSW Welding using conical tool.

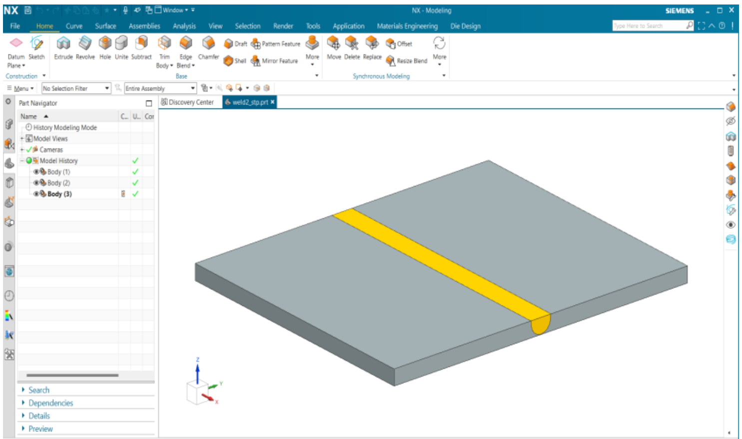

**Figure 5:** Design File Using NX 12.0

The following figures show the transient thermal analysis of FSW Welding using cylindrical tool.

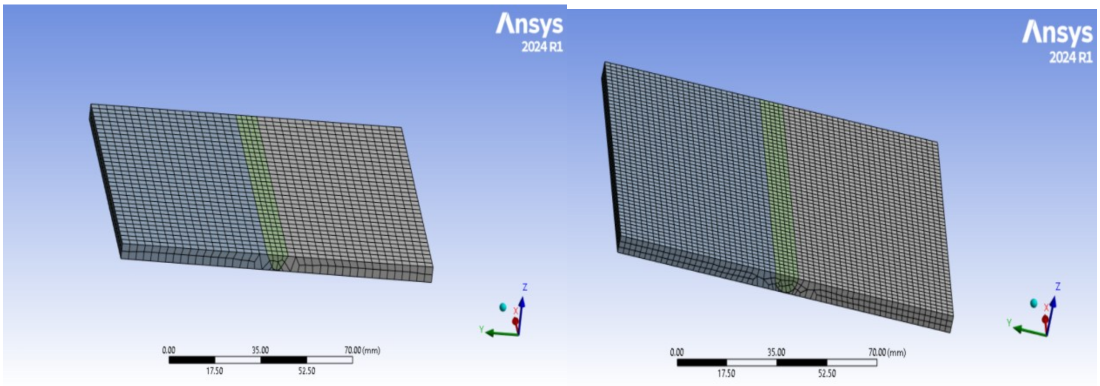


**Figure 6**: Meshed model conical and cylindrical tool plates

Creating a meshed conical and cylindrical tool model with tetrahedral elements (tettra mesh) for transient thermal analysis (e.g., in FSW simulation) is a common step in preparing for finite element simulations. a tetrahedral meshed cylindrical tool model in simulation software like ANSYS.

**4. Results And Discussions**

In ANSYS analysis, Transient thermal analysis formed with uniform initial temperature of 22$^0$C. The design and analysis of welding fixtures based on transient thermal analysis. Welding fixtures is designed to hold and support the workpiece securely during the welding process. The heat transformation from the workpiece could lead the temperature rises and impacts to the welding fixtures using (250$^0$C,300$^0$C, 350$^0$C,) temperature to validate.

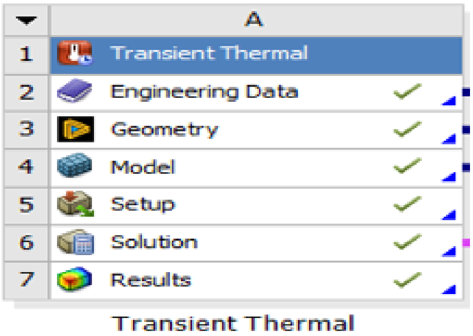


**Figure 7:** Ansys Layout

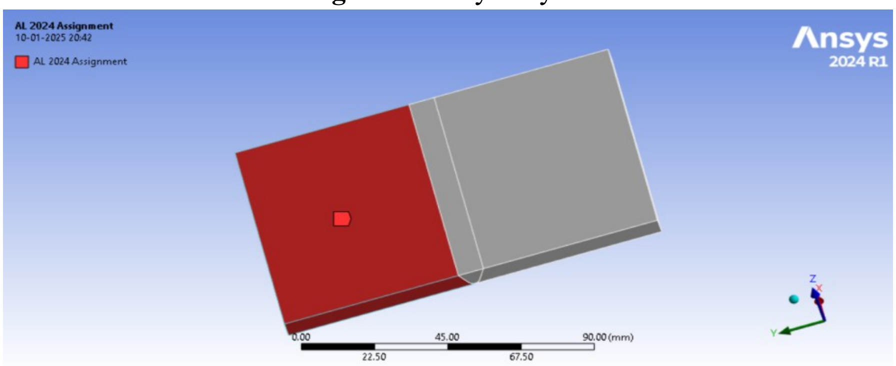


**Figure 8:** Material Assignment for clamping work piece

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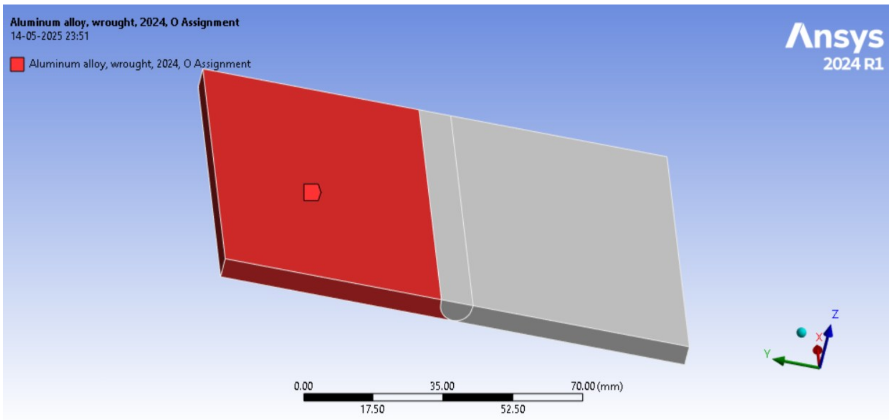


**Figure 9:** Material Assignment for Cylindrical clamping work piece

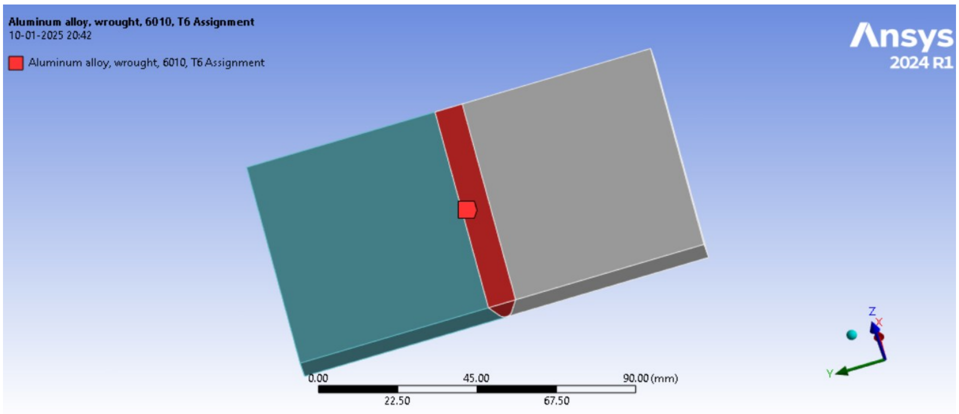


**Figure 10:** nugget zone assignment Al 6010

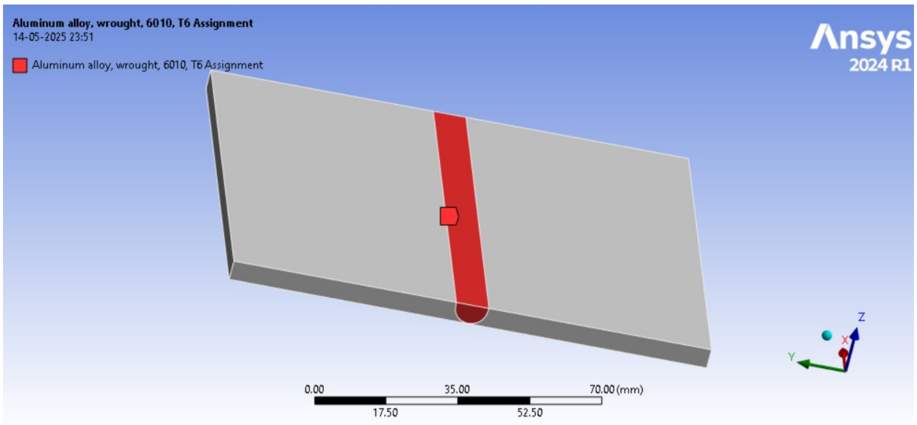


**Figure 11:** Cylindrical nugget zone assignment Al 6010

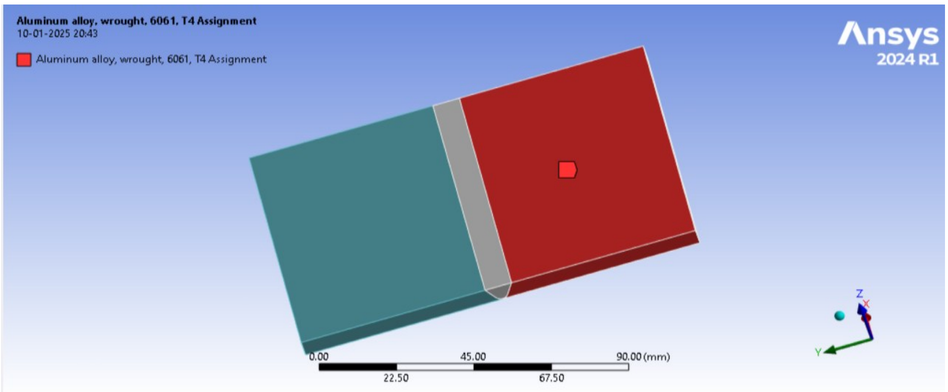


**Figure 12:** Material Assignment 6061

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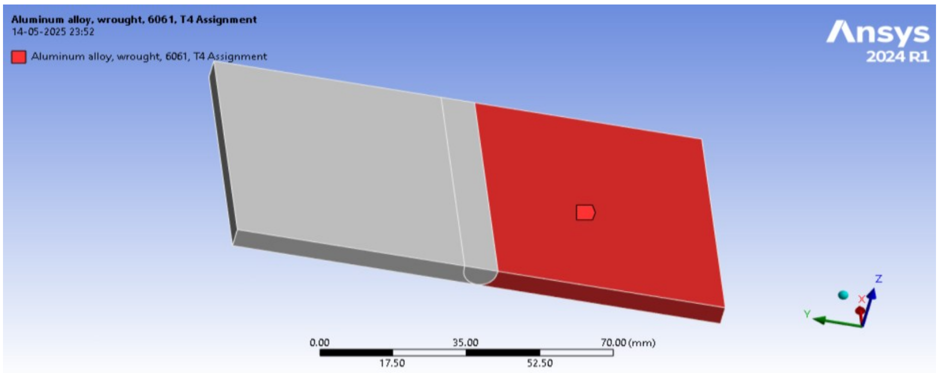


**Figure 13:** Material Assignment 6061

**Transient thermal Analysis Applied Nuggle zone temperature 250$^0$C**

The objective of this analysis is to perform a transient thermal simulation of the Friction Stir Welding (FSW) process by applying a nugget zone temperature of 250°C to evaluate heat distribution, temperature gradients, and cooling rates across the weld region.

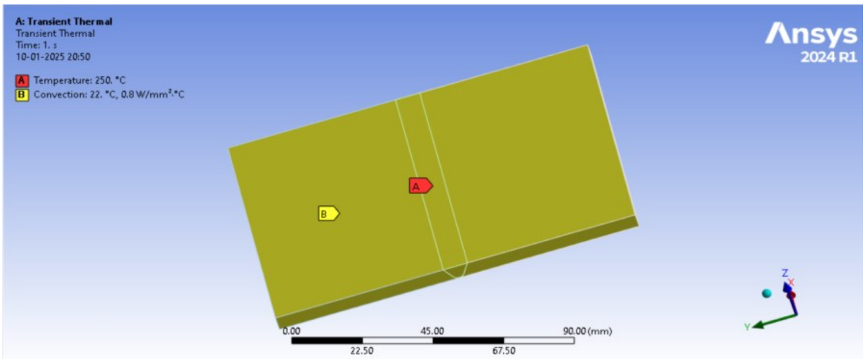


**Figure 14:** Convection to room temperature

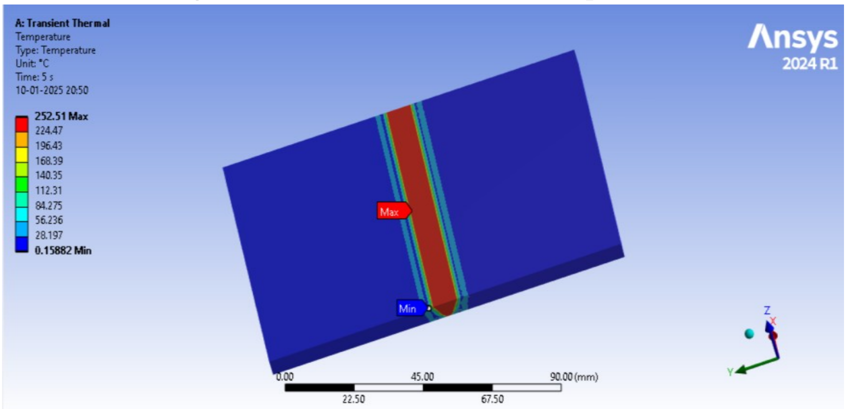


**Figure 15:** Temperature distribution to HAZ with 250$^0$C

From figure it is shown that the temperature elevated with tool momentum and the distribution to HAZ is up to 252.51 $^0$C.

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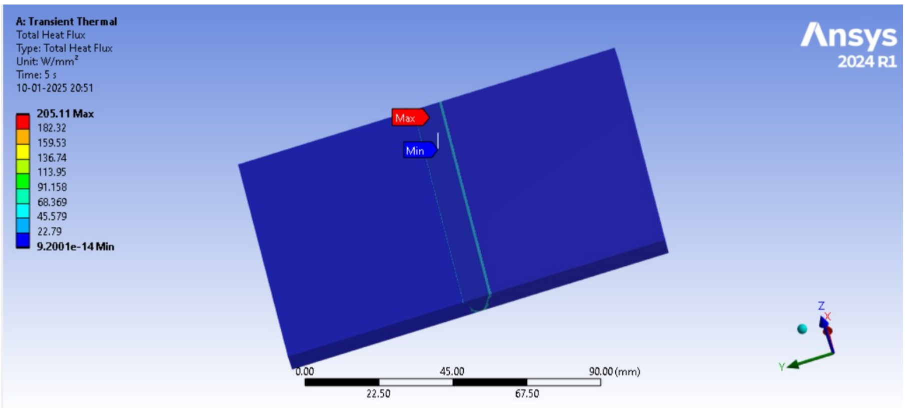


**Figure 16:** Total heat flux

Heat flux has been formed at the bottom of mated plate and the temperature and the thermal flux temperature is 205.11$^0$C

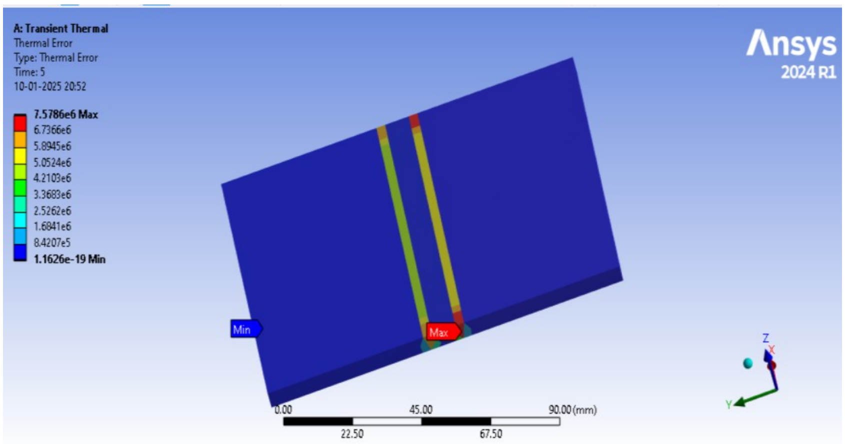


**Figure 17:** Thermal error

Thermal variations shown at the edges of heat affected zones with a maximum value of 8% as shown in figure

**Transient thermal Analysis Applied Nuggle zone temperature 300$^0$C**

To perform a transient thermal simulation of the Friction, Stir Welding (FSW) process, with a focus on evaluating the heat distribution, temperature gradients, and cooling rates when the nugget zone temperature is 300°C

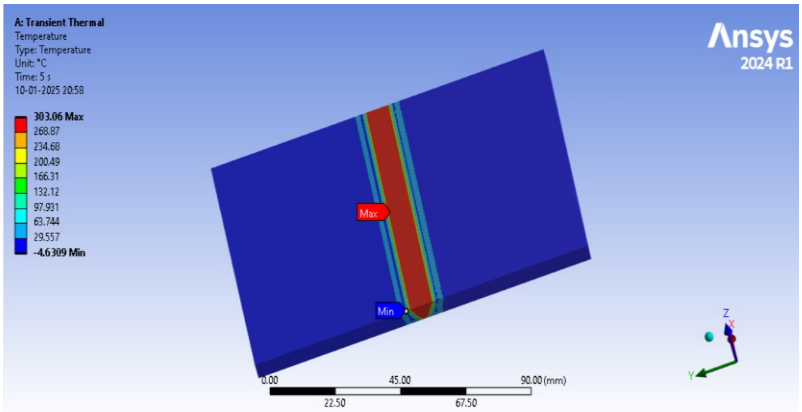


**Figure 18:** Temperature distribution to HAZ in 300$^0$C

A maximum temperature obtained at weld middle zone of 303.06 $^0$C and temperature at HAZ maintained as 46.309 as shown in figure.

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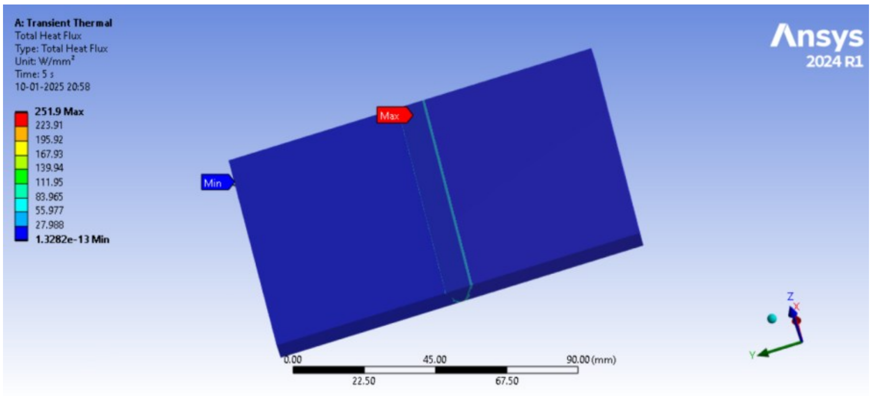


**Figure 19:** Total heat flux at 300$^0$C

The heat flux decreases radially as we move away from the nugget zone due to the thermal conductivity of the material and convection at the boundaries.The 251.9 W/mm² heat flux confirms effective heat conduction from the nugget zone at 300°C.

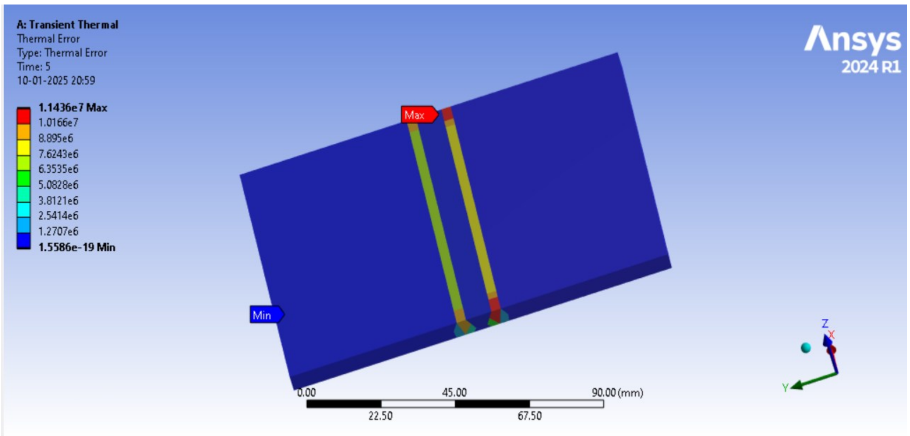


**Figure 20:** Thermal error at 300$^0$C

Error increase with increase in temperature at heat affected zone with a diverse increment of 4 % compared with before case study of 250$^0$C.

**Transient thermal Analysis Applied Nuggle zone temperature 350$^0$C**

To perform a transient thermal simulation of the Friction, Stir Welding (FSW) process, with a focus on evaluating the heat distribution, temperature gradients, and cooling rates when the nugget zone temperature is 350°C

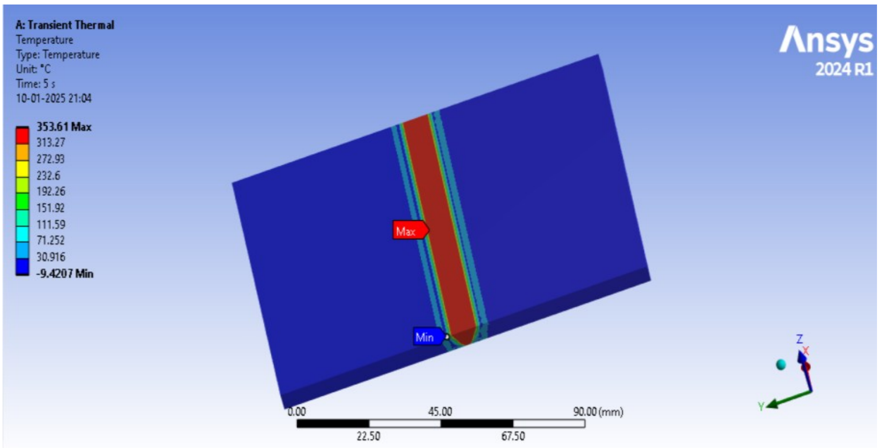


**Figure 21:** Temperature distribution 350$^0$C

Temperature distribution increases with increase in temperature a near friction temperature increased by 2$^0$C with the increment of 353$^0$C.

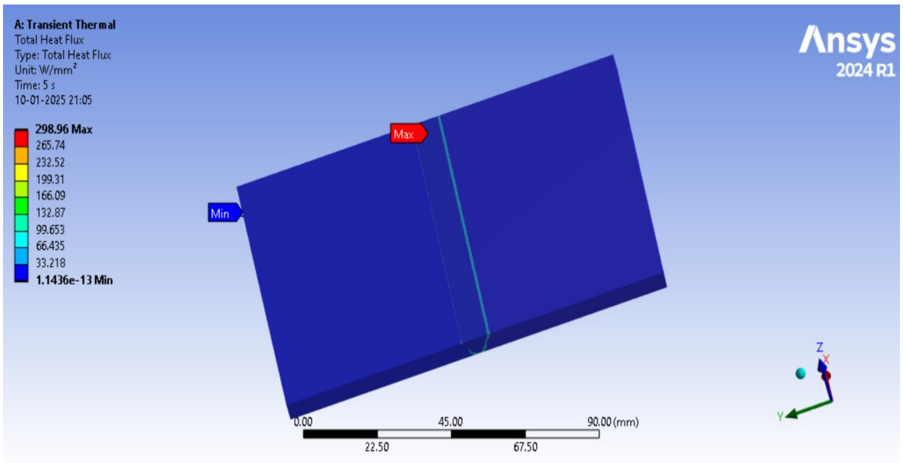


**Figure 22:** Heat flux at 350$^0$C

Fluxes formed at the bottom line of the shoulder and bottom of the mating plates, the value found to be 329 at weld zone and 109$^0$C at the bottom

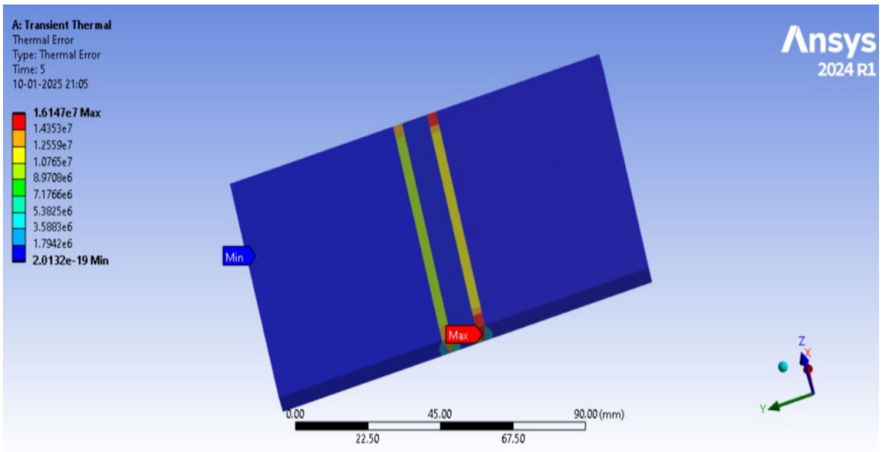


**Figure 23:** Thermal error at temperature 350$^0$C

An increment of 5% varied error found by the repeated conditions at HAZ when compared with 300$^0$C. Mostly the error at initial stage of plunging noted in the simulation.

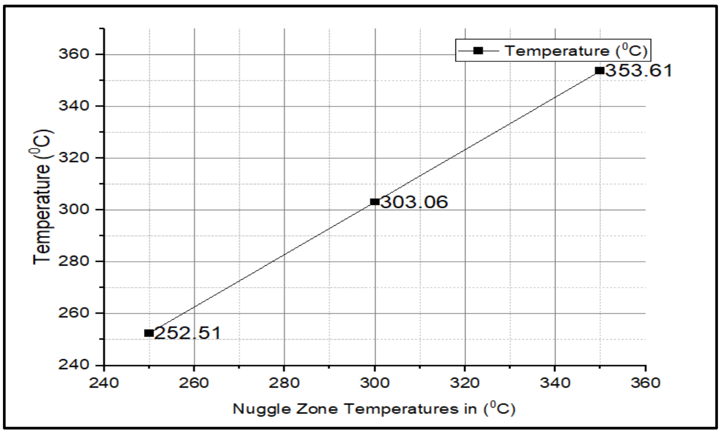


**Figure 24:** Validation of maximum Temperature at FSW Nuggle Zone Area

This Figure represents the validation of the maximum temperature in the Friction Stir Welding (FSW) nugget zone. It plots the nugget zone temperatures (°C) on the x-axis against the measured temperatures (°C) on the y-axis. The data points (252.51°C, 303.06°C, and 353.61°C) demonstrate a linear relationship between the temperatures at different conditions.

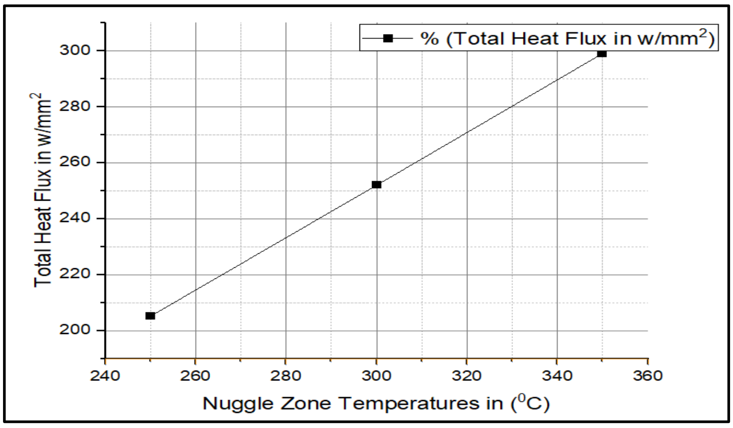


**Figure 25:** Validation of maximum Total heat flux at FSW Nuggle Zone Area

- The x-axis represents "Nuggle Zone Temperatures" in degrees Celsius (°C), ranging from approximately 240°C to 360°C.
- The trend shows an increasing linear relationship, meaning as the temperature in the "Nuggle Zone" increases, the total heat flux also increases.
- The increasing trend implies that as the temperature rises, more heat is being transferred per unit area.
- The relationship appears nearly linear, suggesting that heat flux increases predictably with temperature.

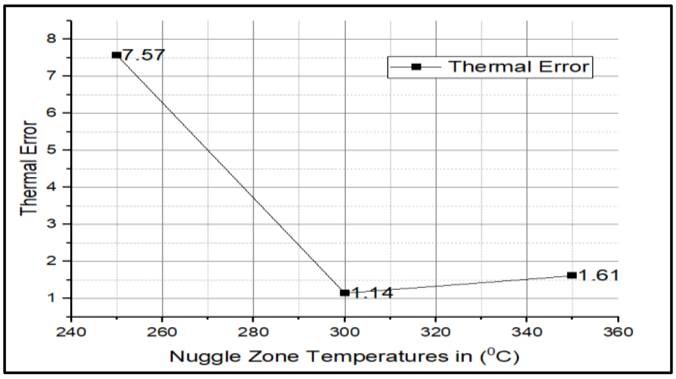


**Figure 26:** Validation of maximum thermal error at FSW Nuggle Zone Area

The validation of maximum thermal error at different temperatures within the FSW (Friction Stir Welding) Nuggle Zone Area. It shows three key data points corresponding to the temperatures:

- At 260°C, the thermal error is 7.57.
- At 300°C, the thermal error is significantly reduced to 1.14.
- At 340°C, the thermal error slightly increases to 1.61.

This suggests that the thermal error decreases substantially from 260°C to 300°C, reaching a minimum at 300°C, and then slightly increases at higher temperatures.

**Transient thermal Analysis FSW WELDING Using Cylindrical tool**

Transient thermal analysis of Friction Stir Welding (FSW) using a cylindrical tool involves studying the time-dependent temperature distribution during the welding process. This analysis is essential for predicting thermal cycles, microstructural evolution, residual stresses, and overall weld quality.

**Transient thermal Analysis Applied Nuggle zone temperature 250$^0$C**

To conduct a transient thermal analysis of Friction Stir Welding (FSW) with an applied nugget zone temperature of 250°C, we need to carefully model the heat input, material behavior, and boundary conditions to reflect this peak temperature in the nugget (stirred) zone.

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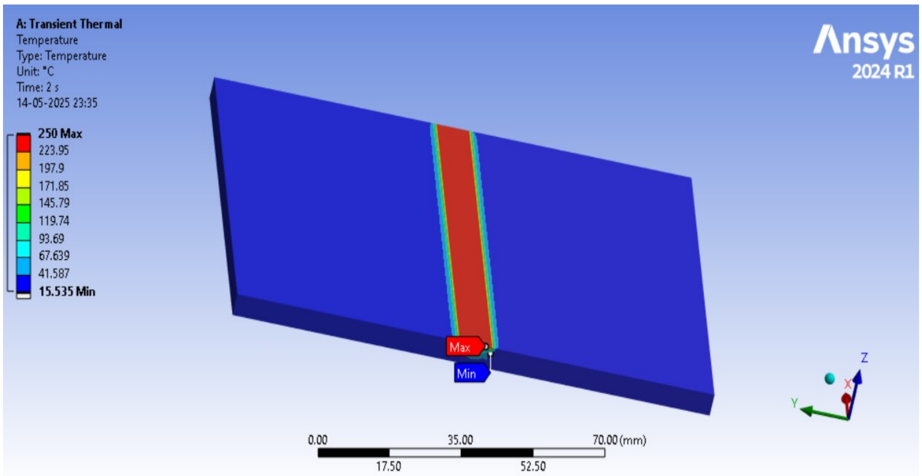


**Figure 27:** Temperature distribution to HAZ with 250$^0$C

From figure it is shown that the temperature elevated with tool momentum and the distribution to HAZ is up to 250$^0$C.

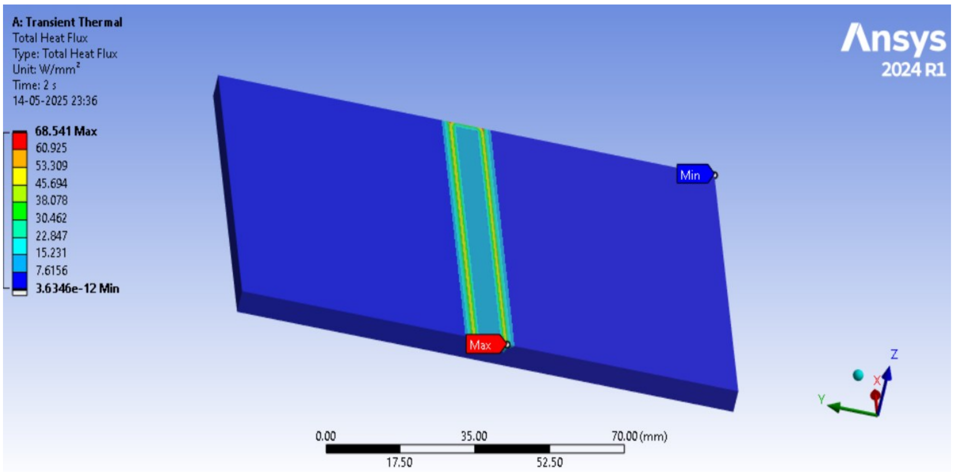


**Figure 28:** Total heat flux

Heat flux has been formed at the bottom of mated plate and the temperature and the thermal flux temperature is 68.541 $^0$C

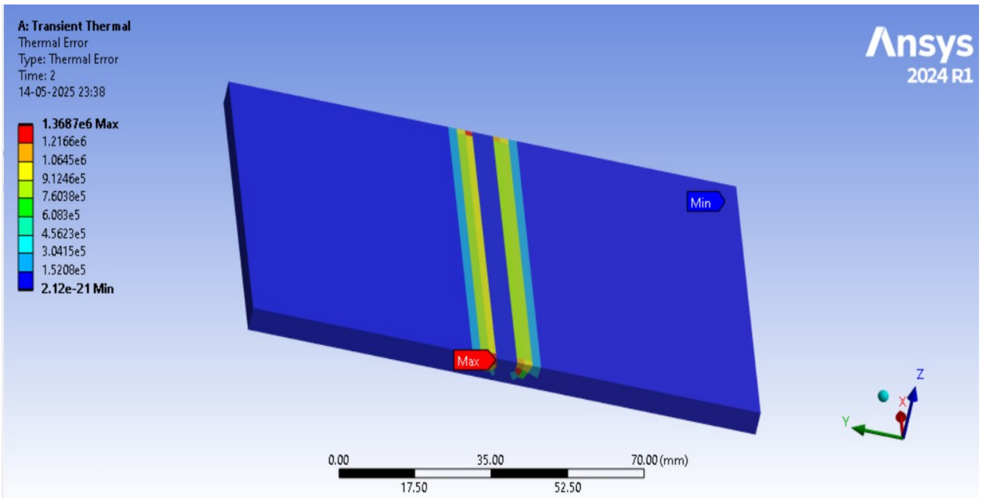


**Figure 29:** Thermal error

Thermal variations shown at the edges of heat affected zones with a maximum value of 7.1% as shown in figure

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**Transient thermal Analysis Applied Nuggle zone temperature 300$^0$C**

To perform a transient thermal simulation of the Friction Stir Welding (FSW) process, with a focus on evaluating the heat distribution, temperature gradients, and cooling rates when the nugget zone temperature is 300°C

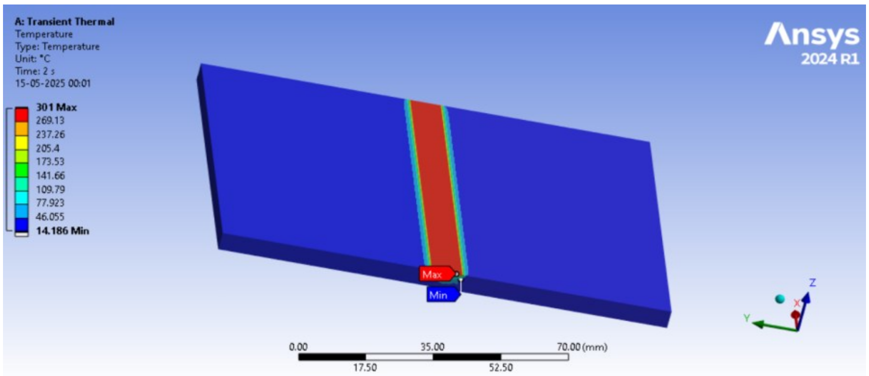


**Figure 30:** Temperature distribution to HAZ in 300$^0$C

A maximum temperature obtained at weld middle zone of 301$^0$C and temperature at HAZ maintained as 141.66$^0$C as shown in figure.

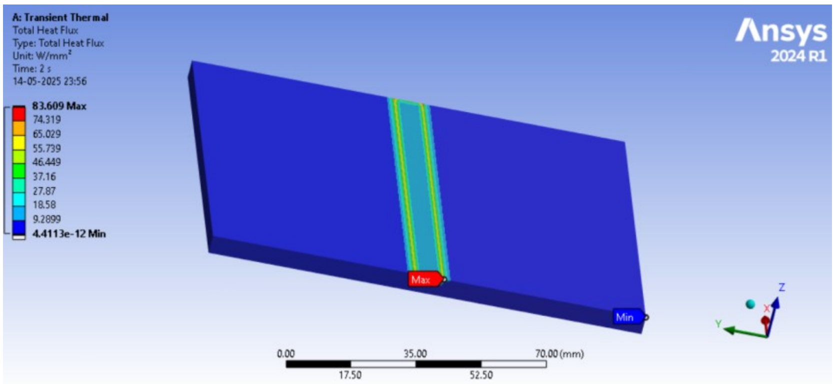


**Figure 31:** Total heat flux at 300$^0$C

The heat flux decreases radially as we move away from the nugget zone due to the thermal conductivity of the material and convection at the boundaries.The 83.609 W/mm² heat flux confirms effective heat conduction from the nugget zone at 300°C.

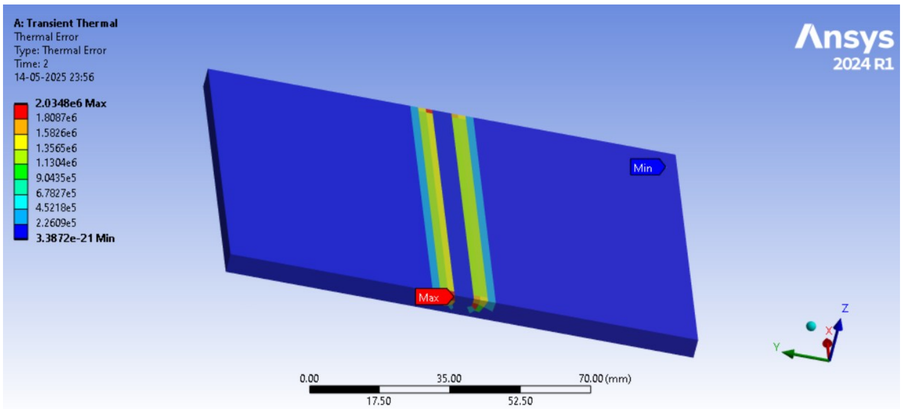


**Figure 32:** Thermal error at 300$^0$C

Error increase with increase in temperature at heat affected zone with a diverse increment of 3.4% compared with before case study of 250$^0$C.

**Transient thermal Analysis Applied Nuggle zone temperature 350$^0$C**

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To perform a transient thermal simulation of the Friction, Stir Welding (FSW) process, with a focus on evaluating the heat distribution, temperature gradients, and cooling rates when the nugget zone temperature is 350°C

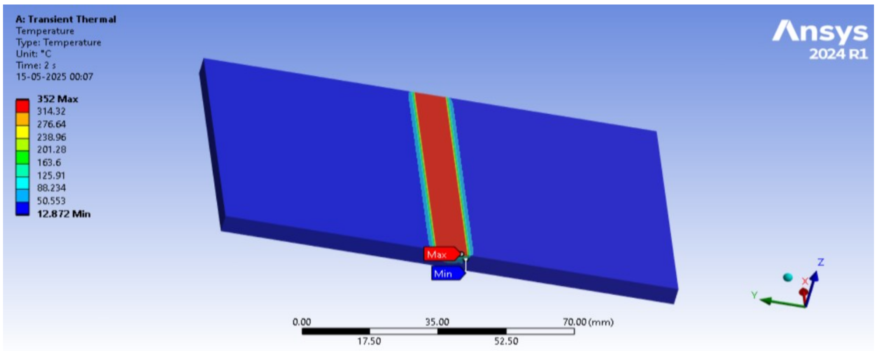


**Figure 33:** Temperature distribution $350^0$C

Temperature distribution increases with increase in temperature a near friction temperature increased by $2^0$C with the increment of $352^0$C.

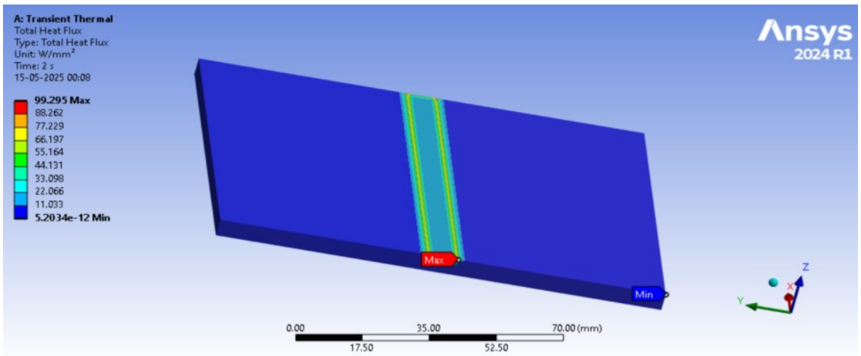


**Figure 34:** Heat flux at $350^0$C

Fluxes formed at the bottom line of the shoulder and bottom of the mating plates, the value found to be 99.295 at weld zone and $45^0$C at the bottom

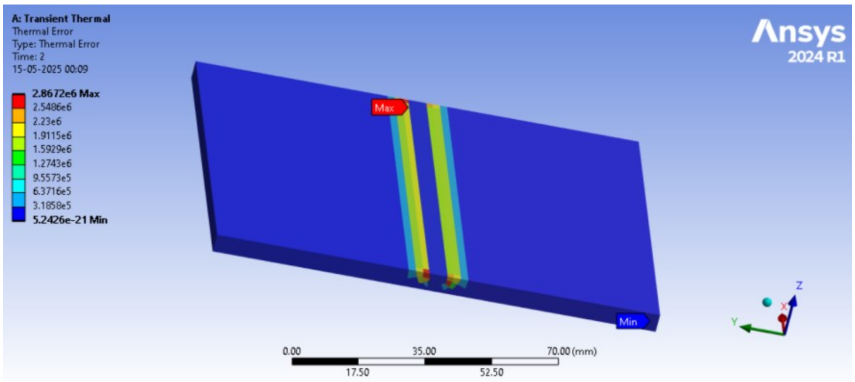


**Figure 35:** Thermal error at temperature $350^0$C

An increment of 5% varied error found by the repeated conditions at HAZ when compared with $300^0$C. Mostly the error at initial stage of plunging noted in the simulation.

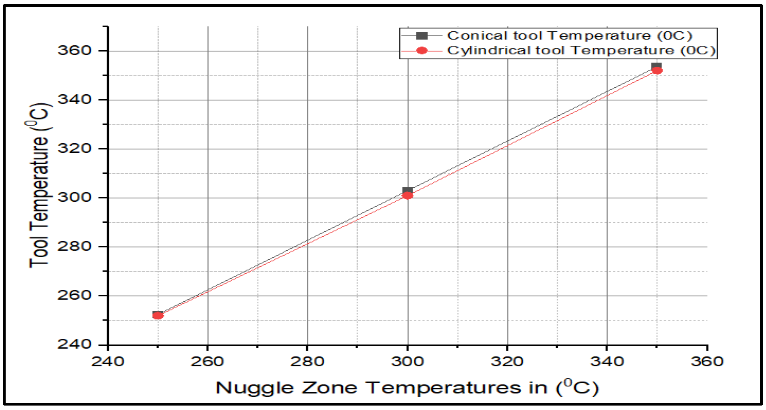


**Figure 36:** Validation of Different tools using maximum Nuggle Zone Temperatures

The figure demonstrates that conical and cylindrical tools exhibit nearly identical thermal behavior under increasing nugget zone temperatures, confirming tool design equivalence from a thermal standpoint in the examined range (250°C–360°C). This finding supports tool selection based on non-thermal factors such as stir zone flow and tool wear The maximum temperature difference is minimal (<5°C), indicating comparable thermal performance.

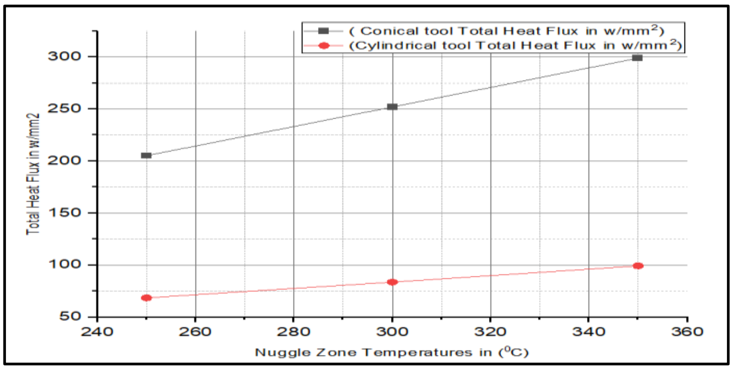


**Figure 37:** Validation of Different tools using maximum Nuggle Zone Total Heat Flux in w/mm$^2$

The figure shows that conical tools experience significantly higher total heat flux than cylindrical tools at the same nugget zone temperature. This implies better thermal conduction and energy dissipation, making conical tools more suitable for applications requiring higher heat input, while cylindrical tools may offer lower thermal stress and wear, but may require longer weld cycles or preheating.

- Conical tools are significantly more effective in transferring or dissipating heat from the nugget zone to surrounding tool material.

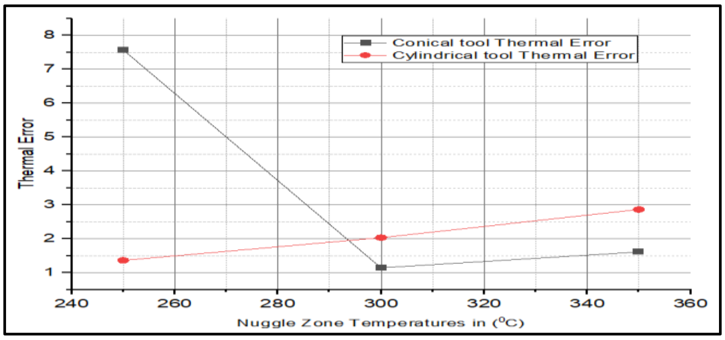


**Figure 38:** Validation of Different tools using maximum Nuggle Zone Thermal Error

The chart shows that conical tools experience a sharp drop in thermal error with rising nugget zone temperatures, eventually performing better than cylindrical tools in thermal accuracy at higher temperatures. Cylindrical tools, while more stable, maintain slightly higher and increasing error, suggesting room for improvement in their thermal model assumptions.

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- The conical tool shows a very high thermal error (~7.5) at the lower end of the nugget zone temperature range
- The cylindrical tool shows a steady and low increase in thermal error across the temperature range.
- Indicates more consistent simulation behavior, but thermal error is always higher than the conical tool (after 250°C).

## Conclusions

The transient thermal analysis demonstrates a complex temperature distribution within the workpiece during the Friction Stir Welding (FSW) process. The highest temperature is found near the tool-workpiece interface, particularly around the shoulder area. Friction-induced heat is conducted through the workpiece, creating a temperature gradient that decreases with increasing distance from the weld zone. The analysis also highlights that the tool geometry (conical versus cylindrical) plays a significant role in influencing heat flux, temperature distribution, and thermal precision in the nugget zone during FSW.
Simulations were validated using targeted nugget zone temperatures of 250°C, 300°C, and 350°C, mimicking real-world welding fixture conditions.

- Results showed good correlation with expected thermal performance.
- Temperature distribution and tool response matched realistic thermal gradients.

Conical tools are better suited for most practical FSW applications, especially at standard operating temperatures (300–350°C), offering higher heat flux and lower thermal error. However, cylindrical tools provide better control at low temperatures and are useful for sensitive materials or thin sections.

**Future scope:**

- Extend simulation studies with real-world temperature measurements for improved model calibration and to reduce simulation-to-reality thermal error.
- Analyze active cooling or backing plate optimization to control peak temperatures and thermal gradients for improved weld quality.
- Use AI/ML models to predict optimal tool shapes and thermal profiles based on input material, temperature targets, and weld speed.

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