

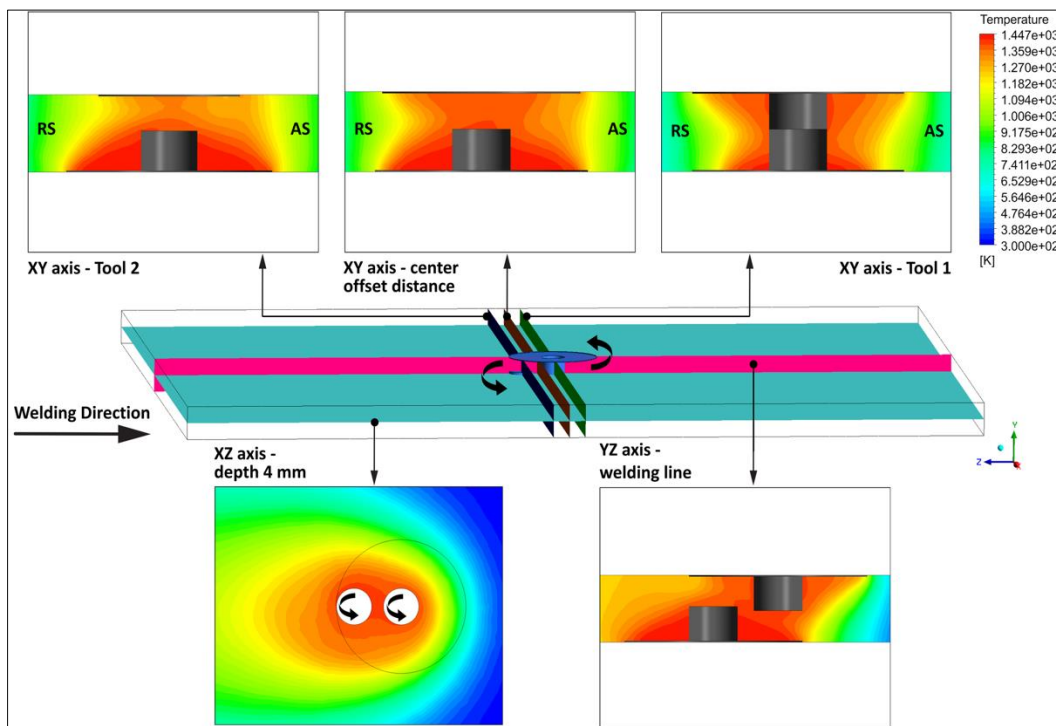
## Effect of tool rotation direction, pin overlap, and pin shape on material flow in one-step double-acting friction stir welding of stainless steel: A modeling study

Eko Prasetya Budiana<sup>1\*</sup>, Rian Firmanda<sup>1</sup>, Essam R. I. Mahmoud<sup>2</sup>, Triyono<sup>1\*</sup>

<sup>1</sup> Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

<sup>2</sup> Department of Mechanical Engineering, Islamic University of Madinah, Medina 42351, Saudi Arabia

✉ [ekoprasetya@staff.uns.ac.id](mailto:ekoprasetya@staff.uns.ac.id), [triyono74@staff.uns.ac.id](mailto:triyono74@staff.uns.ac.id)



### Highlights:

- DA-FSW improves penetration in thick stainless steel plates.
- CFD evaluates heat distribution and material flow during welding.
- Tapered triflate pins increase flow velocity by 15–20%.
- Opposing tool rotation improves mixing and reduces thermal gradients.
- Optimal pin overlap raises heat generation by 12% for stable flow.

### Article info

Submitted:  
2025-06-01

Revised:  
2026-03-15

Accepted:  
2026-03-30



This work is licensed under  
 a Creative Commons  
 Attribution-NonCommercial 4.0  
 International License

### Publisher

Universitas  
 Muhammadiyah  
 Magelang

### Abstract

Stainless steel is widely used in various industrial applications due to its excellent corrosion resistance and mechanical strength. However, conventional fusion welding of stainless steel often leads to several problems such as hot cracking, sensitization caused by chromium carbide precipitation, and large thermal distortion. Friction Stir Welding (FSW), a solid-state joining technique, has been developed to overcome these limitations by producing high-quality joints without melting the base material. Nevertheless, welding thick plates using conventional FSW frequently results in incomplete penetration. To address this limitation, a One-Step Double-Acting Friction Stir Welding (DA-FSW) technique is proposed, in which two tools operate simultaneously from the top and bottom surfaces of the workpiece. In this study, material flow behavior and heat distribution during DA-FSW of stainless steel are investigated using Computational Fluid Dynamics (CFD) simulation. The model considers variations in pin geometry (cylindrical, conical, triflate, and tapered triflate), tool rotation direction, and pin overlap. Stainless steel is modeled as a non-

Newtonian fluid to represent its plasticized behavior under frictional heating. The simulation results show that complex pin geometries such as tapered triflate produce up to 15–20% higher material flow velocity and generate a more uniform temperature distribution (approximately 5–10% variation across the stir zone) compared with simple cylindrical pins. Furthermore, opposite tool rotation directions improve material mixing and reduce temperature gradients, while an optimal pin overlap increases heat generation by approximately 12%, leading to more stable material flow. These results demonstrate that the combination of complex pin geometry, opposing rotation direction, and appropriate pin overlap significantly improves thermal distribution and material flow stability, which are essential for achieving defect-free welds in thick stainless steel plates.

**Keywords:** One-step double-acting FSW; Pin shape; Stainless steel; Material flow; Temperature distribution

## 1. Introduction

Stainless steel is extensively used in the automotive, railway, and construction industries due to its excellent corrosion resistance, durability, and ease of maintenance [1], [2]. The demand for this material continues to grow alongside the advancement of modern industries, which require materials with superior resistance to corrosion and elevated temperatures [3], [4]. These outstanding properties make stainless steel a preferred choice for a wide range of engineering applications.

Fusion welding is commonly employed to join stainless steel components. However, this method presents significant drawbacks, such as hot cracking due to low thermal conductivity and solidification mode transformations that increase cracking risks, particularly when the Cr/Ni ratio is around 1.5–1.6 [5], [6]. High carbon content exacerbates these issues by promoting the formation of chromium carbide ( $\text{Cr}_{23}\text{C}_6$ ) at grain boundaries, leading to sensitization and a reduction in corrosion resistance. Considering that corrosion accounts for over 80% of engineering failures, this is a serious concern [7], [8]. Furthermore, high thermal expansion coefficients often result in distortion during the welding process [9].

As an alternative, solid-state welding techniques such as Friction Stir Welding (FSW) have been increasingly developed [10]. FSW utilizes frictional heat generated by a rotating tool to plastically deform and join materials without melting them [11], thereby avoiding many of the issues associated with fusion welding. The advantages of FSW include improved mechanical properties, fewer welding defects, and a more uniform microstructure [12], [13], [14]. For thick-section applications, however, conventional FSW faces limitations, particularly regarding incomplete weld penetration. To address this, Double-Sided Friction Stir Welding (DSFSW) was introduced, employing alternating welding from both sides of the workpiece to enhance joint strength [15]. Nonetheless, this method still causes distortion in thick materials [16]. As a further innovation, the One-Step Double-Acting Friction Stir Welding (ODFSW) technique was developed, in which two tools operate simultaneously from the top and bottom sides of the workpiece. This approach enables a more uniform distribution of pressure and heat, resulting in improved joint quality and increased welding efficiency [17], [18], [19].

The success of the FSW process depends heavily on key parameters such as tool rotation speed, welding speed, axial force, tool material, and tool geometry [20]. Among these, material flow behavior during welding plays a critical role in determining the final microstructure and mechanical performance of the joint. According to the Eulerian perspective, material flow is driven by the tool pin from the Advancing Side (AS) to the Retreating Side (RS). To investigate this phenomenon, Computational Fluid Dynamics (CFD) simulations offer a powerful and cost-effective method for analyzing heat distribution and flow patterns without the high costs of physical experimentation [21].

Friction stir welding (FSW) has been widely investigated using computational fluid dynamics (CFD) to better understand the complex thermo-mechanical phenomena occurring during the welding process. CFD modeling enables detailed analysis of heat generation, material flow behavior, strain distribution, and temperature fields around the rotating tool, which are difficult to measure experimentally. Previous studies have shown that tool pin geometry significantly influences plastic material flow and defect formation. For instance, tapered threaded pins were reported to improve plastic flow distribution and minimize micro-defects on the retreating side of the weld [22]. Similarly, CFD simulations demonstrated that combining threaded pins with triple facets increased frictional heat generation and enhanced joint homogeneity, particularly for thick

plates [23]. Thermal distribution during FSW also plays a crucial role in controlling plastic deformation and microstructural evolution. It has been reported that counter-rotating tools in synergistic double-sided FSW can refine the microstructure and improve tensile strength by promoting more uniform material flow [24]. Furthermore, temperature control at the tool–workpiece interface helps stabilize the thermo-mechanically affected zone and reduce defect formation, which can be effectively predicted using CFD modeling [25]. In addition, several studies have reported that welding parameters such as rotational speed, traverse speed, and tool geometry significantly influence heat generation and material flow patterns in the stir zone [26], [27], [28].

Despite numerous advancements in understanding material flow during friction stir welding (FSW), most studies have concentrated on conventional tool configurations and more readily weldable materials such as aluminum alloys. In contrast, the application of the One-Step Double-Acting FSW method to high-melting-point materials like 304 stainless steel remains underexplored. This tool configuration introduces unique flow dynamics due to the simultaneous application of axial and rotational forces from both sides of the workpiece, resulting in complex thermomechanical interactions that differ significantly from conventional FSW. Modeling the material flow under this configuration poses additional challenges, as the phenomena involved are highly nonlinear and influenced by multiple interacting parameters such as pin overlap and opposing tool rotation. Experimental validation of flow patterns is especially difficult for 304 stainless steel due to its high melting point, which limits the choice of suitable tool materials and

complicates direct visualization of the material flow. Given these constraints, this study adopts a computational approach using Computational Fluid Dynamics (CFD) to investigate material flow under various pin geometries, tool rotation directions, and pin overlaps. Although modeling techniques for FSW are relatively well established, the novelty of this work lies in its application to a double-acting tool configuration with thick-section 304 stainless steel. It is a rarely explored combination. Furthermore, the simulation is validated indirectly through temperature distribution profiles, which are compared to established experimental data. This approach is justified because temperature distribution governs the material's viscosity, which in turn affects plastic deformation and ultimately material flow behavior. Thus, the proposed study not only addresses a clear gap in the literature but also offers a methodological contribution by adapting simulation-based validation for complex, high-temperature welding conditions. The findings are expected to inform more efficient and reliable FSW practices for stainless steel applications in demanding structural contexts.

## 2. Numerical Method

CFD simulations were employed to analyze the material flow behavior under steady-state conditions using a heat transfer approach. The overall research workflow for the One-Step Double-Acting Friction Stir Welding (ODFSW) process is illustrated in Figure 1. The workpiece material, AISI 304 stainless steel, was modeled as a non-Newtonian fluid whose viscosity depends on both temperature and strain rate, to accurately represent its plastic deformation behavior during the welding process [29].

The FSW tool was assumed to be a rigid body, interacting with the workpiece through frictional con-

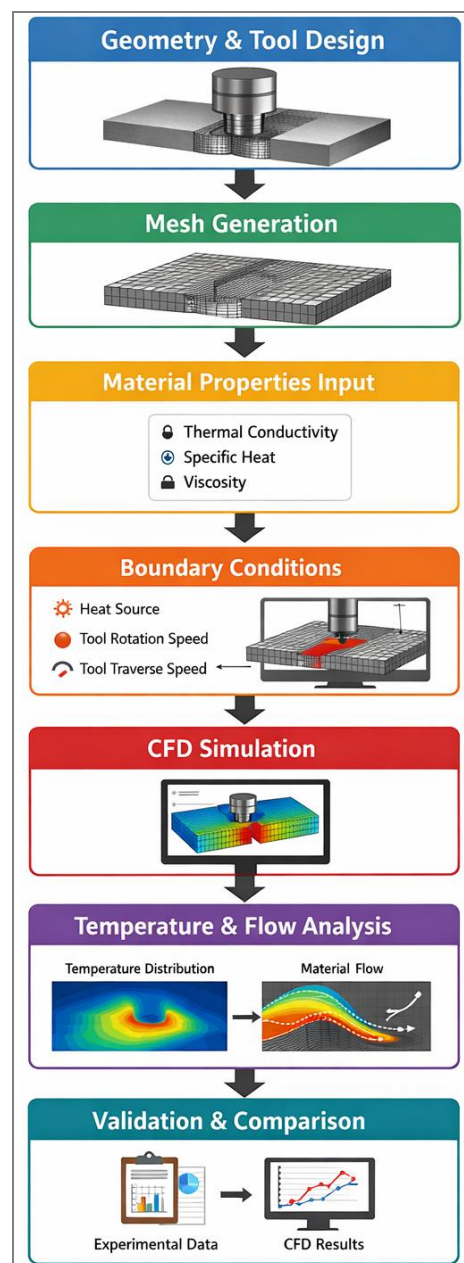
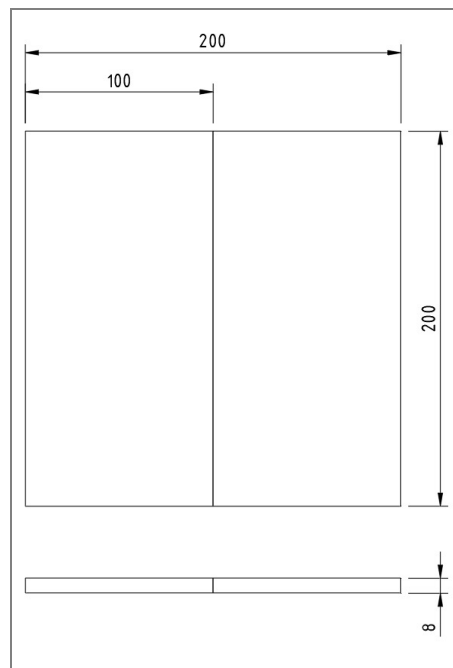


Figure 1.  
Flowchart in modeling of  
FSW material flow

**Figure 2.**  
Geometry of joined  
plate



tact without undergoing deformation [30]. A three-dimensional model was developed to represent two tools operating simultaneously on the upper and lower surfaces of the workpiece. The model comprised two primary geometric domains: the workpiece and the tool. The workpiece had dimensions of  $200 \times 200 \times 8$  mm, as shown in Figure 2. Four different pin geometries were modeled: cylindrical pin, conical pin, triflat pin, and tapered triflat pin, illustrated in Figure 3. Figure 4 provides a schematic of the ODFSW modeling process.

Material properties of AISI 304 are listed in Table 1, while the tool parameters are presented in Table 2. Two tool rotation configurations were modeled: Counter-Counter (CC), as shown in Figure 5a, and Counter-Reversing (CR), as shown in Figure 5b. The FSW process was modeled based on fundamental fluid dynamics principles—mass conservation, momentum conservation, and energy conservation [31]. The continuity equation ensures mass conservation under the assumption of incompressible flow:

Momentum conservation was expressed using the Navier-Stokes equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

where  $u$ ,  $v$ , and  $w$  are the velocity components in the  $x$ ,  $y$ , and  $z$  directions, respectively.

**Figure 3.**  
Pin geometry:  
(a) Cylindrical;  
(b) Conical;  
(c) Triflat;  
(d) Tapered triflate

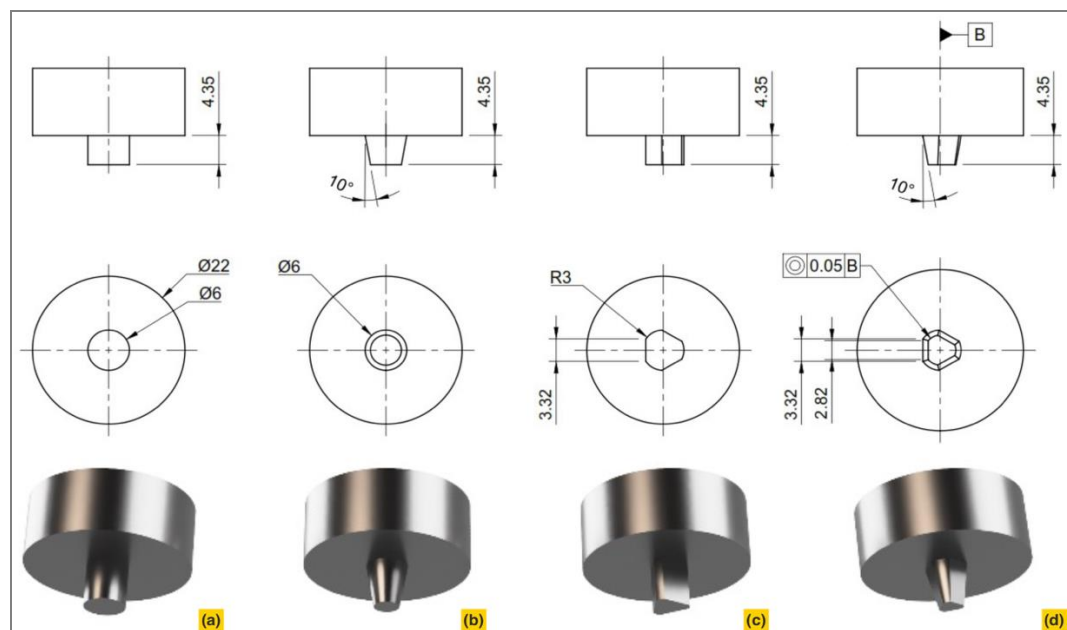
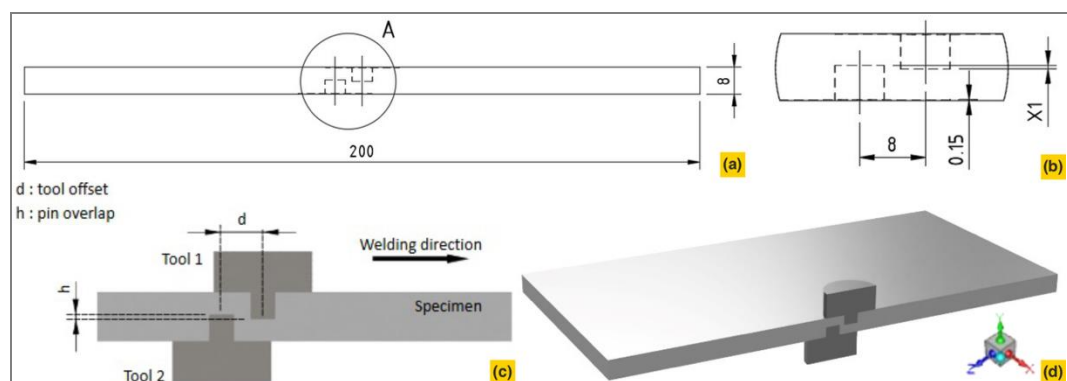
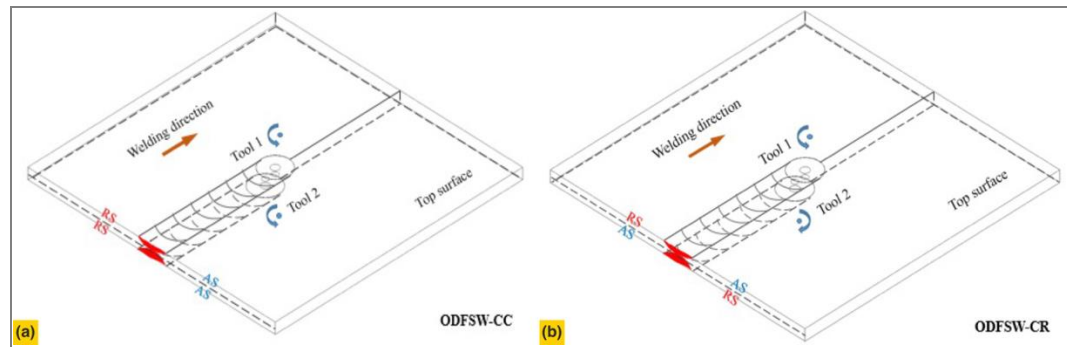


**Figure 4.**  
Tool offset and pin  
overlap illustration in  
one-step double-acting  
FSW:  
(a) Dimension;  
(b) Detail A;  
(c) 2D view;  
(d) 3D view



**Figure 5.**

Tool rotation direction:  
(a) CC;  
(b) CR

Momentum conservation was expressed using the Navier-Stokes equations:

$$\rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho g_x - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2)$$

$$\rho \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \rho g_y - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (3)$$

$$\rho \left( u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (4)$$

where  $\rho$  is the material density ( $\text{kg/m}^3$ ),  $\mu$  is the viscosity ( $\text{Pa}\cdot\text{s}$ ),  $p$  is the pressure ( $\text{Pa}$ ), and  $g_x$ ,  $g_y$ ,  $g_z$  are the gravitational acceleration components.

Thermal behavior was modeled using the energy conservation equation:

$$\rho \cdot C_p \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \dot{q} \quad (5)$$

where  $C_p$  is the specific heat capacity ( $\text{J/kg}\cdot\text{K}$ ),  $k$  is the thermal conductivity ( $\text{W/m}\cdot\text{K}$ ),  $\dot{q}$  is the volumetric heat source ( $\text{W/m}^3$ ), and  $T$  is the temperature ( $\text{K}$ ).

**Table 1.**  
Physical and thermal  
properties of AISI 304  
[32], [33]

| Parameter                        | Value                          |
|----------------------------------|--------------------------------|
| Density ( $\rho$ )               | 8000 $\text{kg/m}^3$           |
| Melting point ( $T_m$ )          | 1723 K                         |
| Thermal conductivity ( $k$ )     | 16.2 $\text{W/m}\cdot\text{K}$ |
| Specific heat capacity ( $C_p$ ) | 500 $\text{J/kg}\cdot\text{K}$ |

**Table 2.**  
Properties of tool

| Parameter                | Value           |
|--------------------------|-----------------|
| Shoulder diameter        | 22 mm           |
| Plunge depth             | 0.15 mm         |
| Pin diameter             | 6 mm            |
| Angle of pin taper       | 10°             |
| Shoulder offset distance | 8 mm            |
| Pin overlap              | 0.5 mm, 1 mm    |
| Pin length               | 4.1 mm, 4.35 mm |

**Table 3.**  
Research parameters  
and number of nodes  
and elements

| Pin overlap | Pin shape        | Nodes  |
|-------------|------------------|--------|
| 0.5 mm      | Cylindrical      | 71,716 |
|             | Conical          | 71,072 |
|             | Triflate         | 71,467 |
| 1 mm        | Tapered triflate | 69,601 |
|             | Cylindrical      | 71,987 |
|             | Conical          | 71,281 |
|             | Triflate         | 71,891 |
|             | Tapered triflate | 69,639 |

Meshing was performed using tetrahedral elements to accommodate the complex geometry. A mesh refinement zone with 0.4 mm element size was applied near the tool area, while a coarser mesh (2 mm) was used around the weld path and workpiece edges, following default settings in CFD software. The number of nodes and elements for each pin geometry is provided in [Table 3](#), and mesh visualizations are shown in [Figure 6](#) and [Figure 7](#).

Boundary conditions were defined to reflect the physical phenomena, particularly thermal aspects, as shown in [Figure 8](#). A heat flux was applied at the tool–workpiece interface, with the initial workpiece temperature assumed to be uniformly 300 K. Convective heat transfer was used to model cooling, with heat transfer coefficients of 30  $\text{W/m}^2\cdot\text{K}$  for air and 240  $\text{W/m}^2\cdot\text{K}$  for the chuck, as referenced in [\[28\]](#).

The workpiece was modeled as a pseudoplastic material with temperature-dependent viscosity. The welding speed was set at 80 mm/min, while the tool rotated at 550 rpm. This rotation induced plastic deformation, leading to material softening and temperature distribution around the tool. Both the inlet and outlet pressures were set to 0 Pa, ensuring that material movement was solely driven by plastic deformation and thermal effects rather than external pressure influences.

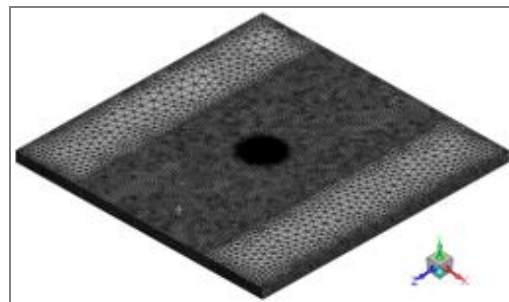


**Figure 6.**  
Meshing geometry

**Figure 7.**  
Tool meshing:  
(a) Cylindrical;  
(b) Conical;  
(c) Triflat;  
(d) Tapered triflat

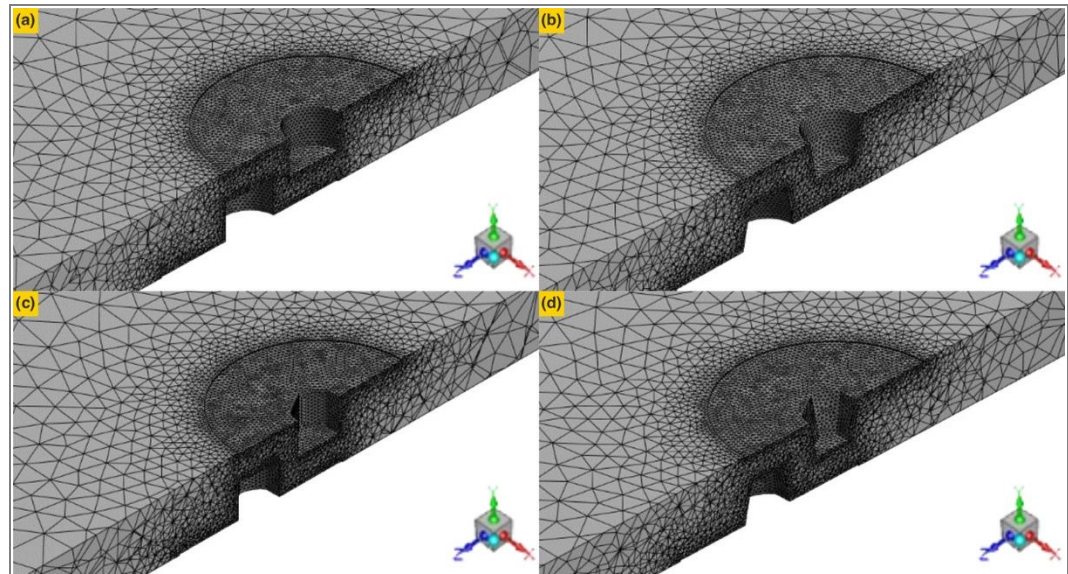


**Figure 8.**  
Boundary conditions

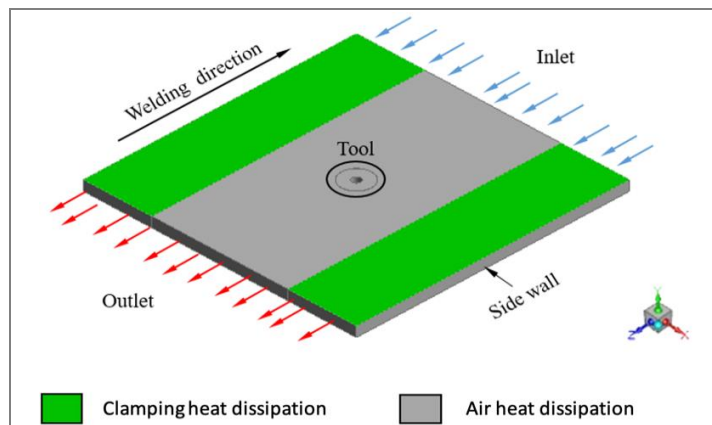
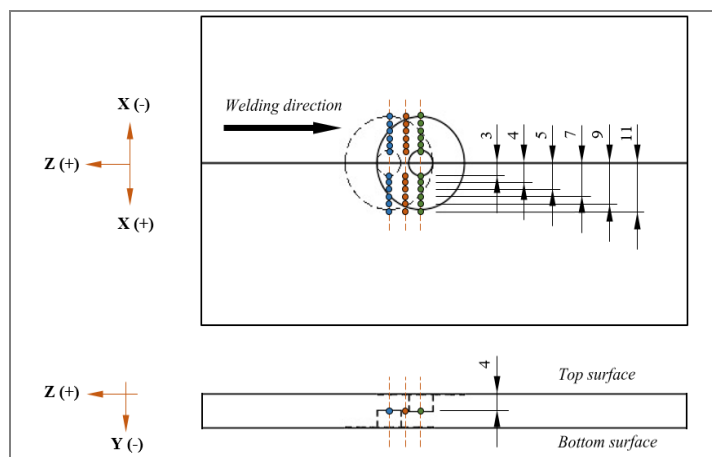
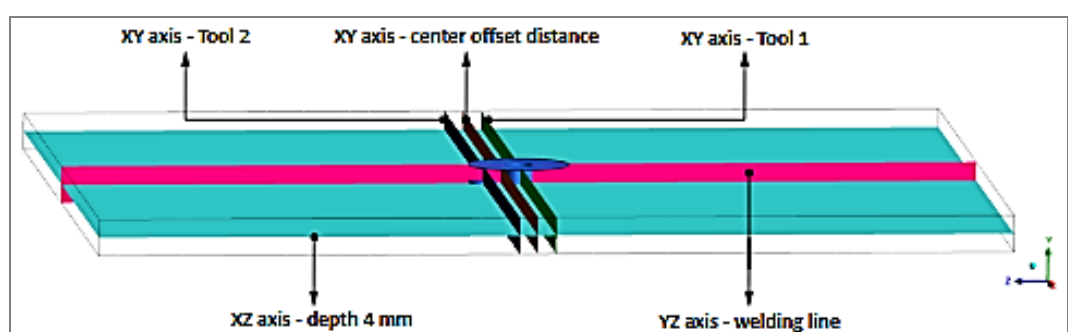


**Figure 9.**  
Points of temperature measurement



Data collection from the simulation included temperature distribution and velocity vector fields at specified points and planes. Temperature measurements, illustrated in [Figure 9](#), were taken at a 4 mm depth using six observation points on both the advancing side (AS) and retreating side (RS), positioned 3 mm, 4 mm, 5 mm, 7 mm, 9 mm, and 11 mm from the tool center. These locations were categorized by position relative to the tools: Tool 1 (T1) marked in green, the middle region (MID) in orange, and Tool 2 (T2) in blue. [Figure 10](#) presents visualizations of the velocity vector field at a 4 mm depth and at the mid-weld plane.

**Figure 10.**  
Selected planes for displaying material flow velocity vectors



### 3. Results and Discussion

#### 3.1. Validation Method

To evaluate the accuracy of the modeling approach developed in this study, a validation process was conducted by comparing the simulation results with experimental reference data reported by Pal *et al.* [28]. In their study, AISI 304 stainless steel was used as the workpiece material, while the tool was made of polycrystalline cubic boron nitride (PcBN). The workpiece dimensions were 150 mm × 140 mm × 6.25 mm, with process parameters including a rotational speed of 550 rpm and a welding speed of 80 mm/min. The temperature data used for validation were obtained from experimental measurements reported in the literature.

The primary goal of this validation was to confirm that the developed numerical model for Friction Stir Welding (FSW) can accurately replicate real-world thermal behavior and is applicable to the One-Step Double-Acting FSW (ODFSW) configuration. Temperature distribution was selected as the key metric for validation, given its fundamental role in influencing material viscosity, plastic deformation, and ultimately, material flow.

Temperature profiles were compared at four locations across the workpiece, measured at distances of 4 mm, 8 mm, 12 mm, and 16 mm from the weld line. The comparison results, presented in Figure 11, demonstrate a strong agreement between the current simulation and the reference data, with an average error of just 3.07%. This low error margin indicates that the model is highly accurate in capturing the thermal behavior of the FSW process.

Using temperature distribution as a validation benchmark is justified due to its direct correlation with the physical mechanisms that drive material flow. Heat generation during FSW

alters the material's viscosity, enabling plastic deformation, which in turn governs flow patterns. Therefore, accurate thermal modeling is essential for reliable prediction of material flow. This indirect validation approach is particularly valuable in complex configurations like ODFSW involving high-strength, high-melting-point materials, where direct observation or tracer-based flow validation is often impractical.

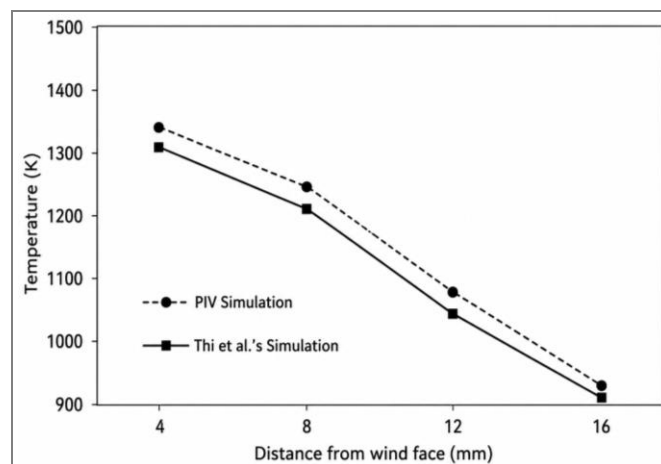


Figure 11.  
Temperature validation

#### 3.2. Temperature Contour

Temperature distribution is a key factor influencing weld quality in the One-Step Double-Acting Friction Stir Welding (ODFSW) process. In this study, temperature was evaluated at three representative positions: tool 1 (T1), the midpoint between the tools (MID), and tool 2 (T2). The analysis considered variations in pin geometry, tool rotation direction, and pin overlap distance. Two overlap distances (0.5 mm and 1 mm) were examined, combined with two rotation strategies: counter-counter (CC) and counter-reversing (CR).

For the cylindrical pin configuration, the temperature distribution is illustrated in Figure 12 for a 0.5 mm overlap. Along the longitudinal direction (XY plane), the CC rotation produced a nearly symmetrical temperature profile through the plate thickness, although localized heat accumulation occurred near tool 2 on the retreating side (RS). At a measurement depth of 4 mm, the maximum temperature reached 1388.83 K at T1 and 1404.76 K at T2, indicating increased friction and plastic deformation due to material accumulation near the second tool. In contrast, the CR rotation direction resulted in a more uniform thermal distribution, with peak temperatures of 1325.82 K at T1, 1340.99 K at MID, and 1376.64 K at T2. This distribution suggests a more stable thermomechanical interaction, as aligning the tool rotation with the welding direction promotes smoother material flow [24]. Along the welding direction (XZ plane), the CC rotation generated a slightly asymmetric heat distribution with heat concentration toward the trailing side. Meanwhile, the CR rotation produced a more balanced temperature field, indicating improved thermal stability during the welding process.

Increasing the overlap distance to 1 mm (Figure 13) generally resulted in higher maximum temperatures for both rotation strategies. The larger overlap increases the contact area between the tools and the workpiece, which enhances frictional interaction and plastic deformation. Despite this increase in peak temperature, the overall temperature distribution pattern remained similar to that observed for the 0.5 mm overlap condition. The influence of pin geometry on the thermal field is presented in Figure 14–Figure 16. Although different geometries produce variations in peak temperature, the overall distribution pattern remains primarily governed by tool rotation direction. Under CC rotation, heat tends to accumulate toward the retreating side, while CR rotation generates a more centralized and uniform temperature distribution. Among the geometries investigated, the conical pin produced a slightly more diffuse temperature field due to its smaller contact area compared to the cylindrical pin [22]. At a depth of 4 mm, the CC rotation produced temperatures of 1373.94 K at T1 and 1390.25 K at T2. Under CR rotation, the temperature distribution was more balanced, with values of 1312.12 K at T1, 1333.89 K at MID, and 1368.17 K at T2.

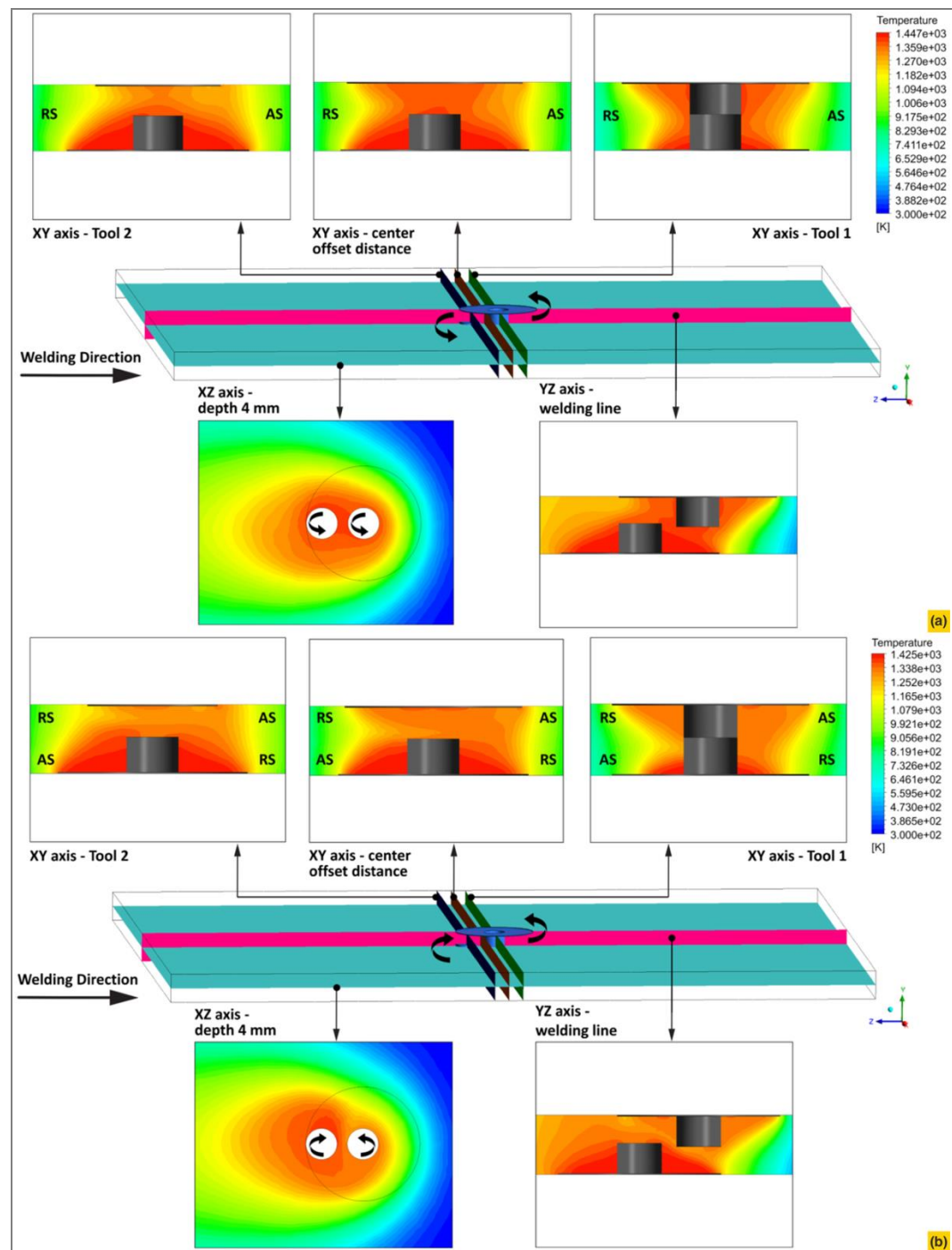


**Figure 12.**  
Temperature contours  
for the cylindrical pin  
with 0.5 mm overlap  
under:  
(a) Counter-counter  
(CC) rotation direction;  
(b) Counter-reversing  
(CR) rotation direction

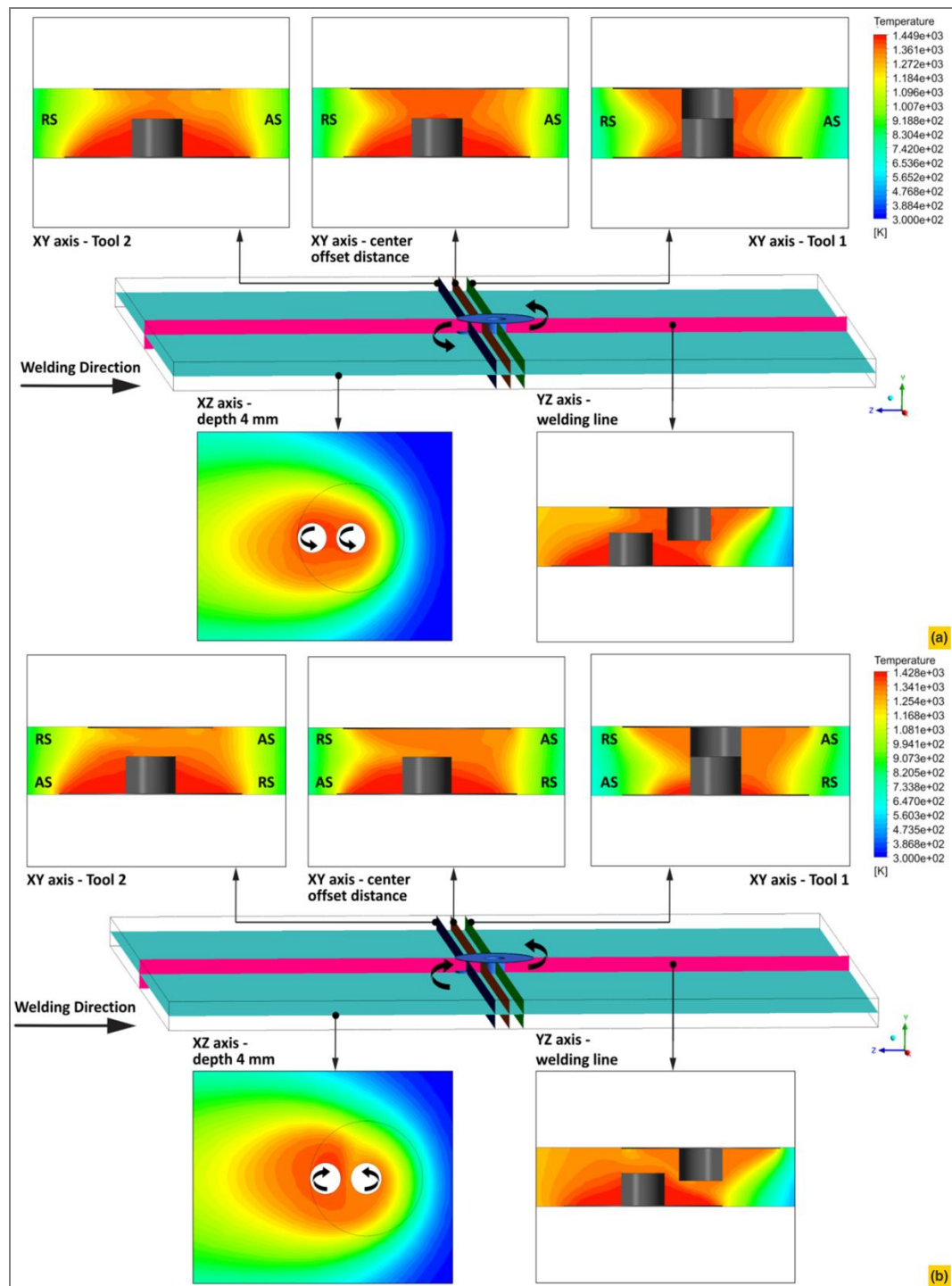


**Figure 13.**  
Temperature contours  
for the cylindrical pin  
with 1 mm overlap  
under:  
(a) Counter-counter  
(CC) rotation direction;  
(b) Counter-reversing  
(CR) rotation direction

The triflate pin generated the highest peak temperatures among the geometries studied. Its flat surfaces enhance stirring action and promote stronger material flow from the retreating side to the advancing side, leading to increased plastic deformation [23]. Under CC rotation, the peak temperature reached 1394.33 K, while CR rotation produced a slightly lower but more uniform temperature distribution. The higher temperature generated by the triflate pin can be attributed to its flat-sided geometry, which increases the contact surface between the tool and the plasticized material. This geometry enhances shear deformation and stirring intensity, resulting in greater frictional heat generation and increased plastic work within the stir zone.

In contrast, the tapered triflate pin generated the lowest peak temperatures because the tapered profile gradually reduces the contact pressure along the pin length. This geometry distributes the deformation more evenly through the thickness, reducing localized frictional resistance and consequently lowering the amount of heat generated during the welding process. In addition, this hybrid geometry combines the gradual penetration of the conical pin with the stirring effect of the triflate profile, resulting in more distributed heat generation. For a 0.5 mm

overlap under CC rotation, temperatures reached 1378.97 K at T1 and 1386.07 K at T2, while CR rotation produced lower values of 1307.68 K at T1, 1327.88 K at MID, and 1369.31 K at T2. The temperature field in the ODFSW process is strongly influenced by pin geometry and tool rotation strategy. Cylindrical pins provide stable heat generation but may concentrate heat near the tool bottom. Conical pins promote deeper thermal penetration, whereas triflate pins intensify stirring and plastic deformation, resulting in higher peak temperatures. The tapered triflate geometry produces more distributed heat with lower temperature peaks. Among the rotation strategies, the CR configuration consistently generates a more uniform and symmetrical temperature distribution along the weld zone, indicating improved thermomechanical stability. In most configurations, the highest temperatures occur near T2 due to cumulative heating caused by sequential deformation under both tools [33]. Increasing the pin overlap further intensifies heat generation by enlarging the tool-workpiece contact area, thereby enhancing friction and plastic deformation during the welding process [34].

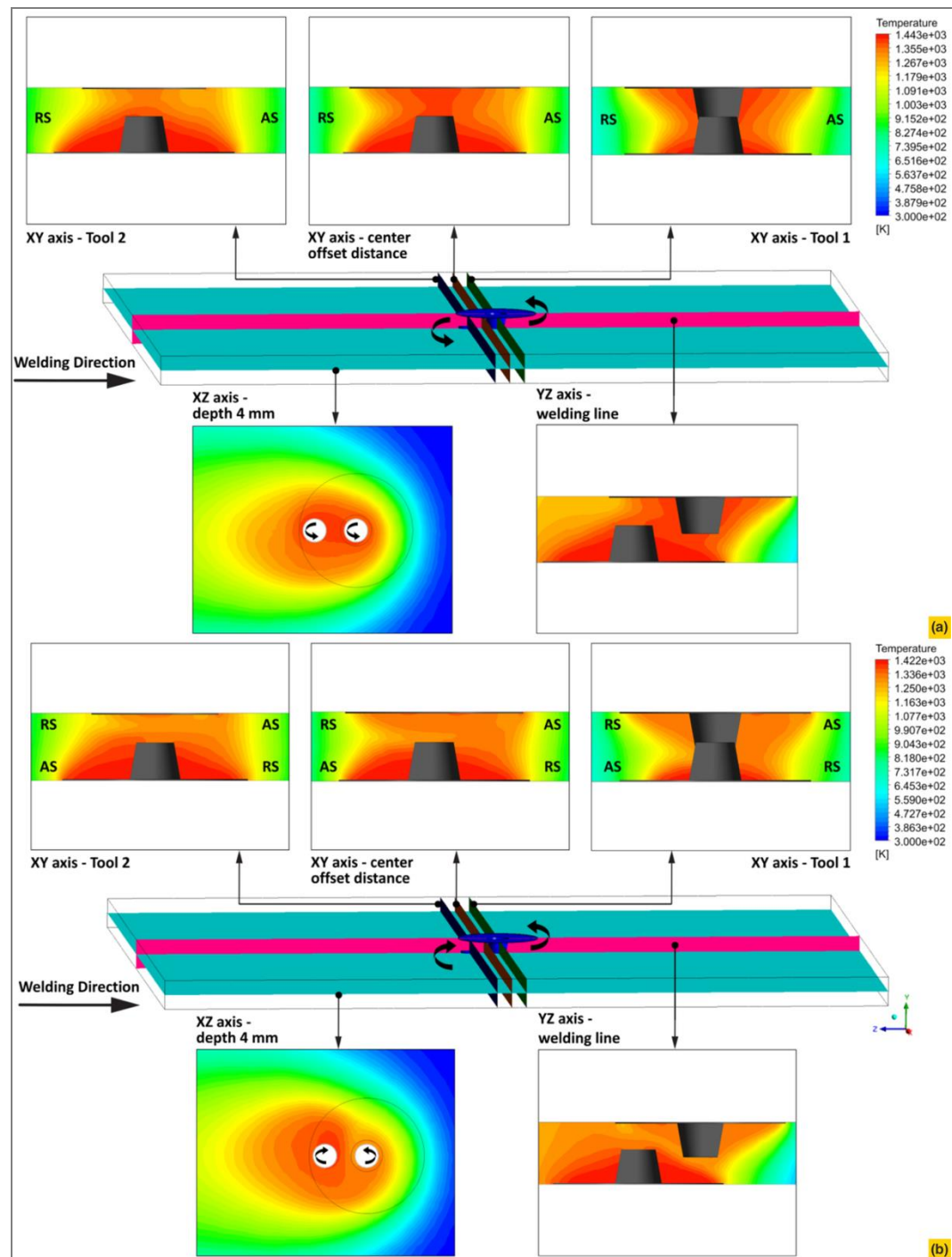


**Figure 14.**  
Temperature contours  
of pin overlap 1 mm:  
(a) Conical-CC;  
(b) Conical-CR

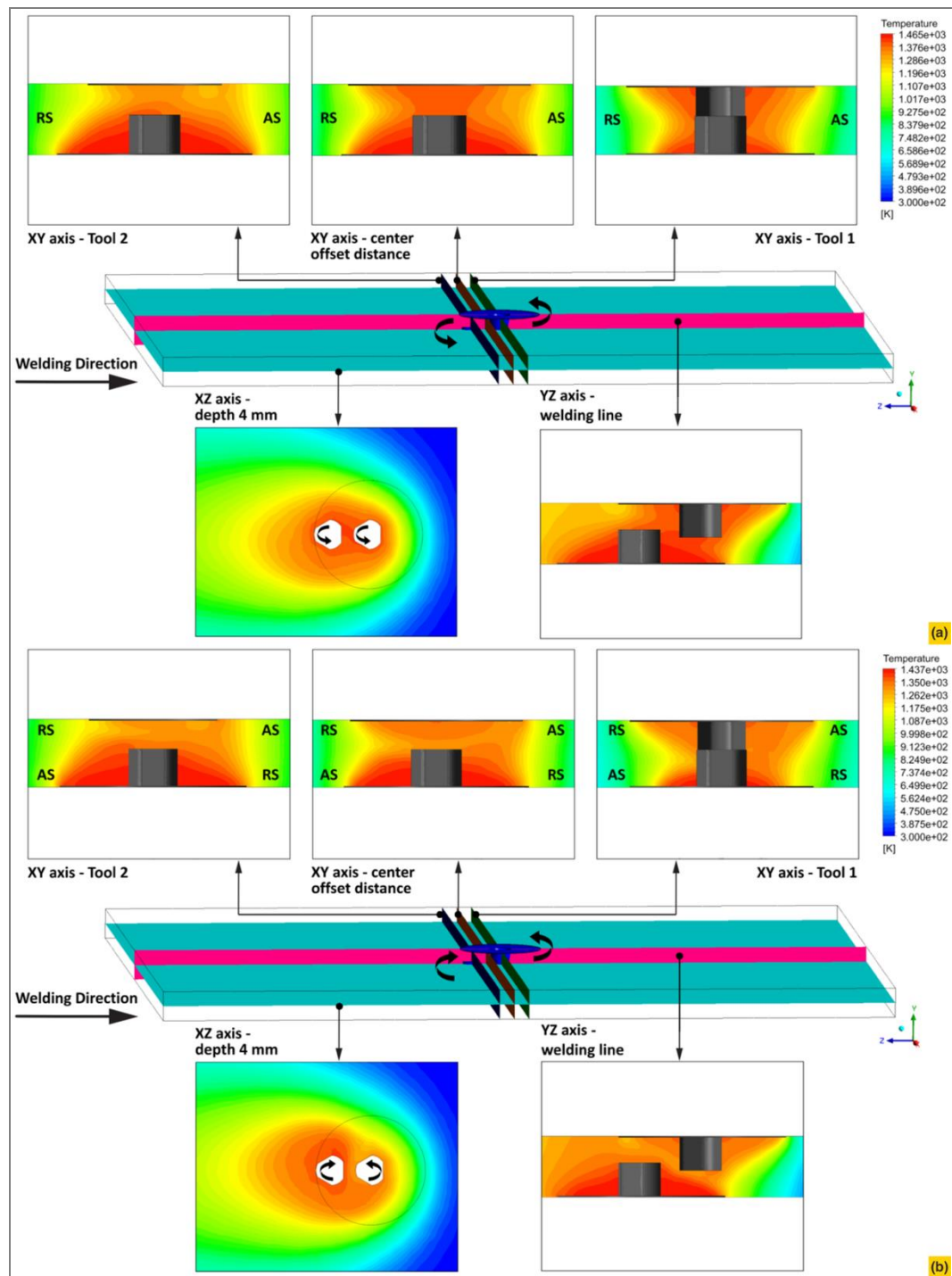


**Figure 15.**  
Temperature contours  
of pin overlap:  
(a) Triflat-CC;  
(b) Triflat-CR

### 3.3. Material Flow

In the FSW process, the advancing side (AS) is defined as the side where the tool rotation direction is the same as the welding direction, while the retreating side (RS) is the side where the rotation direction is opposite to the welding direction. This difference produces asymmetric material flow behavior between the two regions. The velocity vector in FSW simulations illustrates both the direction and intensity of material flow during the FSW process. In general, the material flow tends to follow the direction of tool rotation. This analysis focuses on the 4 mm depth layer of the workpiece surface, which is the dominant region involved in thermomechanical stirring. Material flow behavior is examined along several planes, specifically the XY plane at tool 1, center offset, and tool 2 positions, and along the welding direction on the YZ plane.

As shown in Figure 17 and Figure 18, the cylindrical pin exhibits significant differences in material flow patterns depending on the tool rotation direction. In the CR (clockwise-reverse) direction (Figure 17b and Figure 18b), the material flow is more complex and dynamic than in the CC (counterclockwise) direction (Figure 17a and Figure 18a), with materials from both tools converging

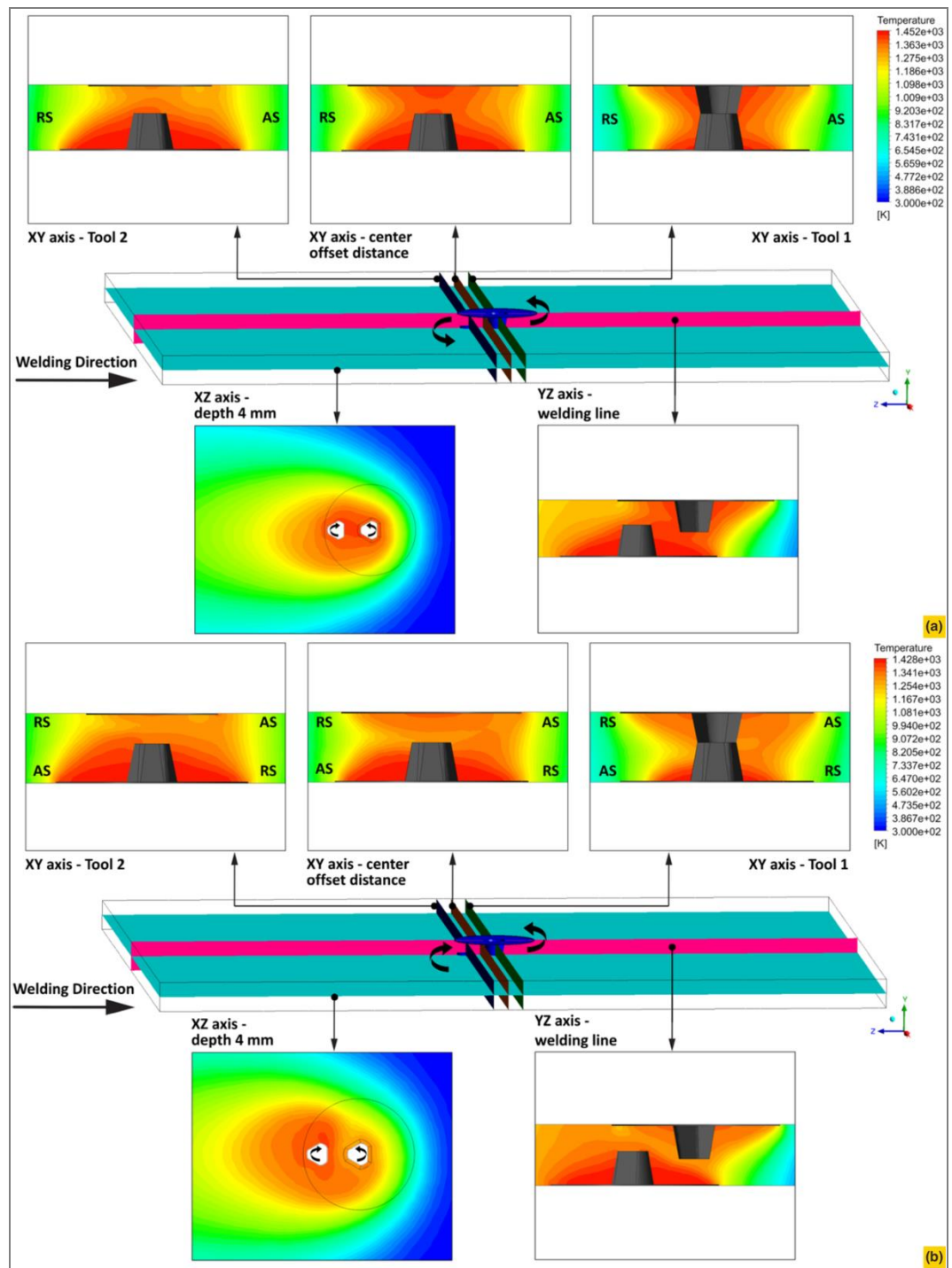


**Figure 16.**  
Temperature contours  
of pin overlap:  
(a) Tapered triflat-CC;  
(b) tapered triflat-CR

and mixing efficiently into a single stable flow. Quantitatively, the material flow velocity in the stir zone ranges between approximately 0.15–0.85 m/s, depending on the rotation direction and overlap condition. Under the CR rotation direction, the maximum velocity near the tool shoulder reaches approximately 0.82–0.85 m/s, indicating stronger stirring and more dynamic material transport. In contrast, the CC rotation direction produces slightly lower peak velocities of about 0.65–0.72 m/s, reflecting a more laminar flow pattern around the tool. The CR rotation promotes aggressive mixing and effectively prevents stagnant zones, as there is no pronounced buildup of material on one side. Under the CR rotation strategy, the flow interaction between the AS and RS regions becomes more balanced, allowing the plasticized material to redistribute more uniformly across the weld zone. This balanced AS–RS interaction reduces the likelihood of stagnant zones and contributes to a more stable material flow pattern. Conversely, in the CC (counterclockwise) direction, the material follows a more laminar path around the tool. At the midpoint between the two tools, opposing flow vectors from each tool collide, causing material to accumulate on the RS (retreating side) of the second tool (T2). This uneven buildup increases the risk of weld defects,

particularly in the region where the flows intersect and disrupt each other. On the advancing side (AS), the combined motion of tool rotation and welding direction increases the relative velocity between the tool and the material, producing stronger plastic deformation and more active material transport. Conversely, on the retreating side (RS), the opposing motion reduces the effective shear interaction, which can lead to localized material accumulation when the flow from both tools intersects.

In addition to rotation direction, overlap distance plays a crucial role in shaping the material flow. As seen in Figure 17b and Figure 18b, a 1 mm overlap creates a larger contact interface between the tool and the material. This enhances friction and plastic deformation, leading to stronger stirring and more thorough mixing. The result is improved flow homogeneity and a reduced likelihood of incompletely stirred or stagnant zones—common problems under a 0.5 mm overlap. The greater friction also contributes to a more uniform temperature distribution across the weld zone [31]. Increasing the overlap distance from 0.5 mm to 1 mm also increases the flow intensity. Under the 1 mm overlap condition, the maximum velocity in the stir zone increases by approximately 10–15%, reaching values close to 0.90 m/s near the tool interface due to the larger contact area and stronger plastic deformation.

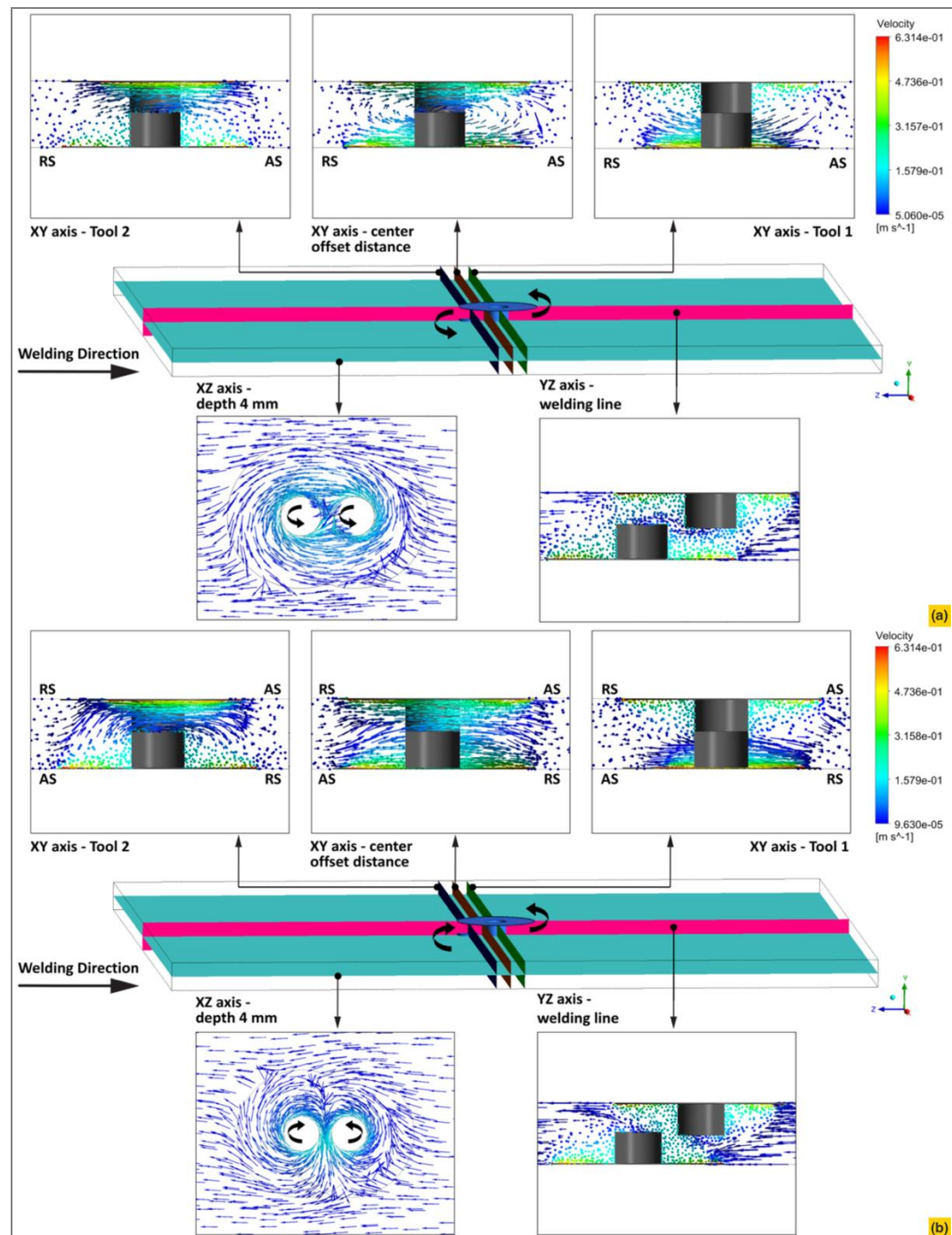


**Figure 17.**  
Material flow of  
cylindrical pin:  
(a) CC-overlap 0.5 mm;  
(b) CR-overlap 0.5 mm

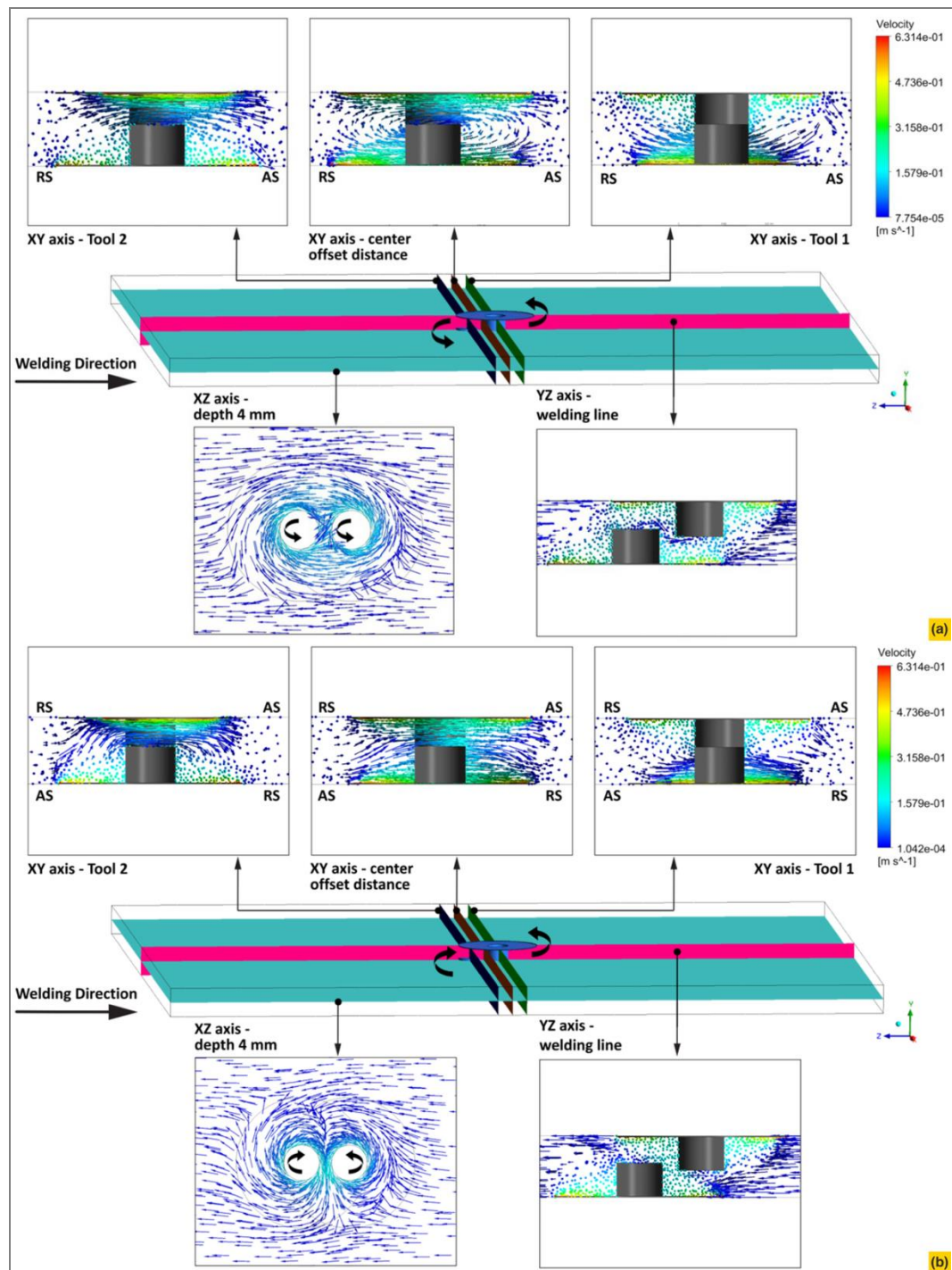


**Figure 18.**  
Material flow of  
cylindrical pin:  
(a) CC-overlap 1 mm;  
(b) CR-overlap 1 mm

The combination of 1 mm overlap with CR rotation direction yields the most favorable flow characteristics. Under this condition, the material flow is evenly distributed across the weld area without signs of excessive accumulation. This ensures enhanced thermomechanical homogeneity, supports consistent heat distribution, reduces the formation of internal defects, and ultimately improves weld quality.

To evaluate the influence of pin geometry, simulations were conducted under these optimal conditions (CR rotation and 1 mm overlap). The cylindrical pin (Figure 19a) generated the most stable and symmetrical flow pattern. Material formed a consistent vortex around the pin with no localized buildup, promoting efficient mixing and even heat distribution along the weld path. In contrast, the conical pin (Figure 19b) directed material flow more laterally and downward due to its tapered profile, which tends to push the material away from the weld center [22]. While the flow was active, the reduced contact area led to lower friction and weaker thermomechanical mixing. However, no significant stagnant zones or problematic accumulations were observed. The triflat pin (Figure 20a) induced a highly aggressive and turbulent flow due to the flat surfaces on its sides

[23]. This geometry encouraged intense mixing within the joint zone, particularly beneficial in early stages of welding. However, the geometry also introduced pressure fluctuations around the pin, causing minor local instabilities. Even so, the CR rotation direction helped prevent material buildup on either side, maintaining an overall balanced distribution. Lastly, the tapered triflat pin (Figure 20b) exhibited the most balanced and homogeneous flow among all geometries. The combination of a conical shape and flat faces produced a moderate downward and lateral flow pattern. While the stirring was less intense than in the triflat pin, the flow was more stable and consistent across the weld zone. This makes the tapered triflat pin an excellent compromise between aggressive mixing and flow uniformity. Among the investigated pin geometries, the triflat pin produces the highest velocity magnitude, with peak values reaching approximately 0.90–0.95 m/s near the pin edges due to the intensified shear deformation caused by its flat surfaces. In contrast, the tapered triflat pin generates slightly lower velocities, typically ranging between 0.60–0.80 m/s, because the tapered geometry distributes deformation more gradually along the pin length, resulting in smoother and more stable material flow.

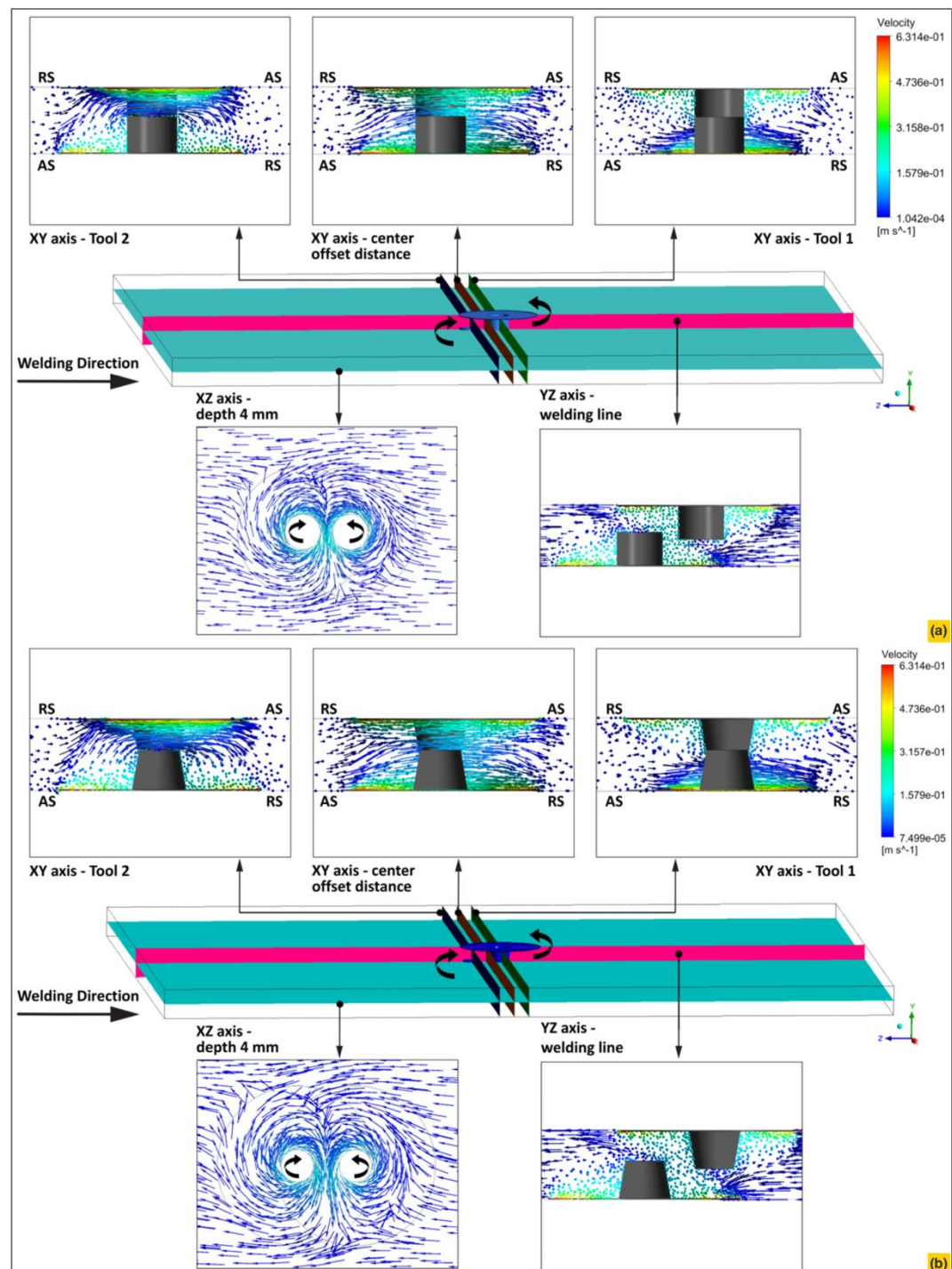


**Figure 19.**  
Material flow variation  
of CR rotation direction  
and pin overlap 1 mm:  
(a) Cylindrical pin;  
(b) Conical pin

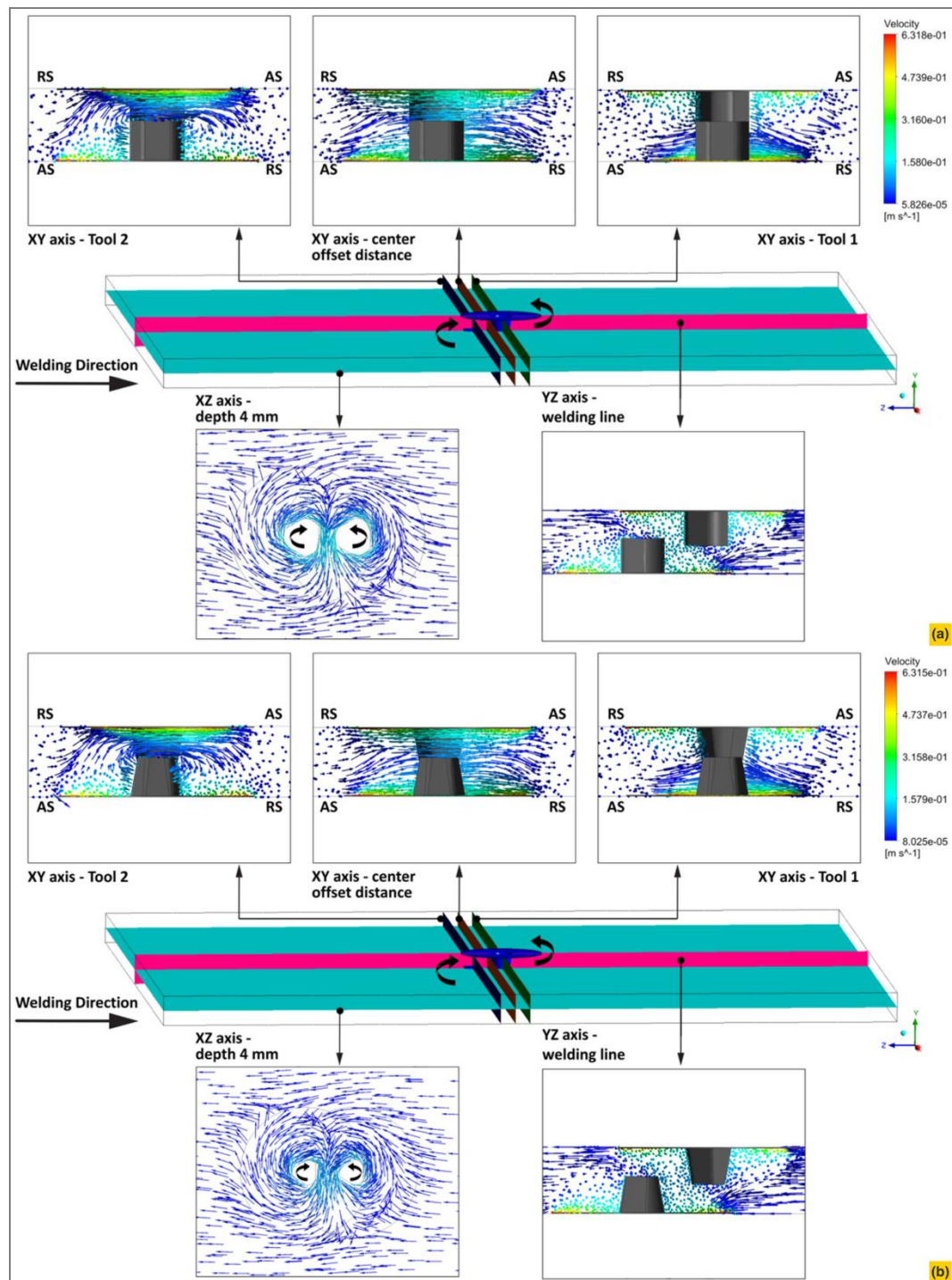


**Figure 20.**  
Material flow variation  
of CR rotation direction  
and pin overlap 1 mm:  
(a) Triflat pin;  
(b) Tapered triflat pin

## 4. Conclusion

This study investigated the influence of pin geometry, tool rotation direction, and pin overlap on the thermal characteristics and material flow behavior during the One-Step Double-Acting Friction Stir Welding (ODFSW) process applied to stainless steel. Using Computational Fluid Dynamics (CFD) modeling, the temperature distribution and velocity vectors within the weld zone were analyzed to better understand the thermomechanical mechanisms governing the process. The results show that the direction of tool rotation significantly affects the stability of material flow. The clockwise rotation (CR) configuration produces a more stable and uniformly distributed flow along the weld path, whereas the counterclockwise rotation (CC) tends to create material accumulation on the retreating side, leading to increased turbulence and localized heat concentration. In addition, increasing the pin overlap from 0.5 mm to 1 mm expands the stirring zone, improves material mixing, and generates a more uniform heat distribution across the weld region. Among the investigated pin geometries, the tapered triflat pin produced the most balanced

thermomechanical behavior. Its combined tapered and flat-surface geometry promotes effective plastic deformation while maintaining controlled heat generation, resulting in more homogeneous material flow. These characteristics contribute to improved stirring efficiency and reduced thermal imbalance within the weld zone. The main contribution of this study lies in providing a comprehensive CFD-based analysis of the thermomechanical interaction in the ODFSW process for stainless steel, particularly highlighting the combined influence of pin geometry, rotation direction, and overlap distance. The findings demonstrate that the configuration consisting of a tapered triflat pin, clockwise (CR) rotation, and a 1 mm pin overlap provides the most stable material flow and thermal distribution. This optimized configuration is expected to improve weld joint quality by promoting uniform plastic deformation, minimizing material accumulation on the retreating side, and reducing the potential for internal defects. These insights can serve as practical guidance for the design and optimization of tool geometry and process parameters in ODFSW applications for high-strength materials.

## Acknowledgements

The authors gratefully acknowledge the financial support provided by Universitas Sebelas Maret, Surakarta, Indonesia, through the Penelitian Kolaborasi Internasional grant, under contract number 369/UN27.22/PT.01.03/2025.

## Authors' Declaration

**Authors' contributions and responsibilities** – The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

**Funding** – Universitas Sebelas Maret, Surakarta, Indonesia, through the Penelitian Kolaborasi Internasional grant, under contract number 369/UN27.22/PT.01.03/2025.

**Availability of data and materials** – All data is available from the authors.

**Competing interests** – The authors declare no competing interests.

**Additional information** – No additional information from the authors.

## References

- [1] V. Matres et al., "Stainless steel reinforcement: New material in the latest draft of second-generation Eurocode 2," *Structural Concrete*, vol. 24, no. 6, pp. 7549–7560, Dec. 2023, doi: 10.1002/suco.202201138.
- [2] T. Olumide Olugbade, "Corrosion Resistance, Evaluation Methods, and Surface Treatments of Stainless Steels," in *Stainless Steels*, IntechOpen, 2022. doi: 10.5772/intechopen.101430.
- [3] M. Ragab, H. Liu, M. M. Z. Ahmed, G.-J. Yang, Z.-J. Lou, and G. Mehboob, "Microstructure evolution during friction stir welding of 1Cr11Ni2W2MoV martensitic stainless steel at different tool rotation rates," *Materials Characterization*, vol. 182, p. 111561, Dec. 2021, doi: 10.1016/j.matchar.2021.111561.
- [4] M. Gong et al., "Standoff-free vaporizing foil actuator welding: Process principle, experimental validation, and mechanisms analysis," *Journal of Manufacturing Processes*, vol. 131, pp. 478–493, Dec. 2024, doi: 10.1016/j.jmapro.2024.09.051.
- [5] J. Ramon, R. Basu, G. Vander Voort, and G. Bolar, "A comprehensive study on solidification (hot) cracking in austenitic stainless steel welds from a microstructural approach," *International Journal of Pressure Vessels and Piping*, vol. 194, p. 104560, Dec. 2021, doi: 10.1016/j.ijpvp.2021.104560.
- [6] M. Divya, T. N. Prasanthi, C. R. Das, C. Sudha, and M. Vasudevan, "Weldability study of 304HCu stainless steel using vareststraint and 'Gleeble' based hot ductility tests," *Materials Today Communications*, vol. 37, p. 106938, Dec. 2023, doi: 10.1016/j.mtcomm.2023.106938.
- [7] Z. Zhang, H. Zhao, H. Zhang, J. Hu, and J. Jin, "Microstructure evolution and pitting corrosion behavior of UNS S32750 super duplex stainless steel welds after short-time heat treatment," *Corrosion Science*, vol. 121, pp. 22–31, Jun. 2017, doi: 10.1016/j.corsci.2017.02.006.

- [8] J. Dong *et al.*, "Microstructural evolution and corrosion responses of friction stir welded SUS301L stainless steel," *Materials Characterization*, vol. 214, p. 114124, Aug. 2024, doi: 10.1016/j.matchar.2024.114124.
- [9] S. Das Banik, S. Kumar, P. K. Singh, S. Bhattacharya, and M. M. Mahapatra, "Distortion and residual stresses in thick plate weld joint of austenitic stainless steel: Experiments and analysis," *Journal of Materials Processing Technology*, vol. 289, p. 116944, Mar. 2021, doi: 10.1016/j.jmatprotec.2020.116944.
- [10] F. C. Liu, Y. Hovanski, M. P. Miles, C. D. Sorensen, and T. W. Nelson, "A review of friction stir welding of steels: Tool, material flow, microstructure, and properties," *Journal of Materials Science & Technology*, vol. 34, no. 1, pp. 39–57, Jan. 2018, doi: 10.1016/j.jmst.2017.10.024.
- [11] N. van Rooyen, M. Bhattacharyya, I. Charit, and M. R. Maughan, "Indentation investigation of 304L stainless steel friction stir weld simulated crack repair," *Materials Science and Engineering: A*, vol. 836, p. 142691, Mar. 2022, doi: 10.1016/j.msea.2022.142691.
- [12] W. Tang, X. Yang, S. Li, B. Du, and H. Li, "Numerical and experimental investigation on friction stir welding of Ti- and Nb-modified 12 % Cr ferritic stainless steel," *Journal of Manufacturing Processes*, vol. 59, pp. 223–237, Nov. 2020, doi: 10.1016/j.jmapro.2020.09.059.
- [13] R. Rajasekaran, A. Lakshminarayanan, M. Vasudevan, and P. Vasantharaja, "Role of welding processes on microstructure and mechanical properties of nuclear grade stainless steel joints," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 233, no. 11, pp. 2335–2351, Nov. 2019, doi: 10.1177/1464420719849448.
- [14] A. S. K. - and K. J. S. -, "Short and Brief Review on Friction Stir Welding," *International Journal For Multidisciplinary Research*, vol. 5, no. 6, Dec. 2023, doi: 10.36948/ijfmr.2023.v05i06.10052.
- [15] C. Du, X. Wang, Q. Pan, K. Xue, M. Ni, and J. Liu, "Correlation between microstructure and mechanical properties of 6061-T6 double-side FSW joint," *Journal of Manufacturing Processes*, vol. 38, pp. 122–134, Feb. 2019, doi: 10.1016/j.jmapro.2019.01.010.
- [16] D. B. Darmadi, M. Talice, A. F. Fahrizal, and E. Siswanto, "Tensile Strength of Double Side Friction Stir Welding Using Varied Length of Pin and Rotating Directions," *Journal of Applied Science and Engineering*, vol. 25, pp. 311–320, 2021, doi: 10.6180/jase.202204\_25(2).0007.
- [17] Y. Zou *et al.*, "A comparative study of microstructure and mechanical properties of conventional and synergistic double-sided FSW joints of 6061 z-aluminium alloy," *Science and Technology of Welding and Joining*, vol. 28, no. 8, pp. 784–791, Nov. 2023, doi: 10.1080/13621718.2023.2227815.
- [18] Hendrato, P. Puspitasari, Jamasri, and Triyono, "Fatigue crack growth rate and mechanical properties of one-step double-side friction stir welded AA6061-T6," *Results in Engineering*, vol. 21, p. 101958, Mar. 2024, doi: 10.1016/j.rineng.2024.101958.
- [19] M. I. Hilmawan *et al.*, "Effect of tools rotational speed on the mechanical properties of one-step double-acting friction stir welded aluminum alloy AA 6061 hollow panel," *International Journal of Lightweight Materials and Manufacture*, vol. 7, no. 3, pp. 467–479, May 2024, doi: 10.1016/j.ijlmm.2024.02.002.
- [20] S. S. Kumar, N. Murugan, and K. K. Ramachandran, "Effect of tool tilt angle on weld joint properties of friction stir welded AISI 316L stainless steel sheets," *Measurement*, vol. 150, p. 107083, Jan. 2020, doi: 10.1016/j.measurement.2019.107083.
- [21] H. Su, C. S. Wu, M. Bachmann, and M. Rethmeier, "Numerical modeling for the effect of pin profiles on thermal and material flow characteristics in friction stir welding," *Materials & Design*, vol. 77, pp. 114–125, Jul. 2015, doi: 10.1016/j.matdes.2015.04.012.
- [22] R. Beygi, M. Z. Mehrizi, D. Verdera, and A. Loureiro, "Influence of tool geometry on material flow and mechanical properties of friction stir welded Al-Cu bimetals," *Journal of Materials Processing Technology*, vol. 255, pp. 739–748, May 2018, doi: 10.1016/j.jmatprotec.2018.01.033.
- [23] H. Ji *et al.*, "Numerical modeling for the mechanism of shoulder and pin features affecting thermal and material flow behavior in friction stir welding," *Journal of Materials Research and Technology*, vol. 21, pp. 662–678, Nov. 2022, doi: 10.1016/j.jmrt.2022.09.070.
- [24] Y. Tang *et al.*, "Effects of tool rotation direction on microstructure and mechanical properties

- of 6061 aluminum alloy joints by the synergistically double-sided friction stir welding," *Journal of Manufacturing Processes*, vol. 126, pp. 109–123, Sep. 2024, doi: 10.1016/j.jmapro.2024.07.067.
- [25] D. Garcia, T. Wang, J. D. Escobar, M. Pole, X. Ma, and K. A. Ross, "In-situ measurement and control of the tool-workpiece interface temperature during friction stir processing of 304/304L stainless steel," *Materials Today Communications*, vol. 38, p. 107672, Mar. 2024, doi: 10.1016/j.mtcomm.2023.107672.
- [26] M. R. Hajiha and A. Farzadi, "Effect of material position and process conditions on defect formation in dissimilar friction stir welding: A CFD-based study," *Materials Today Communications*, vol. 51, p. 114678, Feb. 2026, doi: 10.1016/j.mtcomm.2026.114678.
- [27] A. F. Hasan, "CFD modelling of friction stir welding (FSW) process of AZ31 magnesium alloy using volume of fluid method," *Journal of Materials Research and Technology*, vol. 8, no. 2, pp. 1819–1827, Apr. 2019, doi: 10.1016/j.jmrt.2018.11.016.
- [28] S. Pal and M. P. Phaniraj, "Determination of heat partition between tool and workpiece during FSW of SS304 using 3D CFD modeling," *Journal of Materials Processing Technology*, vol. 222, pp. 280–286, Aug. 2015, doi: 10.1016/j.jmatprotec.2015.03.015.
- [29] R. Nandan, G. G. Roy, T. J. Lienert, and T. Debroy, "Three-dimensional heat and material flow during friction stir welding of mild steel," *Acta Materialia*, vol. 55, no. 3, pp. 883–895, Feb. 2007, doi: 10.1016/j.actamat.2006.09.009.
- [30] F. Yan, Y. Zhang, J. Shen, X. Fu, and S. Mi, "A new calculation method of viscoplastic heat production generated by plastic flow of friction stir welding process," *Materials Chemistry and Physics*, vol. 270, p. 124795, Sep. 2021, doi: 10.1016/j.matchemphys.2021.124795.
- [31] J. Tu, G.-H. Yeoh, and C. Liu, *Computational Fluid Dynamics*, 3rd ed. Elsevier, 2018. doi: 10.1016/C2015-0-06135-4.
- [32] F. O. Borokinni, B. O. Bolaji, B. J. Olorunfemi, K. A. Bello, and O. T. Oginni, "Performance Evaluation of Hybrid MQL-Brass Nano-Fluid Coolant on Aisi 304 SS for Efficient Machining Operation," *ABUAD Journal of Engineering Research and Development (AJERD)*, vol. 6, no. 2, pp. 205–217, Dec. 2023, doi: 10.53982/ajerd.2023.0602.20-j.
- [33] Y. Luo, W. Gu, W. Peng, Q. Jin, Q. Qin, and C. Yi, "A Study on Microstructure, Residual Stresses and Stress Corrosion Cracking of Repair Welding on 304 Stainless Steel: Part I-Effects of Heat Input," *Materials*, vol. 13, no. 10, p. 2416, May 2020, doi: 10.3390/ma13102416.
- [34] I. Hejazi and S. E. Mirsalehi, "Effect of pin penetration depth on double-sided friction stir welded joints of AA6061-T913 alloy," *Transactions of Nonferrous Metals Society of China*, vol. 26, no. 3, pp. 676–683, Mar. 2016, doi: 10.1016/S1003-6326(16)64158-4.