Journal of Engineering and Applied Research (JEAR)

National University of Skills

Summer & Autumn 2024, Vol. 1, No. 2, p. 213-223

Journal Homepage: https://jear.tvu.ac.ir/

doi:10.48301/JEAR.2024.473772.1037

Investigating the Effects of Tool Pin Profile on Strain and Temperature During Friction Stir Welding Process Using CEL Method

Yaghoub Dadgar Asl[1*], Ezatollah Hassnzadeh[2], Mostafa Akbari[3], Hossein Rahimi Asiabaraki[4], Milad Esfandiar[5]

[1,2,3,4,5]Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran.

ARTICLE INFO

Article Type:
Original Research

Received: 08.26.2024
Revised: 10.17.2024
Accepted: 11.03.2024

Keyword:
Friction
Stir
Welding
CEL
Temperature
Strain

***Corresponding Author:**
Yaghoub Dadgar Asl
Email: *ydadgar@tvu.ac.ir*

ABSTRACT

The pin profile in Friction Stir Welding (FSW) has a significant influence on the temperature and strain distribution during the welding process. The shape and geometry of the pin can affect the material flow and heat generation, which in turn impacts the temperature within the weld zone. In this research, the effect of different square, triangular, and cylindrical pin profiles on strain and temperature during FSW was investigated numerically. The coupled Eulerian-Lagrangian (CEL) method was utilized to model the FSW process and further analyze strain and temperature. In this approach, the workpiece is represented using an Eulerian formulation, while the tool is described through a Lagrangian formulation. Results showed that the cylindrical tool generates higher temperatures due to its larger surface area, while the triangular tool keeps the sample cooler with a smaller pin surface area. Despite the triangular tool's longer revolving arm causing greater strain, it results in less pulsation, limiting the strain's impact to a smaller area. The maximum strain generated by the circular tool was approximately 16, whereas the triangular tool produced a maximum strain of 45.

©2024 the authors. Published by National University of Skills, Tehran, Iran. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution-Noncommercial 4.0 International (CC BY-NC 4.0 license) (https://creativecommons.org/licenses/by-nc/4.0/).

E-ISSN: 3060-6357

Introduction

Friction Stir Welding (FSW) is a solid-state joining process that has gained significant attention in various industries [1; 2]. In this technique, a non-consumable rotating tool with a specially designed pin and shoulder is plunged into the workpieces, generating heat through friction and plastic deformation [3]. Without reaching the melting point, the softened material is then stirred and forged together, forming a solid-state weld. The tool design, including the pin profile and shoulder geometry, plays a crucial role in the heat generation, material flow, and final weld quality [4; 5]. The key process parameters, such as tool rotation speed, travel speed, plunge depth, and downward force, must be carefully controlled to achieve the desired weld characteristics. The advantages of FSW include high joint strength, low distortion, no need for filler material, and the ability to join dissimilar materials, making it a preferred choice for applications in industries like aerospace, automotive, shipbuilding, and transportation, where the joining of thin and thick-section components is required [6; 7].

The tool design in FSW is of paramount importance as it plays a critical role in determining the overall quality and performance of the welded joint [8]. The tool, consisting of a pin and a shoulder, is responsible for generating the necessary heat and inducing the desired material flow during welding. The specific design of the pin including its geometry, features, and surface texture can significantly influence heat generation, material mixing, and, ultimately, the mechanical and metallurgical properties of the weld [9]. Similarly, the shoulder design influences the heat input, the flow of the softened material, and the surface appearance of the final weld [10-12]. The effective combination of the pin and shoulder design parameters such as the pin profile, thread patterns, shoulder diameter, and scrolled features allows for the optimization of the material flow, temperature distribution, and defect formation, thereby ensuring the production of high-quality, defect-free welds in a wide range of metallic materials and applications [13; 14].

Numerical methods play a critical role in analyzing and simulating the FSW process, which involves complex and coupled thermal, mechanical, and metallurgical phenomena [15]. The numerical technique in FSW enables the accurate simulation of heat generation, material flow, and microstructural evolution during welding. Numerical models incorporate thermal analysis to predict temperature distributions, mechanical analysis to understand material deformation and flow, and coupled thermo-mechanical analysis to capture the interdependence between temperature, material behaviour, and microstructural changes. Advanced numerical models also incorporate the simulation of metallurgical transformations such as recrystallization and precipitation to predict the final weld microstructure and its impact on mechanical properties [16; 17]. Numerical methods in FSW allow researchers and engineers to optimize process parameters, investigate the effect of various conditions, predict defect formation [18; 19], and explore the joining of dissimilar materials [20; 21], making them an indispensable tool for research, process optimization and industrial applications of this versatile solid-state welding technique.

The Coupled Eulerian-Lagrangian (CEL) method is a powerful numerical approach that has been extensively employed in the simulation of FSW [22]. The CEL method combines the advantages of both the Eulerian and Lagrangian formulations, allowing for the effective modelling of the complex material flow and deformation patterns observed in the FSW process. The tool is typically modeled using a Lagrangian approach in the CEL method, while the workpiece material is represented using an Eulerian framework. This enables the accurate tracking of the free surface of the workpiece and the material flow around the rotating tool, which is crucial for capturing the intricate details of the welding process. The CEL method also allows for the seamless integration of the thermal and mechanical aspects, providing a comprehensive simulation of the heat generation, material deformation, and microstructural evolution during FSW. The ability to handle large deformations, track the evolution of the weld zone and predict the formation of defects make the CEL method a valuable tool for optimizing the FSW process and enhancing the understanding of the underlying physics involved in this solid-state welding technique. Al-Badour et al. [23] applied the CEL technique to anticipate volumetric defects, including tunnel formations, specifically in the FSW of aluminium materials. Similarly, Chauhan et al. [24] utilized the CEL method to forecast the occurrence of defects in FSW. Their model demonstrated high accuracy in predicting critical parameters such as axial force, torque, and the presence of tunnel defects during the welding process. Furthermore, Akbari et al. [25] employed the CEL approach to explore the mixing behavior of materials within the stir zone (SZ) during the FSW process.

This research investigated the influence of tool pin design on temperature and induced strain during the friction stir welding (FSW) process. To achieve this, the CEL method was employed to model the FSW process with three distinct pin geometries. This approach allows for a comprehensive analysis of how variations in tool pin design affect thermal and mechanical properties during welding.

Simulation details

FSW tools with triangular, cylindrical, and square pin profiles were used to study the influence of the pin profile on the temperature (Figure 1). In this study, the researchers used the ABAQUS finite element software to model the FSW process and investigate the strain and temperature profile during the operation. To overcome the significant mesh distortion issues encountered with other methods such as the Lagrangian approach, the researchers employed a three-dimensional Coupled Eulerian-Lagrangian (CEL) technique. In the CEL method, the workpiece was modelled using the Eulerian formulation with EC3D8RT elements, where the nodes remain fixed and the material flows through the mesh network. Conversely, the tool was defined using the Lagrangian formulation. The researchers utilised a uniform volume fraction approach to assign different materials to the workpiece and tool.

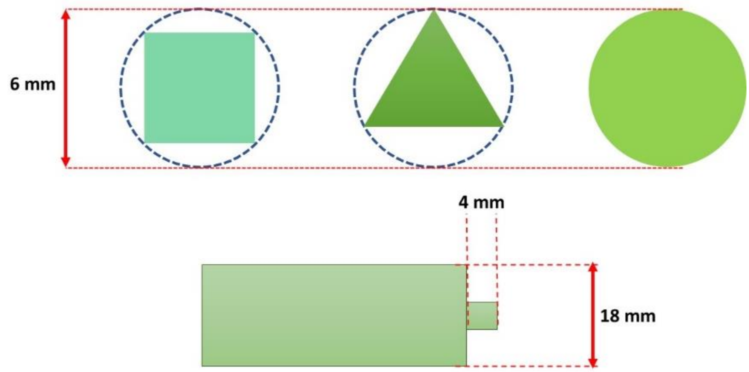

Figure 1. Dimensions of pin profiles used in this research.

In this study, aluminum was selected for simulation. Moreover, FSW was simulated at a traverse speed of 100 mm/ min and a rotational speed of 1250 rpm. In the FSW process, the material flow stress was influenced by the strain, strain rate, and temperature. To accurately capture this behaviour, the researchers employed the Johnson-Cook (JC) constitutive model as the material flow model. The JC model is a commonly used approach that describes the flow stress as a function of these three key parameters - strain, strain rate, and temperature [1]:

$$\sigma = (A + B\varepsilon^n)(1 + C\, ln\left(\frac{\dot{\varepsilon}}{\dot{\bar{\varepsilon}}}\right))[1 - \left(\frac{(T - T_r)}{(T_m - T_r)}\right)^m \tag{1}$$

where A, B, C, n, and m are constants related to the material, T_m is melting temperature (from Table 1), T_r is the ambient temperature, ε represents the plastic strain, $\dot{\bar{\varepsilon}}$ is the normalizing strain rate, and $\dot{\varepsilon}$ is the effective plastic strain rate. The first term of Eq. 1 is the power-law that defines plastic training influences on the flow stress. The second and third terms of the equation considered the effect of the strain rate and temperature. Table 1 illustrates the Johnson-Cook parameters.

Table 1. The constants of the JC model [26].

Material	A [MPa]	B [MPa]	C	n	m
Aluminum	285	94	0.002	0.42	1.34

In the simulation of the FSW, the researchers utilized various convective heat transfer coefficients for different surfaces. To save computation time, a high convective heat transfer coefficient of 6000 W/(m^2·°C) was applied at the bottom of the workpiece, while the backing plate was ignored. To account for natural convection heat loss, a lower equivalent value of 30 W/(m^2·°C) was set at the top surface of the samples. To properly control the movement of the FSW tool, all motion conditions were defined with respect to the tool reference point. Due to the stirring action during the process, there was self-contact within the materials in the Stir Zone (SZ), in addition to the contact between the tool and the workpiece. The researchers defined a general contact interaction to model all the tool and material interactions using Coulomb's law of friction to describe the friction between the tool and the workpieces.

To ensure that material remains within the confines of the domain, it is vital to restrict the material velocity that comes from the bottom and sides of the Eulerian domain in a perpendicular manner. This restriction is important for preserving the simulation's accuracy and reliability (see Figure 2). For effective control of the tool's movements, all motion parameters are set based on the reference point of the tool.

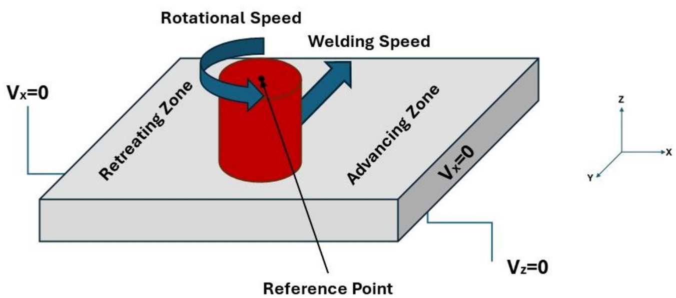

Figure 2. Boundary conditions in the numerical model.

The researchers determined that a mesh size of 1.2 mm (as shown in Fig. 3) was nearly ideal for the described numerical model. They used thermally-coupled 4-node 3D bilinear rigid quadrilateral elements to represent the FSW tool, modeling the tool as an isothermal Lagrangian rigid body. The mesh for the tools was further refined, using 0.7 mm elements to capture the details of the tool geometry and interactions with the workpiece more accurately.

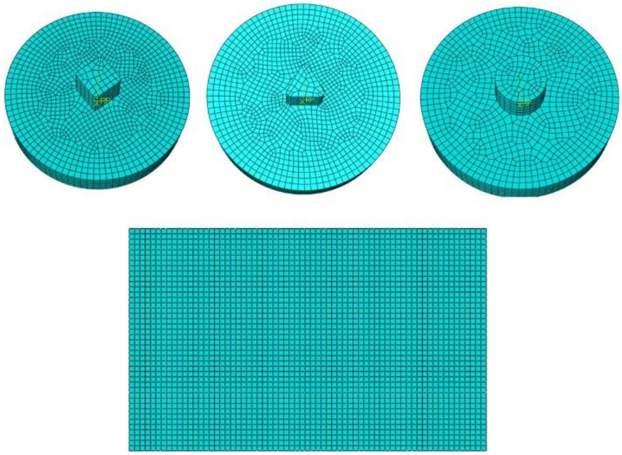

Figure 3. The meshed model used in numerical analysis.

Result and discussion

Temperature is a crucial factor in the FSW process, as it plays a significant role in the material deformation, joint formation, and overall quality of the welded structure. The primary source of heat in FSW is the friction between the rotating FSW tool and the workpiece material [13]. As the tool rotates and traverses along the weld joint, the frictional heating at the tool-workpiece interface generates most of the heat required for the process.

The distribution of temperature within the workpiece is not uniform during FSW. The highest temperatures are typically observed in the Stir Zone (SZ), where the material experiences intense plastic deformation and mixing due to tool rotation and movement. The temperature gradually decreases towards the Thermo-mechanically Affected Zone (TMAZ) and the base metal. Depending on the FSW parameters, such as tool rotational speed, traverse speed, and tool design, the peak temperatures in the SZ can reach up to 80-90% of the melting point of the workpiece material [27]. The material in the SZ and TMAZ experiences rapid heating and cooling cycles during the FSW process, and the heat input and subsequent cooling rates play a significant role in determining the microstructural evolution and the mechanical properties of the welded joint.

The amount of heat produced during FSW is proportional to the frictional and deformation energy generated during the process [28]. This energy depends on factors such as the friction area and friction factor between the shoulder and material surface, as well as the rotational speed of the tool and the pressure applied to the tool shoulder. Figure 4 shows the temperature distribution at the cross-section of joints produced with different pin tools. The results indicated that the temperature changes in all the samples were slightly different from each other. This slight difference was due to the primary source of heat production during the process being the tool shoulder, and since the tool shoulder size was the same for all tools, the temperature difference between the different samples was small.

As shown in Figure 4, the sample produced with the cylindrical tool experiences a higher temperature due to the larger surface area of the pin. On the other hand, a sample produced with a triangular tool experiences a lower temperature in this area due to its smaller pin surface area. These results suggest that the temperature history of the samples produced with different tools is not significantly different.

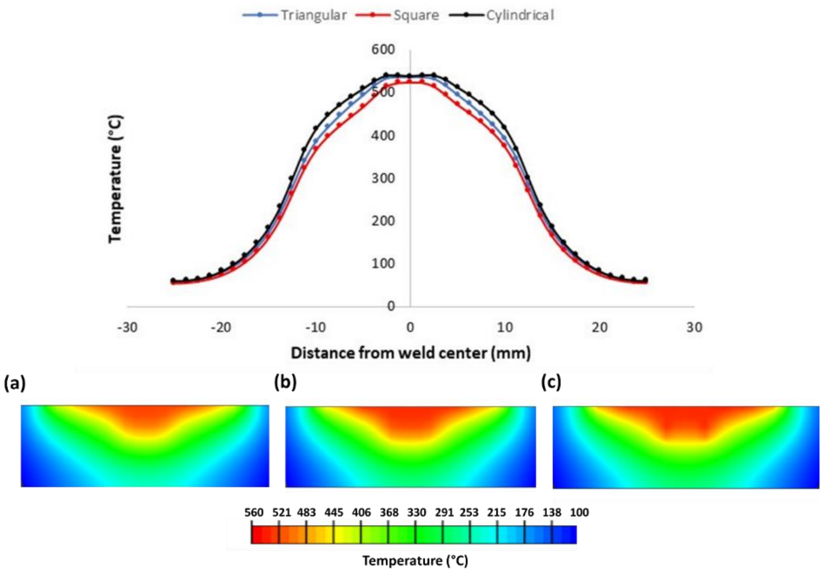

Figure 4. Temperature variation of the weld samples fabricated with (a) triangular, (b) square, and (c) cylindrical pin profiles.

Given that the plastic deformation and temperature history in the SZ significantly impact the microstructure of welds, understanding the strain distribution during friction stir welding is crucial for effective design and process management. Figure 5 illustrates the strain distribution across the cross-section of welds manufactured using various pin types. The strain generated by the cylindrical pin is the lowest compared to other pin designs, indicating insufficient material flow during the welding process. In an analysis of strain induced by different tools, it was observed that the circular tool produced a maximum strain of approximately 16. In contrast, the triangular tool generated a higher maximum strain, which was recorded at 45. Conversely, samples produced with edged pin tools exhibit significantly higher strain levels. Furthermore, the area affected by the strain from tool rotation is larger in tools with edged pins than in those with circular designs. Tool pin profiles that feature flat sides, like triangular and square shapes, have an associated measure of eccentricity, which is the ratio between the tool's dynamic volume swept and its static volume. The triangular tool endures the highest strain level because it has the largest revolving arm compared to other pins. Nevertheless, it generates a minimal pulsation effect, resulting in the strain affecting the smallest area.

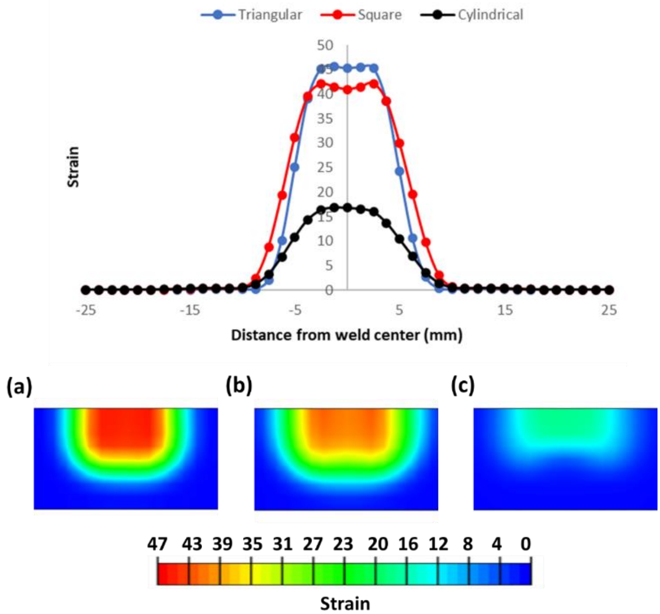

Figure 5. Temperature variation of the weld samples fabricated with (a) triangular, (b) square, and (c) cylindrical pin profiles.

Conclusion

The influence of pin profile on the temperature and strain during FSW was studied. For this reason, the Coupled Eulerian Lagrangian (CEL) technique was applied. The tool was characterized using the Lagrangian formulation, whereas the workpiece was modeled based on the Eulerian formulation. In summary, the following results were obtained:

- The findings showed that the temperature variations among all samples were minimal. This was attributed to the tool shoulder being the main source of heat, and since all tools had the same shoulder size, the temperature differences remained small.

- The joint made with the cylindrical tool generated higher temperatures due to its larger surface area, whereas the triangular tool produced a cooler sample owing to its smaller pin surface area.
- The triangular tool experienced the greatest strain due to its larger revolving arm compared to other pins, yet it produced minimal pulsation, which limited the strain's impact to a smaller area.
- In an analysis, the triangular tool produced a higher maximum strain of 45, compared to the circular tool, which generated a maximum strain of approximately 16.

Disclosure statement and funding

The authors declare no potential conflicts of interest. The present study received no financial support from any organization or institution.

Acknowledgment

We would like to give special thanks to all the participants in this study.

References

[1] Akbari, M., Asadi, P., Aliha, M. R. M., & Berto, F. (2023). Modeling and Optimization of Process Parameters of the Piston Alloy-Based Composite Produced by FSP Using Response Surface Methodology. *Surface Review and Letters*, *30*(06), 2350041. https://doi.org/10.1142/s0218625x23500415

[2] Akbari, M., Asadi, P., & Sadowski, T. (2023). A Review on Friction Stir Welding/Processing: Numerical Modeling. *Materials*, *16*(17), 5890. https://doi.org/10.3390/ma16175890

[3] Patel, M. M., & Badheka, V. J. (2024). A review on friction stir welding (FSW) process for dissimilar aluminium to steel metal systems. *Welding International*, *38*(2), 91-115. https://doi.org/10.1080/09507116.2023.2291064

[4] Kumar, A., Gahlot, P., Kumar, A., & Phanden, R. K. (2024). A state-of-the-art literature review on friction stir welding of 7075-aluminium alloy for tool geometry selection, environmental parameter and mathematical modelling perspective. *International Journal on Interactive Design and Manufacturing.* https://doi.org/10.1007/s12008-024-01922-y

[5] Thomas, R., & Narayana, A. V. (2024, December 1-2). *Effect of tool variables in friction stir welding: A review* [Conference session]. Proceedings of the International Conference on Research Advances in Engineering and Technology - ITechCET 2022, Kerala, India. https://doi.org/10.1063/5.0193843

[6] Koprivica, A., Bajić, D., Šibalić, N., & Vukčević, M. (2020). Analysis of welding of aluminium alloy AA6082-T6 by TIG, MIG and FSW processes from technological and economic aspect. *Machines. Technologies. Materials.*, *14*(5), 194-198. https://stumejournals.com/journals/mtm/2020/5/194

[7] Kumar, S., Mahajan, A., Kumar, S., & Singh, H. (2022). Friction stir welding: Types, merits & demerits, applications, process variables & effect of tool pin profile. *Materials Today: Proceedings*, *56*(1-2), 3051-3057. https://doi.org/10.1016/j.matpr.2021.12.097

[8] Maji, P., Karmakar, R., Kanti Nath, R., & Paul, P. (2022). An overview on friction stir welding/processing tools. *Materials Today: Proceedings*, *58*, 57-64. https://doi.org/10.1016/j.matpr.2022.01.009

[9] Asadi, P., Aliha, M. R. M., Akbari, M., Imani, D. M., & Berto, F. (2022). Multivariate optimization of mechanical and microstructural properties of welded joints by FSW method. *Engineering Failure Analysis*, *140*(7), 106528. https://doi.org/10.1016/j.engfailanal.2022.106528

[10] Devuri, V., Mahapatra, M. M., Harsha, S. P., & Mandal, N. R. (2014). Effect of Shoulder Surface Dimension and Geometries on FSW of AA7039. *Journal for Manufacturing Science and Production*, *14*(3), 183-194. https://doi.org/10.1515/jmsp-2014-0008

[11] Eslami, S., Ramos, T., Tavares, P. J., & Moreira, P. M. G. P. (2015). Shoulder design developments for FSW lap joints of dissimilar polymers. *Journal of Manufacturing Processes*, *20*, 15-23. https://doi.org/10.1016/j.jmapro.2015.09.013

[12] Uygur, I. (2012). Influence of shoulder diameter on mechanical response and microstructure of FSW welded 1050 Al-alloy. *Archives of Metallurgy and Materials*, *57*(1), 53-60. https://doi.org/10.2478/v10172-011-0152-3

[13] Akbari, M., Aliha, M. R. M., & Berto, F. (2023). Investigating the role of different components of friction stir welding tools on the generated heat and strain. *Forces in Mechanics*, *10*(6), 100166. https://doi.org/10.1016/j.finmec.2023.100166

[14] Asadi, P., Mirzaei, M., & Akbari, M. (2022). Modeling of pin shape effects in bobbin tool FSW. *International Journal of Lightweight Materials and Manufacture*, *5*(2), 162-177. https://doi.org/10.1016/j.ijlmm.2021.12.001

[15] Asadi, P., Akbari, M., & Karimi-Nemch, H. (2014). Simulation of friction stir welding and processing. In M-K. Besharati-Givi & P. Asadi (Eds.), *Advances in Friction-Stir Welding and Processing* (pp. 499-542). Elsevier. https://doi.org/10.1533/9780857094551.499

[16] Balokhonov, R. R., Romanova, V. A., Martynov, S. A., Zinoviev, A. V., Zinovieva, O. S., & Batukhtina, E. E. (2016). A computational study of the microstructural effect on the deformation and fracture of friction stir welded aluminum. *Computational Materials Science*, *116*, 2-10. https://doi.org/10.1016/j.commatsci.2015.10.005

[17] Dialami, N., Cervera, M., & Chiumenti, M. (2018). Numerical Modelling of Microstructure Evolution in Friction Stir Welding (FSW). *Metals*, *8*(3), 183. https://doi.org/10.3390/met8030183

[18] Ajri, A., & Shin, Y. C. (2017). Investigation on the Effects of Process Parameters on Defect Formation in Friction Stir Welded Samples Via Predictive Numerical Modeling and Experiments. *Journal of Manufacturing Science and Engineering*, *139*(11), 111009. https://doi.org/10.1115/1.4037240

[19] Türkan, M., & Karakaş, Ö. (2022). Numerical modeling of defect formation in friction stir welding. *Materials Today Communications*, *31*, 103539. https://doi.org/10.1016/j.mtcomm.2022.103539

[20] Akbari, M., Asiabaraki, H. R., & Aliha, M. R. M. (2023). Investigation of the effect of welding and rotational speed on strain and temperature during friction stir welding

of AA5083 and AA7075 using the CEL approach. *Engineering Research Express*, *5*(2), 025012. https://doi.org/10.1088/2631-8695/acca00

[21] Akbari, M., Rahimi Asiabaraki, H., Hassanzadeh, E., & Esfandiar, M. (2023). Simulation of dissimilar friction stir welding of AA7075 and AA5083 aluminium alloys using Coupled Eulerian–Lagrangian approach. *Welding International*, *37*(4), 174-184. https://doi.org/10.1080/09507116.2023.2205035

[22] Salloomi, K. N. (2023). Defect monitoring in dissimilar friction stir welding of aluminum alloys using Coupled Eulerian-Lagrangian (CEL) finite element model. *Advances in Materials and Processing Technologies*, *9*(3), 931-947. https://doi.org/10.1080/2374068X.2022.2106669

[23] Al-Badour, F., Merah, N., Shuaib, A., & Bazoune, A. (2013). Coupled Eulerian Lagrangian finite element modeling of friction stir welding processes. *Journal of Materials Processing Technology*, *213*(8), 1433-1439. https://doi.org/10.1016/j.jmatprotec.2013.02.014

[24] Chauhan, P., Jain, R., Pal, S. K., & Singh, S. B. (2018). Modeling of defects in friction stir welding using coupled Eulerian and Lagrangian method. *Journal of Manufacturing Processes*, *34*, 158-166. https://doi.org/10.1016/j.jmapro.2018.05.022

[25] Akbari, M., & Asadi, P. (2020). Dissimilar friction stir lap welding of aluminum to brass: Modeling of material mixing using coupled Eulerian–Lagrangian method with experimental verifications. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *234*(8), 1117-1128. https://doi.org/10.1177/1464420720922560

[26] Iordache, M., Badulescu, C., Iacomi, D., Nitu, E., & Ciuca, C. (2016). Numerical Simulation of the Friction Stir Welding Process Using Coupled Eulerian Lagrangian Method. *IOP Conference Series: Materials Science and Engineering*, *145*(2), 022017. https://doi.org/10.1088/1757-899X/145/2/022017

[27] Ma'arif, M. S., Purwanto, H., Mahendra, W. J. E., & Oswari, H. (2023). Characteristic of Friction Stir Welding Weld Joint of AA 6061 on Initial Temperature Difference. *MM Science Journal,* (1), 6385. https://doi.org/10.17973/MMSJ.2023_03_2022094

[28] Aziz, S. B., Dewan, M. W., Huggett, D. J., Wahab, M. A., Okeil, A. M., & Liao, T. W. (2018). A Fully Coupled Thermomechanical Model of Friction Stir Welding (FSW) and Numerical Studies on Process Parameters of Lightweight Aluminum Alloy Joints. *Acta Metallurgica Sinica (English Letters)*, *31*(1), 1-18. https://doi.org/10.1007/s40195-017-0658-4