Tribol. Lubr., Vol. 39, No. 3, June 2023, pp. 118~122
Tribology and Lubricants
Short Communication

ISSN 2713-8011(Print) • 2713-802X(Online)
http://Journal.tribology.kr
DOI https://doi.org/10.9725/kts.2023.39.3.118

Finite Element Model for Wear Analysis of Conventional Friction Stir Welding Tool

Hyeonggeun Jo[1], Ilkwang Jang[2], Yeong Gil Jo[3], Dae Ha Kim[4] and Yong Hoon Jang[5†]

[1]*Ph.D. Student, Graduate School, Dept. of Mechanical Engineering, Yonsei University*
[2]*Research Professor, Dept. of Mechanical Engineering, Yonsei University*
[3]*Researcher, Advanced Welding & Joining R&D Group, Korea Institute of Industrial Technology*
[4]*Managing Director, KONASOL R&D Center, KONASOL*
[5]*Professor, Dept. of Mechanical Engineering, Yonsei University*

(Received June 29, 2023 ; Revised June 30, 2023 ; Accepted June 30, 2023)

Abstract – In our study, we develop a finite element model based on Archard's wear law to predict the cumulative wear and the evolution of the tool profile in friction stir welding (FSW) applications. Our model considers the rotational and translational behaviors of the tool, providing a comprehensive description of the wear process. We validate the accuracy of our model by comparing it against experimental results, examining both the predicted cumulative wear and the resulting changes to the tool profile caused by wear. We perform a detailed comparison between the predictions of the model and experimental data by manipulating non-dimensional coefficients comprising model parameters, such as element sizes and time increments. This comparison facilitates the identification of a specific non-dimensional coefficient condition that best replicates the experimentally observed cumulative wear. We also directly compare the worn tool profiles predicted by the model using this specific non-dimensional coefficient condition with the profiles obtained from wear experiments. Through this process, we identify the model settings that yield a tool wear profile closely aligning with the experimental results. Our research demonstrates that carefully selecting non-dimensional coefficients can significantly enhance the predictive accuracy of finite element models for tool wear in FSW processes. The results from our study hold potential implications for enhancing tool longevity and welding quality in industrial applications.

Keywords – Frictional stir welding, Finite element analysis, Tool wear, Archard's wear law, Experiment validation

1. Introduction

Welding of lightweight metals such as aluminium is widely used in aerospace, automotive, and shipbuilding industries. Recently, friction stir welding (FSW) has gained popularity as a solid-state welding technique that utilizes a rotating welding tool to provide superior weld quality and mechanical performance[1]. However, during the FSW process, the tool experiences frictional heat and pressure, leading to wear on the tool surface [2]. This wear phenomenon significantly reduces the tool's lifespan and negatively impacts weld quality[3,4].

To enhance the quality of friction stir welding, it is crucial to study and evaluate the tool wear characteristics. However, most tool wear studies to date have relied on experimental approaches [5-7], which are time-consuming and costly, making it challenging to conduct repetitive experiments. Overcoming these limitations

†Corresponding author: Yong Hoon Jang
Tel: +82-2-2123-5812
E-mail: jyh@yonsei.ac.kr
http://orcid.org/0000-0002-5436-5465
http://orcid.org/0000-0002-6018-9250 (Hyeonggeun Jo)

calls for analytical studies that can analyse tool wear behavior. Furthermore, providing guidelines that account for factors such as mesh size and wear progression time, which are sensitive to wear analysis, holds significance.

Therefore, in this study, we aim to develop a numerical model capable of calculating cumulative wear and obtaining the tool wear profile in friction stir welding.

2. Finite Element Analysis Model for Wear

This study investigated the wear behavior of a convex-type tool commonly used in conventional friction stir welding. Fig. 1(a) shows the overall shape and movement of the tool. In this research, the tool's behavior was examined under a displacement-controlled load of 3 mm, inserted at a rotational speed of 1400 rpm, and transported at a welding speed of 100 mm/min. Fig. 1(b) illustrates the shape and dimensions of the pin's tip and shoulder. The tip has a diameter and height of 3 mm and 2.5 mm, respectively, while the shoulder has a diameter of 20 mm and an angle of 140°. The finite element analysis model applied the material properties of the WC-12%Co tool, which had an elastic modulus of 600 GPa and a Poisson's ratio of 0.2. The tool model consisted of a total of 11,605 hexahedral elements (C3D8), with 4,710 elements representing the contact surfaces.

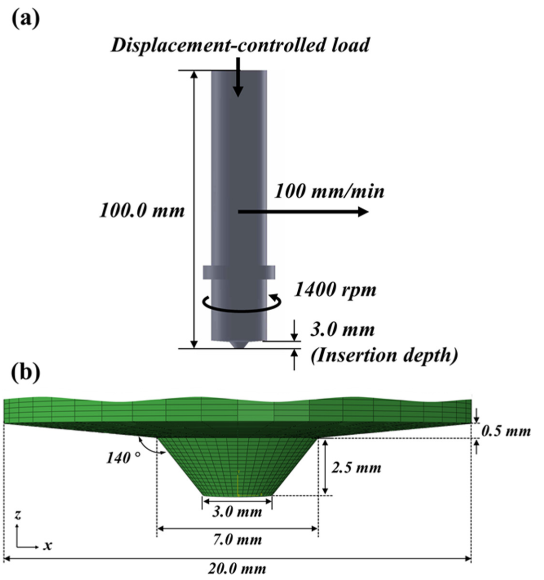

Fig. 1. Conventional frictional stir welding tool behavior (a) and conventional fictional stir welding tool dimension including the finite element(b).

To analyze the wear occurring in the tool, the well-known Archard wear model was employed[8]. Equation (1) represents the Archard wear model, where the wear rate per unit time ($\dot{w}$) is related to the wear coefficient (k), contact pressure (p), material hardness (H), and sliding velocity (V). These parameters can be calculated using the wear coefficient, contact pressure, and relative sliding velocity in the finite element analysis.

$$\dot{w} = k \cdot p \cdot V / H \tag{1}$$

To capture the three-dimensional behaviour of the tool, both rotational and translational motions were considered to calculate the sliding velocity (Fig. 2). The sliding velocity due to rotational motion was determined at each node by substituting the angular velocity with the linear velocity using Equation (2) over the time increments. Subsequently, the rotational sliding velocity and translational sliding velocity, which were converted for each node, were vectorially summed using Equation (3) to obtain the final sliding velocity.

$$\overrightarrow{v_{s_r}} = 2\pi \cdot r \cdot RPM/60 \tag{2}$$

$$\overrightarrow{v_s} = \overrightarrow{v_{s_r}} + \overrightarrow{v_{s_s}} \tag{3}$$

The wear finite element analysis was performed using the commercial finite element software ABAQUS along with the FORTRAN-based subroutine umeshmotion [9]. The wear analysis process is illustrated in Fig. 3.

Firstly, the contact pressure and sliding velocity

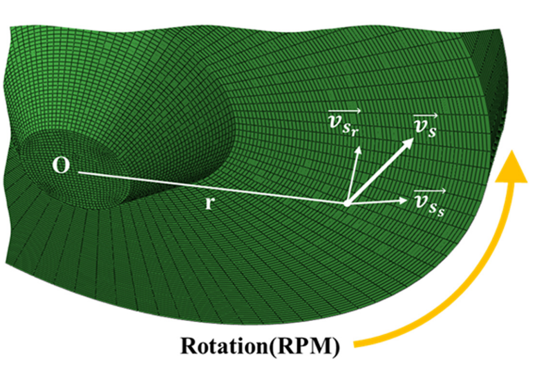

Fig. 2. Definition of tool sliding velocity.

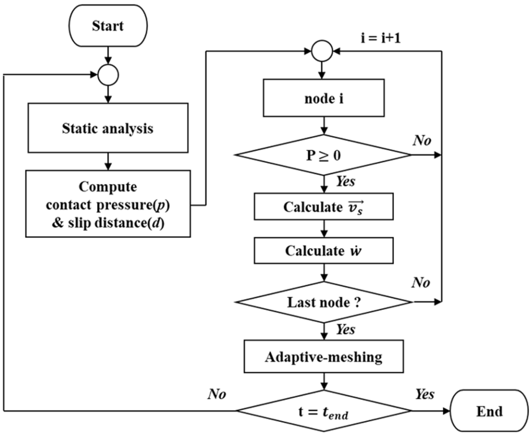

Fig. 3. Program flowchart for wear simulation.

were computed for each node over the time increments, and the wear volume was calculated using the Archard wear equation. Subsequently, iterative calculations were carried out at all nodes within the contact interface, employing adaptive meshing techniques to enhance computational convergence and accuracy with respect to element deformation during the structural analysis [9]. Finally, the analysis concluded upon reaching the final analysis time.

The adaptive meshing technique improves the accuracy of results in structural analysis by reconfiguring elements in regions with significant deformation. This method calculates the wear rate per unit time based on the contact pressure and sliding velocity according to the Archard's wear law, and applies it to the modeling. The mesh is then rearranged into a suitable form. This iterative process determines the cumulative wear. The finite element analysis program used in this study, ABAQUS, reconstructs elements through Eulerian analysis. This process consists of two parts: new element creation (sweeping) and variable redistribution (advection). In the advection step, the Lax-Wendroff technique is employed to account for spatial and temporal changes. This technique has a significant impact on simulations where the contact area changes over time[9].

3. Results and Discussion

In this study, the validity of the wear finite element analysis model was evaluated through two approaches. The first approach involved comparing the experimentally obtained cumulative wear volume with the predicted wear volume obtained from the wear finite element analysis model, in order to assess the adequacy of the modelling conditions. The second approach involved comparing the agreement between the actual surface morphology formed after wear experiments and the predicted surface morphology obtained from the wear finite element analysis model.

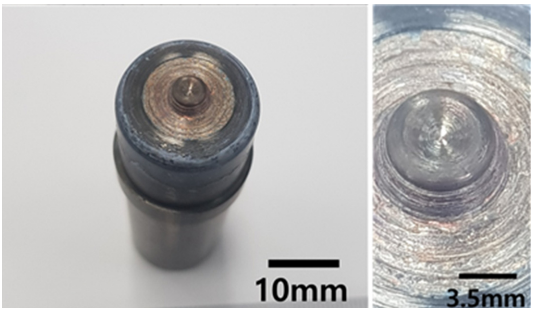

Fig. 4. Appearance of tool after wear test.

To validate the wear finite element analysis model, wear experiments were conducted under actual welding conditions. Fig. 4 shows the external appearance of the tool after the experiments. The welding conditions included a tool insertion depth of 3 mm, a rotational speed of 1400 rpm, and a welding speed of 100 mm/min.

The wear finite element analysis is significantly influenced by the size of elements and the numerical time increment, which can affect the analysis accuracy. Therefore, it is necessary to quantitatively analyse these influences. In this study, a parameter called C_v was used to compare the influences of element size (dx), time increment (dt), and sliding speed (V) on the accuracy of wear analysis for the tool [10], defined as $(V \cdot dt) / dx$. Each C_v condition was calculated for sliding speeds of 1400 rpm, element sizes of 0.2, 0.4, and 0.5 mm, and time increments ranging from 0.001 to 0.05s. Consequently, C_v values of 5.1, 10.3, 25.7, 51.3, and 102.6 were determined.

Fig. 5 depicts the relative error in cumulative wear volume according to the C_v conditions. The relative error represents the difference, expressed as a percentage, between the wear analysis results and the cumulative wear volume obtained from wear experiments. As a result, the combination of (dt, dx) values, specifically (0.005 s, 0.5 mm), (0.004 s, 0.4 mm), and (0.002 s, 0.2 mm), with C_v equal to 10.3, exhibited the smallest relative error. This indicates that the difference between the wear analysis results and the wear experimental results was minimal. C_v increases as dt increases, which implies

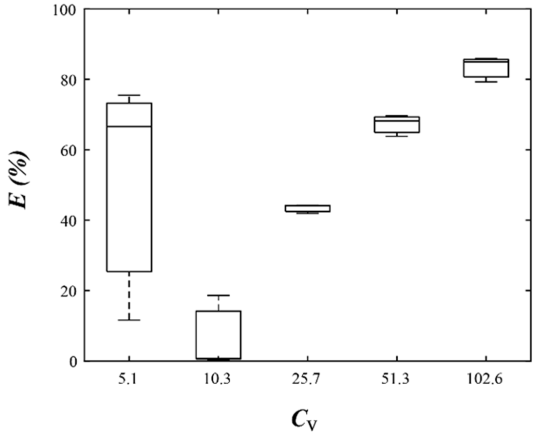

Fig. 5. Error for cumulative wear according to C_v.

that when the time increment is larger, the wear rate calculated per increment also increases, potentially leading to increased errors. Therefore, to ensure reliable wear analysis, both *dx* and *dt* should be considered to select the optimal C_v value.

Subsequently, when comparing the wear analysis results and the tool profile obtained from wear experiments, the combination of (0.004s, 0.4 mm) exhibited the closest resemblance to the experimental profile (Fig. 6) among the three conditions with C_v of 10.3. As shown in Fig. 7, both the experimental and analytical profiles revealed relatively higher wear quantities at the pin center and the contact region between the pin and the shoulder. Furthermore, in the experimental results at positions –8 ~ –6 mm and 6~8 mm along the tool diameter, as well as in the vicinity of –2 mm and 2mm, a melted configuration was observed instead of wear prior to the test. This phenomenon was attributed

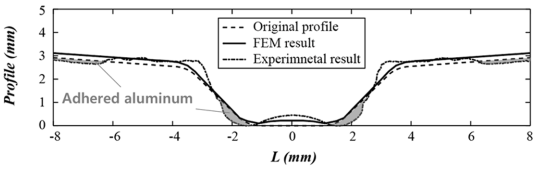

Fig. 6. Tool profile after wear simulation and test

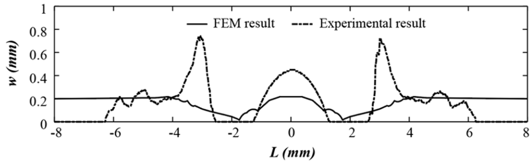

Fig. 7. Cumulative wear after wear simulation and test.

to the adherence of molten material to the tool due to the nature of the welding process, and thus, a wear depth of 0 was assumed for these locations. It was observed that the depth of wear, as determined by both experiments and analysis, exhibited a similar trend in the shoulder region, where wear occurred stably within the –6 ~ –4 mm and 4 ~ 6 mm ranges. The reason for the relatively higher wear in the shoulder region compared to the pin region is believed to be the increasing rotational velocity as the distance from the tool's center increases.

4. Conclusions

This study developed a finite element analysis model capable of calculating the cumulative wear volume of conventional friction stir welding tools and predicting the tool profile after wear. The developed finite element analysis model was validated by comparing the cumulative wear volume and tool profile with experimental results, using the parameter C_v. Present finite element analysis model successfully predicted the actual cumulative wear volume and tool profile if an appropriate C_v value was chosen. Furthermore, we argue that it is crucial to select the optimal value of C_v for each analytical model to ensure the validity of wear analysis, as we have observed variations in the C_v value depending on the structure and mechanical behavior of the analyzed subject, along with reference 10.

Acknowledgements

This work was supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program-Development of robot-based FSW system with 8 kN pressure resistance for the battery housing assembly, 20014820) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea).

References

[1] Thomas, W. M., Nicholas, E.D., "Friction stir welding for the transportation industries", *Mater. Des.*, Vol.18, pp.269- 273, 1997, https://doi.org/10.1016/S0261-3069(97) 00062-9

[2] Wang. J., Su, J. Mishra, R. s., Xu, R., Baumann, J. A., "Tool wear mechanisms in friction stir welding of Ti-6Al-4V alloy", *Wear*, Vol.321, pp.25-32, 2014, https://doi.org/10.1016/j.wear.2014.09.010

[3] Du, S., Liu, H., Gao, Y., Hu, Y., Zhou, L., "Effects

of process parameters on joint formation and tool wear behavior in friction stir welded TA5 alloy", *Int. J. Adv. Manuf. Technol.* pp.2531-2547, 2022, https://doi.org/10.1007/s00170-022-10366-1

[4] Miles, M. P., Ridges, C. S., Hovanski, Y., Peterson, J., Santella, M. L., Steel, R., "Impact of tool wear on joint strength in friction stir spot welding of DP 980 steel", *Sci. Technol. Weld. Join.*, Vol.16(7), pp. 642-647,2011, https://doi.org/10.1179/1362171811Y.0000000047

[5] Zuo, L., Shao, W., Zhang, X., Zuo, D., "Investigation on tool wear in friction stir welding of SiCp/Al composites", *Wear*, Vol.498(9), p.204331, 2022, https://doi.org/10.1016/j.wear.2022.204331

[6] Sahlot, P., Jha, K., Dey, G. K., Arora, A. "Quantitative wear analysis of H13 steel tool during friction stir welding of Cu-0.8%Cr-0.1%Zr alloy". *Wear*, Vol.378(9), pp.82-89, 2017, https://doi.org/10.1016/j.wear.2017.02.009

[7] Bist, A., Saini, J. S., Sharma, V., "Comparison of tool wear during friction stir welding of Al alloy and Al-SiC metal matrix composite", *Proc. Inst. Mech. Eng., Part E: Journal of Process Mechanical Engineering.,* Vol.235(5), pp.1522-1533, 2021, https://doi.org/10.1177/09544089211005994

[8] Goryacheva I.G. Wear models. Contact Mechanics in Tribology. 1st Edition, Chap. 5, pp.163, Springer Science & Business Media, Germany, Berlin, 1998. (ISBN 978-0-7923-2257-0)

[9] Rezaei, A., Van Paepegem, W., De Baets, P., Ost, W., Degrieck, J., "Adaptive finite element simulation of wear evolution in radial sliding bearings", *Wear*, Vol.296(1-2),pp.660-671,2012, https://doi.org/10.1016/j.wear.2012.08.013

[10] Jang, I., Jang, Y. H., "A Comparative Study on Eigen-Wear Analysis and Numerical Analysis using Algorithm for Adaptive Meshing". *Tribol. Lubr.*, Vol.36(5), pp.262-266, 2020, https://doi.org/10.9725/kts. 2020.36.5.262