

У попередньому дослідженні для визначення міцності з'єднання, вигорання та розподілу температур вивчалось зварювання тертям з безперервним приводом (ЗТБП). У даному дослідженні, для оцінювання аналізу температурного циклу було вивчено ЗТБП різномірних металів. Заготовка з алюмінію 6061 (А6061) була зафіксована, а АІSІ 304 оберталася зі швидкістю 1000 об/хв. Розподіл температури вимірювали за допомогою реєстратора даних термомпари ОМЕГА. Термомпару встановлювали поблизу місця з'єднання на відстані 5 мм від стику. В ході комп'ютерного моделювання була розроблена геометрія ЗТБП з використанням ANSYS Design Modeler. З використанням ANSYS academic version Rel. 18.1 проводилося комп'ютерне моделювання з аналізом перехідних теплових процесів в поєднанні зі статичним структурним аналізом. Граничні умови встановлювалися на підставі експериментальних умов, в яких алюміній 6061 був зафіксований, а АІSІ 304 обертався зі швидкістю 1000 об/хв. Виходячи з результатів експерименту можна виміряти температурний профіль як зовнішню поверхню відстані до центру місця з'єднання. З результатів моделювання видно, що профіль температурного циклу збігається з експериментальними результатами. Визначення зв'язку профілю температурного циклу з результатами механічних випробувань є важливим. Вивчення мікроструктури показало, що на стороні нержавіючої сталі немає суттєвої різниці в розмірі і формі зерен. Результати комп'ютерного моделювання показали, що зварне з'єднання алюміній-нержавіюча сталь показує мітки зони термічного впливу поблизу поверхні розділу зварного шва тільки на стороні алюмінію, що було підтверджено результатами експерименту

Ключові слова: зварювання тертям з безперервним приводом, алюміній, температурний цикл, різномірний метал, механічні випробування

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TEMPERATURE CYCLE ANALYSIS OF A6061-AISI304 DISSIMILAR METAL CONTINUOUS DRIVE FRICTION WELDING

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1. Introduction

Dissimilar metal welding had been a trend of research due to many problems and became challenges to be resolved to provide industrial applications. The problems of dissimilar metal welding are different thermal and mechanical properties. Also, this process produces under high friction pressure, and interface temperature, the elements in different materials will show unusual behavior, and thus dissimilar deformation. On another side, dissimilar metal welding is conducted with high thermal conductivity, large differences in forging temperatures, and the formation of brittle intermetallic compounds. One of the solutions for dissimilar metal welding is Continuous Drive Friction Welding (CDFW). Mechanism of friction welding heat is formed by direct conversion of mechanical energy into thermal energy at the interface of the workpieces. A weld under the compressive contact force of one rotating and one stationary

workpiece is produced as a solid-state joining process. The heat is generated at the weld interface because of the continuous rubbing of contact surfaces, which, in turn, causes a temperature rise and subsequent softening of the material. Eventually, the material at the interface starts to flow plastically and forms an upset. When a certain amount of upsetting has occurred, the rotation stops and the compressive force is maintained or slightly increased to consolidate the weld. Aluminum 6061 and AISI 304 are materials that are widely used in the construction field. The investigation of the CDFW process for Aluminum 6061 and AISI 304 was limited. Aluminum is a lightweight metal and resistant to corrosion. Unfortunately, aluminum is difficult to be joined by welding due to having a high heat conductivity. Therefore, studies are aimed at determining the thermal cycle profile and the shape of the flash in CDFW welding by computer simulation and experimental methods to improve the strength of CDFW joints.

2. Literature review and problem statement

Friction welding is a welding method that is generated with the help of heat obtained by the conversion of mechanical energy into thermal energy during friction on the workpieces' interfaces [1]. Continuous drive friction welding is one of the friction welding techniques in which friction occurs between two workpieces. One workpiece is moving and rotates at a constant speed. The rotational speed of the specimen during the welding process is produced by a motor that works continuously. Another workpiece provides contact with the other workpiece that rotates under the axial force within a specified time. Fig. 1 shows the important process parameters of friction welding [2]. Friction time, friction pressure, and upset pressure affect directly the tensile strength of weld joints. Based on the linear statistical analysis of the previous investigation, the effect of factors that significantly affect joint properties can be determined [3, 4].

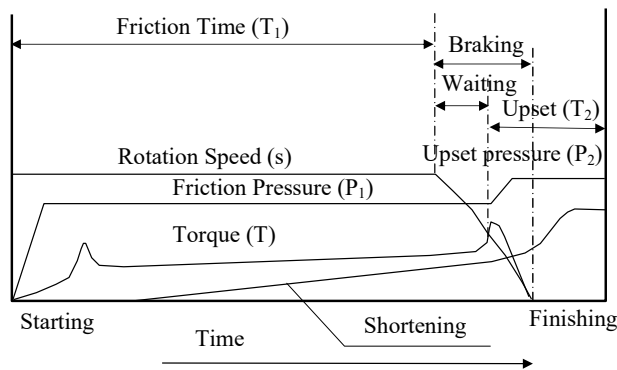


Fig. 1. Process parameters of continuous drive friction welding [2]

The heat affected zone (HAZ) is the area affected by heat during the welding process. HAZ area affects mechanical properties and microstructure of the workpiece welded from the initial state. The area of the HAZ is affected by the heat generated from the welding process. The higher the heat generated, the wider the HAZ area. In the CDFW process, the HAZ is influenced by friction time, friction pressure, and rotational speed. Therefore, in the challenge of the CDFW process, the HAZ area is an important observation to know the effect of process parameters on CDFW connected with HAZ, mechanical properties and microstructure.

Extensive efforts have been made in using computer simulations evolved as a favorite tool to predict process parameters of the CDFW process. By using computer simulation, the initial prediction of process parameters can be constructed to reduce the experimental trial and error and time of production process can be minimized. In the previous study, computer simulation of the CDFW process was investigated by using a 2-Dimensional model [5, 16]. The non-steady 2-D model heat transfer analysis for the low carbon steel friction process was developed by FEM code ANSYS [6]. The advantage of 2D simulation is that the completion of running is speedy, but the results can be plotted only two dimensional. It can be denoted that the shape and ridges of flash depend on the flow behavior of plasticized materials. The limitation of this result is no simulation work, which has produced the actual shape of flash, let alone the characteristic ridges. In

this study, the CDFW process is modeled in 3 dimensions in order to provide more information on the analysis of CDFW process results. Several studies on CDFW with a 3-dimensional model had been investigated for 2024Al Alloy and UNS C23000 Brass [7], UNS C23000 Brass, and AISI 1021 [8] and 2024Al and AISI 1021 [9]. Unfortunately, these studies did not discuss the simulation results with HAZ toward mechanical properties and microstructure. In other studies, the influence of process parameters, including friction pressure, upsetting pressure, and upset time, was discussed on the axial shortening, hardness, microstructure, and tensile properties of the welds [10]. In the other work, the mechanical properties and microstructures of friction welds between aluminum alloy and steel have been characterized [11]. The flow behavior and flash formation in continuous drive friction welding (CDFW) were investigated using a 3D thermo-mechanical coupled finite element method. The higher temperature, a larger region with high temperature, and higher axial pressure will increase material flow velocity and flash dimensions [12]. Maalekian et al. presented four models of thermal generation in the friction process. The four models are constant coulomb friction coefficient, sliding sticking friction, power dissipation by experiment, and the method of inverse heat conduction [13]. In the joining of alumina-6061 aluminum alloy, the HAZ, which occurs on the aluminum side, is very narrow. The effect of rotation and the rate of deformation of aluminum are higher than on alumina [14].

Mechanical evaluation of Aluminum-mild steel dissimilar metal joint showed that the welded materials have lower hardness compared to their base material. The cooling temperature profile prediction of friction welding is in good agreement with the experimental result [15]. In the joining of dissimilar pure metals, maximum heat occurs near the surface but not on the surface due to the presence of convective heat loss from the surface to the environment. The addition of friction time will reduce the tensile strength due to the formation of thicker intermetallic layers in the formation of the eutectoid system [16]. In the case of the 6061-T6 aluminum alloy and AISI 1018 steel friction weld joint, a peak temperature of 383 °C occurred on the steel side and 418 °C on the Aluminum side. Both temperatures were measured near the interface [17]. In joining aluminum with stainless steel, increasing the friction time will increase the tensile strength to the maximum, then decrease with increasing friction time. Longer friction time will cause the formation of intermetallic layers. The intermetallic layer presence on the interface due to this temperature increase will cause a decrease in the tensile strength of the connection [4, 18].

The introduction of silver as an interlayer in aluminum and different stainless steel metal joints affects the increasing tendency of particle fractures. The application of silver interlayer on the dissimilar metal joint will reduce the coefficient of friction, heat generation, and axial shortening of material [19]. A study also has been conducted to improve the mechanical strength of the A6061 CDFW joint by modifying the surface geometry. The application chamfer angle of 30 degrees can increase the tensile strength and decrease the fatigue crack growth rate in the A6061 CDFW specimen of the weld joint [20].

The challenge of CDFW modeling is that dissimilar materials have different thermal and mechanical properties. Under high friction pressure and interface temperature, the elements in different materials will show different behavior

and thus dissimilar deformation. The heat-affected zone area is affected by temperature profile, and it became essential to predict HAZ connected with mechanical properties.

3. The aim and objectives of the study

The study aims to investigate the CDFW process for Aluminum 6061 and AISI 304 by using a computer simulation and experimental solution.

To achieve this aim, the following objectives are accomplished:

- to determine temperature cycle profile of the CDFW process for Aluminum 6061 and AISI 304 by using computer simulation and experiment;
- to observe to find heat-affected zone of the CDFW process for Aluminum 6061 and AISI 304.

4. Methods of research

The material used in this study were Aluminum 6061 and AISI 304 as materials that are widely used in the construction field. The friction welding system used was a lathe with adding hydraulic mechanism, as shown in Fig. 2. Analog to Digital Converter (ADC) Advantech USB-4704 connected temperature and load cell to measure temperature cycle profile and friction pressure of the process. Optical microscopy (Olympus model BX53M) was used to analyze the metallurgical changes at the interface. Tensile and hardness tests of weld cross-sections are carried out to examine the mechanical properties of the resulting welds. Universal Testing Machine (Gotech, model GT-7001-LC50) is used to test the tensile strength of the weld, and Microhardness Tester (Mitutoyo HM-100) is used to test the hardness of the weld zone. Table 1 shows the process parameters of the experiment set in this experiment based on a preliminary experiment that gives friction weld joint A6061-AISI304 that fractured on the aluminum side. Temperature distribution and heat-affected zone of the CDFW process for Aluminum 6061 and AISI 304 were observed.

Table 1

Process parameters of the experiment on CDFW

No	Process Parameter	Value
1	Rotation speed	1,000 rpm
2	Friction pressure	45 MPa
3	Friction time	4 second
4	Upset pressure	125 MPa
5	Upset time	2 second

Test procedure was developed by several steps as described below:

1) The AISI 304 specimen was set on turning chuck, and the A6061 specimen was gripped in fix chuck. Fig. 3 shows the detailed dimension of the CDFW specimen.

2) Prepare the ADCs for temperature and load cell measurement.

3) The AISI 304 specimen was rotated with 1,000 rpm. Friction pressure of 45 MPa was applied to the A6061 specimen according to the friction time variation. The magnitude friction pressure was confirmed by using the load cell measurement.

4) Turning is stopped based on friction time variation, and then the pressure was increased to upset pressure of 125 MPa, applied according to the upset time condition.

5) The temperature was measured starting from the initial process until the welding process is finished. Fig. 4 shows the temperature measurement location. Measurement was taken from 3 minutes to avoid the influence of temperature fluctuation on time at the initial measurement. The computer simulation was used to predict the temperature distribution profile.

6) The specimen was taken out from the CDFW experiment apparatus, and the product was machined into a standard tensile test specimen tested in tension.

7) The broken tensile specimen was then prepared for microstructure observation and hardness test.

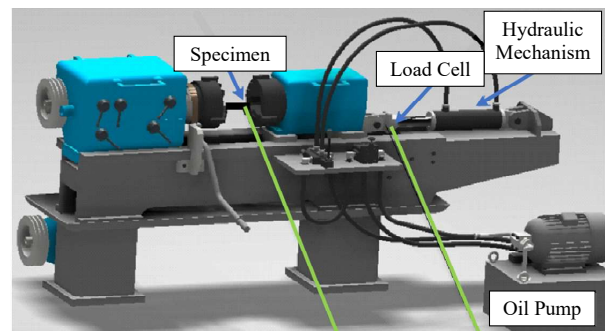


Fig. 2. Schematic diagram of the CDFW experiment apparatus

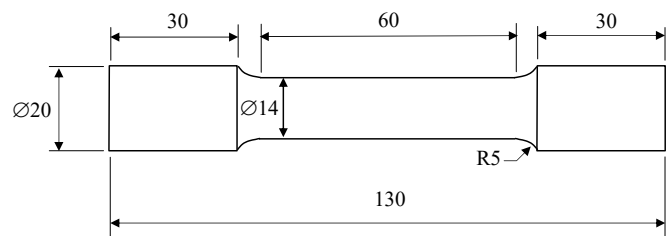


Fig. 3. Detailed dimension of the CDFW specimen [21]

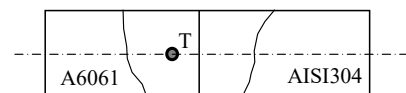


Fig. 4. Schematic diagram of temperature measurement locations (T is the thermocouple position which is located 5 mm from the interface)

In order to ensure the properties of the test material, Aluminum 6061 and AISI 304 are initially examined using a tensile test carried out based on Japan Industrial Standard code of JISZ2241 for conducting a tensile test of metals. The smallest sub-size round specimens are 14 mm in diameter, with a 60 mm gauge, as shown in Fig. 3 [21]. The results are plotted in the stress-strain diagram. The diagram indicates the nominal stress (σ) of Aluminum 6061 is 310 MPa, and the modulus of the elasticity is 68.9 GPa. For AISI 304, the nominal stress (σ) is 505 MPa, and the modulus of the elasticity is 200 GPa.

In the simulation procedure, the first step is to make the geometry of the CDFW model using ANSYS Design Modeler tool [22]. Then, it is connected to finite element method

software, which is ANSYS academic version Rel. 18.1. The boundary condition is set as an experimental condition, which is Aluminum 6061 was fixed, and AISI 304 was turning by using rotation speed as 1,000 rpm (Fig. 5).

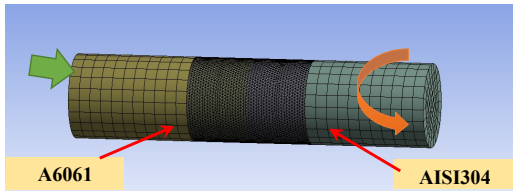


Fig. 5. CDFW Finite Element model

Heat generation at the interface was defined as a heat flux on the connection between Aluminum 6061 and AISI 304.

5. CDFW process for Aluminum 6061 and AISI 304

5. 1. Temperature cycle profile of the CDFW process for Aluminum 6061 and AISI 304

Using the Finite Element Analysis (FEA) technique, the thermal effects of the CDFW process were simulated, then the predicted temperature values were compared with the experimental values. Fig. 6 shows that the trend of the time-temperature plots predicted by the finite element heat flow model has a similar tendency with the experimental measurements on the Aluminum side.

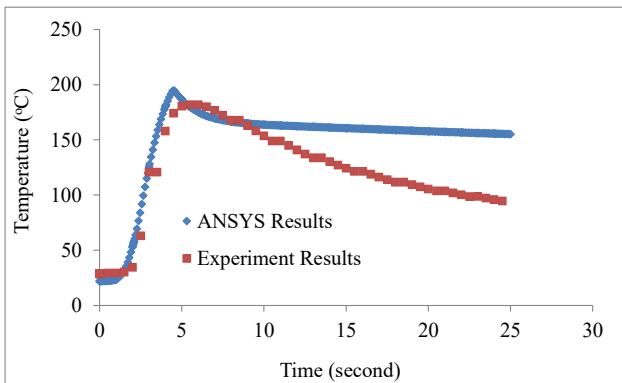


Fig. 6. Comparison between experimental and ANSYS results on temperature cycle profile

The result also shows the rapid heating and cooling processes during the CDFW process. The peak temperature occurred at around 180 degrees Celsius. The value of the temperature has an agreement with the temperature measurement of friction welding of A6063 and 304 L stainless steel reported in [23]. The estimated peak temperature from ANSYS results is also comparable to the experimental result with an error of 7.06 %. The ANSYS model is based on the assumption that the heat generated at the interface is transferred to the base materials.

5. 2. Heat affected zone of the CDFW process for Aluminum 6061 and AISI 304

Tensile testing showed that the ultimate tensile strength of the CDFW joint is 115 MPa. The tensile test specimen was fractured on the aluminum side 4 mm away from the interface. Moreover, the measurement of hardness was carried out three times for each of the same areas. Hardness mea-

surement results are shown in Table 2. The average hardness value on the aluminum side is 106.5 VHN at the distance of 10–15 mm from the interface.

Table 2

Distance from the interface (mm)	Vickers hardness number			
	Hardness (VHN)			
	1	2	3	averages
-15	106.4	106.5	106.5	106.5
-10	106.5	106.5	106.4	106.5
-5	80.4	84.5	88.7	84.5
-2	75.2	74.5	74.2	74.6
-1.5	74	76.8	76.2	75.7
-1	74.2	74	75.8	74.7
-0.5	75.6	77	77.8	76.8
0.5	268.6	267.7	265.4	267.3
3	242.7	243.5	245.1	243.8
10	245.1	243.9	242.3	243.8

Based on the measurement test, it can be described as a connection between microstructure and hardness test, as shown in Fig. 7. At the distance of 5 mm from the interface, hardness decrease is 84.5 VHN and smaller hardness is 74.6 VHN occurred at the distance of 2 mm from the interface. It is thought that high temperature at the interface affects grain size near the interface becoming bigger compared to that of 10 mm away from the interface.

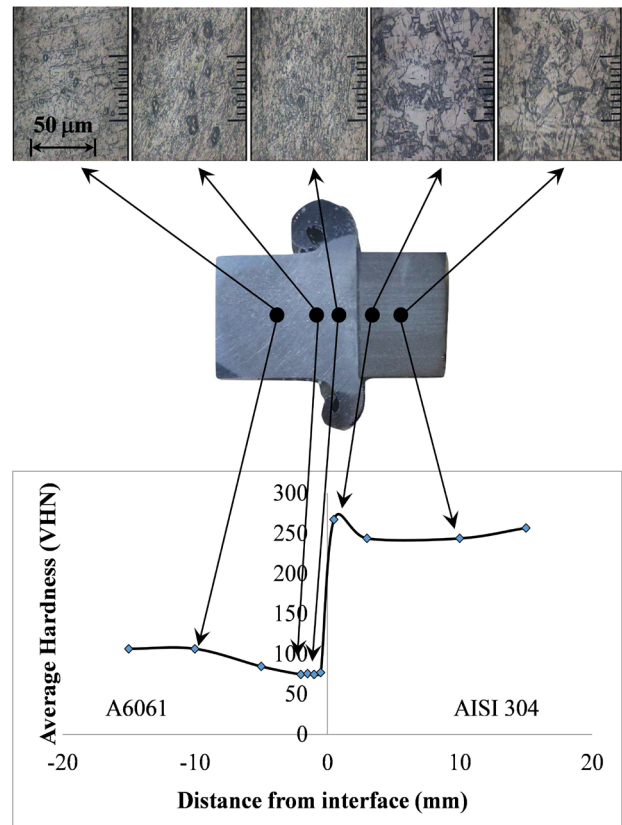


Fig. 7. Connection between microstructure and hardness test

Besides, the flash does not occur on the stainless steel side due to no-flow material. The welded aluminum-stainless

steel joint shows marks of heat affected zone near the weld interface only on the aluminum side, as shown in Fig. 8. There is a difference between experimental and simulation results for flash shape due to the assumption of the material model used bilinear hardening model in FEA.

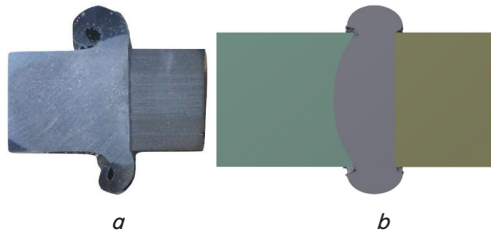


Fig. 8. Heat affected zone near the weld interface on the aluminum (left side) and stainless steel side (right side): *a* – experimental result; *b* – finite element analysis result

6. Discussion of the experimental results

The thermal cycle profile during welding shows the similarity between the computer simulation results and the experimental results. The maximum temperatures achieved based on computer simulations and experiments are almost the same. The time of achieving the maximum temperature is also almost the same. Thus, the computer simulation method can be used to predict the results of welding CDFW at a fast and low cost.

Deformation of SS 304 is negligible due to its higher hardness and yield stress value, lower thermal conductivity, and higher melting point. In this case, because of the low thermal diffusivity of stainless steel, the heat flow is confined to the region near the weld interface. This results in the visible appearance of the heat-affected zone on the aluminum side. The mechanical properties showed this phenomenon as shown in the characteristics of microstructure and hardness test as model analysis to denote the relation between temperature distribution profile and mechanical properties test results.

It is found that the bigger the grain size, the lower the hardness of the aluminum part near the interface of the specimen. It is also shown that the friction weld joint of A6061 and AISI 304 fractured under tensile testing in the lower hardness, which is around 4 mm from the interface. It is thought that due to the heat during friction welding and upset force, the diffusion of chemical components from AISI 304 to A6061 side occurs and vice versa. The trend of hardness near the interface of A6061 and AISI 304 also has

the same pattern, and the existence of diffusion has a role in making good strength at the interface of the friction welding joint of A6063 and stainless steel 304 [24]. The analyzed data are limited to microstructures and microhardness. Still, it can show that the sound friction weld joint was able to be produced with a fracture on the aluminum side, not at the interface. The fracture occurrence on the aluminum side is thought because of a decrease in strength in the HAZ region. Conversely, in the interface area, an increase in strength is due to chemical element diffusion. Detailed examination of chemical elements diffusion around the friction weld interface under the effect of other friction welding parameters will be conducted in the near future.

On the other hand, there is no material flow in the AISI 304 specimen because this part did not endure plastic deformation due to higher yield stress compared to the aluminum A6061 specimen. Hardness test results are decrease noted in the steel zone [4]. Based on microstructure observation, it can be denoted that there is no significant difference in grain size and grain shape on the stainless steel side. In the next study, research is required for varying the welding process parameter to obtain the minimum HAZ area, minimum IMC, and maximum tensile strength.

7. Conclusions

1. The experiment peak temperature occurred at around 180 degrees Celsius. The estimated peak temperature from the simulation result is comparable to the experimental result, with an error of 7.06 %. It is found that the FEA simulation can yield the thermal cycles that occurred on the outer side of the aluminum side during friction welding reached the recrystallization temperature of A6061 and confirmed in good agreement with the result of temperature measurement. It also shows the minimum temperature requirement in friction welding of A6061 and AISI 304 was fulfilled to produce a friction weld joint that breaks on the aluminum side under tensile testing.

2. The welded aluminum-stainless steel joint shows marks of heat affected zone near the weld interface only on the aluminum side. It can be predicted with computer simulation. The width of the heat-affected zone is minimal. Hardness test results are decreased being noted in the steel zone. Based on microstructure observation, it can be denoted that there is no significant difference in grain size and grain shape on the stainless steel side. There is a difference between experimental and simulation results for flash shape due to the assumption of the material model used bilinear hardening model.

Reference

- Sahin, M. (2008). Joining of stainless-steel and aluminium materials by friction welding. *The International Journal of Advanced Manufacturing Technology*, 41 (5-6), 487–497. doi: <https://doi.org/10.1007/s00170-008-1492-7>
- Sahin, M., Erol Akata, H., Ozel, K. (2008). An experimental study on joining of severe plastic deformed aluminium materials with friction welding method. *Materials & Design*, 29 (1), 265–274. doi: <https://doi.org/10.1016/j.matdes.2006.11.004>
- Murti, K. G. K., Sundaresan, S. (1983). Parameter optimization in friction welding dissimilar materials. *Metal Construct*, 331–335.
- Yilbaş, B. S., Şahin, A. Z., Kahraman, N., Al-Garni, A. Z. (1995). Friction welding of St-Al and Al-Cu materials. *Journal of Materials Processing Technology*, 49 (3-4), 431–443. doi: [https://doi.org/10.1016/0924-0136\(94\)01349-6](https://doi.org/10.1016/0924-0136(94)01349-6)
- Li, W., Shi, S., Wang, F., Zhang, Z., Ma, T., Li, J. (2012). Numerical simulation of friction welding processes based on ABAQUS environment. *Journal of Engineering Science and Technology Review*, 5 (3), 10–19.

6. Kimura, M., Inoue, H., Kusaka, M., Kaizu, K., Fuji, A. (2010). Analysis Method of Friction Torque and Weld Interface Temperature during Friction Process of Steel Friction Welding. *Journal of Solid Mechanics and Materials Engineering*, 4 (3), 401–413. doi: <https://doi.org/10.1299/jmmp.4.401>
7. Srija, V., Chennakesava Reddy, A. (2013). Finite Element Analysis of Friction Welding Process for 2024Al Alloy and UNS C23000 Brass. *International Journal of Science and Research*, 4 (5), 1685–1690.
8. Santhosh Kumar, T., Chennakesava Reddy, A. (2015). Finite Element Analysis of Friction Welding Process for 2024Al Alloy and AISI 1021 Steel. *International Journal of Science and Research*, 4 (5), 1679–1684.
9. Raviteja, A., Chennakesava Reddy, A. (2015). Finite Element Analysis of Friction Welding Process for UNS C23000 Brass and AISI 1021. *International Journal of Science and Research*, 4 (5), 1691–1696.
10. Kurt, A., Uygur, I., Paylasan, U. (2011). Effect of friction welding parameters on mechanical and microstructural properties of dissimilar AISI 1010-ASTM B22 joints. *Welding Journal*, 90 (5), 102–106.
11. Taban, E., Gould, J. E., Lippold, J. C. (2010). Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization. *Materials & Design (1980-2015)*, 31 (5), 2305–2311. doi: <https://doi.org/10.1016/j.matdes.2009.12.010>
12. Ji, S., Liu, J., Yue, Y., Lü, Z., Fu, L. (2012). 3D numerical analysis of material flow behavior and flash formation of 45# steel in continuous drive friction welding. *Transactions of Nonferrous Metals Society of China*, 22, s528–s533. doi: [https://doi.org/10.1016/s1003-6326\(12\)61756-7](https://doi.org/10.1016/s1003-6326(12)61756-7)
13. Maalekian, M., Kozeschnik, E., Brantner, H. P., Cerjak, H. (2008). Comparative analysis of heat generation in friction welding of steel bars. *Acta Materialia*, 56 (12), 2843–2855. doi: <https://doi.org/10.1016/j.actamat.2008.02.016>
14. Ahmad Fauzi, M. N., Uday, M. B., Zuhailawati, H., Ismail, A. B. (2010). Microstructure and mechanical properties of alumina-6061 aluminum alloy joined by friction welding. *Materials & Design*, 31 (2), 670–676. doi: <https://doi.org/10.1016/j.matdes.2009.08.019>
15. Seli, H., Ismail, A. I. M., Rachman, E., Ahmad, Z. A. (2010). Mechanical evaluation and thermal modelling of friction welding of mild steel and aluminium. *Journal of Materials Processing Technology*, 210 (9), 1209–1216. doi: <https://doi.org/10.1016/j.jmatprotec.2010.03.007>
16. Meshram, S. D., Mohandas, T., Reddy, G. M. (2007). Friction welding of dissimilar pure metals. *Journal of Materials Processing Technology*, 184 (1-3), 330–337. doi: <https://doi.org/10.1016/j.jmatprotec.2006.11.123>
17. Taban, E., Gould, J. E., Lippold, J. C. (2010). Characterization of 6061-T6 aluminum alloy to AISI 1018 steel interfaces during joining and thermo-mechanical conditioning. *Materials Science and Engineering: A*, 527 (7-8), 1704–1708. doi: <https://doi.org/10.1016/j.msea.2009.10.059>
18. Rn, S., Surendran, S. (2012). Friction Welding to Join Dissimilar Metals. *International Journal of Emerging Technology and Advanced Engineering*, 2 (7), 200–210
19. Kannan, P., Balamurugan, K., Thirunavukkarasu, K. (2014). An experimental study on the effect of silver interlayer on dissimilar friction welds 6061-T6 aluminum mmC and AISI 304 stainless steel. *Indian Journal of Engineering and Materials Sciences*, 21 (6), 635–646.
20. Irawan, Y. S., Razaq, F., Suprpto, W., Wardana, B. S. (2019). Tensile strength and fatigue crack growth rate of chamfered and clamped A6061 friction weld joints. *Eastern-European Journal of Enterprise Technologies*, 6 (12 (102)), 31–39. doi: <https://doi.org/10.15587/1729-4061.2019.154384>
21. JIS Z 2201:1998. Test pieces for tensile test for metallic materials (1998). Japanese Standards Association.
22. Ansys Design Modeller. Ansys Inc. Available at: <https://www.ansys.com>
23. Alves, E. P., Toledo, R. C., Botter, F. G., An, C. Y. (2019). Experimental Thermal Analysis in Rotary Friction Welding of Dissimilar Materials. *Journal of Aerospace Technology and Management*. doi: <https://doi.org/10.5028/jatm.v11.1068>
24. Kimura, M., Suzuki, K., Kusaka, M., Kaizu, K. (2017). Effect of friction welding condition on joining phenomena and mechanical properties of friction welded joint between 6063 aluminium alloy and AISI 304 stainless steel. *Journal of Manufacturing Processes*, 26, 178–187. doi: <https://doi.org/10.1016/j.jmapro.2017.02.008>