Characteristic of friction welding weld joint of AA6061 on elevated environmental temperature

Sugiarto 1, M. Syamsul Ma’arif 1, Djarot B. Darmadi 1, M. Ikram Kido 2
1 Department of Mechanical Engineering, Universitas Brawijaya, Jl. MT Haryono 167, Malang, Indonesia
2 Masters of Mechanical Engineering Students at Brawijaya University
Email: sugik_mlg@ub.ac.id

Abstract. Rotary Friction Welding is a solution in addressing the problems in welding of material difficult to weld by fusion welding, such as AA6061 aluminium alloy. Fusion welding is difficult to apply to aluminium alloy because of porosity and crack which often occur during solidification. From the research on friction welding of AA6061, it can be conclude that excessive welding temperature of friction welding may result in thermal softening in weld zone and HAZ. The excessive cooling rate after friction welding run will affect to formation of hard and brittle of weld zone. Increase of environmental temperature above room temperature will accelerate workpiece to achieve solid state condition and lowering difference between weld peak temperature and initial weld temperature (ΔT) which mean decreasing of cooling rate. In this research, environmental temperature were varied of 27 °C (room temperature), 50 °C, 75 °C, 100 °C, 125 °C dan 150 °C. Some parameters are set constant such as rotation speed of 1600 rpm, friction pressure of 65 bar or 65 kg.cm⁻², friction time (tf) of 6 seconds, forging pressure of 325 bar or 325 kg.cm⁻², forging time of 60 seconds, contact diameter of workpiece of 15 mm and the workpiece chamfer angle of 15°. The contact area is divided into three zones, which are the plastic deformation zone (Zpl), the partial deformation zone (Zpd) and the non-deformed zone (Zud). The higher the environmental temperature will produces the wider plastic zone and plastic deformation zone (Zpl + Zpd). The higher the environmental temperature will causes the yield strength of the AA 6061 friction weld joint to increase which modelled as \( y = 3E-05x^2 + 0.0033x + 16.582 \). Likewise, the tensile strength of the AA 6061 friction weld joint also increases which modelled as \( y = 3E-05x^2 + 0.0025x + 0.1199 \). When comparing the hardness of rotating workpiece side (spin) with workpiece side pressing (press), the previous one is higher at all variations of the temperature. From the photograph of the microstructure of base metal of Al 6061, dark particles (Mg2Si) and gray particles (Fe3SiAl12) are present in the Al matrix. The grain structure of Zud is bigger than Zpd and Zpl. Zpd microstructures at all environmental temperatures form smaller granular structures than base metal grains. Zpl microstructure in workpieces with environmental temperature of 27 °C, 50 °C, 75 °C and 100 °C were formed in small granular structure with Mg2Si (black) and Fe3SiAl12 (gray) structure which spread evenly. However Zpl microstructure with environmental temperature of 125 °C and 150 °C seems to enlarge, especially the structure of Fe3SiAl12 (gray), due to overheat and excessive softening.

Keywords: rotary Friction welding, environmental temperature, AA 6061, mechanical properties.
1. Introduction

Rotary friction welding is one type of friction welding which become solution in solving the difficulty in welding of difficult to weld material by fusion welding. Friction welding has many advantages over fusion welding techniques. Because the process temperature remains below the melting point of the material being welded, there is no need to protect the filler with gas, low distortion and low residual stress in the friction welding process, energy saving process that does not produce smoke, arc flash, or spatter [8]. Because the metal joining process occurs without melting (solid state process), the hydrogen diffusion is low so that it can minimize the occurrence of hydrogen cracking (hydrogen induce cracking). Friction welding is the interaction between a series of thermodynamic processes which is an accumulation of several parameters such as heat input, cooling rate, metal flow and deformation, recrystallization and integration of mechanical connections [20].

Aluminum alloys have been widely used in the aviation, aerospace, container and transportation industries because of their superiority in terms of strength, light weight, fatigue resistance and high corrosion resistance [15; 9; 13]. Applying fusion welding in aluminum alloys is difficult, because it tends to produce defects such as porosity and cracking during solidification [11; 6].

The chemical composition of aluminum alloy has an important role in determining the properties of friction welding results [10]. Microstructure in the weld zone and HAZ in the friction welding joint AA 6061-T6 has a uniform fine grain structure that makes the hardness and tensile strength higher than the base metal [17].

The quality of the friction welding product depends on the heat input and the magnitude of the coupling moments that work during the welding process. The heat input of welding and coupling which occurs is determined by the friction and the compressive force between two workpieces that are joined. This friction produces heat which is able to soften the workpiece interface area and cause plastic deformation. Friction welding parameters which can be optimized to get a good joint include friction pressure, friction time, forging pressure, forging time and rotational speed [22]. While the quality of the friction welding product can be improved by optimizing the welding parameters, the use of interlayers, changing geometric shapes and treatment before or after the welding process [28].

The quantity of heat input \((q)\) in friction welding is influenced by contact area between surfaces \((\Omega_a)\), cross section radius of the workpiece \((r)\), rotational speed \((\omega)\), stationary workpiece pressure relative to the rotating workpiece \((P)\), coefficient of friction from material \((\mu)\) and temperature \((T)\) [4]:

\[
q = \int \! \! P\mu(T)\omega r.\! d\! \Omega_a
\]

The equation is assumed based on the following illustration in Figure 1:

```
Figure 1. Axisymmetric schematic model in the friction welding process [4]
```

The heat produced by welding friction has effect to reduce the hardness of the material being welded compared to the base metal [16]. The chemical composition of aluminum in friction welding has an important role in determining the properties of welds [10]. Too long friction time and high
welding temperature can cause intermetallic phase formation which tends to cause joint brittleness [1]. It was further stated that the weld properties is not only influenced by the interface geometry but also the rotational speed and the forging pressure applied to the workpiece during friction welding. Rotational speed has the biggest effect on the nature of weld results [27]. Microstructure in the welding zone and HAZ in the friction welding joint AA 6061-T6 has a uniform fine-grained structure that makes the hardness and tensile strength higher than base metal (BM). However, if the heat generated by friction and plastic deformation is too high it can cause the weld joint to experience a thermal softening effect, which causes the HAZ strength to be lower than BM [12; 17; 19]. To reduce thermal softening and increase strength, forced cooling has been applied during friction welding. Sharma et al. (2012), studied the effects of air, water, and nitrogen as cooling fluids on the FSW AA7039 process, and stated that water cooling is more superior in improving the mechanical properties of the joint. Other studies also show that forced cooling is beneficial for increasing the mechanical strength of aluminum alloy FSW joints [29; 18; 21; 26]. HAZ on AA 6061 joints is the weakest area and failures often occur in this area during tensile tests. The tensile strength of the FSW joint decrease due to damage in hardened / brittle areas, damage to precipitation and coarse grains caused by an increase in temperature during the FSW. Forced cooling of the FSW accelerates the cooling process, suppresses the formation of coarse grains and maintains a precipitate at the HAZ of AA 6061 joints, thereby increasing tensile strength [14]. By preheating, the intermetallic compound and the precipitate (precipitate) are shifted to the grain boundary during the welding process. These deposits act as a strong barrier to the movement of dislocations and increase resistance to material deformation. This phenomenon can cause obstacles in grain boundaries to develop so as to produce small metal grains and increase joint hardness and strength. Too high of cooling rate and impact pressure in friction welding will produce hard and brittle zone so that susceptible to welding failure. Increasing the environmental temperature above room temperature will accelerate the workpiece to reach a solid state condition and reduce ΔT, which means lowering the cooling rate.

In rotary friction welding, generally three main regions are formed in the joint area, i.e. the plastic deformation zone (Zpl) in the central area of the weld, the partial deformation zone (Zpd) outside the welding area and the unformed zone (Zud) [7]. In another classification, the rotary friction welding joint area was formed in three zones, namely the undeformed zone (UZ) where the hardness is almost the same as the parent metal, plasticized zone (PZ), and partly deforming zone (PDZ) [23].

2. Material and method
This research uses laboratory-scale experimental methods in the process of joining aluminum alloy AA 6061 with a diameter of 15 mm as shown in Figure 3 with rotary friction welding technique as shown in Figure 2. Environmental temperature is varied on 27 °C (room temperature), 50 °C, 75 °C, 100 °C, 125 °C and 150 °C. Some parameters are set constant such as spindle rotation 1600 rpm, friction pressure 65 bar or 65 kg.cm⁻², friction time (tf) of 6 seconds, forging pressure 325 bar or 325 kg.cm⁻², forging time of 60 seconds, contact diameter of workpiece 15 mm and the workpiece chamfer angle of 15°.
3. Result and discussion

The results of the chemical composition test of the specimens made of aluminum alloy AA 6061 using SEM FEI Inspect S-50 EDS and XRF (X-Ray Fluorescence) Tests with the composition is shown in Table 1.

**Tabel 1. Chemical composition of materials of aluminum alloy AA 6061 workpieces**

| Chemical Elements | Percent Weight (W, %) |
|-------------------|----------------------|
| Aluminium (Al)    | 98,07                |
| Magnesium (Mg)    | 0,79                 |
| Silikon (Si)      | 0,47                 |
| Iron (Fe)         | 0,57                 |
| Copper (Cu)       | 0,19                 |
| Manganese (Mn)    | 0,018                |

Important elements in aluminum alloy AA 6061 are Mg and Si elements. The weight percentage of the Mg contained in AA 6061 is 0.8 - 1.2%, and Si is 0.4 - 0.7%, while the weight of aluminum is 95.85 - 98.56% [2]. Thus, based on the results of the chemical composition test of the specimen material as given in table 1, it can be concluded that the specimen is compy with AA 6061 aluminum alloy specification.
From the macro photos it is known that the regional profile is divided into plastic deformation zones (Zpl) which are interface areas at the center of the weld, partial deformation zones (Zpd) and unformed zones (Zud). The produce three zones vary in the size of the area as a result of differences in temperature of environmental temperatur during friction welding. The higher of the environmental temperatur produces a wider plate zone and plastic deformation zone (Zpl + Zpd) as shown in Figure 3.1. The higher temperature of the environmental temperatur also causes the pressing workpiece to experience a greater softening and shrinkage. Aluminum alloy AA 6061 has a melting temperature of 660 °C. By taking the formula of the metal recrystallization temperature in the range of 0.4 - 0.6 x liquid temperature (K), the lowest recrystallization temperature of AA 6061 is at 102 °C. Thus the environmental temperatur of 27 °C - 75 °C is still below the AA 6061 recrystallization temperature. Whereas the environmental temperatur of 100 °C - 150 °C is in the AA 6061 recrystallization temperature area. The impact caused by the environmental temperature which in the range of the recrystallization temperature area causing aluminum AA 6061 to be recrystallized. With the friction and pressure on the workpiece at the recrystallization temperature causes the workpiece to soften and cause the shrinkage of the interface area to increase.

From Figure 4 it shown that in general each welding specimen shows 3 (three) welding zones with different area as a result of the difference in temperature of the working environment during friction welding. The three zones are the plastic zone (Zpl), the plate deformed zone (Zpd) and the unformed zone (Zud).

**Figure 4.** Macro photo profiles of AA 6061 friction welding connection based difference in temperature of the work environment.
non-deformed zone (Zud). The higher the temperature of the work environment produces a wider plastic zone and plastic deformation zone (Zpl + Zpd). The higher temperature of the work environment also causes the pressing workpiece part to experience a greater softening and shrinkage. This can be seen in the pressing part of the workpiece which is getting shorter due to rising temperatures in the work environment. Even at a temperature of 150 °C on the pressing side the undeformed zone (Zud) is only left a little.

Aluminum alloy AA 6061 has a melting temperature of around 660 °C. By taking the metal recrystallization temperature formula in the range of 0.4 - 0.6 x liquid temperature (K), the lowest recrystallization temperature of AA 6061 is at 102 °C. Thus the working environment temperature of 27 °C - 75 °C is still below the AA 6061 recrystallization temperature. Whereas the environmental temperature of 100 °C - 150 °C is in the AA 6061 recrystallization temperature area. The impact caused by the environmental temperature that has entered the recrystallization temperature area causing aluminum AA 6061 has experienced a softening process due to recrystallization. With the friction applied to the workpiece at the recrystallization temperature causes the workpiece to soften and by giving a forging pressure of 325 bar causing the shrinkage of the interface area is greater.

The results of the tensile test of AA 6061 base material are an average yield strength of 25.71 kg.mm⁻² and an average tensile strength of 28.15 kg.mm⁻². Tensile test specimens were made according to American Welding Standards (AWS B4) standards. The results of tensile testing of AA 6061 friction weld based on environmental temperature variations are shown in Figure 5.

![Graph of changes in the yield stress and the tensile stress of the connection AA 6061 aluminum friction welding due to differences in ambient temperature](image)

**Figure 5.** Graph of changes in the yield stress and the tensile stress of the connection AA 6061 aluminum friction welding due to differences in ambient temperature

From Figure 5 it is known that the tensile strength of AA 6061 friction weld joints based on the difference in environmental temperature is lower than the tensile strength of un-welded AA 6061. The increase in ambient temperature causes the yield strength of the AA 6061 friction weld joint to increase according to the equation \( y = 3E-05x^2 + 0.0026x + 18.119 \). Likewise, the tensile strength of the AA 6061 friction weld joint also increases due to an increase in environmental temperature according to the equation of \( y = 3E-05x^2 + 0.0033x + 16.582 \). The increased strength of the joint due to the increase in ambient temperature is caused because the workpiece has experienced heating before being applied to the friction force and forging pressure from outside. The increase in
temperature accelerates the process towards solid state conditions, reduces ΔT, decreases the rate of cooling, inhibits the formation of coarse grains and prevents brittle structure.

The environmental temperature which is at the recrystallization temperature, combined with the friction force and the forging pressure causes a large shrinkage of the interface area. So that even though the tensile strength of the joint increases, it is dimensionally not give advantages. It is recommended that if the temperature of the working environment is at a recrystallization temperature, the friction speed and impact pressure must be small. In general, the increase in yield strength and tensile strength of the connection is not significant, because it has not been able to approach the strength value of the base metal AA 6061. However, the increase in yield strength and tensile strength due to changes in the temperature of the friction welding work environment give fact that the working temperature also plays a role in determining the strength of the friction weld joint.

Hardness testing uses a micro hardness tester by taking a distance of every 0.5 mm from the center of the connection (interface). The results of testing the distribution of violence against test specimens can be seen in Figure 6.

![Diagram](image)

**Figure 6.** Hardness distribution of AA 6061 friction welds based on variations in the temperature of the work environment

From Figure 6 it is known that the hardness of the joint area is higher than the average hardness of base metal AA 6061 which is 97.53 HV. The distribution of hardness in the joint region shows that, the spinning workpiece side has a higher hardness than the pressing workpiece side. That is because the rotating part experiences strain hardening due to pressure so that the hardness is higher. While on the pressing side of the workpiece experience a greater softening process than the side of the spinning workpiece during pressing so that its hardness drops.

Microstructure photographs show dark particles (Mg₂Si) and gray particles (Fe₅SiAl₁₂) that are in the matrix Al. And on the basic metal microstructure AA 6061 shows large Mg₂Si grains and the distance between Mg₂Si particles are far apart at Figure 7.
In the Zud zone the size of the metal grains is greater than Zpd and Zpl. In Zpd and Zpl changes in grain size as a result of heat arising from interface friction and forging pressure. The difference in Zud, Zpd and Zpl is due to the heating process caused by friction and forging process, because heating and forging can cause microstructure changes [7].

At room temperature (27 °C), 50 °C and 75 °C, Zud’s microstructure is still the same as a basic metal microstructure because heat due to friction and forging pressure do not have an impact on Zud at temperatures below 100 °C. Zud microstructure changes occur at temperatures of 100 °C, 125 °C and 150 °C in the form of small and fine granular structures. The Mg2Si (black) grain structure also appears smaller with shorter spacing between the Mg2Si grains as shown in Figure 8. This is due to the recrystallization process which is caused by an increase in the temperature of the working environment starting at 100 °C.

Zpd microstructures at all environmental temperatures form smaller granular structures than base metal grains. Likewise the Mg2Si (black) grain structure appears smaller. The change in Zpd grain structure is caused by the deformation process due to friction and forging pressure.

Deformation and softening causes the unification of the structure between the surface of the workpiece at the welding center or Zpl. Zpl microstructure formed in specimens with environmental temperature of 27 °C, 50 °C, 75 °C and 100 °C in the form of small granular structures with Mg2Si (black) and Fe2SiAl12 (gray) structures spread evenly. However, the Zpl microstructure in specimens
with an environmental temperature of 125 °C and 150 °C appeared to enlarge, especially the Fe3SiAl12 structure (gray), due to overheating and excessive softening. Excessive softening is indicated by the formation of structural deformation grooves in Zpl for specimens with environmental temperatures of 125 °C and 150 °C as shown in Figure 9.

![Figure 9. Zpl microstructure AA 6061 friction welding connection at environmental temperatures of 125 °C and 150 °C (200x magnification)](image)

**Figure 9.** Zpl microstructure AA 6061 friction welding connection at environmental temperatures of 125 °C and 150 °C (200x magnification)

4. **Conclusion**

From macro photographs, it was known that the AA 6061 friction weld joints have three zones, i.e. the plastic deformation zone (Zpl), the partial deformation zone (Zpd) and the non-deformed zone (Zud). The higher the temperature of the environmental temperature produces a wider plastic zone and plastic deformation zone (Zpl + Zpd). The increase in environmental temperature causes the yield strength of the AA 6061 friction weld joint to increase as modelled as $y = 3E-05x^2 + 0.0033x + 16.582$. Likewise strength also increases due to by the equation $y = 3E-05x^2 + 0.0026x + 18.119$. Higher tensile strength is characterized by a wider area of plastic deformation (Zpl + Zpd). The hardness of the rotating workpiece side (spin) is higher than the workpiece side pressing (press) at all variations in the temperature of the work environment. From the photo of the basic metal microstructure of Al 6061, dark particles (Mg2Si) and gray particles (Fe3SiAl12) are present in the matrix Al. Zud grain size is greater than Zpd and Zpl. Zud microstructure changes occur at temperatures of 100 °C, 125 °C and 150 °C with smaller granular structure. Zpd microstructures at all environmental temperatures form smaller granular structures than base metal grains. Zpl microstructure formed in specimens with environmental temperature 27 °C, 50 °C, 75 °C and 100 °C in the form of small granular structure with Mg2Si (black) and Fe3SiAl12 (gray) structure spread evenly. However Zpl microstructure in specimens with environmental temperature of 125 °C and 150 °C seems to enlarge, especially the structure of Fe3SiAl12 (gray), due to overheat and excessive softening.

5. **Acknowledgement**

This research was conducted and financed through the Associate Professor Grant Program of Faculty of Engineering, Universitas Brawijaya of 2019 Budget Year Research Contract number: 20 / UN 10.F07 / PN / 2019.
6. References

[1] A. Ambroziak, M. Korzeniowski, P. Kustron, M. Winnicki, P. Sokobowski, and E. Harapinska, “Friction Welding of Aluminium and Aluminiun Alloys with Steel”, Hindawi Publishing Corporation - Advances in Materials Science and Engineering, Vol. 2014, http://dx.doi.org/10.1155/2014/981653.

[2] ASM, “ASM Handbook Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials”, ISBN: 978-0-87170-378-1, 1990.

[3] ASM, “ASM Handbook, Volume 6, Welding, Brazing & Soldering”, ISBN: 978-0-87170-382-8, 1995.

[4] P. Astrom, “Optimization of Parameters in a Friction Model for Friction Welding”, Lulea University, 2002.

[5] AWS, “AWS B4.0 - Standard Methods For Mechanical Testing Of Welds”, ISBN: 978-0-87171-889-1, 2016.

[6] N.S. Biradar, “Investigation of hot cracking behavior in transverse mechanically arc oscillated autogenous AA2014 T6 TIG welds”, Metall. Mater. Trans. Vol. 43, pp. 3179–3191, 2012.

[7] B. L. Sanyoto, N. Husodo, S. B. Setyawati, and M. Murshid, “Application of Friction Welding (Friction Welding) Technology In The Process Of Connecting Two Low Carbon Steel Steel Pipes”, Jurnal Energi & Manufaktur, vol. 5, 2012.

[8] G.E. Cook, R. Crawford, D.E. Clark, A.M. Strauss, “Robotic friction stir welding”, Industrial Robot: An International Journal, Vol. 31, No. 1, pp. 55–63, 2002.

[9] T. Dursun, C. Soutis, “Recent developments in advanced aircraft aluminium alloys”, Mater., Vol. 56, pp. 862–871, 2014.

[10] E. Ravikumar, N. Arunkumar, and S.G. Samhit, “Characterization of Mechanical Properties of Aluminum (AA6061-T6) By Friction Welding”, 3rd International Conference on Mechanical, Automotive and Materials Engineering (ICMAME’2013), pp. 127-131, 2013

[11] M. Ericsson, R. Sandström, “Influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG”. Int. J. Fatigue, Vol. 25, pp. 1379–1387, 2003.

[12] L. Fratini, G. Buffa, R. Shivpuri, “In-process heat treatments to improve FS-welded butt joints”. Int. J. Adv. Manuf. Technol., Vol. 43, pp. 664–670, 2009.

[13] F. Gharavi, K.A. Matori, R. Yunus, N.K. Othman, F. Fadaeifard, “Corrosion Evaluation of Friction Stir Welded Lap Joints of AA6061-T6 Aluminum Alloy”. Trans. Nonferr. Metals Soc. Chin., Vol. 26, pp. 672–681, 2016.

[14] P. Guangjian, Q. Yan, J.J. Hu, P.J. Chen, Z.T. Chen, and T.H. Zhang, “Effect of Forced Air Cooling on the Microstructures, Tensile Strength, and Hardness Distribution of Dissimilar Friction Stir Welded AA5A06-AA6061 Joints”, MDPI Journal Metals, Vol. 9, No. 304; doi:10.3390/met9030304, 2019.

[15] K.A.A. Hassan, P.B. Prangnell, A.F. Norman, D.A. Price, S.W. Williams, “Effect of welding parameters on nugget zone microstructure and properties in high strength aluminium alloy friction stir welds”, Sci. Technol. Weld. Join., Vol. 8, pp. 257–268, 2003.

[16] H. Seli, A.I. Md. Ismail, E. Rachman, Z.A. Ahmad, “Mechanical evaluation and thermal modelling of friction welding of mild steel and aluminium”, Journal of Materials Processing Technology, Vol. 210, pp.1209-1216, 2010.

[17] K Reddi Prasad, V G Sridhar, “Experimental Investigation On Mechanical Characterization Of Aa6061-T6 Pipe Joints By Continuous Drive Friction Welding”, International Journal of Mechanical Engineering and Technology (IJMET), Vol. 8, Issue 9, pp. 264–273, 2017.

[18] M.A. Mofid, A. Abdollah-Zadeh, C.H. Gür, “Submerged friction-stir welding (SFSW) underwater and under liquid nitrogen: An improved method to join Al alloys to Mg alloys”, Metall. Mater. Trans., Vol. 43, pp. 5106–5114, 2012.

[19] G. Peng, Y. Ma, J. Hu, W. Jiang, Y. Huan, Z. Chen, T. Zhang, “Nano indentation Hardness Distribution and Strain Field and Fracture Evolution in Dissimilar Friction Stir-Welded AA 6061- AA 5A06 Aluminum Alloy Joints”, Adv. Mater. Sci. Eng., pp. 1–11, 2018.

[20] R. Sakano, K. Murakami, K. Yamashita, T. Hyoe, M. Fujimoto, M. Inuzuka, U. Nagao, H. Kashiki, Kobe, Japan, “Development of spot FSW robot system for automobile body members”,

in: Proceedings of the 3rd International Symposium of Friction Stir Welding, 2001.

[21] S.S. Sabari, S. Malarvizhi, V. Balasubramanian, “Influences of tool traverse speed on tensile properties of air cooled and water cooled friction stir welded AA2519-T87 aluminium alloy joints”, J. Mater. Process. Technol., Vol. 237, pp. 286–300, 2016.

[22] S. Mumin, H. Erol Akata, “Joining with friction welding of plastically deformed steel”, Journal of Materials Processing Technology, Vol 142, pp. 239-246, 2003.

[23] P. Sathiya, et.al., “Effect of Friction Welding Parameters on Mechanical and Metallurgical Properties of Ferritic Stainless Steel”, International Journal of Advanced Manufacture, Vol.31, 1076-1082, 2007.

[24] S.V. Safi, H. Amirabadi, M.K. Besharati Givi, “Formation And Distribution of Brittle Structures in Friction Stir Welding of AA 6061 To Copper”. Influence of Preheat, Mechanics, Materials Science & Engineering, ISSN 2412-5954, 2016

[25] C. Sharma, D.K. Dwivedi, P. Kumar, “Influence of in-process cooling on tensile behaviour of friction stir welded joints of AA7039”, Mater. Sci. Eng., Vol. 556, pp. 479–487, 2012.

[26] S. Sinhmar, D.K. Dwivedi, “Enhancement of mechanical properties and corrosion resistance of friction stir welded joint of AA2014 using water cooling”, Mater. Sci. Eng., Vol. 684, pp. 413–422, 2017.

[27] S. Leslie, B. Sasidharan, “Process Parameter Optimization of Friction Welding of Al 6061 with Flat-Convex Interface Geometry”, International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181 IJERTV5IS090224 Vol. 5 Issue 09, 2016.

[28] V.V. Satyanarayana,G. Madhusudhan Reddy, T. Mohandas, “Dissimilar metal friction welding of austenitic–ferritic stainless steels”, Journal of Materials Processing Technology, Vol. 160, pp. 128-137, 2005.

[29] Z. Zhang, B.L. Xiao, Z.Y. Ma, “Influence of water cooling on microstructure and mechanical properties of friction stir welded 2014Al-T6 joints”, Mater. Sci. Eng., Vol. 614, 2014.