Artificial aging heat treatment post-effect on profile and mechanical properties of the AA 6061 friction welding joint

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Abstract. Friction welding is a solution for metal joint problems that are difficult to joint with fusion welding. The quality results of friction welding are highly dependent on process parameters such as friction pressure, friction time, forging pressure, forging time, and rotating speed. There is often excessive softening, hardening of the metal grains, and formation of an intermetallic phase at the weld interface due to too high friction temperatures and too high forging pressures on the alloy. Several studies on AA 6061 concludes artificial aging heat treatment can provide positive changes on the tensile strength and microstructure of AA 6061. The purpose of this study is to find out the effect of post artificial aging treatment toward profile and mechanical properties of AA 6061 friction welding joint. The varied parameters are forging pressure in friction welding of 325 bar, 350 bar, 375 bar and artificial aging heating temperature post-welding of 100 ºC, 150 ºC and 200 ºC. The fixed parameters observed are the connection profile, microstructure, hardness distribution and tensile strength of the joint. Controlled variables include: 1600 rpm spindle rotation, 65 bar or 65 kg cm⁻² friction pressure, friction time tf = 6 seconds, time forging pressure tu = 60 seconds, workpiece contact diameter 15 mm and 15 degrees workpiece chamfer angle. The results are specimens with forging pressures of 325 bar, 350 bar and 375 bar without artificial aging treatment still show clearly interface of Zpl and Zpd zone; whereas in specimens treated with artificial aging, the Zpd and Zpl interface are getting faded which indicating that there is structures homogenization in the Zpd and Zpl zone. The hardness of the joint area increased significantly after artificial aging heat treatment because formed Mg₂Si precipitates were dispersed in the Zpl, Zpd and Zud zones. The post-weld artificial aging heat treatment also resulted in a more even distribution of hardness in the joint area. The highest distribution of joint area hardness occurred in specimens with a forging pressure of 350 bar and artificial aging treatment at 200 ºC. Artificial aging treatment with a temperature of 200 ºC will form Mg₂Si (black) precipitation and Fe₃SiAl₁₂ (gray) particles which are evenly dispersed in the Al matrix in the Zpd and Zpl zones so that their hardness is high. By applying artificial aging heat treatment, the tensile strength of the specimens increases until the artificial aging temperature is 150 ºC; when the artificial aging temperature is raised to 200 ºC, the tensile strength tends to drop back.

Keywords: friction welding, artificial aging, AA 6061, mechanical properties.
1. Introduction
Friction welding is a metal joining process without melting (solid state process). The friction caused by the interaction of the two workpieces will produce heat which can soften both ends of the friction workpiece, so that it is able to soften and finally the joining process occurs [1]. Solid state welding is a welding process that produces coalescence at a temperature below the melting point of the base metal to which it joined. This process involves limited diffusion and deformation to produce joints between similar and dissimilar metals [2]. Friction welding is a form of solid state welding which welding heat is generated by converting mechanical energy into thermal energy at the workpiece interface without using electrical energy or other energy sources to the workpiece. The resulting frictional heat will increase the temperature of the workpiece within a short axial distance from the contacting surface close to the melting temperature. Welding occurs due to the effect of the working pressure, while the heated zone is in the plastic temperature range.

The amount of heat input \( (q) \) in the friction weld is affected by the area of contact between the surfaces \( (Ωa) \), the radius of the cross-section of the workpiece \( (r) \), the rotation speed \( (ω) \), the pressure of the workpiece relative to the rotating workpiece \( (P) \), the coefficient of friction of the material \( (μ) \) and temperature \( (T) \). The amount of heat input is formulated in the equation 1 [1].

\[
q = \int Pμ(T)rωdΩa. \quad (1)
\]

The formula is assumed to be based on illustration described in Figure 1.

Figure 1. Schematic model of symmetrical axis in friction welding process [1]

In rotary friction welding, three main areas will be formed in the interface zone of the friction-welded joint, namely the plasticized deformation zone \( (Z_{pl}) \) around the welding path, the partly deformation zone \( (Z_{pd}) \) and the undeformed zone \( (Z_{ud}) \). Sathiya, P. et.al. [3] also divided the area of the friction weld joint into three zones, namely the undeformed zone \( (UZ) \) where the hardness is almost the same as the main metal, plasticized zone \( (PZ) \), and partly deforming zone \( (PDZ) \).

Friction welding is a solution in metal joining which is difficult to execute with fusion welding. This method is effective for joining metals with low weldability such as non-ferrous metals, non-ferrous alloys, type 416 resulfurized stainless steel, martensitic stainless steel and aluminum alloys. Friction welding is a complex joining process, because it contains physical phenomena, heat changes due to friction, plastic deformation, solidification, structural changes and so on.

Friction welding has several advantages over fusion welding, because it is performed mechanically so it does not require electrical energy or energy from gas combustion. Because the metal joining process occurs without melting (solid state process), diffusion of hydrogen can be minimized so that it is free from hydrogen cracking (hydrogen induce cracking). Friction welding is widely applied in several industries such as the automotive industry, submarine industry, aviation industry, and heavy industry [4,5].

The quality of the friction welding results depends on the heat due to friction between surfaces and the amount of pressure exerted on the workpiece. The heat that occurs between the workpiece surface and the coupling is determined by the rotation speed, the pressing force and the processing time. Friction welding parameters that can be optimized to obtain a good joint are friction pressure, friction time, forging pressure, forging time and rotating speed [6].
characteristics of the joints formed in AA 6061 friction welding are not only influenced by the interface geometry but also the rotational speed and forging pressure applied to the workpiece. The rotation speed has the greatest effect on the properties of the weld [7]. The heat arising from friction and the pressure applied will be able to soften the two workpiece surfaces to be joined. From joining mild steel with aluminum rods using different simulation methods to one dimension, it is known that heat due to welding friction can reduce the hardness of the material being welded compared to the base metal [8]. The lengthy welding time and high temperature of joining aluminum rods with aluminum alloys using friction welding can lead to the formation of intermetallic phases which can lead to brittleness. Chemical elements in aluminum alloys, especially magnesium can aggravate the metallurgical bonding, because it can cause acceleration of the formation of the intermetallic phase at the joint interface, due to the increase in the diffusion coefficient. To improve the plastic properties of the joints, various types of interlayers can be used, such as titanium, nickel, aluminum mixed as titanium-aluminum interlayers, or by providing heat treatment [9]. The quality of friction welds can be improved by optimizing welding parameters, using an interlayer, changing geometric shapes and providing heat treatment before or after the welding process.

Several studies on heat treatment of AA 6061 show that artificial aging treatment is able to provide positive changes in tensile strength and microstructure. AA 6061 subjected to heat treatment under T6 conditions showed a significant increase in hardness when compared without heat treatment. The tensile strength and hardness of AA 6061 increase with increasing aging time. Meanwhile, wear and tear decrease with increasing aging time [10]. The fast cooling of the aging heat treatment of the AA 6061 alloy results in finer grain and higher strength. Higher aging temperature causes shorter time to reach aging. On the other hand, too lengthy precipitation setting time results in a larger size of the precipitate which causes its strength to decrease [11]. The strength of AA 6061 can be increased by artificial aging treatment with a holding time of up to 2 hours. The hardness of AA 6061 increased 27.4% after heat treatment with artificial aging with a holding time of 2 hours. When the holding time is increased above 2 hours it causes the hardness and strength of AA 6061 to decrease again [12]. The heat treatment of aging has a positive effect on the mechanical properties of AA 6061. The higher the aging temperature, the higher the nucleation rate of Mg2Si precipitation. The highest hardness, strength and toughness were achieved at an artificial aging temperature of 240 °C because the Mg2Si precipitation were evenly distributed [13].

The purpose of this research is to solve the joints quality problem of AA 6061 resulted from friction welding. And the specific objective of this research is to find out the results characteristics of the AA 6061 friction welding joints after being given heat treatment by artificial aging with varied forging pressure and temperature of artificial aging.

2. Material and method
This study uses experimental methods at laboratory scale. The test material used is aluminum AA 6061 with a diameter of 20 mm. The varied parameters were forging pressure in friction welding of 325 bar, 350 bar, 375 bar and post-welding artificial aging heating temperature of 100 °C, 150 °C and 200 °C. The fixed parameters observed were joint profile, microstructure, hardness distribution and tensile strength of the joint. Controlled variables include spindle rotation 1600 rpm, friction pressure 65 bar or 65 kg cm⁻², friction time tf = 6 seconds, time forging pressure tu = 60 seconds, workpiece contact diameter 15 mm and workpiece chamfer angle 15°.

The workpiece is first friction welded using a semi-automatic lathe equipped with a forging pressure regulating device on the head. Forging pressure varied from 325 bar, 350 bar and 375
Furthermore, the workpiece that has been joined is given heat treatment by precipitation hardening. Initially, the workpiece is treated with solution treatment with a temperature of 530 ºC and holding time of 2 hours and water cooling. After chilling, it is continued by providing an artificial aging process with temperatures varying from 100 ºC, 150 ºC and 200 ºC and holding time for 2 hours and then air cooling. Constructing test specimens for macro photos, micro photos and hardness tests using wire EDM machines. Meanwhile, the manufacture of tensile test specimens used a CNC TU-2A machine. Tensile test specimens were made according to AWS standard B4.0 [1]. The rotary friction welding scheme in this study illustrated in Figure 2.

3. Result and discussion
The results of the chemical composition test on the test object made of aluminum alloy using SEM FEI Inspect S-50 EDS and XRF (X-Ray Fluorosis) testing based on weight % are 98.07% Al; 0.79% Mg; 0.47% Si; 0.569% Fe; 0.155% Cu; 0.018% Mn.

Specimens with forging pressures of 325 bar, 350 bar and 375 bar without heat treatment still show clearly interface of the Zpl and Zpd zone. However, specimens that were heat treated with artificial aging temperatures of 100 ºC, 150 ºC and 200 ºC showed that the Zpl + Zpd zone was getting smaller with the Zpl and Zpd interface barely visible. This shows that artificial aging heat treatment makes deformed areas become more homogeneous.

From the test results of the hardness distribution in the weld joint area, most of the hardness of the joint area is lower than the hardness of the base metal (average 95 VHN). This is because the deformation process that occurs during friction welding causes softening in the Zpl and Zpd zones so that the hardness decreases. This can be seen in the hardness distribution of specimens with friction pressures of 325 bar, 350 bar and 375 bar without artificial aging treatment with hardness ranging from 60 VHN to 79 VHN. Furthermore, after welding it was given heat treatment by artificial aging, and the hardness increased in the range of 72 VHN to 100.3 VHN. With this artificial aging heat treatment, Mg2Si precipitation will be formed which is dispersed in the Zpl, Zpd and Zud zones. As a result, the hardness in the joint area increases. The artificial aging heat treatment given after friction welding also produces a more even distribution of hardness in the joint area (Zpl and Zpd). This condition is due to the increasingly homogeneous structure of Zpl and
Zpd as described in Figure 3. The temperature of the artificial aging 200 ºC can increase the hardness the highest than 100 ºC, 150 ºC or untreated.

The highest distribution of joint hardness resulted in specimens with a forging pressure of 350 bar and an artificial aging temperature of 200 ºC, followed by specimens with a forging pressure of 375 bar and an artificial aging temperature of 200 ºC (Figure 4). This high increase in hardness was due to the artificial aging treatment with a temperature of 200 ºC, a Mg₂Si (black) precipitation was formed which was evenly dispersed in the Zpd and Zpl areas as shown in Figure 5. In addition, Fe₃SiAl₁₂ particles (gray color) are also formed with a small grain structure which is also dispersed in the Al matrix.

Figure 3. Profile of AA 6061 friction weld joint without and with artificial aging treatment

Figure 4. The distribution of the hardness of the AA 6061 friction welds based on variations in forging pressure and temperature of artificial aging
From the results of the tensile test as shown in Figure 6, it can be explained that the ultimate tensile strength of the AA 6061 friction welding specimen increased after being treated with artificial aging. For, the increase in tensile strength of specimens without artificial aging treatment was caused by an increase in forging pressure from 325 bar to 350 bar and 375 bar. By providing artificial aging heat treatment after friction welding causes the tensile strength of the specimens to increase to an artificial aging temperature of 150 °C, then the tensile strength drops back to the specimens with a pressure of 350 bar and 375 bar with an artificial aging temperature of 200 °C. The highest tensile strength was obtained in specimens with a forging pressure of 325 bar and an artificial aging temperature of 200 °C. This is due to the grain structure in the Zpd and Zpl areas of
the specimens with a forging pressure of 325 bar and an artificial aging temperature of 200 °C which is smaller and softer.

4. Conclusion
Based on the results of data analysis and discussion, and supported by theory and previous research results, it can be concluded that:

- Specimens with forging pressures of 325 bar, 350 bar and 375 bar without heat treatment still show the interface of the Zpl and Zpd areas clearly, while in specimens treated with artificial aging the interface of Zpd and Zpl are getting faded, indicating structural homogeneity in the Zpd and Zpl zones. The increase in the hardness of the joint area was higher due to artificial aging heat treatment in which Mg₂Si precipitates were formed which were dispersed on Zpl, Zpd and Zud.
- The artificial aging heat treatment given after welding also produces a more even distribution of hardness in the joint area, especially in the deformed areas (Zpl and Zpd).
- The highest hardness distribution in the joint area occurs in specimens with a forging pressure of 350 bar and artificial aging treatment at 200 °C, because the Mg₂Si precipitate was formed and Fe₂SiAl₁₂ (gray) particles are evenly dispersed in the Al matrix in the Zpd and Zpl zone. so that the hardness is high.
- By applying artificial aging heat treatment, the tensile strength of the specimens increases until the artificial aging temperature is 150 °C, and when the artificial aging temperature is raised to 200 °C, the tensile strength tends to drop back.

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6. References
[1] P. Astrom, “Optimization of Parameters in a Friction Model for Friction Welding”, Lulea University, 2002.
[2] ASM Handbook Vol 6, 1995, Welding, Brazing & Soldering
[3] P. Sathiya, et.al., 2007, “Effect of Friction Welding Parameters on Mechanical and Metallurgical Properties of Ferritic Stainless Steel”, International Journal of Advanced Manufacture, Vol.31, pp. 1076-1082, 2007
[4] S. Kumar, R. Kumar and Y.K. Singla, “To Study The Mechanical Behaviour Of Friction Welding Of Aluminium Alloy And Mild Steel”, International Journal Mechanical Engineering & Robotics Research, Vol. 1, No.3 , pp.43-50, 2012.
[5] S.S. Bhate and S. G. Bhatwadekar, “A Literature Review Of Research On Rotary Friction Welding”, International Journal Of Innovative Technology And Research (IJITR), Vol. 4, Issue No.1, pp. 2601 – 2604, 2016.
[6] S. Mumin, H.E. Akata, “Joining with friction welding of plastically deformed steel”, Journal of Materials Processing Technology, Vol. 142, pp. 239-246, 2003
[7] 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, No. 09, 2016.
[8] H. Seli, A. Izani Md. Ismail, E. Rachman, Z.A. Ahmad, “Mechanical evaluation and thermal modelling of friction welding of mild steel and alluminium”, Journal of Materials Processing Technology, Vol. 210, pp.1209-1216, 2010.
[9] A. Ambroziak, M. Korzeniowski, P.B. Kustron, M. Winnicki, P. Sokobowski, and E. Harapinska, “Friction Welding of Aluminium and Aluminium Alloys with Steel”, Hindawi Publishing
Corporation Advances in Materials Science and Engineering, http://dx.doi.org/10.1155/2014/981653, 2014.

[10] M. Akash, N. Mani, S. Prajwal, H. Prasanna Kumar, P. Shiva Kumar, K.S. Badarinarayan, “Microstructural Characterization And Mechanical Properties Of Al 6061 Subjected To Heat Treatment Under T6 Conditions”, International Research Journal of Engineering and Technology (IRJET), e-ISSN: 2395-0056, Vol. 03, Issue 05, pp. 3169-3171, 2016.

[11] M. Kumar, M.M. Baloch, M.I. Abro, S.A. Memon and A.D. Chandio, “Effect of Artificial Aging Temperature on Mechanical Properties of 6061 Aluminum Alloy”, Mehran University Research Journal of Engineering & Technology, e-ISSN: 2413-7219, Vol. 38, No. 1, pp. 31-36, 2019, DOI: 10.22581/muet1982.1901.03.

[12] 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, No. 09, 2016.

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