Dissimilar Friction Welding of Aluminum Semi Solid Casting 7075 and AISI 1018 Steel: Mechanical Properties and Microstructural Characterization

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Abstract

Friction welding (FW) means a solid-state welding process that is extensively used due to its various beneficial points such as it can be used with numerous materials, develops the low heat input, easy for manufacturing, and environmentally friendly. Friction welding process parameter values such as friction pressure, friction time, forging pressure, forging time, and rotation speed have great influence on strength of the joints. The main objective of this research is to understand the effects of friction welding parameters on the joint characteristics of aluminum semi solid casting 7075 to AISI 1018 low carbon steel with 10 mm diameters and 100 mm length. The experimental result revealed that rotation speed and forging pressure affected the tensile strength of welded joints with level of significance. With increasing rotation speed and forging pressure, the tensile strength of welded joints increased. Microstructural characterization of FDRZ provided a complete characterization of dynamic recrystallization. The grains sizes were refined with increasing rotation speed while the tensile strength of welded joints increased accordingly.

KEYWORDS: Friction Welding; Aluminum Semi Solid Casting; Dissimilar Joint; Microstructural Characterization

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Introduction

Friction welding is a solid-state joining process used in a wide variety of application in automotive, aviation industries as well as preventive maintenance. The welding process make heat from mechanical friction of spare that movement related. The friction basic principle that is the friction integration works, which one part that roll with high speed and is pressed by another fix parts. During rotation, oxide layers are diffused and heat generation can occurs at both work parts. The work parts are held together as friction can weaken the materials. Since the work parts are rotated continually, the heat occurs and the welded parts are deformed. The oxide layers will be pushed and removed out of the path of the weld (red color lines) and new metal surfaces are held together. An axial pressure/forging pressure is used with rotational friction welding, when the rotating component is stopped immediately, the forging load is applied to complete the joining process [1]. Some advantages of friction welding compared to other solid state welding are (i) short weld times, (ii) no special machine controlled process is required; the machine-controlled friction weld process is consistent and repetitive, a protective atmosphere and joint preparation are minimal for the friction welding process, (iii) different geometrical shapes of work pieces can be welded; join dissimilar materials to reduce material costs [2, 3].

AA7075 (Al-Zn-Mg-Cu) is known to be one of the strongest aluminum alloys. It is widely used in different sectors and commonly used by the automotive and aerospace industries. It has significant corrosion resistance and high strength. This alloy is developed substantial high strength from the sedimentation phases in Mg_2Zn and Al, Cu, Mg. The fusion welding of AA7075 alloy that is quite difficult because solidification and liquation cracking similar to the Heat Affect Zone (HAZ) that have copper is main problem of this alloy. Though with potential to overcome the cracking by using aluminum alloy (Al-Mg or Al-Si) as bonding material, the loadbearing capacity is too low [4]. Furthermore, oxidation and vaporization of zinc can affect the welding such as pores in the welding joints and toxic smoke. Hence use of AA7075 is currently limited to applications that do not involve fusion welding [5].

Welding aluminum to steel is quite interesting especially the derived product will have different properties but have benefits in each component; for example, high thermal conductivity and low strength of aluminum and low thermal conductivity and high strength of steel, demand of aluminum/steel and demand of aluminum/stainless steel, in particular for high temperature use such as a space shuttle and cooking equipments. The application of friction welding of aluminum and steel are a study of friction welding of Aluminum Alloy A356 and AISI 1030 steel. After that the completeness of welded joints is inspected with an optical microscope, a scanning electron microscope (SEM) as well as the inspection of mechanical properties. The research result indicated that an aluminum matrix composite and AISI 1030 steel can be joined by friction welding [6]. The joints were evaluated by mechanical testing and metallurgical analysis. Results of the analysis first suggested that joint strengths on the order of 250 MPa could be achieved. In addition, a thin layer of interline was seen. The level of intermetallic averaged around 250 nanometers and there is complement related to the FeAl and Fe_2Al_5 phases [7]. Effects of friction welding parameter on tensile strength and microstructural characterization of AISI 1020 and ASTM welded joints were different. The study indicated that friction pressure and friction time had great influence on tensile strength. Increasing of friction pressure and friction time brought about an increasing tensile strength. The maximum tensile strength of welded joints obtained was 87% lower than that of the base material. Moreover, the friction welding affected the distribution of atom carbon from a mild steel to steel. This process produced carbon dioxide at the weld interface [8]. In this study, mechanical properties of friction welded steel and aluminum joints were assessed. The experimental results indicated that effect of heat on friction had an impact on the decrease in hardness of welded joints comparable to the base material. The tensile strength of welded joints was lower comparable to the base material due to the incomplete fusion in welding [9].

The review of related literatures found that the friction welded steel to aluminum joints was encumbered by a difference of mechanical and metallurgical challenges such as, the difference in thermal property; coefficient thermal expansion; thermal conductivity, and specific heat capacity that lead to residual stress. The dissimilar friction welding of aluminum and steel can result in multiple intermetallic phases that generally form by solid state reaction. Normally, these intermetallic have an effect on mechanical degradation of joint. The propulsion is main cause the formation of these phase, which dissemination of species base on specific time and temperature of integration process. However, the friction welding of aluminum alloy with low carbon steel is still a significant challenge. Joints involving this material combination are expected to see increasing numbers of industrial applications. As a result, this article is aimed to study mechanical properties and metallurgical characterization of dissimilar friction welding of AISI 1018 low carbon steel and aluminum semi solid casting 7075. Emphasis of this study is focused on microstructural characterization at the interface, mechanical properties by means of strength and hardness. This study reflects the considerable demand and importance for industrial application of dissimilar welded joints between aluminum and steel, particularly in transportation industry.

Materials and Methods

Materials for this study included aluminum semi solid casting 7075 and AISI 1018 low carbon steel. Materials were supplied as rods with diameter of 10 millimeters and length of 100 millimeters. Typical chemical compositions for the two base metals are given in Table 1 and their mechanical properties are shown in Table 2.

Surface preparation is generally not considered a significantly important matter in friction welding as the deformation in the surface layers are eliminated during friction process. However, Bekir, et al. [10] and Atsushi and Takashi [11] indicated that surface preparation may result in the strength of welded joints. In this research, the sample surfaces included a final lathe that resulted in a smooth surface without oxides and achieved work pieces in a vertical axis position which is an important point in the friction welding.

The friction welding process used in the experiment is given in the Fig. 1(a) which has been designed and carried out on the continuous drive friction. The working process of the friction welding machine is combined with a machine base attached with a bed of a lathe machine. Determination of rotation welding speed depends on the rotation cycle of an existing lathe machine which is a welding factor. With regards to the

Table 1 Chemical composition of the base metals.

Elements	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Ni	Al
SSM 7075	0.40	0.50	2.00	0.30	2.90	6.10	0.20	0.28	-	Balance

Elements	C	Mn	P	S	Fe
AISI 1018	0.16 − 0.19	0.8	0.045	0.045	Balance

Table 2 Mechanical properties of the base materials.

Elements	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (Hv)
SSM 7075	228	181	14	107
AISI 1018	395	295	36	152

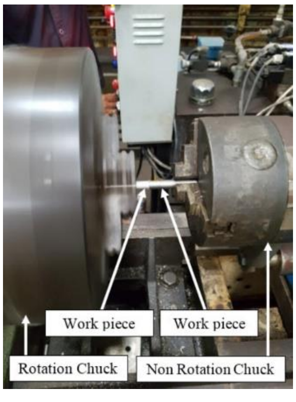
friction welding machine, hydraulic power drives the system which can control friction pressure, forging pressure, friction time, and forging pressure time powered by electricity system. The basic procedure of friction welding process is shown in the Fig. 1(b). The aluminum semi solid casting 7075 is a rotating work-piece and AISI 1018 low carbon steel is a non-rotating work piece and move along the plane. When the welding starts at the determined rotation welding speed as given in Table 3, work pieces are pushed by friction pressure to stay together under an axial pressure. Friction of work pieces at welded joints result in heat flow from inside the work pieces to outside (longitudinal elongation). When the rotation stops, the work pieces are pushed by forging pressure again to combine the work pieces as welded joints.

Important parameters to be used in the friction welding process are rotation speed, friction time, friction pressure, forging time and forging pressure. Experimental plan of the friction welding is given in Table 4 which is implemented by randomized order to assess effect of friction welding parameters and the experimental result has usual value.

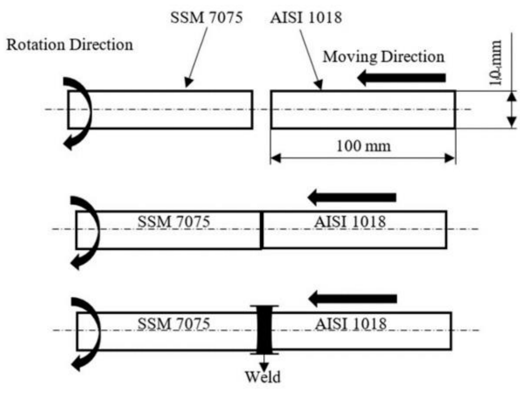
According to the experiment design, 27 welded joint work pieces could be achieved as test specimens. The test specimens were carried out tensile strength of welded joints and included a final lathe pass as required by the ASTM E8M-04 Standard Test Methods for Tension Testing of Metallic Materials [12]. The tensile strength is carried out with a multiple testing machine with force capacity of 500 kN used for testing of microstructural characterization. The welded joints are rubbed with a piece of flannel then etched by a chemical Keller etchant. Vickers micro hardness measurements were taken covering the entire weldment's cross section using a Vickers indenter with 100 gf load for 15

Table 3 Process variables and their scope.

Parameter	Unit	Experiment Level		
		1	2	3
Rotation Speed	rpm	450	675	1000
Friction Pressure	bar	40	40	40
Friction Time	s	6	6	6
Forging Pressure	bar	40	50	60
Forging Time	s	3	3	3



(a)



(b)

Fig. 1 Friction welding process (a) machine setup for friction welding (b) steps in the welding process.

Table 4 Process parameters used in the friction welding experiments.

Experiment No.	Rotation Speed (rpm)	Forging Pressure (bar)	Repetitions (times)
FW1	450	40	3
FW2	450	50	3
FW3	450	60	3
FW4	675	40	3
FW5	675	50	3
FW6	675	60	3
FW7	1000	40	3
FW8	1000	50	3
FW9	1000	60	3

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Results and Discussion

Statistical analysis and Tensile strength

The test result of tensile strength of the welded joints with the friction welding parameters are shown in Table 5. For the friction welding parameter determined the ultimate tensile strength (UTS); experimental samples FW1 to FW9, totally 9 samples; the average minimum tensile strength of 138 MPa and average maximum tensile strength of 201 MPa respectively. The tensile strength of welded joints in all parameters lower than the tensile strength of the two experimental bases; aluminum semi solid casting 7075 (228 MPa) and AISI 1018 low carbon steel (395 MPa). The welded joint test specimens are shown in Fig. 2.

Fig. 2 Tensile weld specimen test.

The assessment of friction welding parameters on tensile strength were analyzed by using analysis of variance (ANOVA); Multilevel Factorial Design. The maximum tensile strength was responsive parameter following ANOVA standard. The analysis result was seen in Table 6. Analysis of variance based on parameter of friction welding was rotation speed and forging pressure with statistical importance. It was found that rotation speed had the greatest influence on the tensile strength of welded joints, followed by forging pressure, and joining parameters between rotation speeds and forging pressure respectively.

The relationship of friction welding parameters in this research was analyzed by using analysis of variance (ANOVA) with a

Table 5 Results of tensile tests.

Experiment No.	Replicate 1	Replicate 2	Replicate 3	Average
FW1	138	137	139	138
FW2	144	145	143	144
FW3	154	156	155	155
FW4	161	163	162	162
FW5	177	179	176	177
FW6	182	180	183	182
FW7	186	189	188	188
FW8	194	193	192	193
FW9	199	203	201	201

Table 6 Analysis of variance for tensile test, using Adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation Speed	2	10534.70	10534.70	5267.30	2769.34	0.000
Forging Pressure	2	1263.40	1263.40	631.70	332.12	0.000
Rotation Speed* Forging Pressure	4	105.20	105.20	26.30	13.82	0.000
Error	18	34.20	34.20	1.90		
Total	26	11937.50				
S = 1.37914 R-Sq = 89.71% R-Sq(adj) = 89.59						

confidence level of 0.95. The coefficient of determination of an ANOVA model interpreted as R2 equals to 89.71%. It meant that different variances in the experiment that can be controllable such as rotation welding speed, friction pressure, friction time, forging pressure and forging time or any factors determined to be stable in the experiment were equal to 89.71%. The rest was approximately 10.29% caused by other uncontrollable factors such as weather or mental state. Therefore, this experimental design is considered at an acceptable level. Considering major factors in the experiment, rotation welding speed and forging pressure were the factors affected the tensile strength as shown in Fig. 3.

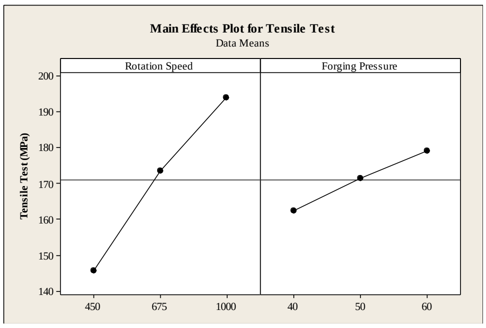

Fig. 3 Main effects plot for tensile test.

It can be seen that when the rotation welding speed was increased, the tensile strength was increased accordingly. In the same direction, when the forging pressure was increased, the tensile strength was also increased. Furthermore, the analysis of joining factors between rotation welding speed and forging pressure revealed the congruent results as that of major factors in the experiment with significant importance as shown in Fig. 4.

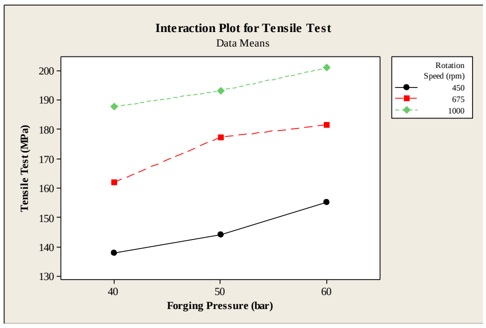

Fig. 4 Interaction plot for tensile test.

Friction welding is a solid state welding process. A process by which materials are softened and welded together is influenced by plastic deformation during frictional welding is performed.

Friction welding process can be divided into 3 different sub procedures or phases: step I – III [13] friction welding produces wear and adhesion due to the summation of friction pressure along the axis and forging pressure. Temperature at the true area of contact between the work pieces increases rapidly and results in

Table 7 Tensile strength for the experiment no.

Experiment No.	Tensile Strength (MPa)	Joint Efficiency for SSM 7075	Joint Efficiency for AISI 1018
FW1	138	60	35
FW2	144	63	36
FW3	155	68	39
FW4	162	71	41
FW5	177	78	45
FW6	182	80	46
FW7	188	82	48
FW8	193	85	49
FW9	201	88	51

the decrease of the materials hardness [14]. For the good friction welded joints, an increase of temperature at the welding joint should be higher than 400 °C to obtain a low level stress in the work pieces so that it is sufficient to gain plastic deformation [15]. Friction pressure and rotation speed play a vital role in determining an increasing of temperature in weld lines [16, 17]. At the end of the first procedure, the results found in the flash of work pieces due to plastic deformation, if in a large number, coefficient of friction will be decreased (materials used for plastic deformation will be lubricant) and the rate of heat generation will be decreased rapidly. In the second procedure, adiabatic process is occurred by plastic deformation and helps maintain the temperature of the contact to be in a balance level between heat generation and heat conduction. The plastic deformation is still occurred with a stable rate under the pressure of friction pressure. The scope of the second procedure depends on duration of forging pressure. The longer duration can increase the heat to the welded joints. In the third procedure, forging pressure that is higher or equal to friction pressures can lead to an occurrence of a big flash and the decrease of pressure along the axis. In this third procedure, welded joints are needed to be plastically deformed which depend on the size of forging pressure. However, duration of the forging pressure also plays a crucial role in welded joints.

The experimental result showed that a combination of higher forging pressure and rotation speed produced an increasing of friction pressure and led to the strongest welding joint. The increasing forging pressure and higher rotation speed triggered so high temperature that materials could be welded with sufficient plastic deformation between the

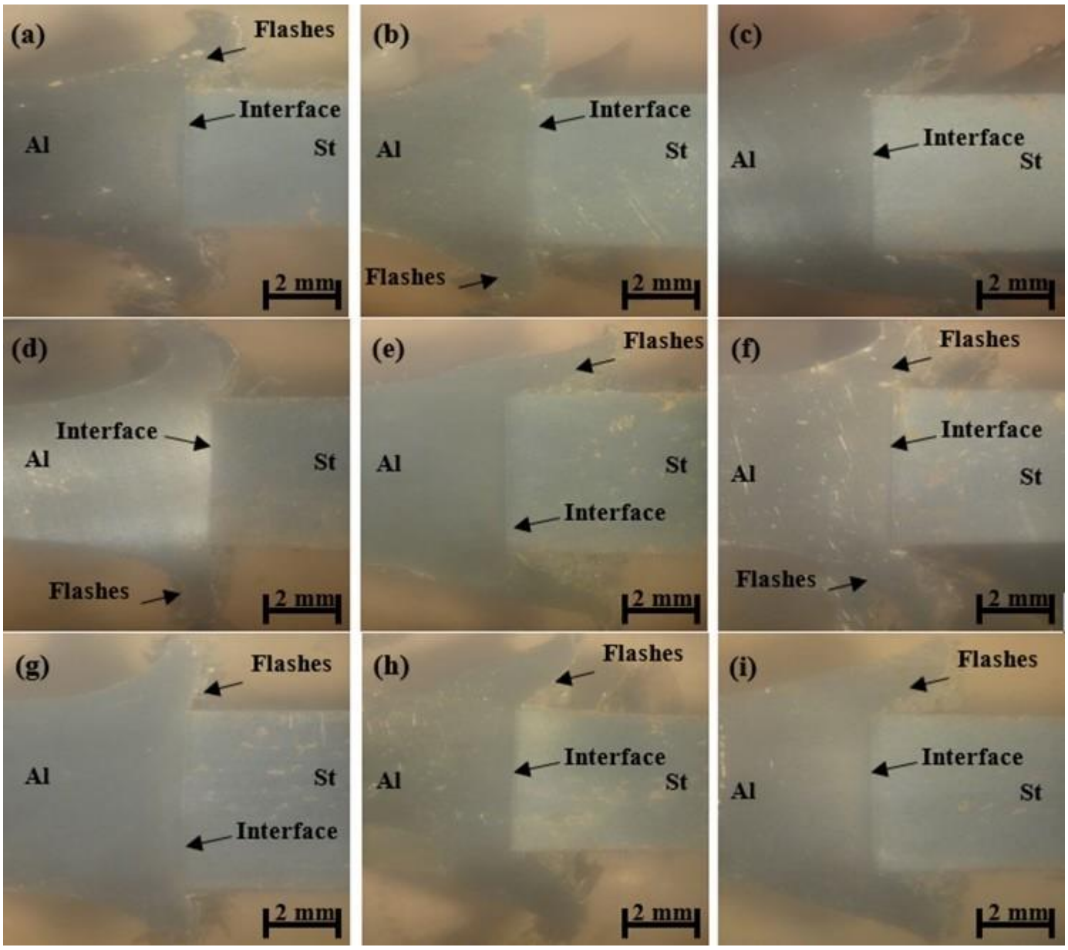

Fig. 5 Macrostructures of friction welds (Al: SSM 7075, St: AISI 1018); (a) 450 rpm / 40 bar, (b) 450 rpm / 50 bar, (c) 450 rpm / 60 bar, (d) 675 rpm / 40 bar, (e) 675 rpm / 50 bar, (f) 675 rpm / 60 bar, (g) 1000 rpm / 40 bar, (h) 1000 rpm / 50 bar, (i) 1000 rpm / 60 bar.

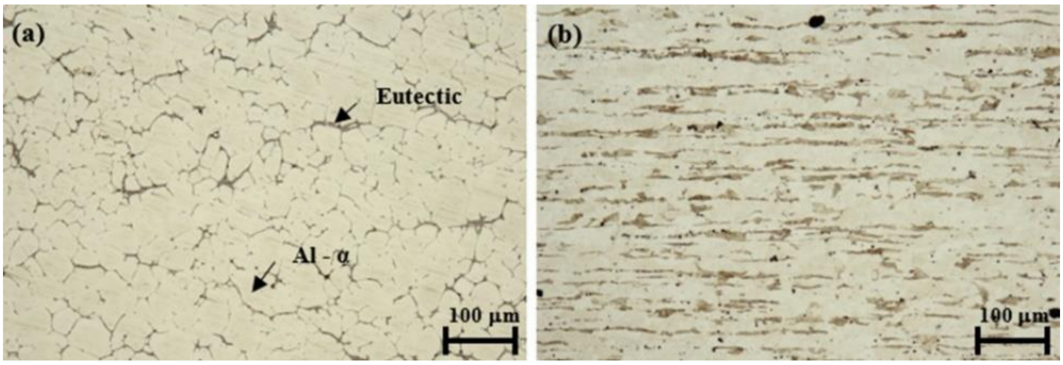

Fig. 6 Microstructures of base metal; (a) SSM 7075, (b) AISI 1018.

first and second procedures. The higher duration of friction time gave rise to a low level of plastic deformation which had to pass on the third procedure. The experimental results revealed that the higher friction time in friction welding produced the sufficient plastic deformation in the third procedure. Khalid Rafi, et al [1] reported that forging pressure was the major factor causing good welding joints especially dissimilar welding. A notice made to this research pointed that the best parameter indicated materials and diameter size of materials probably result in manufacturing process greatly.

Table 7 reveals the result of friction welding to tensile strength of welding joints. It can be noticed that the tensile strength is higher when forging pressure and rotation speed are increased. The forging pressure results in the tensile strength. Similar research results were reported by Kurt, et al [18] finding that forging pressure had an influence on tensile strength. This effect may cause plastic deformation to soft materials with high forging pressure according to the report by Reddy, et al [19]. Moreover, the Table 7 reported the efficiency of welding joints compared to the experimental base materials. It was found that the efficiency of experimental material SSM 7075 was not exceeding 90% compared to the experimental material AISI 1018 which was not exceeding 60%.

Microstructures

The microstructures of 9 different welded joint specimens are shown in Fig. 5. It can be noticeable that welded joints in all cases had no fault. A flash was found at the edge of joints caused by plastic deformation in material with less hardness. The notice found that increasing forging pressure produced more flashes which could be compared to the welded joints under the same condition of rotation speed at FW1 – FS3. According to the mentioned case, it is obvious that plastic deformation commonly occurs during welding process and inside the aluminum of the weld. A similar result [20] and the flashes reveal significant difference in terms of thickness of flash whereas the increasing forging pressure results in the decreasing of flashes [5].

Fig. 6. shows microstructure of previous metal content of SSM 7075 aluminum alloy. Aluminum matrix (α-Al) and eutectic phase ($MgZn_2$) are part of the microstructure of SSM7075 aluminum alloys. The grain characteristics is round and continuous with phase Zn, Mg, and Cu at a region of grain boundaries (the grain boundary is black) [21] and the microstructure of AISI 1018 is a structure with ferrite surrounds graphite in pearlite matrix [8].

Fig. 7. shows microstructure of welded joints under the condition of 9 different experiments. It can be noticeable that the welded joints have significantly different material zones. Recrystallization of each material cannot be seen. The friction welding can divide the welded joints into 3 zones; Heat Affect Zone (HAZ); Fully Dynamic Recrystallized Zone (FDRZ), and Thermal Mechanical Affect Zone (TMAZ) [22]. The FDRZ zone is where the dynamic recrystallization occurs completely and all the grains are refined into fine structures from related welding parameters. The width of FDRZ zone at the side of SSM 7075 is larger than that of AISI 1018 which almost the center of the test specimens.

However, the width of FDRZ zone at the part of SSM 7075 is continually increased when forging pressure and rotation speed are increased which affect directly the weld. Next

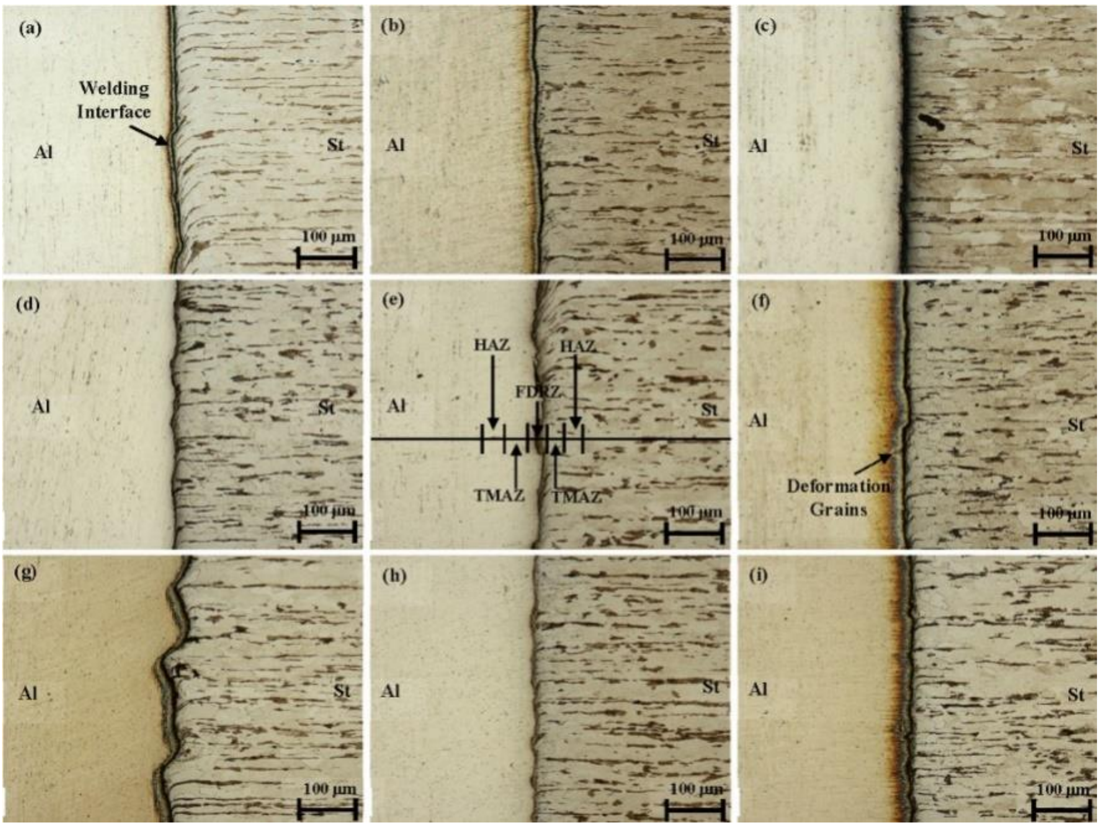

Fig. 7 Microstructures of friction welds (Al: SSM 7075, St: AISI 1018); (a) 450 rpm / 40 bar, (b) 450 rpm / 50 bar, (c) 450 rpm / 60 bar, (d) 675 rpm / 40 bar, (e) 675 rpm / 50 bar, (f) 675 rpm / 60 bar, (g) 1000 rpm / 40 bar, (h) 1000 rpm / 50 bar, (i) 1000 rpm / 60 bar.

to the FDRZ zone is TMAZ zone having long and distorted grains to the direction of the rotation of work piece mechanical cramps. It can be seen that change in grain of SSM 7075 is higher than that of AISI 1018. The fact that change does not occur in the part of AISI 1018 is from too little friction pressure and friction time to generate accumulated heat in the welding line that can produce the grain distortion [6].

Generally, the effect of friction welding by friction pressure and forging pressure can cause breaking of SiC particles at the welding line. This event distributes SiC recrystallization in welded joints [23]. Moreover, the occurrence of composition of 2 metals having different chemical compounds are from the heat generated by the friction pressure and forging pressure. It is referred that the combination of phases between aluminum and steel such as Fe_2Al_5 and $FeAl_3$ can be occurred after distribution of material under high pressure from heat with temperature higher than 400 °C. The procedure of alloy filler during the material welding affects the strength due to a fatigue structure. Therefore, to prevent this problem, high friction pressure and high forging pressure as well as sufficient friction time are required [24 – 27]. In friction welding process, rotation speed and forging pressure play a pivotal role in the welding. When the rotation speed and forging pressure are increased, the temperature will be higher and the width of HAZ zone is larger [28]. Such of these changes are magnified by SEM images in the weld FW9 since it is the weld that is acquired the highest degree of rotation speed and forging pressure and being the weld that has the highest tensile strength as shown in Fig. 8. The assessment point is within the edge of the square frame used for EDX analysis which its results can be viewed from the Fig. 8.

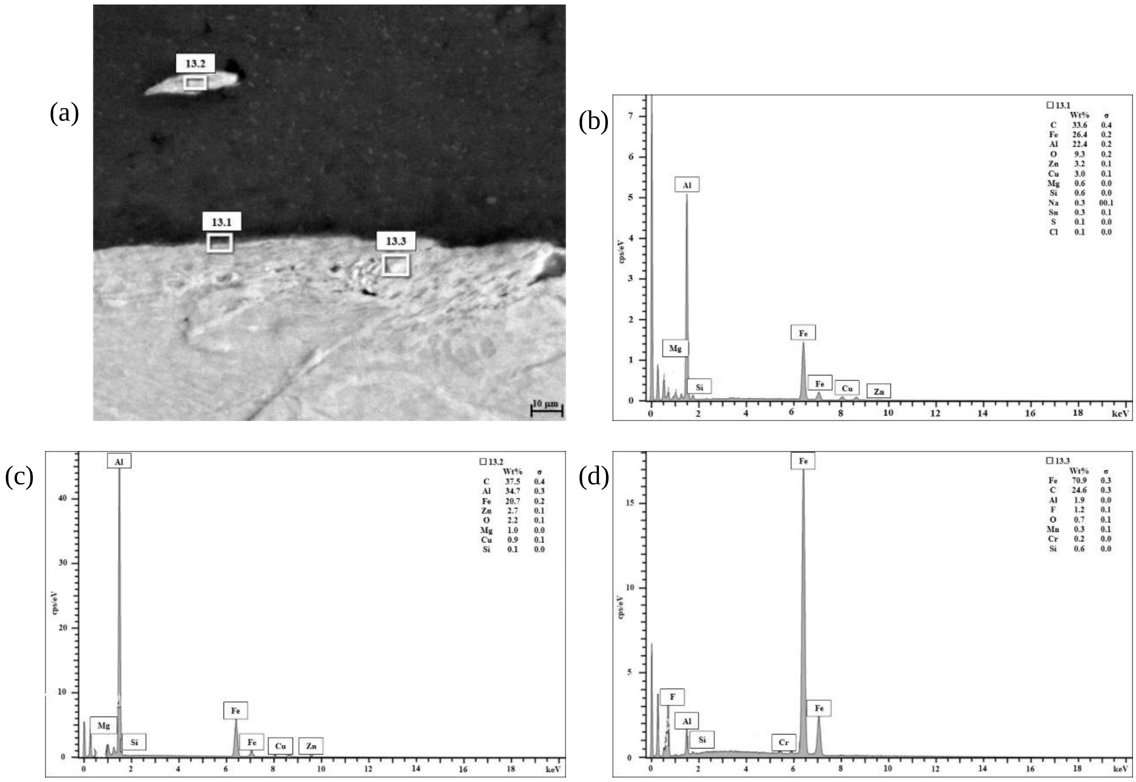

Fig. 8 SEM of the weld; (a) weld zone for FW9, (b) point at 13.1, (c) point at 13.2, (d) point at 13.3.

From the Fig. 8, microstructural parameter estimation is the best parameter. It reveals that a butt welding joint with the two pieces being flat and parallel to each other. Making a combination in phase of metals probably occurs within a melting point generated by the control of two metals welding that leads to the formation of reaction. Fig. 8(a) shows the formation of a combination in phase of metals ($FeAl_3$) at a welded joint. EDX analysis in Fig. 8(b) – 8(d) inspects the existence of Al and Fe in the composition of FeAl phase. A suggestion has been made that making a combination in phase of metals with welding is essential determination for forming suitable chemical bond in dissimilar friction welding [9]. Most welding parameters do not establish satisfactory hardness property since the hardness of weld is affected by the combination in phase of metals at the edge of the butt joint.

Vickers Hardness

The hardness profile of friction weld is shown in Fig. 9. It is the average result from each parameter of rotation speed. The result of hardness indicates difference between aluminum semi solid casting 7075 and AISI 1018 low carbon steel. The hardness near the welding joint edge will be increased and decreased according the previous hardness of that metal. The increasing hardness is from the increasing friction pressure and forging pressure but the decrease in hardness is caused by the exceeding of forging time [18]. The highest hardness is obtained from the area near by the weld. This kind of increasing can be described by the formation of martensite at the weld which is occurred when materials obtain heat and cooling rapidly during the friction welding process. The formation of martensite will reduce the mechanical property of friction welding. However, it will be controlled by welding parameters [29].

To reduce the accumulation of martensite, the highest temperature should be determining to be lower than the temperature generating eutectoid reaction [30]. The reduced temperature produces a reduction in cooling rate of the joints. So, there is a potential that a ferrite structure can be obtained to avoid a phase change to be austenite [29]. In addition, noticing the hardness in the joints, it is found that the increasing of rotation speed affects the increasing of hardness accordingly as shown in the Fig. 10. But this increasing occurs only in the narrow range between 152 – 164 HV. The change in the hardness of joints relates to the occurrence of thermal level and the change of plastic deformation [18, 30 – 31]. From the experimental results, the highest measured hardness at welded joints area is 152 HV at the welding condition FW1 and the highest measured hardness at welded joints area is 164 HV at the welding condition FW8.

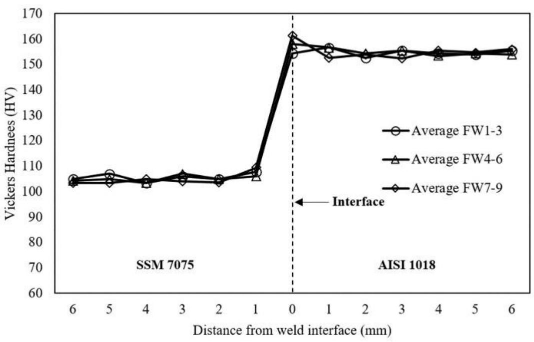

Fig. 9 Vickers hardness distributions of SSM 7075 – AISI 1018 friction welded joint at various welding parameters

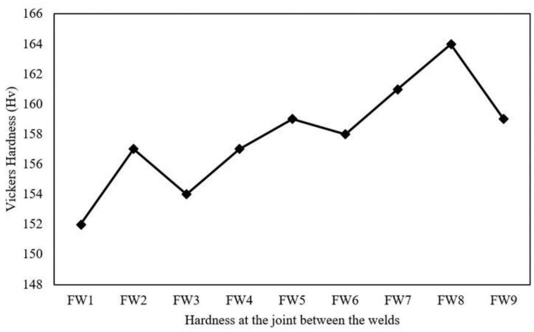

Fig. 10 Vickers hardness interface of SSM 7075 – AISI 1018.

Conclusion

The parameters of friction welding process are rotation speed and forging pressure that have great influence on the tensile strength of friction welded joints with statistical importance. It is found that the rotation speed affects most likely the tensile strength of welded joints, followed by forging pressure, and parameters of rotation speed and forging pressure respectively.

Rotation speed is the important parameter of friction welding. An increasing of rotation speed plays an important role in an increasing of tensile strength. In the same direction with forging pressure, when the forging pressure is increased, the tensile strength is also increased accordingly whereas the minimum tensile strength is 138 MPa at the welding condition FW1 and the ultimate tensile strength is 201 MPa at the welding condition FW9. The tensile strength of welded joints in all parameters is lower than that of the two experimental bases.

The FDRZ zone is the area provides a complete characterization of dynamic recrystallization. The grains sizes were refined with increasing rotation speed while the tensile strength of welded joints increased accordingly. The TMAZ zone provides long and distorted grain, being in the same direction of the rotation of mechanical clamps, influenced by friction pressure and friction time that generate accumulated heat producing the distortion of grain leading to the change.

The increasing of rotation speed results in the increasing of hardness value at the welding joints accordingly. The change in hardness of welding joints relates directly to the occurrence of heating value and plastic deformation. The lowest hardness of the weld is 152 HV at the welding condition FW1 and the highest hardness of the weld is 164 HV at the welding condition FW8.

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References

[1] H.K. Rafi, G.D.J. Ram, G. Phanikumar, K.P. Rao, Microstructure and tensile properties of friction welded aluminum alloy AA7075-T6, Mater. Design. 31 (2010) 2375 – 2380.
[2] M. Maalekian, Friction welding – critical assessment of literature, Sci. Technol. Weld. Jol. 12 (2007) 738 – 759.
[3] S.Y. Bekir, Z.Ş. Ahmet, K. Nafiz, Z. Ahmed, A. Garni, Friction welding of St–A1 and A1–Cu materials, J. Mater. Process. Tech. 4 9 (1995) 431 – 443.
[4] V. Balasubramanian, V. Ravisankar, G.M. Reddy, Effect of post weld aging treatment on fatigue behavior of pulsed current welded AA7 0 7 5 aluminum alloy joints, J. Mater. Eng. Perform. 7 (2008) 224 – 233.

[5] R.K. Gupta, P. Ramkumar, B.R. Ghosh, Investigation of internal cracks in aluminum alloy AA7075 forging, Eng. Fail. Anal. 13 (2006) 1 – 8.
[6] S. Çelık, D. Güneş, Continuous Drive Friction Welding of Al/SiC Composite and AISI 1030, Weld. J. 91 (2012) 222s – 228s.
[7] T. Emel, E.G. Jerry, C.L. John, Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization, Mater. Design. 31 (2010) 2305 – 2311.
[8] W. Radoslaw, Effect of friction welding parameters on the tensile strength and microstructural properties of dissimilar AISI 1020-ASTM A536 joints, Int. J. Adv. Manuf. Tech. 84 (2016) 941 – 955.
[9] S. Hazman, M.I.A. Izani, R. Endri, A.A. Zainal, Mechanical evaluation and thermal modelling of friction welding of mild steel and aluminium, J. Mater. Process. Tech. 210 (2010) 1209 – 1216.
[10] S.Y. Bekir, Z.S. Ahmet, C. Ali, B.J. Abduk Aleem, Investigation into the properties of friction-welded aluminium bars, J. Mater. Process. Tech. 54 (1995) 76 – 81.
[11] H. Atsushi, M. Takashi, On the effect of faying face condition on weldability in friction welding, J. Jpn. Wel. Soc. 50 (1987) 77 – 82.
[12] ASTM E8M-04, Standard test methods for tension testing of metallic materials, ASTM International, 2010.
[13] O.T. Midling, O. Grong, A process model for friction welding of Al-Mg-Si alloys and Al-SiC metal matrix composites; I. Haz temperature and strain rate distribution, Acta. Metall. Mater. 42 (1994) 1595 – 1609.
[14] M. Maalekian, E. Kozeschink, H.P. Brantner, H. Cerjak, Comparative analysis of heat generation in friction welding of steel bars, Acta. Mater. 56 (2008) 2843 – 2855.
[15] H. Zhang, G.Y. Lin, D.S. Peng, L.B. Yang, Q.Q. Lin, Dynamic and softening behaviors of aluminum alloys during multistage hot deformation, J. Mater. Process. Tech. 148 (2004) 245 – 249.
[16] O. Kozo, A. Masatoshi, Measurement of friction temperature under steady state by conventional driving method, J. Jpn. Wel. Soc. 13 (1982) 9 – 14.
[17] S. Andrzej, Thermal effects in friction welding, Int. J. Mech. Sci. 32 (1990) 467 – 478.
[18] A. Kurt, I. Uygur, U. Paylasan, Effect of friction welding parameters on mechanical and micro-structural properties of dissimilar AISI 1010-ASTM B22 joints, Weld. J. 90 (2011) 102 – 106.
[19] R. Winiczenko, M. Kaczorowski, Friction welding of ductile iron with stainless steel, J. Mater. Process. Tech. 213 (2015) 453 – 462.
[20] G.M. Reddy, A.S. Rao, T. Mohandas, Role of electroplated interlayer in continuous drive friction welding of AA6061–AISI 304 dissimilar metals, Sci. Technol. Weld. Joi. 13 (2008) 619 – 628.
[21] N. Mahathaninwonga, T. Plookphol, J. Wannasina, S. Wisutmethangoon, T6 heat treatment of rheocasting 7075 Al alloy, Mater. Sci. Eng. 532 (2012) 91 – 99.
[22] L. Zhida, Q. Guoliang, G. Peihao, Y. Fan, M. Xiangmeng, Continuous drive friction welding of 5A33 Al alloy to AZ31B Mg alloy, J. Manuf. Process. 25 (2017) 153 – 162.
[23] K. Uenishi, Y. Zhai, T.H. North, G.J. Bendzsak, Spiral defect formation in friction welded aluminum, Weld. J. 79 (2000) 184s – 193s.
[24] C. Pan, L. Hu, Z. Li., T.H. North, Microstructural features of dissimilar MMC/AISI 304 stainless steel friction joints, J. Matrr. Sci. 31 (1996) 3667 – 3674.
[25] S. Chainarong, C. Meengam, M. Tehyo, Rotary Friction Welding of Dissimilar Joints between SSM 356 and SSM 6061 Aluminium Alloys Produced by GISS, Eng. J-Canada. 11 (2017) 181 – 191.
[26] P. Peyre, G. Sierra, F.D. Beaume, D. Stuart, G. Fras, Generation of aluminum-steel joints with laser-induced reactive wetting, Mater. Sci. Eng. 444 (2007) 327 – 338.
[27] D. Naoi, M. Kajihara, Growth behavior of Fe2Al5 during reactive diffusion between Fe and Al at solid-state temperatures, Mater. Sci. Eng. 459 (2007) 375 – 382.
[28] O. Canyurt, Estimation of welded joint strength using genetic algorithm approach, Int. J. Mech. Sci. 47 (2005) 1249 – 1261.
[29] C.P. Cheng, H.M. Lin, J.C. Lin, Friction welding of ductile iron and low carbon steel, Sci. Technol. Weld. Joi. 15 (2010) 706 – 711.
[30] H. Fujii, L. Cuia, N. Tsuji, M. Maeda, K. Nakata, K. Nogi, Friction stir welding of carbon steels, Mater. Sci. Eng. 429 (2006) 50 – 57.
[31] P. Sathiya, S. Aravindan, A.N. Haq, Effect of friction welding parameters on mechanical and metallurgical properties of ferritic stainless steel, Int. J. Adv. Manuf. Tech. 31 (2007) 1076 – 1082.