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MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF FRICTION WELDED AISI 304 STAINLESS STEEL TO AISI 1060 STEEL

MIKROSTRUKTURA I WŁAŚCIWOŚCI MECHANICZNE ZGRZEWANEJ TARCIOWO STALI NIERDZEWNEJ AISI 304 ZE STALĄ AISI 1060

Rotary Friction welding is one of the most popular methods of joining similar and dissimilar materials. It is widely used with metals and thermoplastics in a wide variety of aviation, transport and aerospace industrial component designs. This study investigates the influence of friction and upsetting pressures on the hardness, tensile properties and microstructure of the welds. The experimental results showed that as the friction and upsetting pressures increased, the hardness and tensile strength values increased, as well. The tensile fracture of welded joint occurred in the AISI 1060 side. The friction processed joints were evaluated for their integrity and quality aspects by optical and scanning electron microscopy. For the perfect interfacial bonding, sufficient upsetting and friction pressures are necessary to reach the optimal temperature and severe plastic deformation to bring these materials within the attraction range.
Keywords: Welding, Mechanical properties, Microstructure

Zgrzewanie tarciowe jest jedną z najbardziej popularnych metod łączenia podobnych i odmiennych materiałów. Jest ono powszechnie stosowane do łączenia metali i tworzyw termoplastycznych w szerokim zakresie wzorów części przemysłowych w lotnictwie, transporcie i przemyśle kosmicznym. Celem badań jest określenie wpływu tarcia i nacisków na twardość, właściwości wytrzymałościowe i mikrostrukturę spoiny. Wyniki doświadczalne wykazały, że zewzrostem tarcia i nacisków wzrosła twardość i wytrzymałość na rozciąganie. W trakcie prób rozciągania pękanie następowało po stronie stali AISI 1060. Zgrzewane tarciowo spoiny zostały oceniopne pod względem ich integralności i jakości za pomocą mikroskopii optycznej i skaningowej mikroskopii elektronowej. Dla uzyskania idealnego złączenia materiałów potrzebne są odpowiednie naciski i tarcie, aby osiągnąć optymalną temperaturę i intensywne odkształcenie plastyczne.

1. Introduction

Almost all stainless steels contain at least 12%Cr which causes formation of carbides and oxides in the microstructure. Type 304 Stainless Steel is an austenitic steel which has high ductility, excellent drawing, and forming properties. It is essentially non-magnetic. Low carbon content not only means less carbide precipitation in the heat-affected zone during welding but also a lower susceptibility to intergranular corrosion. Typical applications of this steel include; chemical, cooking equipment, cryogenic and pressure vessels, hospital surgical equipment, and marine equipments.

Welding of machinery parts is necessary in most of the engineering applications. Just a few decades ago, materials were classified as weldable and non-weldable, but innovations in technology enabled the joining of most of materials by fusion and solid state welding techniques. Typical fusion welding techniques include: gas welding (Oxyacetylene), arc welding (SMAW, GTAW, and SAW), high energy beam welding (EBW and LBW), plasma and laser welding. Heat sources for these techniques are a gas flame, an electric arc, and a high beam, respectively. However, in the nature of these techniques, rapid heating can cause damage to the work piece, including weakening and distortion. Some of the fusion techniques are applied for various materials [1-3]. The typical solid state joining applications of diffusion welding for various content of the aluminum metal matrix composites [4-6] and FSW [7] have been studied in details. Welding time, applied load, welding temperature and chemical composition of the steel are some of the key parameters to controlling solid state diffusion welding process.

Rotary friction welding is one of the solid state joining techniques which is applied in the joining of similar and dissimilar counterparts. In this technique, machinery components are brought into contact with each other. While one of them is remaining stationary, the other one is rotated with the applied pressure. When the temperature of the interfaces has reached an optimum value for the extensive plastic deformation, the rotation is stopped, while the forging pressure remains unchanged or increases. The application of an axial force main-

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tains intimate contact between the parts, and causes plastic deformation of the material near the weld interface. If the sufficient frictional heat has been produced during softening, larger wear particles begin to expel from the interfaces and axial shortening of the components begin as a result of the expelled upsetting. In general, heat is conducted away from the interfaces thereby developing plastic zone. The plasticized layer is formed on the interfaces; and the local stress system, with the assistance of the rotary movement, extrudes material from the interface into the flash. This has pointed to the fact that the weld integrity is strongly affected by the rate of flash expelled under the appropriate conditions [8]. Friction welding has a lot of advantages over other welding processes. These advantages are; no melting, high reproducibility, short production time, low energy input, limited heat affected zone (HAZ), avoidance of porosity formation and grain growth and the use of non-shielding gasses during welding process. Further, the technique is not only applied to round specimens but also used for rectangular components. It is called linear friction welding and has been recently applied to the steel [9].

Although a large amount of previous studies [6-11] on the friction welding of similar and dissimilar materials has been conducted, mechanical properties of the plain carbon steel to stainless steel joint produced by friction welding method have never been reported up-to-date. Thus, the objective of the present work is to examine the mechanical properties and optimal welding conditions of friction welded joints of these materials.

2. Materials and methods

Chemical composition of plain carbon steel and stainless steel employed in the present study is given in Table1. Cylindrical test specimens of 20 mm in diameter and 160 mm in the length were prepared for friction welding. Before the friction welding, the surfaces facing each other were machined by using a lathe. Before welding, the surfaces of the work pieces were cleaned by a stainless steel brush and acetone to remove the oxide layer and stains. Joining of these two dissimilar alloys was performed on a continuous drive friction welding machine of 300 kN capacity at a constant rotation speed of 2000 rpm, and constant friction time of t=5s. Friction and upsetting pressures were observed on the screen of friction welding machine, and the stages of welding sequence are controlled by solenoid valve. The welding parameters were as follows: friction pressures (P_1): 30, 40 and 50 MPa, upsetting pressures (P_2): 50 and 70 MPa. Tensile test specimens were prepared according to ASTM E8M-00b. Ultimate Tensile Strength (UTS) and yield strength of the welded specimens were determined. Hardness values (VH_1) were determined by using Shimadzu HMV device. Measurements were taken in the welding centre through base metal with a distance of 1 mm and 2.5 mm on either side of horizontal and vertical line, respectively. For tensile strength and hardness test values, at least three specimens were used for each parameter. The microstructure was investigated by the SEM, and the optical microscopy. The AISI 1060 steel specimens were polished and etched with a solution consisting of % 4 Nital. AISI 304 SS etched with a solution of 95% HCl and %5 $OH\text{-}C_6H_2(NO_2)_3$. The grains have various shapes ranging from 10 μm to 300 μm in dimension. Typical microstructures of as received materials are seen in Fig. 1 a and b.

TABLE 1

Chemical composition of the materials tested

Material	*C*	*Cr*	*Ni*	*Si*	*Mn*	*P*
AISI1060	0.42	–	–	0.21	0.45	0.02
Elements wt%						
Material	*C*	*Cr*	*Ni*	*Si*	*Mn*	*P*
AISI 304	0.027	8.1	18.1	0.28	1.81	0.073

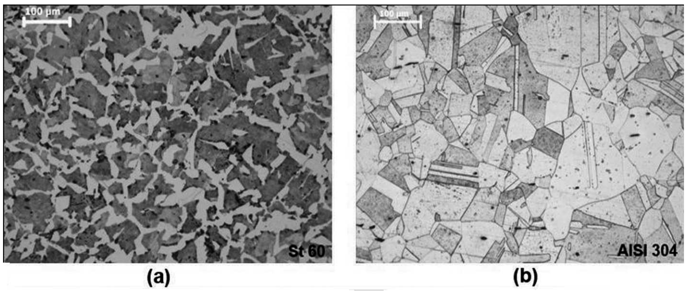


Fig. 1. Microstructure of a) AISI 1060 and b) AISI 304

3. Results and Discussions

3.1. Hardness distribution

Figure 2 a. shows the effect of friction pressures and Fig. 2 effect of upsetting pressures on the hardness distribution in the direction perpendicular to the weld interface of the as-welded specimen. The maximum hardness values of joints were obtained on both sides close to the welding centre line. The hardness values generally increased with increasing friction pressure and upsetting pressures. The increasing hardness values in the welding interface can be related to the microstructure formed in the joint surface as a result of the heat input and extensive plastic deformation. The hardness values of AISI 304AISI 1060 and welding interface were 129 Hv, 254 Hv, and 300 Hv respectively. It can be said that, microstructural evaluations around the interface, diffusion of elements on the sides, work hardening, dislocation density, grain refinement, and formation of precipitations may have caused this increase. Although the work hardening is also effective on the hardening in AISI 304 side, much of the hardening in AISI 1060 steel is a direct result of fine grains, formation of precipitates and rapid cooling from the welding temperature. In the literature, similar hardness profile was also observed for dissimilar material couples [11-13]. It can be said that the hardness properties are influenced by an interactive effect of friction, and upsetting pressures which are combinations of heat input, range of plastic deformation and degree of strain hardening. The influence of the welding parameters on the vertical hardness distribution are shown in Fig. 3 a and b. Both sides of materials are hardened due to the transformation of austenite to the martensite, which is strongly affected by the cooling rate. Hence, all hardness values are higher than the base metal. The highest values were obtained 5 mm away from the centre.

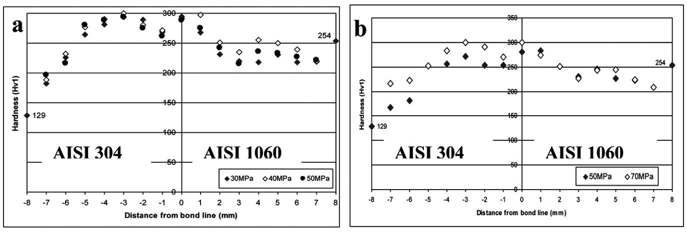


Fig. 2. Horizontal line, hardness distribution of tested materials a) The effect of friction pressure (t=5s, P_2 =50MPa) b) The effect of upsetting pressure (t=5s, P_1 =40)

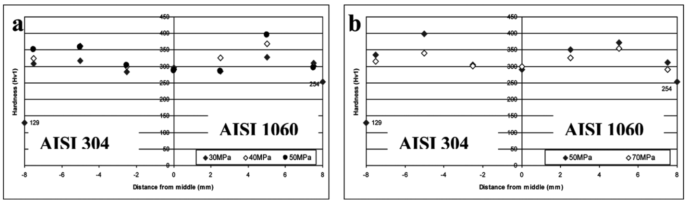


Fig. 3. Vertical line, hardness distribution of tested materials a) The effect of friction pressure (t=5s, P_2 =50MPa) b) The effect of upsetting pressure (t=5s, P_1 =40)

3.2. Tensile strength

The influence of friction and upsetting pressure on the tensile test result is shown in Fig. 4 a and b. From the data, it can be noted that UTS and yield strength increased with an increase in friction and upsetting pressure. The UTS values for the AISI 1060 and the AISI304 were 814 MPa, and 505 MPa respectively [14]. The UTS strength corresponds to about 130% of that of AISI 304 SS part and 81% of that of AISI 1060 structural steel part. The highest UTS and yield strength were obtained with the application of highest friction pressure and upsetting pressure. The joints obtained here were quite ductile in nature and failed in the AISI 1060 side due to the low elongation which was only 17% compared to 70 % for the AISI 304 (Fig. 5). All specimens failed on the AISI 1060 side showed that perfect joint interfaces were obtained under the various tested welding parameters. It is reported that [10, 15] the choice of welding parameters affects the microstructure. If the friction time is held long, a broad diffusion zone with intermetallic phases may be generated. The parameters such as short friction time, low friction and low upsetting pressures will result in a weakly bonded joint. Hence, the superiority of the welds strongly depends on the temperature attained by each substrate during welding process. Therefore, the flow stress-temperature relationship for each metal will have an important influence on the friction welding parameters. However, it is also reported that [16] a good strength can be obtained by a sufficient diffusion and mechanical locking. If optimum welding parameters are used in friction welding, a perfect bonding can be achieved. In general, high friction and upsetting pressures resulted in high toughness and hardness in steel alloys [12]. It is also well known that, for achieving high strength at welding interface, the brittle phases such as σ-phase, δ-ferrite and oxide formations should be removed from the joint surface. In this case, to achieve higher strengths, the friction and upsetting pressures should be as high as possible for a constant friction time. Because the friction and wear help to get rid of contaminants like oxide on the interface, a new surface was formed. At the same time, the upsetting and friction pressures set in to bring the new face within the scope of attraction range [17].

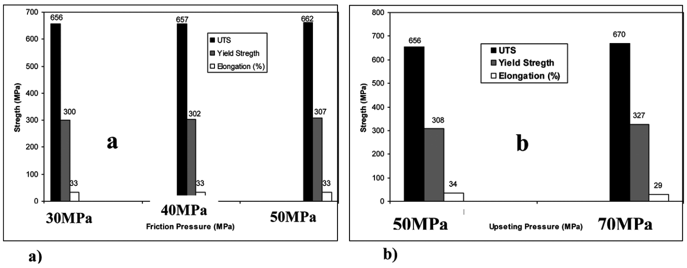


Fig. 4. Tensile test results a) The effect of friction pressure b) The effect of upsetting pressure

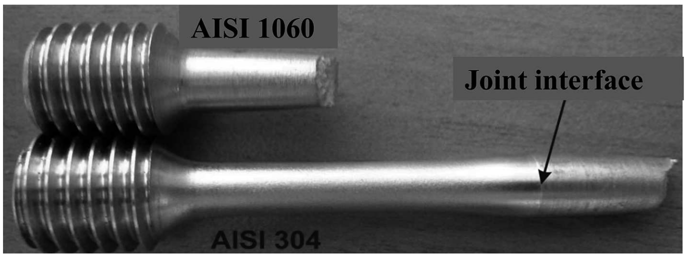


Fig. 5. Tensile test specimen macrograph of fractured surface

3.3. Microstructure

Figure 6 shows the typical microstructural features of the weld. Next to the joint interface, elongated fibrous and severely refined grains can be seen in the HAZ region of both steels perpendicular to the rolling direction. The intensity of orientation was found to be dependent on the welding parameters [16]. It is clearly seen that sufficient friction and upsetting pressure on the joining surface resulted in an adequate locking of the surfaces where extensive plastic deformation and microstructural changes occurred; and these facts gave rise to better tensile response of the joint where recrystallization occured on the AISI 1060 side (more deformation) and grain refinement and strain hardening occured on the AISI 304 steel side (less deformation) which contains high level of Cr that does not normally transform to austenite on heating, further, chromium carbides can form at the ferritic grain boundaries of those containing appreciable carbon content [10]. The width of recrystallized region is mainly affected by the friction and upsetting pressure. An increase in the friction and upsetting pressure resulted in wider size of fine grain region. The change of microstructure and more axial shortening also notably occurred in the AISI1060 side. The same phenomenon has been reported during friction welding of dissimilar welds, namely Fe-Ti, Cu-Ti, Fe-Cu, Fe-Ni [11]. Heat flow occurs preferentially in the material with the greatest thermal conductivity. Due to the different thermal conductivities between AISI 304 (16,2W/m-K) and AISI 1060 (49,8 W/m-K), the specific heat is very large, and hence most of the frictional heat is generated in the AISI 1060 side. The difference in thermal conductivity explains the microstructural changes which occur preferentially in the AISI 1060 side. Similar microstructural observations for the Cu-Ti couples were also reported in Ref. 17. In this study, most of the changes occurred preferentially in the copper side; no evidence of microstructural variation was seen in the vicinity of the interface, and neither grain growth nor grain boundary precipitation was observed. This can be attributed to the difference of thermal conductivity [17]. It can be said that for the perfect interfacial bonding, sufficient upsetting pressure and friction pressures are necessary to reach the optimal temperature and severe plastic deformation to bring these materials within the attraction range. Sathiya et al.[10] found that in the case of stainless steel, a combination of high friction, upsetting pressure and high upsetting time produced high tensile strength and impact values. A bond quality classification system was developed using a novel, non-contact and acoustic emission sensing technique. An efficient, inexpensive and fast production benefit can be achieved by using process monitoring systems [18, 19].

Figure 6 also shows the microstructural changes of ASIS 304 and AISI 1060 sides of weld. During the friction welding process, the temperature near the welding interface would reach just above A_1 temperature which is almost the recrystallisation temperature for the steel. Therefore, extremely fine equiaxed grains were formed in the ferrite and pearlite structure. Moreover, martensitic structure can be seen in this region when the welding interface has reached above A_3 temperature accompanied by rapid cooling [20]. Therefore, the microstructure of AISI1060 steel was transformed to austenite. When the austenitic structure was exposed to top cooling from evaluated temperatures, the microstructure turned into martensite due to the diffusion of carbon to the grain boundary and rapid cooling rate. These results mean that the weld has experienced different thermal histories. The relatively quick cooling rate influenced the microstructure of the weld.

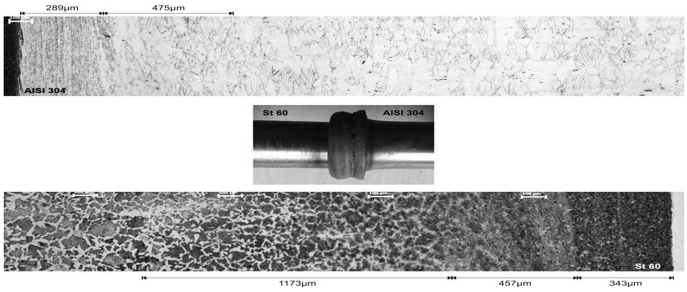
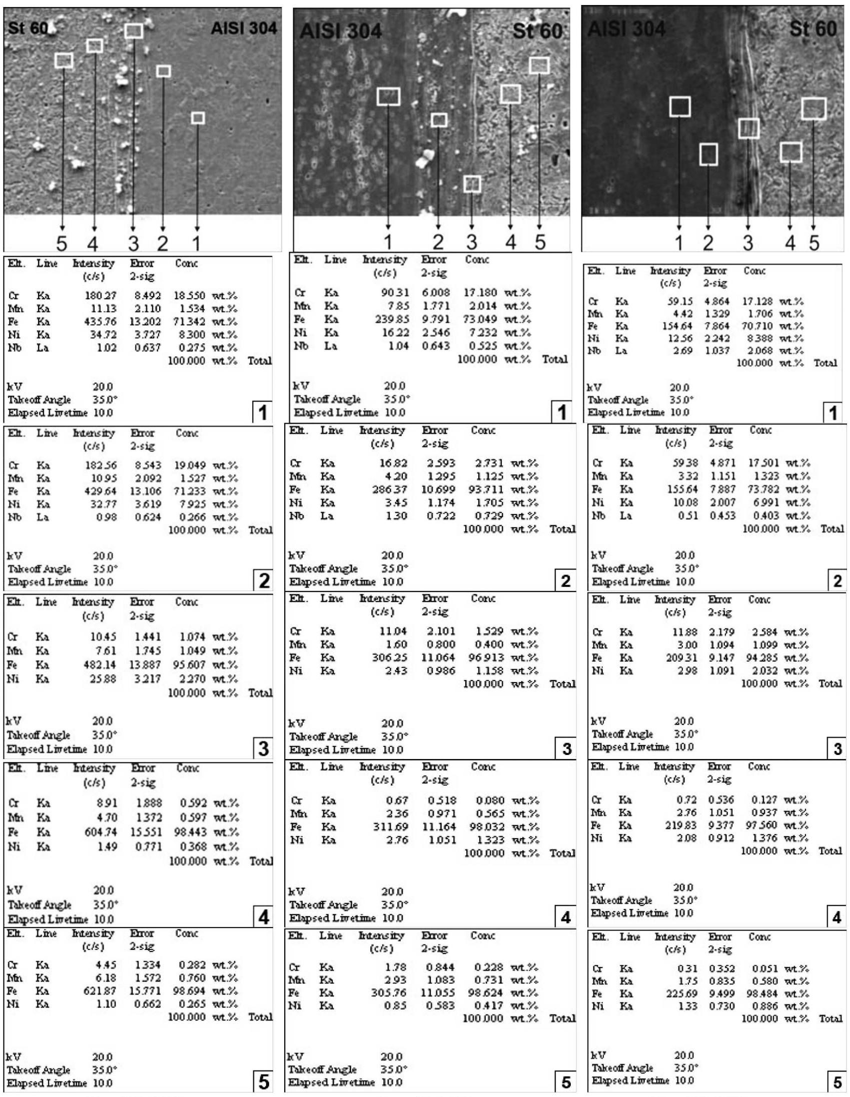


Fig. 6. Typical macro and microstructure of the friction welding parts (t=5s, P_1 = 30MPa, P_2 =50MPa)



P_1=30 MPa **P_1=40 MPa** **P_1=50 MPa**

Fig. 7. Joint surfaces and location of the EDS analysis sites. The effect of friction pressure on the elemental distribution

Changes in the chemical composition of the materials at each side at the bonding zone were investigated by SEM equipped with EDS (Energy Dispersive Spectrometer) perpendicular to the joint plane as shown in Fig. 7. EDS point analysis was used in the examination.

Figure 7 (1) and (2) show EDS analysis points defined on the AISI 304 side, while, (4) and (5) show EDS analysis points defined on the AISI 1060 side. It can be seen that alloying element concentration changed at the joint surface (Point 3) and adjacent to the Point 3 due to the mechanical locking and atomic diffusion. In the joint surface Cr (1.074%) was measured for 30MPa friction pressure. An increase in the friction pressure caused high density Cr content in the surface, where more heat was generated as a result of high friction pressure. It is obvious that smaller diameter of Cr atoms became more mobile and diffusive inside this region. It is also evident that significantly high amounts of Cr and Ni were detected on the AISI 1060 side in Point (4) and (5) in all tested conditions. Presumably, martensite formation, Cr and Ni carbides and intermetallic compounds formed in AISI 1060 side, and those elements made more fragile and brittle inside the HAZ region of relatively low ductile AISI 1060 steel which all the tested tensile specimen failure occurred.

4. Conclusions

Continuous drive friction welding studies on the AISI 304 and AISI 1060 steels have been carried out. From the mechanical property evaluation and the microstructural analysis, the following conclusions can be drawn:

1. Friction welding can be used successfully to join austenitic stainless steel (AISI304) to AISI 1060 structural steel. The processed joints exhibited better mechanical and metallurgical characteristics.
2. The highest hardness values were observed in the interface, but they significantly varied with increasing upsetting and friction pressures. The increase in the hardness at the joint zone may be attributed the microstructural evaluation.
3. The tensile strength of friction welded joints increased with increasing upsetting and friction pressures. The tensile strength of AISI 304 side was higher then that of AISI 1060. Therefore, fracture usually occurs in the HAZ of AISI 1060 steel side.
4. Upsetting and friction pressures play important roles in the structure and mechanical response of the weld.
5. An extensive deformation occurred mostly in the AISI 1060 side due to its flow stress and high thermal conductivity.
6. Typical microstructural features were observed in the welding region. Equiaxed grains were evident adjacent to the joint surface. The width of the region is mainly affected by the welding parameters.
7. The variance in weight of alloying elements can be clearly seen with an analysis of spectrum of elements. EDS measurements clearly show that steel joints consist of carbides and intermetallic compounds. Diffusion of the Cr and Ni is evident in the AISI 1060 side.
8. For this study, the optimal joint performance was attained at a friction pressure of 50 MPa, upsetting pressure of 70 MPa, and upsetting time of 5 sec.

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