THE STRENGTH AND FRACTURE MORPHOLOGY OF SIMILAR AND DISSIMILAR CONTINUOUS DRIVE FRICTION WELDING AISI 304/304 AND AL 6061-T6/304

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الملخص

يُعد لحام الاحتكاك من تقنيات الوصل للعديد من المعادن الحديدية وغير الحديدية المعدن عندما يصعب وصلها بطرق اللحام بالصهر التقليدية. استخدمت طريقة لحام الدفع المستمر CDFW لكلٍ من سبيكة الألمنيوم "Al6061-T6" والصلب المقاوم للصدأ "AISI 304" وهي طريقة بديلة ساهمت في جعل الصلب المقاوم للصدأ وسبائك الألمونيوم أكثر شيوعاً واستخداما. في هذه الدراسة تم اختيار العوامل التصميمية الآتية: زمن الاحتكاك (t1) وضغط الاحتكاك (P1) وضغط الكبس (P2) والتي كان لها تأثير واضح على مقاومة الشد للوصلات الملحومة فيما نُشر من سابق الأبحاث، وكان لها تأثيراً فاعلاً في الدراسة الحالية أيضا. استخدمت منهجية التصميم المتين " Taguchi array L27 (3^3)" وأستخدم مبدئياً اسلوب المحاولات التجريبية لتحديد مدى القيم لكل عامل من العوامل التصميمية. اكتسبت مقاومة الشد للوصلات الملحومة الواصلة بين المعدن الواحد بالمقارنة مع مقاومة نفس المعدن غير الملحوم حيث بلغت الى أقصى كفاءة بقيمة 98%، ولوصلات المعدنين المختلفين الى كفاءة بقيمة 89%. أوضحت نتائج الكشف بالمجهر الإلكتروني أن سطح الكسر لعينات الشد الخاصة بوصلات المعدن الواحد يتبع نسق الفجوات الدقيقة المتصلة وهذا يؤكد نسق الكسر للمعادن المطلية، بينما كان وقع الكسر لوصلات المعدنين المختلفين يتواجد عند خط الوصل بينهما ومشابهاً لعملية نزع السطحين عن بعضهما البعض، كما تحقق أن سطح الكسر يتبع النسق الحلزوني وخط الوصل بين المعدنين المختلفين هو الموقع الملائم للكسر لوجود ما يعرف بالعيوب الحلزونية وكلما قل عدد هذه العيوب تحسنت مقاومة الوصل.

ABSTRACT

Friction welding is a solid phase welding process that is used to join different types of ferrous and non-ferrous metals that cannot be joined by existing fusion welding methods. Continuous drive friction welding CDFW method appears to be an alternative method to make the use of stainless steel and Aluminum alloys more widespread. Friction time t1, friction pressure P1, and forge pressure P2 are being selected as design parameters, which have significant effect on the tensile strength of weld joints. Three levels Taguchi of 27 trials "orthogonal array L27 (3^3)" was adopted to analyse the effect of selected parameters. In the present study, preliminary experimental trials are conducted and used to determine the exact range of each selected parameter. The strength of produced friction joints exhibited comparable strength with the base material with maximum efficiency of 98% for AISI 304/304, and 89% for AISI 304/Al6061-T6 joints. For similar joints, The fracture mode as a microvoid coalescence at the fractured surface confirms the ductile mode of failure, while for dissimilar joints the fracture occurred at the weld line as an interface splitting. Many spiral patterns are observed, which acted as preferential failure sites during tensile testing, and as the numbers of spiral defects decreased, joint strength improved.

KEYWORDS: Taguchi L27; CDFW; AISI 304; Al 6061-T6; Tensile Strength; SEM; Fracture; Morphology.

INTRODUCTION

Friction welding as a solid-state welding process to join a much broader spectrum of similar and dissimilar materials. The joining process is carried out at a temperature below the melting points of the joined metals. By relative motion of two faying surfaces to generate heat and friction welding is performed, this is accompanied by a compressive force which plastically deforms the surfaces resulting in the joint [1-2]. There is a need to develop highly efficient joining methods, which enables producers to achieve higher strength, and quality more consistently than with the fusion welding process. P. Sathiya et al. [2-5] have demonstrated in a series of studies emphasis on the feasibility of the process to join AISI 304 austenitic stainless steel. These investigations have established that fully satisfactory bonded joints, in terms of tensile strength, were obtained with no joint collapsing at the welding line. The welding of aluminum alloy to stainless steel is of particular interest, since the resulting favorable properties of each component, as the high thermal conductivity and low density of Aluminum, and the lower thermal conductivity and the higher tensile strength of stainless steel [5]. The demand for aluminum alloys/stainless steel joints has therefore increased in many industrial areas, owing to their superior properties. A series of publication researches [6-8] have been performed with an object to establish friction-welding process of 6061 Aluminum alloys to AISI 304 austenitic stainless steel. The key joining parameters during CDFW operation comprise (friction time t1 and pressure P1, forging time t2 and pressure P2, and rotational speed N). Usually, these parameters are developed and optimized through a series of trials for a given application [1, 3-5, 9-10]. The microvoid coalescence MVC fracture mode are the feature of ductile fracture are initiated at sites where partial matrix interface failure, and/or complex dislocation interaction. Two growth mechanisms identified, plastic flow at the matrix that surrounds the initiation site, and/or plastic flow enhanced by the decohesion of small particles in the matrix [11]. A typical spiral fracture surface observed by Tacashi [12] in fractured steels/Aluminum alloys jointed by CDFW, and Celik & Ersozlu [13] have defined in their study the spiral defect as a type of defect acts as the sites for preferential failure sites during both fatigue testing and notch tensile testing of such joints. This occurs when the joint strength is detrimentally affected by the formation of hard, brittle intermetallic phase at the bond line region. During tensile loading, the intermetallic layer acts as a site for crack initiation. The aim of this work is to analyze the obtained similar and dissimilar CDFW tensile strength and efficiency results with respect to selected welding parameters, and to make convincing interpretation to the various modes of fracture morphology obtained by SEM.

EXPERIMENTAL WORK

Materials used

Two different types of metallic material have been chosen for the present study, aluminum alloy 6061-t6 (Al-Mg-Si) and austenitic stainless steel AISI 304 with supplied technical data, chemical composition and average measured mechanical properties as shown in Tables (1a, 1b, and 2).

Table 1a: The Chemical Composition of AISI 304 Stainless Steel.

Elements	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**
Contents wt.%	0.041	0.348	1.355	0.026	0.024	18.80	8.21
Elements	Mo	Cu	V	Co	N	W	Fe
Contents wt.%	0.315	0.408	0.061	0.122	0.035	0.009	Balance

Table 1b: The Chemical Composition of Aluminum Alloy Al 6061-T6.

Elements	**Si %**	**Fe %**	**Cu %**	**Mg %**	**Zn %**	**Cr %**	**Al %**
Contents wt.%	0.571	0.148	0.355	1.026	0.024	0.196	Balance

Table2: The Mechanical Properties of AISI 304 and Al 6061-T6.

property	Tensile strength	Yield strength	Elongation %	Reduction of area %
ASTM 304	653 MPa	394 MPa	47.62	73.83
Al 6061-T6	360 MPa	307 MPa	13	11

After machining, and to avoid the effect of cold work, the samples were stress relieved to a temperature of 350˚C for 1 hour followed by air cooling for AISI 304 and for Al 6061 heated up to 100˚C for 20 minutes then cooled in still air. Friction welding **process**; CDFW Thomson Machine (Model 15 Single, Sliding Head-1985, UK) was utilized to perform the welding process [14]. The selected parameters; Based on the pervious works [3, 6] the parameters that have strong effect on the tensile strength of similar and dissimilar friction welded materials and its efficiency are: friction time t1, friction pressure P1 and upset "forge" pressure P2. In this study, spindle speed N, and upsetting time t2 are kept constant. The other parameters such as (t1, P1, and P2) are varied within the range available in the machine setting. Determination of parameters range. Trial and Errors Method was carried out by varying chosen parameters to determine the exact range of each parameter [3, 4, 18]. Figure (1) shows some produced samples of similar and dissimilar friction welds. Three levels Taguchi of 27 trials **[**orthogonal array L(27) S1 to S27 for 304/304 and A1 to A27 for 304/6061-T6**]** was adopted to analyse the effect of three selected parameters (t1, P1, and P2) on the tensile strength of the weld joint and their efficiencies. Tensile testing; Accordant with ASTM (E23-81) the joint strength of friction welded mainly evaluated by tensile testing results, the test samples configuration as shown in Figure (2) were prepared after flash removal by machining off the surface.

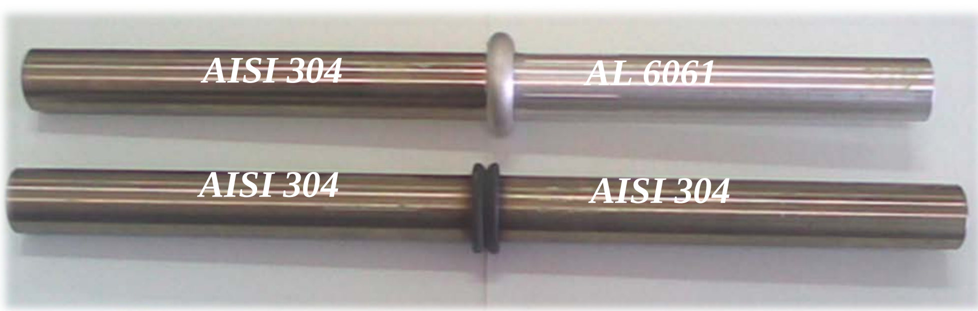

Figure 1: First trail for similar and dissimilar friction weld samples.

All samples were machined with 140 mm gauge in lengths and 22 mm in diameter. The weld interface was set at the center of the gage length as close as possible [2, 15]. For comparison, AISI 304 and Al 6061-t6 base materials test specimens were minimum feeding machined with similar shape as the jointed samples as in Figure (2).

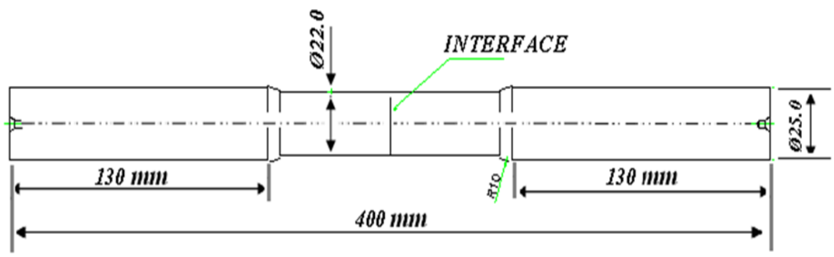

Figure 2: Shape and dimension of tensile test CDFW samples.

Fracture morphology examination

Fracture surfaces morphology of the fractured tensile test samples were comprehensively examined with a scanning electron microscope (SEM) to determine the microscopic fracture mode, and characterize the fine-scale topography of the fracture surface, and establishing the microscopic mechanisms governing fracture. Samples for SEM examination that obtained by being sectioned parallel to the fracture surface with 10mm in thickness. The used equipment was SEM (JEOL JSM-5610 Scanning Electron Microscope, Japan, 2000) to characterize the obtained fracture mode.

RESULT AND DISSUASION

The strength of similar joints; Tensile strength is the main characteristic evaluation considered in this work to identify the quality of CDFW joints. From the obtained tensile strength data of the L27 for austenitic stainless steel welded joints, the high strength obtained in all runs with maximum efficiency of 98 % over a wide range of friction times and pressures, and forge pressures (t1, P1, & P2) indicating the stainless steel is highly tolerant of friction welding, and the continuous CDFW method can successfully be applied for performing weld joints of AISI 304 austenitic stainless steel. Thus, considerably the strength of joints exhibited comparable strength with the base material as concluded in many of previous studies [2, 16]. The highest tensile strength was acquired as 640 MPa with the setup conditions of t1 of one second, P1 of 63.8 bar, and P2 of 85 bar. For dissimilar joints the obtained result of the tensile strength for L27 measurements of AISI 304-Al 6061-T6 friction welded pair are varied in the range of 193.6 to 318.9 MPa with efficiencies range from 54% to 89% respectively. It can be confirmed, the joint tensile strength properties are markedly affected by selected parameter, and there is a narrow operating envelope for attainment of optimum bond line tensile strength properties in a similar manner.

Fracture morphology for similar joints; the as broken tensile samples are investigated visually starting with determination of fracture location along the gage length, followed by fracture surface area visual and SEM examination. AISI 304 as an FCC austenitic stainless steel develops a ductile normal fracture plane of “cup & cone” type of fracture, a broken through the base metal section area as in figure (3a & b). Figure (3a) shows one of the similar joints that fractured closer to bond line of the weld interface with microvoid fracture mode at edge surface, and flat mode controlled by tension loading beyond the edge with limited reduction in cross section area. These findings well agree with other investigators [2, 10, 17] reported that, similar friction weld AISI 304 austenitic stainless steel rupture mostly at the joint zone and partly through the parent material, and the joints had experienced a ductile mode of fracture, with the shear flow of material. P. Sathiya et al. [18] showed same fracture mode but for ferritic stainless steel friction welded joints. As necking begins at the point of stability where the true strain equals to the strain hardening coefficient, with triaxle state of stress is introduced at the center of the necked region "plane strain condition". Under continued straining, many fine micro cracks are initiated in a form of microvoid, then developed as cavities with high stress concentration sites for the cracks to grow and coalesce together in a form of major central crack with equiaxed microvoid coalescence mode, this crack grow laterally and normal to the tensile axis. At the free energy surface "plane stress condition" under the act of resolved shear stress the crack propagates parallel to the localized shear bands at an angle of 45^{o} to the applied normal stress axis, to form the final cup and cone sides of the fractured surface shape. Two out of three distinct known processes of void formation and coalescence (dimples) are distinguished in this study ; the tensile stresses produced equiaxed microvoid and pure shear stresses generate elongated microvoid in the shearing direction. SEM topographic shown the in figure (4a & b).

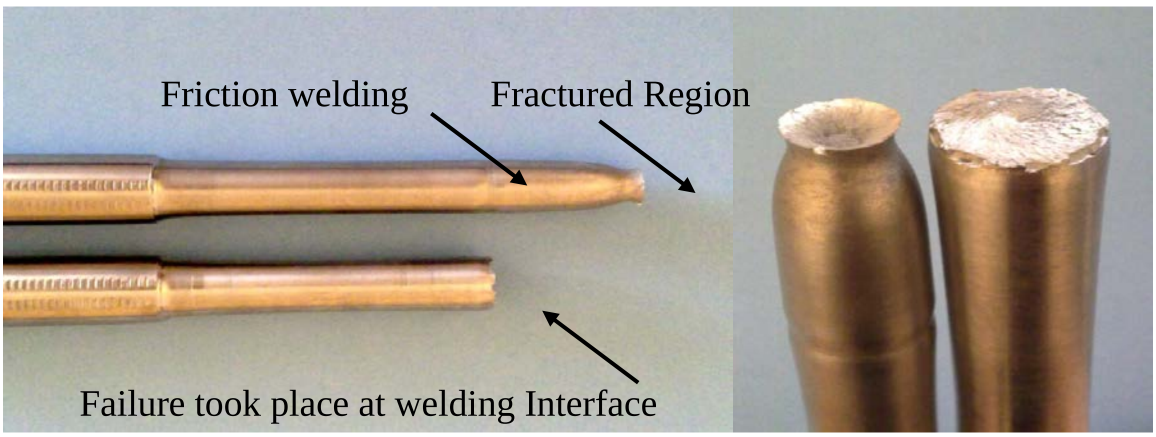

Figure 3a: The fracture location and shape for similar AISI 304.

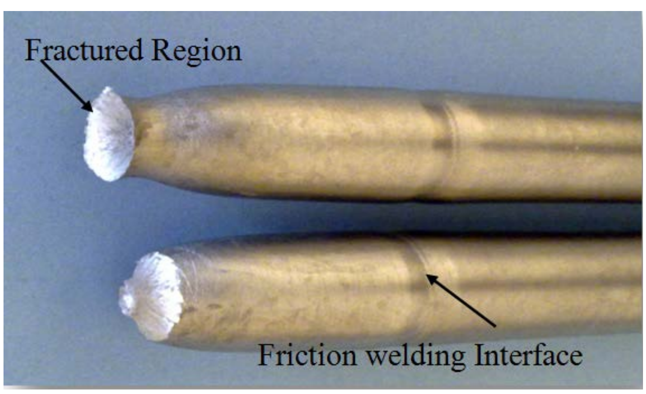

Figure 3b: Tested sample with cup and cone shape of ductile fracture of AISI 304.

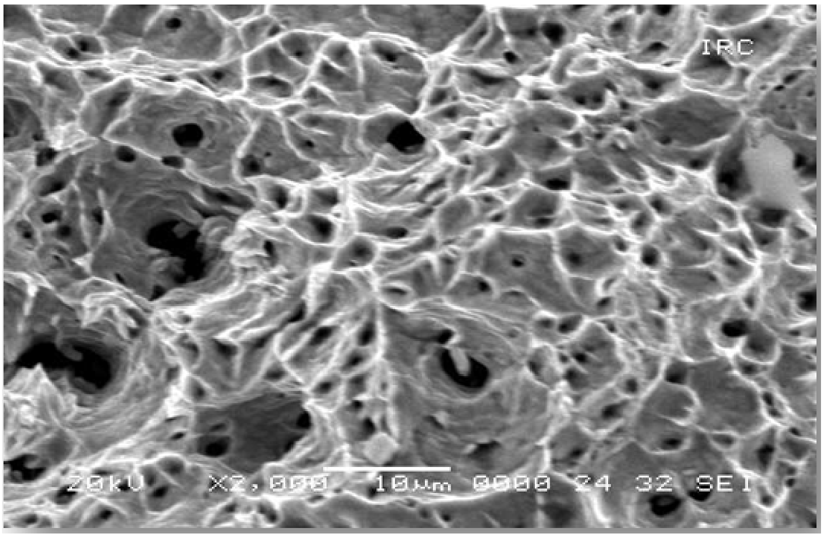

Figure 4a: Eqiaxial microvoid coalescence at normal stress AISI 304, X2000

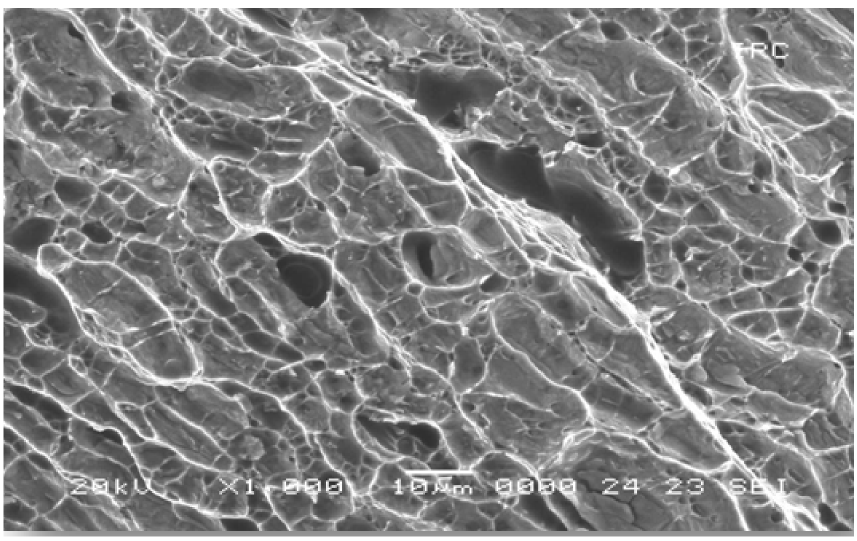

Figure 4b: Elongated microvoid coalescence at sheared region AISI 304, X2000

Fracture morphology for dissimilar joints; with the same investigation steps for pointing the fracture location shown in Figure (5), and examining the fracture mode for similar joints, all dissimilar samples showed a same general mode of fracture, where the fracture occurred at the bond line of the weld interface, and the SEM fractography are presented in Figure (6a & b). SEM micrographs indicates that the fracture took place by interface splitting under the action of tensile force, the brake-off occurred in the weld interface is due to the relatively narrow thermal softened area for the Al 6061 alloy, as result of higher forge pressure applied during the forging stage, this founding is highly agreed with the Hiizu OCHI et. al. [8], as they concluded that, the tensile facture surface approached closer to the weld interface according to increases in the upset pressure, and more metal loosed in a form of flash Figure (6a & b).

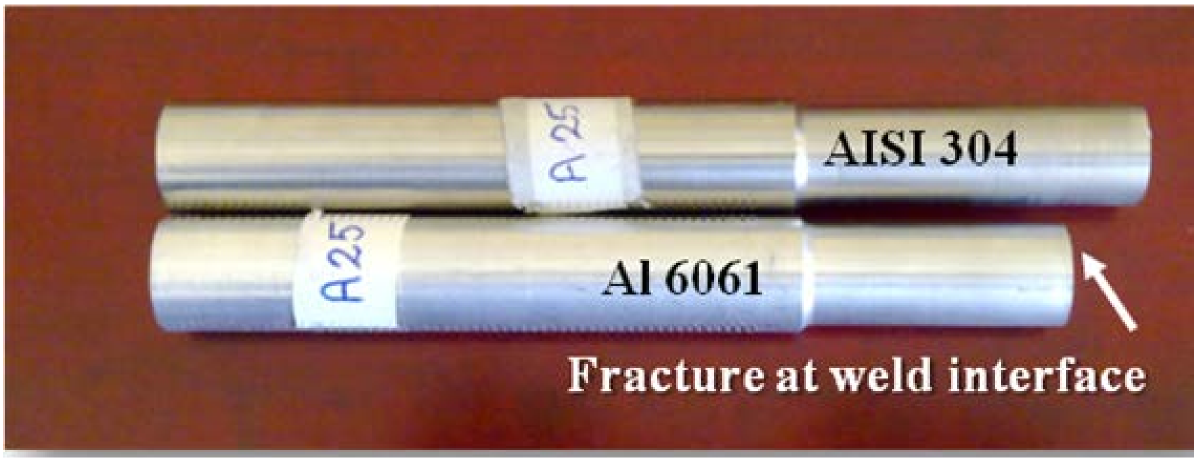

Figure 5: Fracture location for dissimilar at welded sample.

Many spiral patterns are observed at the fracture surfaces pair, which believed to be attributed to the presence of tramp light element such as Magnesium and oxide inclusion [17], as illustrated in figure (7a & b). Spiral as defects are formed in the wake of discontinuities in the flow of plasticized material in the contact region. In the conditions when material highly heated, these induced defects are fluid flow formed where Magnesium rich segregates and inclusions transfer to embedded regions close to the stationary boundary of the joint [19]. Spiral defects acting as sites for preferential failure during mechanical tensile testing of joints made by using low friction pressures [17], as shown in Figure (8). The detailed Fractography observations confirmed that the spiral patterns changed with the weld parameters applied.

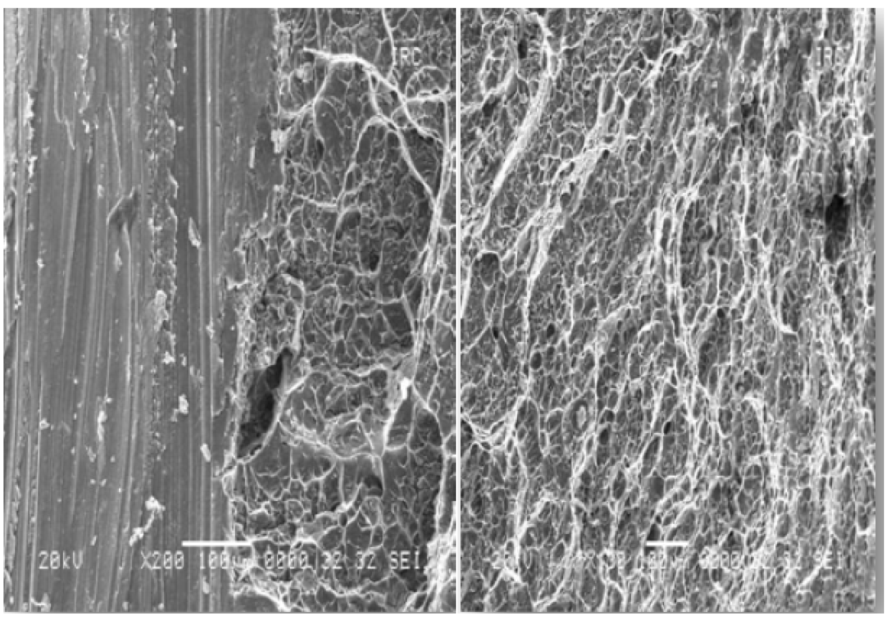

Figure 6a & b: The fracture morphology for tensile sample A26 X200, X100.

As the application of high friction, pressures during welding markedly decreased the incidence of spiral pattern in weld joints. Similar results have also been reported by K. UENISHI et. al. [17], the use of high friction pressures obviously reduced the occurrence of spiral defects in dissimilar welds. The higher forge and friction pressures applied gives higher tensile strength to the joints and the fractures planes are localized in the bulk instead of the interface. From the evident details by SEM photos of A26 it is observed that an amount of fractured aluminum on stainless steel surface with different magnified views of the investigated tensile test samples are shown in figure (9).

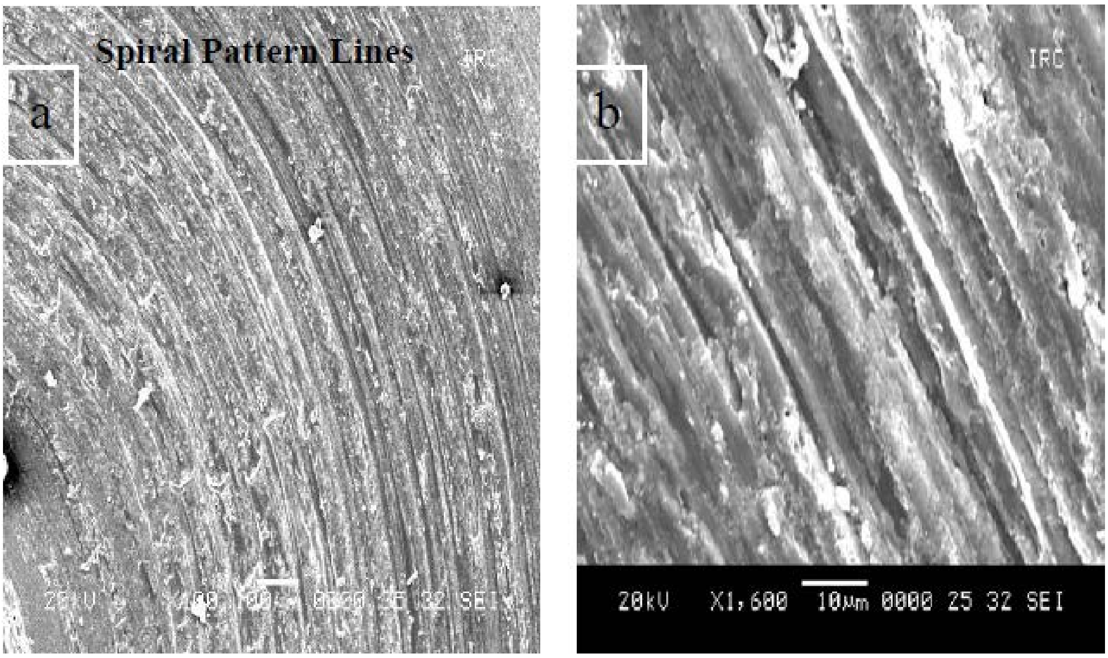

Figure 7a & b: The spiral pattern lines on joint A25X100 & X1600).

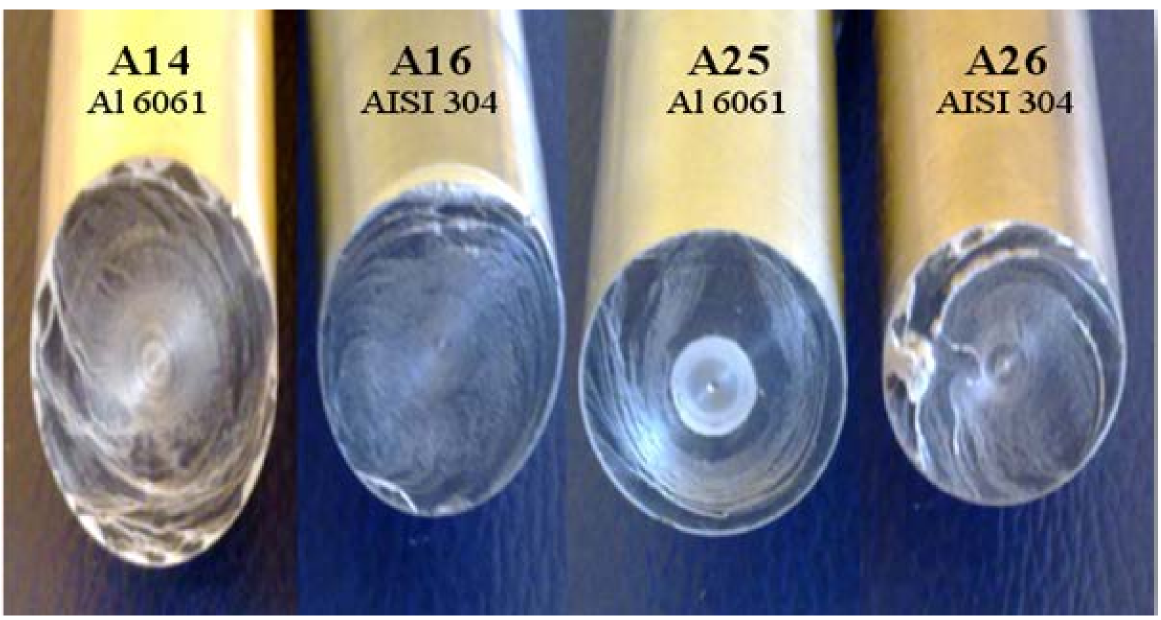

Figure 8: Effect of friction pressure on the change of spiral patterns morphology.

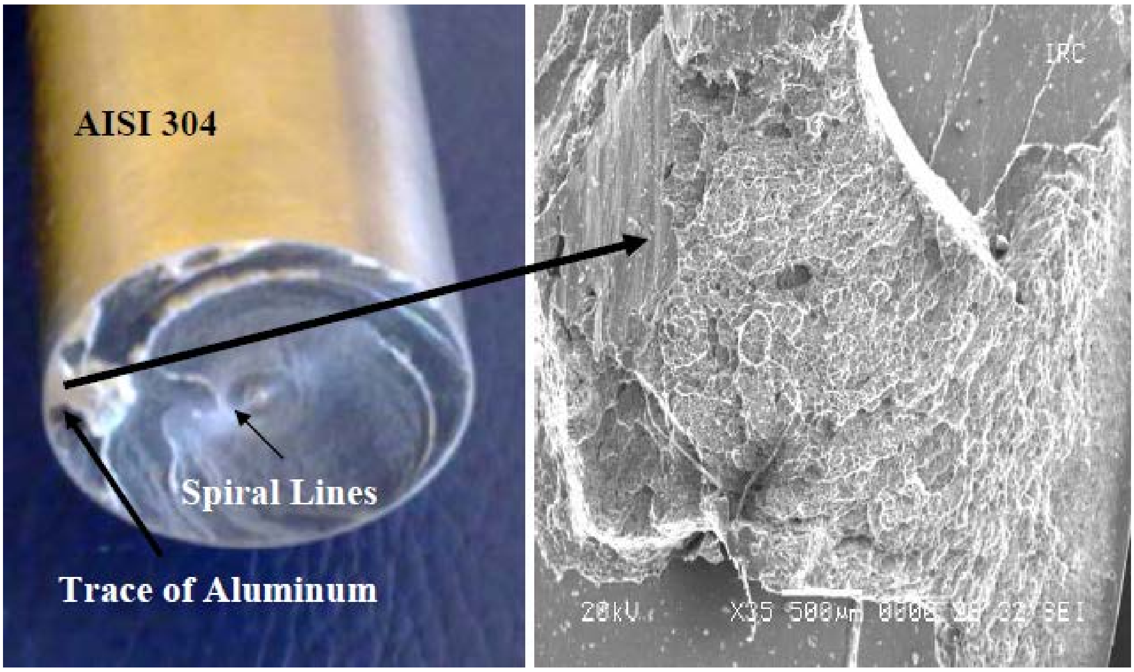

Figure 9: Microscopic features at contact site, showing a dark grey area corresponds to the trace of Al on stainless surface of the joint A26.

CONCLUSIONS

The tensile strength and fracture morphology of similar AISI 304/304 and dissimilar welds of AISI 304/AA6061-T6 produced by continuous drive friction welding (CDFW) are investigated and the main conclusions are as follow:

- Welding technique CDFW has demonstrated its suitability for joining different materials. The welding equipment showed a high reproducibility, with no welding defects such as porosities or cracks apparent in all runs within the investigated range of the selected parameters. An available is successfully adopted machine for performing dissimilar weld joints.
- The strength of friction joints produced exhibited comparable strength with the base material with maximum efficiency of 98% for AISI 304/304 joints which indicating that austenitic stainless steel is highly tolerant to friction welding, and 89% for AISI 304/Al6061-T6 joints which is also considered acceptable for dissimilar metal joints.
- The fracture mode as a microvoid coalescence (dimples) at the fractured surface confirms the ductile mode of failure during tensile testing is dominant.
- The fracture occurred at the weld line as an interface splitting. Many spiral patterns are observed, which acted as preferential failure sites during tensile testing, and as the numbers of spiral defects decreased, joint strength improved.

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