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Characterization and mechanical behaviour of similar and dissimilar parts joined by rotary friction welding

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A B S T R A C T

This work is a contribution to the study of the rigidity of rotational friction welding of cylindrical specimens made on a parallel lathe. We performed welding of three combinations of parts: steel / steel, aluminium / aluminium and steel / aluminium according to three numbers of rotations of the spindle (900, 1250 and 1800 rpm). To control the rigidity and quality of these assemblies, tensile tests are used followed by ultrasonic testing to ensure that the tips are welded and that there are no internal defects. Hardness profile of the welded zone according to the welding parameters was obtained. Metallographic observations have detected the profile of the various zones welded and affected thermally. The results of the mechanical tests showed that a rotation speed of 1250 rpm can produce a very good weld, with other parameters kept constant.

1. Introduction

Rotary friction welding is a fairly new method in the industry for assembling similar and dissimilar materials such as drill pipe, truck axles and hydraulic cylinder rods. This process is obtained by the rapid rotation of one of the two elements to be welded while the other remains motionless in a vice. Then these two components are pressed against each other until the weld bead is obtained. The friction between the parts to be assembled creates heat. The temperature in the contact surface increases without reaching the melting temperature. When the desired temperature is reached, the friction is stopped and the plastic parts are pressed against each other to form the assembly. The process is fast, efficient and therefore economical. No pre-treatment is necessary. There is a small area affected by heat (heat affected zone). No need for welding wire, mixing gas or suction. The most important advantage of friction welding is the fact that it achieves a perfect weld, that is to say an integral weld (weld the surface and not the circumference) because the parts are forged / welded into one set. Friction welding is carried out sustainably. The great advantage of this welding technique lies in the fact that some combinations of materials can be welded, while they are not welded with traditional welding techniques. The process is

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clean, smoke-free, not dangerous, fast and automated, which guarantees the control of its parameters (Fukumoto et al., 1999; Buffa et al., 2006; Winiczenko et al., 2017; Xu et al., 2009; Shubhavardhan & Surendran, 2018, 2019). Accordingly, in the past years several research works have been published for joining different similar joints such as (Fe3Al based ODS alloy (Sketchley et al., 2002), aluminum (Thomas et al., 2002) and molybdenum (Stütz et al., 2018, 2019)) and dissimilar metallic joints such as (AA1050 aluminum/AISI 304 stainless steel (Alves et al., 2010, 2019), AA6082/Ti-6Al-4V (Meisnar et al., 2017), AISI 304L/WC-Co cermet (Cheniti et al., 2019), In718/SS410 (Anandaraj et al., 2020) and ODS-Cu/T91(Zhao et al., 2020) using this welding method in the shape of solid shafts or hollow tubes. Others have focused on characterizing the mechanical properties, residual stress, micro structure and other behaviours of rotary friction welded joints (Li et al., 2016, 2020; Łukaszewicz, 2018; Rößler et al., 2018; Damodaram et al., 2019, Jin et al., 2019; Vairis et al., 2016; Nan et al., 2019).

Research on the characterization of rotating friction welded parts has gained importance in recent years. (Sathiya et al., 2005) studied mechanical and metallurgical characterization in austenitic stainless steel AISI 304 welded by friction. The results showed that the strength of the joints is decreased with an increase in friction time. The detailed fractographic observation confirmed that the rupture occurred mainly in the hinge area and partly through the base material. An experimental study presented by (Rostamiyan et al., 2015) introduces a new combination of two separate welding processes, namely spot welding with friction stirring (FSSW) and ultrasonic welding (USW). To improve the quality of the weld, spot welding with friction stirring is assisted by the ultrasonic vibration of the tool. The results showed that vibration is an important factor affecting shear force and hardness. Beside the vibration, tool rotation speed, pause time and dive depth are also important factors that affect the mechanical properties significantly. Balalan and Ekinci (2018) have studied the effect of rotation speed parameter on mechanical properties of parts joined by Friction Welding. In their work, friction welding of similar material steel AISI 1040 cylindrical parts having 12 mm diameter was successfully realised at different welding parameters. In order to determine mechanical properties of welds, the tensile strength and micro hardness tests as well as microstructural analysis were carried out. Experimental results show that the highest tensile strength is nearly 400 MPa, which is obtained at the parts welded through 1500 rpm. A recent study presented by Winiczenko et al. (2017) is used to determine the mechanical and microstructural properties of a thick alloy (WHA) and aluminium alloy (AA) welded by friction clutch. The authors found a maximum average resistance of 234 MPa, or 84.78% of the aluminium alloy base material, is obtained with a friction time of 3.5 s and a frictional pressure of 40 MPa, respectively.

The purpose of this research work is fabrication of some similar and dissimilar metals such as steel / steel, aluminium / aluminium and steel / aluminium cylindrical specimens using the rotary welding method and then investigating the rigidity of manufactured joints by varying the speed of rotation of the spindle. To control the rigidity and quality of these assemblies, tensile tests are used followed by ultrasonic testing to ensure that the tips are welded and that there are no internal defects, as well as micro measurements. Hardness of the welded zone according to the welding parameters used. Metallographic observations have detected the profile of the various zones welded and affected thermally.

2. Material and testing techniques

The materials used in this work come from the workshops of M'sila University. These are circular bars with diameters of 15 mm. The chemical composition of both parts is determined using a Thermo Fisher Scientific instrument in accordance with ASTM E18 and this is indicated in Tables 1 and 2, chemical analysis of material 1 to identify the material which corresponds to grade A60 (steel) but material 2 corresponds to grade AA 6063 (aluminium). The mechanical behaviour of the two materials was studied using tensile tests. Five specimens were cut to a diameter of 12 mm and then were machined from the specimens as shown in Fig. 1. To avoid any machining effect, the surface test of the workpiece in the length of the reduced section was ground parallel to the axis of the specimen using abrasive papers.

The friction welding is carried out on a parallel lathe with universal carriage and threading model E3N-01; equipped with all the tools necessary for the machining of specimens as shown in Fig. 2a and 2b. The tensile tests are carried out on a hydraulic machine of type WP 310 - GUNT HAMBURG equipped with a load cell with a capacity of 50 kN with a displacement speed that varies between 0 to 425 mm/min. For the metallographic examination, an optical microscope was used; equipped with all the necessary means to examine the specimens (Fig. 4) and for micro hardness tests an indenter *24i* hardness testing machine was used; equipped with all the necessary means to test the specimens (Fig. 5).

Table 1. Chemical composition of material 1 (Steel)

Element	Sn	Mo	Ni	Co	Fe	Mn	Cr	Cu
Wt%	0.010	0.052	0.432	0.146	97.968	0.810	0.165	0.414
Error	±0.004	±0.002	±0.034	±0.062	±0.085	±0.031	±0.012	±0.026

Table 2. Chemical composition of of material 2 (AA 6063)

Element	Sn	Pb	Zn	Al	Fe	Ti	Cr	V
Wt%	0.011	0.004	0.011	99.237	0.326	0.025	0.072	0.030
Error	±0.005	±0.001	±0.002	±0.021	±0.013	±0.003	±0.005	±0.006

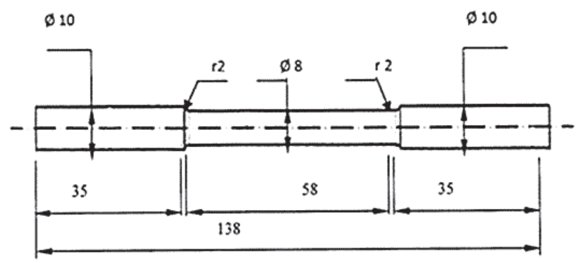

Fig. 1. Friction welding specimen before cutting in the center (dimensions in mm)

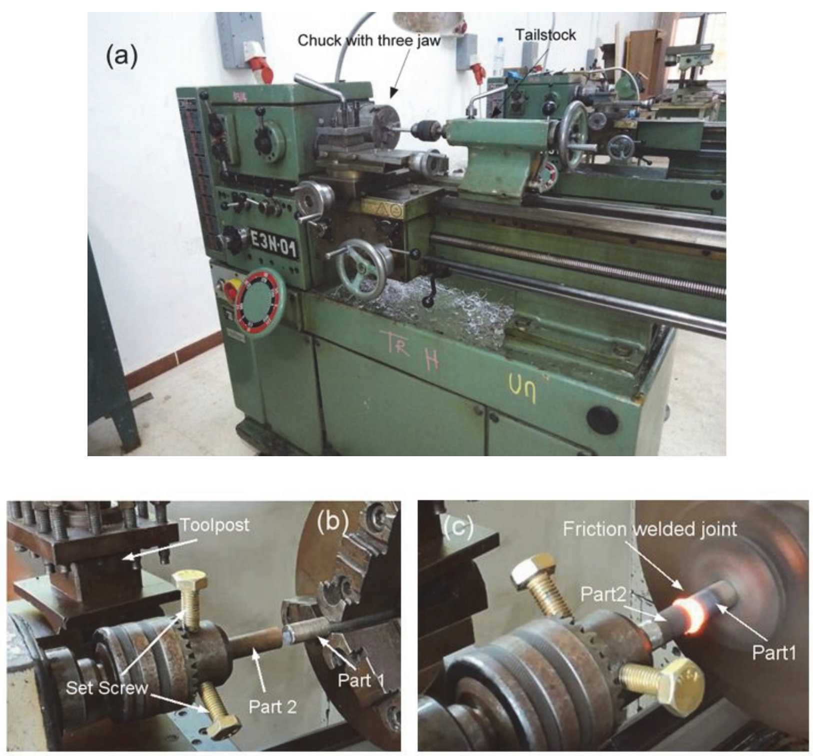

Fig. 2. Test tube of soldering before cutting in the centre.

3. Results and discussion

3.1. Ultrasonic testing

Ultrasonic testing is based on the transmission, reflection and absorption of an ultrasonic wave propagating in the test room. The transmitted wave train is reflected in the bottom of the room and the defects and then back to the transducer (which often acts as transmitter and receiver). The ultrasound tester used is of type D10 +, the frequency of 3 MHz is used for the treatment of surface areas (Fig. 3).

Fig. 3: Ultrasound tester D10 +

After interpreting the signals, we found that the welds were good with no defect. In fact the wave emitted by the transmitter has not changed having encountered no default returns with the initial signal. This proves that the welding was done on all surfaces and not just the circumferences.

3.2. Tensile test

The field of our test was limited to the measurement of the elastic limit (Re): The tensile stress is such that any exceeding of this tensile stress has the effect of causing irreversible plastic deformations in the material which the underwent. The results obtained are given in Table 3 giving the elastic resistances of the welded specimens as a function of the rotational speeds of the spindle.

Table 3. Elastic resistance of welded specimens for different rotational speeds of the spindle

Welded test pieces	900 rpm	1250 rpm	1800 rpm
Steel / Steel	462.70 N/mm²	305.98 N/mm²	222.22 N/mm²
Aluminum / aluminum	87.56 N/mm²	69.83 N/mm²	26.86 N/mm²
Steel / Aluminum	186.81 N/mm²	158.65 N/mm²	147.17 N/mm²

From the results obtained in this Table we found that: For all similar and dissimilar joints an increase in the rotational speed of the spindle produces a decrease in the elastic limit (Re) of the welded parts (that is related to the reduction of the friction), an increase in the rotational speed promotes a great heating in the weld zone resulting in plastic deformations of the material subsequently decreasing the elasticity of the material. A comparison of three material combinations and for the three cases of rotational speed indicates that steel / steel joint has a good resistance, while steel/aluminium and aluminium / aluminium joints show less resistant.

3.3. Micro hardness

Measurements of micro hardness at mid-thickness of the joints, perpendicular to the welding axis were made. Measurements are taken every millimetre, on a polished surface and attacked by a solution composed of nitric acid and alcohol, generally 5 ml / 100 ml allows to partially distinguishing the different microstructures of the layers in the weld bead. The representations of the values of the micro hardness are illustrated in Figs. 4a, 4b and 4c. The micro hardness profiles are identical for the three rotational speeds used;

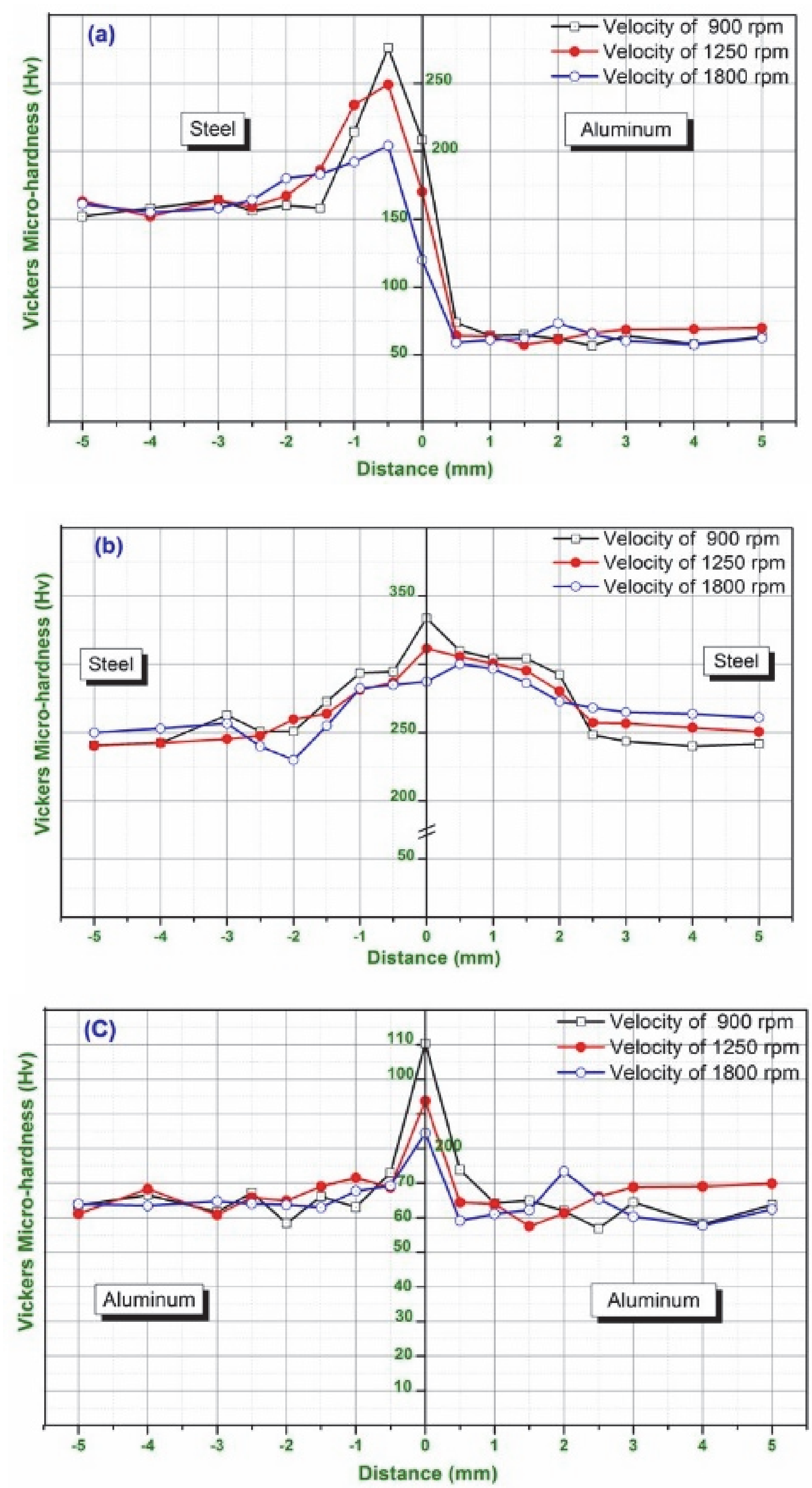

Fig. 4. Variation of the Micro-Hardness of welding for: (a) Steel/ Aluminium, (b) Steel /Steel and (c) Aluminium /Aluminium

The hardness of the samples reaches a maximum at the interface and decreases in the direction of the base material. It is seen that for small speeds (900 rpm) where it is 73HV for Aluminium more than 294HV for steel then it decreases for high speeds (1250 and 1800 rpm). During the friction welding of various metallurgical phenomena occur at the interface such that element diffusion, hardening, grain refinement and precipitation at the interface causes an increase in the hardness value. It can be seen from Fig. 4 that for the different assemblies, the hardness value is high in the melted zone but its value gradually decreases and then becomes constant while going towards the base material. This can be explained by the significant heating of the material in the melting layers of the material then superficial hardening of the contiguous layer. Fig. 4 also shows that the hardness in the layers decreases with increasing the rotation speed.

3.4. The microstructure

The metallographic examination of the welded test specimen taken across the weld allowed us to highlight that the welding has no defects and we can distinguish between the structures in the welding zone. At the junction of two welded materials, two layers (a melted layer and a thermally disturbed fine grain layer was observed) as shown in Fig. 5. Indeed, Figs. 5a, 5b and 5c show the different metallographic and grain structures obtained for similar and dissimilar joints.

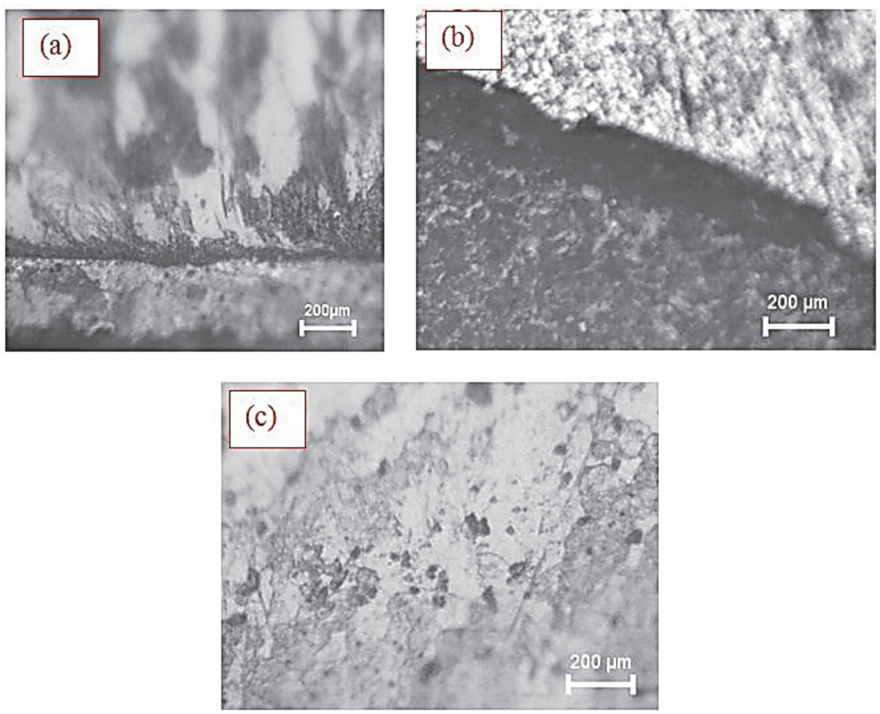

Fig. 5. Metallographic Structures obtained for (a) Steel/Steel (b) Steel/Aluminium (c) Aluminium /Aluminium joints made by rotary friction welding

4. Conclusions

Friction welding is a versatile and innovative welding process that has many applications in different branches of industry. The advantages of friction welding are high quality assemblies, the speed of the process compared to conventional welding processes. In addition, the friction welding process offers important environmental benefits: no welding fumes, no UV or electromagnetic radiation and no filler metal or shielding gas is required. This study has mounted that it is necessary to reduce the rotational speed to increase the friction in order to reach the temperature in the contact surface without reaching the melting temperature. Similar and dissimilar Steel and Aluminium tubes were joined perfectly using this technique. The mechanical properties, micro hardness profile and microstructure of joints were obtained and studied experimentally. The rotation of welding and the type of material had noticeable influence on the quality of fabricated joints.

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