Non-Destructive Testing of Dissimilar Friction Stir Welds

Esther T. Akinlabi *Member*, *IAENG*, Adrian C. S. Levy and Stephen A. Akinlabi *Member*, *IAENG*

***Abstract*—**This paper reports non-destructive testing conducted on dissimilar friction stir welds between 5754 aluminium alloy and C11000 copper. The Friction stir welds of 5754 aluminium alloy and C11000 copper were produced at different tool rotational speeds and feed rates. The tool rotational speed was varied between 600 and 1200 rpm while the feed rate was varied between 50 and 300 mm/min. The visual inspection and the x-ray radiographic testing techniques were employed to conduct the tests; these tests were conducted on the welds to ascertain the joint integrity before characterization to have an idea of the quality of the welds. No visual defects were observed on all the welds considered but the x-ray radiography technique revealed the presence of wormhole defects and discontinuities in some of the welds. It was found that the welds produced at 950 rpm with varied feed rates were the best quality welds produced and this was substantiated with the microstructural evaluation of the joint interface. It was found that these welds have good mixing and metallurgical bonding at the interfaces.

***Keywords*—** friction stir welding, macrographs, metallography micrographs, Non-destructive testing, radiography,

I. INTRODUCTION

A FAIRLY modern technique of welding materials together has established itself as an increasingly popular procedure in the manufacturing industry. This method of welding is formally known as Friction Stir Welding (FSW). FSW has shown great results for joining metals together without significantly altering the original properties of the parent metals. FSW is a solid-state joining process which is applicable to all metals and plastics. The popularity of this welding procedure is due to the fact that unlike conventional welding, it does not create brittle bonds caused by the localized heating of metal and also has narrow Heat Affected Zone (HAZ). The localized heating present in conventional welding techniques effectively alters the chemical composition within that heated section. This severely alters the mechanical properties of the metal and further heat treatment is required to resolve this inadequacy. The advantage of FSW is that the heat is generated internally via a mechanical method and therefore localized heating does not occur. The discovery of this technique took place in 1991 by The Welding Institute (TWI) and is now a widely used process which can be found in the aerospace, aircraft, shipbuilding, railway and automotive industries [1]. FSW operates by simultaneously combining heat caused by friction along with pressure to produce resilient bonds which have been known to be of excellent quality. Another description of FSW is that the frictional heat generated during this process softens the material to produce plastic flow that effectively stirs the material from the sections on both sides and fuses them together to create a solid phase weld [1]. This highly physical process allows for the formation of a mechanically strong joint and is a great alternative to conventional welding processes. A schematic diagram of the FSW process is presented in Fig. 1.

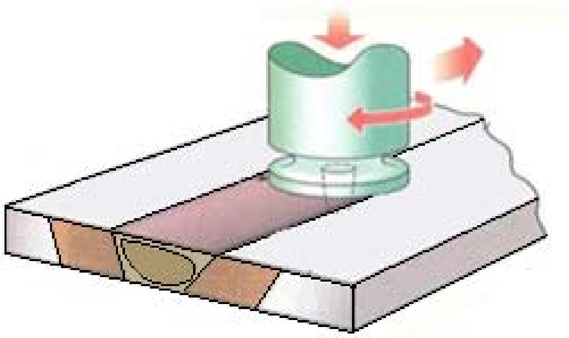

Fig. 1: schematic diagram of the FSW process [2]

Major aspects affecting the quality of the welds are the combinations of the rotational speed and feed rate parameters. These are responsible for generating the heat and the stirring mechanism used to effectively join the materials. These welding parameters employed in FSW process have vast effect on the quality of the welds produced and are known to be the two most important welding parameters which strongly affect the joint integrity [3]. The rotation of the tool results in the stirring and mixing of the material around the rotating pin, while the translation of the tool moves the stirred material from the front to the back of the pin and finishes the welding process. A major weld quality aspect in question is how to be able to detect the internal defect formed in the weld and a Non-Destructive Testing (NDT) technique is most appropriate in this regard. Non-Destructive Testing rose from the necessity to detect flaws within components to avoid detrimental and repetitive failures. NDT is a wide group of analysis techniques used in science and industry to evaluate the characteristics of a material or component without causing

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Dr E. T. Akinlabi is a Senior Lecturer in the Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park, Johannesburg, South Africa, 2006. (Phone: +2711-559-2137; e-mail: etakinlabi@uj.ac.za).

Mr A. C. S Levy is a graduate student in the Department of Mechanical Engineering Science, University of Johannesburg, South Africa, 2006.

Mr S. A. Akinlabi is a doctorate candidate in the Department of Mechanical Engineering Science, University of Johannesburg, South Africa, 2006. (Phone: +277984-77095; e-mail: saakinlabi@uj.ac.za).

damage to it. The techniques used are non-invasive. NDT can be considered as any form of testing or inspecting materials in order to verify the structural integrity of the part without compromising the mechanical or chemical properties of the material, in this case; a weld joint. Because NDT does not permanently alter the article being inspected, they are highly-valuable techniques that can save both money and time. Many different types of NDT methods exist, the most commonly used ones being ultrasonic testing, magnetic particle testing, liquid penetrant inspection, radiographic testing and eddy current testing. NDT is used in almost every field of engineering and can be applied to any types of materials including metals, ceramics, coatings and polymers of different plastics and composites. The detection of these flaws is critical for the safety criteria of all designs. These flaws include cracks, internal voids, surface cavities, delamination, defective welds and any sort of imperfection in the welds that could be detrimental to the performance of the welds. Successful attempts have been made on non-destructive testing techniques on friction stir welds of aluminium and its alloys [4-6]. Li *et al* [4] reported on multiple non-destructive testing methods on FSW of 2219-T6 aluminium alloy. The techniques successfully employed include the x-ray detection, ultrasonic C-scan, ultrasonic phased array inspection and fluorescent penetrating fluid inspection; they concluded that each of the non-destructive technique has its limits. The Ultrasonic C-scan testing was found to do well at detecting porosity and tiny voids in the joints, while the fluorescent penetrating fluid inspection was suitable for revealing the hidden root crack-like flaws. Rosado *et al* [5] utilized the eddy currents probe to detect the imperfections in friction stir welds of aluminium and Hu *et al* [6] also employed a high-precision magnetic sensor to detect the weld defects in aluminium friction stir welds. However, there is no published literature on non-destructive testing on friction stir welds of dissimilar materials. In view of the foregoing, research into the effect of rotational speed and feed rate on defect formation in dissimilar aluminium and copper joints has been published by Akinlabi *et al* [7]. Non-destructive testing for defects is the most effective method of determining the integrity of a friction stir weld, hence research studies into non-destructive techniques of dissimilar joints between aluminium and copper will ultimately lead to achieving optimised setting to produce quality welds and increase material performance in this regard. The successful technique reported in this paper can also be extrapolated to conducting non-destructive tests on other dissimilar FSW joints. The aim of this paper therefore, is to present results of non-destructive testing techniques on dissimilar friction stir welds of aluminium and copper.

II. EXPERIMENTAL SET-UP

The Friction Stir welds consisting of 5754 aluminium alloy and C11000 copper were successfully produced at the Friction Processing Research Institute (FPRI) of Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa with an Intelligent Stir Welding for Industry and Research Process Development System (I-STIR PDS) platform. The dimension of the weld coupon was 600 x 120 x 3 mm and butt joint configuration was considered in this research. The plates were cleaned with acetone to degrease before the welding procedure. The Friction Stir Welds were produced by varying the rotational speeds between 600 and 1200 rpm and the feed rate between 50 and 300 mm/min. The rotational speeds of 600, 950 and 1200 rpm were employed while 50, 150 and 300 mm/min were the feed rates considered representing the low, medium and high settings respectively. The weld matrix considered is presented in Table I.

TABLE I
WELD MATRIX AND SAMPLE DESIGNATION

Specimen Designation	Rotational Tool Speed (rpm)	Feed Rate (mm/min)
A1	600	50
A2	600	150
A4	600	300
C1	950	50
C2	950	150
C4	950	300
L1	1200	50
L2	1200	150
L4	1200	300

The tool employed was threaded pin and concave shoulder machined from H13 tool steel and hardened to 52 HRC. A weld length of 160 mm was produced for every setting. The aluminium alloy side was etched with Keller's reagent and the Cu was etched with the modified Poulton's reagent to reveal the microstructure. The visual inspection on the welds were conducted using an Olympus stereo microscope which creates greater magnification and improved lighting condition of the sample undergoing visual testing while the radiographic tests were conducted using RayzorXPro developed by Vidisco at OSG Testing in Alberton, Johannesburg South Africa.

III RESULTS AND DISCUSSION

3.1 Visual inspection of the welds

A typical weld produced at 600 rpm and 150 mm/min is presented in Fig. 2.

Fig. 2: Friction stir weld of aluminium and copper produced at 600 rpm and 150 mm/min

Due to the nature of the surface appearances of friction stir welded samples, it was difficult to observe any surface defects. No significant cracks, wormhole or other surface deformities were observed in any of the samples produced.

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3.2 Radiographic testing

The results of the radiographic tests conducted on all the welds produced at 600 rpm and feed rates of 50, 150 and 300 mm/min are hereby presented in Table II. This includes the x-ray radiographs and the comments on each sample examined.

TABLE II
PHOTOGRAPHS AND RADIODRAPHS OF WELDS 600 RPM AND FEED RATES OF 50, 150 AND 300 MM/MIN

600 rpm/50mm/min		600 rpm/150mm/min		600 rpm/300mm/min	
Photo-graph	Radio-graph (x-ray)	Photo-graph	Radio graph (x-ray)	Photo-graph	Radio-graph (x-ray)
					
Comments Slight signs of incomplete fusion were observed.		**Comments** Incomplete fusion, wormhole defect.		**Comments** Crack and Void revealed. Low level of Incomplete fusion.	

Although no defect was found on the surface of the welds through visual inspection, from the x-ray radiographs presented in Table I, it was observed that these welds are characterized with incomplete fusion of both materials joined and wormhole defect was also noticed.

The results of the radiographic tests conducted on all the welds produced at 950 rpm and feed rates of 50, 150 and 300 mm/min are presented Table III.

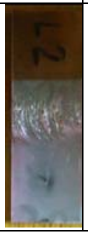
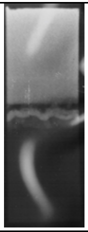
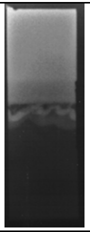
TABLE III
PHOTOGRAPHS AND RADIODRAPHS OF WELDS 950 RPM AND FEED RATES OF 50, 150 AND 300 MM/MIN

950 rpm/50mm/min		950 rpm/150mm/min		950 rpm/300mm/min	
Photo-graph	Radio-graph (x-ray)	Photo-graph	Radio graph (x-ray)	Photo-graph	Radio-graph (x-ray)
					
Comments Complete penetration. No evidence of wormholes, voids, or cracks. Minimum mixing observed.		**Comments** Complete penetration. No evidence of wormholes, voids, or cracks. Moderate mixing observed.		**Comments** Complete penetration. No evidence of wormholes, voids, or cracks. Moderate mixing observed.	

With reference to Table III, it was found that welds produced at a constant rotational speed of 950 at varying feed rates of 50, 150 and 300 mm/min has no evidence of wormhole or defects at the joint interface.

The results of the radiographic tests conducted on all the welds produced at 1200 rpm and feed rates of 50, 150 and 300 mm/min are presented Table IV.

TABLE IV
PHOTOGRAPHS AND RADIODRAPHS OF WELDS 1200 RPM AND FEED RATES OF 50, 150 AND 300 MM/MIN

1200 rpm/50mm/min		1200 rpm/150mm/min		1200 rpm/300mm/min	
Photo-graph	Radio-graph (x-ray)	Photo-graph	Radio graph (x-ray)	Photo-graph	Radio-graph (x-ray)
					
Comments There is a discontinuity at the joint interface.		**Comments** Complete penetration. Good extent of mixing. Uniform mixing.		**Comments** Complete penetration. Good extent of mixing.	

It was observed that the weld produced at 1200 rpm and

The defects found are mainly cracks or voids. It can be seen from the results that increasing the weld travel speed increases the frequency of voids. A1 has no apparent cracks of voids but revealed incomplete fusion of both materials while A2 shows a presence of voids. A4 shows the maximum amount of voids and the highest lack of penetration. With regard to tool rotational speed, it is evident that the extent of mixing is directly related to the medium rotational speed of 950 rpm, thus greater penetration and a more consolidated weld is achieved. Fig. 3 show a graphical summary of the trends observed from the assessment of the radiographs.

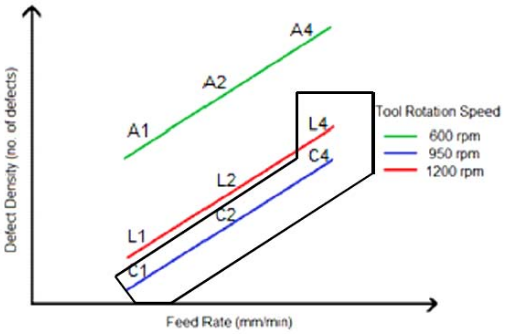


Fig. 3: Defect density versus feedrate (mm/min)

The enclosed area on the graph indicates samples which showed no discontinuities from the radiographs. From the above graph, it is can be deduced that the welding parameters of 950 rpm at 50 mm/min; 150 and 300 mm/min produced the defect-free welds, that is, a medium rotational speed of the tool. It is apparent that increasing the feed rate effectively increase the amounts of defects formed during welding, this can be attributed to the fact that less heat is generated at high feed rate which in turn is not enough to consolidate the weld with exception of the weld produced at 1200 rpm and 300 mm/min which can be interpreted that the high rotational speed at 1200 rpm compensated for the high feed rate of 300 mm/min and hence assisted in consolidating the weld produced at this setting. Also 950 rpm has been found to be the optimum tool rotational speed for defect-free welds [8]. Results show that either increasing or decreasing the rotational from 950 rpm will induce greater formation of defect. These results show a directly proportional relationship between defect occurrence and feed rate. The results also conclude that defects are formed when rotational speed is either too low or too high. The optimised process window is shown to be at medium rotational speed of 950 rpm and low feed rate of 50 mm/min.

3.3 Microstructural evaluation

The microstructure of the interfacial regions of the welds without defects, viz; produced at 950 rpm and feed rates of 50, 150 and 300 mm/min are presented in Fig. 4 (a) to (c).

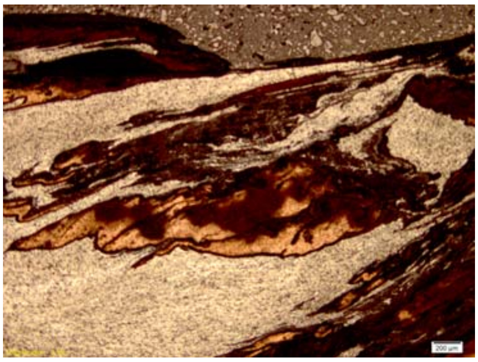


Fig. 4 (a): Micrograp of the interfacial region of weld produced at 950 rpm and 50 mm/min

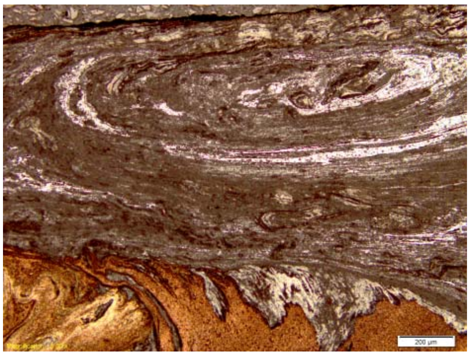


Fig. 4 (b): Micrograp of the interfacial region of weld produced at 950 rpm and 150 mm/min

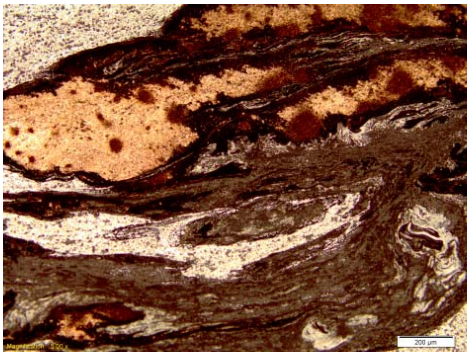


Fig. 4 (c): Micrograp of the interfacial region of weld produced at 950 rpm and 300 mm/min

It was observed that the interfacial regions of the welds produced at 950 rpm and at the varied feed rates considered is characterized with good mixing and recrystallized structure of both materials joined.

IV CONCLUSION

Non-Destructive testing techniques viz: visual inspection and x-ray radiography were successfully conducted on welds produced at various parameter combinations. It can be concluded that the visual inspection of the welds is not the best technique as it was found that although all the welds passed this test and appeared as defect-free welds, the x-ray radiographic testing technique successfully detected the defects present in the welds and can be said to be appropriate in this regard. Only about 44% of the welds were defect-free. Good mixing and metallurgical bonding were achieved in the defect-free welds as revealed in the microstructure of the interfacial regions. An optimum rotational speed for producing defect-free welds of aluminium and copper was found to be 950 rpm.

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