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A MOBILE FIXTURE SYSTEM FOR FRICTION STIR WELDING APPLICATION

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ABSTRACT

In an attempt to provide a more flexible means of achieving friction stir welding (FSW) of Aluminum without the use of expensive FSW machine tool, which are not readily available. This study developed a mobile fixture system (MFS) for FSW on a Vertical milling Machine Tool (VMMT). A conceptual design of a fixture system with a moving work table, which provides for transverse feed (movement) of the workpieces during FSW, was generated. The detailed design of the components of the MFS was done using existing mechanical design formulae. Subsequently, the design was fabricated and evaluated. An ATmega 328P Arduino Uno microcontroller was used to design a control system to automate the MFS worktable movement. Results revealed that the MFS worked smoothly during FSW of AA 1100 materials. The efficiency of its motion accuracy was estimated as 87.2%. Also, the trend of the tensile strength and the hardness value as well as the joint efficiencies of the AA 1100 weldments produced using the developed MFS agreed with existing studies. The MFS can be used for FSW of Aluminum materials on VMMT as well as on pillar drilling machine tool.

Keywords: Friction stir welding, mobile fixture, weldments, mechanical design, control system

1. INTRODUCTION

In the world today, the significance of joining engineering components has led to limitless efforts put in place by engineers to bring about new, easy and cost-effective ways of joining metals. During the manufacturing process various metallic materials are joined together at different location depending on the design concepts of the machineries and equipment been manufactured. The joining of these materials during manufacturing is achieved using welding operation which is a manufacturing process used for creating a permanent joint between two or more metallic parts. The joint, technically refers to as weldment, is usually obtained by coalescence induced by a combination of temperature, pressure, and metallurgical conditions. The electric arc welding (EAW) technique commonly used in the manufacturing process is associated with weldment quality issues like porosity, brittleness, corrosion, cracking etc. These together with other unwanted demerits usually found in the weldments of dissimilar metals obtained using EAW, such as brittle intermetallic compound (IMC) reaction phase formation at elevated temperatures, had shifted the attention of researchers to consideration of gas-tungsten arc welding (GTAW) and gas-metal arc welding of similar and dissimilar metals [1; 2]. When the materials are very soft such aluminum, aluminum alloy, copper and zinc the weld defect is usually more pronounced.

In recent times, however, Friction Stir Welding (FSW) is being applied in the manufacturing of products used in our everyday lives due to its strength, versatility and weld quality. This is a relatively new welding process which has been commonly accepted as a promising method for joining light metallic alloys, especially aluminum, having low melting point [3]. It is a continuous, hot shear, autogenous process involving non-consumable rotating tool of harder material than the work piece material. FSW has attracted considerable interest because of its better weld ability of aluminum alloy weld joint. It has a great potential for welding metals as joint quality is exceptionally high, low cost and the process is very repeatable [3]. It is also expected to produce good quality weldments of metals in comparison to EAW, GTAW and GMAW. Unfortunately, dedicated machine (i.e. Friction Stir welding Machine) purposely built for

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conducting FSW operation is generally not readily available, due to its high cost, which had led researchers to adopt Vertical milling machine tool (VMMT) supported by in-house built fixture for achieving FSW [4].

Basically, the general principle of 3-2-1 location is most commonly used to hold workpieces during the design of fixture. Certain degrees of freedom should necessarily be restricted in the design of FSW fixture, so as to locate and orient the active surfaces of the workpieces with respect to the FSW tool. The main challenge is to curtail the four main forces (see Figure 1) acting on the workpieces during FSW operation.

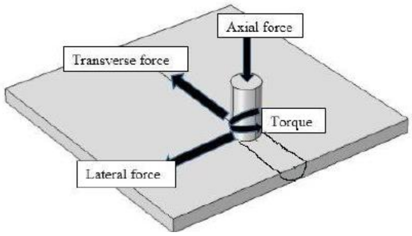

Figure 1: Forces in FSW operation [5]

FSW fixture have been designed, as observed from literatures [6; 7], to comprise (i) base/backing plate (ii) side plates (iii) clamps/clamping plate (iv) bolts/screws as locators and (v) bolts and nuts as holder (vi) Stoppers. A good design of fixture should ensure adequate heat dissipation away from the workpiece to improve the weld quality and performance.

Generally, the existing studies on FSW fixture development can be grouped into two categories. One group involves a situation where the components (backing plate, side plates and clamps) of the fixture are directly held on the milling machine table as a way of assembly [8] while the other group have the elements of the fixture system already assembled together before the assembled fixture is held on the milling machine table for FSW operation [5; 6; 9; 10]. However, while the later approach is preferable for ease of setup both categories are immobile in nature as the workpiece feeding is dependent on the milling machine feed mechanism. This will limit the choice of federate to those available on the milling machine table which oftentimes may not be completely suitable for the investigation at hand as noted from preliminary investigation [4]. If we considered the fact that federate has been established to influence weldment quality during FSW operations [11], this then becomes an important issue which could be handled via the development of a mobile fixture system for use in FSW applications.

Moreover, while some FSW fixture were designed to accommodate only fixed size workpiece width [8; 9] some others were designed to allow a range of workpieces width [5; 6; 10]. The later design allowed flexibility thereby facilitating workpiece preparation for FSW experiments. The design considerations adequate for the development of FSW fixture has been critically examined with some details provided in the direction of systematic design after which a FSW fixture with variable side clamping was developed and utilized for FSW of AA 6101 T6 aluminum alloys successfully [10]. Careful consideration of some of the details provided in line with the basic principle of fixture design will adequately guide FSW fixture design tasks.

Definition of requirement, gathering of necessary information, conceptual design and optimization implementation of the optimum design concept, e t c are some of the processes involved in manufacturing of a machine fixture [12]. Generation and analysis of various design concepts with a view to select the most suitable one to achieve FSW on a VMMT were considered would facilitate development of fixture with very good functionality. However, the elements of the product design consideration matrix used for

concepts evaluation should focus mainly on functionality. Due consideration of the dimensions of the bed of the milling machine(s) on which fixture is to be used [6] as well as the ability to vary the length, width and thickness of the work pieces [5] has been reportedly used in determining the design parameters of FSW fixtures. Other process parameters like the axial, lateral and transverse load, torque, temperature at the thermo-mechanical heat affected zone (TMHAZ) and feed rates should also be carefully considered for mobile fixture.
Mild steel has been used majorly as the material for manufacturing the various components of FSW fixtures because it has high strength and toughness which is required to withstand unbalanced forces and pressure during FSW operation [6; 7; 9]. However, [8] used aluminum-stainless steel for the backing plate to improve heat dissipation of the TMHAZ while [6] utilized mild steel for base plate and stainless steel for the backing plate to achieve better compressive strength and high wear resistance in comparison to mild steel. [13], reportedly considered Cast Iron (C45), Die Steel (D4), Tool Steel and Hard Alloy (H20) using CAD simulate with C45 steel emerged as the best out the four materials considered.

Though, [10] selected carbon steel for manufacturing all components of its fixture, the study reported that other grades of steel can be used depending on the type of material to be joined and thickness of plates. Therefore, for cost effectiveness, it is important that the materials selected for manufacturing of the fixture must be of low cost, functional and readily available. Based on all the issues raised from literatures, this study developed a mobile-fixture system (MFS) for achieving FSW on a Vertical Milling Machine tool (VMMT) and evaluated its performance.

2. RESEARCH METHODOLOGY

A conceptual design of the MFS was developed and simulated to establish its functionality using Creo 7.0, a computer aided design (CAD) software. The detail dimensions of its components (design parameters) required for its fabrication were determined using existing formulae with consideration to relevant dimensions of bed (worktable) of the VMMT and the maximum load up to which it is to be subjected in operation. The VMMT is available in the central workshop of the School of Engineering and Engineering Technology (SEET) at the Federal University of Technology, Akure (FUTA). Worktable (Backing plate) mobility and automated are the unique features incorporated to the MFS concept. Subsequently, the designed fixture was fabricated

2.1. Design Considerations

The relevant design parameters of the VMMT were obtained from the machine while the loads were established from the literature. These include the length and breadth of the milling machine work table, the work table slot design, the range of the VMMT table feed rate and the range of the spindle speed. Based on the VMMT design parameters obtained, a functional conceptual design (exploded view) of the MFS developed for FSW on the machine and its various components is as shown in Figure 2.

The MFS conceptual design comprises of a worktable with integrated backing plate, clamps, frame, leadscrew, leadscrew nut, support shaft, bearing, stepper motor, control panel, U-channel. The worktable is held on the leadscrew which is in turn connected to the stepper motor. The stepper motor drives the leadscrew whom rotational motion is converted to the translational motion of the MFS worktable, forming a feeding mechanism for feeding the workpieces against the welding tool. The stepper motor wires are connected to an AC main through a controller designed for the system using Arduino Uno microcontroller. The controller was provided with a speed control knob programed to provide the user with the ability to vary the welding speed (mm/min) for the MFS feeding task. To prevent workpieces movement during FSW, provisions were made for securing them to the worktable using two clamps and bolts and nuts. Hence, the feeding of the workpiece on the tool utilizes the MFS feed mechanism and is independent of the VMMT. This increases the flexibility of conducting FSW operation. The MFS is designed to be held on the

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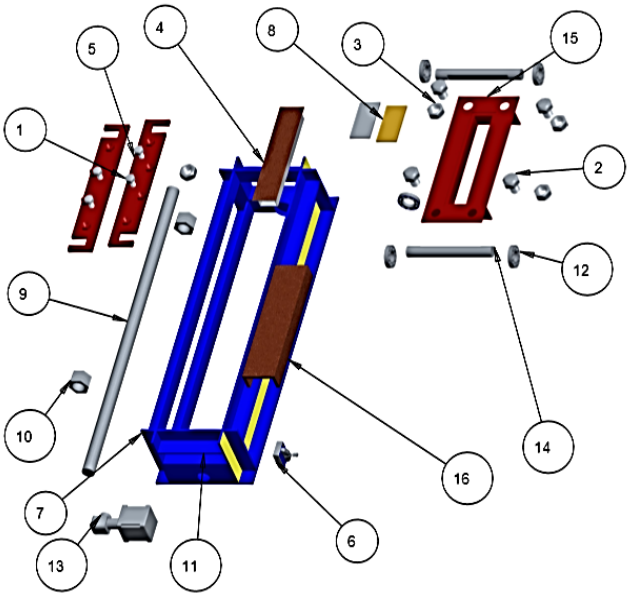
VMMT work table with the aid of 19-size bolts and nuts to ensure its stability and firmness.

The optimum parameters required for obtaining adequate weldment were established as 2-5 kN [13] 6 kN [14] 3.8 to 9.8 kN [15] 26.58 kN [16] 5.884 kN [17] 122 kN [18] 20 – 60 kN [19], 1-3 ^{o} [20] 11.5 – 24 mm/min [16] 37.5-47.5 mm/min [3] 40 to 140 mm/min [21] 50–300 mm/min [22] 14 – 750 mm/min [23] 50mm/min - 100 mm/min and [14] 2000 rpm [14] 2700 – 5400 rpm [16] 1500 to 2500 rpm [15] 45 – 2000 rpm [23] 900-1400 rpm [3] 600 to 1600 rpm [21] 1000–2500 rpm [22] for the axial force, tool tilt angle, feed rate, and the tool rotational speed respectively. This range of values were considered for the detail design of the MFS. Also, parts standardization, ergonomic, availability of materials and ease of assembly and disassembly were given significant consideration for good maintenance reliability and safety.



S/N	PART NAME	QTY
1	13BOLT	4
2	22BOLT	4
3	22NUT	4
4	BACKING_PLATE	1
5	CLAMP	2
6	CONTROL_UNIT	1
7	FRAME	1
8	FSW_WORKPIECE	2
9	POWER_SCREW	1
10	POWERSCREW_NUT	2
11	SMALLBEARINGA	2
12	SMALLBEARINGB	4
13	STEPPR_MOTR	1
14	SUPPORTING_SHAFT	2
15	TABLE	1
16	U_CHANNEL	1

Figure 2: Exploded View of the FSW Fixture

2.3 Design Analysis

The components of the MFS whose detailed design, to estimate the design parameters, were discussed in this section include the main frame, clamps, leadscrew, support shafts and their bearings and stepper motor.

2.3.1. Design of the main frame and the clamps

The mainframe of the MFS has the backing plate and worktable as an integral part. Also, rectangular slots are provided at the base for holding the fixture on the VMMT bed. After due consideration of the design parameters of the VMMT bed, the dimensions/design parameters of the main frame, backing plate, worktable, rectangular clamp and slot, in L x B x H mm, were estimated as 810 x 239 x 148 mm, 265 x 60 x 32 mm, 355 x 150 x 45 mm 355 x 60 x 8 mm and 23 x 40 x 8 mm respectively. Mild steel was selected as the material for the manufacturing of the MFS components as established in the literature because of its good tensile strength, low cost and availability locally [24; 25].

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2.3.2 Design of the supporting shaft and its bearings

The design parameters estimated for the worktable, the backing plate and the clamp, to be supported by the shaft, were utilized to estimate their weights so that the load to which the support shaft is subjected to (Ls) was determined using Equation (1):

$$L_s = W_w + W_b + W_c + F_a \quad (1)$$

Where, W_w, W_b, W_c and F_a represent the weights of the worktable, backing plate, clamp and the axial load respectively. An axial load of 6 kN was considered as the maximum load expected to act on the MFS [13;15].

From Equation (1) it was estimated that the load acting on each of the two supporting shafts is 3430 N. Consequently, according to the procedure given in [26], the diameter of the shaft was determined as 25 mm, using Equation (2).

$$d^3 = \frac{16}{\pi S_S}\sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (2)$$

Where d is the diameter of the support shaft; S_S is the allowable shear stress of the shaft material (N/m^2); K_b is the combined shock and fatigue factor applied to bending moment; K_t is the combined shock and fatigue factor applied to torsional moment; M_b is the bending moment (*N/m*) and M_t is the torsional moment (*N/m*).
Also, the procedure established in [27] for selecting rolling contact bearing was applied so that NSK 6205 single row radial ball bearings with a bore of 0.25 m and outside diameter of 0.052 m was selected for use on the support shaft.

2.3.3 Design of the leadscrew

The leadscrew carries the worktable, the backing plate, the clamps and the supporting shafts, apart from the axial load. Therefore, the load acting on it was estimated to be 6432.54 N using Equation (3).

$$F = W_w + W_b + W_c + 2W_s + F_a \quad (3)$$

Subsequently, using Equation (4) the Lead Screw diameter was determined to be 25 mm after due consideration of appropriate factor of safety and leadscrew sizes commercially available.

$$D = \sqrt{\frac{8F}{\pi\tau}} \quad (4)$$

Where, F is the total force on the leadscrew, W_s is the weight of each of the shafts, D is diameter of the leadscrew and $\tau = 42\ Mpa$ for mild steel [27].

Following the same method of bearing selection used for the support shaft, NSK 6205 single row radial ball bearings with a bore of 0.025 m and outside diameter of 0.052 m was also selected and used for holding the leadscrew.

2.3.4 Finite Element Analysis of the MFS Structural Concept

FEA (Finite Element Analysis) was applied to the generated design concept to conduct stress analysis after the application of the calculated design parameters. The finite element model of the FSW fixture is subjected to 6 kN axial force. The axial force used was selected within the range of axial force for FSW as established from the literature. The FEA was conducted using Creo 7.0 software.

2.3.5 Design and selection of stepper motor for the drive system

Power to move the worktable is derived from a stepper motor connected to the lead screw. Stepper motors are direct current (DC) motors that move in discrete steps. Stepper motor was selected as it can achieve precise positioning and speed might be controlled with the use of appropriate controller. The power requirement, P, of the stepper motor was calculated using Equation (5).

$$P = \frac{2\pi NT}{60} \tag{5}$$

Where, N is the maximum operational speed of the leadscrew in rpm, and T is the maximum torque required to drive the leadscrew.

Therefore, the power required to produce the maximum torque of 80.41 Nm, obtained using Equation 5 on the leadscrew at a speed of 2.5462 rpm (200 mm/min) was determined as P = 21.44 W. Hence, a 1 hp stepper motor with maximum speed of 3000 rpm and voltage range of 0 -16 V was selected to drive the leadscrew.

An ATmega 328P Arduino Uno microcontroller was selected and used to design a control system MFS motion. It is a high performance, low power controller from Microchip which is easy to program.

2.4 Fabrication and Assembly of the Components of the MFS

The production and joining processes employed in this study include marking out, welding operation and machining operations which include milling, turning, drilling, grinding. The mild steel materials used for the fabrication of the MFS were procured at metals market located around Cathedral area, Akure, Ondo state. Thereafter, the fabrication was done at the SEET central workshop, FUTA, Ondo State, Nigeria. Some bought out parts utilized include roller bearings, stepper motor, washers, bolts and nuts. To form the MFS mainframe, mild steel angle iron was cut into the required sizes, according to the estimated design parameters, and joined together using arc welding process. This type of joining process was chosen due to the heavy-duty nature of the job the MFS was designed for. Similarly, mild steel angle iron and u-channel was used to fabricate the clamps and the worktable respectively. The clamping bolt holes were drilled on pillar drilling machine. The two worktable support shafts were made from hardened mild steel, heat treated to soften it for easy machinability. They were turned on the lathe to Ө25 mm and re-hardened later to withstand the load it is being subjected to during friction stir welding process. A power leadscrew of diameter Ө25 mm with square thread was sourced and forced fixed into its bearing to avoid any misalignment that may ensue during operation of the FSW fixture as a result of tolerance.

2.5 Evaluation of the MFS

The accuracy of the MFS transverse speed was validated by operating the MFS using selected specific speeds on the controller and then manually timing the movement of the work relative to the welding tool using a stop clock. The actual distance travelled by the work relative to the tool for a given speed were then determined and compared with the expected distance require to be moved for the period of time they were allowed to move. Hence variation between the actual distance covered and the distance the system is expected to cover as a result of the speed used were compared to estimate the accuracy of the drive system.

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Also, the MFS was engaged on the VMMT to produce weldments of aluminum (AA 1100) plate having a tensile strength of 95.93 MPa and a Hardness of 28 BHN. The workpieces were cut to a dimension of 50 x 100 x 4 mm and welded together using the MFS on VMMT (See Figure 5) for butt type FSW operation.

Three set of experiments with three replicates were conducted using different traverse speeds (i.e. 130 mm/min, 145mm/min and 155 mm/min), a tool speed of 1400 rpm and a tilt angle of 1.8^0. Subsequently, the tensile strength and hardness of the weldments obtained were determined using a computerized Instron Testing Machine model 3369 and a Monsanto Brinell hardness testing machine respectively. An average of three measurements obtained for each weldments sample was recorded as the measured value in all cases to account for possible uncertainty in the measurement procedures. Thereafter, the results obtained were discussed to authenticate the function-ability of the developed MFS.

3. RESULTS AND DISCUSSION

3.1 Finite Element Analysis

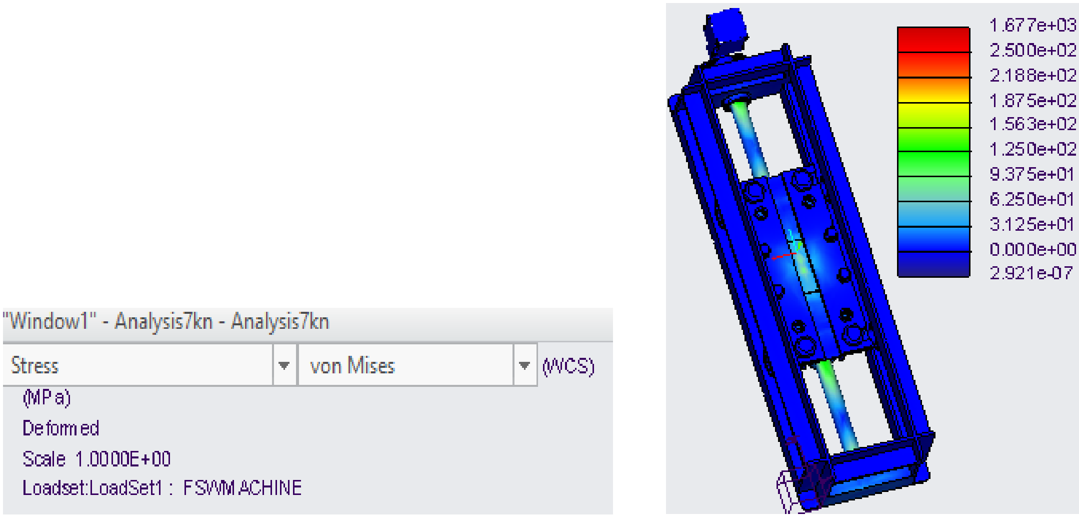
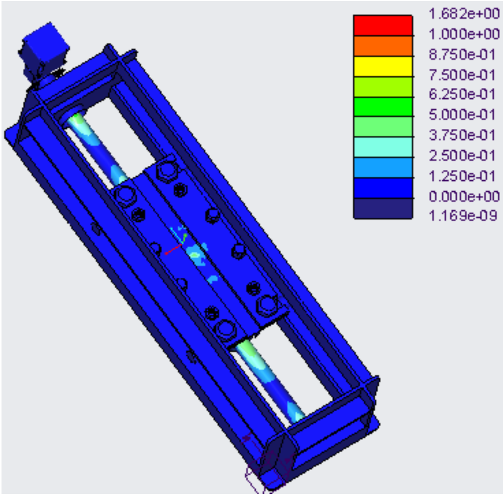


Figure 3: Finite Element Analysis of Friction stir welding fixture



Fixture 4: Failure Index of the Friction Stir Welding Fixture

From Figure 3, the FEA result obtained clearly shows that the developed fixture is saved. The maximum modeling von mises stress is 167 Mpa while yield strength of mild steel used is 250 Mpa meaning that maximum von mises stress is below yield strength of the mild steel material used. For a safety, failure index must not more be greater one. From Figure 4 though the maximum value in the legend is 1.68 but looking at the Figure 4 red colour above one did not appear on the modeling which shows that the failure index is less than one.

3.1 The Developed MFS

The developed MFS is as shown in Figure 5. The system is held on the milling machine bed through the slots provided on the frame using bolts and nuts. Provision is made on the MFS for holding the workpieces to be welded together using the worktable clamps.

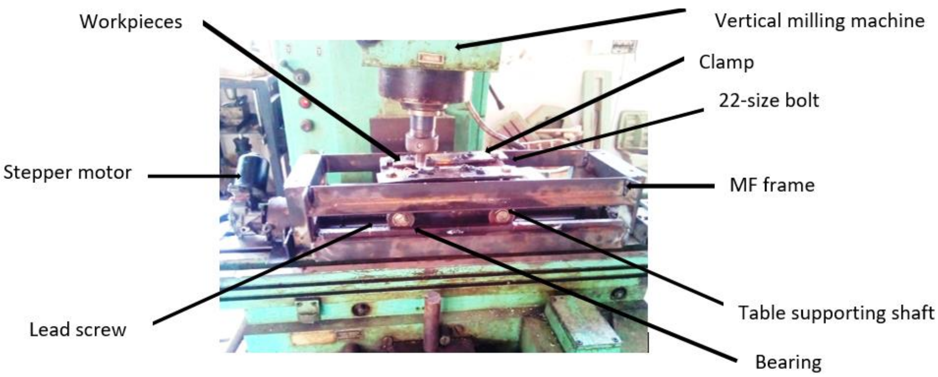


Figure 5: The developed MFS being used for FSW Operation on VMMT

Figure 5 shows the MFS coupled to the milling bed for performance evaluation. The workpieces are held on the worktable with the abutting edges centrally located on the backing plate before being clamped in

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position. The MFS allows free movement of the FSW tool held on the milling machine spindle as the worktable moves transversely during FSW operation. The system was designed to move along the X axis relative to the VMMT bed when positioned on it. This movement is powered by a stepper motor which drive a lead screw directly attached to the worktable on which the workpieces are clamped. The stepper motor is connected to an AC main through a controller designed for the system. The controller makes use of an AC- DC power module to convert the AC from the mains to the DC required to run the stepper motors. The controller was provided with a speed control knob programmed to provide the user with the ability to set the welding speed (mm/min) for the FSW operation so that the VMMT bed movement is no more necessary for the operation.

3.2 Characteristics of the Developed MFS

Table 1 shows the result obtained during the experiment to validate the adequacy of the welding speed for the worktable of the MFS. The expected distance differs from the welding distance covered. This shows that there is variation between the programmed distance per min in the microcontroller and the distance actually covered by the MFS table. However, the variation is considered to be reasonably accurate. From Table 1, the average efficiency of the motion accuracy of the drive system is estimated as 87.2%. This is considered to be good enough for a start and it can be improved further through more tuning of the control system or modelling of the MFS for speed error compensation.

Table 1: Comparison of the Actual distance covered by the MFS worktable and the expected one for a given transverse speed

S/N	Speed (mm/min)	Distance covered				Expected distance (mm)
		Expt. A (mm)	Expt. B (mm)	Expt. C (mm)	Expt. Ave (mm)	
1	135	109	111	114	111.33	135
2	145	126	128	124	126	145
3	155	141	141	144	142	155

3.3 Characteristics of the Weldment Produced using the MFS on VMMT

Figure 6 shows the Friction stir welded joints while Figure 7 shows the graph of average tensile strength of the weldments produced using the MFS as obtained from the 3 experimental runs with 3 different feed rates.

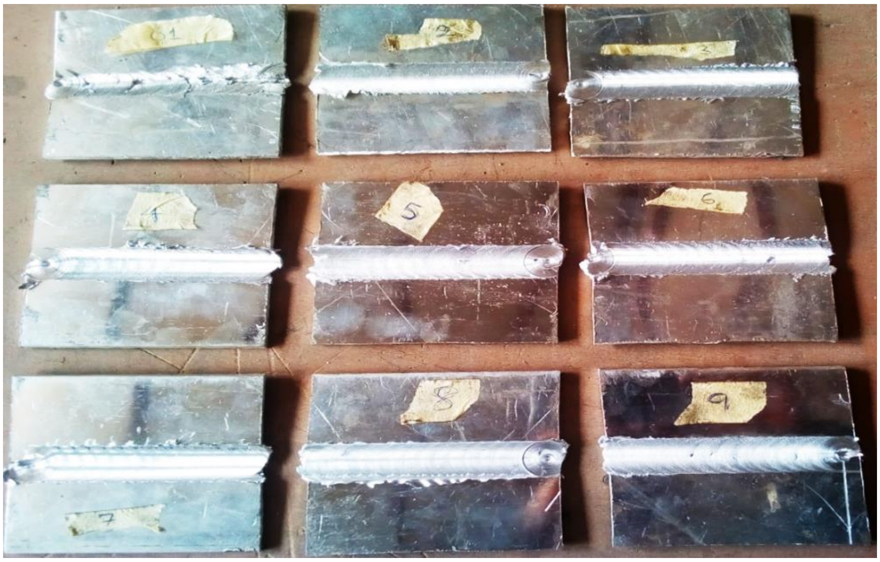

Figure 6: The friction stir welded joints produced using the developed MFS

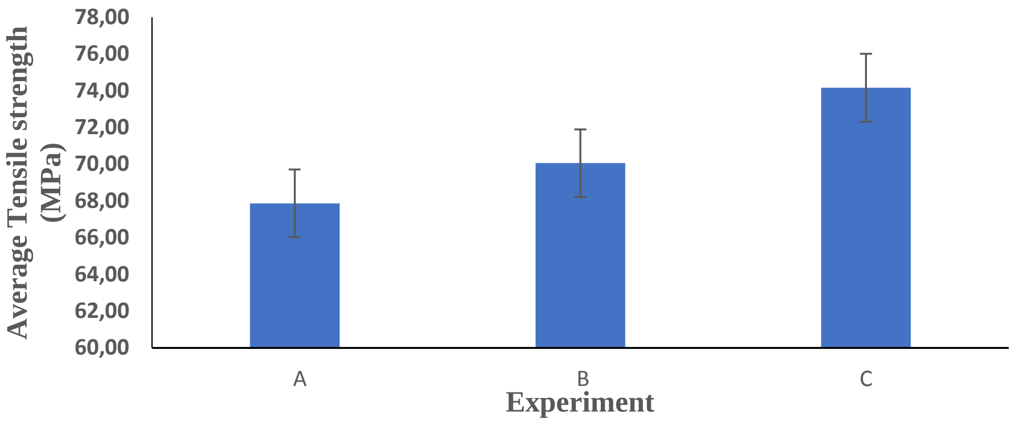

Figure 7: Graph of Tensile Strength (MPa) at the stir zone

From Figure 7, traverse feed rate is directly proportional to the tensile strength of the weldment as Experiment A with 135 mm/min traverse feed rate gave 67.87 MPa tensile strength, 70.06 MPa tensile strength is obtained for experiment B with a federate of 145 mm/min while Experiment C with 155 mm/min gave 74.17 MPa. The tensile strength of the base metal is 95.93 MPa. Hence, the optimum tensile strength of 74.17 MPa is obtained from experiment C with the highest traverse speed of 155 mm/min. This correspond to an average joint efficiency of 73.77 % of the base metal which is suitable when compared with [8; 28; 29; 30].

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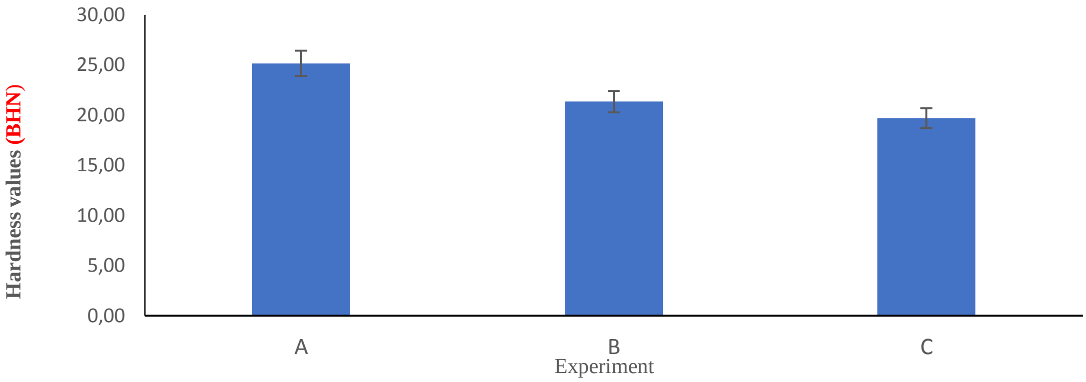

Figure 8: Graph of Hardness (BHN) at the Stir Zone (SZ)

Figure 8 shows the average hardness values of the 3 experimental runs with the three different feed rates. The hardness values of the weldment are inversely proportional to the feed rate within the range of transverse speed used. The base metal (BM) hardness value (as control experiment) was measured to be 28 BHN while the maximum hardness value obtained for the SZ is 25.15 BHN. Compare with the base metal (BM), the lower hardness values exhibited by the SZ and the hardness trend is expected [31; 32]. Based on the hardness values obtained, the average joint efficiency of the weldments produced using the developed MFS was estimated as 78.79%.

4. CONCLUSION

A MFS for FSW of Aluminum materials on a VMMT was developed. The fixture run smoothly in operation and its motion characteristic was found adequate. The mechanical properties of the weldments of AA 1100 produced using the developed MFS agreed with those of other works in literature wherein static fixture were used for FSW. The MFS would provide a more flexible approach to investigation of FSW operations on VMMTs and it is also extendible for use for FSW on pillar drill machine tools.

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