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ORIGINAL ARTICLE

Evaluation of Current, Force and Temperature Signals on Welding Formation of Bobbin Friction Stir Welded AA1100

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ABSTRACT – Understanding process response through measuring process signal provides on-site information in the area of process monitoring, which saves time and costs. The type of signals depends upon the type of process, equipment and machines used through sensors attached on the equipment used in the process. This is an important method for detecting changes in the process that reflect the condition or quality of the weld. The benefits of this method, however, has not been well performed for Bobbin friction welding. This process is different from conventional friction welding due to the different process set-up in term of tooling and parameters, hence the need to evaluate the signal response. Consequently, signal measuring for welding plate AA1100 was carried out. Tool rotation ranged from 750 rpm to 950 rpm with a fixed travel rate of 130 mm/min on a CNC milling machine and a fixed spacing tool. During the joining process, welding temperature, current consumption and welding force were measured. The resulting data were then plotted on the X-Y axis chart and mapped using the welded plate identifying the welding phase. From the welding force and current measurement, it is found that high force and current is detected at the tool entry phase and exit. As the tool moves towards the end of the plate, the temperature increased. The highest current and strength are measured when the spindle speed is at the lowest,

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INTRODUCTION

Weld qualities are one of the important aspects, especially in industries that applied welding techniques. The weld inspection like the non-destructive test (NDT) usually performed for detecting the weld defect, however, consume cost and time as it becomes not economic to apply to the large number of the weld samples that produced through a combination of parameters. To some extent, the welding process can be comprehended in a better way than it is done, if the variation that occurred during the welding process can be recorded at the same rate as weld formed. The chance of detecting the defects can be reduced by utilizing the online monitor system. This online monitor system helps to monitor the weld formation continuously by recording the signal processing during the weld formation using some sort of device. It becomes a necessity of evaluating the process signals to produce a good weld.

Compare to the conventional friction stir welding (CFSW), there was a very limited study on evaluating the process signals in bobbin friction stir welding (BFSW) process. Generally, BFSW is the non-fusion welding which forms the weld via the frictional heat produced using a bobbin tool which softens the material to form the joint. As the bobbin tool traverse forward, the softening material is swept from the advancing side (AS) to the retreating side (RS) at the front of the bobbin tool and the weld is produced at the back of the bobbin tool [1]. The bobbin tool which has an additional shoulder offer benefit such that eliminating the risk of root flaw defects due to the lack of tool penetration [2], providing simpler fixture [3] and reducing the vertical force [4-5] compared with the CFSW.

Signal processing measurement capable to trace any variation that occurred during the welding. It was reported that the BFSW save about 20 to 25% of power consumption than the CFSW and GMAW welding [6]. Longhurst et al. [7] found that the welding force of BFSW process is relatively lower than the CFSW. Esmaily et al. [8] reported that the BFSW produced high heat input than the CFSW due to the presence of the lower shoulder. Various studies in utilising process signals have been adopted by many researchers using CFSW, which explained in [9] but in the case of BFSW, only a few studies [6-8] were recorded. Therefore, this study was conducted to identify the variation that occurred during welds formation in BFSW process by recording the current, force and temperature signals.

METHODOLOGY

The base material (BM) used in this study was 6 mm thick aluminium alloys (AA) 1100. The material was cut into plates with a dimension of 140 mm by long and 140 mm in width. The plates were butt joined via CNC milling machine HAAS VOP-C 3 axis with a fixed gap bobbin tool. The bobbin tool was made from H13 tool steel consist of three main parts; upper shoulder, tool pin and lower shoulder. Both shoulders have a diameter of 25 mm. The upper shoulder was featureless while the lower shoulder having a taper of 5º. The tool pin has a diameter of 10 mm with three flat features on the smooth cylindrical tool pin.

Before welding, the dynamometer Kristler was tightened securely to the worktable of the CNC milling machine which was underneath the jig. The AA1100 plates were placed on the top of the jig. To have proper alignment of the gap between two shoulders to fit with the thickness of AA1100 plate, the dynamometer reading was recorded first. The temperature of the AA1100 during the welding was recorded via PicoLog thermocouple k-type. Seven thermocouples were embedded in the mid-thickness of the plate on the advancing side and retreating side, thus giving a total of 14 thermocouples used. The distance between the placement of the thermocouple (channel) was 10 mm. Only the distance of 35 mm was applied between channel 3 and 4 and channel 6 and 7 to differentiate the thermal position for tool entry, weld phase and tool exit.

Meanwhile, the current reading was measured using the UNI-T232 current clamp meter with a USB connection which clamped at the spindle motor of the CNC milling machine. In this study, the spindle speed varied from 750 to 950 rpm with a constant welding speed of 130 mm/min. These parameters were selected based on the trial test. Figure 1 shows the experimental setup of this study.

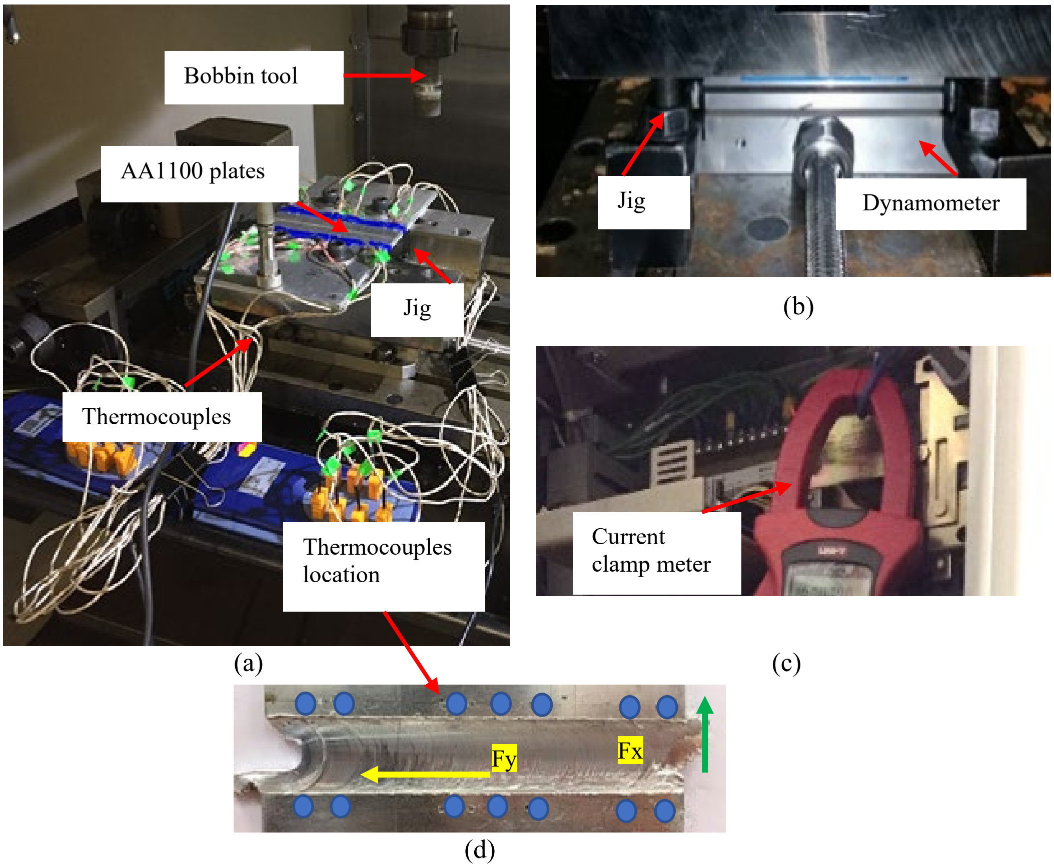


Figure 1. (a) Experimental setup with the placement of (b) dynamometer and (c) current clamp meter. (d) Welding force direction (Fx, Fy).

RESULT AND DISCUSSION

Current Measurement

Figure 2 displayed the current-time plot measured during the BFSW process. All the graph plots for each of the parameters show a similar trend which can be divided into four categories, which are the milling current, tool entry, weld phase, and tool exit. This current measurement trend is compared with one of the weld joints to show the variation in the recorded current signal with the weld produced. Referring to the current plot in Figure 2, the milling current phase is the current needed by the CNC milling machine to operate the bobbin tool to rotate and traverse toward the AA1100 plates without having any contact. All the weld samples exhibited the average value of 1.6A which equivalent to the 663 W at this milling current phase.

When the bobbin tool starts to penetrate to the AA1100 plates, the current value increased remarkably at an average value of 11.5A which equivalent to 4.78 kW. This sudden increase of current at this tool entry phase was due to the action of the bobbin tool that sheared and swept the plate material from AS and meet the new material at the RS. The bobbin tool was constrained with the harder material from the front material when traverse forward [10] causing the CNC machine to consume more current so that the bobbin can move forward. The material was deposited behind the bobbin tool resulting entry tail as displayed in Figure 2.

The peak variation of all plot curves starts to decline when the bobbin tool moving forward as it is believed that the plate material was softened by the tool frictional heat [11]. At the welding phase, two trends can be found in the current plot which is the uptrend and downtrend. The uptrend in the welding phase indicated that the bobbin tool was constrained by force from the opposing shoulders and also the joint formation behind the bobbin tool [10]. The current becomes stable in average value of 6.5A which equivalent to 2.69 kW when the bobbin moved forward. The average current showed a downturn in current reading meaning that the increase of material temperature near the bobbin tool resulting the bobbin tool to have less effort to generate more frictional heat as the material was already softened.

When the bobbin tool reached the tool exit phase, the average current was dropping drastically. This is due to a disruption that stops the softened material to circulate from AS to the RS caused by insufficient material to stir [12] and leaving blowout hole and blowout protrusion at the AS of the weld. As the bobbin tool moved out from the weld, the average current reading was 1.6A meaning that the bobbin tool entering the milling current phase again.

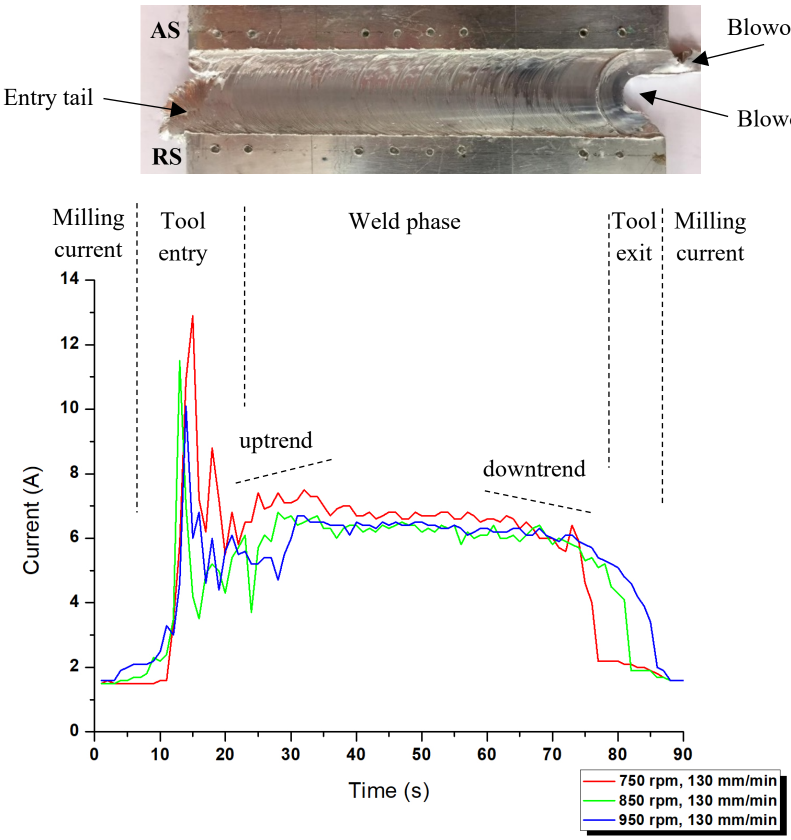


Figure 2. Current measurement plot.

Welding Force Measurement

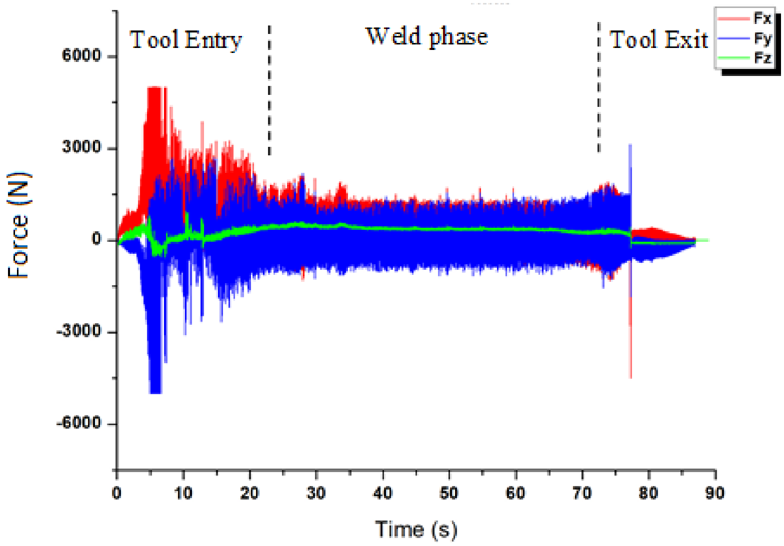
Figure 3 shown the welding force measurement for all weld samples. Three welding forces were recorded in three directions; x, y and z-direction. The force in the x-direction (Fx) is the transverse force which perpendicular to the force in y-direction, whereas the force in the y-direction (Fy) is the traverse force or welding direction. Refer to Figure 1(d) for the direction of the Fx and Fy on the plate. The force in the z-direction (Fz) refers as the vertical force or sometimes known as axial force. As highlighted in Figure 3, all force measurements depicted the similar curve variation which can be divided into three phases which are the phase of tool entry, weld phase and tool exit. Noted that the sign of negative '-' and positive '+' displays the direction of the dynamometer.

At the tool entry, the measurement of the forces depicted a fluctuation trend as the bobbin tool begins to penetrate the AA1100 plate materials. The highest peak at this tool entry phase exhibited approximately 5kN and -5kN by both forces in Fx and Fy, respectively before had a sudden decrease. This is believed that the bobbin tool had worked on softening the AA1100 plate material by generating the frictional heat while traversing and transverse along the line of the joint. On the other hand, the average force value in Fz was about 450N for all welds which is lesser compared with the Fx and Fy.

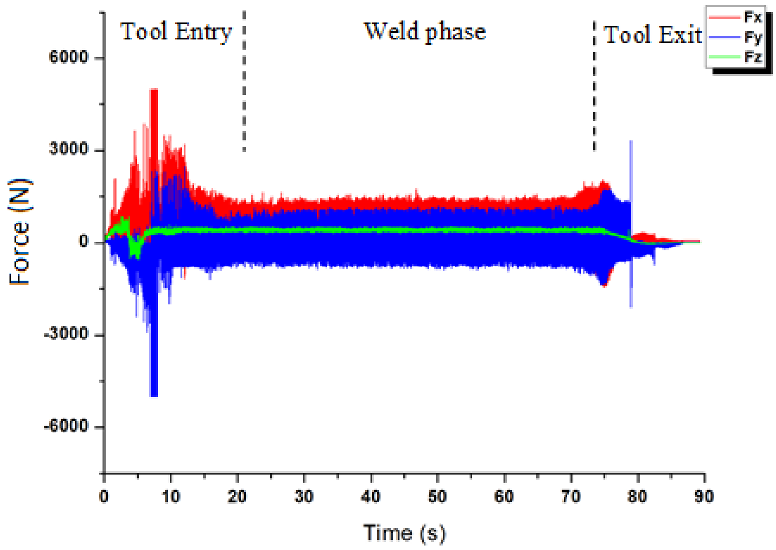
The opposing shoulders, which contact both the upper and lower surface of the plate material allow the force to keep within the distance between shoulders thus minimizing the force value in Fz [9].

The variation of force measurement settles into a steady state at weld phase after a sudden decrease from tool entry phase. The average forces in Fx for all the weld samples were 1.006 kN, 965 N and 879 N for all weld samples processed under 750 rpm, 850 rpm and 950 rpm, which corresponding to the average torque of 90.54 kNm, 86.85 kNm and 79.11 kNm. Meanwhile, for the forces in Fy, the average forces of 914 N, 803 N and 788 N exhibited by the samples joined at a spindle speed of 750 rpm, 850 rpm and 950 rpm, which equivalent to the average torque of 82.26 kNm, 72.27 kNm and 70.92 kNm, respectively. The bobbin tool works on sheared and stirred the softened material from AS to RS and then deposited the material at the back of the tool to form the weld influence the force variation measurement, likewise the current measurement. On the other hand, the force in Fz resulting 428 N, 409 N and 594 N for weld produced at a spindle speed of 750 rpm, 850 rpm and 950 rpm, which believe that there is a misalignment between the gap of shoulders tool and the plate material [8].

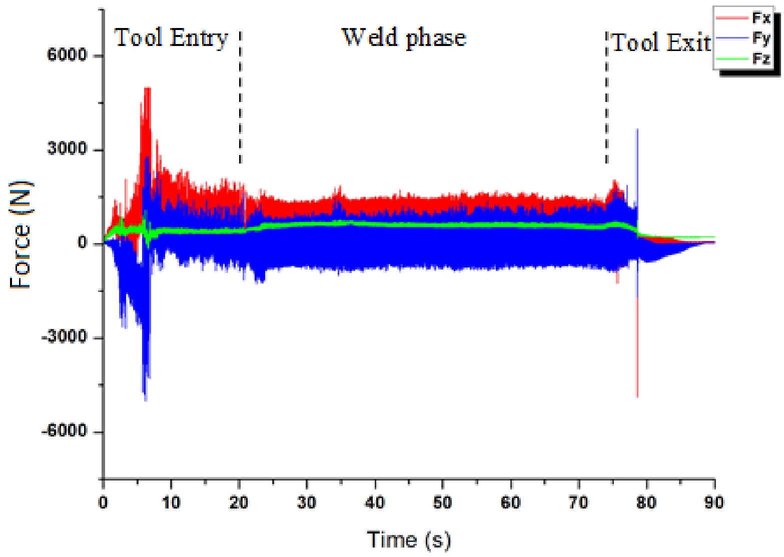
Entering the tool exit phase, the variation of the force measurement depicted a small fluctuation before had a sudden drop reaching zero value. Similar to current measurement, this has happened as there is insufficient material to stir by the bobbin tool resulting in a disruption which leaving a blow-hole.



(a)



(b)

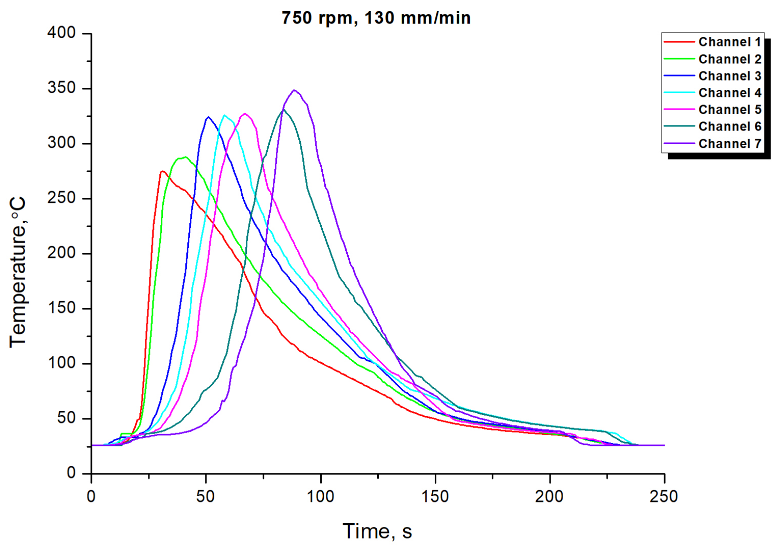


(c)

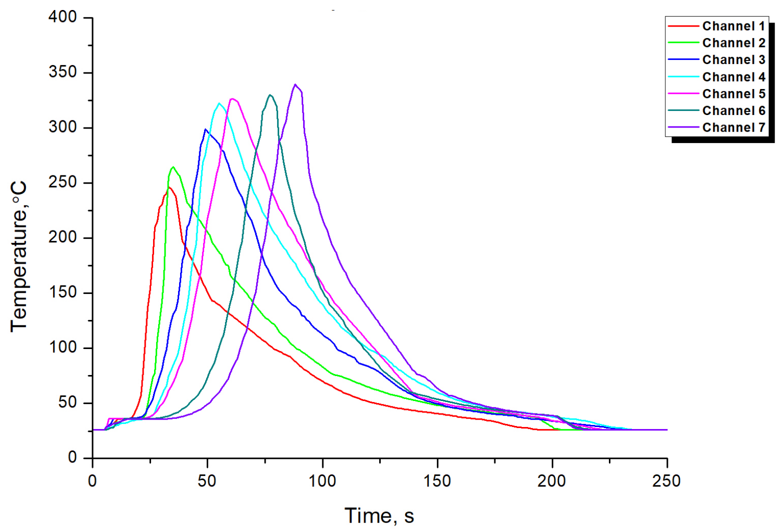
Figure 3. Force measurement of all welds processed at spindle speeds of (a) 750 rpm, (b) 850 rpm and (c) 950 rpm at a fixed welding speed of 130 mm/min.

Temperature Measurement

Figure 4 vividly reveals one of the thermal measurement curve plots recorded under spindle speed of 750 rpm and welding speed of 130 mm/min on AS and RS of the weld. The variation of the curve plot depicted simultaneously increased one after another when the bobbin tool generating frictional heat while travelling through the line of the weld joint. There are three thermal positions were measured which are the tool entry (channel 1 and 2), weld (channel 3, 4 and 5) and tool exit (channel 6 and 7). All the peak temperature at seven channels were displayed in Table 1 and 2 for both AS and RS of the weld.



(a)



(b)

Figure 4. Temperature measurement on the (a) advancing side and (b) retreating side for weld process under spindle speed of 750 rpm and welding speed of 130 mm/min.

According to Tables 1 and 2, it can be observed that the highest peak temperature was ~397 ºC exhibited by the weld produced at a spindle speed of 950 rpm and welding speed of 130 mm/min on the AS. Meanwhile, on the RS the highest peak temperature reached by ~391 ºC. From the tables, it can be seen that the temperature on the AS increased gradually with the increase of the distance of thermocouple position. Whereas the temperature values on the RS decreased slightly than the temperature on the AS although the position of the thermocouples was the same. During the welding, the bobbin tool swept and stirs the solid material from the AS and changes the solid material into the softened material and allow the material flow around the tool pin before retreating and cooled on the RS of the weld. The material in AS more solid than the material on the RS, thus, it requires high frictional resistance and plastic shear forces so that more frictional heat can be produced on AS of the weld [13].

Table 1. Peak temperature of each of the channels on the advancing side of the weld.

Weld	Peak temperature (ºC)						
	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7
750 rpm, 130 mm/min	266	287.98	324.56	326.06	327.11	329.31	348.48
850 rpm, 130 mm/min	268.51	288.90	319.79	330.91	341.46	367.61	373.91
950 rpm, 130 mm/min	288.13	313.58	328.43	356.45	369.76	381.63	397.14

Table 2. Peak temperature of each of the channels on the retreating side of the weld.

Weld	Peak temperature (ºC)						
	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7
750 rpm, 130 mm/min	246.49	264.91	298.91	322.79	326.45	330.19	339.81
850 rpm, 130 mm/min	229.72	276.78	269.38	336.48	342.11	353.19	350.95
950 rpm, 130 mm/min	261.76	279.32	358.61	352.42	340.07	364.87	391.56

To describe further on the phenomenon happened during BFSW, three thermal positions were analysed. At the tool entry, the temperature at channel 1 and 2 rises one after another when the bobbin tool starts to penetrate the AA1100 plate materials. Noted that the increase of spindle speed from 750 to 950 rpm rises the temperature as the high frictional heat was generated by the fast spindle speed. At this moment, the solid material begins to soft and build up the entry tail when the bobbin tool rotated and traverse forward. The temperature kept rising when entering the welding phase (channel 3, 4 and 5). At this point, the softened material was being transported by the bobbin tool to form a weld. The temperature kept increasing when the bobbin tool nearing to the tool exit phase (channel 6 and 7). The reason behind this phenomenon was due to the temperature distribution from the bobbin tool produced during the tool begins to touch the material and while the weld was produced [14,15].

CONCLUSION

In summary, the signal processing, including the current, welding force and thermal measurement and the phenomenon of weld formation in BFSW were discovered and presented here. From the current measurement result, the variation of current data shows that the BFSW only consume about 6.5A which equivalent to 2.69 kW to produce the weld. This current measurement was lower for BFSW compared to the studies conducted using the same material with different fusion welding [16].

The uses of a fixed gap bobbin tool influenced the reading of force measurement. The average force at weld phase recorded in Fx and Fy direction was about 950N and 835N which corresponding to the average torque of 85.5kNm and 75.2kNm, respectively for all the welds. Although the welding force measurement a bit higher at the tool entry phase, however, this issue, possibly is solved by applying slow initial parameters as mentioned by Colligan et al. [17] to avoid the deflected of bobbin tool as well as maintaining the dynamometer. This study also concluded that the highest peak temperature measurement for all welds was found on the AS. This result is consistent with findings found by Esmaily et al. [8] and Xu et al. [13].

Overall, the phenomenon of the weld formation in BFSW can be divided into tool entry, weld phase and tool exit. Both current and force measurements increased remarkably at tool entry as the bobbin start to build a weld. When the tool enters the welding phase, both measurements depicted stable data. A sudden decrease in both measurements found at the tool exit. Meanwhile, the temperature measurement depicted a plot curve that simultaneously increased one after another when the bobbin tool generating frictional heat while travelling through the line of the weld joint. Aligning the current, force and temperature signals with the joint strength which is in other authors investigation, maximum weld strength is found recoded at 102.860 MPa using spindle speed of 950 rpm and welding speed of 130 mm/min. This relate to higher temperature and low force at traverse direction. Further investigation on the signals of a bobbin tool is required to justify the interaction of the process signals to the weld formation.

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