International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

Optimization of Bobbin Friction Stir Welded 1100 Aluminum Alloys using Response Surface Methodology

Siti Noor Najihah Mohd Nasir, Mohammad Kamil Sued, Muhammad Zaimi Zainal Abidin

Abstract*: This paper presents the modelling of the mechanical properties of the bobbin friction stir welded of 6 mm thick AA1100 with control factors of spindle and welding speeds. Face-centered composite design (FCCD) was used to design the experimental work and the results of the responses and the combination of factors were analyzing through analysis of variance (ANOVA). From ANOVA, the result indicates that both spindle and welding speed influence significantly the tensile strength and average hardness at SZ of AA1100. The optimum factors for maximum tensile strength and average hardness of the AA1100 were 950 rpm and welding speed of 130 mm/min. Both models giving a relative small percentage error of 0.8 % and 1.64 % for tensile strength model and average hardness in stir zone (SZ) region, respectively, thus indicate the models were adequate.

***Keywords* : Bobbin friction stir welding, parameter, Response Surface Methodology (RSM), optimization**

I. INTRODUCTION

The demand in joining metals using friction stir welding (FSW) process is increasing predominantly in joining aluminum alloy. The FSW is preferable over the fusion welding because of the absence of the electrode, filler alloy, and shielding gas hence, it is a sustainable process. FSW is accompanied neither radiation and arc formation nor toxic gas emission and therefore considered it as a green process [1]. The FSW only used the single sided shoulder rotating tool and the weld form on one side of the material [2]. The material is softened by heat generation of the tool action that rotated and transverse and later resulting the severe material deformation [3]. The plasticized material is flowed from the tool's front to the edge of the trailing and form the weld joint [4]. Although only one side of the material can be joined via FSW however this process has unbalance heat input, required high vertical force and has the risk of root flaws which caused by the lack of tool penetration [5], [6]. Alternative potential way to improve the limitation encountered in FSW is by introducing the double sided tool shoulder where it is known as bobbin friction stir welding (BFSW).

BFSW is a method that used a rotating tool comprised of two opposing shoulders which connected by tool pin that entirely penetrated into the material to form a weld joint. Both shoulders of the bobbin tool are in contact with material providing a balance heat input from both sides of the material and essentially eliminate the risk of the root flaw. Also the vertical force found to be minimal or zero [7, 8] using BFSW as the force is kept within the tool by the each of the shoulders. Additionally, the presence of other tool shoulder which hold the bottom side of the material made the fixture become simpler than the FSW as no backing plate is required [9]. Although many limitations of FSW can be overcome using BFSW however this method is unfamiliarity presented due to limitation in literature and publication compared to the FSW.

It was reported that the mechanical testing of the weld processed using FSW was higher than the BFSW [10] but in other studies [11] found that the mechanical testing of BFSW weld is slightly higher than the FSW. Although there is a contradict results from both but these findings [10], [11] only applied a certain parameter value and no parameter optimization has clarified. To date, there are several investigations on optimizing the BFSW process. Amin et al [12] optimized the BFSW of AA6061-T6 using the response surface methodology (RSM) found that the increase of either spindle and welding speed increasing the mechanical properties of weld at first and then drop. On the other hand, Trueba et al [13] optimizing the AA6061-T6 using factorial design reported that the increase of spindle speed resulting lower tensile strength of the weld and the increasing of the welding speed will decrease the ductility of the weld. Also the compression force (force generated by the both shoulders on the material to be welded) causing lower tensile strength and ductility of the weld. Findings from Zhao et al [14] indicate that the most significant factor was the welding speed while the spindle speed and compression gap were slightly influence the tensile properties of the AA2219-T87 weld.

To date the studies for optimizing the BFSW process is limited and it is believed this is one of the reason that slows down the application of the BFSW in the industry. Therefore, the aim of this study is to investigate the optimum parameters of bobbin friction stir welded AA1100 and to provide a mathematical model of the process for practitioner use.

Revised Manuscript Received on July 09, 2019.

Siti Noor Najihah Mohd Nasir, Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

Mohammad Kamil Sued, Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka,

Muhammad Zaimi Zainal Abidin, Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka,

II. METHODOLOGY

A. Welding Work

The base material used in this study was 6 mm thick AA1100 plate with dimension of 140 mm long by 140 mm width. The plates were clamped on the jig before butt joined along the longitudinal direction using HAAS VOP-C CNC milling machine. The bobbin tool was made from H13 tool steel with two shoulders of 25 mm in diameter and tool pin of 10 mm diameter. The upper shoulder has flat feature and the lower shoulder has 5° of taper feature. The cylindrical tool pin has three flat feature on it. Fig. 1 shows the welding setup and the bobbin tool geometry. During the welding, the spindle speed was set at range from 750 to 950 rpm and the welding speed was set at range from 130 to 170 mm/min.

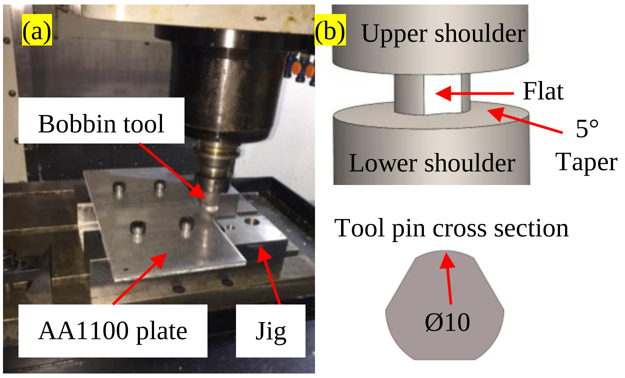

Fig. 1: (a) Welding Setup And (B) Bobbin Tool Geometry

After the completion of the welding, the weld samples were cross sectioned perpendicular to the welding direction for Vickers hardness testing. The microhardness profiles were measured along the centreline of the polished cross sectioned using a Vickers hardness tester (Mitutoyo) with spacing indentation of 1 mm. The microhardness testing was performed with a load of 0.2 kg and dwell time of 10 s. The transverse tensile testing samples were prepared following the ASTM E8/ E8M-13a before undergo the testing using universal testing machine (Mitutoyo) followed the ASTM E8-04.

B. Design of Experiment (DOE)

This study employed the face-centered composite design (FCCD) of two factors with two levels (high, +1 and low, -1) where the factors were spindle and welding speed. Table 1 displays the input factors and its level used in this experimental design. The experimental design was replicated with 4 center points (coded level 0) and thus give a total of 12 welding runs. These center points are needed for estimating the variability of the data. The responses in this study were the average of tensile strength and the average centerlines hardness at the stir zone (SZ) weld region.

Table 1: Input factors and its level

Factors	Levels	
	Low	High
Spindle speed (rpm)	750	950
Welding speed (mm/min)	130	170

III. RESULT AND DISCUSSION

A. Mechanical Testing

All the welds produced were defect free and the result of tensile strength and average hardness at stir zone (SZ) for every weld conditions are provided in Table 2.

Table 2: FCCD result for every welding trials

Run	Factors		Responses	
	Spindle speed (rpm)	Welding speed (mm/min)	Tensile strength (MPa)	Average hardness at SZ (Hv)
1	950	170	99.608	35.16
2	950	130	102.860	35.90
3	950	150	100.023	36.06
4	750	130	92.139	31.74
5	750	150	93.135	32.66
6	750	170	98.987	33.99
7	850	170	98.149	35.14
8	850	150	95.481	34.15
9	850	150	95.486	34.29
10	850	130	96.898	33.76
11	850	150	96.399	34.05
12	850	150	94.573	34.61

B. ANOVA Analysis on Transverse Tensile Strength

The result of the quadratic model for tensile strength in the form of analysis of variance (ANOVA) is highlighted in Table 3. Table 3 reveals that the model F value of 53.72 is significant. In the same manner, the Prob >F for factors A (spindle speed), B (welding speed), A2 (spindle speed), B2 (welding speed) and AB (spindle speed and welding speed) are less than 5% indicate the factors have significant impact on the tensile strength of the AA1100 welds [15]. On the other hand, the Prob > F of the lack of fit value is 0.7790 which larger than 0.05 is insignificant. This insignificant of the lack of fit is desirable as the model is fitted sufficiently to the data [16].

Additionally, the predicted R-squared value is 0.9141 predicts that the response value reliable with the adjusted R-squared value of 0.9599 with the 0.05 differences. The adequate precision represents the signal to ratio is well above 4 indicate adequate model distinction and for this case the adequate precision of 25.449 is adequate signal. Consequently, the response equation of this quadratic model in term of actual factor for the tensile properties of BFSW presented as in (1).

$$\begin{aligned} \textit{Tensile strength} = &+82.33476 + 0.052367\mathrm{A} - 0.33348\mathrm{B} \\ &-1.26243E-003AB + 9.84587E-005A^2 \\ &+4.82309E-003B^2 \end{aligned} \qquad (1)$$

Where A is the spindle speed (rpm) and B is the welding speed (mm/min).

Table 3: ANOVA on tensile testing of AA1100 weld

Source	Sum of Square	Degree of Freedom	Mean Square	F Value	Prob>F
Model	102.67	5	20.53	53.72	< 0.0001 *significant*
Spindle speed, A	55.39	1	55.39	144.89	< 0.0001
Welding speed, B	3.91	1	3.91	10.24	0.0186
A^2	2.59	1	2.59	6.76	0.0406
B^2	9.93	1	9.93	25.96	0.0022
AB	25.50	1	25.50	66.70	0.0002
Residual	2.29	6	0.38		
Lack of Fit	0.63	3	0.21	0.38	0.7790 *not significant*
Pure Error	1.67	3	0.56		
Cor Total	104.97	11			
Std Deviation	0.62		R-Squared	0.9781	
Mean	96.98		Adj R-Squared	0.9599	
C.V.	0.64		Pred R-Squared	0.9141	
PRESS	9.02		Adeq Precision	25.449	

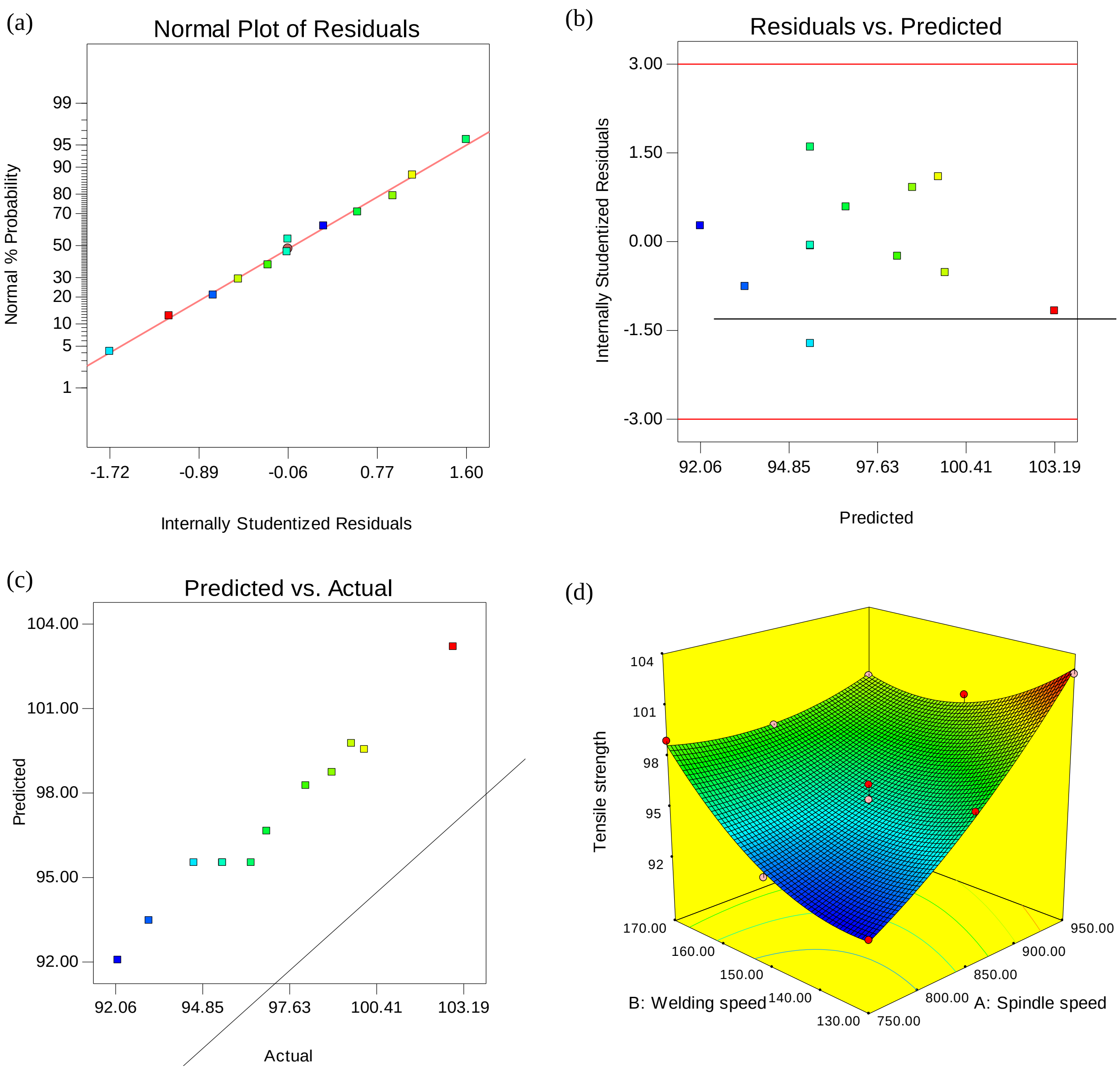

Fig. 2: Diagnostic Plot Based On (A) Normal Plot Of Residuals, (B) Residuals Vs. Predicted, (C) Predicted Vs. Actual And (D) 3D Surface Plot Of Spindle Speed With Welding Speed For Tensile Strength

Table 4: ANOVA On Average Microhardness At Stir Zone Region Of AA1100 Weld

Source	Sum of Square	Degree of Freedom	Mean Square	F Value	Prob>F
Model	16.33	3	5.44	74.43	< 0.0001 *significant*
Spindle speed, A	12.70	1	12.70	173.69	< 0.0001
Welding speed, B	1.39	1	1.39	19.04	0.0024
AB	2.24	1	2.24	30.56	0.0006
Residual	0.59	8	0.073		
Lack of Fit	0.41	5	0.081	1.36	0.4246 *not significant*
Pure Error	0.18	3	0.060		
Cor Total	16.91	11			
Std Deviation	0.27		R-Squared	0.9654	
Mean	34.29		Adj R-Squared	0.9524	
C.V.	0.79		Pred R-Squared	0.8852	
PRESS	1.94		Adeq Precision	28.214	

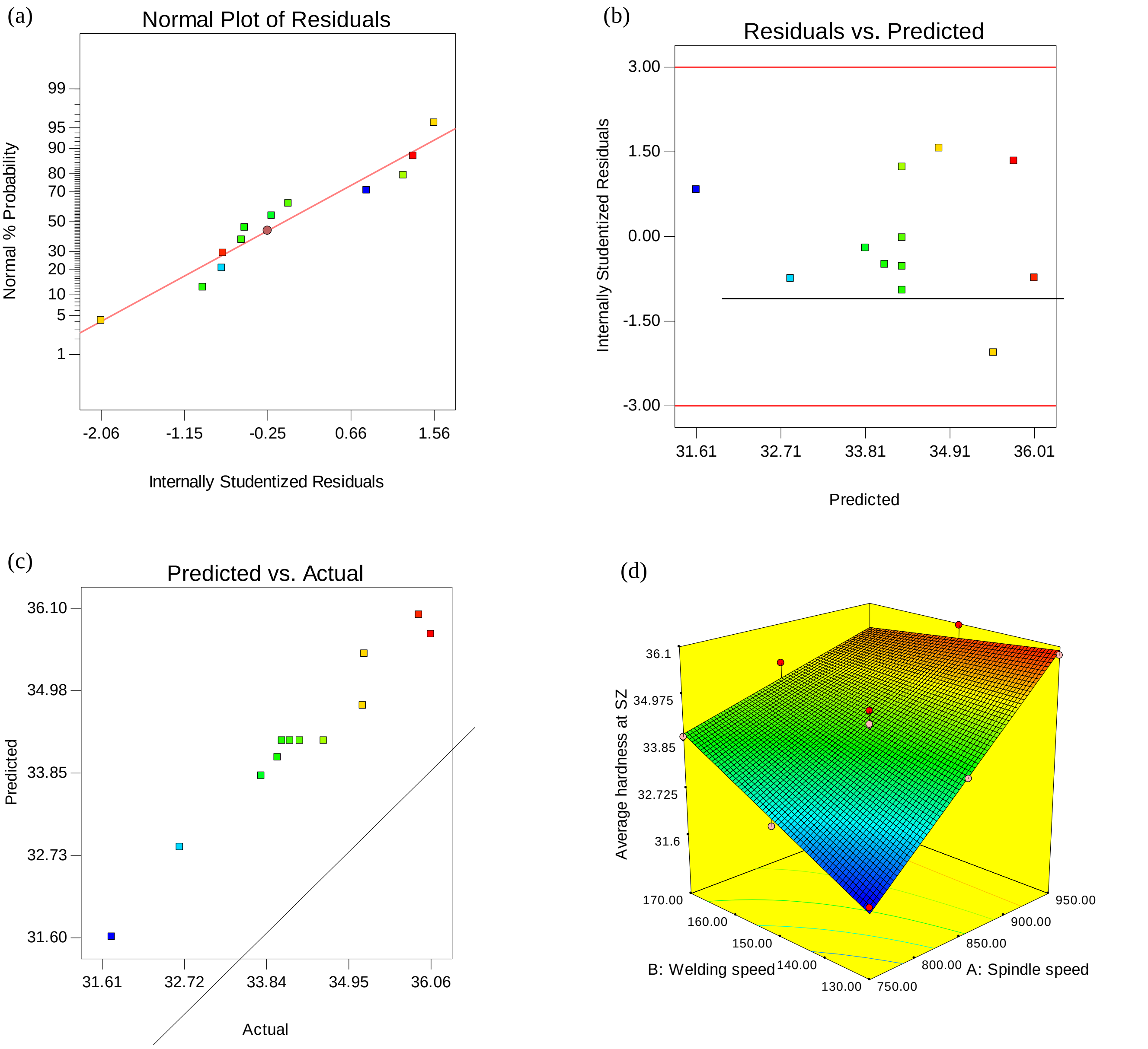

Fig. 3: Diagnostic Plot Based On (A) Normal Plot Of Residuals, (B) Residuals Vs. Predicted, (C) Predicted Vs. Actual And (D) 3D Surface Plot Of Spindle Speed With Welding Speed For Average Hardness At SZ Weld Region

Fig. 2(a) and 2(b) depicted the normal plot of residuals and residuals versus predicted, respectively. The normal plot of residuals in Fig. 2(a) describe that the residuals data normally distributed on the straight line revealing the satisfied of normality condition. Fig. 2(b) displayed the residuals versus predicted plot shows that the all the residuals data appeared in both positive and negative sides randomly meaning that there is no unusual configuration or any evidence pointing to possible outliers [17]. As for the predicted versus actual plot depicted in Fig. 2(c), it shows that the predicted data of the tensile strength are distributed near to the actual straight line which implies the predicted are in good agreement with the experimental outcomes.

Fig. 2(d) shows the 3 dimensional (3D) plot of tensile strength of the weld sample with spindle and welding speed. From the Fig. 2(d) it describes that the increase of spindle speed leading the increase of tensile strength. High spindle speed promotes high heat input from spindle speed increase the grain size of the weld sample and thus increase the strength of the weld. Meanwhile the increase of welding speed increases the tensile strength at first with the value of 102.860 MPa at welding speed of 130 mm/min and then slightly drop at 99.608 MPa using the same spindle speed of 950 rpm. Higher welding speed giving a low heat input thus resulting smaller grain size [18]. To some extent, this attribute to the strong strain hardening which resulting the stress concentration close to the grain boundaries while performing the tensile testing [19]. This stress concentration is hard to release by the movement of the dislocation and later causing initial fracture and the joint strength decreased [20].

C. ANOVA Analysis on Average Hardness at SZ

The same procedure is repeated to deal with the other response, the average hardness at the SZ weld region, resulting the 2F1 model in ANOVA as highlighted in Table 4. The model implies the F value of 74.43 consider the model is significant. The significant model term that significantly impact on the average hardness at SZ weld region are factors A (spindle speed), B (welding speed) and the AB (spindle speed and welding speed) as the Prob>F values are less than 0.05. The lack of fit value is not significant as the Prob>F is more than the 0.05 indicate that the model is fitted and it is desirable [16]. The prediction R-squared of 0.8852 is reliable conformance with the adjusted R-squared of 0.9524 as the difference is within 0.067. The adequate precision of 28.214 is more than 4 indicates that the signal to ratio is tolerable. Through the ANOVA analysis, the final 2F1 models of response equation in terms of actual factor is presented as follows;

$$\text{Average hardness at SZ} = -29.16735 + 0.070426A + 0.34070B - 3.72608E-004AB \quad (2)$$

Where A is the spindle speed (rpm) and B is the welding speed (mm/min).

The diagnostic plot for the average hardness at SZ weld region can be seen in Fig. 3. Similar to the tensile strength model, the normal plot of residuals depicted in Fig. 3(a) reveals that the residuals data distributed following the straight line. Also, the residuals versus predicted plot in Fig. 3(b) shows that the residual data scattered randomly in both positive and negative side indicate that the plot is adequate. Fig. 3(c) displays the predicted versus actual plot shows that predicted data scattered nearly to the actual. These three figures represent that the model is adequate.

Fig. 3(d) depicted the 3D surface plot of average hardness with the spindle and welding speeds. It shows that as the welding speed increase the average hardness increased from 31.74 to 36.1 Hv using the spindle speed from 750 rpm to 950 rpm. The high heat input generated from the spindle speed causing the grain size around the SZ region finer and thus resulting increase in hardness. Besides, the further precipitation during and after cooling significantly influence the hardness in SZ. Wang et al, [21] claimed that the hardness in SZ more increased with the influence of high spindle speed, high remaining of supersaturation, the increase of temperature and exposure time and greater post weld natural aging response. Based on Fig. 3(d), the increase of welding speed increasing the average hardness at first and then slightly drop when the welding speed reached at 150 mm/min at spindle speed of 950 rpm. This influence of the welding speed in consistent with [22]. High heat input generate from low welding speed increasing the grain growth that influence the properties of the weld [12].

D. Confirmation Test

A confirmation test was performed by means of transverse tensile testing and microhardness testing in order to validate the recommended parameters suggested by the FCCD. The maximum tensile strength was 103.19 MPa with the spindle speed of 950 rpm and welding speed of 130 mm/min. Validation from the experiments found that the tensile strength from the experiment was 102.36 MPa is slightly lower that the optimized maximum tensile strength with a maximum error of 0.8 %. On the other hand, the prediction of maximum average of hardness at the SZ region was 36.01 Hv with spindle speed of 950 rpm and welding speed of 130 mm/min. Result from validation indicate that the result of the average hardness at stir zone area was 35.42 Hv and thus giving a maximum error of 1.64 %.

IV. CONCLUSION

The bobbin friction stir welded 6 mm thick AA1100 has been done successfully which widen the application of BFSW on AA1100. Optimization via RSM used for analyzing the influence of both spindle and welding speeds on the mechanical properties of the AA1100 weld. The following conclusions are drawn from the both experimental and optimization;

1. Both spindle and welding speeds had influence the tensile properties of the weld and the average hardness at stir zone weld region.
2. The model of predicts the maximum tensile strength of 103.19 MPa using the spindle speed of 950 rpm and welding speed of 130 mm/min. The differences between the predicted and the experimental tensile strength is within 0.8% error.

3. The prediction of maximum average microhardness is 36.01 Hv by applying the spindle speed of 950 rpm and welding speed of 130 mm/min. The maximum percentage error between prediction and experimental work is 1.64 % which is relatively small.
4. The study on optimizing the AA1100 does not available in literature review yet thus it cannot be benchmarked. However, this study ascertains the possibility of the tensile strength reaching up to ~102MPa which is less 4.67% of base material.

ACKNOWLEDGMENT

Author would like to be obliged to the Ministry of High Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for financial support under Short Term Research Grant (Grant no. PJP/2017/FKP/H18/S01525).

REFERENCES

1. H. I. Dawood, K. S. Mohammed, and M. Y. Rajab, "Advantages of the Green Solid State FSW over the Conventional GMAW Process". Advances in Materials Science and Engineering, vol.2014, pp 1-10, 2014.
2. M. K. Sued and D. J. Pons, "Dynamic Interaction between Machine, Tool, and Substrate in Bobbin Friction Stir Welding". International Journal of Manufacturing Engineering, vol.2016, pp.1-14, 2016.
3. P. Kah, R. Rajan, J. Martikainen, and R. Suoranta, "Investigation of the weld defects in friction stir welding and fusion welding of aluminium alloys". International Journal of Mechanical and Materials Engineering, vol.10, no.26, pp.1-10, 2015.
4. M. Grujicic, G. Arakere, H. V. Yalavarthy, T. He, C. F. Yen, and B. A. Cheeseman, Modeling of AA5083 Material-Microstructure Evolution During Butt Friction-Stir Welding. Journal of Materials Engineering and Performance, vol.19, no.5, pp. 672-684, 2010.
5. P. P. Chikamhi, D. G. Hattingh, and B. Dreyer, "Development of a welding platform and tool for the study of weld and process parameters, during continuous friction stir welding of AA6082-T6 sheets". IOP Conference Series: Materials Science and Engineering, vol.430, pp.1-7, 2018.
6. R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing". Materials Science and Engineering: R: Reports, vol.50, no.1-2, pp.1-78, 2005
7. J. Martin and S. Wei, Friction stir welding technology for marine applications in Friction Stir Welding and Processing VIII, ed, 2015, pp. 219-226.
8. P. L. Threadgill, M. M. Z. Ahmed, J. P. Martin, J. G. Perrett, and B. P. Wynne, "The Use of Bobbin Tools for Friction Stir Welding of Aluminium Alloys". Materials Science Forum, vol. 638-642, pp.1179-1184, 2010.
9. M. K. Sued, D. Pons, J. Lavroff, and E. H. Wong, "Design features for bobbin friction stir welding tools: Development of a conceptual model linking the underlying physics to the production process". Materials & Design, vol.54, pp.632-643, 2014.
10. W. Xu, Y. Luo, W. Zhang, and M. W. Fu, "Comparative study on local and global mechanical properties of bobbin tool and conventional friction stir welded 7085-T7452 aluminum thick plate". Journal of Materials Science & Technology, vol.34, pp.173–184, 2018.
11. M. Esmaily, N. Mortazavi, W. Osikowicz, H. Hindsefelt, J. E. Svensson, M. Halvarsson, et al., "Bobbin and conventional friction stir welding of thick extruded AA6005-T6 profiles". Materials & Design, vol.108, pp.114-125, 2016.
12. S. A. Amin, M. Y. Hanna, and A. F. Mohamed, "Modeling and Optimization of Bobbin Friction for AA6061-T6 alloy Utilizing Response Surface Methodology". Journal of University of Babylon, Engineering Sciences, vol. 26, no.4, pp.1-17, 2018.
13. L. Trueba, M. A. Torres, L. B. Johannes, and D. Rybicki, "Process optimization in the self-reacting friction stir welding of aluminum 6061-T6". International Journal of Material Forming, 2017.
14. S. Zhao, Q. Bi, Y. Wang, and J. Shi, "Empirical modeling for the effects of welding factors on tensile properties of bobbin tool friction stir-welded 2219-T87 aluminum alloy". The International Journal of Advanced Manufacturing Technology, vol.90, no.1-4, pp.1105-1118, 2016.
15. D. C. Montgomery, Introduction to Statistical Quality 6th Edition: John Wiley & Sons (Asia) Pte. Ltd.; 2009.
16. A. Khademi, N. G. Renani, M. Mofarrahi, A. R. Jeddi, and N. M. Yusof, "The Best Location for Speed Bump Installation Using Experimental Design Methodology". Promet – Traffic & Transportation, vol.25, no.6, pp.565-574, 2013.
17. S. Iranmanesh, M. Mehrali, E. Sadeghinezhad, B. C. Ang, H. C. Ong, and A. Esmaeilzadeh, "Evaluation of viscosity and thermal conductivity of graphene nanoplatelets nanofluids through a combined experimental–statistical approach using respond surface methodology method". International Communications in Heat and Mass Transfer, vol.79, pp.74-80, 2016.
18. W. Y. Li, T. Fu, L. Hütsch, J. Hilgert , F. F. Wang, J. F. d. Santos, et al., "Effects of tool rotational and welding speed on microstructure and mechanical properties of bobbin-tool friction stir welding Mg AZ31". Materials and Design, vol.64, pp.714-720, 2014.
19. S. R. Ren, Z. Y. Ma, and L. Q. Chen, "Effect of initial butt surface on tensile properties and fracture behavior of friction stir welded Al–Zn–Mg–Cu alloy". Materials Science and Engineering: A, vol.479 no.1-2, pp.293-299, 2008.
20. L. Zhou, G. H. Li, C. L. Liu, J. Wang, Y. X. Huang, J. C. Feng, et al., "Effect of rotation speed on microstructure and mechanical properties of self-reacting friction stir welded Al-Mg-Si alloy". The International Journal of Advanced Manufacturing Technology, vol.89, no.9-12, pp.3509-3516, 2016
21. F. F. Wang, W. Y. Li , J. Shen , S. Y. Hu, and J.F. dos Santos, "Effect of tool rotational speed on the microstructure and mechanical properties of bobbin tool friction stir welding of Al-Li alloy". Materials and Design, vol.86: pp. 933-940, 2015.
22. H. J. Liu, J. C. Hou, and H. Guo, "Effect of welding speed on microstructure and mechanical properties of self-reacting friction stir welded 6061-T6 aluminum alloy". Materials & Design, vol.50, pp. 872-878, 2013

AUTHORS PROFILE

Siti Noor Najihah Mohd Nasir is a postgraduate student at Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka (UTeM). She obtained her B. Eng and Dip. Eng both majoring in Manufacturing Engineering from Universiti Malaysia Perlis (UniMAP). Her research interest includes the solid state welding, manufacturing process and DOE optimization.

Mohammad Kamil Sued is a Deputy Director of Planning and Academic Development and senior lecture at Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka (UTeM). Obtaining his PhD from University of Canterbury, New Zealand and MSc from University of Manchester, United Kingdom. He best known in the area of friction stir welding, laser scanner, manufacturing process, manufacturing system and dimensional measurement.

Muhammad Zaimi Zainal Abidin is a senior lecturer as well as a Head Department of Diploma Study at the Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka (UTeM). He obtained both his PhD and M. Eng from Shibaura Institute of Technology, Japan. His research interest is in the area of material science engineering.