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Investigation of Vibration Assisted Friction Stir Welding and Comparison with Conventional Friction Stir Welding

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Abstract

Friction Stir Welding (FSW) applications in high strength alloys, such as stainless steel remain limited due to large axial welding force and consequent tool wear. It has been shown that applying the ultrasonic vibration on some processes such as turning and drilling the resultant forces are decreased and process condition is improved. In this paper the influence of applying vibration on FSW was investigated using Simulink and Matlab programming tools. The resultant axial force of conventional FSW and Vibration Assisted FSW (VAFSW) were compared in frequency and time domain state spaces. A good correlation between FSW simulation and experiments was observed. For further investigation of VAFSW the response surface of design of experiment (DOE) method was used. The simulation results indicated that the vibration helps to decrease the axial welding force. Using DOE method the influence of implemented frequency and vibration speed amplitude in FSW was found. Force reduction of 6 to 17% by applying the vibration during the friction stir welding was observed.

Keywords: *Vibration assisted; Friction stir welding; Force analysis; Design of experiments*

1. Introduction

Friction Stir Welding (FSW) is a relatively new solid state joining method that can be used to achieve very good weld quality due to its unique capabilities [10]. The FSW process eliminates some of the weld-ability problems usually associated with fusion welding processes, due to its low heat input [3]. This process utilizes a rotating tool in which includes a pin and shoulder to perform the welding process as shown in Fig. 1 [11]. The main parameters of FSW are plunge depth, tool geometry, tool rotation speed, tool traverse speed and tool tilt angle. The combinations of foregoing parameters demonstrate the mechanical properties of the joint.

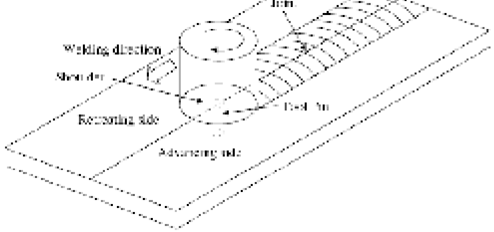

Fig. 1 Friction Stir Welding schematic [11]

It is reported that the strength of the FSW weld is 30% to 50% greater than those produced by arc welding and resistance spot welding while maintaining the fatigue life comparable to riveted panels [6].

Friction stir welding (FSW) has been used for joining low melting temperature materials successfully. However, applications in high strength alloys, such as titanium and stainless steel, remain limited due to large axial welding force and consequent tool wear. Compared with joining of low temperature materials, FSW of steel requires large plunging and stirring forces, which dictate the use of large FSW equipment. Forces generated during FSW process are known to be one of important factors in causing the tool breakage [1]. One of the most critical issues in FSW is the life of FSW tool specifically in steel work-pieces.

Moreover, too much indentation and reduction in the cross sectional thickness of the weld joint can be resulted when increasing the axial force [5].

Since the 1950s, the application of ultrasonic vibration to the plastic deformation of metals has been widely investigated. It was observed that using ultrasonic oscillations in the tooling reduce static deformation forces, increase processing speeds, and improve the quality of the product [8]. These effects have been demonstrated in various manufacturing processes such as machining, drilling, welding, etc [9, 10]. Ultrasonic machining and drilling processes have been successfully implemented in machining tough-to-cut alloys such as titanium [11]. For instance Chandra reported an increase in CBN tool life, about 7 to 8 times more than conventional machining conditions, using vibration assisted machining of Inconel 718 [7].

Engineers at the Marshall Space Flight Center (MSFC) are working on a solid state welding device that uses ultrasonically heated stir welding. This process reduces the loads needed by conventional friction stir welding and is the foundation of future handheld solid state welding for NASA[13].

In this paper the influence of applying vibration on FSW is investigated using Simulink and Matlab programming tools. For FSW modeling a proper transfer function of axial force has been proposed. The resultant axial force of conventional FSW and Vibration Assisted FSW (VAFSW) are compared in frequency and time domain state spaces. A good correlation between FSW simulation and experiments is observed. For further investigation of VAFSW the design of experiment (DOE) method is used. The influence of changing VAFSW process parameters is founded. The simulation results indicate that vibration helps to decrease the axial welding force. Using DOE method the effect of implemented frequency and vibration speed amplitude in FSW are analyzed. The thermal effects on the transfer function when applying the vibration on FSW had been ignored.

2. The FSW dynamic modeling

In this paper the proper empirical model relating the process parameters (i.e., plunge depth, travel speed, and rotation speed) to the process variables (axial welding force) was used to describe their dynamic relationships. The selected dynamic model was compared with the experimental data in ref. [2]. Eq. (1) presents the relation of axial force (F_z^*) and independent FSW parameters as follow:

Eq. 1

$$F_z^* = G(s) f^*(\omega, d, v) = \frac{614.6}{s^2 + 54.57s + 614.6} e^{[illegible]} \omega^{-[illegible]} d^{-[illegible]} v^{[illegible]}.$$

Where G(s) is the transfer function of dynamic model in frequency domain, e, ω, d and υ are exponential function, tool rotation speed (rpm), plunge depth (mm), and the welding speed (mm/min) respectively. The input velocity *v*, spindle speed ω, and plunge depth d are mapped through the nonlinear input gain *f (ω, d, v)*. The linear dynamic submodel represents the dynamic behavior of the average axial force F_z^*. The dynamic model structure used in this paper is shown in Fig. 2.

The dynamic model characterization as well as transfer function is the function of mass and stiffness matrixes of system for this reason the transfer function of dynamic model unchanged by applying vibration.

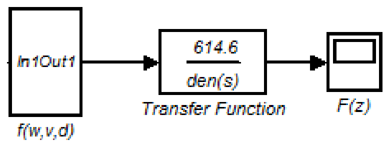

Fig. 2 FSW dynamic model structure

In this research effect of applying vibration in welding speed direction of FSW was investigated. Fig. 3 presents the vibration assisted friction stir welding (VAFSW) dynamic model structure.

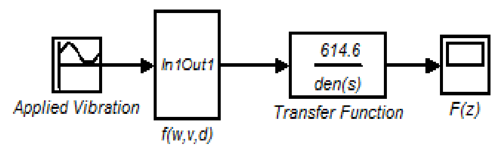

Fig. 3 VAFSW dynamic model structure

3. Simulink and Matlab simulation results

Fig. 4 shows the typical simulated results of axial force in FSW and comparison with VAFSW. The FSW welding axial force simulation results were verified by experimental results of Ref. [2]. As shown in Fig. 4 the axial welding force reduces by applying the vibration.

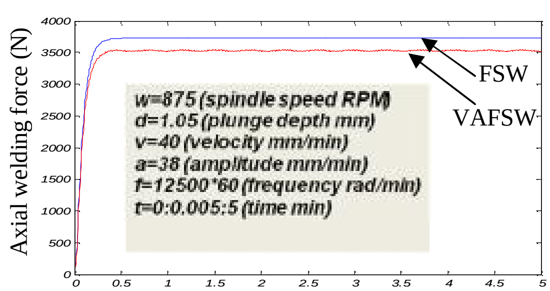

Fig. 4 axial welding force reduction by applying the vibration

4. Design of experimental (DOE) results

The purpose of this part of research is to identify the relationships between the set of design parameters. In this study, the function of axial welding force versus welding processing parameters and vibration specification such as vibration amplitude and vibration frequency was extracted. The relation between design variables and response variables, using the second order regression model function, was extracted by response surface analysis method. In the response surface analysis, an arbitrary value within the available boundary values can be selected for analysis. Since we are running a structured experiment, we can derive not only the main effects influencing the response parameters, but also potential interaction effects between the various design parameters.
Table 1 shows the parameters ranges for VAFSW DOE. There are three levels for each parameter, and a single measurement was taken of each parameter.

The response surface array which is L33 and 5 factors for this experiment is shown in table 2.

Table 1 Parameters ranges for VAFSW

Design Parameter	Name	Units	low	High
Spindle rotation speed	w	RPM	350	1400
Welding velocity	v	mm/min	40	100
Plunge depth	d	mm	0.1	2
Vibration amplitude	a	micron	5	40
Vibration frequency	f	1/s	500	20000

Table 2 Design of experiment array for VAFSW

w	v	d	a	f
350	40	0.10	5.0	20000
1400	40	0.10	5.0	5000
350	100	0.10	5.0	5000
1400	100	0.10	5.0	20000
350	40	2.00	5.0	5000
1400	40	2.00	5.0	20000
350	100	2.00	5.0	20000
1400	100	2.00	5.0	5000
350	40	0.10	40.0	5000
1400	40	0.10	40.0	20000
350	100	0.10	40.0	20000
1400	100	0.10	40.0	5000
350	40	2.00	40.0	20000
1400	40	2.00	40.0	5000
350	100	2.00	40.0	5000
1400	100	2.00	40.0	20000
875	70	1.05	22.5	12500
875	70	1.05	22.5	12500
875	70	1.05	22.5	12500
875	70	1.05	22.5	12500
875	70	1.05	22.5	12500
875	70	1.05	22.5	12500
350	70	1.05	22.5	12500
1400	70	1.05	22.5	12500
875	40	1.05	22.5	12500
875	100	1.05	22.5	12500
875	70	0.10	22.5	12500
875	70	2.00	22.5	12500
875	70	1.05	5.0	12500
875	70	1.05	40.0	12500
875	70	1.05	22.5	5000
875	70	1.05	22.5	20000
875	70	1.05	22.5	12500

The response surface regression was used in estimated regression coefficients for welding axial force in VAFSW. The analysis was done using coded units. The results of response surface regression were listed in table 3.

Fig. 5 shows the contour plot of variation of axial force in VAFSW versus vibration amplitude and plunge depth. It was observed that the value of the axial force increased with increase in the plunge depth and decrease in vibration amplitude.

Table 3 Estimated regression coefficients for welding axial force in VAFSW

term	coefficient
w	-2694.50
v	479.28
d	-244.39
a	-95.00
f	1.50
w*w	1463.54
v*v	-75.46
d*d	100.54
a*a	-20.96
f*f	-9.46
W*V	-247.31
W*d	124.31
W*a	51.56
W*f	-3.94
V*d	-22.94
V*a	86.81
V*f	-2.19
d*a	4.69
d*f	-42.81
a*f	11.19

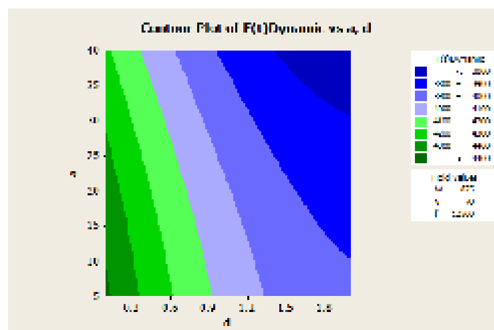

Fig. 5 Contour plot of variation of axial force versus vibration amplitude and plunge depth

Also, there is a decrease in the axial force values with the increase in the plunge depth, which is observed in Fig. 6. It could be seen that vibration frequency has no significant effect in axial force values as shown in Fig. 6 and 7.

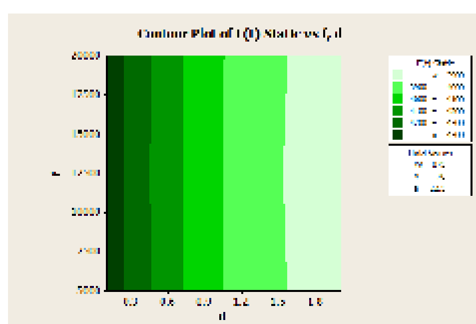

Fig. 6 Contour plot of variation of axial force versus vibration amplitude and frequency

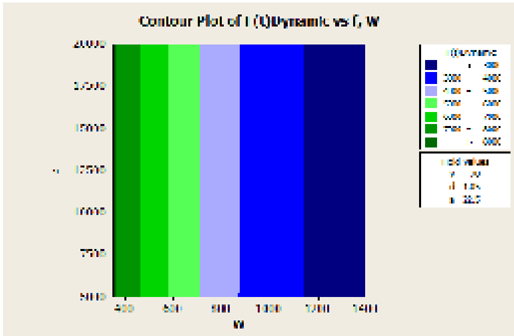

Fig. 7 Contour plot of variation of axial force versus vibration frequency and rotational speed

It was assured that both welding parameters such as welding speed and rotational speed influenced the variation of the axial force as shown in surface plot of Fig. 8.

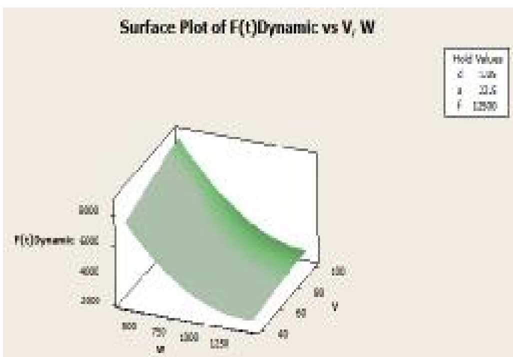

Fig. 8 Surface plot of variation of axial force versus rotational speed and welding speed

The influence of vibration amplitude on welding axial force is more at low welding speeds (40 mm/min) as shown in Fig. 9.

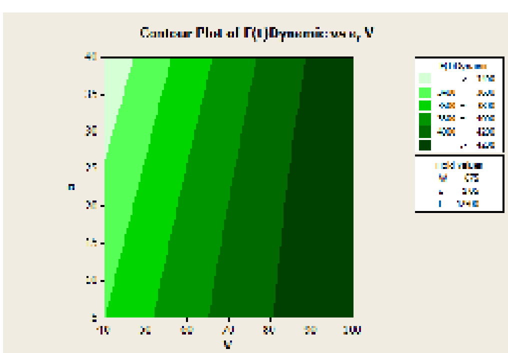

Fig. 9 Contour plot of variation of axial force versus welding speed and vibration amplitude

Conclusions

In this paper the influence of applying vibration on FSW was investigated using Simulink and Matlab programming tools. The resultant axial force of conventional FSW and Vibration Assisted FSW (VAFSW) were compared in frequency and time domain state spaces. A good correlation between FSW simulation and experiments was observed. The response surface of design of experiment (DOE) method is used for further investigation of VAFSW.

It this study it could be also observed from the simulation and programming results that vibration helps to decrease the axial welding forces for welding. Force reduction of 6 to 17% during the friction stir welding was observed when applying the vibration.

References

[1] R. Neugebauer, and A. Stoll, "Ultrasonic application in drilling." Journal of materials processing technology, Vol. 149, No. 1, pp. 633-639 ,2004.

[2] A.P. Reynolds, W. Tang, M. Posada and J. Deloach, “Friction stir welding of DH36 steel”, Sci. Technol. Weld. Join. , Vol. 8, pp.455–460, 2003.

[3] R. Singh, and J. S. Khamba, "Ultrasonic machining of titanium and its alloys: A review", Journal of materials processing technology, Vol. 173, No. 2, pp.125-135, 2006.

[4] P. F. Mendez and T. W. Eagar, "Welding processes for aeronautics", Advanced materials & processes, Vol. 159, No. 5, pp. 39-43, 2001.

[5] P. Kwanghyun, “Development and Analysis of Ultrasonic Assisted Friction Stir welding Process”, Ph. D. thesis in The University of Michigan, USA, 2009.

[6] W. R. Longhurst, “Force control of friction stir welding”, Dissertation for the degree of doctor of philosophy, December, Nashville Tennessee University, 2009.

[7] D. H. Sansome, "Recent developments in oscillatory metal working", Engineering, Vol. 213, No. 4, pp. 243-247, 1973.

[8] J. Tsujino, K. Hidai, A.Hasegawa, R. Kanai, H. Matsuura, K. Matsushima and T. Ueoka, "Ultrasonic butt welding of aluminum, aluminum alloy and stainless steel plate specimens", Ultrasonics, Vol. 40, No.1, pp. 371-374, 2002.

[9] N. Chandra and M. Rahman, “Effect of machining parameters in ultrasonic vibration cutting”, International Journal of Machine Tools & Manufacture, Vol. 48, pp. 965–974, 2008.

[10] NASA’s Ultrasonic Stir Welding Process for Handheld Solid State Welding, Published on internet, www.nasasolutions.com.

[11] A. D. Tyler, C. Sh. Yung and Y. Bin, “Observer-Based Adaptive Robust Control of Friction Stir Welding Axial Force”, IEEE/ASME transactions on mechatronics, 2010.