Torque based weld power model for friction stir welding

J. W. Pew*, T. W. Nelson and C. D. Sorensen*****

For decades, models have been developed for predicting the size of the weld nugget and heat affected zones in fusion welded structures. The basis for these models is the welding heat input, which is fairly well understood for most arc welding processes. However, this traditional approach is not as straightforward for friction stir welding (FSW). To date, no definitive relationship exists to quantify the heat input for FSW. An important step to establish a heat input model is to identify how FSW process parameters affect weld power. This study details the relationship between FSW process parameters and torque for three different aluminium alloys: 7075, 5083 and 2024. A quantitative weld power and heat input model is created from the torque input. The heat input model shows that decreasing the spindle speed or increasing the feedrate significantly decreases the heat input at low feedrates. At high feedrates, the feedrate and spindle speed have little effect on the heat input. Process parameter *v.* heat input trends are verified by measurements of the weld heat affected zones. In addition, this study outlines and validates the use of a variable spindle speed test for determining torque over a broad range of parameters. The variable spindle speed test provided significant improvements over previous methods of determining torque because this new method enabled the torque to be modelled over a broad range of parameters using a minimum number of welds. The methods described in this study can be easily used to develop torque models for different alloys and materials.

Keywords: Friction stir welding, Heat input, Process modelling, Aluminum alloys

Published by Maney Publishing (c) IOM Communications Ltd

Introduction

Despite extensive research into the fundamental nature of friction stir welding (FSW), a definitive model of the power required to create a successful weld has not been determined. Establishing a model for the weld power is an important step to determine an overall heat input model for FSW. A heat input model would allow FSW parameters to be selected for desired weld properties.

In traditional welds, the weld power can be easily set by adjusting the current and voltage. In contrast, the obvious controllable parameters for FSW are feedrate, spindle speed and tool depth. No direct equation can determine the weld power based on these three factors. In addition, the power requirement is strongly affected by the material. Currently, FSW parameters must be established through trial and error, a method that may not result in the optimum heat input and is costly in terms of both time and money.

The necessary power requirement is likely a function of various parameters that include (but may not be limited to) material type, feedrate, spindle speed, tool geometry and tool depth.[1–3]

Department of Mechanical Engineering, Brigham Young University, 435 CTB, Provo, UT 84602, USA

*Corresponding author, email jefferson.w.pew@exxonmobil.com; **nelson@byu.edu; ***sorensen@byu.edu

The purpose of this study is to quantitatively determine the effect of process parameters (feedrate, spindle speed and tool depth) on the weld power in FSW. The results of this study can be easily applied to new alloys and different tool designs to rapidly create weld power models. The results can also be used to determine the ideal heat input for a given alloy.

This first objective of this work was to develop a weld power model which would then be used to subsequently develop a heat input model. Numerous papers in the literature have attempted, in various ways, to model the heat input during FSW. To clarify, the heat input is a measure of energy/length. The weld power is a measure of energy/time. Although the heat input can be calculated by dividing the weld power by the feedrate, many researchers have attempted to measure the heat input directly. Some of the earliest research attempted to measure heat input through thermocouple placement,[4–12] heat affected zone (HAZ) measurements,[13] or a combination of these two methods.[14–16]

Some of the first attempts at measuring heat input through thermocouple placement only considered 2D models.[4–7] Later work increased in complexity to 3D models.[8,9] These models were simple and only considered one alloy, one feedrate and one spindle speed. The depth, which was later found to be a significant factor,[10] was not controlled or was only estimated visually.[5]

© 2007 Institute of Materials, Minerals and Mining
Published by Maney on behalf of the Institute
Received 6 November 2006; accepted 19 December 2006
DOI 10.1179/174329307X197601

Published by Maney Publishing (c) IOM Communications Ltd

Despite the minimalism of these models, some important contributions were made including evidence that thermocouple placement in the material did not significantly alter the heat flow[5] and that preheating of materials changed the peak temperatures reached during welding.[7]

Later research explored the effects of FSW parameters on material temperature. Chao *et al.*[11] varied the feedrate, Song and Kovacevic[12] varied the spindle speed and feedrate, and Tang *et al.*[10] varied the spindle speed and depth. All of these authors indicated a change in the material temperature as parameters were varied, but were not able to predict this change quantitatively. Tang *et al.*[10] reported an increase in the material temperature with increasing spindle speed, but only minimally at higher spindle speeds, possibly indicating a non-linear relationship of heat input with spindle speed.

Only Midling and Rorvik[13] attempted to estimate heat input based solely on the width of the measured HAZ. They varied tool rotation speed, feedrate and tool load showing that heat input decreased with decreasing depth and rotation speed, and increased with decreasing welding speed. Several authors attempted to measure heat input through a combination of thermocouple placement and HAZ measurements.[14–16] However, they chose a limited number of parameters to vary. Gould and Feng[14] looked at two combinations of parameters, while Frigaard *et al.*[15] looked at three different feedrates. Song *et al.*[16] looked at three different spindle speeds. All three authors showed a strong correlation between the maximum temperature and the width of the HAZ. However, based on the narrow range of parameters from these tests, it is impossible to predict a heat input value for parameters outside of those tested.

Linder *et al.*[17] discussed several drawbacks to the thermocouple method of determining heat input. First, the thermal gradients in FSW are often high necessitating precise thermocouple placement. Also, because the FSW process results in severe material deformation, thermocouples can easily move, resulting in uncertainties in the accuracy of the temperature readings. Measuring the HAZ is also a time intensive task as samples must be removed, mechanically polished and indented for each parameter of interest. Likely, owing to these difficulties, that those who have used these methods are able to only report the heat input for one alloy and a limited set of parameters.

Another method of measuring the heat input is to calculate it from the power or torque input into the weld. This technique is much easier in as much as it does not require extensive time in preparing welded plates (as with thermocouples) or in post-weld sample preparation (as with HAZ measurements). Several authors have attempted this method with varying results.[17–25]

Both Zahedul *et al.*[18] and Khandkar *et al.*[19] merely calculated a torque and assumed it to be constant for all parameters. Schmidt *et al.*[20] and Leinart *et al.*[21] measured the torque at one set of parameters in a given alloy and assumed the torque to be constant for all parameters. The problem with both of these approaches is that the torque input is not constant at all parameters.

Only a few authors have attempted to represent power as a function of process parameters. Colegrove and Shercliff[22] presented an equation for power as a function of travel speed, but neglected the spindle speed which was found to be significant by numerous investigations.[1–3,10,11,13,16]

As indicated by some of the previous research, the torque input possibly had a complex, non-linear relationship with the input parameters, prompting several authors to attempt to find a simpler method of determining torque input.[17,23–25] One method was to reduce the number of parameters studied by combining the spindle speed and feedrate into one parameter called 'weld pitch' (measured in advance/revolution). Preliminary research attempting to link the weld power to the weld pitch was inconclusive.[17,23,24] Later, Reynolds and Tang[25] specifically tested the validity of the weld pitch approach for determining the weld power, showing weld pitch not to be a good indicator of weld power.

The few studies exploring the effects of FSW parameters on weld power have only been able to do so qualitatively, i.e. decreases with increasing feedrate. In addition, within these studies, many disagree as to the effect of a given parameter. This is likely because of the small range over which a given parameter is tested.

Clearly, the tests used previously do not have the complexity to capture the actual behaviour of the weld power.[3] The purpose of this research is to develop a method allowing weld power to be easily calculated quantitatively from the weld torque for a broad range of process parameters. Preliminary work[3] has shown that variable spindle speed tests may be a viable means of calculating weld power for any given material. In a variable spindle speed test, the feedrate and tool depth are held constant throughout the weld while the spindle speed is varied continuously. These tests were first reported by Reynolds *et al.*[24,26] to determine forces in FSW over a broad range of parameters.

Experimental

Equipment

The weld power can be calculated from spindle torque through the relationship shown in equation (1)

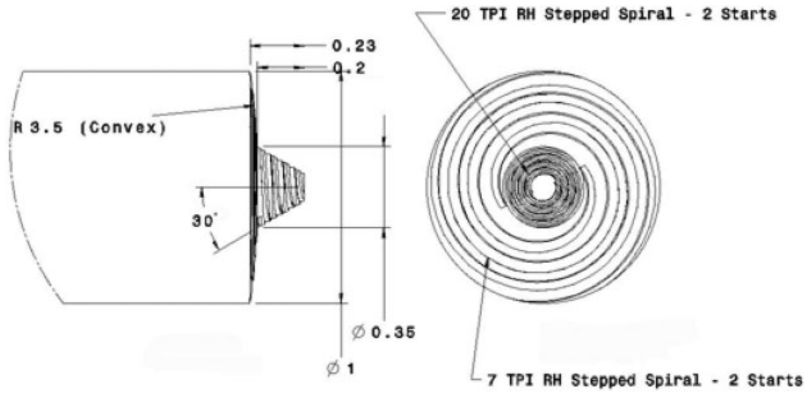
$$\text{Power} = \Omega M \quad (1)$$

In this equation, Ω represents the spindle speed and M represents the torque. Although the FSW machine used for this study can record the motor power output, this power output includes losses that occur within the motor and drive train. For this reason, calculating the weld power from the torque is a more accurate measure of the power into the weld.

The tool used for all testing was a convex, scrolled shoulder, step spiral (CS4) tool made from heat treated H13 tool steel (shown in Fig. 1). As with all CS4 tools, no head tilt was required. The CS4 tool had a pin length of 6·35 mm (0·25 in.) and a shoulder diameter of 25·4 mm (1·0 in.). Only one tool was used for all of the tests. The tool penetration into the material was gauged by a dial indicator attached to the tool holder.

Variable spindle speed validation

Owing to the non-conventional nature of the variable spindle speed tests, preliminary work was performed to determine the usefulness of these tests in describing weld behaviour when some parameters are held constant. First, several welds were made in which all the parameters were held constant. The process forces and

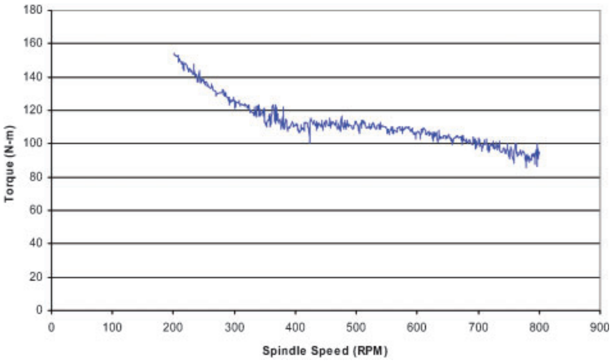


1 Tool geometry used in all welds

torques of these welds were compared against welds made when the spindle speed was varied such that it covered parameters previously tested.

Next, several variable spindle speed welds were completed while changing the direction of the spindle speed ramping was changed. In other words, the spindle speed was ramped from a high value to a low value in some welds and from a low value to a high value in other welds. Changing the direction of the spindle speed ramping did not influence torque.

Finally, several welds were completed while changing the ramp rate (change in spindle speed/metre). Again, the data correlated very well. These results show that the data obtained are not sensitive to the rate of change of the spindle speed over the range of parameters tested.



2 Torque *v.* spindle speed for friction stir weld in alloy 7075: parameters for this weld were 127 mm min^{-1} at shallow depth

Materials

Three alloys were explored in this study: Al 7075-T7351, Al 5083-H32, and Al 2024-T3. These three materials were chosen for two reasons. First, all three had a relatively small friction stir process window. Thus, a set of tests could be defined covering all weldable parameters. Second, all three had distinctly different physical and mechanical properties.

Test plates, 13 cm (5 in.) wide by 16·5 cm (5·4 ft) long, were sheared from larger plates. The plate thickness was 9·5 mm (0·375 in.). The plate thickness was deliberately kept greatly larger than the pin length to avoid interactions between the tool and the anvil.

Preliminary work was performed using each alloy to determine the parameter range for defect free welds. The parameters included tool depth, feedrate and spindle speed. The weld parameters used for each alloy are shown in Table 1. In all of the alloys, it is possible to weld at lower feedrates than those tested. The lower feedrates were left out of the study for two reasons. First, they are impractical for use in most industrial applications. Second, they could later be used as a measure of how well the resulting model could be extrapolated.

Several measures were taken to ensure consistence between welds. First, the spindle speed ramp rate was held constant for all welds of a given alloy. Second, an extra minute of weld time was added to the start of each weld where the spindle speed was held constant. This delay allowed the weld depth to be adjusted appropriately before the period of data acquisition. Third, after each weld, the anvil was cooled to room temperature using dry ice and methanol. This cooling procedure was used to prevent the anvil from preheating the next weld and changing the resulting forces.

Results and discussion

Analysis

A preliminary analysis of the data was made to determine the best method to model the torque and weld power. Torque was plotted in Excel as a function of spindle speed for each weld. All of the welds exhibited a distinctive torque curve. A representative torque curve for alloy 7075 is shown in Fig. 2. This shape can be characterised accurately as a third order polynomial.

To create a model of torque as a function of weld parameters, a regression analysis was performed on the entire set of data from each alloy in Minitab (a statistical software package). The independent variables considered for the model included ‘Feed Rate’, ‘Depth’ and

Table 1 Parameters used for each alloy

Alloy	Feedrates, mm min^{-1}	Spindle speed range, rev min^{-1}	Tool depth, mm
7075	127, 203, 279	200–800	5·2, 5·3, 5·5
5083	127, 203, 279	200–700	5·2, 5·3, 5·5
2024	51, 102, 152	175–350	5·2, 5·3, 5·5

Published by Maney Publishing (c) IOM Communications Ltd

Published by Maney Publishing (c) IOM Communications Ltd

'Spindle Speed' as well as the four interaction terms '(Feed Rate)*Depth', '(Feed Rate)*(Spindle Speed)', 'Depth*(Spindle Speed)' and 'Depth*(Feed Rate)*(Spindle Speed)'. Two additional variables, '(Spindle Speed)^2' and '(Spindle Speed)^3', were also included together with their interaction terms with 'Feed Rate' and 'Depth'. These higher order variables of spindle speed were added because as mentioned previously, the data were described best by third order polynomials. This accounts for a total of 13 possible independent variables in each model.

Backward elimination was used to find a combination of parameters that resulted in the best fit without extra terms. Backward elimination is a statistical tool for removing excess terms from a model. This allows the model to be more accurate because excess variables may simply be describing noise in the data. In this case, the coefficients with the highest P values were removed one at a time until all of the P values were $<0{\cdot}001$.

Once a model had been determined for the entire set of data, an R^2 value was calculated for each individual weld. To check the accuracy of the model, extra welds were made with new parameters. Again, an R^2 value was calculated to determine the goodness of fit of the model to these extra runs.

Once a model had been determined for torque, the weld power (watts) could be calculated using equation (2). In this equation, Ω represents the spindle speed and M the predicted torque (N m). The spindle speed is multiplied by 2π and divided by 60 to convert from rev min^{-1} to radian s^{-1}

$$\text{Weld power} = \frac{2\pi\Omega M}{60} \qquad (2)$$

From the weld power, a predicted heat input can be calculated by dividing the weld power by the travel speed v, as seen in equation (3). This is only an estimate of the heat input because losses maybe depend on the input parameters. For example, the rate of heat loss, through radiation or by conduction to the anvil and tool, may change based on the weld parameters. Graphs were plotted for each alloy to show how these factors changed as a function of depth

$$\text{HI Heat Input} = \frac{\text{PI Power Input}}{v} \qquad (3)$$

Torque input model

A torque model was created as described previously for each alloy. The overall R^2 adjusted values were 93·1% for 7075, 96·9% for 5083 and 97·0% for 2024. The individual coefficients for each alloy can be found in Table 2. Of the original 13 independent variables, 'Depth*(Spindle Speed)^2', 'Depth*(Spindle Speed)^3' and 'Depth*(Feed Rate)*(Spindle Speed) were not found to be significant for any of the alloys. Individual R^2 values for each weld can found in Table 3.

Table 3 R^2 values for individual welds*

Alloy	Feedrate, mm min^{-1}	Depth, mm	R^2
7075	127	5·2	0·888
	127	5·5	0·930
	203	5·35	0·882
	279	5·2	0·863
	279	5·5	0·957
	51	5·2	0·890
	51	5·5	0·778
	203	5·2	0·800
	203	5·5	0·891
5083	127	5·2	0·963
	127	5·5	0·941
	203	5·35	0·907
	279	5·2	0·947
	279	5·5	0·947
	51	5·35	0·915
	102	5·2	0·915
	102	5·5	0·949
2024	51	5·2	0·901
	51	5·5	0·980
	102	5·35	0·922
	152	5·2	0·798
	152	5·5	0·918
	25	5·2	0·823
	25	5·5	0·891
	102	5·5	0·937

*Welds that are in bold print have parameters outside of those used in creating the model.

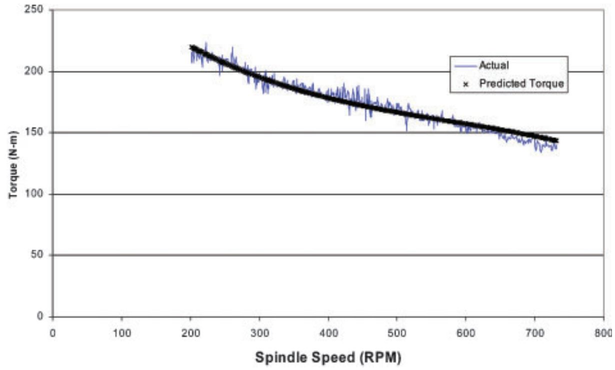
The welds in bold in Table 3 better illustrate the strength of the model. This is because these welds were made with parameters that are outside of those used in creating the model. They demonstrate that the model accurately predicts the torque beyond the initially investigated parameters.

In addition to the calculated R^2 values for each weld, the torque predicted from the model can be plotted with the recorded torque from an actual weld. This gives a visual indication of how well the model predicts actual data. As shown in Fig. 3, the model closely predicts an actual weld and all major trends are captured by the model.

In addition to plotting lines of predicted torque at a given feedrate and depth, a three-dimensional graph can be created that shows how the torque reacts over a large range of feedrates and spindle speeds. This enables the

Table 2 Significant predictors for each alloy and their coefficients

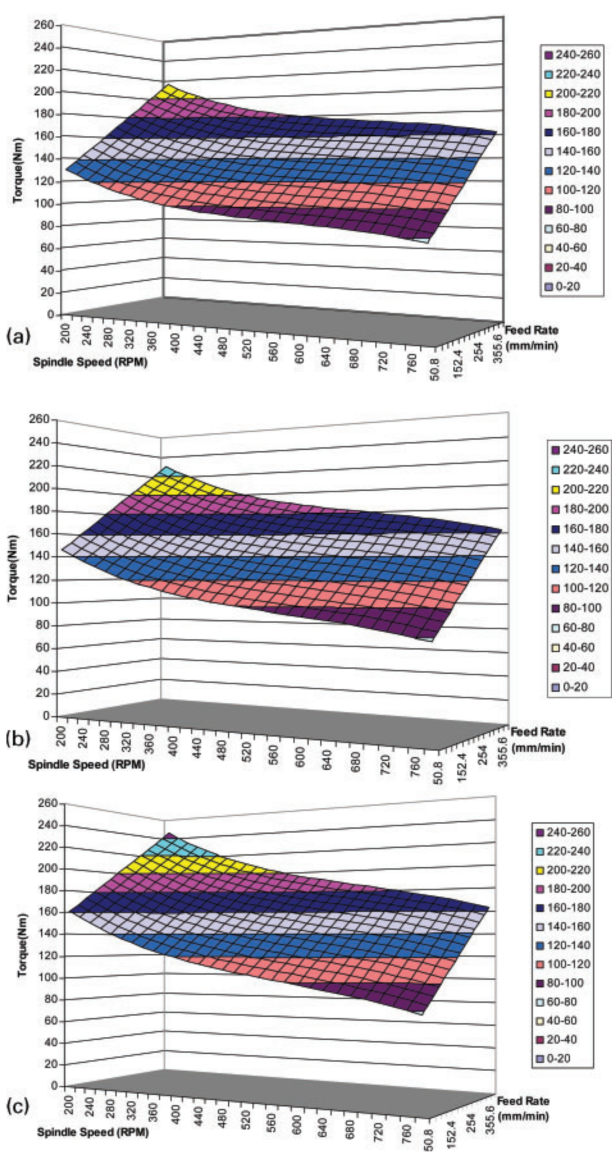
Predictor	7075	5083	2024
Constant	$-636{\cdot}4$	$-208{\cdot}7$	$-812{\cdot}2$
Feed Rate	0·2584	0·2093	–
Depth	159·5	103·9	191·5
Spindle Speed	0·5171	$-1{\cdot}216$	1·347
Feed Rate*Depth	–	–	0·2278
Depth*Spindle Speed	$-0{\cdot}2013$	–	$-0{\cdot}3828$
Feed Rate*Spindle Speed	–	–	$-7{\cdot}635\times10^{-3}$
Spindle Speed^2	$8{\cdot}488\times10^{-4}$	$2{\cdot}005\times10^{-3}$	$1{\cdot}337\times10^{-3}$
Spindle Speed^3	$-4{\cdot}860\times10^{-7}$	$-1{\cdot}087\times10^{-6}$	$-9{\cdot}931\times10^{-7}$
Feed Rate*Spindle Speed^2	–	–	$2{\cdot}030\times10^{-5}$
Feed Rate*Spindle Speed^3	–	–	$-1{\cdot}643\times10^{-8}$



3 Measured torque plotted with predicted torque in alloy 7075: feedrate was 279 mm min^{-1} (11 ipm) and depth was 5·5 mm (0·215 in.); R^2 value was 0·957

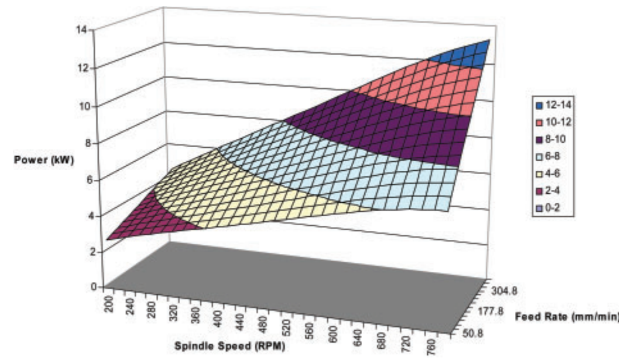
minimum torque to be easily found. In Fig. 4, the torque is plotted for alloy 7075 for the entire range of parameters studied. Plots for the other two alloys were very similar in nature.

Some similarities are shared between all of the alloys. First, the torque always decreases by either individually



a 5·2 mm; *b* 5·35 mm; *c* 5·5 mm

4 Torque in alloy 7075 at different depths



5 Weld power for alloy 7075 at depth of 5·2 mm

increasing the spindle speed, decreasing the feedrate, or decreasing the tool depth. Second, the effect of spindle speed on torque decreases as the spindle speed increases. One hypothesised explanation is that as the spindle speed is increased past a certain point, the characteristics of the material/tool interface changes.

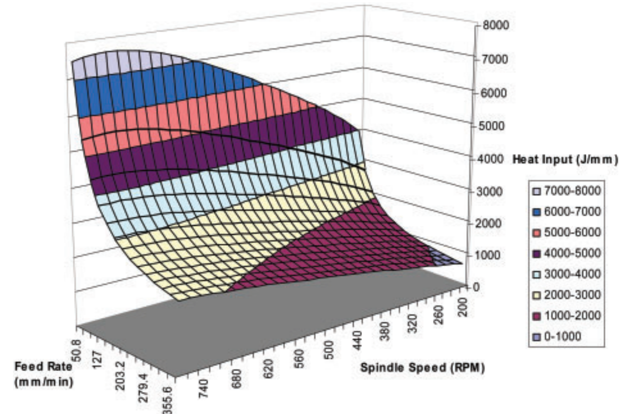
In Al 5083, there is no interaction term between depth and spindle speed. In the other two alloys, the effect of tool depth diminishes as the spindle speed increases such that the tool depth becomes negligible at high spindle speeds. In 5083, increasing the tool depth always increases the torque.

Weld power model

In addition to torque, a weld power model also can be calculated using equation (2). Again, a three-dimensional graph is useful in identifying trends of interest. Figure 5 shows the weld power model for alloy 7075 at a depth of 5·21 mm. As can be seen in Fig. 5, the weld power decreases with decreasing feedrate and spindle speed. The weld power shifts towards higher values as the tool depth increases, but the overall shape of the surface changes very little. The same trends were true for alloys 5083 and 2024.

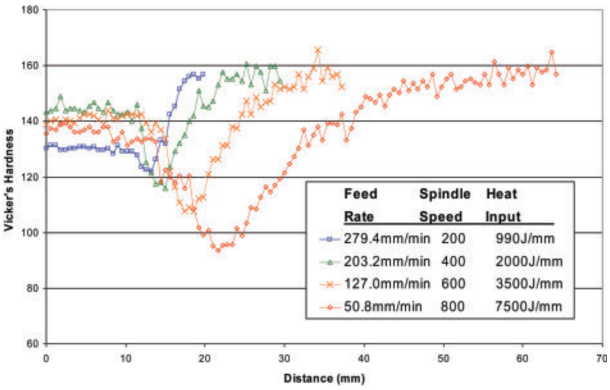
Heat input model

A predicted heat input model can be created from the weld power model using equation (3). The heat input for alloy 7075 is shown in Fig. 6. From this graph, the heat input is shown to decrease with decreasing spindle speed and increasing feedrate. The heat input shifts towards higher values as the tool depth increases, but the overall shape of the surface changes very little. The same trends were true for alloys 5083 and 2024.



6 Heat input in alloy 7075 at depth of 5·2 mm

Published by Maney Publishing (c) IOM Communications Ltd



7 Microhardness results in alloy 7075

For all alloys, the rate of change in heat input decreases rapidly as the feedrate is increased. For example, in Al 7075, at 200 rev min^{-1} the change in heat input from 51 to 102 mm min^{-1} (2 to 4 ipm) is nearly 2000 J mm^{-1} while the difference between 102 and 203 mm min^{-1} (4 to 8 ipm) is ~1000 J mm^{-1}. At the same time, the difference between 203 and 305 mm min^{-1} (8 and 12 ipm) is only 300 J mm^{-1}. Clearly, little benefit is gained by increasing the feedrate above 203 mm min^{-1} (8 ipm) except to make faster welds. If a further decrease in the heat input is required above this feedrate, then it would be more advantageous to decrease either the tool depth or the spindle speed.

HAZ correlation

To test the capability of the heat input model, four welds were made in Al 7075 measuring the width of the HAZ. Two of the welds were selected such that their parameters were at the extremes of the heat input model. The other two welds were at even intervals between the two extremes. All of the welds were run at a constant depth of 5·2 mm. A list of the parameters and predicted heat inputs can be seen in Fig. 7 along with the microhardness test. This figure shows that higher heat input correlates to a greater width of the HAZ. In addition, higher heat input also correlates to greater softening of the HAZ.

Variable spindle speed tests

The previous sections have shown that the torque models created from the variable spindle speed tests are very accurate. The models shown previously can be created from a minimum of only five welds. In the case where the depth is not a factor (full penetration welds), the number of required welds reduces to three.

In comparison, some of the other methods presented in the background would likely require five or six welds at each feedrate and depth to capture the same degree of accuracy presented here. This results from the fact that the torque input is best described by third order polynomials. If three feedrates and depths were examined, the total number of welds required in such a study could easily be 30 welds per alloy. In addition to the benefits of having a reduced number of welds, the variable spindle speed test does not require the extensive preparation time associated with thermocouple placement or the post-weld time associated with microhardness samples as presented by other authors.

Another benefit of the variable spindle speed test is that a statistical regression model can be easily fit to the data. Instead of purely qualitative results, as often presented in previous studies, quantitative results can be obtained. Thus, by using the variable spindle speed test, welds no longer need to be made in a 'trial and error' fashion because the exact effect of each parameter change can simply be calculated. The ease and accuracy of the variable spindle speed tests cannot be understated.

Conclusions

Based on the results and discussion given above, the following conclusions can be made.

1. A new method was developed for determining the weld power. This new method not only captures more information than previous methods, but is also both easier and requires fewer welds than previous methods.
2. Empirical models were developed that accurately describe weld power as a function of parameters for aluminium alloys 7075, 5083 and 2024. The same method likely can be applied to any alloy.
3. The empirical models developed have an accuracy of 93% or greater in predicting the weld power for each alloy. Even welds with parameters outside of those investigated are accurately described by the model.
4. The models correctly predict the trends in widening and softening of the HAZ in Al 7075.

Acknowledgement

This work was funded by the Office of Naval Research, contract no. N00014-05-1-0511, programme manager Dr Julie Christodoulou.

References

1. J. Record: 'Statistical investigation of friction stir processing parameter relationship', Brigham Young University, Provo, UT, USA, 2005.
2. J. Record, J. Covington, B. W. Webb and T. W. Nelson: Proc. 5th Int. Symp. on 'Friction stir welding', Metz, France, September 2004, TWI Ltd., Cambridge, UK.
3. J. Pew, J. Record and T. W. Nelson: Proc. 7th Int. Conf. on 'Trends in welding research', Pine Mountain, GA, USA, May 2005, ASM International, pp 247–251.
4. M. J. Russell and H. R. Shercliff: Proc. INALCO '98, Cambridge, UK, 1998, April 1998, TWI Ltd; pp 197–207.
5. J. C. McClure, W. Tang, L. E. Murr, X. Guo, Z. Feng and J. E. Gould: Proc. 5th Int. Conf. on 'Trends in welding research', Pine Mountain, GA, USA, June 1998, ASM International, pp 590–595.
6. Y. J. Chao and X. Qi: *J. Mater. Process. Manuf. Sci.*, 1998, **7**, 215–233.
7. M. Song and R. Kovacevic: *Int. J. Mach. Tools Manuf.*, 2003, **43**, 605–615.
8. P. Colegrove: Proc. 2nd Int. Symp. on 'Friction stir welding', Gothenburg, Sweden, June 2000, TWI Ltd., Cambridge, UK.
9. H. N. B. Schmidt and J. Hattel: *Int. J. Offshore Polar Eng.*, 2004, **14**, 296–304.
10. W. Tang, X. Guo, J. C. McClure and L. E. Murr: *J. Mater. Process. Manuf. Sci.*, 1998, **7**, 163–172.
11. Y. J. Chao, X. Qi and W. Tang: *J. Manuf. Sci. Eng.*, 2003, **125**, 138–145.
12. M. Song and R. Kovacevic: *Proc. Inst. Mech. Eng. B*, 2003, **217B**, 73–85.
13. O. T. Midling and G. Rørvik: Proc. 1st Int. Symp. on 'Friction stir welding', Thousand Oaks, CA, USA, June 1999, TWI Ltd., Cambridge, UK.
14. J. E. Gould and Z. Feng: *J. Mater. Process. Manuf. Sci.*, 1998, **7**, 185–194.
15. Ø. Frigaard, Ø. Grong, B. Bjørneklett and O. T. Midling: Proc. 1st Int. Symp. on 'Friction stir welding', Thousand Oaks, CA, USA, June 1999, TWI Ltd., Cambridge, UK.
16. M. Song, R. Kovacevic, J. Ouyang and M. Valant: Proc. 6th Int. Conf. on 'Trends in welding research', Pine Mountain, GA, USA, April 2002, ASM International, 212–217.

Published by Maney Publishing (c) IOM Communications Ltd

17. K. Linder, Z. Khandkar, J. Khan, W. Tang and A. P. Reynolds: Proc. 4th Int. Symp. on 'Friction stir welding', Park City, UT, USA, May 2003, TWI Ltd., Cambridge, UK.
18. M. Zahedul, H. Khandkar, J. A. Khan and A. P. Reynolds: Proc. 6th Int. Conf. on 'Trends in welding research', Pine Mountain, GA, USA, April 2002, ASM International, 218–223.
19. M. Z. H. Khandkar, J. A. Khan and A. P. Reynolds: *Sci. Technol. Weld. Join.*, 2003, **8**, 165–174.
20. H. Schmidt, J. Hattel and J. Wert: *Model. Simul. Mater. Sci. Eng.*, 2004, **12**, 143–157.
21. T. J. Leinart, W. L. Stellway, Jr and L. R. Lehman: Proc. 4th Int. Symp. on 'Friction stir welding', Park City, UT, USA, May 2003, TWI Ltd., Cambridge, UK.
22. P. A. Colegrove and H. R. Shercliff: *Sci. Technol. Weld. Join.*, 2003, **8**, (5), 360–368.
23. A. P. Reynolds, W. Tang, Z. Khandkar, J. A. Khan and K. Lindner: *Sci. Technol. Weld. Join.*, 2005, **10**, (2), 190–199.
24. A. P. Reynolds, Z. Khandkar, T. Long, W. Tang and J. Khan: *Mater. Sci. Forum*, 2003, **426–432**, 2959–2694.
25. A. P. Reynolds and W. Tang: Proc. Symp. on 'Friction stir welding and processing', Indianapolis, IN, USA, November 2001, 115–122, TWI Ltd., Cambridge, UK.
26. A. P. Reynolds: Proc. Workshop on 'Friction stir welding', February 2004, Office of Naval Research, Paper No. 2, 2003, Warrenton, VA, USA.

Published by Maney Publishing (c) IOM Communications Ltd