A Look at the Statistical Identification of Critical Process Parameters in Friction Stir Welding

To analyze the effects of nine friction stir welding input parameters on measured process outputs, a 16-run fractional factorial experiment was used

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ABSTRACT. Many fundamental physical relationships governing the friction stir welding (FSW) process remain largely unexplored. Recent studies have aided in the discovery and clarification of many process fundamentals. A 16-run fractional factorial experiment was used to analyze the effects of nine FSW input parameters on measured process outputs. It was confirmed that the most significant input parameters are spindle speed, feed rate, and tool depth. In addition, the distance between the weld and side of the plate had a significant effect on measured Z-force and shoulder depth, and thus should be considered in future studies.

Introduction

Friction stir welding (FSW) is a solid-state joining process having many desirable attributes. It involves forcing a rotating cylindrical tool with a protruding pin into the joint to be welded. Once submerged in the material, the tool is advanced along the joint line. Frictional heating is sufficient to locally soften the workpieces and the rotating motion of the tool 'stirs' the workpieces together. The result is a fully consolidated weld with superior quality and properties to those of traditional arc welds.

There are three primary control parameters available in FSW: spindle speed, feed rate, and tool vertical position. During the FSW process, a number of other variables can be measured, including motor power, tool temperature, and forces. The relationships between the fundamental control parameters and the measured process variables have never been completely explored. The relationship between the inputs and outputs is shown in Fig. 1.

For efficient application of FSW, it is desired that all important process parameters that affect a weld outcome be identified and the sensitivity of operating conditions to these process parameters be characterized. In addition to the three most fundamental parameters, it is believed that there are 'environmental' variables that may need to be controlled. Environmental variables are those not readily controlled during a weld as opposed to variables such as spindle speed that are easily controlled. Perhaps a model similar to that shown in Fig. 1 with the addition of environmental variables is a better representation of the FSW process. The environmental variables may have an impact on the process and affect the final weld quality and performance.

Researchers have previously studied various 'input' control parameters and their relation to many 'output' responses. Their objectives all differ but the underlying purpose is to further analyze fundamentals of the FSW process and explore the relationship between inputs and outputs.

Nishihara and Nagasaka (Ref. 1) varied spindle speed and feed rate and were able to measure tool and anvil temperatures. Nishihara and Nagasaka (Ref. 1) along with Lienert et al. (Refs. 2–4) included tool temperatures as a response, which has not been common during experimentation. Tang et al. (Ref. 5) varied welding load (Z-force), spindle speed, and tools with or without a pin in an effort to investigate the workpiece temperature distribution and heat input. Jandric et al. (Ref. 6) studied the effects of spindle speed and feed rate on weld quality and temperature distribution. Colligan et al. (Ref. 7) investigated the effects of pin design, spindle speed, and feed rate on specific energy, power, plunge force, torque, and X- and Y-forces. Johnson (Ref. 8) varied different plunge depths, feed rates, and spindle speeds to explore their effects on forces and torques. Others have included workpiece alloy as part of their studies (Refs. 2, 8, 9). From these studies and others, a wealth of information is acquired that aids in further studies and in understanding the FSW process.

To date, no known study has taken a statistical approach to accomplish the task of relating inputs and outputs. As previously discussed, there was a need to identify and study primary variables that affect welds. Thus, in the current study, a screening design of experiments was chosen to identify the effect of various weld inputs on selected outputs in an effort to identify critical process parameters.

A screening design of experiments (DOE) is a statistical method used to study many variables simultaneously and quantify their effects on a given response relative to each other. By identifying which variables have a large effect on a response, one can conclude which variables are key input parameters.

This paper utilizes a 16-run screening DOE to analyze the effects of nine inputs on selected outputs. No duplication of experiments is used because the intent is to identify the largest effects and not to com-

KEYWORDS

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**The opinions and conclusions expressed herein are solely those of the author and do not necessarily reflect those of Lockheed Martin.*

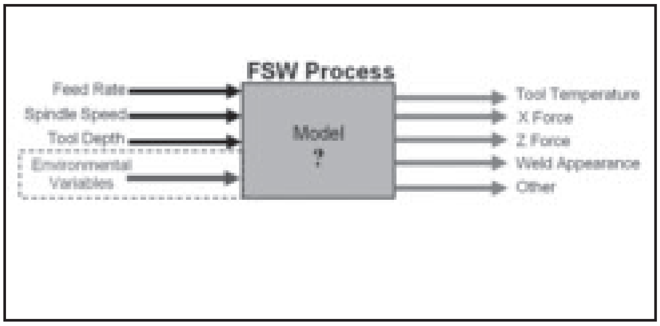

Fig. 1 — Possible relationships describing inputs and outputs of the FSW process.

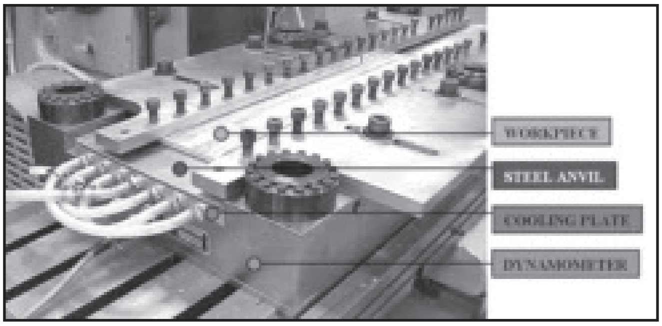

Fig. 2 — Setup of the dynamometer, cooling plate, and workpiece mounting.

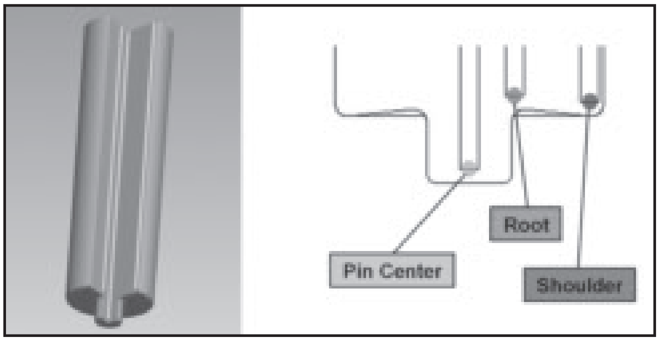

Fig. 3 — Thermocouple locations in the tool. Note: Threads are omitted for simplicity.

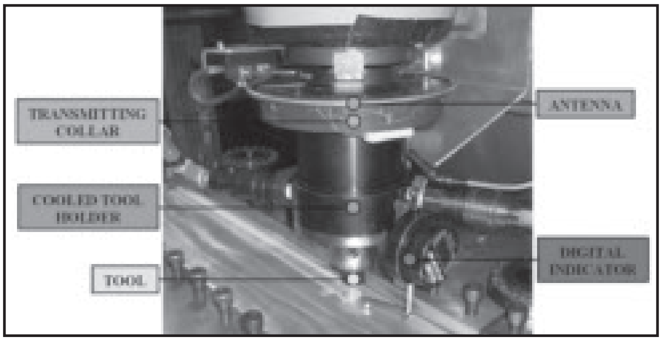

Fig. 4 — Cooled tool holder and electronic indicator used to measure shoulder depth.

pletely explore process relationships. The results aid in understanding process fundamentals and in further investigation of input/output relationships.

Experimental Approach

Design of Experiments

Initial setup of the DOE was done by creating a list of all possible process inputs (factors) and narrowing the list to nine. Factors were eliminated from the list by weighing feasibility and probability of significance based on previous studies (Ref. 10). The three most fundamental factors were included along with six environmental factors. These are detailed in Table 1.

The factors pin length and plunge depth are related. The objective of using plunge depth as a factor is to control the depth of the shoulder relative to the workpiece surface. Since the Z-position of each tool is zeroed on the top surface of the workpiece, different pin lengths (PL) must be accounted for in the plunge.

It was determined that a 16-run screening DOE would best analyze the effect of each factor. Factor levels were chosen from within a known operational window that yielded satisfactory welds. Factor levels were also chosen so the effect would be as apparent as possible. Following statistically sound practices, weld order was randomized. The parameters and levels for each weld are given in Table 2.

Table 1 — Factor Descriptions and Units Used

Factor	Unit	Description
Spindle speed	rev/min	Revolutions per minute of FSW tool
Feed rate	mm/min	Speed of tool advancing through workpiece
Plunge depth	mm	Total distance tool is plunged (pin length + factor value)
Pin length	mm	Distance between outer edge of shoulder and tip of pin along tool axis
Weld cooling	n/a	Coolant circulation in cooling plate during weld
X start distance	mm	Location of plunge relative to edge of workpiece in X-direction
Weld location	n/a	Location of weld relative to edge of workpiece in Y-direction
Preweld cooling	Celsius	Amount of cooling before each weld, measured as the difference between the inlet and outlet temperatures of the cooling plate
Dwell time	seconds	Time between plunge sequence and weld traverse sequence

Although the FSW machine automatically measures many variables throughout the course of a weld, only eight were utilized as ‘responses’ in the analysis. These are X-force, Y-force, Z-force, pin center temperature, root temperature, shoulder temperature, shoulder depth, and motor power. Shoulder depth is actually a derived response (measured digital depth – pin length) and equates to the distance of the shoulder above or below the top surface of the workpiece. Motor power refers to the amount of power required by the FSW machine to turn the spindle under

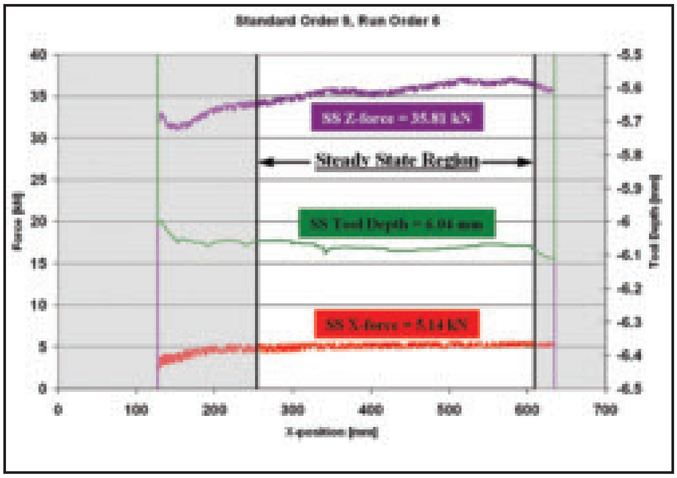

Fig. 5 — Definition of steady-state region used. Responses were averaged over this region.

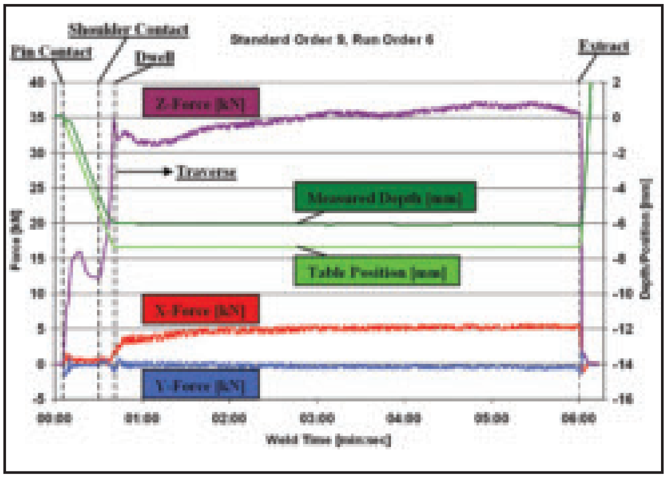

Fig. 6 — Representative plot of weld depths and forces.

load, which includes the power required to overcome frictional losses.

Equipment

Plates were friction stir processed (bead on plate) on a retrofitted Kearney & Trecker knee mill with a PLC/PC controller and data acquisition system. The machine is capable of performing welds over 1000 mm in length and has a maximum travel speed of approximately 790 mm/min. Both Z-position and Z-load control are available. Each axis (X, Y, and Z) is servo-driven and the position and velocity of each axis is monitored and recorded at a frequency of 2 Hz during any weld. The power required by the 22.4-kW spindle motor as well as all other measured parameters discussed hereafter are also recorded at 2 Hz. The spindle has a maximum speed of 1500 rev/min.

Mounted to the bed of the mill is a 1219-mm-long dynamometer capable of sensing forces up to 45 kN in the X-direction, 45 kN in the Y-direction, and 90 kN in the Z-direction with a resolution of 0.004 kN. The maximum possible workpiece width is approximately 305 mm. Fixtures for clamping the workpiece are mounted to the upper surface of the dynamometer.

Conditions unique to the current experiment required that the initial thermal condition of the workpiece and fixtures before each run be controlled. A 15.9-mm-thick liquid-cooled aluminum cooling plate was fabricated. A mixture of ethylene glycol and distilled water was pumped through the plate from a chiller and entered the plate at approximately 20°C. The flow to the plate could be stopped any time by a valve. Coolant inlet temperature, outlet temperature, and a calculated temperature difference (outlet – inlet) for the plate were continually monitored and recorded. A 4.8-mm-thick steel anvil was placed on top of the cooling plate for protection and to give a solid backing surface for the workpiece as shown in Fig. 2.

The material used in this study was AL 7075-T7351 with a thickness of 9.5 mm. The plates were sheared to the nominal dimensions of 680 × 222 mm. The oxide layer was removed with a portable disc sander and the surface was cleaned with methanol prior to processing. The thickness of the plate was predetermined so that only partial penetration welds would be run, eliminating any possible interaction that could exist between the tool and the anvil.

Tools were made from heat-treated H13 tool steel. Key tool dimensions include a shoulder diameter of 25.4 mm, pin diameter of 7.9 mm, and shoulder concav-

Table 2 — Factors and Factor Levels in Screening Design

Standard order	Run order	Spindle speed [rev/min]	Feed rate [mm/min]	Plunge depth [mm]	Pin length [mm]	Weld cooling	X start distance [mm]	Weld location	Preweld cooling [°C]	Dwell time [s]
1	14	300	102	PL + 1.14	4.8	No	25	Edge	3.5	10
2	4	500	102	PL + 1.14	4.8	Yes	25	Center	6	2
3	3	300	203	PL + 1.14	4.8	Yes	127	Edge	6	2
4	15	500	203	PL + 1.14	4.8	No	127	Center	3.5	10
5	5	300	102	PL + 1.40	4.8	Yes	127	Center	3.5	2
6	8	500	102	PL + 1.40	4.8	No	127	Edge	6	10
7	1	300	203	PL + 1.40	4.8	No	25	Center	6	10
8	7	500	203	PL + 1.40	4.8	Yes	25	Edge	3.5	2
9	6	300	102	PL + 1.14	6.4	No	127	Center	6	2
10	9	500	102	PL + 1.14	6.4	Yes	127	Edge	3.5	10
11	12	300	203	PL + 1.14	6.4	Yes	25	Center	3.5	10
12	13	500	203	PL + 1.14	6.4	No	25	Edge	6	2
13	16	300	102	PL + 1.40	6.4	Yes	25	Edge	6	10
14	2	500	102	PL + 1.40	6.4	No	25	Center	3.5	2
15	10	300	203	PL + 1.40	6.4	No	127	Edge	3.5	2
16	11	500	203	PL + 1.40	6.4	Yes	127	Center	6	10

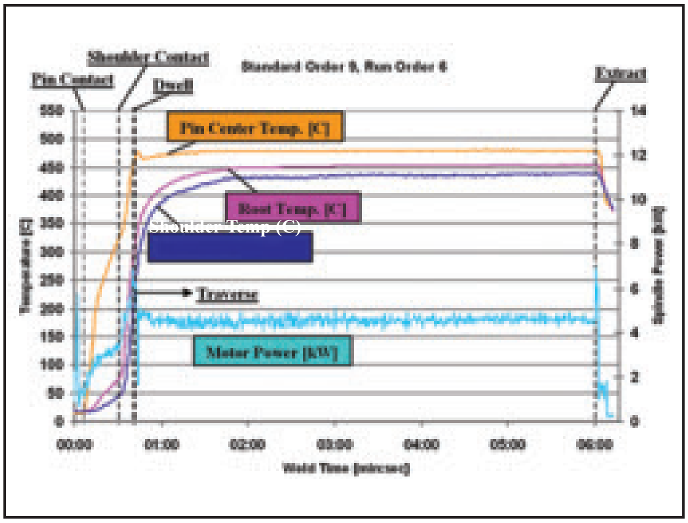

Fig. 7 — Representative plot of tool temperatures and motor power.

ity angle of 6 deg. The pins were threaded with a pitch of 0.91 mm. Pin lengths were 6.4 and 4.8 mm. The tool was used at a tilt angle of 2.5 deg.

Tools were modified to accommodate Type K thermocouples for temperature measurement at three locations within the tool. An EDM drill was used to cut long, straight, squared-bottomed holes to accommodate 1.59-mm-diameter stainless steel sheathed thermocouples at the locations defined in Fig. 3. The titles of each location should be noted (pin center, root, and shoulder). The distance between the thermocouple and tool/workpiece interface at each location was less than 1.27 mm.

A liquid-cooled tool holder was used to minimize heat flow into the machine head, as seen in Fig. 4. The coolant flow rate was approximately 1.9 L/min and is such that while welding there was typically less than 1°C rise in coolant temperature from the inlet of the tool holder to the outlet. Access holes near the top of the tool holder allowed the tool thermocouples to be inserted through the back of the tool.

A transmitting collar assembly is clamped to the rotating portion of the tool holder and houses RF transmitters, which broadcast the thermocouple readings as FM signals. The signals are captured by the receiver by way of a stationary loop antenna. The data are then transferred to the data-acquisition system.

Mounted to the tool holder is an electronic digital indicator for tool depth measurement. It has a range of 25.4 mm and a resolution of 0.02 mm. An extension adapter is connected to the indicator so that weld depth is measured as close to the tool as possible to account for any local changes in tool depth. Readout error associated with attaching such an adapter is estimated to be 0.03 mm or less. The indicator readings are transferred to the data acquisition system throughout the weld.

This digital indicator is used to measure the actual plunge and weld depth as seen in Fig. 4. Due to machine deflection, the programmed plunge depth will not actually be achieved. Thus, it is important to measure the actual tool depth throughout the weld. The indicator is zeroed when the tip of the pin comes into contact with the workpiece.

Friction Stir Processing Procedure

Plates were friction stir processed (FSP) in the following manner. A plate was secured at a predetermined location on the anvil. Preweld cooling was performed to meet the condition specified in the DOE. The plunge sequence was performed at 500 rev/min and at a plunge rate of 12.7 mm/min to the specified depth. The spindle speed during the dwell remained at 500 rev/min. After the dwell, the spindle speed was adjusted to the value dictated by the DOE and the tool began to traverse at a rate of 51 mm/min. The feed rate was then increased at a constant acceleration over a distance of 76 mm until the desired feed rate was obtained. No adjustments in load control or tool depth control were made throughout the processing. Each extract sequence was performed at a spindle speed of 500 rev/min.

Upon completing the 16 welds, the raw data were plotted and organized using a spreadsheet. For each weld, a steady-state (SS) region was identified starting at 127 mm into the weld and ending at 25.4 mm from the end of the weld. For each response of interest, values were averaged over that steady-state region for use in further analysis. This steady-state region, along with the averaged values for three selected responses, is shown in Fig. 5 for the weld listed as standard order 9 (see Table 2).

All extracted data were analyzed using *Minitab*, a statistical software package capable of DOE factorial design analysis. The principal effects of all nine input factors were calculated, and a Pareto chart was created for each given response. This method of analysis shows graphically which factors are most important and significant in reaching a desired response. Conclusions were drawn from the Pareto charts.

Table 3 — Measured Responses Shown in Standard Order (nonrandomized order)

Standard order	SS X-force [kN]	SS Y-force [kN]	SS Z-force [kN]	SS pin center temp. [°C]	SS root temp. [°C]	SS shoulder temp. [°C]	SS motor power [kW]	Shoulder depth [mm]
1	4.942	–0.813	36.453	483	455	446	4.5	0.242
2	4.956	0.089	37.168	515	481	476	5.7	0.200
3	5.558	–0.024	33.719	457	437	435	4.6	0.282
4	7.699	0.542	36.750	503	471	466	5.9	0.336
5	5.320	–0.692	41.987	487	461	454	4.8	0.133
6	4.423	0.155	37.597	515	479	475	5.7	0.073
7	6.518	–0.660	43.879	477	455	447	5.2	0.157
8	7.361	–0.164	44.434	511	478	474	6.4	0.236
9	5.137	–0.374	35.812	480	453	435	4.6	0.276
10	5.394	1.021	33.295	507	470	459	5.6	0.261
11	7.060	0.290	37.617	465	447	438	5.0	0.291
12	8.390	1.115	36.949	501	468	460	6.0	0.305
13	5.371	–0.540	36.218	478	454	440	4.6	0.247
14	6.103	0.956	39.995	513	475	469	5.9	0.084
15	7.237	–0.019	40.560	468	449	439	5.1	0.273
16	8.246	1.219	42.572	506	472	464	6.4	0.174

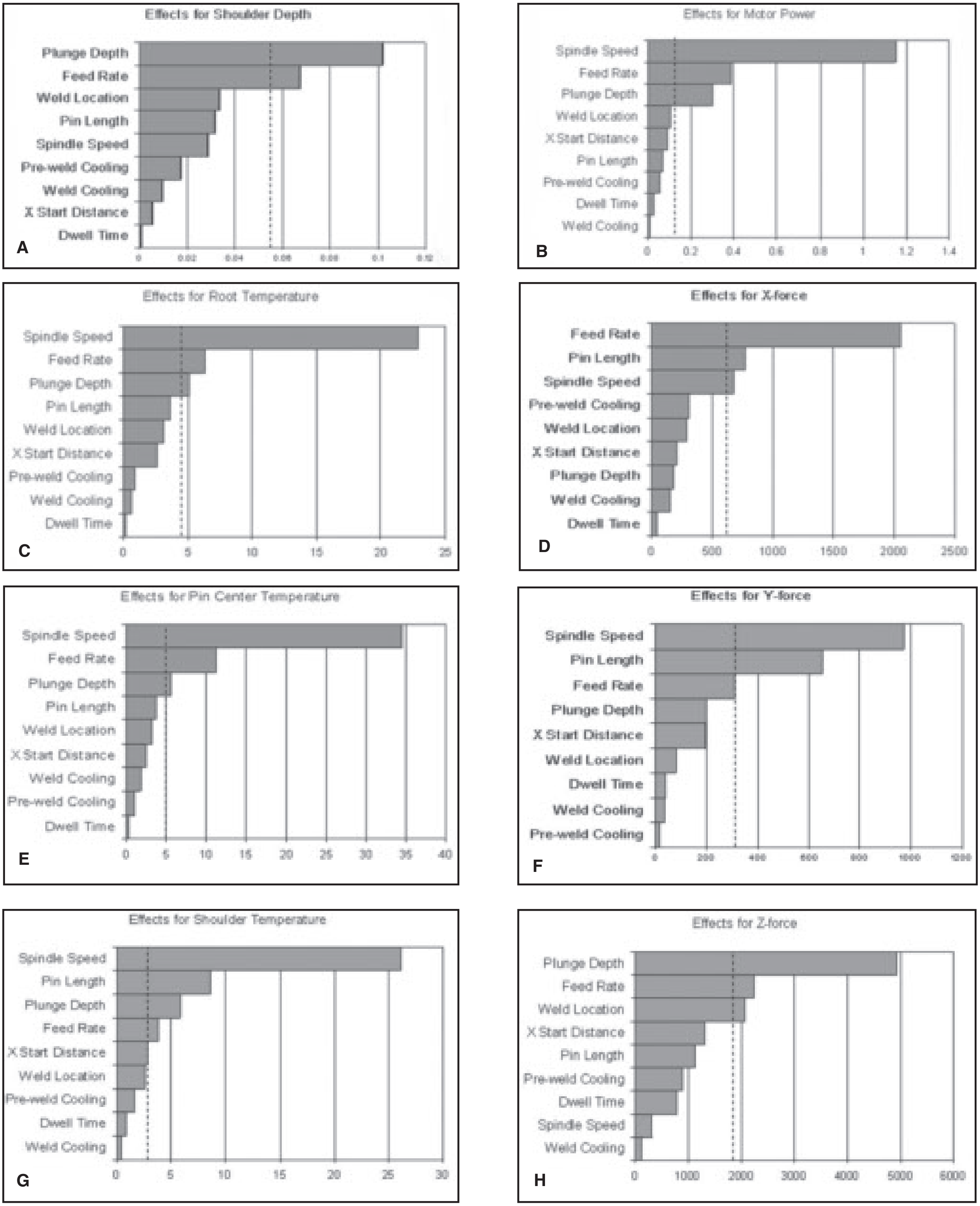

Fig. 8 — Pareto charts of effects of inputs on (A) shoulder depth, (B) motor power, (C) root temperature, (D) X-force, (E) pin center temperature, (F) Y-force, (G) shoulder temperature, and (H) Z-force.

Table 4 — Ranking of Significant Factors for Each Response, One Being the Most Significant

	Responses							
Factor	X-force	Y-force	Z-force	Pin center temp.	Root temp.	Shoulder temp.	Motor power	Shoulder depth
Spindle speed	3	1	–	1	1	1	1	–
Feed rate	1	–	2	2	2	4	2	2
Plunge depth	–	–	1	3	3	3	3	1
Pin length	2	2	–	–	–	2	–	–
Weld location	–	–	3	–	–	–	–	–

Results/Discussion

Temporal Raw Data

Figures 6 and 7 are plots of raw data obtained for the weld listed as standard order 9 and are chosen as representative plots for this study (see Table 2 for input parameters). As noted in the figures, seven of the eight responses and two additional variables (measured depth and table position) are plotted vs. weld time. Measured depth is the actual depth of the tool as measured with the digital indicator and is used to calculate the response shoulder depth. Table position, which is synonymous with plunge depth, is the vertical distance the table travels as dictated by the servomotor. After the plunge sequence, table position and plunge depth are identical in value and do not change until the extract sequence. It should be remembered that these plots are only representative and that each processing run will have its own unique set of values. A brief discussion of these responses as they follow the weld sequence is given below.

As the pin is forced into the material the Z-force increases to approximately 16 kN, then decreases slightly until the shoulder contacts, resulting in the final rise to 35 kN. X- and Y-force traces after shoulder contact are explained in light of the tilt angle of the FSW tool. The rear edge of the shoulder is the first to contact, which, with a counterclockwise rotation in the current setup, produces a negative Y-force. As the pin plunges into the workpiece, the pin center temperature increases, followed by the root and shoulder locations. A more significant rise in temperature at both the root and shoulder locations occurs after the shoulder cavity fills with softened aluminum and as the shoulder comes into intimate contact with the workpiece. As the workpiece material softens during the dwell, the power required by the motor decreases.

No adjustments, load control, or tool depth control were made throughout the processing, which is apparent in the table position trace. The measured depth, however, does not remain constant as it accounts for 0.12 mm of change. The X-force makes an initial jump as the tool begins to traverse and then climbs steadily throughout the traverse, reaching a steady-state value of approximately 5 kN. The Z-force oscillates about a gentle rise throughout the weld, but always remains within 6% of the 35.8 kN steady-state average. The pin center temperature decreases slightly until rising to a steady-state value. The decrease in temperature most likely can be attributed to changes in the spindle speed (this particular weld was reduced to 300 rev/min) and the tool traversing into 'colder' material.

It is notable that the highest measured temperature is at the pin center. This result is consistent for each run in this study. This result is interesting since many analytical approximations for the heat input for FSW attribute maximum heat generation to the outer edge of the shoulder, i.e., at the maximum tool radius (Refs. 11–19). It has been reported that this may also correlate to the location of the maximum tool temperature (Ref. 20). It can be noted that maximum workpiece temperatures have been reported at or near the joint line (Refs. 12, 15, 18, 19, 21, 22). Some have also predicted a maximum temperature near the bottom of the pin when both frictional heating and plastic work are taken into account (Ref. 23). The power required by the spindle remains constant throughout the entire traverse.

Statistical Analysis

A summary of the steady-state averages for each of the chosen eight responses is given in Table 3. The results of the statistical analysis include which 'input' exercises a considerable influence on a response. An effect can be thought of as a proportionality constant relating an input and output. If an equation were to be written, the 'effect' β relates the inputs to a response in the following manner:

$$y = y_o + \frac{1}{2}[\Sigma \beta_i X_i]$$

where y represents the response, y_o is the average response, and β_i is the effect that input parameter X_i has on the response. Thus, the larger an effect is, the greater influence it has in determining the response. The form of this equation is assumed to be linear since there is not enough information in the data to predict any other form.

Figure 8 contains Pareto charts that show the absolute value of the effect, on the x-axis, ranked in decreasing order. The dotted line represents a certain level of significance described by α, which was set to 0.1, a commonly used value. The value α is the probability that the statistical analysis will claim an insignificant effect to be significant. The factors whose effects extend beyond the dotted line are primarily responsible for changes in a given response with a 90% (1- α) confidence level, and are deemed significant.

As α decreases, the dotted line moves to the right, which effectively eliminates more factors but identifies significant factors with a greater certainty. It can be seen that there are only two to four significant factors for each response. Effects may not be compared from one plot to the next in Fig. 8. Table 4 contains a ranking of significant effects (numbered, so "1" is the largest effect) for each response.

Spindle speed, plunge depth, and feed rate are generally the most significant factors that affect the FSW process as confirmed in Fig. 8. The assumption that these factors are the most fundamental is now strengthened. Spindle speed and plunge depth are significant in six of the eight responses. Feed rate is significant in seven of the eight responses. Significant influences of operating parameters on response variables will now be discussed.

Shoulder depth should be affected by plunge depth. This is confirmed in Fig. 8A. Feed rate is also significant as expected. As the feed rate increases, the incoming material will deflect the shoulder so the tool is effectively shallower.

Spindle speed, feed rate, and plunge depth are the three most significant factors in determining motor power as shown in Fig. 8B. Pin length was not shown to be significant, which may be surprising. This may indicate that the shoulder dominates in required motor power, not the pin. Because this study varied the pin length over a small range, the pin length could be significant under other experimental conditions. It is important to note again that motor power in this study is not tool power because it includes losses from friction and the gear train. However, these losses have been quantified through free-wheel experiments to be 1 kW or less for the spindle speeds used in this study.

Common among X- and Z-forces is the significance of feed rate. The most important factors for X-force are feed rate, pin length, and spindle speed as shown in Fig. 8D, 8F, and 8H. The faster a tool is driven through the workpiece and the longer the pin, the larger the required force. It is interesting that plunge depth is not significant for X-force because it has been observed that there is an effect of depth on X-force. Again, there is a heavy dependence of these results on the ranges of parameters used and experimental conditions.

Factors affecting Z-force include plunge depth and feed rate. An unexpected significant effect is weld location. This is likely a good candidate to further consider as an 'environmental' variable that needs to be considered more closely in future studies. It is noted that in welding applications, weld location cannot be controlled. Another unexpected result is that for Z-force, spindle speed has no significant effect as it does for X-force.

For all three thermocouple locations in the tool, spindle speed was the most significant factor in determining temperature. Also common at all three locations is the effect of plunge depth and feed rate. It might be speculated that significant effects for all three temperature locations would be the same. However, this is not the case. Unexpectedly, pin length was a significant factor for the shoulder temperature (Fig. 8G) but not for the pin center and root temperatures.

It is essential to note that this study does not clarify interaction effects between factors. There may be important interactions that are not elucidated here. The screening experiments used in this study do not fully explore all relationships, but only allow identification of the most important ones. Therefore, no conclusion may be made regarding complete relationships. Also, it is vital to note that the significance of these factors is true only for the conditions of this study. For example, a dwell time of 60 s could affect some responses but this study only included 2 and 10 s dwell times.

Weld location and pin length are good candidates to be further controlled as the 'environmental' variables that need to be considered more closely in future studies because of their effect on responses.

This research was performed to provide basic information. It does not seek to comment much on its findings as compared to previous research or to fully explore parameter relationships. This is because results have been contradictory at times. The authors' intent is to 1) identify critical process parameters through a statistical study, 2) present the results publicly, and 3) provide information that other studies may use to fully explore process parameter relationships.

Conclusions

This study used statistical experimentation to study important process parameters and the sensitivity of operating conditions to these process parameters. It is concluded that for the conditions of this study (tool, material, methods, levels, etc.):

- Spindle speed, feed rate, and plunge depth are the three most significant factors of the FSW process.
- Z-force is most affected by plunge depth; feed rate and weld location had secondary effects.
- Spindle speed had no effect on Z-force.
- X-force is most affected by feed rate, followed by pin length, and spindle speed.
- Shoulder temperature is most affected by spindle speed, followed by pin length, plunge depth, and feed rate.
- The location of the weld relative to the sides of the plate affects Z-force.
- The tool temperature at the axis near the end of the pin is higher than the temperature near the root of the pin and at the outside edge of the shoulder.

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References

1. Nishihara, T., and Nagasaka, Y. May 14–16, 2003. *Proceedings of the Fourth International Symposium on Friction Stir Welding.* Park City, Utah: TWI.

2. Lienert, T. J., and Stellwag, W. L. Jr.May 6–10, 2001. *2001 AWS Convention.* Cleveland, Ohio: AWS.

3. Lienert, T. J., Stellwag, W. L. Jr., Grimmett, B. B., and Warke, R. W. 2003. Friction stir welding studies on mild steel. *Welding Journal* 82(1): 1-s to 9-s.

4. Lienert, T. J., Stellwag, W. L. Jr., and Lehman, L. R. May 14–16, 2003. *Proceedings of the Fourth International Symposium on Friction Stir Welding.* Park City, Utah: TWI.

5. Tang, W., Guo, X., McClure, J. C., Murr, L. E., and Nunes, A. C. 1998. *J. Mater. Processing Manufacturing, Sci.* 7: 163–172.

6. Jandric, D., Ouyang, J. H., Valant, M., and Kovacevic, R. December 5, 6, 2001. *11th International Conference on Computer Technology in Welding.* Columbus, Ohio.

7. Colligan, K. J., Xu, J., and Pickens, J. R.: in *Friction Stir Welding and Processing II,* Jata, K. V., Mahoney, M. W., Mishra, R. S., Semiatin, S. L., and Lienert, T., TMS, Warrendale, Pa., 2003, pp. 181–190.

8. Johnson, R. September 26–28, 2001. *Proceedings of the Third International Symposium on Friction Stir Welding.* Kobe, Japan: TWI.

9. Reynolds, A. P., and Tang, W.: *Friction Stir Welding and Processing,* Jata, K. V., Mahoney, M. W., Mishra, R. S., Semiatin, S. L., and Field, D. P., TMS, 2001, pp. 15–23.

10. Record, J., Covington, J., Nelson, T., and Sorensen, C. 2003. Unpublished work.

11. Chen, C., and Kovacevic, R. 2003. *Int. J. Mach. Tool. Manu.* 43: 1319–1326.

12. Chao, Y. J., and Qi, X. 1998. *J. Mater. Processing Manufacturing, Sci.* 7: 215–233.

13. Chao, Y. J., Qi, X., and Tang, W. February 2003. *J. Manu. Sci. E-T ASME* 25(1): 138–145.

14. Colegrove, P. June 26–28, 2000. *Proceedings of the Second International Symposium on Friction Stir Welding.* Gothenburg, Sweden: TWI.

15. Khandkar, M. Z. H., Khan, J. A., and Reynolds, A. P. 2003. *Sci. Technol. Weld Joi.* 8(3): 165–174.

16. Khandkar, M. Z. H., and Khan, J. A. 2001. *J. Mater. Processing Manufacturing, Sci.* 10: 91–105.

17. Reynolds, A. P., Khankdar, Z., Long, T., Tang, W., and Khan, J. 2003. *Mater. Sci. Forum* 426–432(4): 2959–2964.

18. Shi, Q., Dickerson, T., and Shercliff, H. R. May 14–16, 2003. *Proceedings of the Fourth International Symposium on Friction Stir Welding.* Park City, Utah: TWI.

19. Song, M., and Kovacevic, R. 2003. *Proc Instn Mech Engrs Part B: J Eng Manuf* 217(1): 73–85.

20. Ulysse, P. 2002. *Int. J. Mach. Tool. Manu.* 42(14): 1549–1557.

21. Askari, A., Silling, S., London, B., and Mahoney, M.: *Friction Stir Welding and Processing,* Jata, K. V., Mahoney, M. W., Mishra, R. S., Semiatin, S. L., and Field, D. P., TMS, 2001, pp. 43–54.

22. McClure, J. C., Tang, W., Murr, L. E., Guo, X., Feng, Z., and Gould, J. E. June 1998. *Trends in Welding Research*, ASM International, pp. 590–595.

23. Dong, P., Lu, F., Hong, J. K., and Cao, Z. 2001. *Sci. Technol. Weld Joi.* 6(5): 281–287.