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STATISTICAL MODELING AND PREDICTION OF WEAR IN FRICTION STIR WELDING OF A METAL MATRIX COMPOSITE (AL 359/SIC/20P)

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Abstract

This paper examines the relationship between tool wear and process parameters in Friction Stir Welding (FSW) of a Metal Matrix Composite (Al 359/SiC/20p). Metal Matrix Composites (MMCs) are superabrasive materials which consist of ceramic particles dispersed throughout a larger metal matrix. Fusion welded MMC joints are characterized by porosities in the heat affected zone, disturbances in the particle distribution which translate to a reduction in weld strength, and the formation of a deleterious theta phase (Al_4C_3) caused by localized melting. Though these effects can be somewhat mitigated through careful control of heat input, a solid-state joining process such as FSW is a more viable alternative. However, FSW of MMCs is severely complicated by rapid tool wear, a consequence of the contact between the tool and the abrasive particles which give the material its enhanced strength.

The Taguchi method, a statistical analysis technique frequently used in manufacturing engineering, is used to characterize the degree of influence that rotation speed, traversal rate, and length of the weld joint have on wear in FSW of MMCs. The result of this analysis is an empirically derived equation which expresses the dependence of tool wear on the specified process parameters. The software PASW and cross-validation techniques are used to assess the predictive capabilities of the multiple regression model.

Keywords: Friction Stir Welding; Metal Matrix Composites; Tool Wear; Taguchi Method

List of Symbols and Abbreviations

FSW Friction Stir Welding
MMC Metal Matrix Composite
ω rotations speed (rotations/min)
v traverse rate (inches/min)

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l	length of weld (inches)
W	wear of tool probe (expressed as a percent)
P	pixel count of cross-sectional image of tool probe prior to welding
P'	pixel count of cross-sectional image of tool probe after a specified weld distance

1. Introduction

Friction Stir Welding (FSW) is a joining technique developed by The Welding Institute (TWI) of Cambridge, England in 1991 (Thomas et al., 1991). In traditional FSW, a cylindrical rotating tool is plunged into the workpiece, resulting in local plasticization of the material due to shear stress. As the tool traverses along the joint line, the material behind the weld consolidates, forming a welded region consistent with the width of the tool shoulder. As a solid state process, FSW offers several distinct advantages over fusion welding: reduced distortion in the weld zone, the enhanced repeatability inherent in an autogenous process, and lower power requirements (energy input for FSW is estimated as 2.5 percent of that required for a laser weld) (Mishra & Ma, 2005). Additionally, FSW joints typically do not require post-processing (heat treatment, surface grinding, etc.) Applications of FSW are most commonly found in the aerospace industry, where it is used to join materials which are difficult to fusion weld (particularly the Al 2XXX and 6XXX series). In the late 1990s, NASA began using FSW for circumferential welds of the space shuttle's external fuel tank, which is fabricated from Al-Li 2195. NASA has also chosen FSW as the preferred joining method for the Constellation architecture: the upper stage of the Ares I and the Crew Exploration Vehicle (CEV) are two of the structural components which utilize FSW (Ding et al, 2006).

An emerging area of FSW research which is of particular interest to the aerospace industry is the joining of Metal Matrix Composites (MMCs), superabrasive materials valued for their high strength to weight ratio. Due to their high cost and difficulty to machine, MMCs remain a largely application-driven industry, typically reserved for use in structures where the increased strength justifies the additional investment (Kunze & Bamptom, 2005). An MMC material is comprised of two parts: a continuous metal matrix and the harder, reinforcing particles dispersed throughout the matrix. Aluminum MMCs are classified in accordance with standards set forth by the Aluminum Association (Stellwag & Lienert, 2001). For instance, Al 359/SiC/20p indicates that the material consists of 20% Silicon Carbide particulate and 80% Al 359.

As documented by Storjohann et al. (2005), a fusion welded MMC joint is characterized by porosity in the heat-affected zone, the dissolution of reinforcing particles, and the formation of a deleterious theta phase (Al_4C_3) caused by localized melting. Though Storjohann et al. found that these defects could be reduced or eliminated through careful control of the heat input, they conclude that a solid-state joining process such as FSW is a more viable alternative. FSW of MMCs, however, is not without its own set of unique problems, the chief among these being rapid tool wear. Although the physical mechanism underlying tool wear in the FSW of composites is not well-understood, previous experimental studies have attempted to characterize the dependence of wear on process parameters. An investigation published bv Prado et al. (2003) provides a preliminary assessment of the wear of cylindrical threaded tools in the butt welding of Al 6061/Al_2O_3/20p. Prado et al. (2003) observed that the most dramatic wear coincided with higher rotation speeds and lower traverse rates. Data reported in an analogous study by Fernandez and Murr (2003), which considers butt welds of Al 359/SiC/20p, supports a similar conclusion. This paper is not an attempt to reproduce the results of the previous researchers, but instead seeks an empirically based statistical model which can predict tool wear in the joining of the composite material Al 359/SiC/20p. The experiment which serves as the basis for this model utilizes a Taguchi design with three factors at three levels, which together comprise an L_{27} orthogonal design matrix.

2. Experimental Design

The process parameters considered in this study (rotation speed, traverse speed, and length of weld) were selected based on the apparatus limits of the FSW test bed in the Vanderbilt Welding Automation Laboratory. In Taguchi nomenclature, these parameters comprise the factors which are hypothesized to influence the response parameter, tool wear. The levels of the factors were chosen based on the apparatus limits of the Vanderbilt University Welding Automation Laboratory (VUWAL), which uses a Milwaukee #2K Universal Milling Machine modified for FSW. Table 1 summarizes the factors and levels considered in this experiment. The Taguchi methodology used in this work is similar to that used in other published studies, including investigations which characterize tool wear incurred in drilling of metal composites (Davim, 2003a) and tool wear associated with turning of these materials (Davim 2003b).

Table 1. Factors and levels for experimental study

Factor	Level 1	Level 2	Level 3
Rotation speed (RPM)	1000	1500	2000
Traverse speed (IPM)	5	7	9
Length of weldment (inches)	8	16	24

These factors and levels comprise twenty-seven (3^3) test cases, which are represented by the tree diagram in Figure 1 (Berger & Maurer, 2002). The factors in the array are orthogonal (uncorrelated) and each case occurs with equal probability.

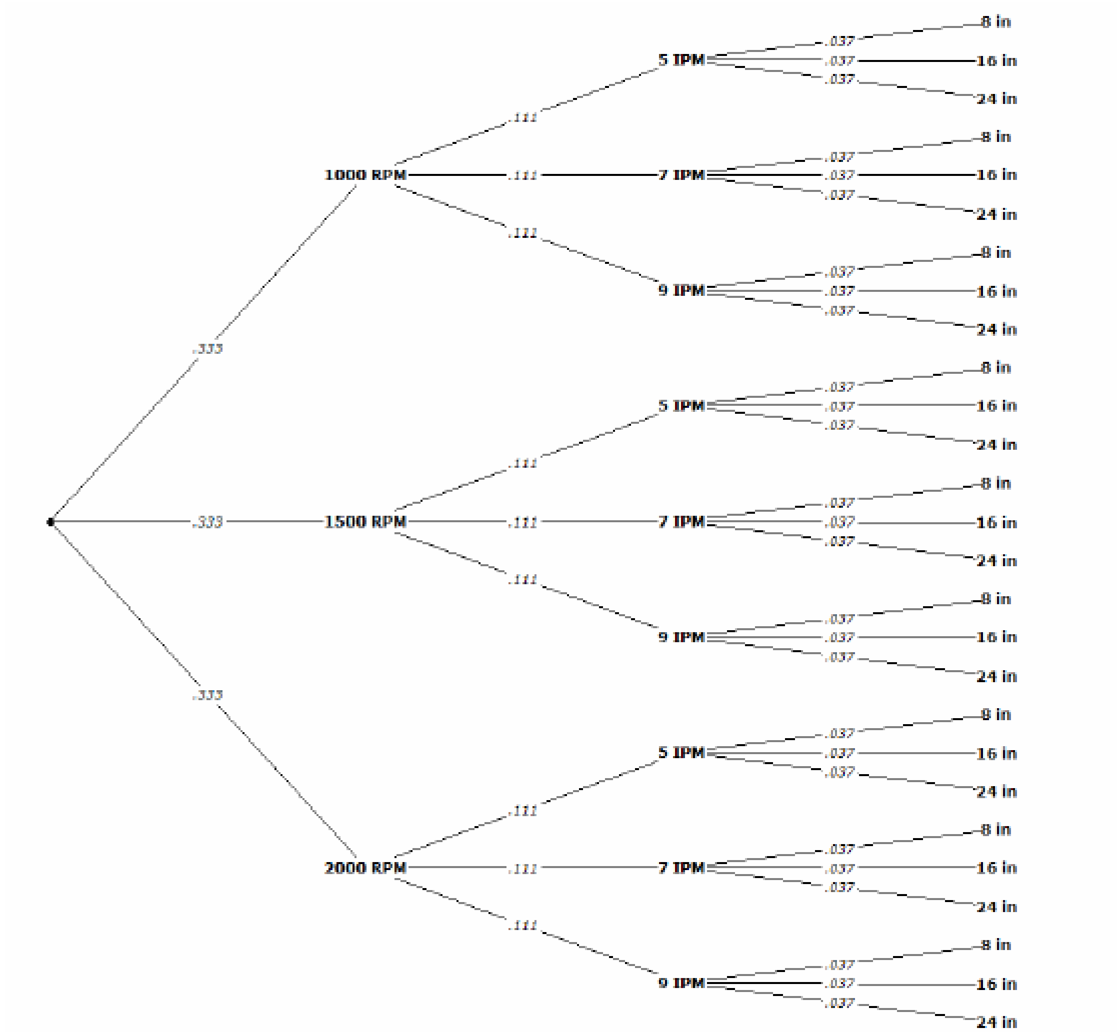

Figure 1. Tree diagram of twenty-seven test cases (values for levels appear in bold and the corresponding probability is indicated to the left of a particular level).

3. Experimental Procedure

Commercial-grade Al 359/SiC/20p material was provided by mc21, a composites manufacturer based in Carson City, Nevada. The material was sheared into rectangular plates measuring 8”x1.5”x.2”; for the experiments, two such plates are aligned adjacently in a butt joint configuration. The tool geometry selected for this experiment was the Trivex, an approximately triangular probe shape which arose from the CFD modeling work of TWI researchers Shercliff and Colegrove (2006), who found that it was effective in reducing traversing forces by 18 to 25 percent and the axial force by as much as 12 percent. The surfaces of the probe are convex and the three vertices, when connected, form an equilateral triangle. Each vertex is located at the center of a circle which contains the other two vertices. The outline of the Trivex shape is shown in Figure 2, which displays a two-dimensional top view of the probe.

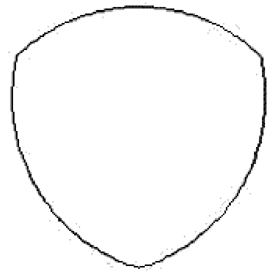

Figure 2. Top view of Trivex probe.

The force reduction associated with use of the Trivex tool makes it ideally suited for the joining of composite materials, in which the tool is subjected to higher forces than in the FSW of an unreinforced Aluminum alloy. Additionally, the Trivex's dynamic volume, the ratio of swept area to probe area , is significantly larger than that of a smooth cylindrical probe. This increased dynamic volume facilitates stirring of the material, which helps to reduce the occurrence of weld defects caused insufficient flow (such as wormholes or voids). The steel Trivex tools used in this study had a swept diameter of 0.25" and a probe length of .185"; the shoulder diameter was 0.75." Samples were welded at a one degree angle of tilt with a plunge depth of 0.009".

Although there were twenty-seven test cases considered in this study, only nine tools were required for the experiments. Each tool corresponded to a particular combination of rotation and traverse speed and was used to weld three eight inch samples in succession. At the completion of each weld, excess Aluminum was removed from the probe by submerging it in a solution of water and Sodium Hydroxide Reagent Grade pellets. The tool was then mounted in an optics bench and close-up images of the probe were taken using a Canon A620 Powershot camera. These images were imported into the imaging software Photoshop, where the wear of the probe was quantified by comparing pre-weld images of the probe with those taken after a given weld traverse distance. The percent tool loss was calculated using equation 1, where P represents the original pixel count of the probe and P' represents the probe's pixel count after some weld distance. A 1 cm square grid fixed behind the tool was used to convert measurements from pixels to square centimeters.

$$\frac{(P - P')}{P} \text{ x } 100\% \qquad \text{(equation 1)}$$

Figure 3 shows the progression of tool wear for a rotation speed of 2000 RPM and a traverse speed of 7 IPM. The features of the Trivex are eroded after only eight inches of weld. After three welds (a weld distance of twenty-four inches), the probe geometry begins to resemble that of a smooth cylinder. The loss of tool material caused by wear is equally discernable in Figure 4, which overlays the images for the 1500 RPM, 7 IPM case.

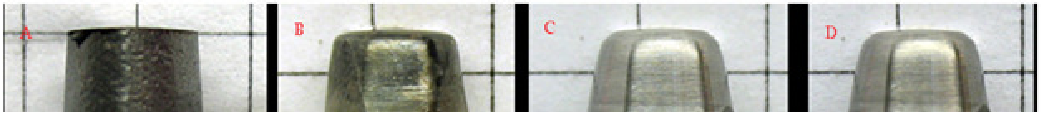

Figure 3. Evolution of wear for 2000 RPM, 7 IPM. A) original probe B) after 8 inches of weldment C) after 16 inches of weldment D) after 24 inches of weldment.

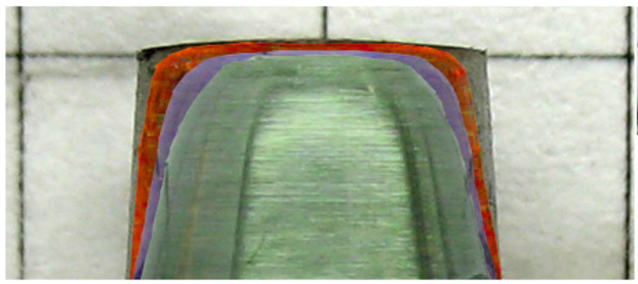

Figure 4. Overlay of tool probe images for 1500 RPM, 7 IPM case.

4. Analysis

The data for the test cases is summarized in Table 2.

Table 2. Array for rotation speed, traverse rate, distance welded and total wear

test	rotation speed (rpm)	traverse rate (in/min)	distance welded (in)	total wear (%)
1	1000	5	8	3.69
2	1000	5	16	5.92
3	1000	5	24	7.55
4	1000	7	8	1.24
5	1000	7	16	2.75
6	1000	7	24	3.79
7	1000	9	8	1.42
8	1000	9	16	4.67
9	1000	9	24	4.97
10	1500	5	8	5.83
11	1500	5	16	15.63
12	1500	5	24	16.05
13	1500	7	8	2.97
14	1500	7	16	12.3
15	1500	7	24	17.16

Table 2. (Continued)

test	rotation speed (rpm)	traverse rate (in/min)	distance welded (in)	total wear (%)
16	1500	9	8	4.03
17	1500	9	16	6.55
18	1500	9	24	15.59
19	2000	5	8	8.37
20	2000	5	16	15.39
21	2000	5	24	25.22
22	2000	7	8	7.15
23	2000	7	16	11.70
24	2000	7	24	17.58
25	2000	9	8	4.04
26	2000	9	16	10.07
27	2000	9	24	14.95

A statistical analysis of the data in the Taguchi L_{27} array was performed using the software package PASW Statistics 17. Least-squares multiple regression was used to construct seven models, which are detailed in Table 3. Though the predictors for each model differ, the outcome variable (percent tool wear) is the same for all cases. Predictors were entered simultaneously using the forced entry method.

Table 3. Multiple regression models for wear of Trivex tool

Model Number	Predictors	R	R^2	Adjusted R^2	F change	Sig. F Change
1	ω	0.585	0.342	0.316	13.006	0.001
2	ν	0.279	0.078	0.041	2.102	0.160
3	l	0.627	0.393	0.369	16.204	0.000
4	ω,ν	0.648	0.420	0.371	8.682	0.001
5	ω, l	0.858	0.735	0.713	33.862	0.000
6	ν, l	0.686	0.471	0.427	10.677	0.000
7	ω, ν, l	0.902	0.813	0.789	33.339	0.000

The multiple regression coefficients R for the models suggest that the predictors which most strongly correlate with tool wear are rotation speed ω and length of weld l. Model 5, which includes both of these predictors, has an R value of 0.858 and an R^2 value of 0.735, indicating that the choice of these parameters accounts for 73.5 percent of the variability in tool wear observed in our sample. The best-fitting linear model is model 7, which includes all three predictors and has an R^2 value of 0.813. Hence the inclusion of the additional predictor ν (travel speed) improves the predictive ability of the model by7.8 percent (for comparison, the predictors ω and l, which correspond to rotation speed and length of weld, account for 34.2 percent and 39.3 percent of the variance, respectively). The adjusted R^2 value for this model, 0.789, differs from R^2 by only 0.024, an indication that the model should generalize well. The ability of the model to account for the variance in tool wear is thus expected to shrink by 2.4 percent (0.788-0.76) when applied to the general population. Though a cursory comparison of the R^2 and adjusted R^2 values can provide a quick assessment of the model's applicability, cross-validation techniques are needed before conclusions can be drawn regarding the model's efficacy. The F statistics which appear in Table 3 measure the significance of the changes in R^2. All models (with the exception of model 2, which considers travel speedas a single predictor) are significant at the 0.001 level.

Table 4. ANOVA table for tool wear model with ω, ν, and *l* as predictors

	Sum of Squares	Df	Mean Square	F	Sig.
Regression	812.749	3	270.916	33.339	1.5E-08
Residual	186.903	23	8.126		
Total	999.652	26			

The ANOVA table for the linear multiple regression model which includes all predictors (model 7) is shown in Table 4. Based on its comparatively large F-value and significance at the 0.001 level, the three-predictor model was retained for further study. The unstandardized coefficients β_i for the tool wear model are summarized in Table 5. The significance values reported for these coefficients are based on the results of the t- test.

Table 5. Unstandardized coefficients for tool wear model

	β_i	Sig.
Constant	-6.028	0.091
l	0.584	0.000
ν	-1.038	0.005
ω	0.009	0.000

In equation form,

$$W = 0.584l - 1.038\nu + 0.009\omega - 6.028 \qquad \text{(equation 2)}$$

where W is percent total tool wear, l is distance welded (in inches), ω is rotation speed (rpm), and ν corresponds to rate of traverse (inches per minute). The regression model is interpreted in terms of the linear weights β_i which map the predictor variables to the outcome variable:

a unit increase (1 RPM) in rotation speed corresponds to a 0.009 percent increase in wear

a unit increase (1IPM) in travel speed coincides with a 1.038 percent decrease in wear

increasing the length of the weld by 1 inch increases the wear by 0.584 percent

The relationships indicated by the regression model are consistent with the results of Prado et al. (2003) in that tool wear is directly proportional to length of weldment and rotation speed and inversely proportional to traverse rate. Based on the significance values of the coefficients (Table 5) and the R values for the various regression models (Table 3), rotation speed and traverse speed are the parameters which have the strongest influence on the wear of the tool. While still significant at the $p<.005$ level, traverse rate has less of an impact on percent wear than ω and/or l.

The regression model is represented in space as three parallel planes in Figure 5; each of the planes corresponds to a specified length of weld and is obtained by substituting l = 8, 16, or 24 inches into equation (2). From the plot, it is apparent that the parameters which minimize wear coincide with low rotation speeds and high rates of traverse. This result seems to agree with an intuitive understanding of the wear process: for a constant weld length, slower RPM and faster traverse rates reduce the amount of time the tool is in contact with the material (and in turn, the abrasive particles which are responsible for wear). Hence our regression model does not imply that the choice of process parameters causes wear directly, but rather that parameter selection influences a latent variable, amount of contact, which governs wear of the tool.

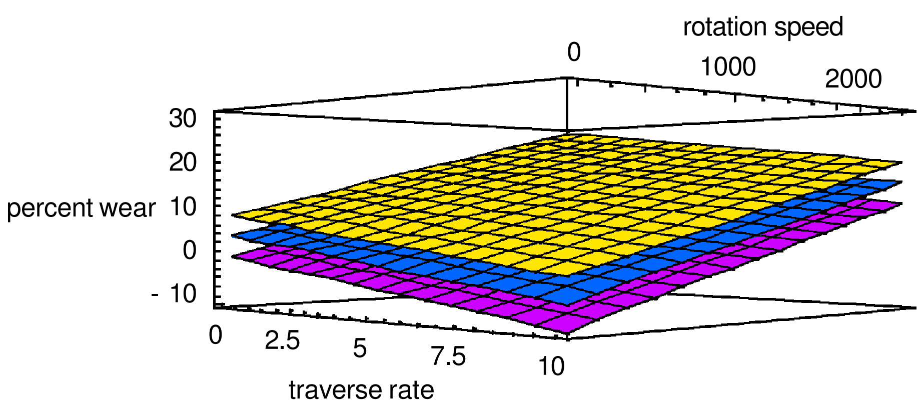

Figure 5. Regression model for Trivex tool. Wear is plotted on the z-axis as a function of traverse speed (x) and rotation speed (y). Each regression plane represents one of three weld lengths: from bottom to top, l = 8 inches, 16 inches, and 24 inches.

It is important to note that the experimental matrix was designed solely to evaluate the effect of process parameters on tool wear; for the purposes of our study, the quality of the resultant weld is a peripheral concern. Microscopic evaluation of the weld cross-sections reveals that all welds, with the exception of the 1500 RPM, 5 IPM case, exhibit wormhole defects. These observed flaws may be a consequence of poor parameter selection (which can result in insufficient heating), the erosion of probe features due to wear (associated with reduced vertical flow), or a combination of both. A central issue in joining MMCs seems to be negotiating a compromise between tool wear and weld quality. From an industry-cost standpoint, parameters should be chosen which will ensure sufficient heating and consolidation of material necessary to produce a strong weld, yet mitigate severe wear of the tool.

5. Cross-Validation Study

Although the R^2 value indicates that the linear model is a good representation of the data in Table 2, the efficacy of the model can be further assessed through cross-validation. Cross-validation studies are used to test the predictive power of the model by applying the regression equation to a separate data set (with the same predictors) than that which was used to construct the model. A popular cross-validation technique which does not require the generation of additional data points is data splitting. Data splitting, as its names implies, involves random extraction of a portion of the data which is used to construct a regression model; the remaining data points can then be compared with the outcome predicted by the model. Unfortunately, the small number of data points in our set precludes use of this method. As an alternative, a few additional welds were performed at parameters different from those used to formulate the multiple regression model. The four parameters chosen for the cross-validation test are listed in Table 6.

Table 6. Parameters for Cross-Validation Study.

Test	ω (rpm)	v (in/min)	l (in)
A	1250	5	8
B	1750	9	8
C	1750	9	16
D	1400	6	8

Table 7 compares the values for percent wear obtained under these conditions with those predicted by the model. The maximum percent error is for case A, which underpredicts the amount of tool wear by 13 percent. Though there are slight discrepancies between the actual and predicated values of percent wear, the measured values exhibit behavior consistent with the trend predicted by the regression model. For instance, cross-validation parameters with comparatively larger values of $\frac{\omega l}{v}$ (such as case C) correspond to greater wear.

Table 7. Comparison of Actual and Predicted Percent Wear Values

Test	Percent Wear (Measured)	Percent Wear (Predicted)	Percent Error
A	5.45	4.72	13.39
B	4.95	5.05	-2.02
C	10.06	9.72	3.38
D	5.45	5.02	7.89

6. Conclusions and Discussion

Tool wear in the Friction Stir Welding of the Metal Matrix Composite Al 359/SiC/20p was characterized for various process parameters using a Taguchi L_{27} orthogonal array. Three factors (rotation speed, traverse rate, and length of weld) were correlated with a single outcome variable, percent tool wear. The multiple regression model ($W = 0.584l - 1.038\nu + 0.009\omega - 6.028$ with an R^2 value of 0.81) indicates that wear is strongly dependent on process parameters. This relationship is of the form $W \propto \frac{\omega l}{\nu}$, where wear W, is inversely proportional to traverse rate, ν, and directly proportional to rotation speed, ω, and length of weld, l.

It should be noted that the accuracy of the model hinges largely on the soundness of our methods for measuring wear. Wear measurements obtained using imaging software are found in the literature (Prado et al., 2003) but employing this methodology rests on two major assumptions:

i) Wear is confined to the probe. Although mechanical gauging does not indicate the length of the probe is increasing, it is possible that some shoulder wear occurs. Previous research has suggested that wear of the shoulder is nominal (Liu et al. 2003).
ii) Wear is symmetric. We assume that the wear observed for the imaged cross-section is characteristic of the amount of wear for other (unimaged) regions of the probe.

The wear measurements are additionally dependent on the contrast capabilities of the camera and the lighting, which clearly delineate the boundary between the edge of the probe and the grid background. The definition of this boundary is of critical importance for the subsequent area calculations. Although photographic methods have some limitations, they tend to be more accurate than mechanical gauging methods.

The factors considered in the experiments were chosen based on previous studies in the literature (Prado et al., 2003; Fernandez & Murr, 2003; Liu et al., 2005). Though the trends predicted by our model are consistent with those reported by Fernandez and Murr (2003), the R^2 value for the three-predictor model indicates that approximately 19 percent of the variability of tool wear in our sample cannot be accounted for by the process parameters (rotation speed, travel rate, and distance welded) included in the design of experiments. This suggests the existence of additional factors which may influence the wear rate. Subsequent studies should consider the effects of tool geometry, percentage reinforcement of the composite material, size and type of reinforcement particles, and/or tilt angle on wear.

The model also tells us little about the mechanism by which wear occurs. We have assumed that the wear is abrasive, initiated by contact between the tool and the abrasive reinforcing particles. However, tribological studies are necessary to determine if there are additional components of wear that are not abrasive, such as adhesion or fretting. The functional relationship between wear and process parameters derived from the multiple regression model may provide additional insight into the wear mechanism. The proportionality between wear and process parameters ($W \propto \frac{\omega l}{\nu}$) is a bit on the nonintuitive side, since wear is usually regarded as a drag phenomenon. If that were the case, the amount of wear would be expected to increase with increasing travel speed, v;

instead, the opposite is observed. The inverse relation between travel rate and wear suggests that wear is governed by shear phenomena, an idea which will be explored in future research. It is hoped that a fundamental understanding of the wear process will point toward tool designs or selection of parameters which reduce the amount of wear.

As a final caveat, the statistical model developed in this study is specific to the Trivex tool and the experimental setup of the Vanderbilt University Welding Automation Laboratory. Future work will focus on the use of dimensionless parameters (such as the $\frac{\omega l}{v}$ term) to reduce the number of variables and thus expand the applicability of similar empirically derived wear models for FSW.

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