CHAPTER

Manufacturing Challenges Associated with the Use of Metal Matrix Composites in Aerospace Structures

Tracie Prater, Ph.D.

NASA Marshall Space Flight Center, Huntsville, AL, 35811, USA

Abstract: Metal Matrix Composites (MMCs) consist of a metal alloy reinforced with ceramic particles or fibers. These materials possess a very high strength to weight ratio, good resistance to impact and wear, and a number of other properties which make them attractive for use in aerospace and defense applications. MMCs have found use in the space shuttle orbiter's structural tubing, the Hubble Space Telescope's antenna mast, control surfaces and propulsion systems for aircraft, and tank armors. The size of MMC components is severely limited by difficulties encountered in joining these materials using fusion welding. Melting of the material results in formation of an undesirable phase (formed when molten Aluminum reacts with the reinforcement) which leaves a strength depleted region along the joint line. Friction Stir Welding (FSW) is a relatively nascent solid state joining technique developed at The Welding Institute (TWI) in 1991. The process was first used at NASA to weld the super lightweight external tank for the Space Shuttle. Today FSW is used to join structural components of the Delta IV, Atlas V, and Falcon IX rockets as well as NASA's Orion Crew Exploration Vehicle and Space Launch System. A current focus of FSW research is to extend the process to new materials, such as MMCs, which are difficult to weld using conventional fusion techniques. Since Friction Stir Welding occurs below the melting point of the workpiece material, this deleterious phase is absent in FSW-ed MMC joints. FSW of MMCs is, however, plagued by rapid wear of the welding tool, a consequence of the large discrepancy in hardness between the steel tool and the reinforcement material. This chapter summarizes the challenges encountered when joining MMCs to themselves or to other materials in structures. Specific attention is paid to the influence of process variables in Friction Stir Welding on the wear process characterizes the effect of process parameters (spindle speed, traverse rate, and length of joint) on the wear process. A phenomenological model of the wear process was constructed based on the rotating plug model of Friction Stir Welding. The effectiveness of harder tool materials (such as Tungsten Carbide, high speed steel, and tools with diamond coatings) to combat abrasive wear is also explored. In-process force, torque, and vibration signals are analyzed to assess the feasibility of in situ monitoring of tool shape changes as a result of wear (an advancement which would eliminate the need for off-line evaluation of tool condition during joining). Monitoring, controlling, and reducing tool wear in FSW of MMCs is essential to implementation of these materials in structures (such as launch vehicles) where they would be of maximum benefit. The work presented here is extendable to machining of MMCs, where wear of the tool is also a limiting factor.

***Address correspondence to Tracie Prater:** NASA Marshall SpaceFlight Center, Huntsville, AL, 35811

Keywords: Metal Matrix Composites, Friction Stir Welding, tool wear, materials joining, advanced manufacturing

NOMENCLATURE

FSW   Friction Stir Welding
MMC   Metal Matrix Composite
RPM   Rotations per minute
SiC   Silicon Carbide
ℓ Length of joint (inches)
ν Traverse rate (inches per minute)
ω Rotation rate (rotations per minute)
W Wear experienced by the tool during welding
D Characteristic reinforcement particle diameter
δ Width of the rotating plug
δ_0 Width of the rotating plug at angular position $\theta = -\pi/2$
δ_{max} Maximum width of the rotating plug
θ Angular position in x-y plane
P Reinforcement fraction expressed as a percentage of workpiece volume
ΔC Cutting arc (angular region where abrasion can occur)
ΔC_{max} Maximum cutting arc
σ Flow stress
t Plunge depth
T_{total} Total torque
R_a Average surface roughness
R_t Peak to valley roughness
R Tool shoulder radius
r Pin shoulder radius

INTRODUCTION

The reliance on ballistic techniques in launch architectures means that weight is often the driving consideration in spacecraft designs. While the lift capacities of vehicles based on current propulsion technologies vary widely, cargo weights comprise only a small portion (typically less than 5 percent) of the vehicle's weight at launch; the vast majority of a rocket's launch weight is derived from structural components and fuel. The structural efficiency of a vehicle can be improved by decreasing the vehicle's dry weight, which translates into increased cargo capacity.

One way to achieve weight reduction is through the selection of lighter materials. The aerospace industry relies primarily on Aluminum alloys, materials

which are lightweight, strong, well-characterized, and abundant. However, the development of advanced materials, in particular composites, has opened the door to even lighter structures which satisfy (and in many cases exceed) the mechanical criteria established for flight-rated hardware. In 2001, NASA changed the material used for the space shuttle's external tank from Al 2219 to an Aluminum-Lithium composite (Al-Li 2195) developed by Lockheed Martin, a substitution which reduced the total weight of the external tank by 7,500 pounds [1]. This reduction enabled the space shuttle to transport the heavier components of the International Space Station slated for the transport system's final flights (and gave NASA the option to consolidate multiple components into a single flight, a significant cost savings over the alternative of multiple launches). The application of traditional fusion welding techniques to join the composite material resulted in mechanically deficient joints. Friction Stir Welding (FSW), a solid-state joining technique pioneered by The Welding Institute (TWI) of Great Britain, was shown to yield defect-free Al-Li 2195 joints with superior mechanical properties. The Friction Stir Welding process is illustrated in Figure 1. With the success of the external tank program, NASA converted much of its manufacturing to utilize the FSW process. The primary structures for NASA's Space Launch System (SLS) and the Orion Crew Exploration Vehicle (CEV) rely extensively on the process to produce reliable, defect free joints.
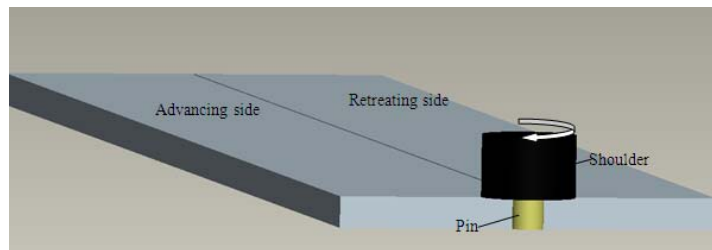

Fig. 1: Illustration of friction stir welding process. The tool, which consists of a pin that penetrates the workpiece material and a larger diameter shoulder that rests on the surface of the material, rotates at rate ω. As the tool advances through the material at traverse speed v, it picks up plasticized material on the advancing side and deposits it on the retreating side. Material behind the tool cools and consolidates to form a welded region.

Since the international space community will be reliant on ballistic launch architectures for the forseeable future, the industry will continue its push for lighter materials, particularly composites, which may require advanced material processing and welding techniques. While FSW is considered a mature process for many Aluminum alloys (including the 2000, 6000, and 7000 series), there is considerable interest in expanding the process to other materials, such as steels, Magnesium alloys, and even Titanium. Another class of materials which are especially amenable to FSW are metal matrix composite (MMCs). MMCs are dual

phase materials which consist of a ceramic reinforcement embedded in a metal alloy (the matrix). They are classified according to the type of reinforcement (reinforcements are typically ceramics such as Silicon Carbide or Aluminum Oxide, but may be in the form of either particulates or fibers), the amount of the reinforcement material that is present (expressed as a percentage of the material's total weight or volume), and the metal alloy which comprises the matrix. The advantages of metal composites lie in their very high strength to weight ratio (which may be more than twice that of conventional Aluminum alloys), temperature resistance, wear resistance, and fatigue life. Fusion welding of these materials produces joints characterized by porosity and cracking [2]. Additionally, the mechanical properties of the joint are negatively impacted by the presence of Al_4C_3, an undesirable precipitate formed by the reaction of molten Aluminum with the reinforcement [3]. Since FSW occurs below the melting point of the matrix alloy, the deleterious theta phase is absent in welds produced using this process. The major barrier to FSW of MMCs is rapid and severe wear of the tool, a consequence of the contact between the tool (typically fabricated from a steel alloy) and the comparatively harder reinforcement particles [3]. Progressive wear of the tool removes features which facilitate material stirring, an effect which increases the likelihood of void development [4].

PROBLEM DESCRIPTION

Since large defects typically coincide with deterioration in mechanical properties, it is important to preserve the tool shape which promotes material stirring and diminishes the probability of a defect formation. When a defect becomes larger as wear progresses, the potential for mechanical failure of the weld may also increase. Preventing unacceptable defects which stem from wear is critical if MMCs are to be used as structural materials in safety-critical aerospace applications, particularly structures which support human spaceflight. To prevent weld-related structural failures, NASA and its commercial partners invest significant time and research into post-process inspection and non-destructive testing techniques (such as ultrasonics and X-rays) to qualify welds of flight hardware. The results of non-destructive evaluation and mechanical tests inform parameterization studies, sets of experiments designed to identify weld parameters which produce joints that meet the criteria for acceptable weld properties. While various parameterization studies for the FSW of MMCs have demonstrated that an operating window of parameters corresponding to defect-free welds can be established for virtually any tool/workpiece combination, these investigations fail to account for defects which may arise as a consequence of the wear mechanism(s) which affect the system [5,6]. Even if parameters used to produce the MMC joint lie within the operating window, there is always a possibility that a defect may

develop as the tool loses volume and the workpiece experiences an accompanying reduction in the flow of plasticized material. This additional layer of complexity and risk means that successful integration of MMCs into aerospace structures will require control of the wear process during joining. Mitigation of wear can be accomplished through careful selection of process parameters (rotation speed, traverse rate, length of weld, tilt angle) and material properties (percentage reinforcement, type of reinforcement, particle size, and tool material). In instances where wear is inevitable (this may be the case for longer welds or scenarios in which coatings fail to guard against wear), in-process monitoring is needed.   As we have emphasized, in-process wear detection is often synonymous with in-process fault detection for FSW of MMCs. Techniques used to sense wear in this setting may be applied to in–process quality control for FSW of conventional alloys.

RELATIONSHIP BETWEEN WEAR AND PROCESS PARAMETERS

The first key to unraveling the tool wear problem in FSW of MMCs is to understand the fundamental physics which underlie the wear process. A study of the variation of wear with FSW process parameters can provide some initial insight. Because FSW includes multiple process variables, experimental design techniques are essential to maximize efficiency in experimentation. The experiments for the preliminary wear study summarized here comprise an L_{27} orthogonal Taguchi array with three factors (rotation rate ω, traverse speed v, and distance welded l) at three levels (Table 1). The deterioration in the cross-sectional area of the tool pre and post-experiment was quantified using imaging software. Tool wear in FSW of MMCs is observed to be circumferentially symmetric – thus the measured degradation in the probe cross-section is assumed to be representative of the volume lost by the entire probe. Figure 2 shows an overlay of close-up images of the tool probe taken after successive welds of Al 359 reinforced with 20% Silicon Carbide particles. The characteristic rounding of the tool that accompanies wear is undesirable, as it reduces vertical stirring of material and frequently coincides with root flaw defects [4].

Table 1. Experimental matrix and results of initial wear study [7]

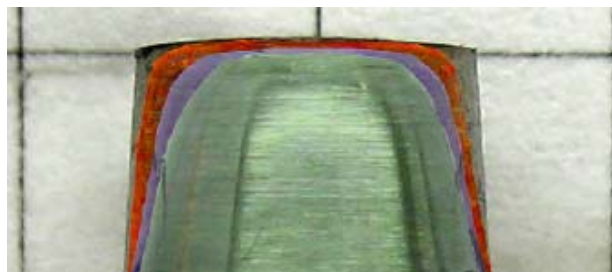| Test number	ω (RPM)	ν (in/min)	ℓ (in)	Percent wear
1	1000	5	8	3.7
2	1000	5	16	5.9
3	1000	5	24	7.5
4	1000	7	8	1.2
5	1000	7	16	2.7
6	1000	7	24	3.8
7	1000	9	8	1.4
8	1000	9	16	4.7
9	1000	9	24	5.0
10	1500	5	8	5.8
11	1500	5	16	15.6
12	1500	5	24	16.0
13	1500	7	8	3.0
14	1500	7	16	12.3
15	1500	7	24	17.2
16	1500	9	8	4.0
17	1500	9	16	6.6
18	1500	9	24	15.6
19	1500	5	8	3.5
20	2000	5	16	7.8
21	2000	5	24	12.9
22	2000	7	8	7.2
23	2000	7	16	11.7
24	2000	7	24	17.6
25	2000	9	8	4.0
26	2000	9	16	10.1
27	2000	9	24	15.0

Figure 2: Successive overlay of probe cross-sections for welds of Al 359/SiC/20p at 1500 RPM rotation rate and 7 IPM traverse speed for (outer to inner) 0, 8, 16, and 24 inches welded [7].

The wear data generated from these experiments was used to construct a multiple regression model (MRM) to estimate the volume loss the tool will experience

during a weld based on the values of three major process parameters [7]. An analog can be drawn between a model of this type and the machinability maps used to identify parameters for machining of abrasive materials which minimize wear yet still produce a cut, hole or other feature with acceptable quality. The expression derived from the regression analysis (Eqn. 1) is strongly correlated with experimental data (the Pearson correlation coefficient is 0.902). With any empirically based predictive model, there are lingering questions as to whether its predictions are only valid under the specific experimental conditions used in the study from which the data originates. While some statistical metrics (such as the adjusted R^2 value) predict how well the model will generalize, a more definitive assessment can be obtained by testing the model on a validation set (a validation set consists of cases separate from those in the original data set which can be used to assess the accuracy of a predictive model). The predicted and observed wear values for the validation set are closely aligned. A direct comparison of observed and predicted values appears in Table 2. The model should thus be applicable to parameter sets different from those used in its construction.

$$W = 0.584\ell - 1.038v + 0.009\omega - 6.028 \qquad (1)$$

Table 2. Comparison of observed and predicted wear for model validation data set.

ω	v	ℓ	Observed wear (% volume loss)	Predicted wear (% volume loss)	Residual	Percent error
12	5	8	5.45	4.72	0.73	13.4
17	9	8	4.95	5.05	-0.1	-2.02
17	9	16	10.06	9.72	0.34	3.38
14	6	8	5.45	5.02	0.43	7.89

Based on the multivariate regression analysis, tool wear in FSW of MMCs is directly proportional to rotation rate and distance welded but inversely proportional

to traverse speed. Together these parameters comprise a dimensionless group $(\frac{\omega l}{v})$ which is linearly correlated with wear (Pearson correlation coefficient 0.82), a relationship expressed in equation 2. Physically, this equation means that each unit increase in the group $\frac{\omega \ell}{v}$ is accompanied by a .0004% increase in percent wear [8]. This constant, like the constants in the multiple regression model (equation 1), can be used to estimate relative changes in wear based on process parameters: for instance, a 10,000-fold increase in $\frac{\omega \ell}{v}$ would correspond to a 4 percent increase in percent wear.

$$W = 0.0004\frac{\omega \ell}{v} \qquad\qquad [2]$$

The regression equation and the associated dimensionless group (which can be used to scale results) are intended to inform parameter selection in FSW of MMCs, enabling operators to select parameters which yield optimal results with regard to both wear and quality. If the length of the weld and the critical value of tool degradation are known, the dimensionless group (or regression model) can be exploited to identify combinations of rotation rate and traverse speed which will maintain wear below a specified level. Similarly, the equations can be used to estimate the life of a steel tool in joining MMCs (i.e. determine the maximum distance which can be welded at a specific set of process parameters before the tool attains a critical value of wear).

CONSTRUCTING AN ANALYTICAL MODEL OF THE WEAR PROCESS

The wear process in FSW of MMCs is unique in that it appears to be a shear, rather than drag, phenomenon (the inverse relationship between wear and traverse speed suggests this). Up to this point, no analytical scheme has been developed to explain the dependence of wear on process parameters or the variation of wear with distance from the shoulder (in experiments, material loss is greatest in the region of the probe tip and smallest at the probe/shoulder interface). The rotating plug model for material flow in FSW, initially developed by Dr. Arthur Nunes of NASA's Marshall Space Flight Center, provides a framework for understanding the physical phenomena which underlie these observed relationships [9]. In this formulation, the probe is surrounded by a plug of plasticized metal (the "rotating plug"). The width of this plug, δ, can be expressed as a function of the process parameters ω and v as well as the angular position θ in the x-y plane (equation 3). As shown in Figure 3, the plug is symmetric about the y-axis and varies in thickness from $\delta= \delta_0$ at $\theta = -\pi/2$ to $\delta_{maximum}$ at $\theta = \pi/2$.

$$\delta = \delta_0 + \frac{v}{\omega}(1 + sin\theta) \qquad (3)$$

The analytical model can be slightly modified to account for the presence of abrasive particles (such as the inclusions found in Al-MMCs). The model as it applies to FSW of MMCs is shown in Figure 4. The model indicates that for a given particle diameter D, wear occurs only when the particle is able to span the width of the shear zone and impinge on the tool surface, removing material as the tool rotates past it. This model is consistent with experimental results -- parameters which correspond to thinner shear zones result in greater wear, while parameter sets associated with larger values of δ experience less wear [9]. The rotating plug model suggests a piecewise condition for abrasion: wear only occurs at locations where the radius of the particle exceeds the width of the shear zone ($\frac{D}{2} > \delta$). The proposed corollary implies that wear is also affected by material properties, such as particle size and percentage reinforcement.
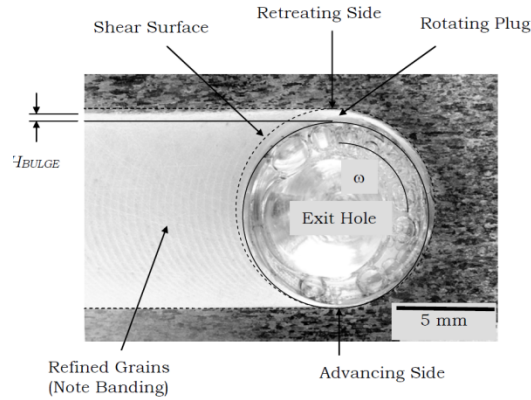

Figure 3: The rotating plug model superimposed on a plan view of the extraction point (exit hole) for a friction stir weld.
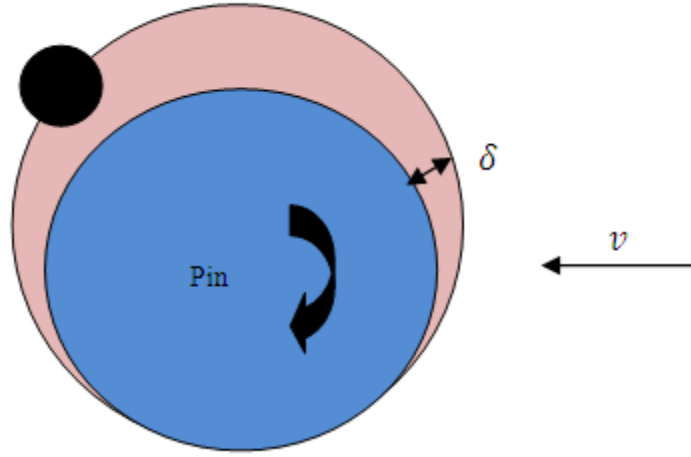
Figure 4: Rotating plug model applied to FSW of MMCs. Pink shaded region indicates the rotating plug (thickness δ). The solid black circle represents an abrasive particle present in the workpiece material.

The rotating plug model in this context can be used to define the region where scoring of the tool by abrasive is possible. The original model additionally predicts that the shear surface widens along the length of the tool (Figure V), rendering the region near the tip of the probe the most susceptible to abrasive action. The percent wear predicted by the model is calculated from equation 4, where D is the diameter of the reinforcement particle, P is the proportion of reinforcement relative to the entire workpiece volume, ω is the rotation rate, v is the traverse speed, l is the length of weld, and R is the radius of the pin. ΔC_{max} is the maximum value of the cutting arc (the angular region where abrasion can occur) The derivation of this expression is detailed in references 9 and 10. It assumes that the depth to which the particle impinges on the tool surface is equivalent to ½ the particle diameter. The volume of material removed is integrated over the length of the tool where abrasion is possible (a distance estimated as ½ the probe length). The deterioration in the width of the cutting arc ΔC with increasing distance from the probe is also accounted for. The model reflects trends and its predictions are closely aligned (generally within 10 percent) of experimental values [9,10].

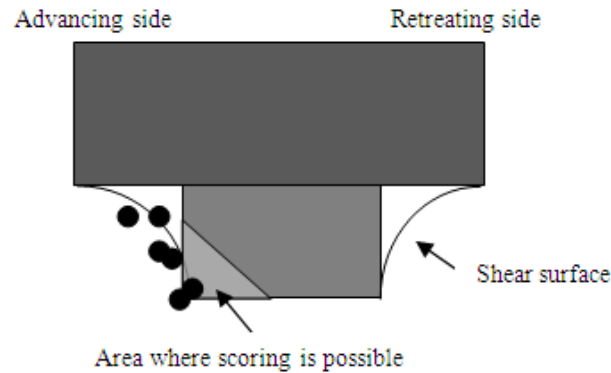$$\% \ wear = \frac{5D\Delta C_{max}P\omega l}{24Rv} \qquad (4)$$

Figure 5: Growth of plug in axial direction along length of tool probe. Black circles represent abrasive particles.

Tracer experiments based on the work of K. Colligan (who used steel shot tracers embedded along the joint line to study material flow in FSW) were used to test the effects of particle size [11]. For each of these experiments, a tool was used to join Al 6061 plates containing a specific size of SiC particulate (the particles were contained in a 0.10"x0.10"x0.10" slot milled along the advancing face of the joint). The wear of the tool probe is assessed post-weld through weighing, contact profilometry, and SEM microscopy. As predicted by the plug model, the amount of wear is strongly dependent on particle size. Figure 6 plots the percent weight lost by the tool during welding as a function of inclusion particle size.
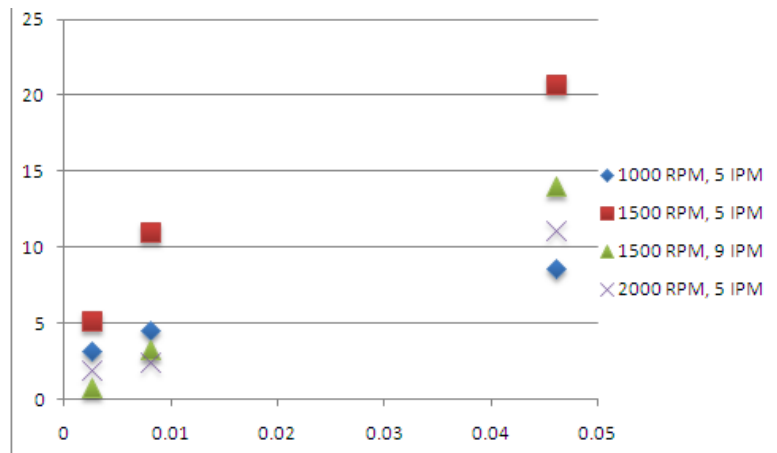

Figure 6: Plot of percent weight reduction for FSW probe versus particle size. Each data series represents a separate set of parameters [10].

Contact profilometry is used to compare surface topology among FSW tool probes used to weld joints containing particles of three different sizes (FEPA grade F150, F60, and F14). Changes in surface texture parameters (particularly average roughness R_a and peak to valley roughness R_t) with wear are dramatic and the proportional increase in roughness (as compared with the unworn probe) varies directly with particle size [10]. That larger particles produce greater wear is an expected outcome, but the results of the particle size experiments are significant in several ways:

1) They provide further evidence for the rotating plug model of wear, which suggests that wear for this process should be strongly dependent on particle size (since larger particles are more likely to span the clearance δ between the probe and the rotating plug and impinge on the tool surface).
2) From a material design perspective, experimental outcomes indicate that one potential avenue to minimize wear in FSW of MMCs is to select materials containing reinforcement particles which lie at the upper end of the FEPA scale.
3) The experimental technique, adapted from Colligan's work, presents an economical alternative to custom manufacturing of MMCs with specific particle sizes for the purposes of materials research.

COMBATTING WEAR: SELECTION OF TOOL MATERIALS

SEM analysis of the samples from the particle tracer experiments conclusively identified the wear mechanism as abrasion (Figure VII). It follows that the best method to combat wear in this instance is to use a tool material which is harder than the reinforcement particles. Based on classical theory, abrasive should not be present in a system for which the hardness ratio (defined as the ratio of the hardness of the tool to the hardness of the abrasive) is greater than 1. The best candidate for a wear-resistant tool material is diamond, but the cost of monolithic diamond tools precludes their use in all but the most mission-critical manufacturing applications. Diamond coatings are a more economical alternative. The major obstacle to the implementation of coated tools is the coating's tendency to delaminate under the stresses imposed by the joining process. When delamination occurs, the (often superior) wear behavior of the coated tool regresses to levels associated with that of the substrate; a strong bond between substrate and coating is thus needed to prevent delamination and preserve the wear-resistant characteristics of the coated tool. The effect of the hardness ratio on wear in FSW of MMCs was tested using four different tool materials (O1 tool steel, WC, WC micrograin, and WC coated with diamond) in two materials (Al 359/SiC/20p and Al 359/SiC/30p) at ω=1000 RPM and $v = 3$ IPM. The brittle behavior of ceramic and refractory metals

significantly narrows the process window for FSW. Concerns about tool fracture generally drive conservative parameter selection (a higher rotation rate coupled with a comparatively slower traverse speed tends to reduce the occurrence of tool failure). Figure 8 compares the cumulative wear of the candidate materials over 4 feet of weldment. The wear resistance of the coated tool is superior, but the margin between the performance of the diamond and WC-Co probes is small [12].
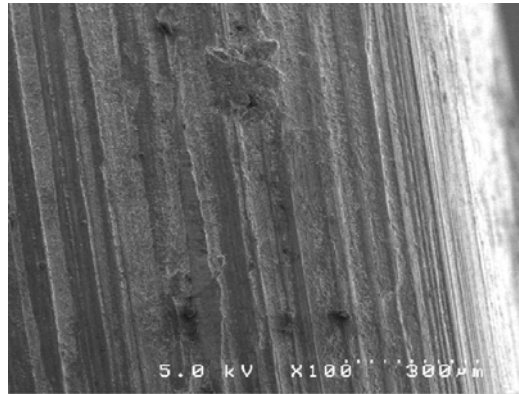

Figure 7: SEM image (100X) of worn FSW probe. The surface exhibits circumferential, parallel grooves characteristic of abrasive wear processes.
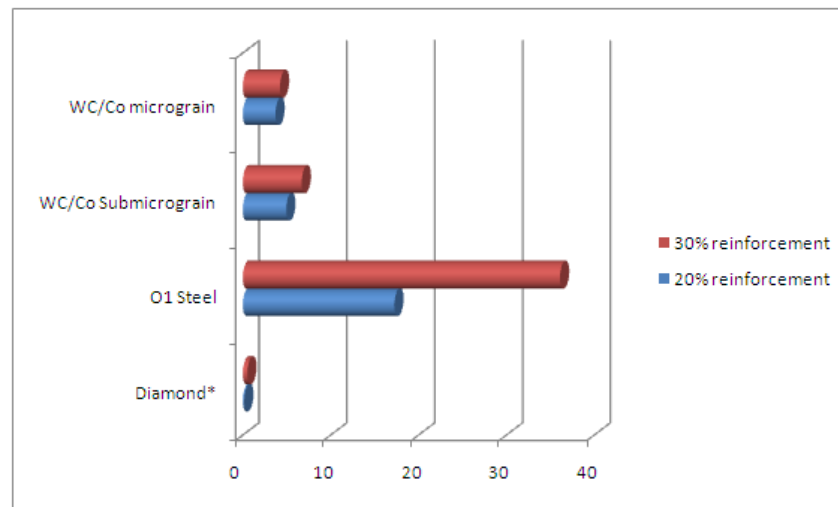

Figure 8: Plot of % wear versus tool material. Each cylinder represents the % wear recorded for the corresponding tool material after three 14" long welds (at 1000 RPM/3 IPM) in an Al 359 MMC with either 20% or 30% SiC reinforcement [12].

IN SITU SENSING OF WEAR USING TORQUE

An examination of the equation for torque derived from the rotating plug model (equation 5) reveals that radial deterioration of the probe during joining of MMCs by FSW should correspond to a decrease in the magnitude of the torque experienced by the tool. Simulations by Gibson, Prater, et al. showed that *in situ* estimates of wear could be made using an adaptive torque controller [13]. According to Nunes's equation for torque based on the rotating plug model, the torque signal is sensitive to flow stress σ, temperature, and plunge depth t as well as geometry (shoulder and pin radii R and r, respectively). These additional (and sometimes coupled) dependencies make it difficult to isolate changes in the torque signal that can be attributed solely to the radial loss of tool material. Nonetheless, in-process sensing merits further investigation as this capability would minimize disruption of the manufacturing process (currently tools must be taken off-line to evaluate them for signs of wear). Figure IX shows the evolution of the torque signal (measured from motor current) over a 6 ft weld of Al 359/SiC/20p for a conventional tool material (O1 steel hardened to RC 50). The steady-state torque signal for each pass was correlated with the amount of wear. Over the course of several experiments using longer panel welds, this analysis demonstrated that the change in torque signal with wear is detectable and presents a potential means of on-line monitoring for wear (and perhaps other FSW phenomena). The primary application of wear sensing would be for longer welds of reinforced Aluminum alloys (such as longitudinal welds of fuel tanks) where an off-line *in media res* evaluation of wear is not desirable.

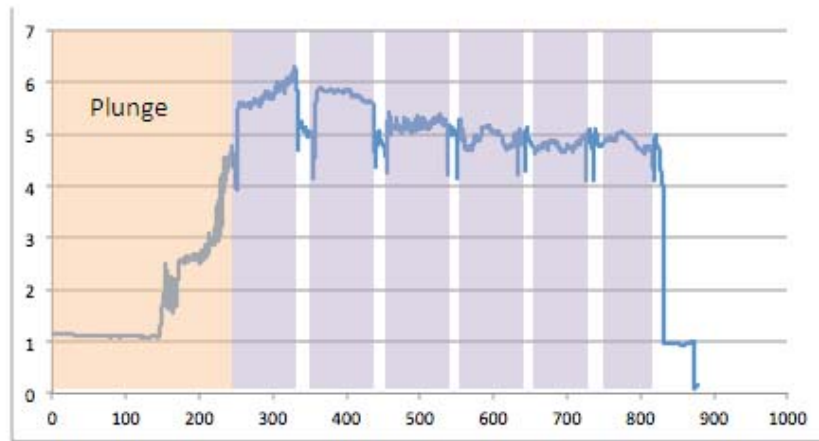$$T_{total} = \frac{2\pi R^3}{3}(1 + 3\frac{r^2 t}{R^3})\sigma \qquad (5)$$

Figure 9: Plot of motor current (in amperes) versus time (in seconds) for 6 ft long weld of Al 359/SiC/20p at 1400 RPM and 9 IPM. Shaded regions indicate successive 12" weld passes along panel.

CONCLUSIONS

The ultimate goal of the research presented here is to extend the usability of metal composites to aerospace structures, an outcome which can only be achieved by solving the problem of wear encountered in joining MMCs to themselves or other materials. MMCs possess a wide range of properties which make them well-suited for aerospace applications. Their material properties (strength, fatigue life, wear resistance) represent a significant improvement over both Magnesium and conventional, unreinforced Aluminum alloys. Additionally, MMCs are customizable materials: the constituency of an MMC (the matrix alloy, the reinforcement material, and the percent in which this reinforcement is present) can be manipulated to obtain the desired value of a mechanical property. While the weight of an unreinforced Aluminum alloy and an MMC are virtually the same, the greater strength associated with the MMC reduces the volume of material required for a specific design. The properties of MMCs reflect their status as prime materials for use in aerospace structures, but weldability (not cost) is the primary barrier to their inclusion in aerospace structures. The work presented in this dissertation seeks a fundamental understanding of this wear process, knowledge which is paramount to controlling and/or eliminating wear in FSW of MMCs (and thus expanding the applications in which these materials can be used).

Despite its impact on joining metal composites and other high-strength alloys, little is known about tool wear in FSW. The studies summarized in this chapter serve as a starting point for understanding this largely neglected aspect of friction stir welding research. The most important aspects of this work are: 1) identification of the wear mechanism, 2) development of empirically based models which predict the amount of tool wear based on process parameters and material properties, 3) advancement of tool materials and coatings which prevent and/or mitigate wear, and 4) an evaluation the feasibility of sensing techniques which can provide information regarding the condition of the tool in-process. The collective results of these studies set forth an informed strategy for material selection of both tool and workpiece materials to minimize tool wear. A combination of careful material selection, control of process parameters, and monitoring of torque and other process signals that correlate with wear can reduce volume loss to a degree that enables the production of defect free welds. The development of a fundamental understanding of wear phenomena in FSW is necessary and essential for control and mitigation of wear processes, thereby extending the use of these materials to aerospace industry applications where they would be of maximum benefit [14].

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