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# Friction Stir Welding of Metal Matrix Composites for use in aerospace structures ☆

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ABSTRACT

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 the Orion Crew Exploration Vehicle. A current focus of FSW research is to extend the process to new materials which are difficult to weld using conventional fusion techniques. Metal Matrix Composites (MMCs) consist of a metal alloy reinforced with ceramics and have a very high strength to weight ratio, a property which makes 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. Since FSW 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 work characterizes the effect of process parameters (spindle speed, traverse rate, and length of joint) on the wear process. Based on the results of these experiments, a phenomenological model of the wear process was constructed based on the rotating plug model for FSW. The effectiveness of harder tool materials (such as Tungsten Carbide, high speed steel, and tools with diamond coatings) to combat abrasive wear is explored. In-process force, torque, and vibration signals are analyzed to assess the feasibility of on-line 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 the implementation of these materials in structures (such as launch vehicles) where they would be of maximum benefit.

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## 1. Introduction

Over the past half-century, ballistic launch methods have been the (almost exclusive) means of transporting cargo from earth's surface to orbit. The reliance on ballistic techniques means that weight is often the foremost consideration in spacecraft designs: even the preeminent rocketeer, Werner von Braun, was initially skeptical that lunar missions could be accomplished using a one-shot approach. While the lift capacities of vehicles based on current propulsion technologies vary widely, cargo weights comprise only a small portion (typically less than 5%) of the vehicle's weight at launch; the vast majority of a

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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. 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 3400 kg [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. In light of these results, NASA converted much of its manufacturing to utilize the FSW process. In 2006, Al–Li 2195 was selected as the material for the Ares I upper stage and the Orion Crew Exploration Vehicle, both elements of the Constellation program. The structures in NASA's next generation heavy-lift launch vehicle, the Space Launch System (SLS), will also rely extensively on FSW.

The selection of lightweight and strong materials continues to be a guiding consideration in design of aerospace vehicles. Since the international space community will be reliant on ballistic launch architectures for the foreseeable 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 (Fig. 1) 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, depending on the percentage reinforcement), temperature resistance, wear resistance, and fatigue life. Compared with Al 2219-T8 (a common aerospace alloy), an Al-MMC reinforced with 30% SiC has approximately the same density, but the elastic modulus, tensile strength, and specific modulus for the MMC are 60%, 15%, and 70% greater than Al 2219, respectively. For MMCs with a higher degree of reinforcement, the gap between these properties for Al MMCs and conventional Al alloys only widens. Fusion welding of MMCs produces joints characterized by porosity and cracking [2]. Theta-phase precipitates ($Al_4C_3$) are formed when molten aluminum reacts with reinforcement particles. Particle segregation during fusion welding creates a strength-depleted region along the joint-line, degrading joint strength [2]. 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. Progressive wear of the tool removes features which facilitate material stirring, an effect which increases the likelihood of void development [3].

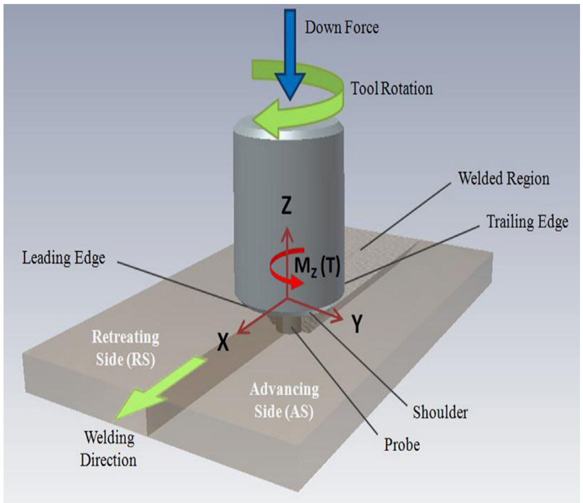


**Fig. 1.** Illustration of Friction Stir Welding process. The tool, which consists of a pin that penetrates the workpiece material and a larger diameter shoulder that rests on the surface of the material, rotates at rate $\omega$. As the tool advances through the material at traverse speed $\nu$, it 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 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 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 for aerospace applications, as a failure in any of the welds used to assemble flight hardware could be disastrous. To prevent weld-related structural failures, NASA invests 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. Traditional qualification is based on the results of parameterization studies, sets of