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Wear resistance performance of AlCrN and TiAlN coated H13 tools during friction stir welding of A2124/SiC composite

Akeem Yusuf Adesina*, Fadi A. Al-Badour, Zuhair M. Gasem

Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

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ABSTRACT

Tool wear during friction stir welding (FSW) of hard particulate reinforced aluminum metal matrix composites (Al MMCs) are more prominent due to the tool interaction with the particulates at high strain rate. Considering the excellent mechanical and wear resistance properties of cathodic arc PVD coatings, they are expected to abate the wear of tools during FSW of Al MMCs. Hence, it is the aim of this study to investigate the contribution of cathodic arc PVD deposited AlCrN and TiAlN coatings in alleviating tool wear during FSW of Al MMCs. AlCrN and TiAlN coated H13 FSW tools were used to butt weld 8 mm thick aluminum alloy 2124 reinforced with 17 vol % SiC of 3 µm particle size. Interestingly, the coated tools exhibited significant improvement in wear resistance of about 92 and 80%, respectively, over the bare H13 tool. Over 97% reduction in the wear of the FSW tool was recorded during the plunging stage with the use of the coated tools. Additionally, AlCrN and TiAlN coated tools considerably improved the surface finish of the welded Al MMC. The coated tools demonstrated superior wear resistance due to the improved scratch crack resistance, high mechanical and oxidation resistance properties of the coatings. Dominant wear mechanisms on AlCrN and TiAlN coated tools were abrasive erosion and chipping off by sharp and hard SiC particles while severe striation and oxidation characterized the wear mechanism of the bare tool. The use of these coatings did not deteriorate the weld properties, rather some improvement in the hardness of the nugget zone was observed due to the characteristic dynamic stirring and refinement of the Al matrix and SiC particles.

1. Introduction

Joining aluminum metal matrix composites (Al MMCs) by conventional fusion welding methods is challenged by susceptibility to various problems induced by the high heat input of fusion welding processes. These traditional welding processes often deteriorate the joint mechanical properties due to formation of highly heterogeneous weld, solidification shrinkages, susceptibility to porosity, initiation of brittle intermetallic phases from interfacial chemical reactions between matrix and particulates and the different thermal expansion coefficients as well as segregation [1–4]. These have hampered meeting the increasing demand of Al MMCs in the industries despite their excellent properties. Their high strength to weight ratio at wide range of temperatures, improved creep and wear resistance, thermal and chemical stability, and improved fatigue and high formability properties have attracted attention in a wide range of applications most importantly in the aerospace, automotive and marine industries. Thus, among the alternative solid-state welding processes, friction stir welding (FSW) process for joining Al MMCs has been found to possess more potency to overcome the aforementioned challenges associated with fusion welding of Al MMCs [3].

The joint in FSW is formed due to frictional heating, with temperature still under the melting point of the adjoining workpieces, stirring and solidification of severely plastic deformed materials [3–5]. The FSW process induced dynamic recrystallization in the weld zone which result in fine equiaxed microstructure with improved joint properties [6,7]. Sequel to the low heat input, problems of segregation of ceramic reinforcement in the Al MMCs, formation of shrinkages and thermal stresses due to large difference in the coefficient of expansion can be avoided in addition to the characteristic refined microstructures formed [6,8,9]. However, the combined effect of the severe plastic deformation and the consequent increase in temperature due to frictional heat put the rotating tool in harsh condition and often leads to significant tool wear during FSW of Al MMCs [10]. Since dynamic recrystallization occurs as a result of localized or large-scale shearing of the materials around the rotating tool [11], tool wear in the case of hard particulate reinforced Al MMCs are more prominent due to the tool interaction with the particulates at high strain rate [10–12].

* Corresponding author.
E-mail addresses: adesina@kfupm.edu.sa (A.Y. Adesina), fbadour@kfupm.edu.sa (F.A. Al-Badour), zuhair@kfupm.edu.sa (Z.M. Gasem).

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Prado et al. [11] investigated the tool wear of threaded tool steel in FSW of 5 mm thick 6061-T6 Al + 20 vol% Al_2O_3 in a butt configuration at different rotation speeds. They observed considerable tool wear with increasing rotation speed up till 1000 rpm having the maximum tool wear. With higher rotation speeds to 1500 and 2000 rpm, the tool wear decreases slightly. Based on the study of Prado et al., Shindo et al. [12] evaluated the tool wear in FSW of 4 mm thick Al359 + 20% SiC at different weld speeds with a fixed 1000 rpm rotation speed. The authors [12] used 0–1 hardened steel with right-hand threaded FSW tool to produce the joints. The study showed that tool wear was higher at weld speeds below 3 mm/s, and after 11 mm/s it was extrapolated that no further tool wear occurred after the tool reached the self-optimized shape. However, initial tool wear can also proceeds without attaining an optimized shape at high wear rates [12]. Both have attributed the tool wear in FSW of Al MMCs to the particle erosion and abrasive from the reinforcement via the rotational and translational vortex flow [11,12]. Tool wear during FSW poses serious challenges to researchers especially in developing and welding of advanced Al MMCs and this is evident from the numerous reports on tool wear during FSW of Al MMCs [10,13,14]. Besides the excessive cost effect of tool wear, contamination of the weld by debris from the worn tool is of considerable concern. Various tool materials have been developed [15–20] to counter the problem of FSW tool wear, however, tool wear, premature failure due to brittleness and high tool cost are challenges encountered with these materials. Therefore, properties such as high strength, improved fracture toughness, enhanced hardness, excellent thermal properties (stability, conductivity and expansion), chemical inertness with both the workpiece material and the environment and cost effectiveness remains a vital concern for FSW tool material [21–24].

One alternative to these problems is the use of hard coatings to improve the surface properties of the tool and thus protect the tool from abrasion, elevated temperature oxidation, diffusion and adhesion which are the common wear mechanisms [20,25]. A multilayer TiC/TiN CVD coating was deposited on Si_3N_4 FSW tool for friction spot welding of DP980 steel in a lap joint configuration by Oshahi et al. [26]. Upon using the uncoated Si_3N_4 tool, it was observed that the tool decomposed thus caused weld contamination due to dissolution of silicon and nitrogen. This situation was prevented with the TiC/TiN coated tool. Similarly, TiAlN-coated high speed steel (HSS) tool was utilized for FSW of 3 mm thick silicon carbide reinforced aluminum alloy (AA2124/SiC/25p) plates [27]. However, the properties and the contribution of the TiAlN coating on the tool performance and wear resistance were not evaluated. Batalha et al. [28] also investigated the wear behavior of a 5 µm thick PVD AlCrN coated FSW WC-6%Co tool. But due to fracturing of the tool pin during the plunging stage as result of high plunging force exceeding the compressive strength of the tool. Thus, the contribution of the AlCrN coating could not be evaluated. Casalino et al. [29] and Devanathan and Babu [30] have used AlCrN and TiAlN coated FSW tool, respectively, for FSW of 3 mm thick AA5754H11 aluminum alloy and 4 µm thickness for FSW of LM 25 Al alloy reinforced with 5% SiC particles. It is proposed in both studies that the coatings improve the thermal stability and wear resistance of the tool. However, experimental details evaluating and quantifying the contribution of the coatings were missing.

Considering the limited and scarce studies conducted in evaluating the performance of coatings in reducing FSW tool wear, as well as the continuous improvement of the mechanical properties and distribution of the reinforcement in Al MMCs via advanced powder metallurgy and modern manufacturing processes, there is need to develop comprehensive understanding and investigate coatings with improved properties that can withstand the harsh conditions during FSW of Al MMCs. Thus, this study is aimed at investigating the contribution of cathodic arc PVD deposited AlCrN and TiAlN coatings in alleviating the tool wear during FSW of Al MMCs.

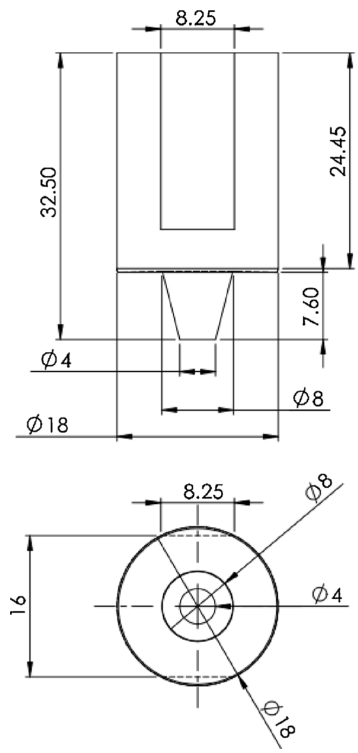

Fig. 1. Schematic diagram showing the dimensions (in mm) of the FSW tool.

Table 1
Deposition parameters for the coatings.

Coating Parameters	AlCrN and TiAlN coating deposition parameters
AEGD etching duration	30 min
Nitrogen gas flow rate	500 sccm (99.996 % Purity)
Planetary rotating speed	2 rpm
Cathode charge	800 A h
Coating temperature	450 ± 20 °C
Coating pressure	8.5×10^{-2} – 6.5×10^{-2} mbar
Coating bias voltage range	Between −80 and −100 V
Deposition rate and duration	~ 5 µm/hr | 80 min
Coating thickness	6–8 µm

2. Experimental details

2.1. Material and tool design

The Al MMC workpiece used in this study is an aerospace grade aluminum alloy 2124 (main elements are Al-Cu-Mg) reinforced with 17 vol% SiC (AA 2124-17% SiC) supplied by Aerospace Metal Composite Limited designated as 2124/SiC/17p. The reinforcement has an average particle size of 3 µm and manufactured via mechanical powder metallurgy process using high energy mixing process and thereafter hot isostatic pressed (HIP) to formed panels of 400 × 400 x 8 mm. The HIP panels were then solution heat treated and cut into strips of 200 × 50 x 8 mm and then face milled to properly align the strips for the FSW process.

The FSW tool was designed from chromium and molybdenum hot work tool steel H13 grade. This grade was selected due to its hot-hardness property, better hardenability and its excellent combination of high toughness and resistance to thermal fatigue. The tool is designed as a thread-less frustum-shape tool due to the line-of-sight PVD deposition process. This makes it practically difficult to deposit coatings on tools with complex geometry or hidden features. The tool has a shoulder diameter of 18 mm and pin root diameter of 8 mm tapered to 4 mm. The schematic diagram of the tool showing the dimension is