Ceramic Coatings via Friction Stir Processing: Challenges and Drawbacks for Industrial Applications

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Abstract: The scope of this article is to highlight the limits of Friction Stir Processing (FSP) as a method for producing metal-matrix compositesurface layers. Compared to other processes for ceramic coatings, FSP is an uncomplicated technique that presents many advantages in term of costs and environment protection. Still, there are some unresolved problems before further industrial-scale applications of friction stir processing as additive manufacturing technology. This paper focuses on aluminum alloys since they are widely used materials for the aircraft and automotive industry and the challenges encountered in coating via FSP are similar to other materials

Key-Words: Coatings, fiction stir processing (FSP), metal-matrix composite (MMC), ceramic reinforcement particles

1 Introduction

Friction stir processing (FSP) has evolved from a welding technique to surface engineering technique after British researchers from TWI (The Welding Institute) patented it in 1991.Nowadays, Friction Stir Processing (FSP) mostly refers to surface modification while for welding is used Friction Stir Welding (FSW).

Both FSP and FSW involve heating, plastic deformation, microstructural modification and material movement in a solid state transformation by a simple process that consists in applying a downward force on a rotating tool and then moving it along the surface of the workpiece[1]. Process principle and parameters are illustrated in Fig.1

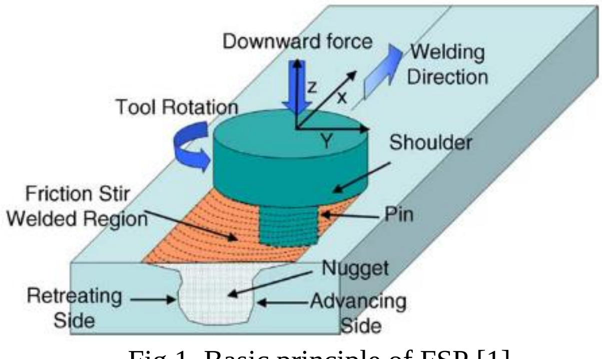

Fig.1. Basic principle of FSP [1]

The tools for FSW/FSP are generally designed with a pin to produce friction-generated heat and simultaneously mix the material below it. There are many tool configurations from pinless tools to various shapes for pins and tool shoulders[1], [2]. The effectof tool materials, tool geometry and dimensions were the object of many studies concerning friction stir welding and processing [3]–[11].

Another important aspect of friction stir is related to the selection of process parameters. As seen in Fig.1, there are four process parameters:

- Rotational speed
- Traverse speed
- Normal force
- Tilt angle of the tool (not shown in Fig. 1 since tilt angle is null).

The influence of one or many process parameters was intensely studied on various materials, attempting to find the optimal combination of parameters for a specific material processed with a specific tool [3], [12]–[17].

Regarding surface improvement, FSP enhances mechanical and tribological properties in the processed area with or without introducing reinforcement particles in the surface layer. In the first case, small ceramic particles are mechanically embedded in the softened base material of the workpiece. In the latter case, the surface layer modification consists mainly in grain size reduction and consequently, the properties are improved.

Although the benefits of FSP are important, it is crucial to outline the current limits and problems to overcome in order to use friction stir at an industrial scale.

This paper focuses on perspectives and drawbacks in using FSP for coating large surfaces of metal and alloyed parts with ceramic reinforcement particles and creating ceramic metal matrix at the surface. It provides a brief review limited to aluminum-ceramic metal composites completed with authors' experimental study.

2 FSP for Al Matrix Composites

2.1 Critical review

Aluminum alloys are probably the most interesting materials for reinforcement with ceramic particles due to their wide scale use in aerospace and automotive industry. These light materials can be considerably improved by using FSP in an economic and environmental friendly way.

In Table 1 are presentedFSP process details for reinforcing different aluminum alloys with ceramic particles: tool material and design, process parameters, ceramic particle size and grain size modification after FSP. Grain size in the processed zone is an important indicator of the effectiveness of FSP since a more refined microstructure has superior properties.

Table 1: Summary of FSP conditions for ceramic reinforcement of Al alloys surface layer

WorkpieceMaterial	Tool	Rotation speed (rpm)	Traverse speed (mm/min)	Special conditions	Reinforcement particles size	Grain size in stirred zone	Ref.
6082 Al/Al_2O_3	H13steel Tool with pin	1000	135	groove filled with Al_2O_3 powder 4 overlapped passes	Al_2O_3: ~50 nm	~660 nm	[18]
6061 Al/Cr_2O_3	H13steel Conical threaded pin	630	100 mm/min	Cr_2O_3 powder applied on Al6061 plate by atmosphere plasma spray 6 overlapped passes	$Al_{13}Cr_2$: <100 nm $Al_{11}Cr_2$: <100 nm	~6 μm	[19]
Al/Mg/CuO	NA material Tool with pin	500	15	Al/Mg/CuO powder metallurgy 4 overlapped passes	Al_2Cu: ~ 200nm Mg O < 1 μm	~600 nm	[20]
5754 Al/Si_3N_4	NA material Tool with pin	1400	100	groove filled with Si_3N_4 powder 2-4 overlapped passes	Si_3N_4: ~140 nm	~7μm	[21]
Alumix 431D/SiC	PVD TiN/ZrN Tapered pin	454	88	Al/ two types of SiC powder metallurgy	SiC: 610 nm SiC: 6.25 μm	NA	[22]
Al/Al_2O_3	H13steel Tool with pin	800-1360	30-200	Al/Al_2O_3 powder metallurgy	Al_2O_3: ~92 nm	1.4-2 μm	[23]
6061 Al /SiC/Gr	H13steel Tapered threaded pin	3000	40	groove filled with SiC/Gr powder Axial force 5KN	SiC: ~5 μm Gr: ~5 μm	NA	[24]
Al/SiO_2	NA material Tool with pin	500-2000	15-90	Al/SiO2 powder metallurgy	Al_2O_3: ~20 nm	~1.5μm	[25]
Al5083/ Gr/Al_2O_3	H13 tool steel	1250	20	groove filled with Al_2O_3/Gr powder, 3 passes	Al_2O_3: ~80 nm Gr: 10-15 μm	NA	[26]

Data presented in Table 1 show that small grain size are obtained in the ceramic layer, regardless of the tool, the size of ceramic particles or other process conditions. Another important aspect is the variation of FSP conditions:

- rotational speed from 457 rpm to 200 rpm and traverse speed from 100 mm/min to 200m/min
- single passes or multiple passes more or less overlapped
- different methods for deposition of ceramic powder on the workpiece before FSP

- all the tools have pins of different shapes and sizes
- the preferred material for FSP tools is H13 chromium hot-work steel

Although all studies reported significant improvement of hardness and other properties after producing ceramic-aluminum matrix at the top layer, there are limits anda few aspects still need to be clarified.

2.2 Limits and drawbacks

One important issue is that FSP is a thermomechanical process and all transformations depend on the heat generated by the rotating tool pressed on the surface and on the normal force applied by the tool (or plunge depth of the tool). It is difficult if not impossible by now to separate the amount of energy transformed in heat and the amount of energy that produces plastic deformation. Therefore, is hard to predict the outcome of the process, so it is still a matter of trial and error in choosing process parameters. In Fig.2

Another problem is that for industrial purposes large surfaces need to be treated, while the studies are done on very limited surfaces of one or more passes of a few centimeters in length. The problem is that if the plunge depth of the tool is kept constant, the normal force varies due to temperature modification in the workpiece. Consequently, it is hard to obtain uniform surface in terms of microstructure and properties, dimensional accuracy and roughness.

Very few studies concern macroscopic aspects of the surface after FSP, yet this is crucial for industrial applications and friction stirred ceramic layers have poor surface roughness.

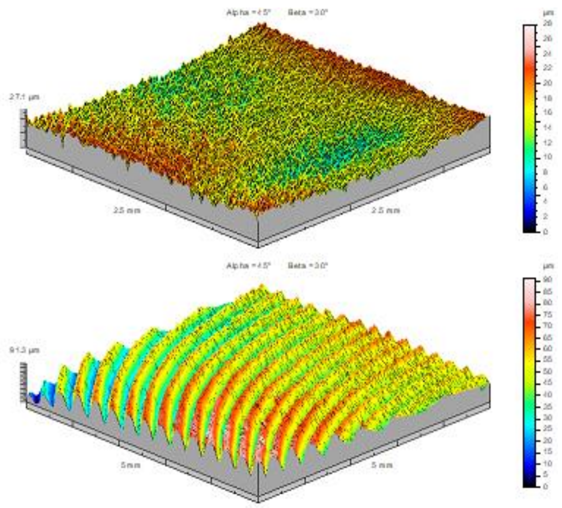

Fig.1. Surface roughness before FSP (above) an after FSP (below)

In Fig.2 average surface roughness increased from Ra 1.4μm (untreated 5083A) to Ra 8.16μm after FSP coating with a mix of 60/40 Al_2O_3 and TiO_2.

4 Conclusion

Invariably, all studies are stating that there are numerous advantages for welding and surface processing such as:

- increased weld resistance
- no need for additional welding material
- possibility of welding dissimilar materials
- refined microstructure
- increased hardness, wear resistance and corrosion resistance
- enhanced reduced energy consumption
- no waste produced during process
- possibility of using conventional machines tools such as milling machines or lathes

Above-mentioned benefits indicate a great potential of FSP in producing ceramic layer, but further research is necessary overcome its limits and make it available for industrial applications.

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