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Friction surfacing of Ti–6Al–4V: Process characteristics and deposition behaviour at various rotational speeds

V. Fitseva *, H. Krohn, S. Hanke, J.F. dos Santos

Helmholtz-Zentrum Geesthacht GmbH, Institute of Materials Research, Materials Mechanics, Solid State Joining Processes, Max-Planck Str. 1, 21502 Geesthacht, Germany

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ABSTRACT

By the process of friction surfacing, coatings are generated from metallic materials at temperatures below their melting range. The high degree of deformation while depositing leads to grain refinement in the microstructure, which has a positive effect on the mechanical properties of the layer. The applicability of the process has been described for a large number of materials. The deposition of Ti–6Al–4V has been reported in one publication but was not systematically studied. Therefore, the main aims of the present work are to define the process parameter fields for the deposition of Ti–6Al–4V leading to flash and defect free coatings and associate them with geometric features of the deposited layer.

This investigation has shown that Ti–6Al–4V coatings can be effectively deposited onto a Ti–6Al–4V substrate by friction surfacing. A wide range of process parameters was established in which coatings of high quality have been obtained. The consumption rate control has been implemented as an efficient mode for the deposition of Ti–6Al–4V coatings. Temperature measurements at the coating interface have been accomplished showing that the coating material has been deformed in the β-phase. Furthermore, the homogeneity of the coating surface has been established to be a function of the rotational speed. The coatings exhibited a defect-free bond at the interface with the substrate. Two process parameter ranges with respect to the flash formation have been established. One of them enables flash-free coatings and the other generates coatings with flash formation on the retreating side, which can be controlled by the rotational and deposition speeds. Moreover, an increase in the rotational speed has been shown to lead to an increase in the coating thickness and width as well as an increase in the deposition efficiency up to 39 %.

1. Introduction

The development of functional coatings has become an important part of the manufacturing industry. Friction surfacing (FS) is a technology by which coatings for local surface improvement in similar and dissimilar configurations can be deposited, i.e., the layer and the substrate materials can be similar or dissimilar. Layers deposited by FS can extend the service life of components such as turbine blades, rails and medical implants by repairing worn parts, reducing wear and improving anti-corrosion properties [1,2].

The FS process was first patented by Klopstock and Neelands in 1941 [3]. The technology was then lost for many years until a Russian engineer rediscovered it in 1950 [4], and since 1986, the process has been used frequently as has been reported in the literature [5].

As a solid-state process, this technology is used to deposit layers at process temperatures below the melting range of the coating material and it allows the deposition of metallurgically incompatible materials. The process involves a rotating consumable metal rod that is applied onto a substrate under an axial load. The relative motion between the rod and the substrate results in frictional heat being generated at the interface that plasticises the rod tip. The plasticised rod material is then deposited onto the substrate with excessive softened material ascending around the rod forming a flash (Fig. 1). The edge of the layer, at which the direction of the rotational velocity is the same as the deposition direction is denominated the advancing side (AS), and the edge where the rotational velocity vector is contrary to the deposition direction is defined as the retreating side (RS) (Fig. 1). The severe plastic shear deformation and the thermal cycle imposed by the process alter the original microstructure of the consumable rod, leading to recrystallization, grain refinement and, depending on the processed material, phase transitions [6]. The impact on the substrate is limited, compared to fusion welding processes, due to the comparably low heat input [7].

The parameters with the strongest impact on the FS process are the deposition speed, the rotational speed of the consumable rod and the axial load. Further relevant factors include the diameter of the consumable rod, the thermal conductivity of the substrate and the joint configuration, i.e., either similar or dissimilar. The coating thickness, width and bond quality are dependent upon all these parameters [8].

* Corresponding author.
E-mail address: viktoria.fitseva@hzg.de (V. Fitseva).

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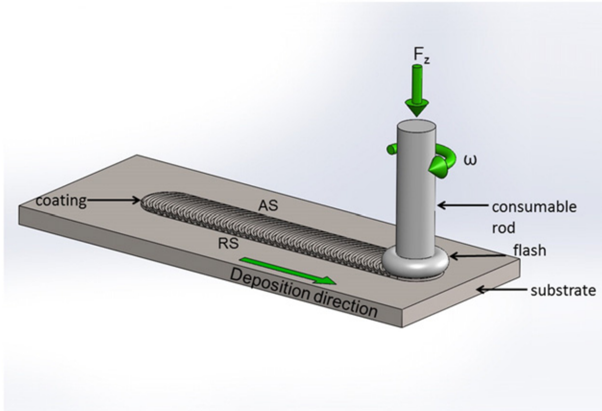

Fig. 1. Schematic description of the friction surfacing process.

A number of studies on FS have been published reporting the successful deposition of aluminium alloys, stainless steel and various other steel grades [9,10]. Moreover, Rao et al. [11] have published a feasibility study on applying various materials onto non-ferrous substrates, including commercially pure titanium as rod material deposited onto a Ti–6Al–4V substrate. Continuous titanium coatings could not be produced and further studies have not been published since.

The aims of this work are to demonstrate that Ti–6Al–4V can be deposited successfully using the FS process and to establish a range of process parameters for the deposition of Ti–6Al–4V onto a Ti–6Al–4V substrate. Furthermore, this study attempts to establish a relationship between the process parameters, the process stability and the layer geometry. Successful deposition of titanium alloys can be used in various applications, such as aircraft turbine blade roots and hip joint replacements. Focus of further studies will be the potential to improve mechanical properties, especially the susceptibility to wear and fretting fatigue.

2. Experimental details

The FS equipment used for these experiments has been custom-designed for high process loads and is capable of delivering 60 kN axial force, 6000 min^{-1} rotational speed and 200 Nm of torque. It can be operated in a force or rod consumption rate (RCR, i.e. shortening of the rod per unit of time, also denominated as the burn-off rate) controlled modes. The machine is equipped with sensors for the simultaneous monitoring and recording of forces in three directions and with a torque sensor implemented in the spindle. The axial force is controlled via an electrically driven ball screw. The dynamic electric motor for the spindle provides a constant rotational speed during the process. The working space measuring 0.5 m x 1.5 m enables the coating of larger components. The machine has a flash cutting device to trim excessive plasticised material off the rod, which otherwise would block rod feeding (Fig. 2).

Table 1
Chemical composition of the base materials (wt.%).

	Material	Fe	C	N	H	O	Al	V	Ti
Consumable rod	Ti–6Al–4V	0.05	0.02	0.03	0.002	0.16	6.1	3.8	Bal.
Plate	Ti–6Al–4V	0.14	0.005	0.009	–	0.113	6.32	3.98	Bal.

As titanium reacts with oxygen at temperatures above 400 °C producing a brittle oxide layer, argon was used as shielding gas to avoid the contamination of the rod and the substrate from the atmosphere. A custom built shielding gas cup was used during the experiments.

Ti–6Al–4V (ASTM F 136-08) hot-rolled plates with dimensions of 300 mm x 100 mm x 10 mm were used as the substrate for the depositions. A Ti–6Al–4V alloy in a rolled condition was used as the consumable rod with a diameter of 20 mm. This is an alpha-beta-phase Ti alloy containing Al (6 wt.%) and V (4 wt.%). Aluminium stabilises the alpha-phase, which is hexagonal, and vanadium stabilises the beta-phase with a cubic body-centred lattice [12]. The chemical composition and properties of the Ti–6Al–4V as provided by the supplier are shown in Tables 1 and 2.

Cross sections of the deposits have been prepared according to standard metallographic practices. After grinding and polishing, the samples were etched with a Kroll solution (5 ml hydrofluoric acid, 5 ml nitric acid and 90 ml distilled water) to reveal the microstructure. The layer geometry was observed by an optical microscope (Leica Microsystems DM IRM).

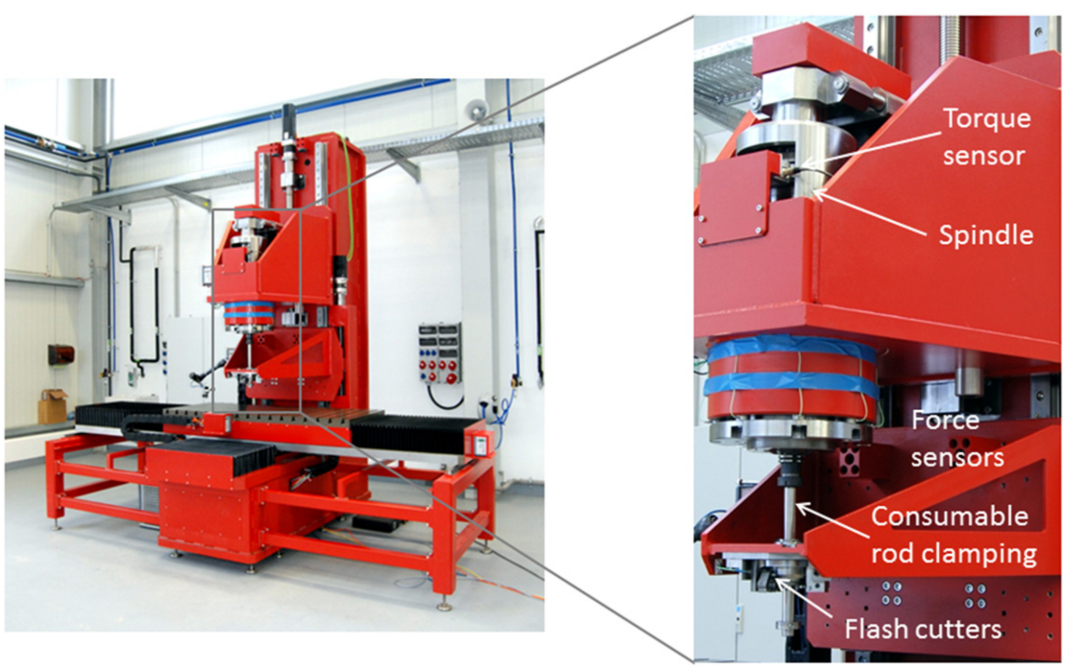

Fig. 2. Friction surfacing equipment.