Surface & Coatings Technology 207 (2012) 310–318

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Microstructures and properties of friction surfaced coatings in AISI 440C martensitic stainless steel

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ARTICLE INFO

Article history:
Received 20 April 2012
Accepted in revised form 1 July 2012
Available online 11 July 2012

Keywords:
Friction surfacing
Martensitic stainless steel
Coatings
Corrosion
Wear

ABSTRACT

While martensitic stainless steel AISI 440C is an attractive material for wear protection in many industrial applications, it is difficult to realize satisfactory coatings in this material using conventional weld overlay processes. Friction surfacing, a promising solid-state process, can help in this regard. In the current study, alloy 440C coatings were successfully made on low carbon steel substrates using friction surfacing. Bend and shear tests on coated specimens indicated excellent coating/substrate bonding. Microstructures, corrosion behavior, and wear performance of these coatings were compared with standard heat treated alloy 440C bulk material. While friction surfaced coatings in alloy 440C exhibited superior corrosion resistance to standard heat treated alloy 440C bulk material, their wear resistance was found to be somewhat inferior. Apart from these studies, experiments were conducted to assess the potential of the process for wide area coverage. Studies show that it is possible to achieve well-bonded coatings consisting of multiple overlapping tracks with excellent inter-track bonding. Overall, the current study demonstrates that friction surfacing is a very useful process for producing wear resistant coatings in difficult-to-fusion-deposit materials such as alloy 440C martensitic stainless steel.

1. Introduction

Martensitic stainless steel AISI 440C is one of the strongest and hardest of the martensitic class of stainless steels. It is used in bulk form in a variety of industrial applications such as hot working dies and tools, propellers, pump impellers, ball bearings and races, bushings, valve seats, industrial knifes, etc., where high strength or wear resistance and moderate corrosion resistance are needed. Despite its high hardness and wear resistance, alloy 440C is seldom used as a hardfacing material at present due to its poor fusion weldability [1].

Friction surfacing is a promising technology for producing metallurgically bonded coatings in difficult-to-fusion-deposit materials like alloy 440C. While the process of friction surfacing is known for more than 50 years, it has remained dormant for many years. The process was given a serious consideration in 1980s, especially in UK, which, however, did not lead to any main stream industrial applications. In recent years, there has been a resurgence of interest in friction surfacing, driven by the need for superior coating solutions. The enormous success of friction stir welding, for which friction surfacing is widely considered as the forerunner, has also prompted researchers all over the world to give it a fresh consideration.

Friction surfacing can be carried out using standard friction stir welding machines in load control mode; however, dedicated friction surfacing machines are now commercially available. The process begins with rotating a consumable rod (mechtrode), under some constant axial force, against a substrate (Fig. 1). Frictional heating results in softening and plastic deformation of the mechtrode material. After a short dwell time, the substrate is made to move. As this happens, hot metal from the mechtrode gets deposited onto the substrate, resulting in a track of metallurgically bonded coating along the line of traverse. Usually, the track is as wide as the diameter of the mechtrode. Being a solid-state process, friction surfacing is free from problems such as solidification cracking and dilution [2]. Compared to other solid-state cladding processes such as explosive cladding, friction surfacing has the following advantages: (i) the process is simple and versatile, (ii) it can be used for depositing coatings in a variety of materials, including hard and less ductile materials and (iii) the process is suitable for the selected area coverage.

There have been quite a few recent publications on friction surfacing. Among the materials successfully friction surfaced to date on steel substrates include austenitic stainless steels AISI 304 [3,4], AISI 310 [5,6], AISI 316L [7], and AISI 321 [8]; martensitic stainless steels AISI 410 [9], AISI 416 and AISI 431 [10]; tool steels AISI H13 [11], AISI D2 [12], AISI ASP30 [13]; Ni-base alloy Inconel 600 [14]; and aluminum [14,15]. Further, friction surfacing of copper on copper [12], magnesium alloy AZ91 on magnesium alloy AZ31 [16], Al–Cu alloy AA2017 on Al–Mg alloy AA5052 [17], Stellite 6 on AISI 316L [18], aluminum matrix composite (AA2124/SiC$_p$) on cast Al–Si alloy A356 [19] and Ti alloy Ti–

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doi:10.1016/j.surfcoat.2012.07.001

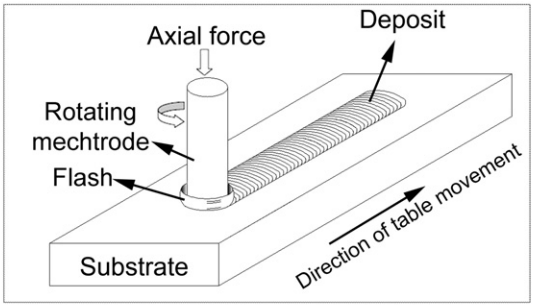

Fig. 1. Schematic illustration of friction surfacing process.

6Al–4V [20] have been successfully demonstrated. For friction surfacing of harder materials on softer substrates, Chandrasekharan et al. [21] proposed the use of a starter plate. Using this approach, steel coatings on aluminum alloy AA5083 have been realized. This idea can similarly prove to be valuable in dealing with many other coating/substrate combinations.

Some investigators have used friction surfacing for repairing defective or service-damaged components. Work by Yamashita and Fujita [22], de Macedoa et al. [6], and Hanke et al. [23] shows that friction surfacing can provide a superior alternative to conventional fusion weld repair. Further, friction surfacing has been shown to be suitable for layer-by-layer additive manufacture of three dimensional metallic parts [24]. Vitanov and co-workers have developed computer algorithms for friction surfacing process parameter selection and optimization [25,26]. The thermal cycles involved in friction surfacing have been studied by several different investigators for various coating/substrate combinations [12,13,27–29]. While considerable progress has been made in understanding the thermo-mechanical phenomena involved in the process [13,21,30–32], the mechanism of friction surfacing is yet to be fully understood. Similarly, it is not clearly known as to what factors govern the friction surfacability of materials. More importantly, much of the published information on friction surfacing to date is limited to single-track deposits. However, industrial utilization of friction surfacing for depositing corrosion or wear resistant coatings is critically dependent on whether the process can lend itself to wide area coverage or not.

With regard to friction surfacing of martensitic stainless steel AISI 440C, available information is very limited. Li and Shinoda [33] carried out underwater friction surfacing of alloy 440C on steel substrates to investigate the suitability of the process for underwater repair. Coatings were also attempted in air. In both cases, satisfactory coatings were achieved. Underwater friction surfacing was found to result in better deposition efficiency, finer coating microstructures, and higher hardness compared to friction surfacing in air. More recently, Katayama et al. [34] successfully produced a track of alloy 440C coating on the outer surface of a 89 mm diameter pipe (5 mm wall thickness) of austenitic stainless steel AISI 316L all around the pipe circumference. It was reported that the overlaid material showed fine grain size and was not diluted by the base material. In both of these studies, while successful friction surfacing of alloy 440C was demonstrated, coating microstructures and performance characteristics have not been investigated in detail.

In the current work, friction surfacing of martensitic stainless steel AISI 440C is attempted on steel substrates. Coating microstructures were investigated in detail and an attempt is made to explain the microstructure evolution in these coatings. The bond strength of the coatings was investigated using bend and shear tests. The performance characteristics of the coatings were investigated using corrosion tests and wear tests. An attempt is also made to investigate the suitability of the process for wide area coverage.

2. Experimental details

Martensitic stainless steel AISI 440C consumable rods (chemical composition in wt.%: 0.98C–17.8Cr–0.44Mn–0.30Si–0.02S–0.02P) of 100 mm long and 16 mm diameter in hot rolled and annealed condition were used. Annealing was done at 750 °C for 1 h, followed by furnace cooling. Friction surfacing experiments were conducted using a commercially available friction surfacing machine (Make: RV Machine Tools, Bangalore, India) in ambient atmosphere. Single-track coatings (about 100 mm long, 14 mm wide and 1 mm thick) were made on a low carbon steel (0.12C–0.4Mn–0.01S–0.02P) plate (150 mm × 100 mm × 10 mm). Prior to friction surfacing, the substrate was milled and ground to obtain a flat and even surface, free from oxide scales. Initially, a number of friction surfacing experiments were conducted for process parameter optimization. The aim was to obtain a well-bonded coating of about 1 mm thickness and 12 mm width. The process parameters were systematically varied in the following ranges: mechtrode rotational speed — from 800 to 1500 rpm, axial pressure — from 20 to 70 MPa, substrate traverse speed — from 1 to 6 mm/s. A dwell time of 30 s was used in all the cases. Based on these experiments, a broad process window (1000 to 1300 rpm mechtrode rotational speed, from 40 to 60 MPa axial pressure, and 2 to 4 mm/s substrate traverse speed) was established for good coating formation. Coatings produced using various process parameter combinations, within the above process window, were metallographically examined. In general, use of higher mechtrode rotational speeds was found to result in narrower coatings. While lower axial pressures resulted in more pronounced lack of bonding at the deposit edges, higher axial pressures resulted in thinner coatings. The coating thickness was also found to decrease with increase in substrate traverse speed. These observations are consistent with the findings of earlier investigations [11,25]. In essence, a process parameter combination involving 1200 rpm mechtrode rotational speed, 50 MPa axial contact pressure, and 3 mm/s substrate traverse speed was found to produce the best results. Fig. 2a shows a typical single-track friction surfaced (FS) coating produced using this combination of process parameters.

In order to understand the microstructural evolution in alloy 440C FS coatings, temperature measurements were carried out in the vicinity of the rotating consumable rod/substrate interface during the initial dwell period using a calibrated infrared camera (CEDIP JADE mercury cadmium telluride camera commercially available from Flir System, Croissy-Beaubourg, France) capable of measuring temperatures up to 1500 °C. The camera calibration involved the following. A black body device (emissivity: 0.96 to 0.98) is heated to different known temperatures. The radiation is captured by the camera and a digital photon

Fig. 2. Typical single-track (a) and multi-track (b) friction surfaced coatings in alloy 440C.