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Fabrication of graded surfacing layer for the repair of failed H13 mandrel using submerged arc welding technology

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ABSTRACT

A graded surfacing layer for repairing a failed mandrel was prepared on the surface of H13 steel using the homemade flux-cored wires via submerged arc welding technology. The microstructure of the designed surfacing layer was controlled by modifying its chromium content based on the Fe-Cr binary phase diagram. The as-welded microstructure, phases, chemical composition, microhardness and wear resistance of the resultant surfacing layer were analyzed using optical microscopy (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD), direct reading spectrometry, Vickers hardness testing and dry sliding wear testing. These results showed that the surfacing sample could be divided into seven zones based on cross sectional micrographs of the substrate, sublayer, wear layer and four fusion zones. The sublayer consists of a large amount of ferrite, lower bainite and carbides, which showed the lowest microhardness of 237 $HV_{0.2}$. The wear layer was composed of martensite, lower bainite, residual austenite and carbides with a microhardness of 356 $HV_{0.2}$ that was 80 $HV_{0.2}$ higher than that of the H13 steel substrate. The weight loss of the H13 steel substrate after wear testing for 20 min was 25.3 mg, which was around 1.7 times that of the wear layer (15.1 mg), whilst wear scar with smaller width and depth was observed on the surface of the wear layer. This indicates that the wear resistance of the wear layer was better than for the H13 steel substrate. No appreciable cracks were observed in the four fusion zones after the surfacing process, suggesting that good fusion had occurred between the H13 steel substrate, sublayer and wear layer.

1. Introduction

Mandrel is an important tool for seamless steel tube production that plays an important role in preventing the deformation of steel tube. Pussegoda et al. (1991) emphasized that the quality of mandrel used for manufacturing was important to the surface quality of steel tube, its production efficiency and the overall cost of the production process. Post-hot deformation quench and temper treatment process that produces high strength mandrel have been developed. Mandrel is subjected to highly aggressive working conditions for a long period of time, which is not only subjected to considerable radial rolling forces, but also large frictional forces arising from contact between the mandrel and the steel tube. Baines (2001) have described the use of lead to simulate longitudinal rolling of hot steel tube through grooved rolls under laboratory conditions. The mean deformation pressure and the contributions to this pressure from the homogeneous, frictional and redundant work components were analyzed. Zhao et al. (2009) investigated the friction states and friction coefficients between rolling tubes and the mandrel under different rolling forces and mandrel velocities, which demonstrated that the friction coefficient increased along the rolling direction. Mandrel was found to crack and eventually fail after a sufficiently large number of successive production runs. According to Rütti et al. (2007), these cracks were caused by rotation-bending fatigue, which resulted in a new mandrel design being introduced that exhibited a minimum safety factor of 2.3 to reduce the incidence of fatigue failure. Akiyama et al. (2000) studied the mechanism of crack initiation in mandrels for seamless steel tube production, which suggested that crack initiation was induced by thermal shock. A new method was proposed to improve mandrel lifetime. In general, crack formation and wear are the major reasons for mandrel failure. When a working mandrel becomes worn or cracked, then it must be replaced to ensure the quality of the steel tube and the safety of the rolling process, which can result in a significant increase in production costs and unexpected stoppages of the rolling process for long period of time. Therefore, the repair of a failed mandrel is of great significance for saving operational costs and natural resources.

A three step process is used to repair the mandrel in industry. Firstly, surface defects (craters and cracks) in the mandrel must be

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removed, followed by a surfacing process and electrodeposition of hard chromium. The surfacing process is critical for the repair of the physical properties and dimensions of the mandrel, which has been widely used to repair many kinds of dies because of the advantages of the low repair costs, the use of simple equipment, high bonding strength between the surfacing layer and substrate and the large thickness of the surfacing layer. Yang et al. (2011) reported that a new type of flux-cored wire was applied to repair continuous casting rolls using submerged-arc hardfacing technology, which resulted in an increase in welding performance and wear resistance. Jhavar et al. (2013) have reviewed the use of various materials in the manufacturing of dies, modes of failures that occur under different working conditions and various repair options including surfacing technology, which presented that although the advent of newer processes has eased out the challenge of repairing, the selection of appropriate repair material and methodology was still an area that needs a specialized attention and dependent on numerous techno-economic factors. Numerous reports have focused on the selection of repair materials and technologies to repair mandrel, however, there are relatively few reports on the design of the graded surfacing layer with special properties.

AISI H13 hot work tool steel has been widely adopted for manufacturing mandrels due to its good mechanical properties, such as strength, toughness and thermal stability and so it is extremely important to repair and strengthen this type of mandrel. For example, Tian et al. (2010) have studied the microstructure and mechanical properties of H13 mandrel steel under different quenching temperatures, reporting that the higher quenching temperature could improve strength, fracture toughness and thermal fatigue performance. Gasem (2013) investigated the cracking in a multiple gas-nitrided H13 aluminum extrusion mandrel, suggesting that the fracture toughness of single-nitrided H13 mandrel was better than that of an un-nitrided H13 mandrel.

In this work, a graded surfacing layer was prepared on the surface of H13 steel using the homemade flux-cored wires via submerged arc welding technology. The microstructure of the designed surfacing layer was controlled by modifying its chromium content based on the Fe-Cr binary phase diagram. The as-welded microstructure, microhardness and wear resistance were characterized.

2. Experimental

2.1. Material and process

The substrate used in this investigation was a failed H13 mandrel (as shown in Fig. 1) that removed surface defects. Its chemical composition is given in Table 1. The surfacing layer was prepared using the submerged arc welding under direct current reversed polarity with preheat at 250 ~ 300°C. The other welding conditions were as follows: welding voltage of 17 ~ 25 V, welding current of 100 ~ 140 A, wire extension of 15 ~ 20 mm and welding speed of 5 mm/s. A schematic showing the submerged arc welding process used in this study is shown in Fig. 2.

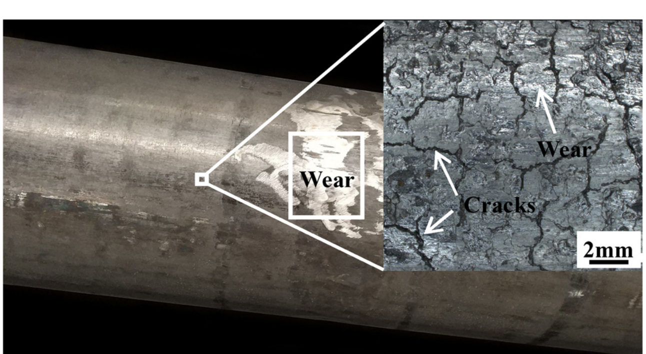

Fig. 1. Actual failed H13 mandrel.

Table 1
Chemical composition of AISI H13 steel [wt.%].

C	Si	Mn	Cr	Mo	V	P	S	Fe
0.32	0.87	0.32	5.32	1.32	0.88	0.016	< 0.001	Balance

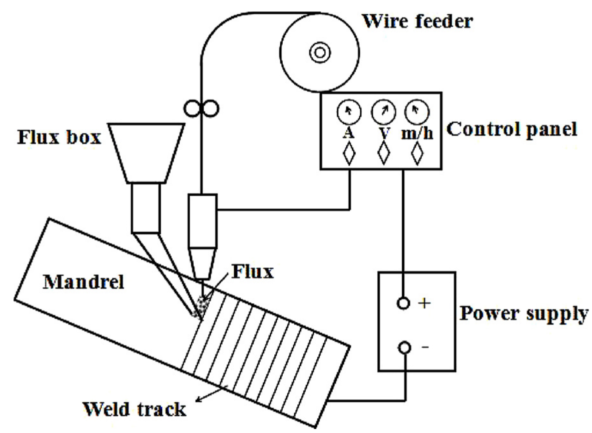

Fig. 2. Schematic of the submerged arc welding process.

2.2. Experimental methods

The microstructure of cross section of surfacing sample was characterized using a VHX-2000 3D optical microscope (OM) and Hitachi S4800 field emission scanning electron microscope (FESEM). A Brook D8 X-ray diffractometer (XRD) with Cu Kα generated at 40 kV and 40 mA was used to analyze the phases present in the surfacing layer. The diffractometer was rotated through 20 ~ 90° with a step value of 0.02°. A SPECTRO-MAXx direct-reading spectrometer was used to measure chemical composition.

Surface properties were studied by measuring surface microhardness and wear resistance. Microhardness tests were conducted using a MH-6LVickers microhardness tester under a 200 g load for 15 s, with values presented as the average of ten measurements after the highest and lowest values were discarded. Wear resistance tests were carried out using a MM-200 dry sliding wear tester fitted with a ring (50 mm in diameter, 10 mm in width) made of GCr15 bearing steel under a load of 49 N for 20 min at a rotational speed of 200 r/min.

3. Design of surfacing layer

High microhardness and wear resistance are regarded as necessary surface properties to prevent the deformation and wear of mandrel. H13 steel used as substrate has poor weldability due to its high carbon content, which can result in cracks being formed in the surfacing process. Consequently, a sublayer with good plasticity, toughness and tensile strength was prepared on the surface of H13 steel, beneath the wear-resistant surface layer.

The physical properties of a material are determined by its microstructure which is dependent on its chemical composition. Ukai et al. (2017) have reported the development of oxide dispersion-strengthened / ferrite-martensite (ODS / F-M) steels and their mechanical properties, demonstrating that structural control was successfully conducted by using α-γ phase transformation for ODS martensitic steels based on Fe-Cr binary phase diagram (Fig. 3), which was sufficient to withstand the levels of mechanical loading reached in some core structures. In this work, the microstructure of the surfacing layer was found to be mainly α phase, with no γ phase being observed in the alloy when chromium content was > 13.4 wt.% (Fig. 3). For this reason, a ferrite sublayer