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Effects of preheating and carbon dilution on material characteristics of laser-cladded hypereutectoid rail steels

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ABSTRACT

The impacts of preheating conditions and carbon dilution on the microstructural and mechanical properties of laser cladded rails using single and double cladding layers have been investigated for a hypereutectoid steel grades typically used under heavy haul conditions. The microstructures in the HAZ showed that formation of martensite, which has a detrimental effect on behaviour in wheel-rail contact, was successfully inhibited by increasing the length of the preheated region using a preheating temperature of 350 °C. Dilution of carbon from the hypereutectoid substrate was observed and its effect on the microstructures of the 410L ferritic stainless-steel deposits was investigated. The formation of ferrite in the 410L cladding layers was attributed to the very low carbon content, and no carbide formation was observed on boundaries of the ferritic grains. The thickness of dilution band was determined to be approximately equal to the thickness of the first cladding layer. Texture measurement obtained by EBSD showed a random trend owing to the formation of martensite in diluted bands. Strong solidification fibre texture was developed for double deposition, particularly in the second deposit. Mechanical characterization of the 410L deposits undertaken in terms of Vickers microhardness, shear and tensile yield strengths, and ultimate tensile and shear strengths were correlated with the observed microstructural morphologies.

1. Introduction

Material degradation in the form of wear and rolling contact fatigue (RCF) in the rail head is induced by the complex contact between wheels and rails. Remedial actions such as rail grinding or wheel machining, and eventually component substitution, contribute a significant part of the cost of railway network operation. Regular maintenance or even replacement of the damaged components can also lead to disruptions in rail haulage operations, and adverse economic impacts.

Applications of surface engineering techniques, i.e. laser glazing and laser cladding, either to repair existing damage or during manufacture, have been attempted to extend component service lives and maintenance intervals, while conserving the properties of the parent rails. Previous studies [1] addressing the localized damage on railhead surfaces by the utilisation of the laser surface treatments, particularly laser cladding technique, have demonstrated encouraging results and promising potential as techniques for alleviating the rate of component degradation. Briefly, the laser cladding process is a melting process in which a focused laser beam is utilized to deposit a coating of the selected material onto the target surfaces. Dimelfi et al. [2] and Aldajah et al. [3] performed laser glazing of a pearlitic rail substrate and obtained reductions in the surface friction coefficient and lateral forces, respectively. Shariff et al. [4] investigated the effects of laser hardening and laser melting on wear performance of the T-12 Indian rail steel and reported that the friction coefficient was marginally deducted. Niederhauser et al. [5] examined the mechanical properties of the B-82 Swedish rail steel cladded with Co-Cr alloys and showed a consistent and promising fatigue performance. Ringsberg et al. [6] performed finite element analysis on the European pearlitic UIC 900A (R260) steel cladded with Co-Cr alloys and found that the laser cladding and grinding processes decreased the safety margin against fatigue failure.

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Franklin et al. [7] validated Ringsberg et al.'s FEA results by conducting laboratory experiments of cladded R260 rail samples under simulated wheel-rail contact conditions. They showed that laser cladded (InfraStar) rail materials survived 200,000 cycles of water-lubricated twin-disc testing without crack formation, whereas UIC (260 grade) 900A base material showed severe cracking after only 4000 cycles. Furthermore, the cladded rails with the InfraStar materials were field tested by Hiensch et al. [8] and showed no RCF damage over one year in the rail track where the non-treated rail showed clear RCF damage.

Evaluation of the mechanical performance and metallurgical characteristics of the rail steels after cladding are vital in the development of future rail maintenance strategies. The previous studies [2–8] were performed using eutectoid carbon rail steel grades. In the current investigation, the effect of the higher carbon levels associated with premium rail grades such as those used under heavy haul conditions on the characteristics of the cladding layers and the heat-affected zone is studied.

For such an application, information on two fundamental issues, i.e. effects of the higher carbon levels on the characteristics of the cladding layers, and martensitic formation in heat affected zone (HAZ) of the parent rail is scarce in the open literature. The formation of hard and simultaneously brittle phases in the HAZ is expected to increase the susceptibility to cracking under cyclic, dynamic or high impact loading conditions. In addition, the effects of carbon dilution from the higher carbon substrate on the mechanical and microstructural characteristics of laser cladded deposits, which has been investigated in this paper, is crucial in controlling the quality and preserving the chemical composition and properties of the laser deposits.

Hence, these fundamental issues are addressed by examining material property data and correlating them to the microstructures of the cladding material and rail substrate. Furthermore, the proposed heat treatment regime in this paper, which hinders the formation of martensite in the HAZ of laser cladded rails, should facilitate the utilisation of laser cladding technology in railway applications.

Therefore, the present study focused on the development of a heat treatment regime to prevent martensite in the HAZ by altering preheating conditions and its effects on the characteristics of the laser cladded rails. The preheating conditions were varied by altering the preheating length of the rail and over which the cladding was then applied. Furthermore, results of the study revealed the influence of diluted carbon from a high carbon rail upon a low carbon laser cladding deposit. In this paper, a functionally graded rail will be established by utilizing a fibre laser to fuse an extra layer of 410L stainless steel onto a 600-mm high-strength hypereutectoid rail piece. Microstructural evolution of the 410L deposits and the resultant HAZ were characterized via optical microscopy (OM), Scanning electron microscopy (SEM) and Electron Backscattered Diffraction (EBSD). By combining with the results of X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDS) microanalysis and scanning transmission electron microscopy (STEM), dilution from the substrate to the cladding layers was observed. Mechanical properties were also obtained via Vickers microhardness and shear punching tests. Ultimately, the relationships between microstructural characteristics and mechanical properties of the functionally grade rails were determined.

2. Experimental procedure

2.1. Materials

A premium rail grade produced by Nippon Steel Sumitomo Metals Corporation (NSSMC) was selected as the rail substrate. This grade exhibits higher strength and is more wear resistant compared to the head hardened rail grade, as described in AS 1085.1-2002 [9]. The rail grade selected for the trial complies the requirements outlined in EN 13674-1 for the R400HT grade [10]. Details of the actual composition and that specified for R400HT grade are summarised in Table 1a.

The depositing material was selected to be the 410L stainless steel with average particle diameter of 150 μm due to its greater compatibility with the laser cladding process, excellent protection to corrosion and abrasion, and reasonable strength and toughness [11–13]. The dimensions over, which the cladding was applied, were chosen based on the experience with in situ rail repairs being 200–800 mm long. Therefore, to simulate the rail repair with full constraint and a representative heat sink during a laser cladding deposition, the repair length using laser cladding was chosen to be 400 mm on a 600-mm long rail. This would allow the critical parts of the repair, such as the transient state condition at the start and end of the cladding layer and the steady state condition in the middle of the rail sample, to be investigated. Generic geometric sizes of the deposited layers and rail steel substrates are depicted in Fig. 1. Rust and contaminants were removed by grit-blasting before cladding.

2.2. Laser cladding process parameters

In this study, a laser coaxial nozzle containing a 4 kW IPG fibre laser gun and a Sultzer-Metco twin-10 powder feeder were controlled by a Motoman XRC SK 16X 6-axis CNC unit to scan over the rail's surfaces to be cladded. A melt pool is therefore generated by simultaneously melting the injected powder and the rail substrate. To protect from undue oxidation, shielding gas of 50% Argon and 50% Helium was used around the melt pool. The optics setup produces a concentrated circular laser spot made by the beam on the rail surface with 5 mm in diameter. Two separate specimen groups with different pre-heating lengths and number of deposited layers were prepared as shown in Table 2.

To ensure no porosity and cracks on the surface and throughout the laser deposits, specimens were cladded in the rail-longitudinal direction using laser power of 3.2 kW, traverse speed of 1000 mm/s and powder feed rate of 26.4 g/min. These processing parameters were experimentally achieved and proven by many trials which were reported previously by the authors [14].

2.3. Characterization of microstructural and mechanical properties

Prior to microstructural characterization, specimens from the two groups were sectioned selectively in both rail-transverse and longitudinal directions to obtain representative metallographic specimens. The resulting specimens were mounted, polished and etched with a two-stage etching procedure; in the first stage, a 2% Nital etchant was used to reveal the rail steel substrate's microstructure and a Kalling's no. 2 (5 g $CuCl_2$, 100 ml HCl and 100 ml ethanol) solution was used in the second stage to investigate the microstructure of the deposits. The etched metallographic specimens were then analysed using a Nikon Eclipse optical microscope and a JEOL 7001F FEG scanning electron microscope.

To investigate the diffusion behaviour of carbon, a focused ion beam (FIB) milling method was employed using the FEI Quanta 3D FIB workstation. FIB samples were sectioned using a Buehler IsoMet low speed saw machine equipped with a diamond blade to minimize the preparation artefacts. Site-specific in-situ lamellae were extracted from the obtained FIB samples in a virtually stress-free manner. The following main steps were applied to fabricate exquisitely the thin foils for STEM analyses: 1) Depositing platinum (Pt) to cover and protect the area of interest, 2) Rough ion milling, 3) Performing J-cut, 4) Lifting out the lamella, 5) Mounting the lamella on a copper grid, 6) Thinning the lamella and 7) Finally polishing procedures were conducted on the foils. STEM images were taken in high-angle annular dark-filed (HAADF) mode using a FEI Tecnai G2 F20 S-TWIN microscope operating at an accelerating voltage of 200 kV.

The EDS microanalysis was performed using the Bruker XFlash 6130 T Silicon Drift Detector (SDD), which was installed on the Tecnai F20. Both the Bruker D8 Advance ECO X-ray diffractometer with Co K_α and the *HKL* Nordlys S EBSD camera operating in conjunction with