Laser Cladding for Railway Repair: Influence of Depositing Materials and Heat Treatment on Microstructural Characteristics

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ABSTRACT

The contact between train wheels and rail tracks is known to induce material degradation in the form of wear, and rolling contact fatigue in the railhead. Laser cladding, a state of the art surface engineering technique, is a promising solution to repair damaged railheads so as to alleviate the rates of degradation and extend the component longevity. In this paper, effects of cladding material and heat treatment on microstructures of laser treated rails is presented. Laser cladding of premium hypereutectoid rail, four different depositing materials, and different heat treatments were investigated. For the preheating length of 400 mm, equal to the cladding length, the formation of martensite in heat affected zone (HAZ) was not hindered by the application of preheating to 350 °C on the rail-longitudinally deposited railhead of the four materials. Consequently, cracking in the clad and HAZ was expected. An uncracked microstructure with excellent microstructural consistency across the entire rail-longitudinally deposited railhead and its HAZ was established using a heat treatment combination consisting of pre-heating, post-heating, and slow cooling, regardless of the depositing materials.

KEYWORDS: Laser cladding; Hypereutectoid rail grade; Microstructure; HAZ; Heat treatment.

1 INTRODUCTION

Due to the presence of rolling contact fatigue (RCF) and wear damages at contact surfaces, frequent maintenance or even replacement of railway components are often required in modern railway infrastructure (Cannon et al., 2003). The resulting network downtime and expenditure are, therefore, significant. The surface treatment of damaged railway components, particularly the laser cladding technique, has been demonstrated as a promising solution so that composite coatings can be applied on either new or used engineering components to obtain superior surface properties. Recent studies have demonstrated improvements in the RCF performance of the laser treated components (Wang et al., 2014; Lewis et al., 2015). Technically, laser cladding is a melting process in which laser beam is used to fuse the desired material addition onto a substrate. A schematic of the typical laser cladding process is shown in Fig.1.
With the aim to enhance surface properties and corresponding tribological performance of rails and track components while conserving the properties of parent rail substrate, many research groups have applied laser depositing techniques, consisting of laser glazing and laser cladding, to various rail grades. Shariff et al (Shariff et al., 2010) studied the application of laser glazing treatment on the T-12 Indian standard rails with a 10-15 µm thick graphite layer. Using similar technique, Aldajah (Aldajah et al., 2003) reported a fine solidified microstructure in the treated rails. Investigations performed by Niederhauser et al. (Niederhauser and Karlsson, 2005) on the fatigue behaviour of B 82 steel, widely used for railway wheels in Sweden, cladded with Co-Cr alloys showed consistent and favorable fatigue behaviour results of the cladded specimens. Similarly, Ringsberg et al (Ringsberg et al., 2005) studied the RCF behaviour of a Co-Cr alloy layer cladded on the pearlitic UIC 900A (R260) rail steel. Under the InfraStar project, Franklin et al (Franklin et al., 2005) worked on laboratory tests and Hiensch et al (Hiensch et al., 2005) conducted actual field tests regarding RCF and wear behaviour of the laser cladded UIC 900A (R260) rails.
The present work aims to investigate the influence of depositing materials and heat treatment on microstructural and mechanical characteristics of hypereutectoid rails. The 410L stainless steel, 420 stainless steel, Stellite 6 and Stellite 21 were selected as the clad materials owing to their high strength, excellent resistance to abrasion and corrosion, and great laser compatibility (Zhong et al., 2002; Krishna and Bandyopadhyay, 2009; Cabrol et al., 2015; Krakhmalev et al., 2015). Consequentially, laser cladding of these materials were performed on a premium hypereutectoid rail grade using a 4 kW IPG fibre laser. The microstructural evolutions of the 410L depositing layer and the heat affected zone (HAZ) of the rail substrate were analysed via optical microscopy (OM) and Scanning Electron Microscopy (SEM). Comparison in mechanical properties between different depositing materials was obtained by utilizing shear punch testing. Indications of wear resistance of cladding layer were obtained via Vickers indentation, thereby, the correlation between the microstructural characteristics and the wear performance was also established.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

A premium hypereutectoid rail grade, often used in high axle load applications with high traffic, was selected as the model substrate. The composition complies with the EN 13674 requirements for R400HT grade. The actual composition and R400HT specifications are provided in Table 1a. Four different depositing materials, namely 410L stainless steel (~150 μm), 420 stainless steel (~150 μm), Stellite 6 (45-106 μm) and Stellite 21 (45-125 μm), were centrally cladded onto the hypereutectoid rail head. Fig. 2 shows the schematic of a typical laser cladded rail section with a defined coordinate system. The chemical composition of the powders is listed in Table 1b. Prior to applying the laser treatment, the rail portions were ground, polished and cleaned.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
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<tr>
<td>410L</td>
<td>Bal</td>
<td>0.01</td>
<td>0.51</td>
<td>0.47</td>
<td>0.01</td>
<td>0.01</td>
<td>0.08</td>
<td>12.7</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>Bal</td>
<td></td>
</tr>
<tr>
<td>420SS</td>
<td>Bal</td>
<td>0.24</td>
<td>1.17</td>
<td>0.63</td>
<td>0.01</td>
<td>0.01</td>
<td>0.22</td>
<td>12.6</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>Bal</td>
<td></td>
</tr>
<tr>
<td>Stellite 6</td>
<td>0.09</td>
<td>0.99</td>
<td>0.02</td>
<td>1.58</td>
<td>&lt;0.01</td>
<td>0.03</td>
<td>0.72</td>
<td>28.3</td>
<td>0.01</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.10</td>
<td>Bal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stellite 21</td>
<td>0.16</td>
<td>0.23</td>
<td>0.59</td>
<td>0.86</td>
<td>0.01</td>
<td>0.01</td>
<td>2.28</td>
<td>27.0</td>
<td>5.20</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.05</td>
<td>Bal</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Parameter sets applied for comparative study of heat treatment.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Heat treatment procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>Preheating to 350 °C (HTA)</td>
</tr>
<tr>
<td>Group 2</td>
<td>Preheating to 350 °C, post-heating (PWHT) to 350 °C and then was slow-cooled to room temperature by using ceramic blanket (HTB).</td>
</tr>
</tbody>
</table>

Fig. 4 Micrograph showing the HAZ and substrate of the rail-cross sections at (a) left gauge corner, (b) middle section, (c) right gauge corner and (d) a representative longitudinal section under the 410L - Fig. 4.1, 420SS - Fig 4.2, Stellite 6 - Fig.4.3 and Stellite 21 - Fig. 4.4 deposited layers with preheating heat treatment only and one depositing layer (Group 1). (M=martensite)

2.2 Laser cladding process parameters

The laser cladding process was carried out by concurrently melting the addition and substrate materials using a laser coaxial head comprising of 4 kW IPG fibre laser gun and a Sultzer-Metco twin-10 powder feeder. This laser head was manipulated by a Motoman XRC SK 16X 6-axis CNC unit. The laser beam was optically modified to deliver a concentrated circular laser spot with a spot size of 5 mm diameter on the surface of the substrate. Shielding gas of 50% Argon and 50% Helium around the laser beam was used to avoid undue oxidation during the process.
The system was air-cooled. Two groups of specimens were produced by altering the heat treatment procedure as shown in Table 2. Laser power, scanning speed, and powder feed rate, cladding direction were remained constant at 3.2 kW, 1000 mm/s, 26.4 g/min and rail-longitudinal, respectively.

![SEM micrographs of the sub-regions in the Group 1 HAZ. (a) Partially molten zone featuring a metallurgical bond at the top. In the middle, (b) Coarse-grained HAZ characterized by fully pearlitic structure and (c) Fine-grained HAZ characterized by partially and fully pearlitic structure, and (d) Inter-critical HAZ characterized by spheroidite at the interface under the 410L rail-transversely deposited clad (Group 1).](image)

3 RESULTS AND DISCUSSION

3.1 Influence of heat treatment and depositing materials on microstructural properties of the HAZ

The optical micrographs of the rail transverse sections at (a) left gauge corner, (b) middle section and (c) right gauge corner, and (d) a representative rail longitudinal section depicting the heat affected zone (HAZ) and the unaffected substrate under the 410L, 420SS, Stellite 6 and Stellite 21 cladding layers are shown respectively in Fig. 4.1-4.4 for Group 1. Multiple sub-regions in the HAZs were developed as a result of the substrate microstructure subjected to the effects of heating and cooling during the laser cladding process.

Generally, four sub-regions were detected inside the Group 1 HAZ. (i) Partially molten zone featuring a metallurgical bond between the clad and substrate shown in Fig. 5(a). (ii) Coarse-grained HAZ, in rail-transverse sections, characterized by bainite at the middle section as shown in Fig. 5(b), and martensite was observed in this zone at all the right gauge corners for Group 1 as shown in Fig. 4.1-4.4(c) and occasionally at middle sections shown in Fig. 4.2(b). Whereas in the rail-longitudinal sections, regardless of the depositing materials, martensite was discerned in all sections of this zone, as shown in Fig. 4.1-4.4(d). (iii) Fine-grained HAZ with a combination of pearlite and bainite shown in Fig. 5(c). (iv) Spheroidised or partial spheroidised microstructure and located adjacent to the unaffected substrate and the furthest from the
interface shown in Fig. 5(d).

Fig. 6.1-6.4 shows the micrographs of the rail transverse sections depicting the HAZ and base material under the 410L rail-longitudinally deposited clad (Group 2) at (a) left gauge corner, (b) middle section and (c) right gauge corner beneath the 410L, 420SS, Stellite 6 and Stellite 21 cladding layers, respectively. A representative microstructure of the rail longitudinal sections of the Group 2 specimens is shown in Fig. 6.1-6.4(d).

Fig. 6. Micrograph showing the HAZ and substrate of the rail-cross sections at (a) left gauge corner, (b) middle section, (c) right gauge corner and (d) a representative of the longitudinal sections under the 410L - Fig. 6.1, 420SS - Fig 6.2, Stellite 6 - Fig.6.3 and Stellite 21 - Fig. 6.4 rail-longitudinally deposited layers with preheating, post heating and slow cooling and one deposited layer (Group 2). (TM=Tempered martensite)

For the Group 2 specimens, the four sub-regions were also found with the analogous microstructural characteristics to those in the HAZ of the Group 1 specimens. (i) The partial molten zone featuring a metallurgical bond is discerned in Fig. 7(a). The microstructures in (ii) the coarse-grained HAZ with bainitic morphology, (iii) fine-grained HAZ with a combination of pearlite and bainite, and (iv) Spheroidised or partial spheroidised microstructure are shown in Fig. 7(b)-(d), respectively. It is noted that these morphologies are observed in all specimens of the rail transverse sections. When subjected to a modification in heat treatment, in the longitudinal sections there are corresponding changes in morphology and microstructural characteristics, (ii) the aforementioned coarse-grained HAZ and (iii) fine-grained HAZ were replaced with tempered martensite as shown in Fig. 6.1-6.2(d), or even bainitic morphology as shown in Fig 6.3-6.4(d). Unlike the Group 1 longitudinal sections, no cracking was found in those of Group 2.
Fig. 7. SEM micrographs of the sub-regions in the Group 2 HAZ. (a) Partially molten zone featuring a metallurgical bond at the top. In the middle, (b) Coarse-grained HAZ characterized by fully pearlitic structure and (c) Fine-grained HAZ characterized by partially and fully pearlitic structure, and (d) Inter-critical HAZ characterized by spheroidite at the interface under the rail-longitudinally deposited clad (Group 2).

The findings altogether suggest that the application of pre-heating temperature of 350°C in Group 1 was, by itself, incapable of preventing the martensitic transformation in the HAZ in all of the depositing materials, particularly at the left gauge corner sections where the starting laser runs are, but not at the middle and the right gauge corner sections where the ending laser runs. This phenomenon is related to the heat dissipation of the applied preheating temperature, as the laser source is traveling from the left gauge corner to the right gauge corner. The microstructural features of the left gauge corner were more clearly revealed by the means of SEM, and was seen to consist of bainite as shown in Fig. 5(b). For longitudinal sections, the resulted HAZ’s microstructure was martensite, which agrees with those of the transverse sections and suggests that the preheating temperature of 350 °C at the length equal to the 400 mm cladding length is insufficient to hinder the formation of martensite in the HAZ. The martensitic microstructure is known to result in lower toughness and increased cracking tendency compared to other microconstituents for a given C content. Cracking was, therefore, detected in the HAZ as evident in Fig. 4.3(c). The involvement of PWHT in the Group 2 heat treatment regime is to mitigate the residual stresses, as a hardness control method and enhance material strength for the deposited layers and if not eliminate martensitic formation in the HAZ, then to reduce the cracking tendency of the martensite formed in the HAZ by its tempering effects. Tempered martensite was observed instead, particularly at the starting and ending of the laser tracks. This implies PWHT has limited effectiveness in avoiding martensite formation in the HAZ, but it was able to lower the cracking tendency in the HAZ, as there were not as many evident cracks. However, this is
based on the observation of one sample, the assessment of more samples are required to fully establish the effect of PWHT on the reduction of residual stress levels and the tendency to avoid crack formation.

Fig. 8. Micrograph showing the HAZ and substrate of the rail-cross sections at (a) left gauge corner, (b) middle section, (c) right gauge corner and (d) a representative of the longitudinal sections under the 410L - Fig. 8.1, 420SS - Fig 8.2, Stellite 6 - Fig.8.3 and Stellite 21 - Fig. 8.4 rail-longitudinally deposited layers with preheating heat treatment only and two deposited layers (Group 1). (M=martensite)

3.2 Microstructural properties of the HAZ with two depositing layers

Microstructural characteristics observed in the HAZ for the rail-longitudinally deposited rail with two depositing layers followed the aforementioned trends. The four sub-regions were also found with the analogous microstructural features to those in the HAZ of the Group 1 and Group 2 specimens with one layer as shown in Fig. 8 and Fig. 9, respectively. Martensite remained discernible at the right gauge corners of the transverse sections and at the ending/starting locations of the longitudinal sections for the Group 1 due to the rapid heat dissipation caused by thermal sinking effect of bulk rail substrate.

Tempered martensite was detected instead of martensite owing to the tempering effects of PWHT in the heat treatment of Group 2. However, (iii) the fine-grained and (iv) spheroidised or partial spheroidised microstructure developed twice in two separate regions across the HAZ’s thickness. This is attributed to the overlapping of HAZs in multiple layer deposition. By utilizing layer by layer deposition, heat penetration into substrate caused by the laser source into the substrate was eventually lessened owing to heat absorption and built-up thickness of the previously deposited layer. Therefore, the second layer HAZ appeared thinner and in the central of the previous HAZ. The second layer did not assist in avoiding formation of martensite, it also
resulted in a higher probability of martensite. The resulting overall substrate temperature in the second layer was expected to be lower that of the first layer as there was longer distance for thermal diffusion. As a result, martensite was mostly found in the HAZ of second layer as evident in Fig. 8 and 9. Measurements of HAZ’s thickness on the four depositing materials of the Group 1 (preheating only) and Group 2 (preheating, PWHT and slow cooling) shown in Fig.10 are in accord with the previous microstructural observations. The variation in HAZ’s thicknesses between one and two deposited layers are not substantial for most of the depositing materials.

This suggests the thickness of HAZ is likely independent of number of the deposited layers. Theoretically, PWHT did not play a major role in determining the HAZ’s thicknesses excepting for the 420SS deposited layer. However, differences of few hundred micrometers in thickness values of the HAZ between the Group 1 and Group 2 specimens were detected. It is possible that there might be some processing discrepancies such as the misalignment the laser beam and powder focus, or wearing of the powder nozzle which led to the loss of depositing materials.

Fig. 9. Micrograph showing the HAZ and substrate of the rail-cross sections at (a) left gauge corner, (b) middle section, (c) right gauge corner and (d) a representative of the longitudinal sections under the 410L - Fig. 9.1, 420SS - Fig 9.2, Stellite 6 - Fig.9.3 and Stellite 21 - Fig. 9.4 rail-longitudinally deposited layers with preheating heat treatment only and two deposited layers (Group 2). (TM=Tempered martensite)
3.3 Comparison of mechanical properties of the laser cladded layers

One of the main stress modes developed under wheel-rail contact is shear which acts at an angle to the loading direction (Johnson, 1987). Depending on the friction coefficient or creepage, the maximum shear can be either located at rail surface or subsurface, where rolling contact fatigue (RCF) damage is commonly detected. RCF damage is found to increase with greater shear stress (Magel, 2011). Therefore, it is crucial to evaluate shear strength of the laser treated rails by means of shear punch testing, and compare to that of virgin rails. Furthermore, shear punch testing is also an effective method to assess other material properties, namely yield strength (YS), ultimate tensile strength (UTS), etc., when the material availability is limited (Hankin et al., 1998; Hankin et al., 2000; Guduru et al., 2005). Fig. 10 shows the average load-displacement curves of five measurements for the aforementioned

![Fig. 10. The heat affected zone (HAZ)'s thickness under the 410L, 420SS, Stellite 6 and Stellite 21 deposited layers subjected to different heat treatments and number of layers.](image)

![Fig. 11. Comparison of the load – displacement curves with corresponding ultimate shear strength (USS) values acquired for the 410L, 420SS, Stellite 6 and Stellite 21 deposited layers subjected to similar heat treatments and processing parameters.](image)

To establish a reference stiffness curve, a rail sample of 0.6 mm thickness was made out of the rail material complied with the R400HT specification. The solid pearlitic rail steel sample required a shearing force of 5380 N and the corresponding ultimate shear strength (USS) of 937±8 MPa to fail with typical elastic-plastic behaviour as shown in Fig. 11. Similar measurements for the four depositing materials with also 0.6 mm thickness reveal different mechanical behaviour from that of the rail. It can be observed in Fig. 11 that the 420SS, Stellite 6
and Stellite 21 depositing materials exhibited fast brittle fracture, which means very little plastic deformation experienced upon fracture, with failure loads of 8445 N, 5198 N and 5815 N and their corresponding USS of 1407±29 MPa, 909±19 MPa and 1005±20 MPa, respectively. On the other hand, similar to the rail, elastic-plastic deformation was observed for the 410L samples, and its failure load and USS were 4550 N and 791±7 MPa, which are 84% of those of the rail. Correlation between ultimate shear and tensile data has been well-established from previous studies (Guduru et al., 2005; Sellamuthu et al., 2013). Thus, a proven estimation of the ultimate tensile strength of 1423±12 MPa can be made for the 410L deposited layer. Furthermore, Pun et al (Pun et al., 2014) reported that the ultimate tensile strengths (UTS) of two comparable premium rail grades were 1384 MPa and 1429 MPa, which suggests the UTS of 410L depositing layer is still within the acceptable range. All the other depositing materials’ predicted UTS values are also well beyond the upper limit of the range.

4 CONCLUSIONS

In this study, the influence of different laser depositing materials and heat treatment procedures applied on a hypereutectoid rail steel was investigated. The following conclusions can be drawn from the obtained results:

Regardless of the number of deposited layers and depositing materials utilized, application of preheating at the heating length equal to the cladding length (Group 1) was insufficient to prevent the formation of martensite in HAZ. Addition of PWHT and slow cooling in Group 2 specimens were proven to provide beneficial tempering to the HAZ’s microstructure, particular in those with martensite. Non-cracked and consistent HAZ across the entire rail-longitudinally deposited railhead, therefore, was able to be achieved.

Adding a second layer did not change the thickness of HAZs, but refined the HAZ’s microstructure. If the heat treatment applied (Group 1) involves only preheating, an increase in the number of layers may introduce greater chance for the development of martensite, since there is more time for cooling the substrate’s preheated temperature.

The 420SS, Stellite 6 and Stellite 21 specimens showed brittle fracture behaviour in the shear punch test, whereas the 410L specimens behaved in an elastic-plastic manner similar to the virgin rail. All the used laser deposited materials showed potential capability to improve the characteristics of rails to withstand the wheel-rail contact load in a typical heavy haul railway system.

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