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Investigation on laser cladding of rail steel without preheating

Christian Brunner-Schwer[a,*], Max Biegler[a], Michael Rethmeier[c,b,a]

[a]Fraunhofer Institute for Production Systems and Design Techology, Pascalstraße 8-9, 10587, Berlin, Germany
[b]Bundesanstalt für Materialforschung und –prüfung, Unter den Eichen, 87 12205, Berlin, Germany
[c]Institute of Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587, Berlin, Germany

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. Rails with a pearlitic microstructure have proven to provide the best wear resistance under severe wheel-rail interaction in heavy haul applications. High speed laser cladding, a state-of-the-art surface engineering technique, is a promising solution to repair damaged railheads. However, without appropriate preheating or processing strategies, the utilized steel grades lead to martensite formation and cracking during deposition welding.
In this study, laser cladding of low-alloy steel at very high speeds was investigated, without preheating the railheads. Process speeds of up to 27 m/min and laser power of 2 kW are used. The clad, heat affected zone and base material are examined for cracks and martensite formation by hardness tests and metallographic inspections. A methodology for process optimization is presented and the specimens are characterized for suitability. Within the resulting narrow HAZ, the hardness could be significantly reduced.

Keywords: High speed laser cladding; rail tracks; pearlitic microstructure; preheating

1. Introduction

Considerable masses are transported on the rails of the railroad network every year. Vehicles with axle loads of up to 22.5 t regularly roll over the tracks [1]. These loads are absorbed by the rails. The result is enormous stress on the material and corresponding wear [2] making regular maintenance of the

* Corresponding author. Tel.: +49 30 39006-399
E-mail address: christian.brunner-schwer@ipk.fraunhofer.de.

superstructure inevitable. A large part of the operating costs of rail track networks is accounted for by reworking and preventive measures such as grinding, weld repairs and rail replacement [3].

As a track and guiding element, the rail fulfills the task of transmitting wheel loads, guiding the wheels safely, and offering the vehicles low rolling resistance by making the track as smooth as possible. It is subjected to high dynamic forces in the longitudinal and transverse directions, resulting in bending and torsional stresses. It is subject to wear and rolling contact fatigue due to sanding and sliding. To withstand these stresses, the rail must have high fatigue strength, adequate yield/tensile strength and hardness, and high resistance to brittle fracture. [4]

The materials used for rails are unalloyed or low-alloy steels whose strength values can be increased by exploiting manufacturing or processing mechanisms. The strength is adjusted via the chemical composition mainly by the three alloying elements Carbon (C), Manganese (Mn) and Chromium (Cr). However, these cannot be used in arbitrarily large quantities as they impair the weldability of the steel. [5]

In addition to the widely used grinding process, deposition welding is a complementary method of repairing worn or damaged rails [4]. Manual arc welding [4] and, in some cases, submerged arc welding [3] are the established processes in practice. Preheating is usually carried out by means of a gas torch [6]. In recent years, a large number of studies have been published on the possible use of laser cladding (Laser-DED) for the welding repair of rails as an alternative process [7]. A large proportion of recent publications on this subject address the possibilities of improving the wear protection of rails by applying various coating materials by means of laser cladding. Lai et al., for example, use the 410L stainless steel in combination with preheating and post-heating [8]. Seo et al. compare coatings of Stellite 21, Hastelloy C, Inconel 625 with the uncoated condition [9]. And Roy et al., for example, are additionally investigating SS420 and Stellite 6 coatings in combined pre- and post-heating strategies [10, 11]. In addition to wear behavior, the potential for corrosion protection by laser cladding is also covered in the literature [12, 13]. The heat introduced by the laser process, however, results in a large temperature gradient in the heat affected zone (HAZ). In combination with the rail steel, this can result in an area of pronounced martensite formation in the HAZ. This in turn negatively affects mechanical properties, leading to embrittlement [2], decrease of strength/toughness [14] and tendency of fatigue damage [13, 15]. In order to prevent this and to be able to use the advantages of new coatings, the rail must be preheated to at least 450° C before the deposition welding can start. This step, however, is very time-consuming and prevents large-scale coating of rails using the Laser-DED technology. One approach to reduce preheating is to drastically reduce the size of the critical HAZ so that, in combination with the coating process' own process heat, preheating can be avoided completely. In this study, exactly this approach is pursued where the size of the HAZ is reduced by adjusting the process speed of the cladding process.

2. Experimental procedure

2.1. Materials and Experimental Setup

For the investigations presented, rail steel of the european type R350HT was used as the substrate material. R350HT rail steel, which is designed for higher stresses, is used for medium axle loads, high-speed rail traffic and also for components such as frogs in switches [16]. The steel achieves a tensile strength of 1175 MPa through heat treatment and a carbon content of at least 0.70 %. It has a pure pearlitic microstructure consisting of mixed crystal and cementite. Due to slightly accelerated cooling during the manufacturing process, a fine lamellar structure is formed on the running surface, which leads to an increase in strength and hardness. [4] The steel is difficult to weld due to the high carbon equivalent. A type 316L (1.4404) stainless steel was selected for the cladding material. For demonstration purposes, a very weldable steel was used here, one that also enables a precise differentiation from the HAZ in the micrograph. The stainless steel was used as spherical metal powder in a particle size range of 45 µm to 90 µm. The tests were carried out in a conventional laser processing system TruLaser Cell 7020 made by Trumpf. The laser processing system has a 2 kW Yb:YAG disk laser and optics with a nominal focal length of 200 mm. A laser-DED nozzle was used as the coating nozzle, which coaxially feeds the powder through an annular gap into the process zone. The laser direct energy deposition (Laser-DED) process is used as the processing method. The process is already described in the literature (e.g. [17]) and is also defined in the standard DIN EN ISO 17296-2. Table 1 summarizes the relevant process parameters. The cladding speed was specifically chosen to be very high in order to keep the heat input particularly low and thus the HAZ as small as possible. Three samples with increasing numbers of layers were produced in this way: one sample with one layer, one sample with two layers and one sample with three layers. Between the deposition of the layers, the workpiece was given time to cool down to room temperature. The working distance was adjusted after each layer to keep the same distance between processing head and surface. The metallographic preparation of the samples was carried out according to Klemm 1. The Vickers hardness measurements were done in accordance with the standard.

Table 1. Process parameters

Parameter	Unit	Value
Cladding speed	m/min	27
Powder mass flow	g/min	15.5
Laser power	W	1500
Laser spot diameter	mm	0.6

3. Results and Discussion

Fig. 1 summarizes the metallographic cross-sections for the three samples. For each sample, an overview image is shown in which the location of the hardness measurements is marked in blue. In addition, the location of the detailed section shown on the right is marked with a black square in the overview image. As the number of deposited layers increases, the thickness of the coating also increases from an average of 160 µm to 430 µm. In all samples, but especially in samples a) and b) (Fig. 1), defects are increasingly visible. In particular, cracks running perpendicular to the base material are dominant, the length of which corresponds approximately to the thickness of the first layer. In contrast, the uppermost layers of samples b) and c) (Fig. 1) are almost free of defects. In all three samples, there is a complete metallurgical bond to the substrate, which is, however, impaired by the described cracks. The emerging cracks likely result from the very high temperature gradients at the transition zone between the coating and the base material. In combination with the different coefficients of thermal expansion of the materials (approx. 18.0 1/K for 316L vs. 11.5 1/K for Railsteel), this leads to considerable stresses in this zone, which are then relieved through cracks.

The average depth of the HAZ of the three samples is 91 µm (σ = 8.2µm) for the single layer coating and 102 µm (σ = 3.1 µm) and 98 µm (σ = 10 µm) for the two- and three-layer coating respectively. The average single-layer coating thickness is 160 µm, so it can be assumed that a multi-layer coating has no influence on the size of the HAZ. Nevertheless, the properties of the HAZ are influenced by a multilayer coating. In the cross-sections, a tempering effect in the HAZ can be clearly identified by subsequent traces a) and by further layers b) and c) (Fig. 1). This influence is also reflected in the hardness values of the HAZ. The hardness of the HAZ is significantly increased in an area that has not been subjected to additional heat by subsequent traces or layers (compare HAZ of the hardening series on the far right in Fig. 1 a)). With a value of 861 HV0.5, this zone is in a range that is typical for a martensitic microstructure, Fig. 2 a). This tempering effect is recognizable in the micrographs by the dark coloring of the HAZ, comparable to that of the base material. Fig. 2 opposes the hardness curves of the three samples. The hardness points within the HAZ are highlighted in blue. In general, the hardness values of the coating and the base material are in the range of the respective material properties.

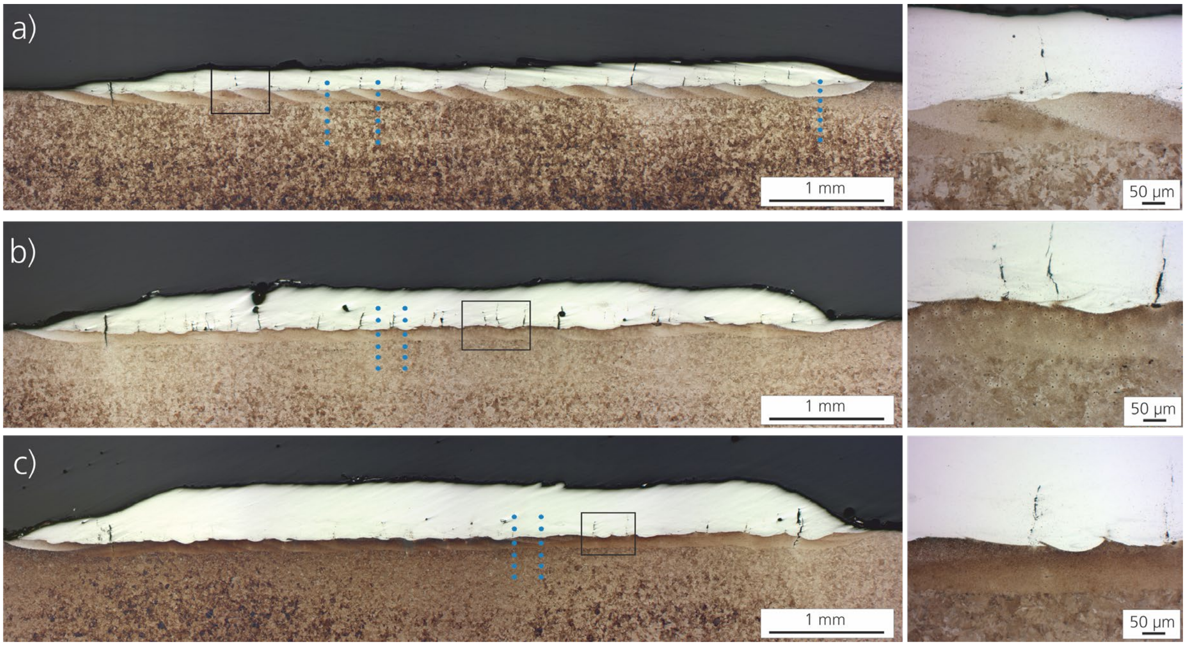

Fig. 1. Overview and detail of a (a) Single-layer coating; (b) Coating with two layers; (c) Coating with three layers; the black frame marks the position of the detail image and the blue dots indicate the position of the hardness probes

With hardness values of 544 HV0.5 to 624 HV0.5, the tempered HAZ is between the high martensitic hardness and the hardness of the rail steel under consideration. Thus, the goal of achieving a hardness in the HAZ similar to that of rail steel has not been fully achieved, but it has come significantly closer to this range. Considering the small dimensions of the HAZ and the possibility of reducing the size of the HAZ even further by optimizing the parameters, it is considered quite feasible to reduce the hardness in the HAZ even more without preheating. The smaller the HAZ, the more pronounced the tempering effect on this zone could be.

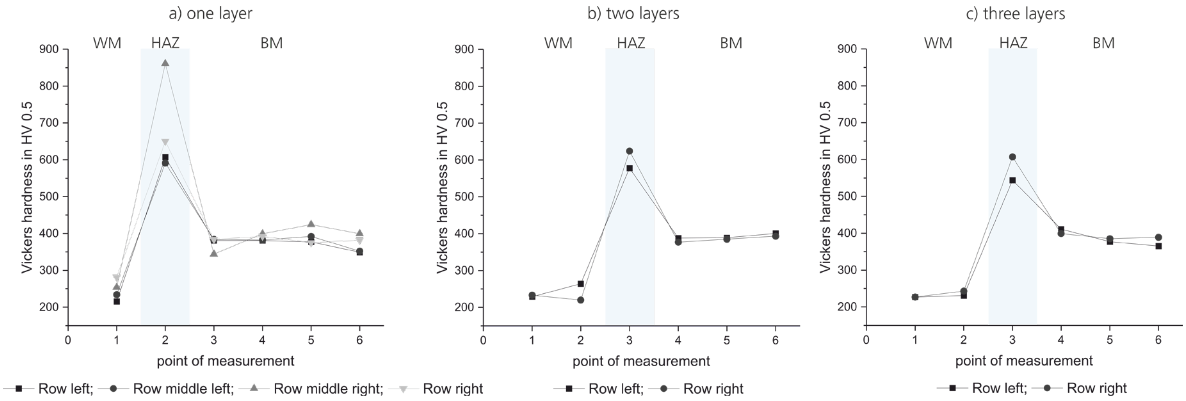

Fig. 2. Hardness values of the measurement series for the samples (a) Single-layer coating; (b) Coating with two layers; (c) Coating with three layers; In addition, the following areas are labelled: weld metal (WM), heat influence zone (HAZ), base material (BM)

4. Conclusion

The short study presented investigated how Laser-DED coatings form on modern rail steel with a carbon content of more than 0.7 %. By choosing process parameters with very high feed rates of 27 m/min, and thus low energy per unit length, the depth of the HAZ could be kept very small. The following conclusions can be drawn from this short feasibility study:

- Rail steel can be processed without external preheating by the laser DED, even without the risk of extreme hardening in the HAZ. Nevertheless, the hardness values in the very narrow HAZ with values between 544 HV0.5 to 624 HV0.5 remain high compared to the base material.
- The additional heat from subsequent tracks and layers can already lower the hardness of the very small HAZ considerably. It is assumed that this effect increases with decreasing HAZ size.
- The coatings still show considerable defects in the form of cracks, especially in the vicinity of the base material.
- It is assumed that the cracks as well as the depth of the HAZ can be further reduced by adjusting the process parameters.

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