Laser welding on Rails

by

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Abstract

Within railway engineering practice continuous rails is created by welding lengths of rail. Conventional rail welding processes include aluminothermic/thermite welding and flash-butt welding. Both welding processes result in a large width of the weld and heat affected zone (HAZ). The weld and HAZ show irregularities along the rail surface including hardness variations, microstructural disturbances and/or inclusions. This makes welds in particular susceptible to damage. Laser welding of rails is proposed to create welds with a smaller weld and HAZ width.

This thesis investigates the feasibility of laser welding for rails. The evolution of microstructures in R260Mn rail steel has been studied using x-ray fluorescence, dilatometry, optical microscopy, scanning electron microscopy and hardness measurements. From the data obtained from these experiments and thermal models that have been constructed, an appropriate set of welding conditions was determined and used for laser welding. The welding conditions considered are laser power, welding speed and pre-heating temperature. The main focus was put on welding speed and pre-heating.

Preliminary welds consisted of a mainly martensitic and thus unacceptable microstructure. By selecting the welding conditions accordingly, the cooling rate could be decreased to form a pearlitic microstructure instead. Especially pre-heating was found to be a valuable method to reduce cooling rate and achieve an acceptable weld in terms of microstructure. The welded samples did contain welding defects like solidification cracking and porosity. The amount of welding defects is observed to decrease for higher welding speeds.

It can be concluded that laser welding can be used to achieve an acceptable weld in terms of microstructure, especially when a pre-heating is applied to the rails. Further optimisation of the welding conditions may resolve welding defects.
Acknowledgements

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## Contents

1 Introduction .......................................................... 1  
  1.1 Thesis aim and structure ................................................. 2

2 Background ........................................................... 3  
  2.1 Rail Steels ...................................................................... 3
  2.2 Conventional Rail Welding Processes ................................. 4  
    2.2.1 Thermite Welding .................................................... 4
    2.2.2 Flash-butt welding ................................................... 5
  2.3 Laser Welding .............................................................. 6

3 Experimental Procedures ............................................... 9 
  3.1 Characterisation of Rail Steel ........................................... 9  
    3.1.1 Sample Geometry ..................................................... 10
    3.1.2 Dilatometry Parameters .............................................. 12
  3.2 Preliminary Welding ..................................................... 12 
    3.2.1 Sample Geometry ..................................................... 12
    3.2.2 Welding Parameters .................................................. 13
    3.2.3 Optical Microscopy, Scanning Electron Microscopy and Micro-Hardness Testing 13
  3.3 Thermal Modelling ...................................................... 14 
    3.3.1 Geometry ............................................................ 14
    3.3.2 Principles of the model ............................................. 14
    3.3.3 Fitting Procedure ................................................... 16
  3.4 3 kW Welding Experiments ............................................. 17 
    3.4.1 Sample Geometry ..................................................... 17
    3.4.2 Welding Procedure .................................................. 17
  3.5 8 kW Welding Experiments ............................................. 18 
    3.5.1 Sample Geometry ..................................................... 18
    3.5.2 Welding Parameters .................................................. 19

4 Results and Discussion .................................................. 21  
  4.1 Base Material .......................................................... 21  
  4.2 Dilatometry ............................................................. 24 
    4.2.1 Results ........................................................... 24
    4.2.2 Discussion ......................................................... 29
  4.3 Preliminary Welding ..................................................... 30 
    4.3.1 Results ........................................................... 30
    4.3.2 Discussion ......................................................... 33
  4.4 Thermal Modelling ..................................................... 34 
    4.4.1 Fitting ............................................................ 34
    4.4.2 Results and Discussion ........................................... 35
  4.5 3 kW Welding Experiments ............................................. 36
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5.1 2 mm/s room temperature welded sample</td>
<td>36</td>
</tr>
<tr>
<td>4.5.2 4 mm/s room temperature and 300°C pre-heated welded samples</td>
<td>39</td>
</tr>
<tr>
<td>4.6 8 kW Welding Experiments</td>
<td>45</td>
</tr>
<tr>
<td>4.6.1 Results</td>
<td>45</td>
</tr>
<tr>
<td>4.6.2 Discussion</td>
<td>50</td>
</tr>
<tr>
<td>5 Conclusion</td>
<td>53</td>
</tr>
<tr>
<td>5.1 Future Research</td>
<td>54</td>
</tr>
</tbody>
</table>
# List of Figures

1.1 Thermite welding process, by dr.ir. I.Y. Shevtsov. ........................................... 1  
2.1 Hardness traverse along a flash-butt weld by Saita et al. [1]. ............................... 6  
3.1 Dilatometry sample geometry and size. .................................................................. 10  
3.2 54E1 profile dimensions taken from NEN-EN 13674:2011 [2]. .......................... 11  
3.3 Indication of the sample-making, the dashed lines indicate cuts. ........................... 12  
3.4 Fixed positions at which images of the microstructure are taken throughout this study. 13  
3.5 Mesh used for modelling. ....................................................................................... 14  
3.6 Schematic representation of the conical heat source [3]. ........................................... 15  
3.7 Weld and HAZ dimensions considered in fitting the model. ................................. 16  
3.8 Definition of peak and plateau temperature. ............................................................ 16  
3.9 Thermocouple placement on top surface of the samples. ......................................... 17  
3.10 Pre-heating procedure with acetylene and oxygen. ................................................. 17  
3.11 Milling down the rail head to acquire a flat surface for welding. ........................... 18  
3.12 Laser welding setup and sample dimensions for joint welds. ................................. 18  
4.1 TTT diagram of R260Mn with Pearlite, Bainite and Martensite [4]. .......................... 21  
4.2 Microstructure of R260Mn Pearlitic Rail steel. ......................................................... 22  
4.3 Pearlitic microstructure of R260Mn rail steel. ............................................................ 22  
4.4 Lamellar configuration in the pearlitic base material. ............................................... 22  
4.5 Brinell Hardness measurements carried out on material from the web. ..................... 23  
4.6 Dilatometry results of R260Mn for different cooling rates. ..................................... 24  
4.7 Microstructure of the 2°C/s sample. ........................................................................ 25  
4.8 Microstructure of the 5°C/s sample. ........................................................................ 26  
4.9 Microstructure of the 10°C/s sample. ...................................................................... 26  
4.10 SEM image of the microstructure of the 2°C/s sample. .......................................... 27  
4.11 SEM image of the microstructure of the 5°C/s sample. .......................................... 27  
4.12 SEM image of the microstructure of the 10°C/s sample. ........................................ 27  
4.13 Macrograph of welded samples of ProRail. ............................................................ 30  
4.14 The microstructure of the Weld metal (sample 2). ................................................ 31  
4.15 The microstructure of the HAZ1 (sample 2). ........................................................ 31  
4.16 The microstructure of the HAZ2 (sample 1). ........................................................ 32  
4.17 SEM image of the microstructure of the HAZ2 (sample 1). .................................... 32  
4.18 Temperature profile of the 2 mm/s RT weld ~2 mm from the weld centre line. ....... 35  
4.19 Temperature profile obtained from the model for 4 mm/s welds. .......................... 35  
4.20 Prior austenite grains in the weld metal of the 3kW, 2mm/s welded sample. .......... 36  
4.21 The microstructure of the weld metal of the 3kW, 2mm/s welded sample. ............. 36  
4.22 The microstructure of the HAZ1 of the 3kW, 2mm/s welded sample. .................... 37  
4.23 The microstructure of the HAZ2 of the 3kW, 2mm/s welded sample. .................... 38  
4.24 The microstructure of the weld metal of 4 mm/s RT (left) and 300°C pre-heating (right). ......................................................... 39
4.25 SEM image of the microstructure of the weld metal of 4 mm/s RT (left) and 300°C pre-heating (right). ........................................ 40
4.26 SEM image of the microstructure of the HAZ1 of 4 mm/s RT (left) and 300°C pre-heating (right). ........................................ 40
4.27 SEM image of the microstructure of the HAZ2 of 4 mm/s RT (left) and 300°C pre-heating (right). ........................................ 40
4.28 Martensite patches present in the HAZ1 ........................................ 42
4.29 SEM image of the area scanned with EDS ........................................ 43
4.30 TTT diagram with increasing Manganese concentration (MAP STEEL MUCG83) [4]. 44
4.31 TTT diagram with increasing Carbon concentration (MAP STEEL MUCG83) [4]. 44
4.32 Effect of C and Mn on the Ms temperature (MAP STEEL MUCG83) [4]. .... 45
4.33 Macrograph of the 8 kW, 2 mm/s (a) and pre-heated 4 (b) and 6 mm/s (c) welded samples respectively. .............................. 45
4.34 The microstructure of the weld metal of the 8 kW, 2 mm/s RT welded sample. ... 46
4.35 The microstructure of the HAZ1 of the 8 kW, 2 mm/s RT welded sample. .... 46
4.36 The microstructure of the HAZ2 of the 8 kW, 2 mm/s RT welded sample. ..... 46
4.37 The microstructure of the weld metal of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample. .................. 47
4.38 SEM image of the microstructure of the weld metal of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample. ........ 47
4.39 The microstructure of the HAZ1 of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample. .................. 47
4.40 SEM image of the microstructure of the HAZ1 of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample. ........ 48
4.41 The microstructure of the HAZ2 of the 8 kW, 4 mm/s RT (left) 300°C pre-heated (right) welded sample. .................. 48
4.42 The microstructure of the weld metal of the 8 kW, 6 mm/s 300°C pre-heated welded sample. ........................................ 49
4.43 The microstructure of the HAZ1 of of the 8 kW, 6 mm/s 300°C pre-heated welded sample. ........................................ 49
4.44 The microstructure of the HAZ2 of the 8 kW, 6 mm/s 300°C pre-heated welded sample. ........................................ 49
4.45 Temperature profiles of modelled 2 kW 13 and 26 mm thickness welds. .... 50
# List of Tables

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Rail steel compositions (Vignole rail) [2]</td>
<td>3</td>
</tr>
<tr>
<td>3.1</td>
<td>Composition of rail material (batch 1)</td>
<td>9</td>
</tr>
<tr>
<td>3.2</td>
<td>Composition of rail material (batch 2)</td>
<td>10</td>
</tr>
<tr>
<td>3.3</td>
<td>Dilatometry parameters and exact dimensions</td>
<td>12</td>
</tr>
<tr>
<td>3.4</td>
<td>Welding parameters used for the welding samples of ProRail.</td>
<td>13</td>
</tr>
<tr>
<td>4.1</td>
<td>Brinell Hardness measurements on base material from the web.</td>
<td>23</td>
</tr>
<tr>
<td>4.2</td>
<td>Transformation start and finish temperatures measured with dilatometry.</td>
<td>24</td>
</tr>
<tr>
<td>4.3</td>
<td>Vickers Hardness measurements on the 2 and 10°C/s sample.</td>
<td>28</td>
</tr>
<tr>
<td>4.4</td>
<td>Vickers Hardness measurements on the 5°C/s sample.</td>
<td>29</td>
</tr>
<tr>
<td>4.5</td>
<td>Penetration depth of welded samples of ProRail.</td>
<td>30</td>
</tr>
<tr>
<td>4.6</td>
<td>Vickers Hardness measurements on sample 1.</td>
<td>33</td>
</tr>
<tr>
<td>4.7</td>
<td>Final values of the fitting parameters related to the heat source used in the model.</td>
<td>34</td>
</tr>
<tr>
<td>4.8</td>
<td>Weld dimensions of the model compared to the real weld.</td>
<td>34</td>
</tr>
<tr>
<td>4.9</td>
<td>Vickers Hardness measurements on the 2 mm/s RT welded sample.</td>
<td>38</td>
</tr>
<tr>
<td>4.10</td>
<td>Vickers hardness measurements on the 4 mm/s RT and 300°C pre-heated weld.</td>
<td>41</td>
</tr>
<tr>
<td>4.11</td>
<td>Local composition of certain phases determined with EDS.</td>
<td>43</td>
</tr>
</tbody>
</table>
Nomenclature

BHN  Brinell Hardness Number
EDS  Energy-dispersive X-ray spectroscopy
FZ   Fusion Zone
HAZ  Heat Affected Zone
OM   Optical Microscopy
RT   Room Temperature
SEM  Scanning Electron Microscopy
XRF  X-Ray Fluorescence
Chapter 1

Introduction

Within railway engineering practice a distinction is made between jointed track and continuous welded rail. In jointed track, lengths of rail (about 30 m) are bolted together using steel plates. However most modern railways use continuous welded rails, which offers better comfort for passengers. To connect rail ends together to form continuous rails, the rail ends are welded. Conventional rail welding processes include Aluminothermic/Thermite welding, Flash-butt welding and arc welding. The most commonly used processes are Aluminothermic and Flash-butt welding.

Aluminothermic is a casting welding process. The rail ends are joined together by pouring molten steel into a mould fixed over both rail ends. Partial melting of the rail ends, and mixing with the molten steel from the thermite secures a good joint between both rail ends. Flash-butt welding is an automated process in which the heat for welding is supplied by a high voltage applied across both rail ends. The rail ends are pressed together creating a joint between both rail ends.

Figure 1.1: Thermite welding process, by dr.ir. I.Y. Shevtsov.

There are some drawbacks however to these rail welding processes. Both thermite and flash-butt welding result in a large weld and Heat Affected Zone (HAZ). For thermite welding the width of the weld is dependent on the gap between both rail ends before welding. The width of thermite welds at the top of the rail can be up to 70 mm. The HAZ width is typically in the range of 20 mm on either side of the weld [1]. For Flash-butt welding, the weld width typically is 30-45 mm (including HAZ) [1]. The problem with the large weld and HAZ is that weld show irregularities along the rail surface. These include hardness variations, microstructural disturbances and/or inclusions. Together with possible geometry errors and welding imperfections, this makes welds in particular susceptible to damage [5].
By decreasing the width of the HAZ zone and weld up to a certain level, the weld and HAZ may become invisible to the wheel, and defects induced by the rail-wheel contact will not appear. To decrease the size of the weld and HAZ, laser welding is proposed. Laser welding offers many benefits compared to the conventional welding processes, including deep narrow welds and a smaller HAZ. In this report the feasibility of laser welding on rail steels is investigated.

1.1 Thesis aim and structure

The purpose of this research project is to investigate the feasibility of laser welding on rail steels. The emphasis lies on microstructural aspects of the welding process. Conventional rail steels have a pearlitic microstructure; it is therefore desirable that the weld metal and HAZ of laser welded rails also have a pearlitic microstructure. The microstructural development of weld metal and HAZ of laser welds is investigated in terms of the formation of certain phases and related properties, specifically hardness of different areas of the weld. By manipulating the thermal cycle experienced by the material due to welding, it is endeavoured to obtain the desired pearlitic microstructure. Methods of manipulating the thermal cycle are by changing welding parameters and by pre-heating the material before welding.

In chapter 2, more background information is presented to introduce the reader to the basics of rail steels, rail welding and laser welding. Chapter 3 describes the material used and experimental procedures involved in the research. In chapter 4 the results of each part of the research are presented and discussed. First research on the base material is discussed, followed by investigation of preliminary welds. After the initial research thermal modelling is discussed, describing the methods used to come to an appropriate set of welding parameters. Subsequently, these welding parameters are used to perform actual welding on the rail steel. The welds made with these parameters are investigated in terms of microstructure and defects. Investigation includes Optical Microscopy, Scanning Electron Microscopy and Micro-Hardness testing. To conclude the research, welds have been made with a higher power laser on an actual rail configuration. Finally, based on the results obtained conclusions are drawn and direction for future research are provided.
Chapter 2

Background

2.1 Rail Steels

Rails are subject to many different kinds of loading, which affect the surface life of the rails. These loadings include wear, plastic deformation and fatigue. Rail steels are designed to withstand these loadings, however ordinary rail steels are reaching their limits in terms of resistance against damage induced by these loads.

Table 2.1: Rail steel compositions (Vignole rail) [2].

<table>
<thead>
<tr>
<th>Quality</th>
<th>%C</th>
<th>%Si</th>
<th>%Mn</th>
<th>%Cr</th>
<th>Hardness (HBW)</th>
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<tbody>
<tr>
<td>R200</td>
<td>0.40 – 0.60</td>
<td>0.15 – 0.58</td>
<td>0.70 – 1.20</td>
<td>max. 0.15</td>
<td>min. 200</td>
</tr>
<tr>
<td>R220</td>
<td>0.50 – 0.60</td>
<td>0.20 – 0.60</td>
<td>1.00 – 1.25</td>
<td>max. 0.15</td>
<td>min. 220</td>
</tr>
<tr>
<td>R260</td>
<td>0.62 – 0.80</td>
<td>0.15 – 0.58</td>
<td>0.70 – 1.20</td>
<td>max. 0.15</td>
<td>min. 260</td>
</tr>
<tr>
<td>R260Mn</td>
<td>0.55 – 0.75</td>
<td>0.15 – 0.60</td>
<td>1.30 – 1.70</td>
<td>max. 0.15</td>
<td>min. 260</td>
</tr>
<tr>
<td>R320Cr</td>
<td>0.60 – 0.80</td>
<td>0.50 – 1.10</td>
<td>0.80 – 1.20</td>
<td>0.80 – 1.20</td>
<td>min. 320</td>
</tr>
<tr>
<td>R350HT</td>
<td>0.72 – 0.80</td>
<td>0.15 – 0.58</td>
<td>0.70 – 1.20</td>
<td>max. 0.15</td>
<td>min. 350</td>
</tr>
<tr>
<td>R350LHT</td>
<td>0.72 – 0.80</td>
<td>0.15 – 0.58</td>
<td>0.70 – 1.20</td>
<td>max. 0.30</td>
<td>min. 350</td>
</tr>
<tr>
<td>R370CrHT</td>
<td>0.70 – 0.82</td>
<td>0.40 – 1.00</td>
<td>0.70 – 1.10</td>
<td>0.40 – 0.60</td>
<td>min. 370</td>
</tr>
<tr>
<td>MHH</td>
<td>0.72 – 0.80</td>
<td>max. 0.80</td>
<td>0.80 – 1.10</td>
<td>max. 0.60</td>
<td>min. 375</td>
</tr>
<tr>
<td>R400HT</td>
<td>0.90 – 1.05</td>
<td>0.20 – 0.60</td>
<td>1.00 – 1.30</td>
<td>max. 0.30</td>
<td>min. 400</td>
</tr>
</tbody>
</table>

R = Rail
370 = Brinell Hardness (HBW)
Mn = alloyed with Manganese
Cr = alloyed with Chromium
L = Low-alloyed
HT = Heat Treated

Ordinary rail steels have a carbon content of about 0.6-0.7 wt.% (see table 2.1). Their microstructure is pearlitic, a mixture of alternating lamellae of ferrite (soft) and cementite (hard, brittle). The hardness can be increased by reducing interlamellar spacing or increasing the fraction of cementite [6]. The reason for mainly choosing pearlitic rail steel material lies in its superior wear resistance. It has frequently been reported that pearlitic steels show superior wear resistance compared to other rail steels like bainite [7, 8, 9]. It is stated by Myung Lee and Polycarpou [9] that the wear resistance of pearlitic steels are due to the high work hardening under severe stress conditions up to depths well below the running surface. Bainitic rail steels do not show such an amount of work hardening. Pearlitic rail steels are however inferior in fatigue behaviour compared to bainitic rail steels. Fatigue in rail steels occurs in the form of Rail Contact Fatigue (RCF). High contact forces induce small defects which may eventually lead to fracture or break-out of material (squats) [5].
The pearlitic steels seem to reach their limit in improving properties to withstand RCF, in particular. Therefore, bainitic steels are proposed to replace the pearlitic grades [8]. For railway applications it seems a trade-off must be made between RCF and wear behaviour. Wear on pearlitic rails can be minimised by choosing higher hardness rails, however less wear will result in more RCF damage. Wear removes microcracks which are the leading cause of RCF damage. By minimising the amount of wear, RCF damage will become more dominant. Bainitic rail steels show superior RCF behaviour, however the main problem with these steels lies in their inferior wear resistance. The better RCF resistance of bainitic rail steels is linked to the absence of surface and near surface cracks due to the higher wear rate [9]. On top of that Aglan and Fateh [10] showed that the Average Fracture Toughness for a J6 Bainitic steel was higher (52 MPa$\sqrt{m}$) than for a premium pearlitic steel (41 MPa$\sqrt{m}$). However, it should be noted that Aglan and Fateh [10] did not exactly know what rail quality the pearlitic steel was.

2.2 Conventional Rail Welding Processes

Currently the most commonly used welding processes within railway engineering practice in the Netherlands are Flash-Butt welding, Thermite-/Aluminothermic welding and enclosed arc welding. Since Flash-Butt welding and Aluminothermic welding are preferred over enclosed arc welding, the laser welding process will only be compared to these welding processes. Enclosed arc welding is only used when the other processes cannot be made use of [11] (i.e. for hard to reach places and cases for which thermite welding moulds cannot be placed accordingly).

2.2.1 Thermite Welding

Thermite welding is a casting welding process. Thermite consist of iron-oxide and aluminium powder with some alloying elements to improve the weld metal properties. Igniting the thermite will start a highly exothermic reaction in which the aluminium reduces the iron-oxide with molten steel and aluminium oxide as a product. The molten steel is poured in a mould (structured to fit the rail profile), to fill up the gap/joint between both rail ends. The molten steel is well above melting temperature, the rail ends sticking into the mould will therefore partially melt, making sure the weld will make a good joint between the weld and rail material. Thermite welding is beside flash-butt welding the preferred choice of welding (in the Netherlands). Thermite welding however does come with its limitations. The lifetime of thermite welds is less than that of flash-butt welds [12]. The main reason behind the use of thermite despite its shortcomings is the relatively low cost of fabricating a weld as stated by Schroeder and Poirier [13].

Thermite weld material has a (columnar) dendritic microstructure in which the dendrites grow from the fusion line to the weld centre-line. Prior austenite grains transform in a fine pearlite decorated with pro-eutectoid ferrite. NEN-EN-14730:2014 [14] prescribes that the microstructure of thermite welds must be pearlitic. However for grades R260 and R260Mn some amount of grain boundary ferrite is accepted [2].

Hardness values of thermite welds are dependent on the parent rail material. The most common rail steel used for straight rails in the Netherlands is R260Mn. According to NEN-EN-14730:2014 [14] for R260Mn rails weld centre-line hardness should be in the range of 280 ± 20 HBW.
2.2.2 Flash-butt welding

Flash-butt welding is an automated welding process that can either be carried out in a facility or on site with a mobile device. The heat required for the welding process is supplied in the form of a voltage that is applied across the faces of rail that are to be welded together. The rail faces are brought together, due to an electric discharge local contacts are molten or evaporated. The welding process consists of 5 consecutive steps: Pre-flashing, Pre-heating, Flashing, Upsetting and Trimming [1].

Procedure

Before pre-heating the rail surfaces are prepared by pre-flashing. Irregularities, roughness or mismatch are removed (evaporated) due to the small contact points that will experience high electric discharges. Pre-heating is performed by bringing the rail faces in contact with each other, a pulsed electric discharge creates heat in the rail ends. During pre-heating melting of the rail faces is prevented. During flashing the rail faces are pressed together lightly, drops of molten steel will be repelled outward by electro-magnetic forces. A metal vapour forms around the to be welded area which will act as a shielding gas. Upsetting starts once both rail ends are warm enough, the rail material has become soft. Upsetting is performed pressing together both rail ends under a higher load (approx. 500-600 kN) [1]. Spongy/molten steel is pressed outwards and a bulge is formed. The material undergoes plastic deformation. The bulge produced in the upsetting phase is removed in trimming phase with a trimmer.

Microstructure

The width of flash-butt welds is approximately 30-45 mm [1]. Because of the absence of molten material in the joint with flash-butt welding (no solidification), the whole weld section can be treated as an HAZ. There are 3 regions that can be defined in terms of their microstructure in a flash-butt weld. The grain growth zone, recrystallised region and the partially transformed region [15].

The grain growth region is closest to the middle of the weld. In this region grain diameter decreases with increasing distance from the centre. The grain growth region is about 20 mm thick. The microstructure consists of both ferrite and pearlite.

The recrystallised region is located further away from the centre of the weld. The size of grains in this region is less than in the grain growth zone. The thickness of the region in the middle of the head, web and base is about 13 mm. The microstructure in this region is also both ferrite and pearlite.

The partially transformed region is the farthest away from the weld centre line. The initial pearlite grains in this region contain a lot of small ferrite grains. The size of these initial pearlite grains is the same as the pearlite grains in the base material.

For all regions, the ferrite phase occupies about 5-10% of the microstructures. Ferrite covers about all of the grain boundaries of the pearlite grains with the exception of the partially transformed region. The rail material used by Mansouri and Monshi [15] is comparable in composition with R220 rail steel. The amount of ferrite in the weld and base material will be significantly less for welded rails in the Netherlands (R260Mn and higher hardness).

Because of the nature of the flash-butt welding process, no effects due to solidification of weld material, like deudritic structures, are present [15]. Molten metal and oxides are pressed out of the butt joint in the upsetting phase, thus no solidification takes place within the joint. Recrystallisation is due to the plastic deformation that has occurred in the rail ends during the upsetting phase.
Hardness

For a flash butt weld in rail with 390 HV hardness, the hardness at the centre of the weld is about 20 HV less than that of the base material as reported by Saita et al. [1]. At the edges of the HAZ much lower hardnesses are measured of about 270-280 HV. This is due to softening/tempering of the material. The complete hardness distribution is shown in figure 2.1.

![Figure 2.1: Hardness traverse along a flash-butt weld by Saita et al. [1].](image)

2.3 Laser Welding

Laser welding belongs to the fusion welding processes. More specifically, laser welding is part of the power beam welding processes. Power beam welding uses a beam of high energy density ($>10^{10}$ Wm$^{-2}$) to melt the to be joined metal parts [16]. In the case of laser welding this power beam is a laser. The laser is a monochromatic, coherent light beam of high intensity, generated by using heat or irradiation from a solid or a gas. To achieve a high intensity beam, the beam is forced to run back and forth through the medium by using mirrors. The laser beam leaves the laser medium through a partially translucent mirror. The power density is further increased by focussing the beam.

The medium used for lasers is either a solid or a gas. This divides lasers in two groups depending on their medium. The solid-state lasers with a solid medium, and the gas lasers with a gas medium. The solid matrix used in solid state lasers usually is $\text{Al}_2\text{O}_3$ or a Yttrium Aluminium Garnet (YAG) embedded with an active element (Cr or Rare Earth element like Nd). Most common of the solid state lasers is the Nd:YAG laser [16].

---

1 Solid state lasers work by creating an inverted population of excited states, this way stimulated emission can occur. A simple example to interpret this is by doping the Fermi-level on n-side above the conduction band and the p-side below the valence band. The conduction band on the n-side will fill with the electrons (from the valence band) of the p-side (which are above the Fermi-level), up to the Fermi level on the n-side. When the junction is biased electrons can flow to the conduction band of the p-side and then fall back into the empty states in the valence band of the p-side emitting photons [17].
Solid State Lasers

Solid state lasers are usually activated by intensive radiation with light. The medium is in the shape of a cylindrical rod, with on both sides a mirror. One of the mirrors is partially translucent. The active element of the solid medium determines the wavelength of the laser, the Nd:YAG laser has a wavelength of 1.06 µm. The fibre laser is a special type of the solid state lasers. The fibre medium is ‘pumped’ by high power multimode single-emitter diodes. The single-mode fibre core is doped with rare-earth ions like Nd, Er, Yb and Tm. The pump light is injected into the cladding of the fibre and passes through the active core, producing a population inversion. Fibre lasers have the advantage of a higher efficiency and better beam quality than the more conventional solid state lasers [16].

Physics behind laser welding

Laser welding can be separated into 2 modes of operation, conduction mode and deep penetration/keyhole mode. When the energy density of the laser beam is small, the absorbed beam energy is conducted as heat from the surface into the metal. A semi-spherical weld pool is formed. These conditions mark the conduction operation mode [16].

When the laser energy density exceeds a certain threshold, the temperature increases sharply and is high enough for (strong) evaporation of the metal to occur. The laser beam will penetrate into the surface and a longitudinal hole (keyhole) forms in the metal. Because of the deeper penetration multiple reflections of the laser occur, as a result each reflection will cause some absorption of the laser beam energy. Absorption of the laser beam energy can be over 80% of the initial beam energy. The shape of the keyhole and the surrounding liquid flow is influenced by many different factors of which the evaporation rate and surface tension have the largest effects. The evaporated metal can form a plasma plume above the metal surface. Scattering of the laser beam by this plume affects the stability of the welding process. A gas flow can be used to expel the plasma plume from the surface. Modelling of the keyhole formation is difficult due to the large amount of parameters that influence the keyhole [16].

Advantages and Disadvantages

Advantages of laser welding over more conventional welding processes is that the laser beam can be manipulated by optical means (lenses, mirrors, fibres). This way the heat source can be positioned and re-adjusted in a precise and rapid manner. It also enables automation of the welding process. Because of the high energy density, the welding speed for laser welding can be increased. Because of the higher welding speed the heat input will be less. The result is a relatively small HAZ and lower residual stresses (shrinkage) [16]. Other advantages include deep penetration and a narrower FZ [18]. The disadvantages of laser welding are the high investment costs and personal risks of working with a laser.

Specific problems of the laser welding process include reflection of the laser beam on the metal surface. More reflection means less absorption of energy and therefore more power is required to make the weld. In the case of CO₂-lasers absorption for steel is only 12% while copper and aluminium absorb only 2% of the laser energy [16].
Laser welding process for Rails

According to Atabaki, Yazdian and Kovacevic [18] laser beam welding offers many benefits compared to conventional fusion welding methods. The benefits include deep penetration, narrower fusion zone (FZ), smaller heat affected zone (HAZ) and lower residual stresses. Smaller length of irregularities in the weld may result in less damage. This is important for the pearlitic steel grades, however it may be even more important for the bainitic grades. A significant part of maintenance costs comes from welds [19]. If maintenance costs on the rail would go down with but maintenance costs on the welds would stay about the same, the introduction of bainitic steels would not be as valuable as it could be.

Hybrid Laser-Arc Welding

Hybrid laser-arc welding is a technique which combines the advantages of both laser and arc welding. The laser welding process has the reputation to produce high penetration narrow welds and the ability to focus the heat input in a very small area which allows for increased welding speed. The increased welding speed in turn results in less total heat input and reduced chances of induced thermal stresses. However due to the narrowness of the welds, the bridging ability of the laser welding process is poor and therefore requires high precision fit-up of the workpieces [20].

The arc welding process has excellent bridging ability. On top of that arc welding offers the option to add filler material to the weld. However, the lower energy density makes the process slower resulting in higher heat input and therefore more thermal distortion or thermal stresses [20].

When both processes are applied to the same weld pool the advantages of both processes compensate the drawbacks. The high energy density of the laser makes higher welding speeds possible while the arc welding improves the bridging ability of the hybrid process [20].
Chapter 3

Experimental Procedures

This study is aimed at researching the feasibility of laser welding rails. At first the characterisation of rail steels are studied, including the chemical composition, dilation behaviour and the microstructure. ProRail has performed welding on pieces of rail head, these welds are investigated as a start by means of Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Micro-Hardness Testing. By means of temperature modelling and the results from the dilatometry experiments, an appropriate set of welding parameters can be found. Using the appropriate parameters, welds are made to validate the constructed models. These models allow to predict the thermal profile at any position.

3.1 Characterisation of Rail Steel

For this study the rail steel grade R260Mn was selected. The rail material was taken from 54E1 (UIC54) profile rails (see figure 3.2). As explained in section 2.1, this is a pearlitic rail steel. Currently R260Mn is the standard used rail grade in the Netherlands for straight track.

During research rail material of different batches of material has been used. The composition of two of these batches has been determined with X-ray Fluorescence (XRF). The carbon content cannot be determined by XRF and is assumed to be 0.7 wt% [2], the XRF results are normalised accordingly. The composition of both batches is given in tables 3.1 and 3.2. The composition of both batches is quite similar, therefore exact composition of future batches have not been considered.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration (wt%)</th>
<th>Absolute error (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>97.4</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>0.6 [2]</td>
<td>NA</td>
</tr>
<tr>
<td>Mn</td>
<td>1.62</td>
<td>0.06</td>
</tr>
<tr>
<td>Si</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>Cr</td>
<td>0.038</td>
<td>0.007</td>
</tr>
<tr>
<td>Cu</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Cl</td>
<td>0.014</td>
<td>0.004</td>
</tr>
<tr>
<td>S</td>
<td>0.009</td>
<td>0.003</td>
</tr>
<tr>
<td>P</td>
<td>0.008</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Table 3.2: Composition of rail material (batch 2).

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration (wt%)</th>
<th>Absolute error (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>96.9</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>0.6 [2]</td>
<td>NA</td>
</tr>
<tr>
<td>Mn</td>
<td>1.61</td>
<td>0.06</td>
</tr>
<tr>
<td>Si</td>
<td>0.49</td>
<td>0.02</td>
</tr>
<tr>
<td>Na</td>
<td>0.33</td>
<td>0.02</td>
</tr>
<tr>
<td>Al</td>
<td>0.051</td>
<td>0.008</td>
</tr>
<tr>
<td>Cr</td>
<td>0.025</td>
<td>0.005</td>
</tr>
<tr>
<td>Cl</td>
<td>0.015</td>
<td>0.004</td>
</tr>
<tr>
<td>S</td>
<td>0.012</td>
<td>0.003</td>
</tr>
<tr>
<td>P</td>
<td>0.011</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Information about phase transformations within the material must be acquired before continuing with actual welding. Experiments were conducted to investigate the dilation behaviour during a typical weld thermal cycle. The resulting microstructures encountered for different cooling rates were determined using OM, SEM and Micro-Hardness testing. In addition from the data obtained, thermal expansion coefficients and the starting temperatures of phase transformations were obtained.

3.1.1 Sample Geometry

The samples used for dilatometry are made out of R260Mn rail steel, the material was cut from the foot of the rail. The samples are small cylinders of radius \( \sim 4 \) mm, and length \( \sim 10 \) mm (see figure 3.1).

Figure 3.1: Dilatometry sample geometry and size.
Figure 3.2: 54E1 profile dimensions taken from NEN-EN 13674:2011 [2].
3.1.2 Dilatometry Parameters

The cooling rates used for dilatometry are chosen in such a way that both high cooling rate transformations and slow cooling rate transformations are investigated. The cooling rates and sample dimensions of each individual dilatometry test are given in table 3.3.

Table 3.3: Dilatometry parameters and exact dimensions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cooling Rate (°C/s)</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R260Mn</td>
<td>214</td>
<td>9.86</td>
<td>4.24</td>
</tr>
<tr>
<td>R260Mn</td>
<td>40</td>
<td>10.37</td>
<td>4.01</td>
</tr>
<tr>
<td>R260Mn</td>
<td>20</td>
<td>9.47</td>
<td>3.98</td>
</tr>
<tr>
<td>R260Mn</td>
<td>10</td>
<td>10.30</td>
<td>4.14</td>
</tr>
<tr>
<td>R260Mn</td>
<td>5</td>
<td>9.18</td>
<td>3.98</td>
</tr>
<tr>
<td>R260Mn</td>
<td>2</td>
<td>9.36</td>
<td>3.92</td>
</tr>
<tr>
<td>R260Mn</td>
<td>1</td>
<td>10.29</td>
<td>4.04</td>
</tr>
</tbody>
</table>

3.2 Preliminary Welding

ProRail has made sample welds in the rail head with a high-power laser (16 kW). The sample welds on these rail heads are investigated by means of OM, SEM and Micro-Hardness testing.

3.2.1 Sample Geometry

The as-received samples were laser bead on plate welded rail heads. Samples were taken out of the rail head to include the weld, HAZ and some of the base material as indicated in figure 3.3. A crack present in each of the samples gives an indication of the depth of the weld for cutting.

Figure 3.3: Indication of the sample-making, the dashed lines indicate cuts.
3.2.2 Welding Parameters

Welding of the rail head was carried out in focus, with the laser beam perpendicular to the to-be-welded surface. The focal point of the beam was positioned at the surface. The laser bead on rail welds are made in the longitudinal direction of the rail. The laser beam created a weld pool in the material and upon passing of the heat source the weld pool solidified. The reason for not making an appropriate joint lies in lacking experience in laser welding of rails. The welding parameters used for making the welds are given in table 3.4.

Table 3.4: Welding parameters used for the welding samples of ProRail.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Power (kW)</th>
<th>Welding speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>16.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Sample 2</td>
<td>10.5</td>
<td>16.7</td>
</tr>
<tr>
<td>Sample 3</td>
<td>16.0</td>
<td>25</td>
</tr>
<tr>
<td>Sample 4</td>
<td>16.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Sample 5</td>
<td>10.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Sample 6</td>
<td>16.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

3.2.3 Optical Microscopy, Scanning Electron Microscopy and Micro-Hardness Testing

The samples were ground and polished up to 1 µm grid. Etching is carried out with a 2% NITAL solution by swiping to reveal the micro- and macrostructure of the welds, etching time is several seconds. Images of the microstructure taken with OM (Keyence VHX-5000) and SEM (JEOL JSM-IT100) are taken at fixed positions throughout this study. In the weld metal near the fusion line, the HAZ near the fusion line and in the HAZ near the base material. Figure 3.4 shows an illustration of these positions. Full page images of the microstructures shown throughout this report can be found in Appendix A.

![Figure 3.4: Fixed positions at which images of the microstructure are taken throughout this study.](image)

To identify each of the phases observed by OM and SEM, the hardness of the phases is measured. Four measurements are taken in the weld metal, HAZ1 and HAZ2. For phase specific measurements only 3 measurements are carried out. The procedure for OM, SEM and Micro-Hardness testing is the same throughout this study.
3.3 Thermal Modelling

To find welding parameters that would result in an appropriate weld, a thermal model was constructed. With the model, the cooling rate within the material can be estimated and the microstructure of welds at different pre-heating temperatures can be predicted.

3.3.1 Geometry

The laser welding equipment at TU Delft has a power output of only 3 kW. Compared to the power output used on the samples of ProRail (16 kW), this is significantly less. The choice was made to decrease the size of the welding samples that will be used for welding. In order to be able to weld on a flat surface a plate of rail steel was extracted from the rail. The most convenient method was to extract material from the web of the rail. From the web, samples were milled with dimensions of 160x33x13 mm\(^3\). The same dimensions were used for the model.

3.3.2 Principles of the model

The model was made with the COMSOL Multiphysics 5.2 software. The simulated material has a rectangular shape of size 160x30x13 mm\(^3\). The laser runs along the centreline in the longitudinal direction from 5 to 155 mm out from the edge. The bottom of the block is insulated to simulate the ceramic tiles used during the real welding. The other surfaces are subject to an outward heat flux assumed to be \(h=10\, \text{W/m}^2\text{K}\) due to natural convection, and radiation loss with \(\varepsilon = 0.79\) (oxidised steel) [21]. The surrounding environment is assumed to be at a temperature of 293.15 K.

Temperature dependent properties have been assigned. Heat capacity and thermal conductivity are derived from the material properties as described by Wu et al. [22]. Wu et al. listed material properties of rail steel at different temperatures. When these were plotted a linear relationship was observed. The slope was assumed to be correct, however the thermal conductivity was assumed to be lower. The density was taken from Wu et al.[23]. The material properties that have been used are:

\[
C_p = 0.12817 + 452.48\, \text{J/kgK}, \quad \rho = 7850\, \text{kg/m}^3 \quad \text{and} \quad k = 0.01937 + 25\, \text{W/mK}.
\]

![Figure 3.5: Mesh used for modelling.](image)

The mesh used for modelling was made out of tetrahedral elements. Along the centreline on the top surface, the mesh size is made to be extremely fine (a predefined setting in COMSOL). The mesh size gradually increases further away from the centreline on the top surface (up until normal size) (see figure 3.5. The temperature profile during laser welding is quite steep near the weld, therefore a finer mesh is required near the weld. Further away from the weld the temperature gradients will not be that high.
Heat Source

There are various possibilities when it comes to modelling a heat source. Just a grasp of the possibilities are mentioned in Zain-ul abdein et al. [3], like conical, spherical, elliptical, or a combination of these three. The heat source used for this model is based upon the one used by Zain-ul abdein et al. [3], a conical heat source with a gaussian distribution (see figure 3.6). However, in this model a circular surface heat source with a gaussian distribution is added.

The original heat source formulation from Zain-ul abdein et al.[3] is:

\[ Q_v = Q_0 \exp \left( -\frac{3r^2}{r_c^2} \right) \]

with,

\[ r_c = r_i + (r_e - r_i) \frac{z - z_i}{z_e - z_i} \]

\[ Q_0 = \frac{9\eta P}{\pi(1 - e^{-3})} \frac{1}{(z_e - z_i)(r_e^2 + r_e r_i + r_i^2)} \]

Here, \( P \) is the power output of the laser, \( \eta \) is the efficiency of the heat source, \( z_e \) and \( z_i \) are the z-coordinate and \( r_e \) and \( r_i \) are the radii of the top and bottom sphere of the cone, respectively. The \( \exp \left( -\frac{3r^2}{r_c^2} \right) \) can be modified to make it suitable for a moving heat source in a Cartesian coordinate system [24] and ends up in the following form, where \( v_{laser} \) is the propagation speed of the laser and \( x_1, y_1 \) and \( z_1 \) are the initial coordinates of the laser spot on the sample:

\[ \exp \left( -3 \frac{(x - x_1 - v_{laser} t)^2 + (y - y_1)^2 + (z - z_1)^2}{(r_i + (r_e - r_i) \frac{z - z_i}{z_e - z_i})^2} \right) \]

The surface heat source is formulated as follows [25]:

\[ Q_{surf} = \frac{2\eta_{surf} P}{\pi r_b^2} \exp \left( -\frac{(x - x_1 - v_{laser} t)^2 + (y - y_1)^2}{r_b^2} \right) \]

Here, \( \eta_{surf} \) is a separate efficiency for the surface heat source and \( r_b \) is the radius of the surface heat source.

The total heat input from the heat source is then defined as:

\[ E_{tot} = B Q_{surf} A_{surf} + (1 - B) Q_v V_{cone} \]

\( B \) serves to divide the total laser output over both heat sources in a certain degree.
3.3.3 Fitting Procedure

In order to fit the model to a real weld, a weld was made with 3 kW power and 2 mm/s propagation speed. The temperature on the surface beside the weld is measured during welding. The basis upon which the modelling parameters are chosen is by matching the dimensions of the weld in the simulation to the dimensions of the real weld made with the 3 kW laser. The dimensions that are taken into account are shown in figure 3.7. The dimensions in the model should match as good as possible with the dimensions of the real welds. In practice the aim was to match dimensions within 0.5 mm with the real dimensions.

Apart from the dimensions of the weld, the temperature profile $T(x, y, z, t)$ of the model has to match that of the real temperature profile measured with the thermocouples during welding. Characteristics of the temperature profile that are considered are peak temperature, plateau temperature, and the cooling rates of both peak and plateau temperature. The definition of peak and plateau temperature is described in figure 3.8.

Figure 3.7: Weld and HAZ dimensions considered in fitting the model.

Figure 3.8: Definition of peak and plateau temperature.
3.4 3 kW Welding Experiments

From the thermal model welding parameters are derived that would make an appropriate weld. The selected welding parameters are used to make welds that are investigated by means of OM, SEM and Micro-Hardness.

3.4.1 Sample Geometry

The samples for welding were manufactured as described in section 3.3.1. The welding thermocouples are placed on the top surface as indicated in figure 3.9.

![Figure 3.9: Thermocouple placement on top surface of the samples.](image)

3.4.2 Welding Procedure

Welding of the samples was performed in focus, with the laser beam perpendicular to the top surface. Welding is carried out along the centreline in the longitudinal direction of the sample. No shielding gas was used during welding. After welding the end of the weld was cut off, a cross-section of the weld was taken from the remainder of the sample. The cross-section was ground, polished and etched (see section 3.2.3) for OM, SEM and Micro-Hardness.

Some of the samples have been pre-heated before welding. The pre-heating was performed with a burner using acetylene and oxygen, only the top surface was heated (see figure 3.10). Thermocouples are placed on the bottom surface of the sample to monitor the pre-heating temperature. By placing the thermocouples on the bottom surface, it was made sure that the sample was heated through-thickness.

![Figure 3.10: Pre-heating procedure with acetylene and oxygen.](image)
3.5 8 kW Welding Experiments

In order to make a full penetration weld on rails it is necessary to weld with a higher power laser. Therefore, laser welding with an 8 kW laser was carried out at Cranfield University. To make a successful weld with an 8 kW laser the knowledge gained from welding with the 3 kW laser was used for higher powers. The model from section 3.3 cannot be used since it is not elaborate enough to include the 8 kW welded samples. Fitting the model for welding with 8 kW will also require actual welding to be carried out beforehand to fit the weld dimensions.

3.5.1 Sample Geometry

The samples were made out of an intact rail (R260Mn 54E1). The rail profile was kept intact since the foot offers options to more easily mount the samples for milling and welding. The head of the rail was removed up to a depth of 15 mm to obtain a flat surface for welding (see figure 3.11). The samples for the joint welds are 50 mm in length each.

Figure 3.11: Milling down the rail head to acquire a flat surface for welding.

For each experiment a pair of samples is required. The samples were to be joined with a single pass in the transverse direction on the rail head. The two pieces of rail were fixed together by tack welding in the foot and at the top of the web to ensure a minimal gap between both ends (see figure 3.12).

Figure 3.12: Laser welding setup and sample dimensions for joint welds.
3.5.2 Welding Parameters

Welding of the samples was performed in focus, with the laser beam perpendicular to the milled surface of the rail head. The samples are welded in a single pass on the milled top surface of the rail head. No shielding gas was used during welding. After welding cross sections were prepared. The cross-sections were ground, polished and etched (see section 3.2.3) for OM, SEM and Micro-Hardness.

As a first assumption, for the welding parameters it was assumed that the penetration depth increases linearly, which means that the laser power per unit volume is also quite similar. If this assumption does not hold, it is assumed the heat input per unit volume increases. Thus, the increase of depth of penetration becomes less for increasing laser power. From this reasoning it is chosen to use the same welding speeds as for the 3 kW welds (8 kW, 2 and 4 mm/s). On top of that, 8 kW 6 mm/s welds have been made. A pre-heating of 300°C was chosen.

Pre-heating was carried out by placing the tack welded sample into a furnace (450°C). The pre-heating temperature was monitored using a thermocouple attached to the sample. The samples were pre-heated to 350°C in order to have time for transporting the sample to the 8 kW laser.
Chapter 4

Results and Discussion

4.1 Base Material

Based on the material composition of the first batch (table 3.1) a TTT-diagram is computed with the program MAP_STEEL_MUCG83 based on the work of Bhadeshia [4]. Figure 4.1 shows the computed TTT-diagram. TTT-diagrams are not ideal for describing phase transformations during welding, CCT diagrams are better suited for this purpose. However, from the TTT-diagram in figure can already be seen that pearlitic transformation is preferential over bainitic transformation. Therefore, it can be concluded that bainitic transformation will most likely not occur.

Figure 4.1: TTT diagram of R260Mn with Pearlite, Bainite and Martensite [4].

Optical Microscopy and Scanning Electron Microscopy images of the base material were obtained. Figures 4.2 to 4.4 show the pearlitic microstructure of the base material.
Figure 4.2: Microstructure of R260Mn Pearlitic Rail steel.

Figure 4.3: Pearlitic microstructure of R260Mn Rail steel.

Figure 4.4: Lamellar configuration in the pearlitic base material.
NEN-EN 13674:2011 [2] prescribes hardness (Brinell) to be measured on the centre line of the rail head, however since welding experiments are carried on plate material taken from the web it was decided to measure hardness on the web material. Figure 4.5 shows the positions at which the hardness was measured. The results of the hardness measurements are given in table 4.1.

![Figure 4.5: Brinell Hardness measurements carried out on material from the web.](image)

Table 4.1: Brinell Hardness measurements on base material from the web.

<table>
<thead>
<tr>
<th>Hardness (HBW)</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>309</td>
<td></td>
<td></td>
</tr>
<tr>
<td>310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>311</td>
<td>311</td>
<td>2.35</td>
</tr>
<tr>
<td>310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>315</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NEN-EN 13674:2011 [2] prescribes R260Mn rail steels have a hardness of 260 to 300 HBW. The hardness measurements carried out on the web of the rail have an average hardness of 311 HBW. However, R260Mn rail is produced by hot rolling and is cooled in air. The thickness in the web is significantly less than in the rail head. Therefore, it is expected that the cooling rate is higher in the web, resulting in a slightly higher hardness.
4.2 Dilatometry

4.2.1 Results

Dilatometry

The results of the dilatometry tests are shown in figure 4.6. The start and finish temperatures of each transformation are given in table 4.2. The transformation start and finish temperatures were derived as the temperature at which the dilation behaviour of the material started to deviate from its linear path.

![Dilatometry results of R260Mn for different cooling rates.](image)

Figure 4.6: Dilatometry results of R260Mn for different cooling rates.

<table>
<thead>
<tr>
<th>Cooling Rate (°C/s)</th>
<th>Transformation Start Temperature (°C)</th>
<th>Transformation Finish Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>264</td>
<td>Unfinished</td>
</tr>
<tr>
<td>40</td>
<td>256</td>
<td>71</td>
</tr>
<tr>
<td>20</td>
<td>261</td>
<td>83</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>585, 235</td>
<td>380, 60</td>
</tr>
<tr>
<td>2</td>
<td>612</td>
<td>547</td>
</tr>
<tr>
<td>1</td>
<td>624</td>
<td>NA</td>
</tr>
</tbody>
</table>
For cooling rates of $10^\circ$C/s and higher transformation start temperatures are $\sim 258^\circ$C, and transformation finish temperatures $\sim 70^\circ$C. This is the martensitic transformation. For cooling rates $2^\circ$C/s and lower transformation start temperatures are $\sim 618^\circ$C, the transformation finish temperature is $547^\circ$C. This is pearlitic transformation. The transformation finish temperature of the $1^\circ$C/s could not be measured, the heat generated from the phase transformation could not be dissipated by the dilatometer to ensure the $1^\circ$C/s cooling rate during the phase transformation. For cooling rates in between $2$ and $10^\circ$C/s mixed transformation takes place. The first transformation starts at $585^\circ$C and stops at $380^\circ$C, this is the formation of pearlite. The second phase transformation starts at $235^\circ$C and finishes at $60^\circ$C, this is the formation of martensite.

OM, SEM and Micro-Hardness

To confirm the relationship between transformation behaviour and microstructures obtained, the samples of 2, 5, and $10^\circ$C/s cooling rate are investigated by means of OM, SEM and Micro-Hardness. These samples are in the range at which transformation temperatures start to change significantly. Optical microscopy images of the microstructure are shown in figures 4.7 to 4.9. Figures 4.10 to 4.12 show images of the microstructure taken by means of SEM.

Figure 4.7: Microstructure of the $2^\circ$C/s sample.
Figure 4.8: Microstructure of the $5^\circ$C/s sample.

Figure 4.9: Microstructure of the $10^\circ$C/s sample.
Figure 4.10: SEM image of the microstructure of the 2°C/s sample.

Figure 4.11: SEM image of the microstructure of the 5°C/s sample.
From figure 4.7 can be seen that the resulting microstructure of the 2°C/s sample is pearlite. This is more clearly seen in figure 4.10. The microstructure of the 5°C/s sample consists of two phases. A matrix of martensite (acicular light grey phase) in which areas of pearlite are present (dark lamellar phase) (figures 4.8 and 4.11. The 10°C/s sample has a martensitic microstructure. There is some pearlite present in the microstructure, however less than in the 5°C/s sample (figures 4.9 and 4.12).

**Micro-Hardness**

To verify the phases identified with OM and SEM, Micro-Hardness measurements are carried out. For the 2 and 10°C/s samples HV-5kg was used since only one phase was present. For the 5°C/s sample 2 phases are present. For this sample HV0.05 measurements are performed in order to take hardness measurements in both phases separately. The results from hardness testing are given in tables 4.3 and 4.4.

Table 4.3: Vickers Hardness measurements on the 2 and 10°C/s sample.

<table>
<thead>
<tr>
<th></th>
<th>Hardness</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°C/s</td>
<td>766 HV5</td>
<td>769</td>
<td>6.35</td>
</tr>
<tr>
<td></td>
<td>769 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>777 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>762 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2°C/s</td>
<td>336 HV5</td>
<td>379</td>
<td>3.11</td>
</tr>
<tr>
<td></td>
<td>335 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>337 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>330 HV5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4: Vickers Hardness measurements on the 5°C/s sample.

<table>
<thead>
<tr>
<th>5°C/s</th>
<th>Hardness</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martensite</td>
<td>880 HV0.05</td>
<td>857</td>
<td>84.0</td>
</tr>
<tr>
<td>947 HV0.05</td>
<td>745 HV0.05</td>
<td>854 HV0.05</td>
<td></td>
</tr>
<tr>
<td>Pearlite</td>
<td>372 HV0.05</td>
<td>379</td>
<td>6.11</td>
</tr>
<tr>
<td>380 HV0.05</td>
<td>384 HV0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The measurements of both the 10 and 2°C/s samples show clear results, confirming the 10°C/s to be martensite (769 HV5) and the 2°C/s to be pearlite (335 HV5) (table 4.3).

For the 5°C/s sample both phases are measured separately (table 4.4). For the martensite the highest measurement is 947 HV0.05 while the lowest is 745 HV0.05. Despite the high standard deviation, it is still clear that this is martensite. The hardness is too high for bainite and pearlite. The measurements for the pearlite also have a high standard deviation with an average of 379 HV0.05. The measured hardness values show a wide variation, since making an indent at the right place is quite difficult. Also, indents are relatively large compared to the area in which a certain phase is present, leading to interaction with the surrounding phase.

4.2.2 Discussion

Regulation concerning welding of rail steels dictate that pearlitic microstructures are required [14]. Judging from the dilatometry results and microstructures observed in the samples can be concluded that in order to obtain a pearlitic microstructure cooling rates above 5°C/s are to be avoided. A suitable solution for limiting the cooling rate is by pre-heating. Welding parameters can be chosen accordingly to match cooling rates of in between 5 and 10°C/s. By preheating the cooling rate is further decreased to ~2°C/s, resulting in a pearlitic microstructure. Welding parameters that can be freely chosen are: power output of the laser, welding speed and possibly pre-heating temperature.

Comparing the results of the dilatometry to the computed TTT diagram of section 4.1, it can be observed that for cooling time shorter than ~10 s (~800 to ~450°C), martensite is formed. This corresponds to cooling rates of ~35°C/s. The dilatometry results show martensite still forms for cooling rates in between 5 and 10°C/s. However, it should be kept in mind that dilatometry experiments are better compared to CCT diagrams. TTT diagrams are constructed by cooling to a certain temperature, and keeping the temperature constant for a certain time. CCT diagrams are constructed by constant cooling at a certain rate, similar to the dilatometry experiments. It is expected that for a CCT diagram the pearlite and bainite nose both shift to lower cooling rates.
4.3 Preliminary Welding

4.3.1 Results

Optical Microscopy, SEM and Micro-Hardness testing have been conducted on the 16 kW preliminary welds made by ProRail. Figure 4.13 shows an overview of the welded samples. The penetration depth of each individual weld is given in table 4.5.

![Macrograph of welded samples of ProRail.](image)

The macrograph (figure 4.13) of the etched samples shows the presence of large welding defects in the welds. These defects include a solidification crack and (macro-)porosity in each weld. The macrograph also shows the effect of the different welding parameters. Samples 1 to 3 are welded with 16 kW with increasing welding speed (12.5 to 25 mm/s). With increased welding speed the width and depth of the weld and HAZ decreases. Samples 4 to 6 are welded with 10.5 kW with increasing from 8.3 to 16.7 mm/s, and show a similar trend in cross-section features. However the penetration depth is less than for their 16 kW counterparts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Power (kW)</th>
<th>Welding speed (mm/s)</th>
<th>Penetration Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.0</td>
<td>12.5</td>
<td>19.3</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>16.7</td>
<td>17.9</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>25</td>
<td>16.0</td>
</tr>
<tr>
<td>4</td>
<td>8.3</td>
<td>12.5</td>
<td>18.3</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
<td>16.7</td>
<td>15.0</td>
</tr>
<tr>
<td>6</td>
<td>13.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Solidification cracks are formed during and after solidification. During solidification a microstructure with columnar grains is formed. While the grains cool down and contract, stresses are build up. Due to the workpiece surrounding the weld, the grains are highly constrained resulting in the build-up stress causing a crack. Cracking is observed in the centre of the weld due to alloying elements and impurities segregating in front of the solidification front. The segregated material ends up in the centre of the weld. Being the weakest material in the weld, the crack is formed in the centre of the weld. From the macrograph (figure 4.13) can be observed that all of the welded samples show the solidification crack opened up in the bottom of the weld. The weld is thicker in the bottom, resulting in more stress being build up.

Porosity is the result of gasses forming during laser welding. During laser welding a keyhole shape weldpool (deep and narrow) is formed. Since the material is not fully penetrated, gasses forming during welding cannot escape through the bottom of the weld. The gasses become entrapped in the solidified weld metal (porosity).
OM and SEM

Figures 4.14 to 4.17 show images of the microstructure in samples 1 and 2. The reason the microstructure of only these samples is shown is that the welds do not show significant differences in microstructure.

Figure 4.14: The microstructure of the Weld metal (sample 2).

Figure 4.15: The microstructure of the HAZ1 (sample 2).
Each of the samples shows columnar prior austenite grains (solidification structure) growing from the fusion line to the centre of the weld (figure 4.14). Within the prior austenite grains the microstructure is martensite. No grains can be distinguished within the prior austenite grains, the black areas on the prior austenite grain boundary is most probably a ferritic phase which coloured black due to over-etching. Pro-eutectoid ferrite forms in steels with up to 0.8wt.%C and tends to form on grain boundaries or on inclusions present within the prior austenite grains [26].

The HAZ1 has a martensitic microstructure, no grains can be recognised as prior austenite grains are not decorated with ferritic constituents (figure 4.15). The HAZ2 has a mixed microstructure consisting of both martensite and pearlite. In the OM image the pearlite has turned black due to over-etching, however images taken with the SEM show this phase to be pearlite (figure 4.17).
Micro-Hardness

Table 4.6 shows the results of the micro-hardness measurements carried out to verify the phases identified with OM and SEM. HV-1kg was used for general measurements, HV-0.025kg was used for phase specific measurements in the HAZ2.

<table>
<thead>
<tr>
<th></th>
<th>Hardness</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weld</strong></td>
<td>751 HV1</td>
<td>750</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>751 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>767 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>732 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>779 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HAZ1</strong></td>
<td>747 HV1</td>
<td>755</td>
<td>7.30</td>
</tr>
<tr>
<td></td>
<td>751 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>763 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>759 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HAZ2</strong></td>
<td>516 HV1</td>
<td>557</td>
<td>48.9</td>
</tr>
<tr>
<td></td>
<td>539 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>546 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>628 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HAZ2-Pearlite</strong></td>
<td>365 HV0.025</td>
<td>361</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>359 HV0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HAZ2-Martensite</strong></td>
<td>636 HV0.025</td>
<td>646</td>
<td>40.4</td>
</tr>
<tr>
<td></td>
<td>690 HV0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>611 HV0.025</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The hardness value of the weld and HAZ1 are 750 HV1 and 755 HV1, respectively. Both hardness values confirm that the microstructure of the weld and HAZ1 are martensite.

The HAZ2 has a lower hardness value due to the pearlitic phase present (361 HV0.025). The martensite in the HAZ2 has hardness of 646 HV0.025. The hardness value of the martensite is lower for the phase specific measurement, and higher for the pearlite, since interaction with the surrounding pearlitic phase is inevitable. The general hardness measurement averages out to a hardness value of 557 HV1.

4.3.2 Discussion

As a result of the preliminary welding trials it was found that the cooling rate for the welding parameters used was too high. The weld metal and HAZ1 are martensitic. The HAZ2 has a mixed microstructure of both martensite and pearlite. The martensitic weld metal and HAZ are not acceptable. These welds would perform poorly in terms of fatigue behaviour due to cracks easily propagating through the brittle and hard martensite. As a side note, for an aluminothermic weld in R260Mn rails the running surface hardness of the weld centre has to be $280 \pm 20$ HBW [14], which is about 295 HV [27]. This finding has resulted in the definition of a research project aiming to understand the microstructural evolution in laser welded rail steels, and to define a processing window in which properties are acceptable.

\[
\frac{\partial T}{\partial t} = \frac{2\pi k(T - T_0)^2}{W} \quad \text{with,} \quad W = \frac{P}{v} \quad [16]
\]
From the dilatometry data can be concluded that the cooling rates for the preliminary welds were more than 5°C/s. There are a number of options to decrease the cooling rate. The simple equation on the previous page for the cooling rate for the weld centre with three-dimensional heat flow, shows that increasing the heat input $W$ decreases the cooling rate $\frac{dT}{dt}$. The heat input can be increased by either increasing the laser power $P$ or decreasing the welding speed $v$. Another option is to apply pre-heating to the material and thereby increasing $T_0$. The cooling rate is influenced substantially by pre-heating (note the squared relationship).

Since these sample show quite some (macro-)porosity, decreasing the welding speed may not be an option. More evaporation during welding causes more gasses to become entrapped. On top of that lower welding speed will result in a higher penetration depth, which in turn may also cause more gasses to become entrapped.

### 4.4 Thermal Modelling

In order to determine appropriate welding conditions that will result in an acceptable hardness and microstructure in the weld, thermal models in conjunction with the CCT data were applied.

#### 4.4.1 Fitting

The thermal models were fitted to obtain agreement with the experimental results. The models were then used to find conditions with specific cooling rates. In table 4.7 the fitting parameter values are given which are found fitting the model. It is aimed to get the weld dimensions from the model within 0.5 mm in comparison to the real welds. The eventual dimensions of the modelled weld are given in table 4.8.

Table 4.7: Final values of the fitting parameters related to the heat source used in the model.

<table>
<thead>
<tr>
<th>2 mm/s RT</th>
<th>$r_c = 0.52mm$</th>
<th>$z_c = 12mm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta = 0.70$</td>
<td>$r_i = 1.0mm$</td>
<td>$z_i = 4.0mm$</td>
</tr>
<tr>
<td>$\eta_{surf} = 0.50$</td>
<td>$r_B = 1.1mm$</td>
<td>$B = 0.45$</td>
</tr>
</tbody>
</table>

Table 4.8: Weld dimensions of the model compared to the real weld.

<table>
<thead>
<tr>
<th>2 mm/s RT</th>
<th>W (mm)</th>
<th>W+HAZ (mm)</th>
<th>D (mm)</th>
<th>D+HAZ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>5.0</td>
<td>11.7</td>
<td>9.3</td>
<td>~12</td>
</tr>
<tr>
<td>Model</td>
<td>4.5</td>
<td>11.5</td>
<td>9.7</td>
<td>~12</td>
</tr>
</tbody>
</table>

A comparison is made between the temperature profile of the model and real weld. The temperature measurements during the 2 mm/s RT weld are located at on the top surface next to the weld. Figures 4.18 shows a plot of both the modelled and real temperature profile.
Fitting of the model based on the weld dimensions proved to be successful. All dimensions could be fitted to within 0.5 mm from the real value. For the temperature profile an overall good fit is achieved. The peak temperature value of the model is matched to within ~20°C of the real temperature measurement. The cooling rates in the model of both peak (80°C/s) and plateau region (1.8°C/s) correspond quite well with that of the real measurement (79 and 1.8°C/s, respectively).

From the temperature profile measurements carried out on the 2 mm/s RT case, it can be seen that the plateau temperature of the model is overestimated by about 90°C (~17%). The model is however still useful, if this overestimation is kept in mind. Further modification of the model and more time for better fitting may resolve the issues of difference in plateau temperature.

### 4.4.2 Results and Discussion

Using the model a set of parameters can be selected for welding. Figure 4.19 shows the temperature profiles obtained from the model for a 4 mm/s weld (both RT and 300°C pre-heated). The temperature profile was obtained from the same location as the thermocouples were placed during welding.
If the 17% overestimation of the plateau temperature for the 2 mm/s weld is assumed to be the same for the 4 mm/s welds, the real plateau temperatures of the RT and PH weld are \(\sim 280\) and \(\sim 526^\circ C\), respectively. It is expected that the RT weld will have a mixed microstructure of martensite and pearlite since the plateau temperature is close to the Ms temperature (\(\sim 258^\circ C\)). The 300°C pre-heated weld will be pearlitic since the plateau temperature of \(\sim 526^\circ C\) is too high, and the cooling rate of \(\sim 1^\circ C/s\) is too low for the martensitic transformation to occur. The bainitic transformation is not expected since the TTT-diagram from section 4.1 (figure 4.1) shows that the pearlitic transformation is preferential over bainitic transformation.

### 4.5 3 kW Welding Experiments

The parameters selected using the thermal model have been used to make 4 mm/s welds at both RT and 300°C pre-heating temperature. The weld made for fitting of the thermal model, and the newly made 4 mm/s welds have been investigated by means of OM, SEM and Micro-Hardness testing.

#### 4.5.1 2 mm/s room temperature welded sample

**Results**

Figures 4.20 to 4.23 show the microstructure of the 3 kW 2 mm/s RT weld in the weld metal and HAZ.

![Prior austenite grains in the weld metal of the 3kW, 2mm/s welded sample.](image)

Figure 4.20: Prior austenite grains in the weld metal of the 3kW, 2mm/s welded sample.
Figure 4.21: The microstructure of the weld metal of the 3kW, 2mm/s welded sample.

Figure 4.22: The microstructure of the HAZ1 of the 3kW, 2mm/s welded sample.
OM and SEM (figures 4.20 to 4.23) show the 2 mm/s RT welded sample is pearlitic throughout the weld metal and HAZ. Especially in the images taken with SEM, the lamellar structure of the pearlite can be clearly distinguished. In the weld metal the prior austenite grains are decorated with ferrite on the grain boundary (see figure 4.20). The HAZ is fully pearlitic with decreasing grain size for increasing distance from the fusion line. The higher temperature near the fusion line allows grain growth.

Micro-hardness measurements are conducted to confirm the presence of certain phases. Table 4.9 shows the results of the hardness measurements on the 2 mm/s RT sample. HV-1kg was used in the weld metal to be able to measure within the prior austenite grains. All other hardness measurements are carried out with HV-5kg.

Table 4.9: Vickers Hardness measurements on the 2 mm/s RT welded sample.

<table>
<thead>
<tr>
<th></th>
<th>Hardness</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld</td>
<td>324 HV1</td>
<td>323</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td>322 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>327 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>320 HV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAZ1</td>
<td>321 HV5</td>
<td>340</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>341 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>350 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>346 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAZ2</td>
<td>288 HV5</td>
<td>287</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>288 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>282 HV5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>289 HV5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The measured hardness values are in line with the optical microscopy and SEM images. The average hardness values of weld, HAZ1 and HAZ2 (323 HV1, 340 HV5 and 287 HV5, respectively) correspond with a pearlitic microstructure. The HAZ2 has the lowest hardness despite the smaller grain size. Because of the intercritical temperature conditions in this part of the HAZ, areas of the original pearlite of the base material is present, this might explain the lower hardness.
Discussion

From the temperature profile obtained for fitting the thermal model of section 4.4, could already be observed that the 2 mm/s RT welded sample is completely pearlitic. The plateau temperature of $\sim 540^\circ C$ is high enough for pearlitic transformation to take place. The TTT diagram from section 4.1 shows that the nose of the pearlite curve is at $\sim 460^\circ C$.

The 2 mm/s RT welded sample being pearlitic shows that it may be possible to make an acceptable weld without pre-heating. However, due to the limited size of the specimen welded at TU Delft, the entire specimen heats up, thereby reducing the cooling rate significantly. In the case of a joint weld between two rail end the required heat input to heat up the entire specimen is much larger. It is expected that the cooling rate will be higher with larger samples.

4.5.2 4 mm/s room temperature and 300°C pre-heated welded samples

Results

With the parameters selected from the model a 4 mm/s weld is made at both RT and with a 300°C pre-heat. The microstructure of both welds are compared in figures 4.24 to 4.27. The penetration depths of the RT and pre-heated sample are 7.3 and 8 mm respectively.

![Figure 4.24: The microstructure of the weld metal of 4 mm/s RT (left) and 300°C pre-heating (right).]
The microstructure in the weld metal of the 4 mm/s RT sample is a mix of martensite and pearlite, similar as encountered in the 5°C/s (cooling rate) dilatometry sample (see figure 4.24). However, the amount of pearlite present is higher than in the case for the 5°C/s dilatometry sample in section 4.2.1. In the pre-heated sample a pearlitic microstructure is formed. Apart from pearlite, acicular ferrite is present (see figure 4.24).
The HAZ1 of the 4 mm/s RT welded sample consists of martensite and pearlite. However, compared to the weld, the pearlite is only present in small quantities. The grain size is less in the HAZ2 and more pearlite is present, due to the intercritical conditions in this part of the HAZ. In the pre-heated sample the HAZ is pearlitic with small amounts of ferrite present. Closer to the base material the grain structure is finer (see figures 4.26 and 4.27).

To confirm the presence of the phases identified with OM and SEM, Micro-Hardness measurements are carried out. For all measurements HV-5kg is used. See table 4.10.

Table 4.10: Vickers hardness measurements on the 4 mm/s RT and 300°C pre-heated weld.

<table>
<thead>
<tr>
<th></th>
<th>Room Temperature</th>
<th>300°C Pre-heat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hardness Average</td>
<td>Standard Dev.</td>
</tr>
<tr>
<td>Weld</td>
<td>531 HV5</td>
<td>519</td>
</tr>
<tr>
<td></td>
<td>523 HV5</td>
<td>516</td>
</tr>
<tr>
<td></td>
<td>506 HV5</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>517 HV5</td>
<td>316</td>
</tr>
<tr>
<td>HAZ1</td>
<td>716 HV5</td>
<td>737</td>
</tr>
<tr>
<td></td>
<td>736 HV5</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>759 HV5</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>336</td>
</tr>
<tr>
<td>HAZ2</td>
<td>654 HV5</td>
<td>614</td>
</tr>
<tr>
<td></td>
<td>619 HV5</td>
<td>294</td>
</tr>
<tr>
<td></td>
<td>602 HV5</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>582 HV5</td>
<td>298</td>
</tr>
</tbody>
</table>

The 4 mm/s RT sample has a measured average hardness in the weld metal of 519 HV5. The weld metal is mix of martensite and pearlite. The hardness value measured corresponds with that of the mixed microstructure (average of the hard martensite, and softer pearlite). The HAZ1 has a higher average hardness value of 737 HV5, since the amount of pearlite present is significantly less than in the weld metal. The HAZ2 has a lower average hardness (614 HV5 on average), which can be expected because of the higher amount of pearlite present.

The pre-heated sample has lower hardness values in general, compared to the RT sample. Because of the pre-heating the plateau temperature (see section 3.3.3) is higher, thus having a low cooling rate at temperatures where pearlitic transformation can occur. In the weld metal an average hardness of 319 HV5 is measured. For the HAZ1 the measured hardness is 332 HV5 on average, and for the HAZ2 it is 301 HV5 on average. The measured hardness values confirm the pearlitic microstructure observed with OM and SEM. The highest hardness is measured in the HAZ1, for the weld metal it is slightly lower. This is due the presence of ferrite in the weld metal. The higher single hardness measurement (510 HV5) in the HAZ1 is due to a patch of martensite in the microstructure (see figure 4.28). Further investigation of this patch showed that a few long, flat patches of martensite are present in the HAZ.

For the HAZ2 the measured hardness is also lower, even though the grains are considerably smaller. In the intercritical region not all of the pearlite transformed to austenite during heating. Some of the pearlite from the base material is still present which has a lower hardness.
Discussion

The microstructure that has formed in both the 4 mm/s RT and 300°C pre-heated welded samples, is in line with what was expected from the thermal modelling. The plateau temperature of the RT sample was expected to be close to the Ms temperature, forming a martensitic microstructure with some amount pearlite. This is the case for both the weld metal and HAZ. The pre-heated sample was expected to have a plateau temperature high enough to form a pearlitic microstructure. The sample turned out to have a pearlitic microstructure, however some ferrite is present.

From the comparison between both the RT and the 300°C pre-heated welded sample can be concluded that pre-heating can indeed be used to obtain the preferred pearlitic microstructure. Further research into welding and pre-heating parameters can eventually lead to further control on the hardness of the rail material along the weld and HAZ. If obtaining the right microstructure without pre-heating (like in the case of the 2 mm/s weld) becomes problematic on larger scale welding, pre-heating may be the most viable option to consider. Pre-heating is a common procedure performed for conventional rail welding processes. Further research into options for controlling the pre-heating and implementing this with the laser welding may therefore be worth researching.

The 4 mm/s 300°C pre-heated sample has pearlitic weld metal with acicular ferrite in the pearlite grains. Acicular ferrite tends to form on inclusions present within grains [28]. Since quite an amount of acicular ferrite formed within the weld metal it is suspected inclusions are embedded into the weld metal as a results of contamination during the welding. Using a shielding gas may decrease the amount of acicular ferrite forming.

The martensite patches observed in the HAZ are suspected to be the result of segregation of Mn in the steel (during the production process). From EDS (see figure 4.29 and table 4.11) can be seen that the Mn-content in the martensite (measurements 4 and 5) is about 0.5 wt% more than in the surrounding pearlite (measurements 1 and 2). The pearlite embedded in the martensite (measurements 3 and 6) has a manganese content of about 1.8 wt%. Manganese and carbon act as austenite stabilisers in steels. Figures 4.30 to 4.32 shows that both carbon and manganese have the effect of retarding pearlite formation and lowering the martensite start temperature. The pearlite nose in the TTT diagram is shifted to the right. The regions with increased Mn-content will remain austenitic at lower temperatures. Carbon diffuses into the austenite, stabilising the austenite further. The austenite eventually transforms into martensite at low temperatures.
The martensite patches observed in the HAZ may become a problem for the performance of the weld in terms of fatigue. Possible future solutions may include post-weld heat treatments like tempering. Tempered martensite will be more forgiving in terms of fatigue performance. Research should point out whether the detrimental properties of the martensite can be decreased enough by tempering.

Table 4.11: Local composition of certain phases determined with EDS.

<table>
<thead>
<tr>
<th>Area</th>
<th>Fe (wt.%)</th>
<th>Si (wt.%)</th>
<th>Cr (wt.%)</th>
<th>Mn (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>97.98</td>
<td>0.30</td>
<td>0.05</td>
<td>1.57</td>
</tr>
<tr>
<td>002</td>
<td>98.13</td>
<td>0.28</td>
<td>0.10</td>
<td>1.47</td>
</tr>
<tr>
<td>003</td>
<td>97.72</td>
<td>0.32</td>
<td>0.08</td>
<td>1.81</td>
</tr>
<tr>
<td>004</td>
<td>97.20</td>
<td>0.39</td>
<td>0.11</td>
<td>2.13</td>
</tr>
<tr>
<td>005</td>
<td>97.32</td>
<td>0.37</td>
<td>0.08</td>
<td>2.15</td>
</tr>
<tr>
<td>006</td>
<td>97.62</td>
<td>0.35</td>
<td>0.09</td>
<td>1.88</td>
</tr>
<tr>
<td>007</td>
<td>97.640</td>
<td>0.33</td>
<td>0.09</td>
<td>2.05</td>
</tr>
<tr>
<td>008</td>
<td>97.48</td>
<td>0.37</td>
<td>0.09</td>
<td>2.00</td>
</tr>
<tr>
<td>009</td>
<td>97.36</td>
<td>0.34</td>
<td>0.11</td>
<td>2.07</td>
</tr>
<tr>
<td>Average</td>
<td>97.58</td>
<td>0.34</td>
<td>0.09</td>
<td>1.90</td>
</tr>
<tr>
<td>Deviation</td>
<td>0.32</td>
<td>0.04</td>
<td>0.02</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Figure 4.29: SEM image of the area scanned with EDS.
Figure 4.30: TTT diagram with increasing Manganese concentration (MAP_STEEL_MUCG83) [4].

Figure 4.31: TTT diagram with increasing Carbon concentration (MAP_STEEL_MUCG83) [4].
4.6 8 kW Welding Experiments

4.6.1 Results

Figure 4.33 shows the macrograph of the 8 kW welded samples. Only the pre-heated samples and 2 mm/s sample are shown since these are the welds that may be acceptable in terms of microstructure and hardness. From the 2 mm/s sample can immediately be seen that large defects (including macro-porosity and cracks) are present. The 4 and 6 mm/s pre-heated samples show less defects. The 4 mm/s sample has some porosity in the bottom of the weld and a small solidification crack at about a third of the weld depth. The 6 mm/s welded sample has a large pore in the bottom of the weld, and some porosity in the top left of the weld.

Figure 4.33: Macrograph of the 8 kW, 2 mm/s (a) and pre-heated 4 (b) and 6 mm/s (c) welded samples respectively.

Figures 4.34 to 4.36 show the OM and SEM images for the 2 mm/s weld. The penetration depth of the welded sample is 12 mm.
The weld material of the 2mm/s weld consists mostly of pearlite, with some amount of martensite. The HAZ1 is completely martensitic with negligible amounts of fine pearlite (black) present. The HAZ2 consists of both martensite and pearlite. The pearlite that is present is untransformed pearlite from the base material. Pearlite that has transformed to austenite formed martensite during cooling.
Figures 4.37 to 4.41 show the OM and SEM images for the 4 mm/s welds, both RT and 300°C pre-heat. The penetration depths of the RT and pre-heated sample are 13.4 and 14.0 mm respectively.

Figure 4.37: The microstructure of the weld metal of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample.

Figure 4.38: SEM image of the microstructure of the weld metal of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample.

Figure 4.39: The microstructure of the HAZ1 of the 8 kW, 4 mm/s RT (left) and 300°C pre-heated (right) welded sample.
The 8 kW, 4 mm/s welded samples are quite similar to the microstructures obtained with the 3 kW laser. The weld metal consists of martensite and a fine pearlite for the RT sample. The measured hardness of the weld metal in the RT sample is 670 HV5, which corresponds with the observed microstructure. The pearlite present in the weld metal decreases the average hardness. The 300°C pre-heated sample has weld material which is pearlitic with ferrite. The measured average hardness of 317 HV5 corresponds with the pearlitic microstructure.

The HAZ1 for the RT sample is similar to the weld metal, however the amount of fine pearlite present is much less. The HAZ1 is almost completely martensitic, therefore the measured hardness (782 HV5) is higher than for the weld metal. For the pre-heated sample the HAZ1 is completely pearlitic, without ferrite. The measured hardness of 393 HV5 corresponds with that of a very fine pearlite.

The HAZ2 for the RT weld is a mix of martensite and small grains of pearlite. A banded structure of mainly martensite and mainly pearlite is observed. The hardness of 371 HV5 corresponds with that of the untransformed pearlite together with the martensite. For the pre-heated weld the HAZ2 consists of a small grained pearlite. The measured hardness of 293 HV5 confirms the observed microstructure.
Figures 4.42 to 4.44 show the OM images for the 6 mm/s 300°C pre-heated welded sample. The penetration depth of the weld is 13.4 mm.

Figure 4.42: The microstructure of the weld metal of the 8 kW, 6 mm/s 300°C pre-heated welded sample.

Figure 4.43: The microstructure of the HAZ1 of the 8 kW, 6 mm/s 300°C pre-heated welded sample.

Figure 4.44: The microstructure of the HAZ2 of the 8 kW, 6 mm/s 300°C pre-heated welded sample.
The 8 kW, 6 mm/s welds have the same microstructures as their 4 mm/s counterparts. Differences are subtle. The 300°C pre-heated weld has weld metal which is predominantly pearlitic with some ferrite. The measured hardness (333 HV5) correspond with that of pearlite. The HAZ1 consists predominantly of pearlite, however some amount of martensite is present (most clearly seen in the OM images). The amount of martensite decreases with increasing distance from the fusion line. The hardness of 466 HV5 is too high for pearlite, however the small amount of martensite present does explain the increased hardness. The HAZ2 is completely pearlitic, which is confirmed by the measured hardness of 292 HV5.

4.6.2 Discussion

Comparing the 3 and 8 kW 2 mm/s weld a different microstructure is observed. The 3 kW welded sample is completely pearlitic. However, the weld made with 8 kW is martensitic. Since the 8 kW contains small amounts of martensite in the weld and is completely martensitic in the HAZ1, it can be concluded that with the experiments conducted at Cranfield University the cooling rates are higher, or a lower plateau temperature is reached. This can be explained by the larger samples for the 8 kW experiments. These samples weigh about 5.4 kg compared to the 0.5 kg samples used for the 3 kW laser. The increased amount of material acts as a larger heat sink.

The effect of increased sample size and therefore larger heat sink can be seen from figure 4.45. The figure shows the modelled temperature curve of the 3 kW, 2 mm/s welding with the actual thickness of 13 mm and a curve of thickness 26 mm. By doubling the sample size the cooling rate in the peak is slightly increased. However the most important change is the decrease in plateau temperature from approximately 650 to 400°C. If the plateau temperature is decreased to temperatures close to the Ms temperature, martensite will form instead of pearlite.

![Figure 4.45: Temperature profiles of modelled 2 kW 13 and 26 mm thickness welds.](image-url)
The main difference between 3 and 8 kW 4 mm/s samples is the amount of fine pearlite in the weld material for the RT welds (more for 3 kW), and the amount of side-plate ferrite in the pre-heated welds (more for 3 kW). In the RT HAZ1 the same is observed, the amount of fine pearlite is less than or the 3 kW case. For the pre-heated samples no notable difference is observed between 3 and 8 kW. For both weld and HAZ1 the small differences between 3 and 8 kW can be accounted for by taking into account the size of the samples.

The banded structure observed in the 8 kW, 4 mm/s, RT welded sample is suspected to be the result of pearlite transforming preferentially over martensite, resulting in a more carbon rich austenite which will easily form martensite upon cooling.

The 8 kW, 6 mm/s 300°C pre-heated sample is similar in microstructure compared to its 8 kW, 4 mm/s counterpart. However martensite is observed in the HAZ1. The reason martensite is present in the HAZ1 is attributed to the same reasoning as is described for the banded structure in the 8 kW, 4 mm/s RT welded sample.

From the results of both the 3 and 8 kW welds can be concluded that obtaining an acceptable weld with laser welding is indeed possible. Welding conditions can be optimised accordingly to obtain a weld with pearlitic weld metal and HAZ. However in both the 3 and 8 kW welds acicular ferrite was observed in the weld metal. The effect of acicular ferrite on the mechanical and fatigue properties of the weld has not been investigated. Further optimisation of welding conditions or using a shielding gas may be able to resolve this issue. For some welds grain boundary ferrite was observed, according to NEN-EN 13674:2011 this is acceptable for R260Mn rail which is used in this research. If the amount of grain boundary ferrite is to be reduced, optimisation of welding conditions may resolve this issue.
Chapter 5

Conclusion

The feasibility of laser welding as a welding process for rail steels was investigated. To do so, the chemical composition, microstructure and dilation behaviour of the base material was studied. Preliminary welding turned out to result in an undesirable microstructure and hardness of the weld. In order to come to an appropriate set of welding conditions thermal models have been constructed. Together with temperature profile data obtained from an actual laser weld, the model was fitted to obtain agreement with the experimental results. The model was used to find welding conditions which result in an appropriate weld. Welding parameters that could be freely chosen are laser power output, welding speed and possibly pre-heating temperature. The welding conditions selected with the model were used for welding, after which the welds were investigated by means of OM, SEM and Micro-Hardness testing. Since making a full penetration weld on rails requires higher power lasers than used during the research, the effect of upscaling was investigated by welding intact rails with a higher power laser. These welds were investigated by means of OM, SEM and Micro-Hardness testing.

- Investigation of the base material revealed the microstructure to be pearlitic. The carbon content could not be determined and was therefore taken from NEN-EN 13674:2011 [2]. Data obtained from dilatometry experiments showed that in order to obtain an acceptable weld microstructure and hardness, cooling rates above 5°C/s should be avoided.

- Preliminary welding resulted in welds with weld metal and HAZ with a martensitic microstructure. The hardness in the weld metal and HAZ (>700HV) exceeds what is acceptable for thermite welds [14].

- Thermal modelling turned out to be successful. Weld dimensions of the model could be fitted to experimental result to within 0.5 mm. Cooling rates of both peak and plateau temperatures in the temperature profile matched to within ~1°C/s. However the plateau temperature is overestimated by the model. The actual temperature is 90°C lower. From the model a welding speed of 4mm/s with 300°C pre-heating and 3 kW laser output was selected.

- The pre-heated welds made with the condition selected from the model have a pearlitic microstructure throughout the weld metal and HAZ. Apart from pearlite, acicular ferrite is present in the weld metal. In the HAZ, prior austenite grains are decorated with ferrite. The acicular ferrite is suspected to be the results of inclusions [28]. Using a shielding gas during welding may reduce the amount of acicular ferrite. In the HAZ of the weld, patches of martensite were observed. It is suspected this is the results of segregation of manganese. A post-weld heat treatment may reduce the detrimental effects of the martensite patches.
• Welding with a higher power 8 kW resulted in problems in terms of welding defects. With higher welding speed the amount of defects reduced. 4 mm/s 300°C pre-heated welds resulted in a similar pearlitic microstructure as observed with 3 kW laser output. The amount of acicular ferrite in the weld metal is less. No ferrite is observed in the HAZ. 6 mm/s 300°C pre-heated welds resulted in a similar pearlitic microstructure. However, the weld metal contains no ferrite. The HAZ contains a martensitic phase, the amount of martensite decreases with increasing distance from the fusion line. The presence of martensite is suspected to be of the same reason as observed in the 3 kW 4mm/s 300°C pre-heated welds, however in the 8 kW sample this is more pronounced.

It can be concluded that laser welding of rail steels can result in an appropriate weld in terms of microstructure and hardness. However further optimisation of welding conditions can still lead to improvements of microstructure and hardness.

5.1 Future Research

The work presented in this thesis is only the start of further research into laser welding for rail steels. This study presented an investigation on the feasibility of laser welding for rail steels. All results presented in this thesis require further optimisation. Therefore recommendations for future research are proposed.

This study mainly focused on the microstructure of laser welded samples. Hardness measurements were merely a means of verifying the nature of observed phases. Further optimisation of welding conditions can improve the mechanical properties of the weld. Hardness can be optimised accordingly.

Only one grade of rail steel (R260Mn) was used during this study. It is not known how other grades of rail steel will perform when laser welding is applied. Therefore it may be necessary to investigate at least one heat-treated rail steel grade.

During this study the focus was mainly put on welding conditions and pre-heating. However post-weld heat treatments may offer another valuable solution for problems encountered after laser welding. Post-weld heat treatments may offer a solution to small amounts of martensite present in the weld and HAZ by tempering the martensite. Tempered martensite is more forgiving in terms of fatigue properties.

The 8 kW laser welding showed that upscaling laser power introduces problems with welding defects, especially solidification cracks and porosity become a problem. If higher penetration depths are demanded for full penetration welding of the rails increasing the laser power may become a problem. Therefore, research into hybrid laser welding may be a solution. Instead flat rail ends an opening angle could be ground on the rail ends. The laser can be focussed at the depth of this opening, while the arc welding fills up the opening gap at the top of the rail. Another advantage of hybrid laser welding is that the hardness of the weld can be further optimised by choosing an appropriate filler wire material.


Appendices

Appendix A

In this Appendix the images of the microstructures shown in the report are put as full page images.

The microstructure of the weld metal of the 3 kW, 2mm/s welded sample.
The microstructure of the weld metal of the 3 kW, 2mm/s welded sample.
The microstructure of the HAZ1 of the 3 kW, 2mm/s welded sample.
The microstructure of the HAZ2 of the 3 kW, 2mm/s welded sample.
The microstructure of the weld metal of the 8 kW, 6mm/s pre-heated welded sample.
The microstructure of the weld metal of the 3 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the weld metal of the 3 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the HAZ of the 3 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the weld metal of the 3 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the weld metal of the 8 kW, 2mm/s welded sample.
The microstructure of the HAZ1 of the 8 kW, 2mm/s welded sample.
The microstructure of the HAZ2 of the 8 kW, 2mm/s welded sample.
The microstructure of the weld metal of the 8 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the weld metal of the 8 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the HAZ1 of the 8 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the HAZ1 of the 8 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the HAZ2 of the 8 kW, 4mm/s RT (left) and 300°C welded samples.
The microstructure of the weld metal of the 8 kW, 6 mm/s pre-heated welded sample.
The microstructure of the weld metal of the 8 kW, 6 mm/s pre-heated welded sample.
Appendix B

In this appendix the hardness profiles of the 3 kW laser welded samples are shown. The measurements were taken from base material to HAZ2, HAZ1, weld metal, HAZ1, HAZ2 and base material.

Hardness profile of the 3 kW, 2 mm/s welded sample.

Hardness profile of the 3 kW, 4 mm/s RT welded sample.

Hardness profile of the 3 kW, 4 mm/s 300°C welded sample.