Additive processes are new opportunities to manufacture directly metallic parts with high technicality. Technologies like Laser Engineering Net Shaping (LENS), Direct Metal Deposition (DMD), Electron Beam Melting (EBM) or Wire Arc Additive Manufacturing (WAAM) can manufacture parts with good mechanical skills. However, Additive processes are currently under improvement. One real benefit of additive manufacturing (AM) is the freedom of design to simplify assemblies (by reducing the number of components). Another benefit is the reduction of material wastage and time to market. Hybrid manufacturing [1]-[2] and functionally graded materials [3]-[4] material are also innovative processes to build parts.

For WAAM, the heat source is a welding generator and the feedstock is a wire. This technology is suitable for manufacturing large scale components. WAAM aluminium alloy is currently limited by solidified defects such as porosity and solidification cracks. Porosity is the major problem of aluminium alloys [5].

The most benefit of WAAM is the ability to manufacture large scale components quickly. Several improvements can be highlighted. The freedom of manufacturing offers the possibility to deposit material with 5axis paths whereas standard AM is limited to 2.5D path. This article aims to show the methodology of manufacturing on single curvature sheet of aluminium alloy.

### 2. STATE OF THE ART

#### 2.1 TYPICAL WAAM SYSTEM

Several researchers have investigated wire arc additive manufacturing [6]. The motion system is often a robotic arm (5-6 axis) which flexibility is adapted to the process requirements and offers great possibilities as tool flexible orientation and large workspace. Three different welding systems are used for WAAM:
- **GMAW**: Gas Metal Arc Welding;
- **GTAW**: Gas Tungsten Arc Welding;
- **PAW**: Plasma Arc Welding.

A multi-process manufacturing platform including WAAM, HSM, and LMD processes implemented in the laboratory is shown on Figure 1. This equipment is adapted for hybrid manufacturing (Additive and Subtractive).

#### 2.2 SYSTEMS IMPROVING BEAD QUALITY

Several systems or technologies can be added to WAAM process to improve bead quality, the manufacturing conditions or the microstructure of the bead. For example, technologies developed for welding as Cold Metal Transfer, which is an improved GMAW welding process, can improve deposit by reducing the heat impact. This aims to reduce the heat brought to the deposit. The basic CMT consists on moving forward and backward the wire during welding (Figure 2).

Several improvements were developed based on CMT process:
- **CMT Pulse**: This process combines a pulsed cycle with a CMT cycle and so inputs more heat. The pulses are controlled and adjustable way results in a huge breadth of performance and flexibility.
- **CMT Advanced**: This process is cooler than CMT. In fact, the polarity of the welding current is made an integral part of the process-control. The polarity reversal takes place in the short-circuit phase, thereby ensuring the proven stability of the CMT process. The thermal input is tightly controlled, extremely high gap bridge-ability and an up to 60% bigger deposition rate.
- **CMT Advanced Pulse**: By combining negatively poled CMT cycles and positively poled pulsing cycles, this process achieves absolute precision and the very greatest mastery of the arc.

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To improve microstructure, a rolling system can be implemented to generate a stress on the deposit after welding. Different rolling loads can be applied up to 80kN for example. The load can also be controlled. A solution is to combine rolling and manufacturing on the same machine. Microstructure is really improved by this operation. In fact, the microstructure is refined and reduces residual stresses [8]. However, this solution is limited to simple parts because the roller is generally profiled and not adapted for large sections, others solution could be used in this case.

Protection can also be improved with a local shielding gas. This solution consists on injecting a laminar flow of shielding gas after the welding. The deposit is protected during cooling period and the oxidation effect is reduced. The gas flow rate is generally set to 10 l/min. The laminar shielding device significantly improved the protection compared to conventional protection by reducing the oxygen contamination levels [6]. Once again, this system is interesting to improve microstructure but it is limited to simple paths. The shielding, to be efficient, must follow the path. For filling or high curvature paths, this equipment will not protect the bead as single wall bead.

2.3 PATH STRATEGY

To manufacturing a single wall, the path is quite easy to generate but for massive components, path strategies must be adapted for filling without lack of material which will reduce the part strength. Several strategies can improve the part filling [6].

For filling paths, a new parameter appears, called Center distance [7]. To set these parameters, several models have been developed. The optimal distance calculated between two beads is about 0.738w (w is the bead width).

Depending on the shape of the part, it is sometimes necessary to add material to do a homogeneous filling. The second goal of path strategy optimization is also to smooth the path and reduce the number of start/stop of welding. Several approaches have been developed to generate specific paths to WAAM [8].

2.4 STATE OF THE ART / SYNTHESIS

WAAM related research can be divided into two categories, currently investigated. The first one aims to improve microstructure, bead quality and ensure good mechanical skills by highlighting the influence of parameters and systems added on WAAM process. However, by adding these systems, the freedom of fabrication is reduced and presented samples are often single bead walls. The second deals with path strategy. The goal is to include process requirement in the path generation and select the best path strategy to ensure the filling.

Test parts are often limited to 2.5D paths on planar sheet. That is why, it may be valuable to explore more complex parts including 5 axis paths and non-planar substrate. The goal is to demonstrate WAAM benefits to simplify assembly by reducing the number of components and add structure directly on arch sheets.

3. PROPOSED METHODOLOGY TO MANUFACTURE WAAM PARTS ON CURVED SHEET

3.1 METHODOLOGY

Manufacturing on curved substrates is quite different than planar. Hence, it is necessary to measure the geometry before deposition. This stage is performed using the motion system. Several points are saved to calculate the real radius of the sheet and begin the modelling.

The next stage consists in slicing. The stiffener geometry is sliced by curved sections into curves. The distance between sections is set by the layer height (Figure 3) (LH) to keep the stick out distance (distance between the contact tube and the deposit area) constant. This parameter is essential to maintain good and constant deposit conditions.

Figure 1: WAAM system and GMAW torch.

Figure 2: CMT process stages.

Figure 3: Slicing parameters for path generation.
The layer height is set to 1.8 mm for all types of walls (vertical and horizontal). The path is post-processed with a specific algorithm developed in the laboratory for three or five axis manufacturing. To validate the paths, the robot movements are simulated to generate a tool path trajectory, including tool axis rotation. Figure 4 summarizes these stages including clamping and sheet measurement.

### 3.3 SYNTHESIS

Several issues appear with non-planar substrate. In fact, it is necessary to know the shape of the substrate before manufacturing. Clamping system must also be adapted to the sheet and not distort it. Adjustable clamps are a solution to work with different geometries.

### 4 EXPERIMENTS

#### 4.1 MANUFACTURING ON PLANE SHEET

A first experiment has been performed on a planar sheet to validate manufacturing of stiffeners. (Figure 5).

The goal is to manufacture two stiffeners on a 500 x 500 mm curved sheet (indicated radius 500 mm). The structure geometry is shown on Figure 6. The sheet measurement consists in acquiring nine points on the clamped sheet. The clamped system is composed of four linear contacts (around 80 mm each) on each corner. The altitude of the clamped is adjustable: No load is applied on the sheet not to generate deformation before manufacturing. The goal of this system is to prevent the sheet deformation by heating the surface of the sheet. The average radius calculated is 521 mm.

To improve the mechanical link on the first layer, the welding surface was mechanically prepared. The travel speed was also reduced to increase the heat impact only on the first bead. For the rest of the walls, the travel speed was set to 800 mm/min. The tool orientation was perpendicular to the sheet curvature to keep the torch angle at 0°. Each wall was manufactured by zigzag strategy. To manufacture horizontal walls, the torch angle is set at 20° (Figure 8).

#### 4.2 MANUFACTURING ON CURVED SHEET

This structure is composed of a central wall and two horizontal walls. The horizontal walls are similar to cornice welding. However, this experiment shows that it is not necessary to reduce the WFS. Welding parameters and travel speed are kept constant for the whole of the part.

The part is exposed on Figure 9.
6. CONCLUSION

In this paper, a methodology was proposed to manufacture stiffeners with WAAM process on curved sheet. The interest of five axis tool path has been demonstrated to increase the accuracy of the part produced and curved sheet.

WAAM requires to combine welding and motion parameters to build components with the most constant conditions as possible. That is why, slicing parameters must be set correctly to ensure good manufacturing conditions. Manufacturing on curved sheet requires to know correctly the substrate geometry to ensure correct deposit conditions. Clamping systems are also complex to do?

7. ACKNOWLEDGEMENTS

The authors would like thank the partners of this DGA/DGAC funded research project: Stelia Aerospace, CT Ingenierie, Constellium and Ecole Centrale de Nantes (ECN). The goal of this project is to develop AM processes for aerospace structural components.

8. REFERENCES


ABSTRACT

Additive Manufacturing (AM) for metal part can be divided in to different types: The powder technology and the wire technology. Usually, powder is adapted for high precision component whereas wire is used for structural components and large scale part. One of the main benefits of AM is to simplify assemblies by reducing the number of components and also to provide a large freedom of design.

A standard AM system consists of a combination of three blocs: a motion system, a heat source and a feedstock. For Wire Arc Additive Manufacturing (WAAM), the heat source is a welding generator and the feedstock is a wire. The motion system could be a 6 axis robot or a CNC machine.

The welding process used in this paper is Cold Metal Transfer (CMT). The welding torch is fixed on a 6 axis robot. In contrast with usual AM which is generally limited to planar substrates, the goal of this paper is to manufacture structural stiffeners on curved aluminium alloy sheets. These stiffeners are made of walls welded on a substrate having a simple curvature. Before the manufacturing process, the first issue is the curvature measurement of the sheet which is a major problem to deal with. The second issue consists of AM paths generation. These are different from a classic AM paths, which are 2D. Hence, the layer is a 3D path, depending on the sheet curvature. The third issue is the sheet metal fixation on the manufacturing table: the shape of the sheet must not move and the fixation must not distort the sheet. The final issue is the manufacturing process itself: the heat creates residual stresses and thermal deformation during the deposition.

Finally, to improve the mechanical link between the walls and the metal sheet, the strategy on the first layers is different than the rest of the wall. Different welding modes are selected to improve the size of the melted area and the link with the substrate. To quantify the effect of manufacturing strategy, the strength of the different wall is measured by using a tensile machine.

Keywords: Wire Arc Additive Manufacturing, Cold Metal Transfer, Aluminium alloy, 5 axis manufacturing.
**In-situ Gauge Corner Restoration of Tramway Track Made of the Wear Resistant and Weld Restorable ML330 Steel**

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### 1. Context

**1.1 Context**

Tramway networks are characterized by tight track radii curves in which the rails are subjected to very high curving forces that result in high rates of side and vertical wear that are the key factors dictating the lifespan of the tracks. The cost of rail in embedded track accounts for ~12% of total installed costs and hence enhancing rail life improve the life cycle cost of the track by reducing the requirement for frequent track renewals. This is not only financially rewarding but also reduces the inconvenience for the customer caused by the service disruption during track renewal.

Thus a first requirement of a rail steel grade for tramways is its wear resistance. However, the arduous contact conditions in the very tight radii curves coupled with high number of axle passes result in the unavoidable side wear of the gauge face of the rails and hence to the need to weld-restore them to re-build the head profile. Hence a second requirement of a rail steel is its ability to be weld restored in-situ.

Generally, the restoration is carried out in-situ at night under a wide range of meteorological conditions (temperature, hygrometry, wind…). Although manual metal work welding can be undertaken to restore worn rails, use of submerged arc welding is far more productive and cost effective as it permits the gauge corner restoration process (GCR) to be automated and allows the works to be carried out in-situ. GCR is achieved by depositing austenitic stainless steel beads on the worn corner of the rail, after pre-grinding to prepare the surface and make it free of rust. The complete restoration route including the pre-grinding, the bead deposition and the final grinding giving the rail its initial profile, is performed with the use of a specific automatic welding machine.

British Steel developed ML330 [1] a high strength pearlitic steel grade containing about 0.78% of carbon and 1.25% of manganese, having a unique combination of wear properties and weld restorability, for use in curves where combating the rate of wear is critically important to realizing longer rail life.

In a traditional weld restoration process, a rail made of high carbon equivalent steel like ML330 would require to be pre-heated up to 350°C in order to avoid the formation of hard and brittle martensite, susceptible to hydrogen cracking, in the heat affected zones when cooling down to room temperature. Such a process is not practical for tramway tracks because high preheating temperatures will damage the surrounding polymers in which the rails are embedded. Moreover, due to dilution effect and the use of a stainless steel as filling material, according to Schaeffler diagram, the weld can also be sensitive to hot cracking.

ML330 steel composition was specially tailored in order to meet both the wear resistance and the weld restorability requirements. The objective of the article is to describe and validate the restoration procedure [2] implemented for ML330 steel grade and to show how this steel was designed in order...
to improve its weldability while ensuring a great hardness. The following part is dedicated to the ML330 steel grade and specially the metallurgical background supporting its weldability. In this part, the characteristics of the steel grade is presented in regard with welding defects like cold cracking or heat affected zone brittleness. The third part is devoted to the restoration route implementation and characterization. In this part, the specific features of the restoration route are pointed out and linked to the weldability of the material and the restoration conditions requirements.

2. THE CONSTITUTIVE MATERIAL OF THE GROOVED RAIL AND ITS WELDABILITY

ML330 is a pearlitic eutectoid steel which chemical composition is given in table 1. The high carbon content gives the rail a high hardness in as-rolled conditions. Compared to the standard R260G grade, additions of Si and V provide further hardening of the perlitic ferrite through solid solution and carbide precipitation, and hence a superior wear resistance. Due to the high carbon and alloying element content, ML330 steel grade is susceptible to cold cracking during a welding process. This defect is associated with the formation of high carbon martensite in the heat affected zone during the cooling down. A large amount of martensite formed can make the HAZ brittle. The restoration is performed by Submerge Arc Welding process with austenitic stainless steel as filler material. Due to dilution between the base steel and the filler material in the weld pool, and according to the Schaeffler diagram, the weld bead is subjected to hot cracking.

2.1 COLD CRACKING

Cold cracking is driven by three factors: internal stresses, martensite and hydrogen. Internal stresses are due to both the heterogeneous distribution of the temperature during welding and the thermal expansion and stretching of the material. The internal stresses arise at quite low temperature, at the end of the cooling down of the weld. At high temperatures, the flow stress of the heated zones (HAZ and molten zone) is low, allowing a plastic accommodation of the thermal deformation. During cooling, to the thermal stretching of the material should be added the volume expansion or stretching associated with the phase transformation. In the case of high carbon steel, the volume expansion induced by the martensite transformation compensates the thermal stretching of the material. Martensite is formed during cooling starting at Ms and finishing at Mf. The martensite content of the HAZ depends on the metallurgical sensitivity of the steel grade and on the cooling rate. In other words, the minimum cooling time that could be applied avoiding the formation of martensite depends mainly on the chemical content of the steel. Hydrogen is generated by the ionization of the water within the arc. It diffuses from the weld pool into the austenite HAZ at high temperature. The solubility and diffusion rate of hydrogen in austenite are very different than that in ferrite or martensite (see figure 1). During cooling, depending on the metallurgical phases of the HAZ and the molten zone, the potential excess of hydrogen can be entrapped within the HAZ or the molten zone close to the transition zone. The excess of hydrogen accumulates at the grain boundary where it applies pressure. According to figure 1, it is clear that retained austenite in the HAZ, acting as a hydrogen sink, will be beneficial to reduce the risk of cold cracking. The combination of the internal stress and the additional pressure due to hydrogen applied on the brittle martensitic structure of the HAZ can lead to cold cracking. Many solutions can be implemented in order to avoid cold cracking. One of them consists in decreasing the cooling rate in order to enable the formation of perlite and hence to avoid a too large amount of martensite in the HAZ. In order to do that, a minimum nominal energy coupled with a pre-heating of the parts can be carried out. For ML330, this solution would require preheating temperatures above 350°C. Another solution consists in post heating the welded parts. The post heating prevent the welded parts from cooling down to room temperature, thus moderating the internal stress level within the weld. The post-heating temperature is maintained during a dwell-time sufficiently long to allow the hydrogen to diffuse out of the HAZ. The complete cooling is then performed slowly in order to generate temperature gradient as low as possible preventing internal stress from rising. In the case of the ML330 steel grade, Mₘ and Mₜ are low, and hence a limited pre heating temperature is efficient for controlling and limiting the martensite transformation. The martensite transformation induced volume expansion reduces the internal stress. The composition of the ML330 grade has been specifically tailored to lower the Mₘ to below 175°C and Mₜ to close to ambient. The consequences of this are:
• a low pre-heating temperature (below the maximum temperature admissible by the polymer embedding the rail) is able to interrupt the martensite transformation, enable about 50% retained austenite in the HAZ to be kept, thereby providing benefits of enhanced toughness and a hydrogen sink, and then being able to transform into perlite;
• when the cooling continues, thermal stretching is compensated by the volume expansion associated with the martensite formation. Thus, the level of internal stress can be drastically reduced.

Typical values of Mₘ and Mₜ are given in table 2 for the main grooved rails steel grades (according to the BS EN14811 rail standard). The table provides also the expected retained austenite content at 80°C for each grade. Thanks to the low value of Mₘ, a post heating treatment can be applied at a temperature above Mₜ, a dwell time of about 2 minutes at this temperature.

Table 1: Chemical composition of the ML330 steel grade.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>V</th>
<th>Cr</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>N</th>
<th>H</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>%max</td>
<td>0.85</td>
<td>1.4</td>
<td>1</td>
<td>0.15</td>
<td>0.1</td>
<td>0.03</td>
<td>0.025</td>
<td>0.01</td>
<td>0.008</td>
<td>2.5ppm</td>
<td>20ppm</td>
</tr>
<tr>
<td>%min</td>
<td>0.7</td>
<td>1.1</td>
<td>0.65</td>
<td>0.07</td>
<td>0.008</td>
<td>0.025</td>
<td>0.01</td>
<td>0.008</td>
<td>2.5ppm</td>
<td>20ppm</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Diffusion and solubility of hydrogen within ferrite and austenite according to temperature.
leading, after cooling, to a bainitic structure without any martensite. The TTT diagram of the ML330 of Figure 2 was simulated with the software FORGE. NxT® on the base of the chemical composition of the steel and an initial grain size of 1, this last one corresponding to the grain size in the HAZ at the beginning of its cooling down. According to this diagram, a dwell time of 90s at 550°C allows the avoidance of martensite formation and promotes a pearlitic structure.

2.2 HOT CRACKING

The high carbon and manganese content of the steel and the austenitic nature of the filler material can lead, according to Schaeffler diagram, to hot cracking. 
Usual solution to avoid hot cracking consists in choosing the filler material and controlling the dilution rate between the filler material and the base metal. Control of the dilution rate can be achieved through the process parameters and in the case of SAW process the polarity of the arc. Hot control sensitivity can be reduced also by limiting both the weld pool size and the solidification velocity. The weld pool size control allows avoiding high segregation during solidification and a moderate solidification velocity avoids the formation of a grain structure favoring segregation. Lastly, hot cracking can be avoided by the use of basic flux with SAW or Covered Electrode Arc Welding.

For the grooved rail restoration, a 307 austenitic stainless steel grade is deposited by SAW using a basic flux. The dilution rate of the first pass is often higher than that of the following ones. In such case, it is possible to use for the first pass a stainless steel with a higher amount of Chromium or Molybdenum in order to decrease the hot cracking sensitivity of the first pass and to enlarge the range of dilution rate leading to a sound well bead. In the case of the automatized restoration of the tramway rail, it is not convenient and productive enough to change the filler material between the first and the following passes.

2.3 BRITTLENESS OF THE HAZ

Because of the high carbon content of the ML330 steel grade, the martensite formed in the HAZ has to be tempered in order to improve the brittleness of the weld. The successive beads are stacked in such a way that the HAZ of a bead will be tempered by the subsequent layers. A last sacrificial bead that will be completely removed by the final grinding of the rail profile is deposited at the end, enabling to achieve full tempered HAZ.

3. RESTORATION OPERATING PROCEDURE AND APPLICATIONS

On the figure 3, one can see a cross section of the grooved rail. The worn zone of the rail is located vertically on the right side of the groove. The restoration route first consists in a grinding of the worn surface to make it free of rust. The ground surface dimension corresponds to a rectangle of about 7 mm wide and 20 mm high.

Table 2: Typical Ms and Mf values for the main grooved rail grades.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C (%)</th>
<th>Mn (%)</th>
<th>Si (%)</th>
<th>Ms °C</th>
<th>Mf °C</th>
<th>% Ret. γ at 80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>R200</td>
<td>0.40 - 0.60</td>
<td>0.70 - 1.20</td>
<td>0.15 - 0.58</td>
<td>300</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>R260</td>
<td>0.62 - 0.80</td>
<td>0.70 - 1.20</td>
<td>0.15 - 0.58</td>
<td>200</td>
<td>50</td>
<td>38</td>
</tr>
<tr>
<td>ML330</td>
<td>0.70 - 0.78</td>
<td>1.00 - 1.30</td>
<td>0.65 - 0.90</td>
<td>170</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 2: TTT diagram of the ML330 steel grade obtained by simulation with FORGE.NxT software.

Figure 3: Cross section of the grooved rail and the main dimensions of the restoration zone.

After grinding, the rail is pre-heated by propane or acetylene burners. The pre-heating temperature is limited to the range of 110°C - 130°C to ensure the rail head will be perfectly dry while avoiding any damage of the polymer embedding the rail. During welding works, the minimum rail head interpass temperature shall not be lower than 80°C. According to the chemistry of ML330, this temperature between Ms and Mf keeps about 50% of retained austenite.

The restoration zone is made of 6 to 8 stacked beads. The 8th bead is a sacrificial layer which function is to temper the HAZ of the 7th pass. The sacrificial layer is completely removed during the final grinding to profile of the rail. Figure 4 illustrates the overall distribution of the passes constituting the restored area. Stack gaps at the beginning and the end of the restoration beads are implemented in order to prevent the weld pool from collapsing, to avoid the accumulation of internal stresses at the bead root.
and to achieve full tempering of the HAZ of the preceding layer.
A first test was carried out under in-situ (outdoor) conditions. The process parameters used for these trials are gathered in table 3.

Table 3: Welding parameters.

<table>
<thead>
<tr>
<th>Welding parameters</th>
<th>First passes</th>
<th>Sacrificial passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire feed speed</td>
<td>2.3m/min</td>
<td>2.3m/min</td>
</tr>
<tr>
<td>Voltage</td>
<td>29V</td>
<td>29V</td>
</tr>
<tr>
<td>Welding speed</td>
<td>60cm/min</td>
<td>72cm/min</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>3.2mm</td>
<td>3.2mm</td>
</tr>
</tbody>
</table>

Figure 5: Structure and hardness along the core of the rail.

The restoration is characterized by analyzing the cross section of the restored zone at different position along the rail. The characterization consists in observing the presence or not of cold cracks within the HAZ and in the molten zone and the presence or not of hot cracks in the molten zone. Hardness measurements are also performed from the molten zone to the base metal in order to check if un-tempered martensite areas can be found in the HAZ.

The results of this first trial are the following. First, along the core of the rail, no hot or cold cracks are observed in the analyzed cross section. Hardness measurements show that the hardness is quite higher in the HAZ than in the base metal. Nevertheless, as shown in figure 6, the microstructure of the HAZ is made of pearlite-bainite (HAZ of the first pass in figure 6.a) or tempered martensite (HAZ of the last passes in the figure 6.b).

Figure 7 shows the results obtained in the strike-off zone. On this figure one can observe a cold crack that occurred along the HAZ of the first pass. The corresponding hardness and structure (see figure 8) show that the HAZ of this zone is made of not tempered martensite. The same results can be observed at the strike-on.

At strike-on and strike-off, the thermal cycle is more severe than in the core of the rail. This difference is due to the heat diffusion int the part of the rail situated before (strike-on) and after (strike-off) the restored part of the rail. Moreover, in the core of the rail, the cooling of the welded zone is moderated by a pre-heating performed during the process is approaching and by a post-heating achieved by the process while it is moving away.

In order to take into account these particular thermal characteristics of the strike-on and the strike-off, two items were added to the restoration route:
- the pre-heating zone is extended including 1 m of rail before and after the restored zone (see figure 4) ;
- the strike-on and strike-off zones are post-heated locally.

Figure 6: Microstructure of the HAZ of the restored zone along the core of the rail, a. In the HAZ of the last passes, b. in the HAZ of the first pass.

Figure 7: Cold cracking in the strike-off zone.

Figure 8: Microstructure and hardness in the HAZ at Strike-On and Strike-Off.
The post-heating of the extremities of the restored zones is carried out at a temperature of 450 °C +/- 150 °C during 120s. According to the Time Temperature Transformation diagram of ML330 available in Figure 1, at 550 °C, a dwell time of 90s is long enough to avoid the formation of martensite and to form pearlite. By applying the post-heating locally, the post-heating temperature is maintained at strike-on and strike-off, while the temperature at the contact surface between the polymer and the rail is maintained under its critical value of 190 °C. The post-heating at each extremity should be applied immediately after the strike-on and strike-off without waiting for the complete achievement of the pass.

On Figure 8, one can see the effect of the post-heating operation on the hardness measured in the HAZ of the strike-on zone. The obtained hardness in the HAZ along the pass at strike-on corresponds to the base metal hardness indicating that there is no formation of martensite and proving the efficiency of the post-heating.

The HAZ microstructure observed at strike-off and strike-on (see figure 10), being made of bainite and tempered martensite, confirms the efficiency of the local post-heating in avoiding the formation of a complete brittle martensitic structure.

For the test, post-heating is applied manually by acetylene blowpipes. This operating procedure doesn’t allow an accurate control of the temperature within the rail that should be at the aimed post-heating temperature in the vicinity of the strike-on and strike-off zones and under the critical temperature at contact with the polymer. In order to better control the post-heating, a special device shown in figure 7 based on infrared heating was developed by ARR Rail Solutions Ltd under a project supported by the UK government through UKTram, a tramway network body, and in partnership with British Steel.

The above attributes provide to the high carbon and high hardness rail a total weld-ability and therefore the guarantee of the integrity and consistency of repair layers. This unique combination of properties offered by British Steel ML330 high performance grooved rail solves the industry problem of both vertical and side wear in a single rail product to maximize serviceable life.

4. CONCLUSIONS

British Steel developed ML330 a high strength pearlitic steel grade containing about 0.78% of carbon and 1.25% of manganese, having improved wear properties in as-rolled condition, for the grooved rail used in curves. ML330 rails can be welded restored following a specific procedure including low temperature pre-heating of the rail and post-heating of the strike-on and strike-off zones. The chemical composition of the ML330 was tailored so that Ms is below 175 °C and Mf is close to ambient. These unique attributes eliminate the risk of cold cracking of the weld HAZ even with a pre-heating temperature of about 110°C, thus preserving the polymer embedding the rail. However, the pre-heating is not efficient enough to prevent cold cracking at the strike-on and strike-off positions. Hence, one needs to apply either a local post-heating of the strike-on and strike-off positions of each bead at a temperature above Ms with a dwell time of 90s at 450 °C leading to a HAZ free of martensite, or to use bespoke infrared heaters to control the thermal flow of the ends of the rail.

The above attributes provide to the high carbon and high hardness rail a total weld-ability and therefore the guarantee of the integrity and consistency of repair layers. This unique combination of properties offered by British Steel ML330 high performance grooved rail solves the industry problem of both vertical and side wear in a single rail product to maximize serviceable life.

5. REFERENCES