1. INTRODUCTION

Continuous welded rail is standard practice on heavy haul railroads. Today's standard axle loads in excess of 30 tonnes would not be possible on classical jointed track. But such high axle loads also pose a great challenge for welded joints, as widely reported at previous Heavy Haul Congresses.

A new mobile flash-butt welding process using a welding robot is an important development specifically for the needs of heavy haul traffic, offering a fully automatic and reproducible welding process, excluding any human errors. The power supply is DC instead of AC current which greatly helps to raise the welding quality.

2. FOUR DECADES OF MOBILE FLASH WELDING

Few developments have influenced the cost-efficiency of railway track technology as much as the introduction of long rails and in particular continuous welded track. As essential procedures for the welding of the rails, flash butt welding and aluminothermic welding very soon became established as standard processes. At first, electric flash butt welding was only possible in stationary plants and the aluminothermic procedure was reserved for mobile welding. In view of the outstanding quality of flash-butt welding the call came very early on, to be able to use this on track worksites too.

Electric resistance welding of rails has been applied on the railways since around 1930. From the sixties the Paton Institute in the Ukraine was involved in the development of a mobile flash-butt welding unit and the first machines became available around 1965. Early in 1970 Plasser & Theurer became acquainted with this development and built the first K 355 PT machine in 1973. Austrian Federal Railways (ÖBB) [1] was the first railway to put it into operation. From 1974 the new technique was used regularly by the ÖBB in the course of the production of continuous welded railway tracks.

The technology was further developed, major steps were:

- To integrate the trimming unit into the welding head. Trimming knives shaped like the rail profile cut off the surplus material so that a protuberance of less than 1 mm is left behind.
- Change the dimensions of the welding head so that the trailing edge of the rail foot is lower than the bottom of the jaws. Rails lying in the track no longer have to be lifted so that the welding head can grip.
- Control of the operation by a microprocessor which minimises operating errors.
- Introduction of a computer-controlled recording and analysing system. The program is designed to display, record and analyse the welding process. It displays the welding current, the force applied and the stroke and gives exact information if the weld was performed within the programmed parameters.
- Integration of an automatic high capacity rail pulling device into the mobile welding machine. Closure welds on long welded rails can be performed below the neutral rail temperature. This superstretch unit clamps the rails with jaws at the rail head and aligns the rail ends hydraulically.
Then the rails are stretched by pulling to the calculated extent. Now the welding head is lowered and the rails are welded. By automatic, synchronous operation of welding head and puller, the welding can be done in this tensioned state.

Today welding machines are built in different designs by a number of suppliers according to the operating requirements. There are

- fully rail-mounted machines,
- road-rail machines based on a commercial truck or an earth-moving machine,
- container design – housing all components in a container of standard dimensions,
- self-loading machines, and
- machines with an additional rail stretcher.

Plaser & Theurer developed the APT 500 series (figure 1 and 2) and the APT 600 with an integrated rail puller (figure 5).

2.1. Application on heavy haul railways in North America

The demands on the welded joints of heavy haul railways are particularly high. From August 1988 the test centre of the AAR in Pueblo, Colorado (today TTCI), tested the effects of the increase of the axle loads from 33 to 39 US tons (29.4 to 34.7 metric tons). The results were presented in a Workshop held by the International Heavy Haul Association from 14th to 17th October 1990 in Pueblo, Colorado[2].

In one 5° curve (radius = 349 m) and one 6° curve (radius = 291 m), welded joints that had been produced using different welding methods were subjected to fatigue loading tests. The results in brief:

![Figure 1: Welding head API 560, based on the Paton welding head](image1)

![Figure 2: Welding process of in-track welding machine API 500](image2)

![Figure 3: Mobile flash-butt welder with integrated rail pulling and stretching unit, APT 600](image3)

**Aluminothermic welding**

<table>
<thead>
<tr>
<th>Axle Load</th>
<th>Traffic load</th>
<th>Outside rail</th>
<th>Inside rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>33 t</td>
<td>65 Mio tons</td>
<td>29%</td>
<td>0%</td>
</tr>
<tr>
<td>39 t</td>
<td>66 Mio tons</td>
<td>67%</td>
<td>13%</td>
</tr>
<tr>
<td>39 t</td>
<td>82 Mio tons</td>
<td>83% in 5° curve, 92% in 6° curve</td>
<td></td>
</tr>
<tr>
<td>29 t</td>
<td>144 Mio tons</td>
<td></td>
<td>75%</td>
</tr>
</tbody>
</table>

Table 1: Failure rates of aluminothermic welding
**Mobile flash butt welding**

Due to the small number of welds (welding head K 355 A) no statistical statements could be made, however clear trends were detectable:

- With standard head hardened rails (induction hardening), the failure rate on the outside rails with the mobile welding method was slightly higher than with stationary welding.
- The failure rate of the inside rail welds was virtually identical to the stationary welds.
- Head hardened outside rails showed double the failure rate without air quenching.
- Air quenching of the inside rail does not show any advantage.

The superior strength of the flash butt welds and the satisfactory results of the mobile electrical welding resulted in the implementation of mobile flash butt welding as standard on the main lines of the American heavy haul railways. For example up to now Plasse & Theurer has supplied twelve mobile welding machines to North American railroads.

**2.2. Worldwide application of mobile flash-butt welding**

For high capacity railways with high speed or heavy haul operation the quality and reliability of welds is a crucial feature. Therefore flash-butt welding nowadays is the preferred method of rail welding on such railways. The majority of production field welds is done with mobile flash-butt welding machines, but also for closure welds on continuous welded tracks and for repair welds there is a growing demand for mobile flash-butt welding.

With the increase of speeds and axle loads also the quality demands on welds are rising. Acceptance standards have become more stringent and some can hardly be met by the units available today.

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**Table 2: Failure rates of stationary flash butt welding**

<table>
<thead>
<tr>
<th>Axle Load</th>
<th>Traffic Load</th>
<th>Curvature</th>
<th>Outside Rail Failure Rate</th>
<th>Inside Rail Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>33 t</td>
<td>160 Mio tons</td>
<td>5°</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>33 t</td>
<td>160 Mio tons</td>
<td>6°</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>39 t</td>
<td>145 Mio tons</td>
<td>5°</td>
<td>5%</td>
<td>9%</td>
</tr>
<tr>
<td>39 t</td>
<td>145 Mio tons</td>
<td>6°</td>
<td>2%</td>
<td>4%</td>
</tr>
</tbody>
</table>

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**3. BACKGROUND FOR THE DEVELOPMENT OF A NEW WELDING ROBOT**

The new European welding standard EN14587-2 is significant for the increased demands on mobile flash-butt welding. Therefore, based on the experience and knowledge of the last four decades, Plasse & Theurer started to develop a genuine automatic welding robot. The aim was not only to meet the new requirements but also to set new standards in welding quality and to make the performance of closure welds an integrated capability of the machine.

**3.1. European welding standard EN 14587-2**

This standard, which came into force in 2009, specifies the requirements for the approval of a flash-butt welding technique "by mobile welding machines at sites other than a fixed plant". Apart from greater accuracy of the geometry after the welding as well as higher breaking strength and fatigue strength, the conditions for the welding sequence are also specified. For example the clamping devices that are used to hold the rails firm: they should not cause any damage that might subsequently lead to the formation of cracks in the rail. During the welding process it is not permitted to interrupt the burn-off once the process has begun and upsetting must be performed immediately with the sufficient upset force. The excess upset must be trimmed automatically and the weld must be in compression during removal of the excess upset.

All welds must be carried out according to programmed and automatic sequences. The welding parameters are determined by means of welding tests and should not be altered once approval has been given.

Table 3 shows the maximum permitted offset of the rail ends after welding:

The permitted tolerance of the weld bead after trimming is shown in table 4:

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**Table 3: Offset tolerance**

<table>
<thead>
<tr>
<th>Position of the offset</th>
<th>Maximum permitted offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically in the centreline of the running surface</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Horizontal at the aligned head side or the running edge, measured 14 mm below rail surface</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Horizontal at both edges of rail foot</td>
<td>2.0 mm</td>
</tr>
</tbody>
</table>
### Table 4: Tolerance of weld bead after trimming

<table>
<thead>
<tr>
<th>Zone</th>
<th>Position of bead</th>
<th>Maximum bead permitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Whole bead profile, from lower edge of the head on the running edge side to the lower edge on the opposite side</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>1+</td>
<td>Treated surface at the underside of the head</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>2</td>
<td>Web, from the upper transition radius down to start of the lower transition radius</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>3</td>
<td>Rail foot, including the outside radii from web to rail foot edge and the whole underside of the rail foot.</td>
<td>2.0 mm</td>
</tr>
</tbody>
</table>

Every new welding process has to be certified. The approval tests have to be carried out on weld samples of rail type (profile) 60E1 or 60E2 and steel quality R260. The samples have to be tested by a certified body. The main test phases are:

- Visual check
- Trimming and examination of weld bead
- Offset of rail ends
- Magnetic particle test or dye penetrant test
- Bending test
- Macro examination
- Micro examination
- Hardness test $P_{-30HV30, +60HV30}$ $P$ = average measured hardness of the rail before welding
- Fatigue strength test

Table 5 shows the limits of deviations in weld geometry at ambient temperature.

The evenness of the weld has to be measured with a steel ruler of one meter length; the weld has to be positioned in the centre of the ruler. The horizontal evenness refers to a position 14mm below rail surface. The class which has to be applied is to be defined by the infrastructure operator. Typically class 1 and class 2 are required. Because of the wheel-rail interaction, negative values should be avoided.

Table 6 shows the demands of the bending test:

#### 4. THE NEW WELDING ROBOT

The increased quality requirements to be met by a mobile flash-butt welding process demanded further development of the existing welding process. Plasser & Theurer took this opportunity to re-engineer the flash-butt welding process from scratch. The result of this development is the APT 1500 R welding robot (figure 4).

#### 4.1. The welding process

An important advance is that the process of aligning the rails has been included in the automatic work sequence. In practical operation this means that the welding robot only has to be lowered onto the welding area. Then the fully automatic work process begins, starting with the height alignment of the rails. To do this, the auxiliary clamps raise the rails to the highest points which immediately achieves

### Table 5: Geometrical tolerances in mm

<table>
<thead>
<tr>
<th>Alignment of weld</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
<th>Class 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically at the running surface</td>
<td>+0.3</td>
<td>+0.4</td>
<td>+0.3</td>
<td>+0.3</td>
<td>+0.2</td>
</tr>
<tr>
<td>Grindinly at the running surface</td>
<td>-0.1</td>
<td>0</td>
<td>-0.2</td>
<td>-0.15</td>
<td>-0.1</td>
</tr>
<tr>
<td>Horizontally at rail head</td>
<td>+0.3</td>
<td>± 0.4</td>
<td>± 0.5</td>
<td>± 0.5</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Grindinly at rail head</td>
<td>0</td>
<td>± 0.4</td>
<td>± 0.5</td>
<td>± 0.5</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Evenness of running surface measured over the grinding length</td>
<td>0.15</td>
<td>0.20</td>
<td>0.20</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 6: Minimum demands on bending strength for common rail profiles

<table>
<thead>
<tr>
<th>Rail profile</th>
<th>Minimum bending [mm]</th>
<th>Minimum bending force for acceptance and production [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel qualities R220, R260, R260Mn and R350HT</td>
<td>Steel quality R220</td>
</tr>
<tr>
<td>60E1 and 60E2</td>
<td>20</td>
<td>1500</td>
</tr>
<tr>
<td>54E1</td>
<td>30</td>
<td>950</td>
</tr>
<tr>
<td>54E2</td>
<td>25</td>
<td>1170</td>
</tr>
<tr>
<td>49E1</td>
<td>30</td>
<td>1250</td>
</tr>
</tbody>
</table>
the required slight upward inclination. The clamping jaws hold both rails firm. Four distance transducers measure the exact alignment of the top of the rail. After selecting the running edge, there is an accurate lateral alignment. The automatic aligning process is now completed.

After applying the current-carrying clamps, the welding process commences with the unstable phase. Any impurities are burned out of the rail cross-sections. This is followed by the stable phase with a continuous input of current for a uniform burn-off. After this within the progressive phase there is an increase of current to burn out impurities such as air inclusions or material defects. After completion of the progressive phase the upset stroke is performed immediately and directly afterwards the excess upset is trimmed off. During trimming the weld is in compression as defined in the standard, moreover all clamping jaws remain closed and they additionally support the rail as it cools. Pressure measurements in the two pulling cylinders have also shown that the trimming process has a negligible effect on the forces applied. Afterwards, the current-carrying clamps and the clamping jaws are opened and the welding robot can be raised. A welding report is compiled automatically by the software from the parameters continually recorded during the welding (fig. 5).

The software was written by EN 50128-certified programmers. Identification data are entered for every weld such as line kilometre; GPS coordinates of the position of the weld, machine operator, date, etc. The welding graphs (current intensity, advancing speed and force versus time) are stored.

4.2. Current supply

Another special feature of the newly developed welding robot is that it is the first in the world to use a supply of alternating current with a mid-frequency of 1,000 Hz. This high frequency makes it possible to use very small transformers. The welding is powered by direct current which means there is no other dependency on the impedance of the electric circuit. After rectification of the alternating voltage, the high frequency produces a very low residual ripple of the electric welding voltage which has a very positive effect on the welding quality.
to prepare the two rail ends to be welded. The current-carrying clamps are independent of the clamping jaws.

4.5. Integrated closure welding

Another advance in technology is the ability of the APT 1500 R to perform closure welds without an additional pulling device. Responsible for this are several constructional features and the three most important are:

- The maximum pulling distance of 200 mm. This enables closure welds to be performed under a wide variety of conditions.

- The tractive force, which at 1500 kN is very generous. The longitudinal forces involved in closure welds are the friction force necessary to pull the rails, the stretching force caused by the temperature difference, and the upset force. Calculations show that even rails up to 720 meter length can be pulled without difficulties.

- The trimming process: trimming must be carried out immediately after the upset stroke. Clamping jaws and trimming tools are therefore positioned so that it is possible to trim the weld immediately after the upset stroke without having to open the clamping jaws. This fulfils an important requirement of the standard which states that the weld shall be in compression during removal of excess upset.

4.6. Closure welding using the pulsation welding process

The incorporated optional pulsation welding process with uniformly oscillating rail ends brings a number of advantages such as shorter burn-off lengths and less time needed for welding. The gap between the rail ends can be very small compared to the standard process. This enables closure welds to be performed with minimal difference to the neutral temperature and also reduces the length of track where rail fastenings have to be loosened.

4.7. Field experience

The first machine is used in Austria since 2011 by a contractor. Till the end of 2012 (which was the first year of commercial use) more than 1000 welds have been done. Most of the welds are revenue welds of 120 meter long rails, but about 150 welds are closure welds. No weld failures have been reported.

5. CERTIFICATION OF THE WELDING ROBOT

The new welding robot has been successfully certified in Germany and Austria according to EN14587-2. The test samples were rails UIC60E1 and UIC54E2 of rail quality R260. The high standards required by EN14587-2 were not only fulfilled, but surpassed by the welding robot.
rail is 1980 kN, but a greater number of samples did not break because the force of the rig is limited to 2000 kN. The mean deflection is 53.4 mm and rail consumption 21.4 mm, a reduction of about 15 mm compared to the standard method. The welding time is reduced from 133.4 seconds to only 85 seconds.

6. SUMMARY

Flash-butt welding is now performed as a fully automated process using very stable mechanical engineering and servo technology. It provides high precision, optimised time sequences of each phase of work, shorter burn-off lengths and greater strength of the welds. This innovative technology offers the features needed to meet the increased demands of heavy haul and high-speed traffic.

REFERENCES


[2] Brave, G, FAST/HAL Rail Weld Performance; Proceedings of Workshop on Heavy Axle Loads, Pueblo, Colorado, October 14-17 (1990), 11-1...11-11