# Improving the Performance of Aluminothermic Rail Welding Technology, through Selective Alloying of the Rail Head

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**Summary:** The service performance of aluminothermic welds in railroad rails reflects their ability to support the service loads, which may be increased locally due to impact loading. For high strength rail steels used for high axle load conditions, a short preheat welding process in conjunction with a high portion hardness may be used to reduce impact loading. Such welds may exhibit reduced structural performance compared with that available using lower hardness portions. A 2-component aluminothermic welding procedure which combines a lower hardness portion for the foot and web regions of the rail with selective alloying of the head has been developed to overcome these limitations. Finished welds provide improved structural behaviour compared with existing processes used for high strength rail grades, whilst retaining the batter performance of the latter. Mechanical testing of aluminothermic weld metal from base and alloyed regions has been undertaken in order to quantify the improvements in weld properties. In-track testing under a range of loading conditions is currently in progress.

**Index Terms:** railroad research, rail welding, weld batter, fatigue

## 1.0 INTRODUCTION

The service performance of welds in railroad rails may be considered in terms of:

- the structural behaviour of the welded joint, ie the integrity of the joint and its ability to support the service loads, and
- the batter[1] behaviour of the running surface, which is influenced by the distribution of mechanical properties such as yield strength or hardness between parent rail, softened zone and weld metal [1], and in turn may influence the extent of impact loading as wheels traverse the weld(s).

For aluminothermic welds, the above characteristics are influenced by process parameters such as weld collar design, gap width, preheat conditions and portion chemistry. Thus for current high strength rail steels intended for use under heavy axle loads, a portion hardness of 340-360 HB is typically used. This level of hardness provides adequate resistance to weld batter, provided the width of the heat-affected zone (HAZ) is minimised, for example by using a short-preheat process. However higher hardness portions exhibit reduced weld metal toughness compared with that available using softer portions (eg. hardness 230-250 HB).

Structural failure of welds under high axle load conditions may occur by horizontal split web (HSW) or “big dipper” defects, which are typical of Australian iron ore haulage systems [2]. Weld characteristics which are relevant to this failure mode include the fatigue crack propagation behaviour (typically the threshold stress intensity ($\Delta K_{th}$) and fracture toughness ($K_{IC}$) values), and the level of residual stresses in the web [3]. Failure in longitudinal bending may also occur, initiating at lack-of-fusion or shrinkage defects in the foot of the rail; this failure mode is addressed in current [4] and proposed [5] aluminothermic weld specifications by the bending fatigue test.

Web failures may initiate at welding defects such as shrinkage cracks or hot tears, or slag inclusions at or immediately below the surface of the weld collar. Hence it is important that both the design of the welding process, and the procedures for installation of welds into track, are such that the quality of finished welds is satisfactory with regard to such defects.

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[1] Defined as the variation in longitudinal profile along the running surface of the rail, resulting from differential wear and plastic deformation between the parent rail and the weld.

The Elektro-Thermit GmbH, via its research and development organisation (Hans Goldschmidt Forschungs und Entwicklungs GmbH), and its Australian subsidiary (Thermit Australia Pty Ltd), have developed a 2-component aluminothermic welding procedure which combines a lower hardness portion for the foot and web regions of the rail with selective alloying of the head, using vanadium, to increase the hardness of this region, and hence its resistance to weld batter.

The 2-component welds exhibit improved fracture toughness in the lower hardness region (web and foot) compared with that obtained in the selectively-alloyed head. This difference translates into a significant improvement in fatigue characteristics of finished welds.

## 2 DESCRIPTION OF 2-COMPONENT WELDING PROCESS

### 2.1 Consumables

The moulds are characterised by a triple riser casting system (Figure 1), which provides improved solidification characteristics. The Thermit steel is poured simultaneously in the main foot riser and into the welding gap, resulting in simultaneous down and up casting. The mould landing area is approximately 4 mm above the running surface. The remaining gap between the moulds and the running surface is closed by ceramic strips glued on top of the rail head by a specially-developed gauge. The moulds can be centrally positioned to the gap by the same gauge. A tool is used for covering the moulds to avoid ingress of luting sand into the moulds. The same tool can be used for positioning the universal clamping device.

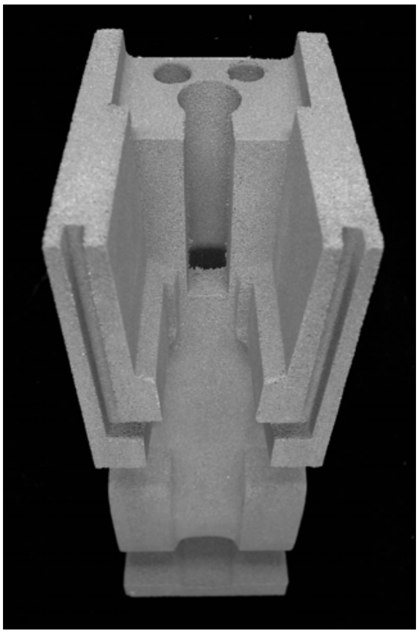


Figure 1: Moulds for triple riser casting system

The desired wear resistance of the rail head is ensured by a selective secondary process. A metal container containing the alloying additions is positioned below the plug (Figure 2). The container forms part of the plug, and hence is inserted into the mould cavity immediately following the preheat stage, and is positioned slightly above the upper surface of the rail (Figure 3). The metal stream is directed into the moulds so that it is impossible for the stream to touch the metal container during the tapping operation. When the Thermit steel reaches the top of the rail head, it melts the metal container and releases the alloying addition.

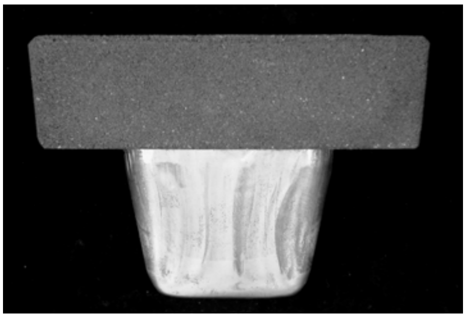


Figure 2: Plug for selectively alloying the rail head

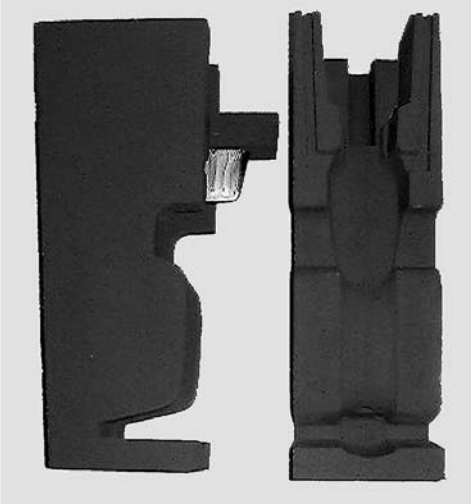


Figure 3: Positioning of alloy container relative to the rail head

The plugs are marked according to the various rail grades (Table 1).

**Table 1: Plug identification for various rail grades**

| Rail Grade | Plug marking |
|---|---|
| 900A | 900 |
| 1080 | 1100 |
| HH | 1200 |

The base portion corresponds to Z70 grade with a hardness of 230±20 HB.

The 2-component procedure may use either the long-life or single-use (SU) crucibles. The latter type is made from a bonded refractory material encased in a steel container, and incorporates the self-tapping thimble [6]. Advantages of the SU crucible over the long-life crucible include a reduction in the equipment required, a more simplified procedure, and more consistent tapping times.

## 2.2 Welding parameters

The welding process is characterised by the following parameters:

Crowning of the rail: 1.6-1.8 mm
Welding gap: 28-30 mm
Burner: 3 rows
Gas pressures: Oxygen: 400 kPa
Propane: 150 kPa
Burner height: 50-55 mm
Preheating time: 49 kg/m rail: 3 min
54 kg/m rail: 3.5 min
60 kg/m rail: 3.5 min
>60 kg/m rail: 4-4.5 min
Shearing time: 6.5-7 min after tapping

## 3.0 WELD PROPERTIES

The majority of the development program to date has been carried out on the UIC60 rail section. Additional development tests are currently in progress using the AS68 kg/m rail section (equivalent to AREA 136 lb/yd rail).

Characterisation of the weld properties has included the distribution of the secondary (head) alloying additions in finished welds and the resulting microstructures and hardness distribution, mechanical tests to quantify the improvements in ductility and fracture toughness, and slow bend tests to demonstrate compliance with the relevant specifications [4,5].

## 3.1 Chemical composition and hardness

Figure 4 shows the variation in vanadium content and hardness along a vertical plane at the weld centreline of a 2-component weld in UIC60 Head Hardened (HH) rail. The increase in vanadium content is restricted to the head region, extending to 40 mm below the top of the rail.

The vanadium content is varied to achieve the desired hardness level in the head. Figure 5 shows the general relationship between the vanadium content and average hardness for the Grades 900A, 1080 and HH rails. The vanadium content of the Z70 base portion is 0.05-0.10%, corresponding to a hardness of 250-260 HB.

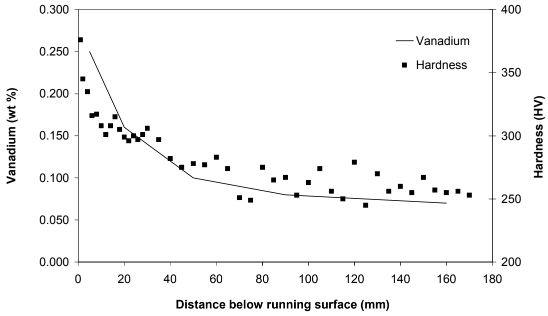


Figure 4 Vertical harness distribution at weld centreline in 2-component welds in UIC60 HH rail

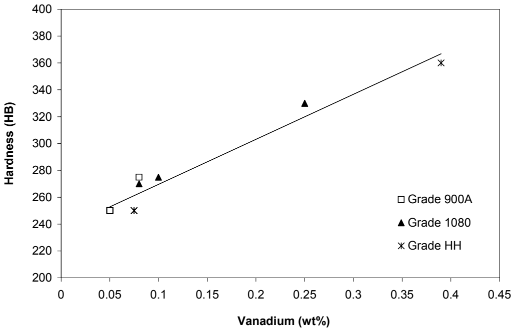


Figure 5 Variation in head hardness levels with vanadium content: Grades 900A, 1080 and HH rails

Hardness values at the running surface, measured in accordance with the draft European standard for aluminothermic welds [5], show an average of 272 HB for welds in Grade 900A rail, and 358 HB for welds in Grade HH rail. These values comply with the requirements of the specification.

More extensive hardness measurements at the running surface, covering the full extent of the weld metal, indicate that the vanadium secondary-alloying addition is distributed uniformly throughout the weld metal, with minimal variation in hardness associated with segregation effects. Average hardness for a total of 9 test welds in Grade HH rail was 363 HB, with a standard deviation of 13 HB.

The width of the heat-affected or softened zone in the parent rail, which is the primary region of weld batter, is similar to that obtained using conventional aluminothermic welding procedures. This dimension is influenced by the material characteristics in the parent rail, preheat conditions, and the size of the Thermit portion. Welds in Grade HH rail, for example, show a HAZ width of approximately 20 mm when measured in accordance with the draft European standard [5], ie at a hardness of 25 HV below the average hardness of the parent rail (Figure 6).

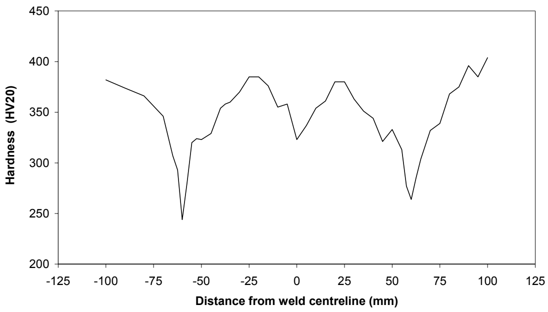


Figure 6 Longitudinal hardness distribution in 2-component weld; HH grade rail

*(traverse 5 mm below running surface)*

### 3.2 Slow bend tests

Table 2 summarises the average slow bend test results for test welds in Grades 900A, 1080 and HH rails.

**Table 2: Slow bend test results**

| Rail grade/hardness (HB) | Mean fracture load (kN) | Mean deflection (mm) |
|---|---|---|
| 900A/275 | 1440 | 19.5 |
| Cr-Mn/335 | 1420 | 13.0 |
| HH/350 | 1475 | 17.5 |

All welds met the minimum requirement of 1130 kN for the UIC60 rail section [5].

### 3.3 Tensile behaviour

Table 3 summarises the tensile behaviour, based on longitudinal specimens from the head, web and foot regions.

**Table 3: Tensile test results**

| Rail grade/hardness (HB) | 900A/275 | Cr-Mn/335 | HH/350 |
|---|---|---|---|
| 0.2% P.S. (MPa) | | | |
| Head | 514 | 773 | 848 |
| Web | 490 | 564 | 561 |
| Foot | 492 | 493 | 534 |
| UTS (MPa) | | | |
| Head | 849 | 927 | 964 |
| Web | 790 | 739 | 804 |
| Foot | 815 | 805 | 776 |
| Elongation (%) | | | |
| Head | 8.6 | 1.6 | 0.7 |
| Web | 5.5 | 2.5 | 5.1 |
| Foot | 7.0 | 6.4 | 5.3 |

As expected, the yield and tensile strength increases between the rail foot and the head, with a corresponding reduction in elongation. In the foot, elongation values up to 7% were obtained with the softer Z70 base portion in the Grade 900A rail.

### 3.4 Compression behaviour

Plain strain compression testing has been used to examine the work-hardening characteristics, which are related to material response in the wheel-rail contact region. The test procedure, which is described by Gunasekera et al [7], has previously been used to characterise the behaviour of rail and wheel steels [8]. Material properties are described by the relationship:

$$\sigma = K\varepsilon^{n} \qquad (1)$$

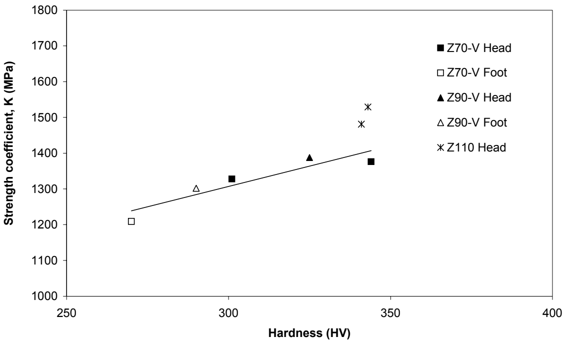
where: $\sigma$ = true strain (MPa)
$K$ = strength coefficient (MPa)
= stress at $\varepsilon = 1.0$
$\varepsilon$ = true strain
$n$ = work-hardening exponent

A high value of the work-hardening exponent, n, in conjunction with increased yield or 0.2% proof stress, implies that the material will resist both the onset of plastic strain during initial loading cycles, and the accumulation of plastic strain (described as “ratchetting” behaviour) under the cyclic loading conditions which occur in the wheel-rail contact region [9]. A third parameter, material ductility or strain-to-failure, is related to the total amount of plastic strain which can be accommodated prior to the onset of surface cracking, and hence the development of rolling contact fatigue damage [10].

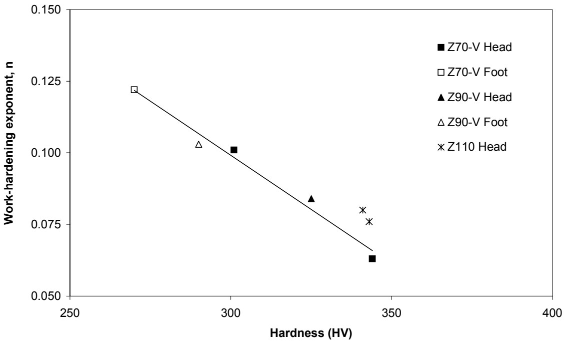
The tests included specimens from standard Triple Riser welds manufactured using Z110 portions, for comparison purposes. Table 4 summarises the test results; Figures 7(a) and 7(b) show the relationships between the initial hardness of the weld metal and K and n, respectively.

**Table 4: Compression test results**

| Weld type | Position | Mean hardness (HV20) | K (MPa) | n |
|---|---|---|---|---|
| Z70-V | Head | 344 | 1376 | 0.063 |
| | | 301 | 1328 | 0.101 |
| | Foot | 270 | 1209 | 0.122 |
| Z90-V | Head | 325 | 1388 | 0.084 |
| | Foot | 290 | 1302 | 0.103 |
| Z110 | Head | 343 | 1529 | 0.076 |
| | | 341 | 1481 | 0.080 |



(a) Strength coefficient



(b) Work-hardening exponent

Figure 7 Compression test results

The strength coefficient (K) increases as expected with increasing hardness, while the work-hardening exponent (n) decreases, in a similar manner to previous data for rail and wheel steels [8]. At the higher hardness levels, the values for the V-alloyed Z70 and Z90 base portions approach those of the higher carbon Z110 portion.

## 3.5 Fracture toughness

Table 5 summarises the fracture toughness behaviour, which indicates a difference of ≥10 MPa√m between the head and foot regions across the three rail grades. At the highest hardness level (Grade HH rails), the value of 31.5 MPa√m is similar to that reported previously for Z110 portion welds manufactures using the SkV-F process [11].

**Table 5: Fracture toughness of head-alloyed welds**

| Rail grade/hardness (HB) | | 900A/275 | Cr-Mn/335 | HH/350 |
|---|---|---|---|---|
| $K_{IC}$ (MPa√m): | Head | 40.0 | 31.5 | 31.5 |
| | Web | 38.4 | 41.9 | 36.8 |
| | Foot | 51.2 | 46.8 | 41.3 |

The increase in fracture toughness levels in the web and foot regions of the weld improve the resistance to fracture at defects such as web cracks. For example, Figure 8 shows the influence of fracture toughness on the critical defect size for a horizontal web crack such as that associated with HSW defects, calculated using Linear Elastic Fracture Mechanics (LEFM) techniques. At a defect depth of 5 mm, increasing the fracture toughness from 30 MPa√m to 40 MPa√m increases the fracture stress by one-third, from 220 MPa to 290 MPa. This fracture stress represents the sum of residual stresses, and those induced by torsional loading on the rail web [3].

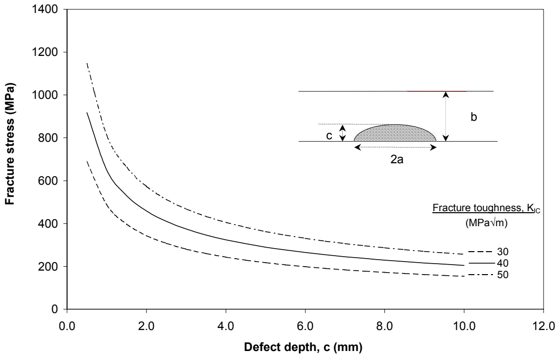


Figure 8 Relationship between fracture stress and critical defect size for web crack

## 3.6 Microstructure

The weld metal microstructure consists of a pearlitic matrix with grain boundary ferrite and ferrite precipitates in the matrix (Figure 9). The ferrite in the rail head, which has an overall hardness of 275±20 HB on the running surface, possesses a mean hardness of 290 HV whereas the ferrite in the weld metal in the foot (overall hardness 245±20 HB) is softer with an average hardness of 200 HV.

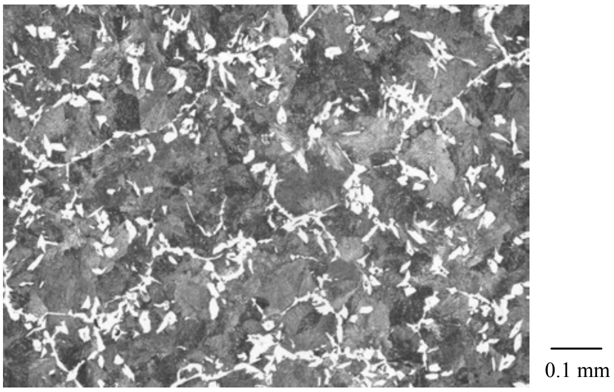


Figure 9 Microstructure of head region of 2-component weld in Grade HH rail (Nital etch)

With increasing vanadium in the rail head the hardness of the ferrite increases. A mean hardness of 350±20 HB on the running surface corresponds to an average ferrite hardness of 350 HV. In the rail foot the mean ferrite hardness amounts to 215 HV for an overall hardness of 250±20 HB.

Reduced micro-porosity and inclusion content is observed in the weld metal microstructure through the centre of the weld. This can be attributed to the design of the triple riser process, which provides improved feeding and solidification characteristics.

### 3.7 Discussion

Cast microstructures which are inherent in the aluminothermic welding process demonstrate limited ductility which reduces further when the weld metal hardness increases. Such microstructures become more sensitive to weld defects. The 2-component aluminothermic welding procedure combines a lower hardness portion for the foot and web regions of the rail with selective secondary alloying of the head, thereby offering improvements in terms of the structural behaviour of the welded joint.

Mechanical properties of the 2-component welds are comparable to existing aluminothermic welds such as the Thermit SkV-F process. For example, the fracture load and deflection under slow bend test conditions comply with current standards. However these properties do not represent the fundamental material performance offered by a soft base Thermit portion and the secondary head alloying. The major benefit is shown by the fracture toughness and tensile ductility, which increase from the rail head to the rail foot, and with decreasing hardness on the running surface.

The elongation in the rail head is typical for Thermit steels of this strength [11]. However the average 6% elongation in the rail foot, for all hardness levels investigated so far, is considered high for a cast microstructure. The different elongation behaviour as a function of the running surface hardness is due to a change in the alloying mechanism for the vanadium. The ferrite possesses a considerable solubility for vanadium which is incorporated into the ferrite crystal [12]. The strength of the ferrite increases and causes an increase in hardness and hence tensile and yield strengths.

In the region directly subjected to wheel-rail contact stresses, the work-hardening behaviour of the lower carbon, V-alloyed weld metal in the Grade HH rails approaches that of the higher carbon (Z110) portion, with similar values of ductility (as measured by the tensile test). Variations in the work-hardening behaviour are expected to result from the differences in microstructure, in particular the proportion of ferrite, between the two weld formulations, such that the behaviour of the V-alloyed welds may be modified by altering the composition of both the base portion and the head alloying addition.

The fracture toughness is almost independent from the vanadium alloying mechanism, but increases from the rail head to the rail foot due to the softer Thermit portion in the web and foot of the weld. A $K_{IC}$ value of more than 51 MPa√m was measured at a weld hardness of 275 HB (standard rail grade; UTS 880 MPa). For head hardened rails with a hardness on the running surface of 350 HB a $K_{IC}$ value of 41.3 MPa√m was obtained. These fracture toughness levels are similar to those reported for the corresponding rail steels [13].

## 4.0 IN TRACK TESTS

### 4.1 Australian heavy haul systems

Preliminary in-track testing has commenced under heavy haul (30-35 tonne axle load) conditions in the Pilbara iron ore railways. In this case the process was used to install a rail plug (closure) of new head-hardened rail into a section of worn standard carbon rail. A top-of-rail hardness traverse on one of these welds (Figure 10) indicates that the weld metal hardness is similar to that obtained with Z110 welds. In addition, surface hardness levels were similar in the two rail types, but with a considerable wider HAZ in the worn standard carbon rail. This is typical of the in-track installation of new welds into rail which has been heavily work-hardened; the deformed pearlite microstructure in the work-hardened region softens more readily during the welding process, resulting in a HAZ width which may be up to 10 mm wider than that in the corresponding new rail.

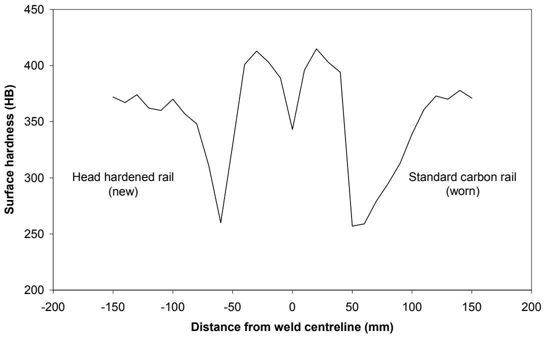


Figure 10 Longitudinal hardness distribution at running surface; 2-component weld in 68 kg/m rail

Figure 11 shows a general view of the weld collar of this weld, including the connection point of the triple risers on the upper foot. Figure 12 shows a close-up view of the running surface, including the differences in extent of HAZ batter between the head hardened rail (left of figure) and standard carbon rail (right of figure). These differences are reflected in the longitudinal profile along the centre of the running band (Figure 13).

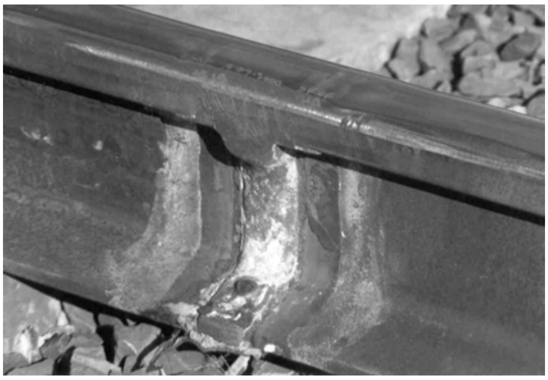


Figure 11 General view of 2-component weld in 68 kg/m rail

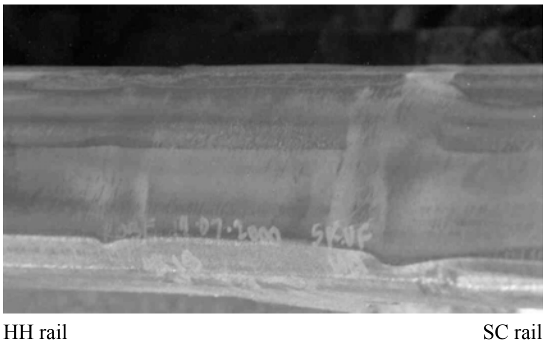


Figure 12 Contact band appearance in 2-component weld; 68 kg/m rail

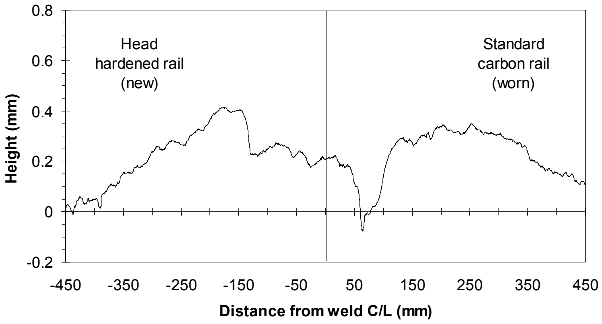


Figure 13 Longitudinal profile at running surface; 2-component weld in 68 kg/m rail

### 4.2 Europe

The performance of this new welding technology, called High Performance Weld, has also been investigated under various European track conditions. Between May and September 2000 track tests has been carried out in high speed tracks of Austrian Railways ÖBB and German Railway DB AG as well as in the heavy haul line of Norwegian Ofot-Track.

In Austria welds were executed in a UIC60 switch of grade 900A and in UIC60 head hardened rails located in a sharp curve. With DB AG standard carbon rails were welded. In Norway an S54 head hardened rail of 370 HB was installed reflecting the high wear rate caused by the axle load of 28 tonnes. The hardness at the running surface of the welds was adjusted to the rail grades, namely 280 HB and 350 HB with Austrian Railways, 280 HB with Deutsche Bahn and 370 HB in the Ofot-Track. The various hardnesses on the running surface were achieved by altering the vanadium addition. The difference in the composition of the weld metal and thereby in the mechanical properties were proven by vanadium analyses taken from the foot and head riser.

The THERMIT portion itself was identical for all rail grades in Austria and Germany, i.e. a Z70 portion resulting in a weld metal hardness of 230 HB. For the high strength rail used in Norway a Z90 portion was applied with a hardness of 280 HB. As a result, the weld hardness on the running surface is by far higher compared to the web and foot.

Figure 14 shows the track conditions in the Austrian system and Figure 15 a finished weld.

Since the date of installation all welds are regularly checked and are performing to the satisfaction of the customer.

Figure 14 General view of test site, ÖBB system

Figure 15 Finished weld

## 5.0 SUMMARY

Elektro-Thermit GmbH & Co. KG and its research subsidiary, Hans Goldschmidt Forschung-und Entwicklungs-GmbH, have developed a 2-component aluminothermic welding procedure which combines a lower hardness portion for the foot and web regions of the rail with selective alloying of the head. The procedure is applicable to rail grades ranging from standard grade (UTS 880 MPa) up to Head Hardened rails. The secondary alloying is by means of vanadium additions to increase the weld metal hardness in this region to a level equivalent to the parent rail. The base portion (Z70) with a mean hardness level of 230 HB provides improved ductility in the rail foot.

Finished welds based on such a soft Thermit portion provide improved structural behaviour compared with existing welding processes. The fracture toughness of the lower hardness region (web and foot), when using a Z70 base portion, is approximately 40 MPa√m up to 50 MPa√m, compared with 30 MPa√m to 40 MPa√m for the higher hardness head region. Tensile ductility in the rail foot is also improved, with a mean elongation of 6%. These enhanced mechanical properties translate into a significant improvement in the ductility and thereby into the service behaviour of the finished welds for the most common rail grades.

Besides the improved weld integrity a unification of the Thermit portion grades has been achieved. A base portion of the Z70 grade with a standardised hardness of 230 ± 20 HB may used to obtain a running surface hardness between 275 and 350 HB.

In-track testing of the new welding procedure is currently in progress, to examine the service performance under a range of axle load conditions.

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