

Recent Experiences with the Performance of Aluminothermic Rail Welds under High Axle Loads

G A Offereins* and P J Mutton†

*B.Eng., M.IEAust.
Manager Track and Signals, BHP Iron Ore Pty Ltd

†Dip. Met., M.App.Sc., M.IEAust.
Principal Research Fellow, BHP Institute of Railway Technology, Monash University

SUMMARY: Aluminothermic welding is used by BHP Iron Ore Pty Ltd for all field welding requirements. The preferred process utilises a short preheat and a portion hardness of 340-360 HB to provide weld characteristics compatible with high strength rail grades used in mainline tangent and curved track. In response to recent failures in aluminothermic welds, and in recognition that such welds represent one of the major limitations to further increases in axle loads, a program was undertaken to reduce the risk of premature failures, and to develop improved rail welding and track maintenance practices which would meet the performance demands of higher axle loads. Alternative aluminothermic welding procedures were assessed using a combination of laboratory and in-track testing. A detailed analysis of weld failures and extensive in-track instrumentation program were undertaken to correlate failure modes with the in-track loading environment. Revised inspection procedures, including radiographic testing, were used to identify defective welds and audit welding procedures. The results of this program highlight the limitations of existing aluminothermic welding procedures as axle loads approach 40 tonnes, and provide the basis of a performance-based specification for aluminothermic welding of rails for high axle load conditions.

INTRODUCTION

The BHP Iron Ore Pty Ltd (BHP-IO) railroad comprises over 650 route kilometres for the transport of iron ore from several mine-sites in the Pilbara region of Western Australia to processing and ship-loading facilities at Port Hedland. The majority of tonnage (~90 million gross tonnes (MGT) per annum) is carried on the Newman mainline and Yandi spur, at nominal axle loads of up to 37 tonnes. Train configurations typically comprise 4 Dash 8 or 3 AC6000 locomotives and 224 cars in locotrol consists, operating on a 9-train daily schedule.

The majority of the above track is laid on concrete sleepers (600 mm spacing), with continuously-welded rails of either head hardened (HH) or low alloy heat treated (LAHT) grades. Rails are welded into 400 m strings using a Chemetron AC flashbutt welder; this unit was recently upgraded with an improved control system, to allow the higher strength LAHT grades to be welded.

The majority of field welding is carried out using aluminothermic procedures; such welds are primarily associated with replacement of rail (or weld) defects, installation of insulated rail joints, and track construction activities. A short preheat aluminothermic welding process with a portion hardness of 340-360 HB is preferred, to provide hardness levels in finished welds which are comparable with the high strength rail grades. Of particular concern are the hardness levels in the fusion zone, and the width of the heat-affected zones (HAZ's). Welds that exhibit low fusion zone hardness levels or wide HAZ's are susceptible to batter (localised deformation and flow), which results in increased impact loading and may contribute to premature failure of the weld(s). The extent of weld batter can be limited by rail grinding, which is carried out as part of a preventative maintenance strategy to control surface-initiated rolling contact fatigue (RCF) damage and maintain the desired rail profiles. At this stage rail grinding is not specifically carried out to control weld batter.

Two recent developments have prompted a re-appraisal of the performance of aluminothermic welds under high axle load conditions; these were:

- an increased incidence of premature failures in relatively new welds, in both tangent and curved track, and;
- an assessment, using failure mode and effects analysis (FMEA) procedures, of the consequences of further increases in axle loads to 40 tonnes on component performance.

Notwithstanding the necessity to address the cause(s) of premature failures, the FMEA approach provided an opportunity to examine the long-term viability of aluminothermic welding procedures under current and projected operating conditions. The program that was subsequently undertaken involved:

- examination of failed welds;
- a review of current welding processes and in-track welding procedures;
- measurement of the loading conditions at, and the response of, aluminothermic welds in tangent and curved track;
- a re-appraisal of the laboratory testing techniques used to assess the performance of aluminothermic welds under high axle loads; and
- implementation of radiographic examination of new welds.

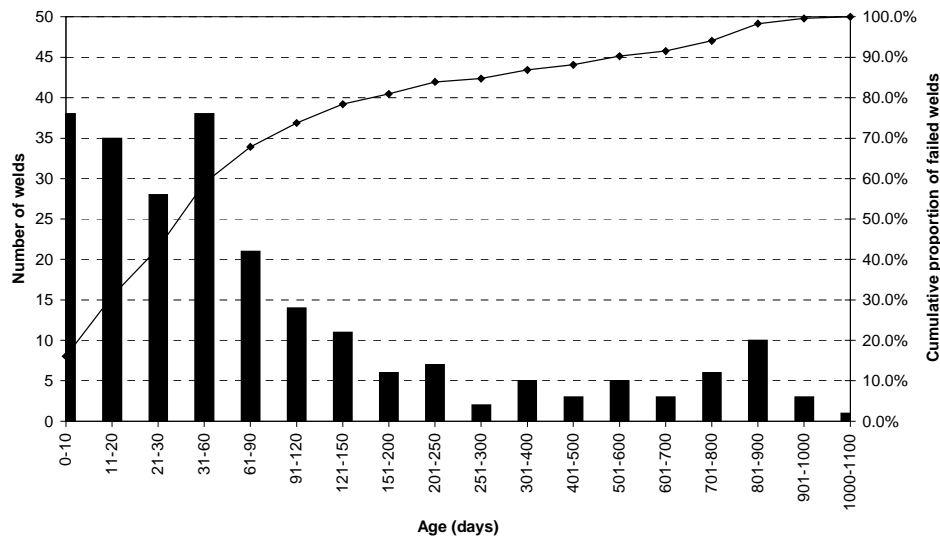
The program covered short preheat processes available from the two main manufacturers, and included single-use crucibles, and the use of post-weld treatments to modify residual stress levels.

WELD FAILURE CHARACTERISTICS

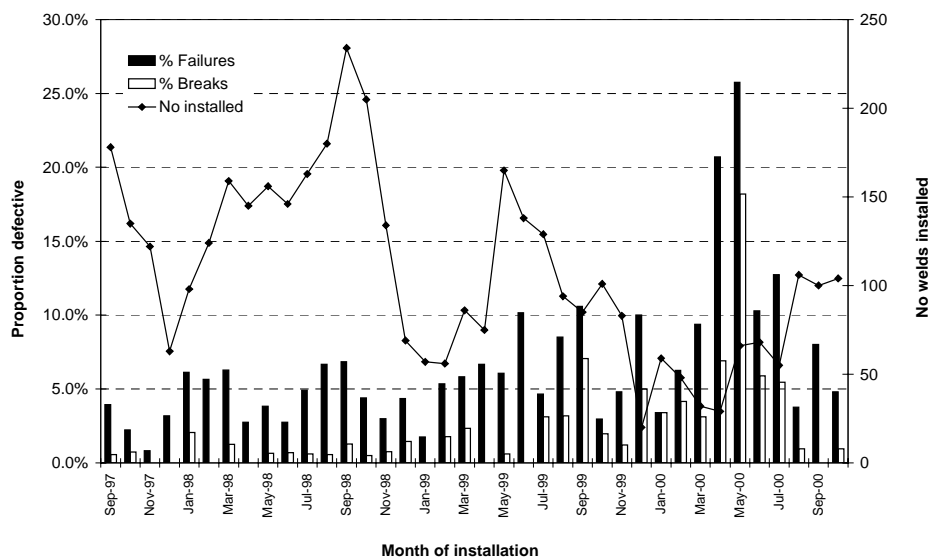
During the 18 month period to June 2001 failures in aluminothermic welds comprised approximately 75% of all broken rail reports for the Newman mainline. Of these, the majority occurred in newer welds, i.e. welds installed less than 6 months previously. The tendency for early failures in aluminothermic welds under high axle load conditions is consistent with previous trends (Figure 1(a)). Hence tracking weld failure rates as a function of time in service provides a clear indication of the acceptability or otherwise of welding procedures.

A review of weld defect and failure statistics over a two-year period to October 2000 also indicated an increase in the number of ultrasonic defects in aluminothermic welds, coinciding with periods during which the number of new welds decreased (Figure 1(b)).

The two main failure types were straight-break or vertical fractures either at the weld centreline or at the edge of the weld collar or reinforcement, and split-web or "S" fractures starting in the web [1]. Most of the failures were of the split-web type, which present a greater derailment risk than straight-break failures. Split web fractures contributed to two derailments during August-September 2000.



(a) Weld failures versus service period



(b) Defective and failed welds vs month of installation

Figure 1: Failure statistics for aluminothermic welds – September 1997 to October 2000

Straight-break failures

The majority of straight-break failures were found to be associated with centreline shrinkage defects in the foot (Figure 2), which initiated a vertical fracture up the centreline of the weld. Examination of failed welds and an audit of welding procedures indicated that the most likely cause of the defect was insufficient preheat. However test welds manufactured in accordance with the consumable supplier's recommended procedures were also found to exhibit some centreline shrinkage, albeit of smaller size than in welds that had failed in track. This indicated that the process was inherently prone to centreline shrinkage when used with the 68 kg/m rail section.

Straight-break failures also occurred as a vertical fracture at the edge of the weld collar, initiating in the upper web region (100-110 mm above the rail foot), at the surface of the web. The initiation region coincided with a broadening of the fusion zone in which weld metal extended some 10-15 mm beyond the weld collar. Inclusions present at the initiation site in some, but not all, failed welds were identified as slag arising from the portion reaction.

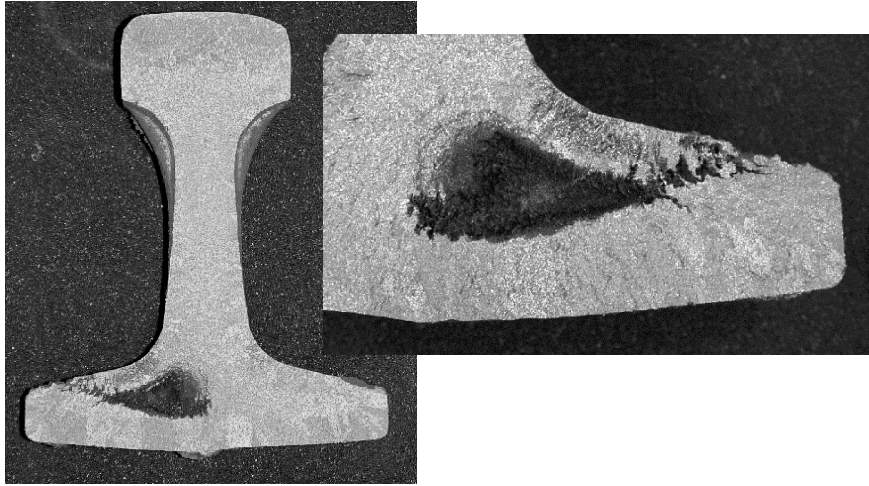


Figure 2: Centreline shrinkage defect in foot of short-preheat aluminothermic weld

Straight break failures were more likely to occur in the colder months, when rail temperatures fell readily to below the stress-free temperature. An additional factor was the distribution of residual stresses in the web. A heat-blocking procedure was previously introduced to reduce the probability of split-web failures by lowering residual stresses in the vertical direction. However incorrect heat-blocking procedures were found to increase the magnitude of longitudinal residual stresses in the vicinity of the weld collar, increasing the risk of tensile failures adjacent to the weld collar. The use of the heat-blocking procedure was subsequently discontinued.

Split-web fractures

Horizontal split-web (HSW) or “big dipper” failures are a relatively common failure mode in both flashbutt and aluminothermic welds in the Pilbara heavy haul railroads [2, 3]. The factors that contribute to this failure mode are well understood [4], with most failures occurring in curves of 600-900 m radius due to the cyclic nature of torsional stresses in the web. What was unusual about the recent spate of split-web fractures was that the majority occurred in tangent track.

Most split-web fractures showed a weld defect (inclusion, slag, etc) on the fracture surface, and no sign of fatigue crack growth. This indicated that the fractures started at the weld defect and progressed rapidly, possibly under loading from one or two wheels. Examination of the defect in several failed welds showed that it was mainly alumina (aluminium oxide) slag arising from the portion reaction.

The examination of failed welds therefore indicated that:

- the short-preheat welding process was prone to centreline shrinkage, even in welds produced using recommended procedures;
- optimising weld characteristics in terms of the hardness distribution (to minimise weld batter) could, under some circumstances, compromise the structural performance of the weld and increase the probability of weld failure;
- weld quality was variable, with slag inclusions in the web (at the edge of the weld collar) of particular concern; and
- the loading conditions to which welds were subjected were more severe than anticipated, particularly when compared with previous data for high axle load operations [2, 3].

REVIEW OF WELDING PROCESSES AND PROCEDURES

Auditing of in-track welding procedures is carried out on a regular basis, in conjunction with the consumable manufacturer(s) and/or supplier(s). In addition, there is an ongoing program to monitor and assess developments in rail welding procedures that may be applicable to BHP Iron Ore’s railroad

operations. As part of the latter program, a single-use crucible welding procedure had previously been approved for in-track use. Over 200 of these welds had been installed in mainline, with relatively few defects and no failures up to the present time. However the manufacturer withdrew the process after a weld failed in another railroad.

Subsequent developments in aluminothermic welding procedures that became available were an improved short preheat, Triple Riser (TR) process from Thermit Australia Pty Ltd, and the single-use crucible PLK process from Railtech Australia Ltd. Both of these processes underwent an initial assessment program in the laboratory, with emphasis on the following characteristics:

- the hardness distribution as measured by a longitudinal traverse immediately below the running surface of the rail;
- quality and cleanliness of the weld metal, in particular the presence or otherwise of inclusions in the web, shrinkage defects in web and foot, and surface imperfections such as hot tears in the web;
- tensile properties of the weld metal, in particular those relating to catastrophic failure in an overload situation;
- the distribution of residual stresses in the web, and the magnitude of vertical stresses developed under simulated service loading conditions; and
- split-web fatigue behaviour.

The hardness distributions obtained in Thermit TR and Railtech PLK welds were similar, with an increase in HAZ width compared with the SkV-F process (Figure 3). This indicated that weld batter would be more severe than with the SkV-F process, although this could be offset by using a slightly harder portion (subject to availability from the manufacturer(s)). Previous in-track test programs had identified a minimum fusion zone hardness of 340 HB in order to control weld batter to acceptable levels. The width of the HAZ could be reduced slightly by using one of the LAHT rail types rather than the HH grade.

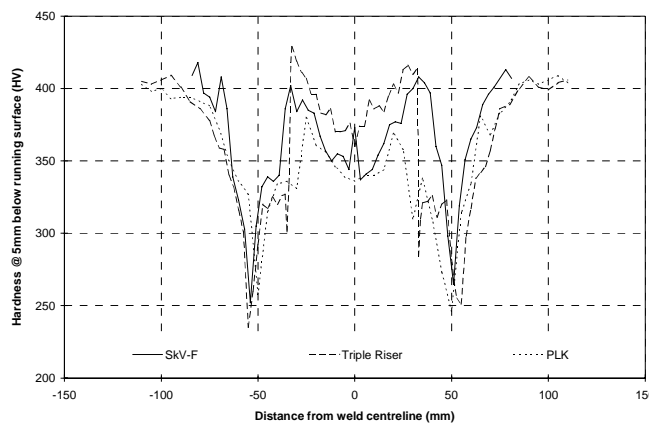


Figure 3: Hardness distribution in aluminothermic welds (HH rail)

Figure 4 compares the various weld types in terms of the level of residual stress levels and stresses induced by application of an eccentric vertical load on the rail head (to simulate split-web behaviour); the data are for vertical stresses measured at the weld centreline. Residual stress levels are lower in the longer-preheat PLK process, although the shape of the weld collar results in higher stress levels under eccentric vertical loading.

Previous studies of the split-web behaviour of aluminothermic welds [2, 3] have made use of fatigue crack propagation data such as the fracture toughness and the threshold stress intensity factor to determine the stresses required for fatigue crack initiation from a pre-existing defect, or weld fracture. For an overload failure, the relevant parameter is the fracture toughness (K_{IC}), with a range of 25-35 MPa \sqrt{m}

typical of aluminothermic weld metal [5, 6]. For the current program, a more expedient test procedure was required.

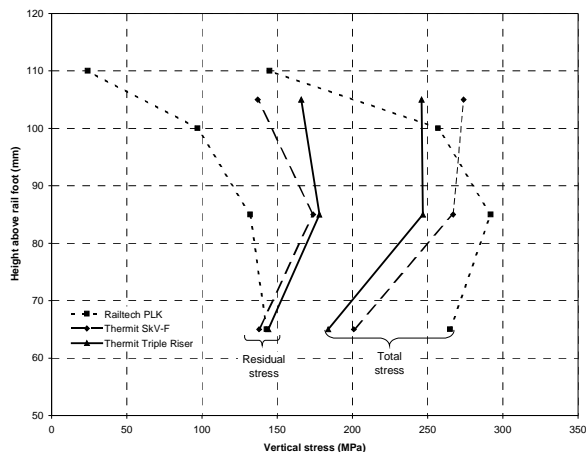


Figure 4: Distribution of vertical stresses at weld centreline

The approach taken was to examine the notch sensitivity of the weld metal by means of tensile tests, using a procedure loosely-based on the ASTM standard [7]. Specimens were prepared from the web of the weld, and a small notch machined into the gauge length to simulate a slag inclusion at the edge of the weld collar. A comparison of the tensile strength with corresponding data for un-notched specimens provided an indication of notch sensitivity. Table 1 summarises typical data for the SkV-F and TR processes; in the un-notched condition the mean UTS was 805 MPa, reducing by an average of 14% in the notched condition.

Table 1: Tensile properties of un-notched and notched weld metal

Weld Type	0.2% Proof Stress (MPa)	Elongation (%)	UTS		
			(Un-notched) (MPa)	(Notched) (MPa)	<u>Un-notched</u> / <u>Notched</u>
SkV-F	787	1	809	667	1.21
TR	745	2	802	723	1.11

Test welds were also subjected to split-web fatigue tests [8], during which a vertical load of 200 kN was applied at an eccentricity of 22.5 mm from the centreline of the head to simulate torsional loading on the web. Welds were required to complete 5 million cycles without failure.

Welding procedures that were approved on the basis of the laboratory test program were subsequently used for in-track welding. This initially involved a limited number of trial welds, during which welding gangs were trained in the new procedures. Use of the newer procedures was subsequently expanded, subject to the availability of welding consumables. The TR process is currently used for all field welding in the Newman mainline and Yandi spur, with the exception of step- or junction-welds involving rails of varying head losses. Trials of the PLK process commenced in July 2001. The performance of these welds are being monitored in terms of weld batter and results from the rail flaw inspection program. In addition, selected welds have been instrumented as discussed below.

WELD INSTRUMENTATION PROGRAM

The initial examination of failed welds indicated that fracture occurred rapidly, with little or no evidence of fatigue crack growth. This, plus the relatively high number of split-web failures in tangent track, indicated that the loading conditions at welds were more severe than anticipated. An instrumentation program was therefore undertaken to quantify these loading conditions and the resultant response of the welds, taking into consideration the following aspects:

- track location (curved and tangent track);
- wheel and rail profiles;
- the longitudinal profile at the weld(s), including peaking or dipping associated with alignment of the rail ends during the welding procedure, and localised dipping attributable to the hardness differential across the weld(s);
- vehicle speed;
- wheel tread irregularities (wheel flats).

The instrumentation layout included load bridges at the weld(s) and the preceding plain rail, in order to measure vertical loads at both locations and derive impact factors for the weld, and single gauges for the measurement of vertical and/or longitudinal stresses in the web and foot of the weld(s). Measurement of longitudinal profiles at the welds was by means of a laser-based dip gauge [9]; Figure 5 shows examples of weld profiles.

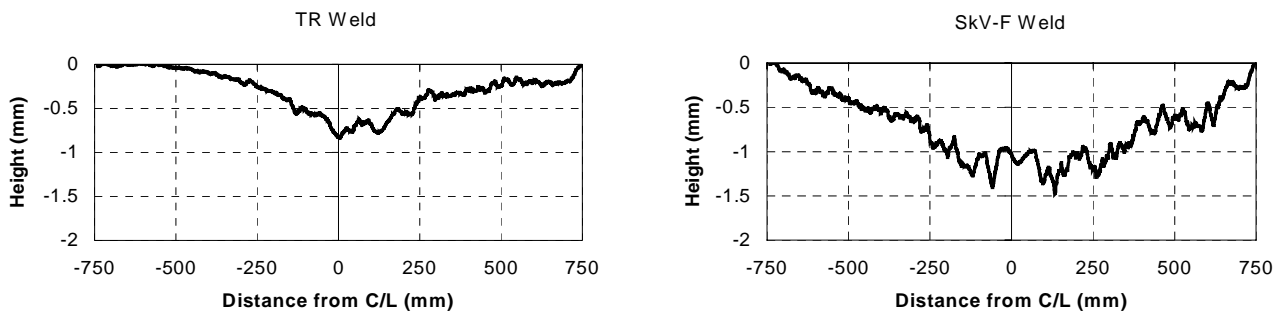


Figure 5: Longitudinal profiles at welds

Figure 6 shows calculated dynamic impact factors vs train speed for a dipped and peaked weld. Figure 7 shows the relationship between the depth (or height) of the irregularity at the weld and the dynamic impact factor at mainline speed (70-75 kph). Dynamic impact factors were generally ≤ 1.6 , and decreased with reducing train speed below 50 kph. Poor support under dipped welds (ballast pumping) contributed to increased impact loading (compared with equivalent fully-supported welds, and wheel tread irregularities (wheel flats) were found to increase impact factors at welds to approximately 2.5.

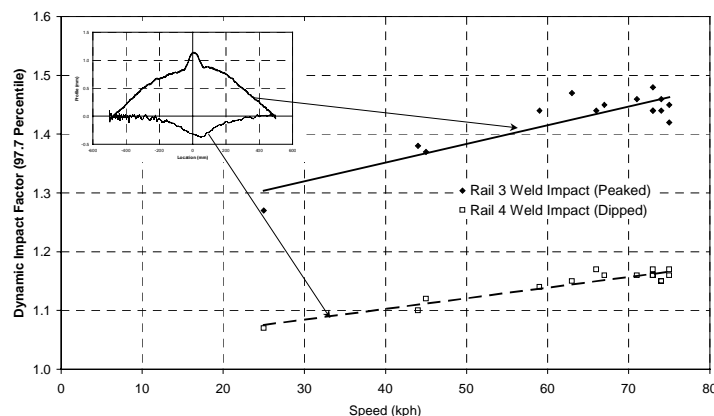


Figure 6: Dynamic impact factor vs train speed (tangent track)

The instrumentation program enabled the response of the different weld collar shapes to be compared under in-track loading conditions. Use was made of vertical stresses measured at the weld centreline (100 mm above the rail foot), as this related to the split-web failure mode. Figure 8 show the web stress response of SkV-F and TR welds in tangent track, compared with the equivalent position in the preceding plain rail. The SkV-F weld collar shape resulted in an apparent increased sensitivity to vertical load eccentricity than in the TR weld. In general, however, the incidence of high web stress values was

primarily determined by wheel-rail contact conditions, with contact towards gauge or field sides of the rail head promoting increased stresses. Vertical stresses of >150 MPa tension were measured in both

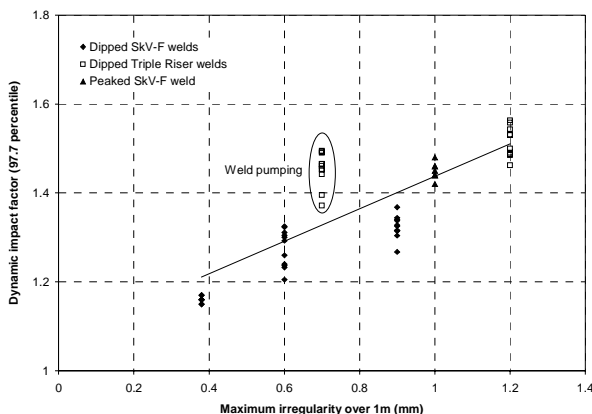


Figure 7: Dynamic impact factor at mainline speed vs weld irregularity size

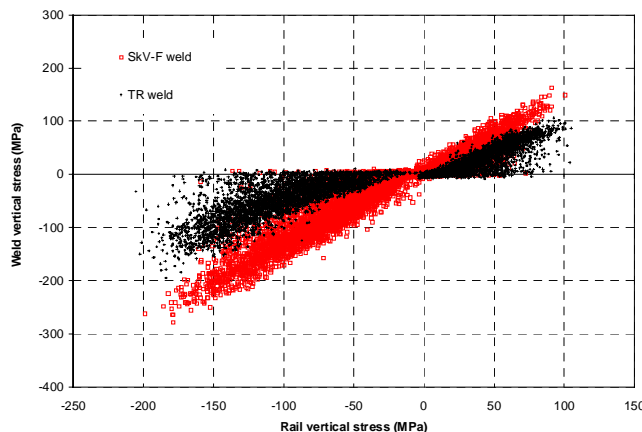


Figure 8: Comparison of web stress response in SkV-F and TR welds (tangent track)

tangent and curved track locations, with maximum tensile stresses of up to 250 MPa obtained in some instances in curved track. At these stress levels the probability of overload failure (split-web mode) was significantly higher. The tendency for eccentric loading of the rail head was influenced by wheel profile condition (and hence trips since service), bogie condition, and rail profile. Revisions to the low rail profile in high degree ($\geq 2^\circ$) curves to shift the contact band away from the field side of the head subsequently resulted in a decrease in peak tensile stress levels in the web (Figure 9).

Apart from residual stresses and those resulting from wheel loading, welds are subjected to thermal stresses, the magnitude of which is dependent on the stress-free temperature at the weld. Rapid changes in rail temperature during colder weather increase the probability of straight-break failures at welds. A program has recently been implemented to assess the distribution of stress-free temperatures in mainline, in conjunction with routine monitoring of rail temperature and rail end gap data whenever track is cut for the installation of new welds. Preliminary results from the latter measurements indicate that in some track sections the stress-free temperature may be considerably higher than the value of 37°C recommended on the basis of previous studies.

NON-DESTRUCTIVE INSPECTION TECHNIQUES

Non-destructive inspection of aluminothermic welds has historically involved a one-off manual ultrasonic testing of new welds following installation, and automated testing as part of the regular rail flaw detection program (currently undertaken on a 7-day cycle). Both procedures are incapable of reliably detecting

defects such as centreline shrinkage in the foot of aluminothermic welds. A program of radiographic testing was therefore initiated in September 2000, with emphasis on all welds installed over the preceding 12-month period. This program has subsequently continued to include all new welds immediately after

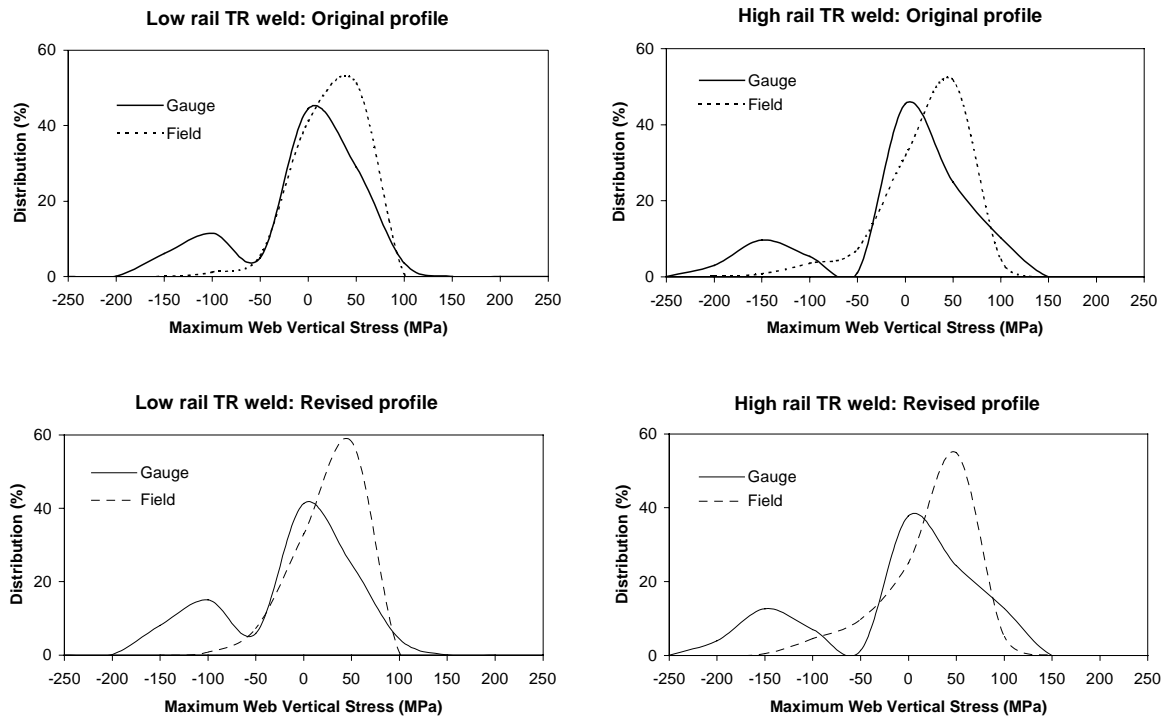


Figure 9: Distribution of web stresses in TR weld (curved track), showing influence of revised low rail profile

installation, and selected testing of older welds for comparison purposes. The tests are carried out by the rail flaw inspection contractor. The radiographic inspection procedure uses a gamma-ray source, and covers the web and both sides of the rail foot. The technique is capable of discriminating between shrinkage defects and slag inclusions, both of which can be rated in terms of size (length of shrinkage defect or diameter of inclusions) and number. Calibration of the radiographic data has been carried out, where possible, by sectioning and examination of welds that have been removed from track.

Initial results for the short-preheat process indicated a high proportion (close to 50%) of the newer welds (less than 12 months old) exhibited centreline shrinkage (CLS) in the foot of the weld. The corresponding proportion in older welds was somewhat lower, perhaps reflecting the fact that welds with unacceptable levels of CLS had since failed and been removed from track. By comparison, the TR and PLK process welds exhibit negligible CLS defects.

Both straight-break and split-web failure types have been associated with the presence of slag inclusions at the edge of the weld collar. A significant advantage of the radiographic testing has been the ability to detect and size these inclusions, although it was not possible to locate these in the transverse direction (through the web thickness). Inclusions located at the edge of the weld collar are considered more detrimental in terms of potential crack initiators. Approximately 75% of the short-preheat welds exhibited significant inclusion levels in the web, while the TR and PLK weld types have lower inclusion numbers. The single-use crucible procedures, in particular, are capable of providing much cleaner welds. Determining the incidence of inclusions in the web has allowed welding practices to be monitored, with increases in inclusion numbers possibly associated with a decrease in tapping times or pick-up from the crucible or crucible cover (for multi-use crucibles).

CLOSING REMARKS

The increased incidence of defects and failures in aluminothermic welds in the Newman mainline and associated tracks have highlighted the inherent limitations of this welding process as axle loads approach 40 tonnes. The current approach to testing and approval of aluminothermic welding procedures therefore encompasses the following aspects:

- is the process technically sound, i.e. is it capable of producing consistent and high quality welds with the desired performance characteristics if the recommended procedures are followed?
- is the process inherently robust, i.e. is the quality of finished welds dependent on the operator(s) attention to following recommended procedures such as setting up of the rail ends, gap widths and preheat conditions?

Welding processes such as those with single-use crucible processes offer significant advantages, not only from the perspective of improved weld quality, but also because the process is easier to use and hence more attractive to the welding crews.

Since the change-over to the TR process, the incidence of split-web failures in newer welds has decreased to negligible levels; however straight-break failure continue to occur during the colder months. This has been partly attributed to continued use (but since discontinued) of heat-blocking to modify the residual stress distribution. Only a limited number of PLK welds have been installed in track, with no failures or defects reported to date. The in-service behaviour of both weld types continues to be monitored on regular basis, with particular emphasis on weld batter behaviour, which is expected to be slightly inferior to that of the SkV-F process. The extent and severity of weld batter has also increased through other factors, such as the introduction of the AC6000 locomotives, which are capable of operating at higher adhesion limits.

The weld dip gauge [9] is being used to assess the alignment and longitudinal profile of new welds, and also to monitor weld batter on a continuing basis. This gauge provides detailed longitudinal profiles over a distance of ± 500 mm from the weld centreline, and hence is capable of assessing weld batter which is attributable to the hardness variation across the welds, and the dipping or peaking associated with alignment and peaking of the rail ends during welding. The severity of localised dipping at welds has also been assessed during routine track condition monitoring using accelerometers mounted on the axle boxes of the track recording car (Figure 10), although further work is required to calibrate the resultant acceleration levels against weld condition. An extension of the latter approach involves using instrumented axle boxes on ore cars, in conjunction with measurement of spring nest deflections as a means of assessing track condition.

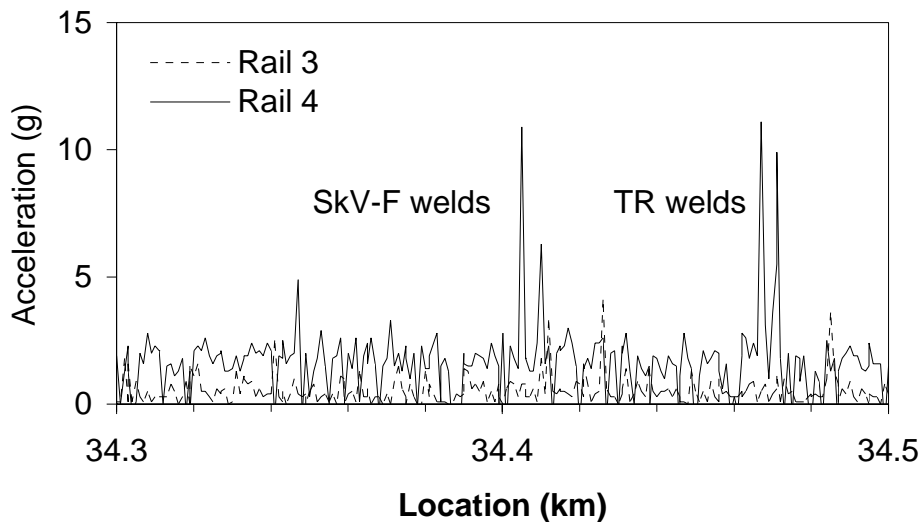


Figure 10: Axle box acceleration levels over aluminothermic welds (track recording car)

One outcome of the in-track weld monitoring program is evidence of variability in the longitudinal profile of new welds, possibly as a result of the set-up and finish grinding procedures. This has immediate consequences in terms of increased impact loading at welds, and associated deterioration in track condition (due to ballast pumping). Further work is aimed at improving this aspect of the field welding procedures.

The recent improvement in defect and failure rates in newer aluminothermic welds has provided an indication of the success or otherwise of the current approach to assessing and approving welding procedures for in-track use. However the question still remains as to the long-term viability of aluminothermic welding of rails as axle loads approach or exceed 40 tonnes. The laboratory test program is aimed at measuring characteristics such as hardness and strength levels, stress distributions (residual and under simulated service loads) and fatigue performance, and hence provides an indication of the maximum loading conditions or stress levels that the weld(s) can sustain without increasing the risk of failure. The in-track instrumentation program has demonstrated that the loading conditions at aluminothermic welds are severe, with the geometry of the weld, the longitudinal and transverse profiles at the running surface, and rail and/or sleeper support conditions influential in determining the level of impact loading and the resultant stress levels in the weld(s). In particular, wheel-rail contact conditions that promote eccentric loading of the rail head, in conjunction with lateral loads arising from bogie steering forces or vehicle response(s) to track geometry errors increase web vertical stresses to unacceptable levels. These aspects require attention if aluminothermic welding of rails is to be continued as the primary field welding procedure.

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ABSTRACT

Aluminothermic welding is used by BHP Iron Ore Pty Ltd for all field welding requirements. The preferred process utilises a short preheat and a portion hardness of 340-360 HB to provide weld characteristics compatible with high strength rail grades used in mainline tangent and curved track. In response to recent failures in aluminothermic welds, and in recognition that such welds represent one of the major limitations to further increases in axle loads, a program was undertaken to reduce the risk of premature failures, and to develop improved rail welding and track maintenance practices which would meet the performance demands of higher axle loads. Alternative aluminothermic welding procedures were assessed using a combination of laboratory and in-track testing. A detailed analysis of weld failures and extensive in-track instrumentation program were undertaken to correlate failure modes with the in-track loading environment. Revised inspection procedures, including radiographic testing, were used to identify defective welds and audit welding procedures. The results of this program highlight the limitations of existing aluminothermic welding procedures as axle loads approach 40 tonnes, and provide the basis of a performance-based specification for aluminothermic welding of rails for high axle load conditions.

KEYWORDS

Rails (railroad), rail welding, aluminothermic welding.