OFFICE OF THE national rail safety regulator

ONRSR Technical Review

Wheel Failure Incidents and Other Data in the Hunter Valley: 2013–2015

safe railways for Australia

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Office of the National Rail Safety Regulator

Level 1, 75 Hindmarsh Square, Adelaide SA 5000

PO Box 3461, Rundle Mall, Adelaide SA 5000

Phone: 08 8406 1500

Fax: 08 8406 1501

E: contact@onrsr.com.au

W: www.onrsr.com.au

www.twitter.com/ONRSRAustralia

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1 Background

From 2013 to 2015, Operator A experienced eight wheel failure incidents (that is, involving fractures and large thermal cracks) in its heavy haul Hunter Valley operations. The incidents involved two types of 120 tonne coal wagons, namely:

> Type 1 vehicles (seven incidents), which are not equipped with electronically controlled pneumatic (ECP) braking systems but have bogies which are fitted with AR-1 steering arms (full steering capability), and

> Type 2 vehicles (one incident), some of which were fitted with frame braced (partial steering capability) Barber bogies, which came from older, scrapped wagons.

Given the significant number of wheel failures that had occurred in a relatively short period and coupled with the fact that there could be potentially very high consequences, the Office of the National Rail Safety Regulator (ONRSR) commissioned MetallTech Pty Ltd[1] (MetallTech) to conduct a global metallurgical review covering all eight events. It should be noted that, prior to this engagement, MetallTech had previously contributed to the individual investigations relating to three of the incidents.

Accordingly, this report is a review of the metallurgical and associated factors covering all eight wheel failure incidents and has been issued for the benefit of like-for-like railways.

2 Summary of the eight incidents

A summary table of the incidents was produced by ONRSR – see Appendix 1. The wagon numbers, dates and failure types of the incidents were:

> Type 1, vehicle A	May 2013	Shattered rim initiated by thermal crack
> Type 1, vehicle B	July 2014	Thermal cracks
> Type 1, vehicle C	August 2013	Shattered rim; unknown initiator
> Type 1, vehicle D	November 2014	Thermal crack
> Type 1, vehicle E	May 2015	Thermal cracks
> Type 2, vehicle	August 2015	Shattered rim initiated by thermal crack
> Type 1, vehicle F	October 2015	Thermal cracks
> Type 1, vehicle G	November 2015	Thermal cracks

The eight incidents comprised:

> 3 wheels with shattered rims, with 2 initiating at thermal cracks and 1 unknown

> 5 wheels with thermal cracks

> 7 wheels were produced by Company A and 1 by Company B

> Service life/rim thickness

- Company A - 10 to 18 years/22 to 26mm
- Company B - 5 years / 50mm

> Detection methods

- 1 WILD[2] impact alarm (465kN reading)
- 1 derailment (highest WILD reading was 326kN two days before the incident)
- 6 visual at inspections and maintenance interventions

[1] Metalltech Pty Ltd provides metallurgical and materials consulting services to the rail industry.
[2] WILD – Wheel Impact Load Detector

3 Referenced documents

The documents reviewed in this investigation were mostly reports and data produced by the principal stakeholders (Operator A and ONRSR) and investigation reports commissioned from subcontractors, as described below. The document descriptions below are grouped by the wagon number / incident date, plus a general group.

The documents specifically referenced in this metallurgical review are listed separately in the bibliography, followed by listings of all the documents reviewed. Additional data included a large number of photographs, including those contained in stakeholders' reports. It should be noted that some of these documents have not been attached as part of this report.

Type 1, vehicle A May 2013

> Operator A Technical Report & Appendices

> Operator A System Safety Report

> Company A, Bureau Veritas & MetallTech metallurgical reports

Type 1, vehicle B July 2014

> Bureau Veritas metallurgical report

Type 1, vehicle C August 2013

> Operator A Technical Report & Appendices

> Company A and MetallTech metallurgical reports

Type 1, vehicle D November 2014

> Operator A Technical Report

> Company A metallurgical report

> ONRSR incident review reports

Type 1, vehicle E May 2015

> Operator A Site Logs

Type 2 vehicle August 2015

> Operator A Technical Report & data

> Company A and MetallTech metallurgical reports

> OTSI incident report

Type 1, vehicle F October 2015

Type 1, vehicle G November 2015

> Operator A Site Logs

General

> Operator A cracked wheel report recommendations and status spreadsheet[3]

> Operator A risk assessment spreadsheet[3]

[3] Not included in this report with availability subject to the approval of Operator A

4 Wheel failure mechanisms

The failure of three wheels by shattered rim was significant in many ways, not the least of which was the initiating defects that were not detected beforehand. If the other five wheels had continued in service, they too were likely to develop into shattered rim failures.

Shattered rim failure was originally and typically used to describe sub-surface fatigue cracking caused by rolling contact stress and propagating approximately parallel to the tread, with the fatigue cracking initiated at large non-metallic inclusions (typically aluminium oxides). The term has become more general, now describing a similar fatigue cracking pattern formed from any defect. For two of the shattered rim Operator A wheels, the initiator was a large thermal crack, and for the other wheel, the initiator was probably also a thermal crack. The initiator in this wheel may have been an inclusion, however, none were found in the metallographic examinations, although such inclusions cannot be discounted, as they can be sparsely and unevenly distributed.

Thermal cracks form radially in the wheel tread due to excessive heat input from tread braking. A common cause is misaligned brake gear leading to overhanging brake blocks. This concentration of brake block force on the outer edge of the rim leads to excessive heat build-up at the edge, forming thermal cracks. Other potential causes of high heat input leading to thermal cracking are dragging parking brakes and abnormal service brake operation (e.g. the consist containing the Type 2 vehicle had had train handling and abnormal braking events on three consecutive days a month prior to the incident).

Thermal cracks can form in a wheel at any life stage (e.g. the Type 1, vehicle B wheel was 50mm rim thickness), however, a thin rim wheel is more susceptible as the thin outer section is a vulnerable region of lower rigidity and heat capacity, with a higher propensity to unusual thermal distortion. Thin rim was a factor in 7 of the 8 incidents (that is, 22 to 25mm in the shattered rim incidents and 23.5mm to 26mm in the thermal crack incidents).

Fatigue is the main mechanism in propagation of large cracks in wheels (as seen in the shattered rim failures and it is the predominant mechanism in thermal crack propagation after initial formation). A factor for thin rim wheels is their high stress age, making them more susceptible to fatigue cracking, that is, the stresses of operation over a long period of cycles, particularly in the thin rim condition, place the material well along the fatigue stress/cycle curve, needing only a step-change factor, such as a thermal crack, to precipitate fast growing fatigue cracking.

5 Literature standards relating to shattered rims

The Operator A report on Type 1, vehicle A wheel failure incident considered a number of reports and a standard in the literature.

> A peer reviewed relevant technical paper concerned finite element and fractured mechanics modelling, with insights into the history and factors of shattered rim. The initiators in the studied wheels were large internal inclusions and it was surmised a shattered rim fatigue crack was initiated under a very high wheel load, such as an impact, which caused a high level equivalent stress intensity factor (Δk_{eq}). High Δk_{eq} occurs with a combination of high wheel load, large crack size, thin rim and large crack depth. The study did not include thermal cracked wheels, however, the conclusions on stress intensity are very relevant to the Operator A wheel failures as high wheel load, thin rim and large thermal cracks cause very high Δk_{eq}. It is probable Δk_{eq} is so high in these circumstances that service wheel loads may initiate shattered rim cracking (that is, without requiring additional loading from an impact)

> Peer reviewed relevant technical paper concerned wheel failures originating at inclusions, with shelling caused by rolling contact fatigue (RCF). Thus, it provided little insight into the thermal crack / shattered rim Operator A failures.

> A peer reviewed relevant technical paper was a deterministic mechanic model of subsurface crack propagation, not useful for life prediction of cracked wheels, thus of little assistance in the Operator A situation.

> A peer reviewed relevant technical paper is a wheel design tool. One observation in the standard is particularly relevant to the Operator A failures – Clause 7.2.1 states "The wheel configuration (at the condemning limit) is quite sensitive to the development of large thermal stresses.", thus a thin rim is susceptible to thermal cracking from high thermal inputs.

6 Contributing factors

Factors potentially contributing to large crack formation in wheels include bogie characteristics, material grade, rim thickness, sustained thermal input, residual stress levels, tread geometry and material parameters such as inclusion micro cleanliness, mechanical properties and fracture toughness.

6.1 Bogie characteristics

The wagons involved in the incidents had some form of steering bogies[4], which have the potential to promote fatigue induced wheel failures (rather than failures because of wear). Steering bogies have significantly reduced flange wear but a much more defined and narrower wheel / rail contact band.

This latter feature would promote rolling contact fatigue. In addition, wheel re-profiling interventions are less frequent giving fewer opportunities to identify and remove any suspect thermal activity and tread defects.

Due to the conventional braking system fitted to Type 1 vehicles, some in a train consist would experience differential braking demands and associated higher thermal inputs.

6.2 Material grade

Of the Company A wheels, six were AAR Class B and one (Type 2 Vehicle) was Class C (Company A micro-alloyed Class C) and the Company B wheel was Class C. These results indicate wheel class and material grade was not a factor in the failures.

6.3 Rim thickness

Seven of the failed wheels had thin rims (22 to 26mm), indicating it is a major factor in development of large cracks.

The one exception to thin rim failure was Type 1, Vehicle B, which had 50mm rim thickness. Large thermal cracks were clustered in one quarter of the wheel circumference, a most unusual situation.

6.4 Sustained thermal input

Sustained thermal inputs from abnormal brake related events can contribute to wheel failures. Such events include faulty slack adjusters, malfunctioning triple valves, parking brake not fully released and overhanging brake blocks.

[4] Type 1 vehicles are equipped with AR-1 steering arms (full steering capability), but are not fitted with electronically controlled pneumatic (ECP) braking systems. The bogies in Type 2 vehicles, some of which were frame braced (partial steering capability) Barber bogies, came from older, scrapped wagons. Although only one failure was related to a non-Type 1 vehicle (i.e. Type 2), the service life of wheels under these bogies was influenced by some degree of steering within the bogie – see Appendix Item 1

Train handling and abnormal braking was a factor in one incident (Type 2 vehicle) and four of the failed wheels had overhanging brake blocks, with the other four unknown. At the time of the Type 1, vehicle D wheel failure it was recognised by Operator A that 15% of Type 2 vehicle brake blocks were overhanging due to wear in the brake beam lateral restraint. Brake block overhang is a major factor in development of rim edge thermal cracks, thus was a strong likely factor in the eight wheel failures.

The cluster of thermal cracks in the thick rim of Type 1, vehicle B was almost certainly due to thermal overload, although it is probable material quality was implicated (see (6.7) Microcleanliness and (6.9) Fracture Toughness).

6.5 Residual stress

The wheels are specified with rim quenching at manufacture to increase hardness levels and induce residual compressive hoop stress, which reduces the propensity to cracking. The level of compressive stress is lower the further from the tread and can vary in the near-surface zone below the tread due to the thermal effects of braking.

Three of the failed wheels were tested for residual stress, with two retaining some compressive stress (Type 1, vehicles B and C) and one having reversal to tensile stress (Type 1, vehicle D). On this limited sample, it seems the residual stress level is a minor factor in the development of large cracks, with other factors having much greater influence.

6.6 Tread geometry

Wheel profile does not necessarily relate to cracking except the patterns may be indicative of abnormal conditions. Abnormal wear can indicate abnormal brake operation and / or abnormal bogie dynamics. Abnormal geometry, such as rim edge angularity, indicates some unusual operating condition.

Of the five wheels tested by a metallurgical laboratory, the profile of one was of no interest as it had been turned before testing (Type 1, Vehicle B) and the profiles of the other four were of interest:

> Type 1, vehicle A Not profiled - photos showed considerable rim edge angularity and it was noted in the Operator A report

> Type 1, vehicle C Profiled - showed significant wear from lateral displacement of the wheelset and significant rim edge angularity

> Type 1, vehicle D Profiled - showed normal profile except for significant rim edge angularity

> Type 2 vehicle Profiled - Company A reported "...no significant deviation from the original profile", however, the photos indicated slight rim edge angularity

The Operator A report into Type 1, vehicle C wheel failure incident addressed the issue of rim edge angularity extensively, including proposing a mechanism of the cause. No firm conclusions were reached and no connection with wheel failures was drawn.

6.7 Microcleanliness

Large non-metallic inclusions can be initiators in shattered rim failures.

Metallographic and fractographic examination of four of the wheels showed microcleanliness was not sub-standard, indicating material quality with respect to inclusions was not a factor in these failures. Microcleanliness examination of the Type 1, vehicle B wheel showed alumina (aluminium oxide) inclusions were slightly high, and a tensile test specimen had a material flaw, which was almost certainly a large inclusion. The close clustering of large thermal cracks in the wheel is probably another indication of scattered, large alumina inclusions (that is, the thermal cracks initiated at alumina inclusions). A cluster of alumina inclusions would not be unusual, as they can be sparsely and unevenly distributed.

6.8 Tensile properties and hardness

Tensile properties and hardness are obviously important in the performance of wheels and the property levels should not degrade throughout the service life.

Of the five wheels tested by a metallurgical laboratory, three were tensile tested and had results complying with specification. The five wheels were hardness tested and had results complying with specification. These results indicate material quality with respect to tensile properties and hardness, neither original levels nor degradation, was not a factor in the failures.

6.9 Fracture toughness

Fracture toughness of wheel steels is an important property in resisting both formation and propagation of cracks. The common test method indicating fracture toughness is the Charpy impact test.

Of the five wheels tested by a metallurgical laboratory, three were Charpy tested, with two having low results (Type 1, vehicles A and B) and one complied with specification (Type 1, vehicle C). The Type 2 vehicle (Company A micro-alloyed Class C wheel), while not tested for toughness, displayed excellent fracture toughness in the mode of fracture in the plate. These results indicate material quality with respect to fracture toughness was not a defining factor in the failures, except perhaps for Type 1, vehicle B, where one very low result and low average result (that is 4J and 9J) are another indication of poor material quality of the wheel.

7 Detection of failed wheels

Detection of the failed wheels was by:

> Type 1, vehicle A - Alarm from the WILD system with a 465kN impact reading, prompting an immediate inspection

> Type 1, vehicles B, C, D, E, F & G - Visual detection by personnel during inspections and maintenance

> Type 2 vehicle - Catastrophic fracture and derailment

For Type 1, vehicle C, the WILD showed escalating readings, which were below the 250kN low alarm threshold. This was despite a huge crack penetrating to both the tread and underside of the front rim. The reason the WILD impact readings were well below the alarm level was the crack had not progressed to the point where there was breakout and collapse of the rim, just spalling-like chipping at the tread part of the crack. There is no doubt the crack would have progressed quickly, perhaps within a couple of weeks, to the catastrophic breakout/collapse condition.

8 Comments on measures implemented or contemplated by Operator A

In response to the wheel failures, Operator A studied the issues stemming from the incidents and implemented measures to prevent formation of threatening cracks. These responses were covered in the investigation reports for each of the wheel failure incidents and in various additional documents produced in the intervening periods

8.1 Possible causal factors in wheel failure

The possible factors from Operator A's perspective are listed below. For each factor, the comments represent the opinions of MetallTech from laboratory test reports, consideration of the metallurgical aspects and review of the supplied documents.

8.2 Low rim thickness

The existing minimum permissible rim thickness on wheel turning had been 25mm with the minimum allowable thickness (in service) 22mm. Subsequently, the minimum rim thickness on wheel turning was then increased to 28mm and the removal from service criteria changed, to wheel rims under 25mm with a WILD impact reading above 200kN or any wheel rims under 23mm. Despite the implementation of these changes, Operator A still reserves the right to revert to the old threshold of 22mm minimum allowable rim thickness. An engineering review of wheel stresses with respect to low rim thickness was contemplated, however, as Operator A had limited expertise in the area, it was decided to "avoid elevated stresses" by "controlling rim thickness" by means of the above measures.

Comment Although unsupported by quantitative data, the ad hoc decision to increase rim thickness parameters gives a significant improvement in resistance to crack formation. As the rim thickness of the eight failed wheels varied from 22 to 26mm (discounting the outlier 50mm rim), it is doubtful the new 23 / 25 / 28mm minimum thicknesses will completely eliminate the risk of large crack formation, unless complementary measures provide synergy.

8.3 Rim edge angularity

Rim edge angularity occurred in at least three of the failed wheels (Type 1, vehicles A, C & D) and probably in the Type 2 vehicle, with the three 2015 failures unknown. Despite Operator A's investigations into the mechanism of rim edge angularity and a link with the failures, the phenomenon remains largely a mystery.

Comment The high proportion of failed wheels with rim edge angularity strongly suggests a link between the two. There is an obvious link with thin rims, wherein the rim was unable to support the working stresses, causing plastic deformation. It is likely that sustained high temperatures were a factor (that is, strength reduces with increasing temperature, eg. data for wheel steel could not be obtained, but information on other steels suggests yield strength reduction factors of about 0.9 at 200°C and 0.8 at 400°C).

8.4 Overhanging brake blocks

Due to a known problem of wear in the brake beam lateral restraint in the Type 1 vehicles. Operator A has instigated modification of bogies at next scheduled overhaul to prevent excessive lateral brake beam float and, as a temporary measure before overhaul, install strip inserts in the brake beam pocket wear liners to limit float.

Comment It strongly appears brake block overhang is a major factor in formation of thermal cracks in Type 1 wheels. Thus, the measures being taken to limit brake beam float to prevent block overhang should have a major impact on preventing failed wheels.

8.5 Train handling & abnormal braking

In at least one of the wheel failures, train handling and abnormal braking were factors in the incident due to high heat loading into the wheels. Operator A has investigated how to mitigate these factors, including crew training and investigation of the operational factors and locations where high heat loads are a potential problem. Other abnormal braking events can be classified as equipment breakdown (e.g. faulty slack adjuster and malfunctioning triple valve) or operational shortcoming (e.g. handbrake not fully released). These factors need to be addressed in maintenance practices and operational training.

Comment Any measures to reduce heat loading into wheels will be of benefit in preventing crack formation and probably rim edge angularity.

8.6 Maintenance practices

Operator A has taken measures to increase inspection awareness and implemented special inspections. It is likely the last three failed wheels were discovered due to the heightened inspection regime.

Comment The earlier wheel failures have apparently concentrated Operator A's corporate focus and brought about positive changes in inspection and maintenance practices. However, there have been no additional engineering controls implemented that could be more effective than the WILD system and a number of Operator A's recommendations have not been actioned.

8.7 WILD system

WILD readings have provided data allowing detection of wheel failures, but the system alerts failed to prevent a catastrophic failure (that is, Type 2 vehicle). The WILD system is not a reliable method to detect wheel defects as it relies on specific characteristics (to be present at the time of negotiating the trackside device) to be effective. Shortcomings of WILD include: the fact it is primarily a track protection system not designed for wheel fault monitoring; the manual and somewhat convoluted nature of the communication from the rail infrastructure manager to Operator A; and the manual, part- time decision making process at Operator A. Operator A has investigated the use of WILD, including a review of impact warning limits, however, any changes or insights have not yet been published.

Comment The WILD system is an imperfect means of detecting wheel cracks as high impacts are not produced until cracking has reached the extent of a breakout or collapse of the rim. Furthermore, the magnitude of the impact from a tread discontinuity can be substantially reduced by normal wheel/rail interaction causing plastic flow of the metal around the crack. Additionally, the system produces little or no useable readings from large thermal cracks. Changes to the impact warning limits, communication channel or decision-making process would likely result in only a marginal increase in its effectiveness, unless changes were very comprehensive, which would likely have a significant, negative operational impact.

8.8 Condition monitoring

The other wayside condition monitoring system currently in use by Operator A (at its train servicing facility) is the electronic roll-by inspection system for measuring dimensional parameters, but it has no functionality to detect cracks. Operator A has contemplated a system that can detect cracks, however, the results of any investigation have not been published.

Comment Installation of wayside monitoring to detect cracks, if such a system exists, would considerably lower the risk of large cracks reaching the catastrophic stage.

Item 1 - 120 Tonne Coal Wagon Wheel Failures in the Hunter Valley (2013 onwards)

Wagon & Bogie ID	Material Specification	Service Life (years)	Rim Thickness (mm)	Make & Year of Wheel	Detection Date	Defect Detection Method	Defect Details Upon Initial Detection	Remarks (noting that this is a common wheelset in this class and can be used in any of the bogie types, W69 low stress (S-Plate) wheel, WS202, G class PUBs, etc).
Type 1 vehicle A	TRS 0139 Class B	13 1.2Mkms	23.9	Company A 2000	31/05/13	WILD[2] at Metford (465kN)	Sub-surface defect.	Wheel turns 2004, 2007 & 2010. Travelled approx. 1.2 million kms since new. Travelled 350,000kms since last turn in June 2010. Two opinions, shattered rim sub-surface initiation (BV[3]) or thermal crack (Company A)
Type 1 vehicle B	Class C AAR M107/M208 J36 design	5 (55 months) 450,000kms	50 44 (after machining)	Company B 2008	09/07/14	Manual during regular maintenance activity, crack detected in wheelset	Rim edge thermal, significant cracks (7 off) propagating from the rim edge.	Crack detected after WST (wheelset) overhaul (prior to reinstallation). Some evidence lost since wheel was profile machined (6mm removed) prior to the metallurgical analysis conducted by BV[3]. Poor fracture toughness. Youngest of the failed wheels to date.
Type 1 vehicle C	Class B AAR M107/M208	18	22 (Hollowing evident)	Company A 1995	25/08/13	Manual during maintenance at OATSF[4]	Crack detected on underside of rim and had propagated through to the tread surface.	WILD readings were starting to escalate; however, the peak reading (207kN) was still below the 250kN limit. Pronounced tread hollowing evident with the wheel at the end of its 3 year service interval & was due for removal during SM[5]. Both wheels exhibited rim edge angularity.
Type 1 vehicle D	Class B AAR M107/M208	18	23.5 (front face)	Company A 1995	04/11/14	Manual during changeout of adjacent wheel at OATSF	Rim edge thermal, single fracture propagated across the tread & down the rim.	WILD reading on the adjacent wheel (i.e. on the other side of the axle) prompted a wheelset change. Hence, was this particular wheel also inspected? Three large thermals with multiple small thermals around the rim edge.
Type 2 vehicle	Class C with vanadium AAR M107 (Company A micro-alloyed Class C)	17	25	Company A 1998	28/08/15	Derailed	MPI[6] revealed six thermal cracks located at a number of locations around the circumference of the wheel tread. One crack had propagated beyond the tread and into the damaged rim front face.	Prior to fitting to the Type 1 vehicles, three piece Barber frame braced bogies were initially fitted to another wagon type, but due to structural issues, were eventually replaced with the Type 2 vehicle car bodies. This was the first generation micro-alloyed C Class wheel material. Portion of flange and web had dislodged from the wheel. Missing piece of wheel was not recovered. Peak WILD reading was 326kN.
Type 1 vehicle E	Class B AAR M107/M208.	17	26	Company A 1998	25/09/15	Manual during extra inspection at OATSF	Rim edge thermal, fracture detected by maintenance staff.	MPI then identified a second large fracture and a series of smaller cracks. Similar tread hollowing evident on both wheels (of the wheelset) with no evidence of brake block overhang or any pronounced step change on the flange or at the root of the wheel flange. No WILD readings. Low fracture toughness noted. No planned metallurgical report by PN.

Type 1 vehicle F	Class B AAR M107/M208	14	23	Company A 2001	06/10/15	Manual during planned inspection at OATSF	Rim edge thermals, eight thermals plus smaller ones around outer rim edge	Some evidence of overhanging brake blocks. Larger thermals had progressed through the rim. Wild reading of 140kN. Possible related hot wheel incident at Belford on 01/03/15. No planned metallurgical report by operator A.
Type 1 vehicle G	Class B AAR M107/M208	10	24	Company A 2005	07/10/15	Manual during inspection of stored train at GTSF (additional to TMP)	Rim edge thermals, series of rim edge thermals (Class 4) but with no cracks through the rim.	Some evidence of brake block overhang. No WILD readings. Inspection resulting from CM identification of thin rim WST. No planned metallurgical report by operator A.

Notes
[1]WILD – Wheel Impact Load Detector
[3]BV – Bureau Veritas
[4]OATSF – Operator A Train Servicing Facility has an electronic roll-by facility that is manned between 0900-1700 hours Monday to Friday only. On this basis, at best, only approximately 60% of suspect wheels will be captured.
[5]SM – Scheduled Maintenance, usually occurs at three yearly intervals.
[6]MPI – Magnetic Particle Inspection