Railway Accident Investigation Unit Ireland

INVESTIGATION REPORT

Broken rail, Newbridge, Kildare, 23rd February 2023

RAIU Investigation Report No: 2024-R001

Published: 18th January 2024

Report Description

Report publication

Where the report has been altered following its original publication, details on the changes will be given.

Report structure

This report is written to conform as closely as possible to the structure set out in the "Commission Implementation Regulation (EU) 2020/572 of 24 April 2020 on the reporting structure to be followed for railway accident and incident investigation reports" having regard to "Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety".

Reader guide

All dimensions and speeds in this report are given using the International System of Units (SI Units). Where the normal railway practice, in some railway organisations, is to use imperial dimensions; imperial dimensions are used, and the SI Unit is also given.

All abbreviations and technical terms (which appear in italics the first time they appear in the report) are explained in the glossary.

Descriptions and figures may be simplified in order to illustrate concepts to non-technical readers.

Further information

For further information, or to contact the RAIU, please see details below:

RAIU
2nd Floor, 2 Leeson Lane
Dublin 2, Ireland.

email: info@raiu.ie
website: www.raiu.ie
telephone: + 353 1 604 1050

Preface

The RAIU is an independent investigation unit within the Department of Transport which conducts investigations into accidents and incidents on the national railway network including the Dublin Area Rapid Transit (DART) network, the LUAS light rail system, heritage and industrial railways in Ireland. Investigations are carried out in accordance with the Railway Safety Directive (EU) 2016/798 enshrined in the European Union (Railway Safety) (Reporting and Investigation of Serious Accidents, Accidents and Incidents) Regulations 2020; and, where relevant, by the application of the Railway Safety (Reporting and Investigation of Serious Accidents, Accidents and Incidents Involving Certain Railways) Act 2020.

The RAIU investigate all serious accidents. A serious accident means any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact on railway or tramline safety regulation or the management of safety. During an investigation, if the RAIU make some early findings on safety issues that require immediate action, the RAIU will issue an Urgent Safety Advice Notice outlining the associated safety recommendation(s); other issues may require a Safety Advice Notice.

The RAIU may investigate and report on accidents and incidents which under slightly different conditions might have led to a serious accident.

The RAIU may also carry out trend investigations where the occurrence is part of a group of related occurrences that may or may not have warranted an investigation as individual occurrences, but the apparent trend warrants investigation.

The RAIU investigation shall analyse the established facts and findings (i.e. performance of operators, rolling stock and/or technical installations) which caused the occurrence. The analyses shall then lead to the identification of the safety critical factors that caused or otherwise contributed to the occurrence, including facts identified as precursors. An accident or incident may be caused by *causal, contributing* and *systemic factors* which are equally important and should be consider during the RAIU investigation. From this, the RAIU may make safety recommendations in order to prevent accidents and incidents in the future and improve railway safety.

It is not the purpose of an RAIU investigation to attribute blame or liability.

Summary

1 On the morning of the 23rd February 2023, as the 07:00 hrs Newbridge to Grand Canal Dock passenger service (Train P402) travelled on the *Up line* near Newbridge, Co Kildare; the driver (Driver P402) saw an *abnormal Continuous Automatic Warning System* (CAWS) *downgrade* on the train's in-cab display.

2 At 07:11 hrs Driver P402 reported this abnormal CAWS downgrade to the Mainline Signalman.

3 At 07:24 hrs the driver (Driver A501) of the 06:30 hrs Carlow to Dublin Heuston passenger service (Train A501) also reported a CAWS downgrade in the same area to the Mainline Signalman. The Iarnród Éireann Infrastructure Manager (IÉ-IM) Signalling, Electrical & Telecommunications (SET) Department were advised, and an SET member of staff was dispatched to site to investigate the suspected fault.

4 Twenty-eight passenger trains travelled over the affected line, with drivers continuing to report abnormal CAWS downgrades as they approached the affected area; these drivers were advised to continue and obey lineside signals which were working normally.

5 The SET staff member discovered a *broken rail* at 10:52 hrs and trains were stopped on the affected line immediately.

6 The broken rail was found to have fractured through a flash butt welded joint. The rail had been installed on the 28th January 2023 (five days earlier).

7 The *flash butt welding* of the rail had been carried out off-site at IÉ-IM's Portlaoise Rail Welding Plant where rails are joined to make longer "*strings*" of welded rail.

8 The mechanism of failure for the broken rail was slag inclusion in the welding process causing a lack of fusion in the toe of the *rail foot*. The lack of fusion created a cracking initiation point which propagated from that location, probably starting from when the rail was handled or manoeuvred during delivery or installation; the crack then progressed through the remainder of the rail section in a single rapid event due to rapid overload.

9 The RAIU have identified the following possible causal factors which may have resulted in the lack of fusion:

- CaF-01 – An interruption to the flash butt welding process;
- CaF-02 – Insufficient cleaning of the rail ends resulting in the inclusion of slag during the flash butt welding process.

10 The following contributory factor was identified, in terms of the cleaning of the rail ends:

- CoF-01 – The current design of the rail end cleaner and the safety barrier restricted effective visual inspection of the rail ends; as a result, it is possible that residual contamination could have gone undetected at this stage.

11 A systemic factor related to the cleaning of the rail ends is as follows:

- SF-01 – This risk associated with not cleaning the rail ends adequately was not identified in any risk assessments at Portlaoise Rail Welding Plant; and as such control measures to address these risks have not been identified.

12 As a result, the RAIU make the following safety recommendations:

- Safety Recommendation 2024001-01 – IÉ-IM should risk assess whether the existing rail end cleaning equipment and processes adequately control the risk of weld contamination and identify improvements where required;
- Safety Recommendation 2024001-02 – IÉ-IM to investigate altering the monitoring and detection parameters of the rail welding machine to be able to identify and highlight possible anomalies in the welding process;
- Safety Recommendation 2024001-03 –IÉ-IM to revise the risk assessments for the Portlaoise Rail Welding Plant to ensure risks in the production process affecting the quality of rail welds are understood and control measures are identified.

Contents

RAIU Investigation and its context

Decision & motivation to investigate this occurrence

13 On the 24th February 2023, the RAIU on-call investigator received a notification of a broken rail on the Up line at Newbridge on the Cork mainline.

14 The RAIU conducted a preliminary examination and the RAIU's Chief Investigator made the decision to conduct a full investigation into the incident, given its impact on railway safety (*Article 20* (2)(c) of Directive (EU) 2016/798, Article 20, Obligation to Investigate), as under slightly different circumstances the incident may have led to serious accident with the potential for a fatality or serious injuries, due to risk of derailment as a result of the broken rail.

Scope & limits of investigation

15 The RAIU have established the scope and limits of the investigation as follows:

- Examine the processes around the production of welded rail strings and their handling, delivery and installation on site;
- Establish the sequence of events leading up to, during and after the incident;
- Identify any other precursors which led to the incident;
- Establish, where applicable, causal, contributing and systemic factors;
- Examine the training of staff involved in the incident.

Technical capabilities & investigation methods

16 The RAIU's Chief Investigator allocated RAIU Senior Investigators, trained in accident investigation, to conduct this investigation, as appropriate.

17 For this investigation, a metallurgical specialist consultant was engaged by the RAIU to assist in reviewing evidence.

18 During the investigation, the RAIU collated evidence through the submission of Requests for Information (RFIs) to the IÉ-IM Safety Department, the IÉ-RU Safety Department and site visits. Related to this investigation, the RAIU collated and logged the following evidence:

- The reporting and response to the incident;
- Photographs taken on the day from the site;
- CCE-PLM-WKI-012 Rail End Cleaning Process for New and 2nd Hand Rail, version 1.0, 27th November 2014;
- CCE-PLM-WKI-014 Flash butt Welding Process for New and 2nd Hand Rail, version 2.0, 26th July 2019;
- CCE-PLM-WKI-020 Bend Test Process for New and 2nd Hand Rail, version 1.0, 27th November 2014;
- CCE-PLM-OPS-066 CWR Production at Portlaoise Rail & Sleeper Depot, version 2.1 26th July 2019;
- CCE-PRSD-SSOW-56 CCE Safe System of Work – CWR Train Discharging of Rail, version 3.0, 11th February 2019;
- CCE-TMS-323 Technical Standard for the Stressing of Rail, version 2.1, 16th April 2019;
- CCE-TMS-362 Management of Rail Failures and Requirements for The Testing of Rails, version 1.2, 5th April 2012;
- CCE-TRK-WKI-003 Rail Test Work Instructions (Ultrasonic), version 1.0, 7th February 2011;
- CLRPMS2023_003 Offloading CWR Train Cork Line Rehabilitation Project Method Statement, version 1.0, 1st Jan 2023;
- CLRPMS2023_101 Panel Relaying Works PR 1 Cork Line Rehabilitation Project Method Statement, 26th January 2023;
- IÉ-IM Correspondence with Geismar post incident;
- IÉ-IM Service and maintenance records for the flash butt welding machine at Portlaoise; October 2021 and March 2023;
- IÉ Rule Book 09/13;

- IÉ General Appendix – Section J In Cab Signalling; version 9.0, 15th November 2021 (updates 2013 hard copy issue);
- IÉ Signalling General Instructions 2007;
- IÉ-IM Voice data recorder communications between the Mainline Signalman and those responding to the incident;
- IÉ-IM Training and competence records for the rail welding plant operatives;
- IÉ-RU driver training material extracts;
- RAIU Measurements of rails stored at Portlaoise;
- RAIU photographs and observations of the rail welding plant;
- RA13702 (Revision of RA8554) Loading Rail Bellview Waterford Port version 1.0, 11th July 2017;
- RA4248-50 Rail Cleaner Revised, version 3.0, 24th June 2016;
- RA5118-21 Using the Welding Line Welder, version 1.0, 5th June 2013;
- Risk Assessment 2018 - Welding Line, version 1.0, 13th September 2018;
- Safe Systems of Work for the offloading of the Continuous Welded Rail (CWR) train;
- Serco Report - Investigation of Broken Flash Butt Weld, Issue 1, published 2nd March 2023, produced by Serco Rail Technical Services (to be known in this report as the Serco Report);
- Welder data record weld no 187615 13th October 2022.

Communications & evidence collection

19 Communications were conducted through established processes (such as RFIs).

20 Relevant stakeholders were issued the draft investigation report for comment, comments were reviewed and responses on their comments returned. In this instance the stakeholders were: IÉ-IM, IÉ-RU and the Commission for Railway Regulation (CRR)[1].

21 All relevant parties co-operated fully with the RAIU investigation; with no difficulties arising.

[1] The CRR is the National Safety Authority (NSA) for the Republic of Ireland and is responsible for the regulatory oversight of the Safety Management System (SMS) and enforcement of railway safety in the Republic of Ireland in accordance with the Railway Safety Act 2005 and the European Railway Safety Directive.

Description of the occurrence & background information

Description of the occurrence type

22 The incident involved a broken rail on the Up line near Newbridge on the 23rd February 2023. In terms of categorisation, the EU Agency for Railways categorisation for this occurrence is an: Incident – Infrastructure.

Background to the occurrence

23 The broken rail occurred between Newbridge and Sallins & Naas Stations, County Kildare at a location 24 miles and 300 yards from Dublin Heuston on the Cork mainline (see Figure 1), approximately 2 kilometres (km) from Newbridge Station. The railway line is a on a low embankment which transitions into a cutting after the location of the broken rail.

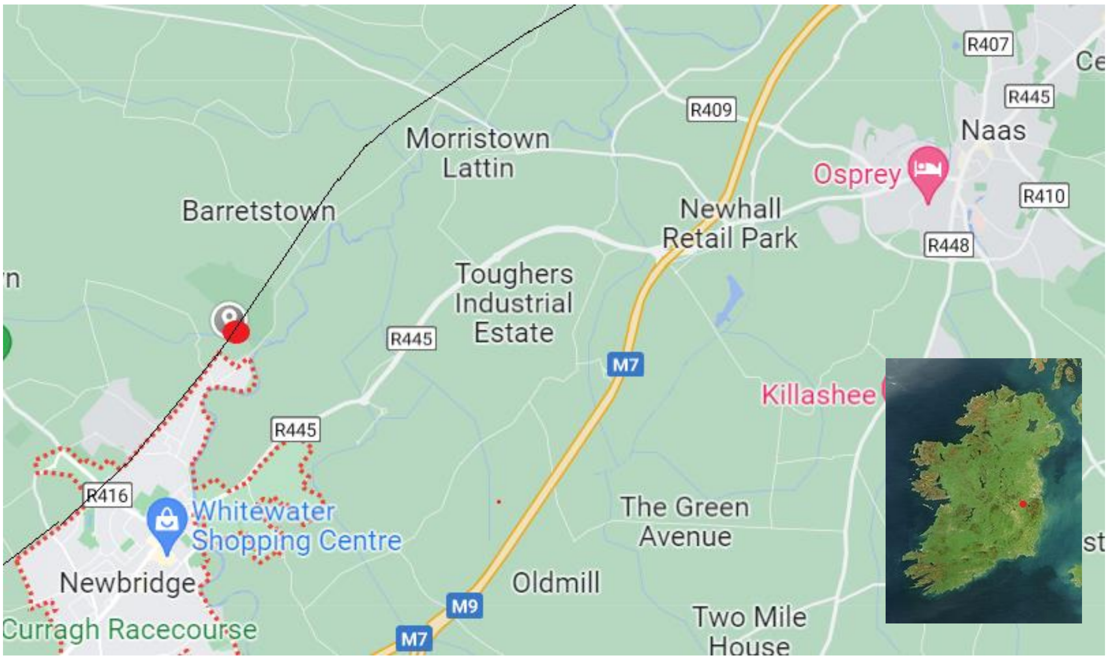

Figure 1 – Location of the broken rail

24 The rail that broke had been delivered to the site on the 20th January 2023, in readiness for an engineering possession of the line on the 28th January 2023 when it was installed. These works formed part of the Cork line relaying programme where complete sections of track were being renewed.

25 The weather at the time of the rail break was dry and cold. On the morning of the 23rd February, the air temperature at the nearest inland weather station to Newbridge (Oak Park) was recorded as being -1.8 ºC at around the time the break was likely to have occurred.

Deaths, injuries & material damage

26 There were no injuries as a result of the incident.

27 The damage in the incident was confined to the broken rail.

Other consequences as a result of the incident

28 As a result of the broken rail, the Up line was temporarily closed between 10:52 hrs and 12:07 hrs to carry out a temporary repair. Eight trains were directly delayed with a total of 267 delay minutes attributed to the incident.

29 An *Emergency Speed Restriction* (ESR) of 25 miles per hour (mph) (40 kilometres per hour (km/h)) was subsequently imposed until a permanent repair could be carried out to the section of rail.

Parties & roles associated with the incident

IÉ-IM

30 IÉ–IM is the infrastructure manager who owns, maintains and operates the railway infrastructure in Ireland and operates under a Safety Authorisation certificate issued by the CRR. The IM Safety Authorisation is issued in conformity with Directive (EU) 2016/798, S.I. No 476 of 2020 and Commission Regulation (EU 2018/762). The authorisation was renewed on the 24th March 2022 for a period of five years. The IÉ-IM departments involved in the incident and relevant to this investigation are:

- IÉ-IM CCE Department – The CCE directs the Technical Support, Business Support and Safety sections within the Civil Engineering Department of IÉ-IM. This department carries out the inspections and maintenance of track and structures and is divided into three different geographical areas, with offices based at Dublin, Athlone and Limerick Junction;
- IÉ-IM SET Department – Carries out the maintenance and repair of the SET equipment on the infrastructure;
- IÉ-IM Operations Department – Operates the signalling system and monitors the operation of the network and provides the first level of response to incidents. The network is controlled from Centralised Traffic Control (CTC) Dublin and several other signalling control locations.

31 The IÉ-IM roles involved, directly and indirectly, and respective experiences at the incident, are as follows:

- The Mainline Signalman – responded to the reports of abnormal CAWS downgrades from traincrew;
- The SET Technician – went to the location of the suspected fault and located the broken rail;
- The CCE Permanent Way Inspector (PWI) – went to location of the suspected fault and arranged the subsequent response to the broken rail;
- The CCE plant operatives – located at Portlaoise Rail Welding Plant who operate the rail end cleaning machine and rail welding machine. These operatives receive external training on the rail welding machine and shadow an operator before being permitted to work unaccompanied.

IÉ-RU

32 IÉ–RU is the railway undertaking who operated all of the scheduled services that ran over the affected section of line on the 23rd February 2023. The RU also employed the drivers and maintained the rolling stock involved. The RU operates under a Safety Certificate issued by the CRR. The RU Safety Certificate was renewed on 23rd March 2018 for a period of five years (valid at the time of incident).

33 The following IÉ-RU roles involved indirectly, were as follows:

- Driver P402 – Driver of Train P402 (07:00 hrs Newbridge to Grand Canal Dock) who first reported the abnormal CAWS downgrade on the in-cab display;
- Driver A501 – Driver of Train A501 (06:30 hrs Carlow to Dublin Heuston).

34 Both drivers were in date for competency assessments and issued with European Train Driving licences and Complementary Certificates.

35 Drivers of the subsequent services also reported CAWS downgrades in the same location.

Rolling stock

36 Trains P402 and A501 which first reported the abnormal CAWS downgrades were both operated by Class 22000 Intercity railcars.

37 The Class 22000 railcars are a diesel multiple unit (DMU) type used on intercity and some local services on the IÉ-RU network (see Figure 2). Each unit is formed of between three and five vehicles in normal service. Each vehicle is independently powered, and these are capable of being driven from a driving cab at each end. Two or more units can be coupled together and driven by a single driver.

38 Trains P402 and A501 were both formed of four vehicles each. The total length of each train was approximately 94.8 metres (m) with a mass of 189 tonnes. The maximum permitted speed of the unit is 100 mph (160km/h)

Figure 2 – Class 22000 Intercity railcar

Operations

39 The affected section of the Cork mainline is used by passenger trains and a limited number of freight services.

40 The maximum permissible speed on the Up line where the broken rail was found was 90 mph (145 km/h) for passenger trains and 50 mph (80 km/h) for freight trains.

41 The affected line is known as the Up line, with trains normally operating in one direction.

Infrastructure

Signalling & Communications

General Description

42 The signalling at the location is three and four aspect colour light signalling controlled from CTC located at Dublin Connolly. It is operated to the Track Circuit Block regulations. Train detection is by axle counters.

43 The train radio system enables direct communication between train drivers and the Mainline Signalman.

44 The infrastructure and all passenger trains using it are also equipped with the CAWS system which repeats the signal aspect in the cab between a given point on approach to the signal, through the signal section until the approach to the next signal in the direction of travel.

45 There is no train protection system installed on the Cork mainline.

General description of the track infrastructure

46 The railway at this location consists of a double track line with flatbottom CWR mounted on concrete sleepers in ballast, see Figure 3.

Figure 3 – Flat bottom track as installed at the location

47 The track on the affected line was recently re-laid as part of the Cork Line Rehabilitation Project with new rail, sleepers and ballast.

Rail

General description of rail parts

48 The rail at the location is “E1” profile rail with a weight of 54 kilogram/metre (kg/m). This is a standard “flat bottom” rail section widely used across Europe. The terms for parts of the rail section, these are detailed in Figure 4.

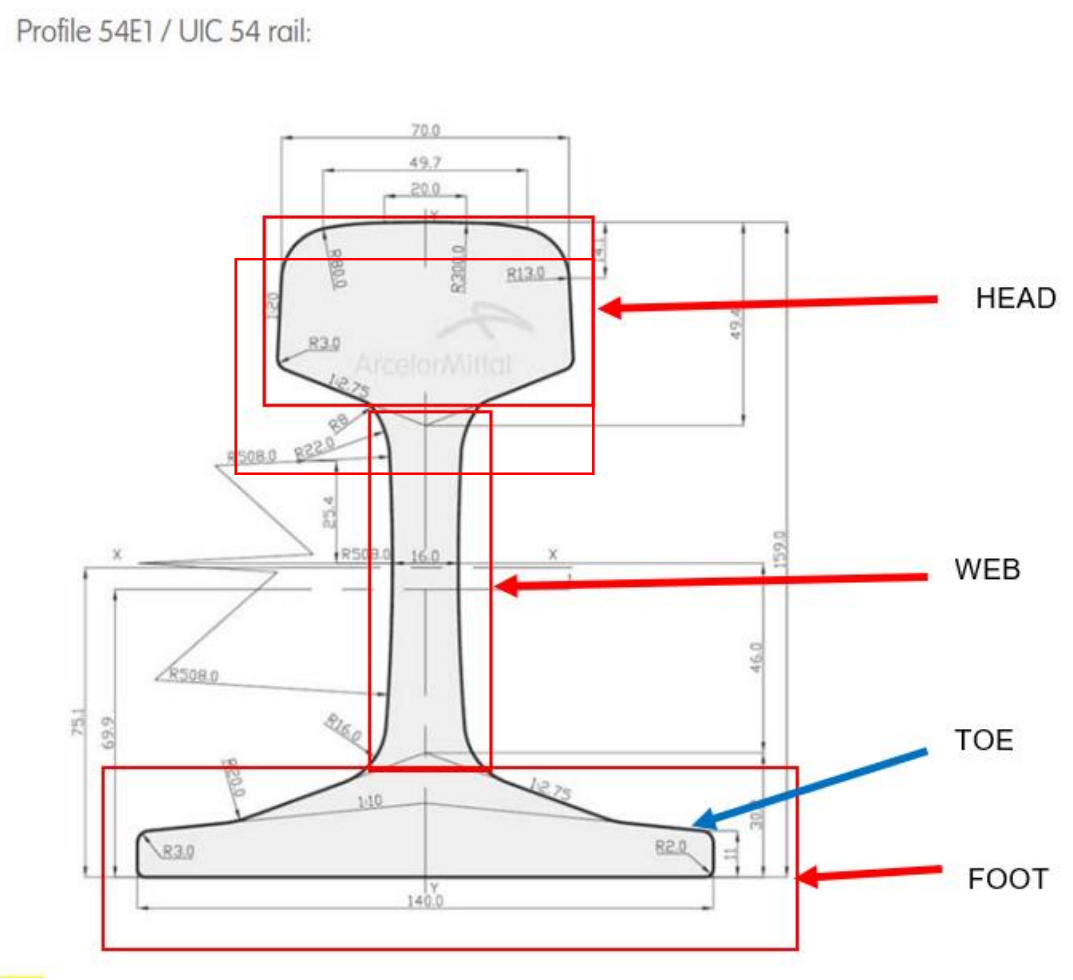

Figure 4 – 54kg/m E1 rail profile (source Arcelor Mittal)

Rail production, procurement & transit to Portlaoise

49 IÉ-IM purchase 54 kg/m E1 profile rail from Arcelor Mittal who manufacture it at their Gijon plant in Spain (formerly Ensidesa). The rail is purchased though an ongoing contract in place since 2018.

50 The rail is supplied in 36 m lengths and shipped to Waterford Port.

51 Arcelor Mittal follows EN Standard EN13674-1 Vignole railway rails 46 kg/m and greater (EN13674-1) which defines rail production quality standards. The rail production process includes *ultrasonic* and *eddy current testing* for the detection of the presence of abnormalities and defects in manufacturing and the inclusion of slag and “flat spots” into the material. The testing of the full width of the foot of the rail is not mandated in the standard. The dimensional tolerances of the rail are also defined, which includes the squareness of the rail ends.

52 The rail is handed over to the IÉ-IM and inspected at the quayside and then collected at approximately bi-weekly intervals by train for transport to Portlaoise Rail Welding Plant, where the rail is stored in stacks whilst awaiting welding with paint applied to the foot of the rail to identify the rail type (Figure 5).

Figure 5 – Rail ends in the stacks before welding

Portlaoise Rail Welding Plant

General description of Portlaoise Rail Welding Plant

53 The Portlaoise Rail Welding Plant is owned and operated by IÉ-IM. It is used to produce the strings of welded rail in factory environment in 144 m lengths and is capable of welding both new and second-hand rail.

54 Portlaoise Rail Welding Plant delivered approximately 1,600 welds in the six-month period between October 2022 and March 2023.

55 Rails go through the following stages and equipment in Portlaoise Rail Welding Plant:

a. Rail end cleaning – This is carried out by the rail end cleaner / brush which removes surface corrosion from the rail ends with abrasive brushes (of relevance to the investigation and further discussed in paragraphs 58 to 65);

b. Flash butt welding – This is carried out by the welding machine which joins the rails and shears or trims off surplus metal from the "*upset*" zone[2] of the weld where the material is forged together (of relevance to the investigation and further discussed in paragraphs 66 to 73);

c. Quenching – This is undertaken in the quenching unit to ensure controlled cooling of the welded joint to maintain mechanical properties of the rail. The quench requires the rail to air cool to 400 ºC before it will operate;

d. Pressing – Carried out in the hydraulic rail press which corrects any small misalignments in the rail by applying mechanical force;

e. Grinding the rail surfaces – The rail grinder removes any excess material from the running surfaces of the rail to ensure a consistent and correct profile;

f. Finish grinding – This finishing process removes any "bluing"[3] from the surface of the rail and occurs outside the rail welding plant building on the loading ramp where rails are stored awaiting loading. This uses portable grinding equipment.

56 The processes in Portlaoise Rail Welding Plant are documented in procedures and work instructions which form part of the IÉ-IM Safety Management System.

---

[2] Upset zone – The zone where the two parts being welded are forged together and material is extruded from the joint.

[3] Bluing is term used for discoloration caused by particular oxides during welding which can cause uneven surface corrosion if not removed.

57 IÉ-IM adheres to EN standard EN14587-1 Flash Butt Welding of Rails Part 1- new R220, R260, R260mn and R350ht Grade Rails in a Fixed Plant (EN14587-1). This is a voluntary standard, it is not directly referenced in the procedures applied to Portlaoise Rail Welding Plant.

Rail ending cleaning

58 The rail end cleaning machine (see Figure 6), manufactured by Geismar, cleans the rail end surfaces before welding to ensure good electrical contact by the welder and remove any contamination from the surfaces to be welded.

Figure 6 – The Rail Cleaner/ Brush from the operating position

59 The process for operating the rail end cleaner / brush is described in detail in CCE-WKI-PLM-012 Rail End Cleaning Process for New and 2nd Hand Rail (CCE-WKI-PLM-012).

60 The operator positions both rail ends into the cleaner via the conveyor system, then selects the cleaning cycle.

61 The machine will automatically align the rail ends and indicate when they are in position. Once started by the operator, it automatically carries out the cleaning sequence.

62 The operator moves the rail using the conveyor controls on the rail end cleaner to the welder, having determined that the rail end cleaning is “satisfactory”.

63 The design of the rail end cleaner and the safety barrier restricts effective visual inspection of the rail ends (see Figure 6); as a result, it is possible that residual contamination could go undetected.

64 It is noted that IÉ-IM have undertaken multiple risk assessments covering the rail welding plant and machines, however, these appear to be restricted to occupational health and safety. The risk assessments do not consider risks arising from the production process (e.g. contamination of the rail ends causing weld defects) which may impact the safe running of trains; and as such control measures to address these risks have not been identified.

65 The rail end / brush cleaner requires brushes changing at one and a half to three weekly intervals in its normal pattern of use. The machine automatically indicates to the operator when the brushes are to be replaced.

The rail welding machine

66 The rail welding machine was constructed by Kzeso in 2017 and supplied by Geismar. It is a K1000 model flash butt welding machine with “automatic alignment and integral stripper”. The operation of the machine is detailed in CCE-PLM-WKI-014 Flash butt Welding Process for New and 2nd Hand Rail.

67 Flash butt welding is a resistance welding process which is widely used in a static rail welding plants where the machinery is permanently installed. In the welding machine, electrical current is used to create an arc or flashing between the ends of two rails held in very close proximity. This heats the rails sufficiently to melt the surface of the rail, in the process expelling particles of oxides (e.g. rust) and contaminants. Following the flashing or heating phase, the rail ends are forged together by a mechanical force (see Figure 7).

68 The operator is required to move the rails along the conveyor into the machine and then align the rails running surfaces using the controls on the machine. The automatic alignment manipulator is then placed on the head of the rails and the machine will self-adjust for the alignment which is confirmed on the control panel. Finally, the operator physically feels across the joint by hand and if necessary, makes an adjustment. The operator is not required to space the rails apart.

69 The operator must select the correct welding programme based on the rail type and input the weld number.

70 The operator starts the extraction system and commences the welder. The welding cycle is automatically controlled, including the flashing, forging and stripping of the excess material displaced from the upset zone, which is then "stripped" or sheared off with a tool whilst it is still in a plastic state (see shearing tool in Figure 7).

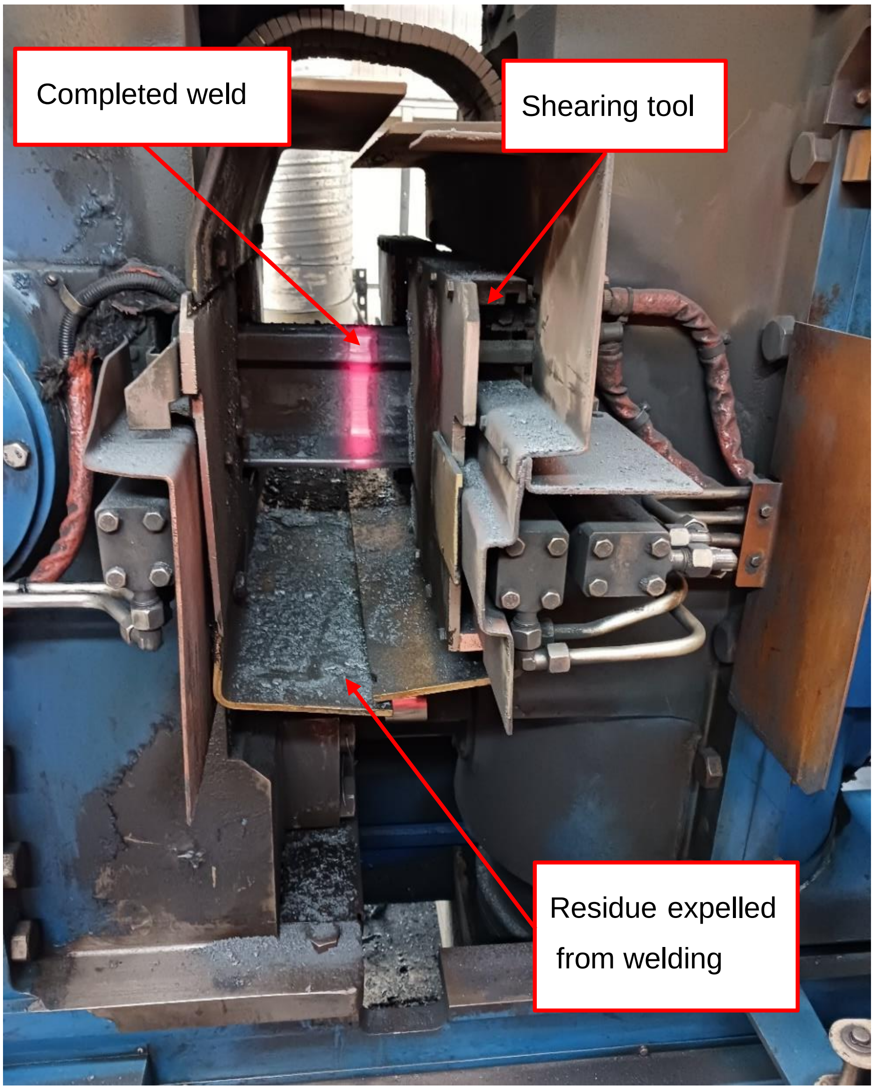

Figure 7 – Flash butt welder with a completed weld in situ

71 At the end of the weld process, the operator is required to check if the weld has passed on the display before visually checking the weld and attaching an ID tag to the rail. The welding machine displays “ok”[4] if no issue is identified. This is based on the measurement of multiple parameters during the automatic welding process.

72 A lack of fusion can occur if the weld becomes contaminated with slag. These can form within a few seconds if the flashing process is not occurring across the whole weld joint surface and expelling material outwards. This localised disruption can be caused by contamination present on the rail ends, variations in the gap of the two sections of rail being welded or moisture. The formation of oxides in small quantities are not detected by the welding machine.

73 The annual servicing of the welding machine is carried out by the supplier Geismar under contract, who in turn engage a sub-contractor. The welding machine last received an annual service before the broken rail was welded in October 2021 when no issues of note were identified. The next service was due in October 2022, however, this service did not take place until March 2023, as a result of a backlog of work by the supplier following Covid-19.

74 A weekly sample checking approach is used to gain assurance on the integrity of the welds, with these being subject to a “bend test” where a section of rail with the weld is cut out and subject to a test of mechanical deflection in a testing rig. This is specified in work instruction CCE-PLM-WKI-020 Bend Test Process for New and 2nd hand rail (CCE-PLM-WKI-020)[5].

[4] Note, in the six months prior to the failed weld being produced, only one instance of a weld “Fail” was recorded by the machine. Welds which are rejected by the machine (identified on the display as a “Fail”) are cut out of the rail string and the ends re-welded.

[5] Records show the requirement in CCE-PLM-OPS-066 CWR Production at Portlaoise Rail & Sleeper Depot (CCE-PLM-OPS-066) to test one per week had been complied with and all had passed. This method and frequency are consistent with the EN14587 standard.

Rail delivery and installation

75 Following welding, the rail is transferred to the CWR delivery train (see Figure 8). This is formed of flat wagons equipped with racks and rollers to carry strings of welded rail to site. At one end of the train, a special wagon is equipped for feeding rails off the train and down a trailing removeable ramp as the train slowly moves along. The rails are placed on the line ready for re-railing or on an adjacent line and then are manipulated in to place later.

Figure 8 – Long welded rail delivery wagons

76 The method for handling rails and the equipment to be used is described in a documented Risk Assessment Method Statement (RAMS). For the relaying works at Newbridge on the 28th / 29th January 2023 a Project Method Statement (CLRPMS2023_003) was issued by the Cork Line Relaying Project office which incorporated the RAMS.

77 During the delivery and handling process, the rail is subject to manoeuvring and manipulation exposing it to some internal forces such as internal bending moment, shear, and axial forces; this is normal practice, if the rail is handled correctly this should not damage the rail unless a defect is present.

78 The rail was subsequently welded in situ to other sections of rail in situ on the 8th February 2023. To prevent buckling from expansion in hot weather the rail was placed under tension or “stressed” when welded as the rail temperature was 0ºC.

Routine track inspection and finding defects

79 The short interval between the rail being installed on the 28th January 2023 its subsequent failure on the 23rd February meant the only routine inspection of the rail was through the weekly *track patrols* (three undertaken since the rail was installed), with the last occurring on the 20th February[6].

[6] IÉ-IM do carry out the following types of track inspection activity which provide an opportunity to detect track defects: ultrasonic testing carried out by a train equipped with *Sperry* monitoring equipment on a twice a year basis and track recording vehicles which carry out measurements of track geometry and the rail profile but do not test the integrity of the rail, however, due to the short time interval, the rail was not subject to these prior to breaking. However, it was noted that none of these inspection methods described has the capability to detect the initial crack in the foot of the rail. Train borne ultrasonic testing equipment as used by IÉ and other networks has limitations when travelling at speed and only hand-held equipment is capable of this. As a result, the testing of the full rail profile is normally only undertaken on a very localised basis for rail welds carried out in-situ or for suspected defects.

Post-incident inspection of the weld & welder

Serco Report

80 IÉ-IM followed their documented procedure CCE-TMS-362 Management of Rail Failures and Requirements for the testing of rails (CCE-TMS-362) and removed the broken section of rail for metallurgical testing. This was carried out by IÉ-IM's specialist provider Serco.

81 Serco conducted a visual examination of the broken rail ends. This revealed a darkly corroded transverse crack at the foot of the rail, which further chemical analysis determined a "small number of days exposure". The remainder of the fracture face was not corroded and was typical or recent rapid overload (see Figure 9). The "overload" refers to the stresses acting on the remaining un-cracked cross-section, rather than the bulk stress on the rail as a whole. The presence of the initial crack would have resulted in a very significant degree of stress concentration at the tip of the crack. This would have been many times greater than the bulk stress applied to the rail.

Figure 9 – Complete fracture face showing rail foot crack

82 Serco's metallographic examination found "conclusive evidence of a lack of fusion along the surface including decarburisation, fissures and slag inclusions" (see yellow arrowed sections in Figure 10).

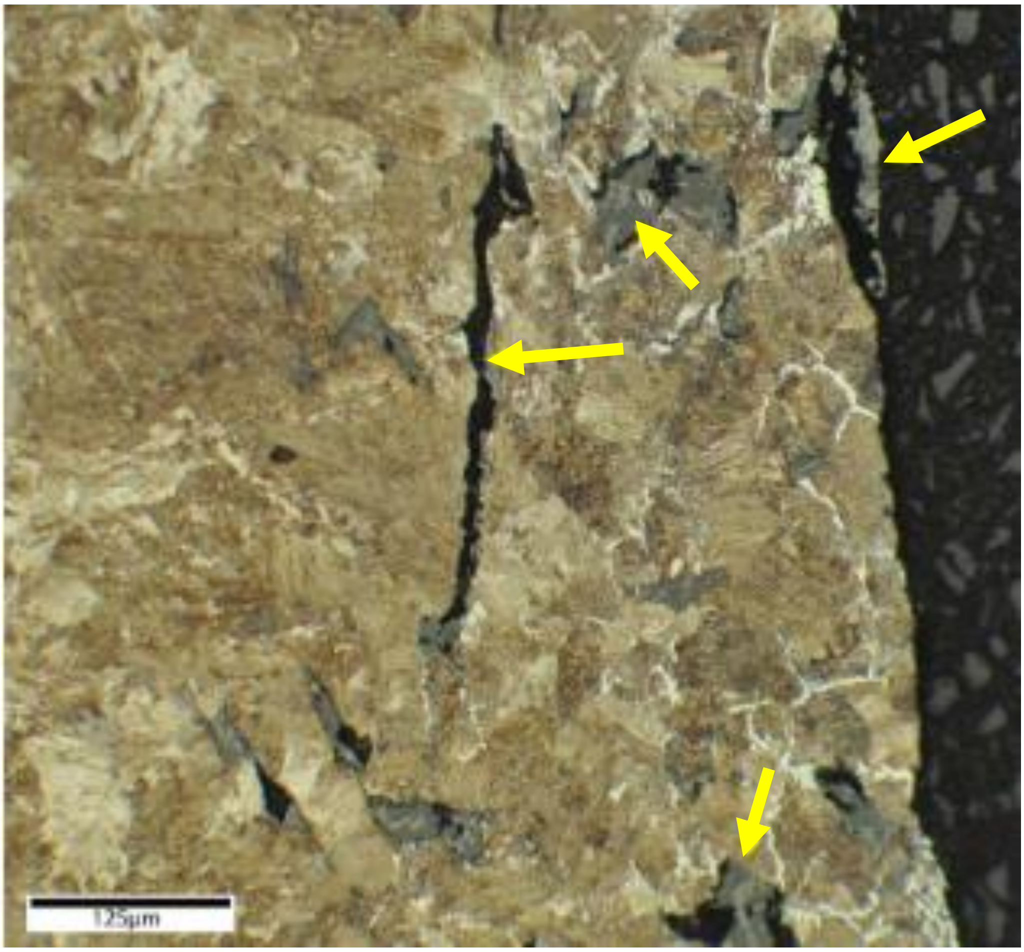

Figure 10 – Slag inclusions and slag filled voids indicated by the yellow arrows

83 A further feature found at the outer edge of the crack initiation was that at the edge of the rail there was a lip on one half of the rail and a corresponding chamfer on the other part in a "cup and cone" profile (see Figure 11).

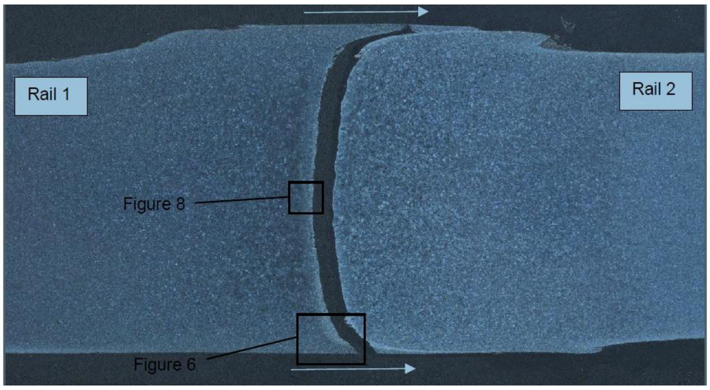

Figure 11 – Rail toe showing cup and cone profile of lip

84 Whilst most of the lip showed signs of ductile tearing, where the crack had initiated, this lip had a different angle and crack surface to the rest of the lip. This localised difference was attributed to the shearing / trimming of the hot material in the upset zone which rounded the profile of the embedded slags (as outlined in paragraph 70). The only explanation (of the different lip / cone surface) "was that the toe at this position was unfused during the trimming process".

85 The Serco Report concluded "Based on the findings of this investigation it is the opinion that a lack of fusion in the toe of the foot from an unknown flash butt welding process problem had provided the initiation point for a crack to propagate rapidly across the foot on the gauge side until it reached the web/foot transition whereupon it arrested[7]. It is likely that crack propagation occurred in a single stage possibly during movement of the rail string on site, as it is understood that the rail was manoeuvred several times until it was finally in position. The rail remained in the cracked condition for a period of time, estimated to be a small number of days until it failed completely by rapid overload".

[7] i.e. the cracking stopped at this stage.

Geismar Report

86 Geismar were supplied with the Serco Report and records from the welding machine for review as part of the investigation.

87 At the time of welding for the affected broken rail, Geismar identified a possible “short circuiting” event (identified by “Short C” red text in Figure 12) in the welding sequence, which resulted in the welding machine reversing or stalling (identified by “machine reversed, or stalled” blue text in Figure 12) to the flashing process. However, this was not sufficient to trigger the machine to identify the weld as a “Fail” on the operator display (as described in Footnote 4).

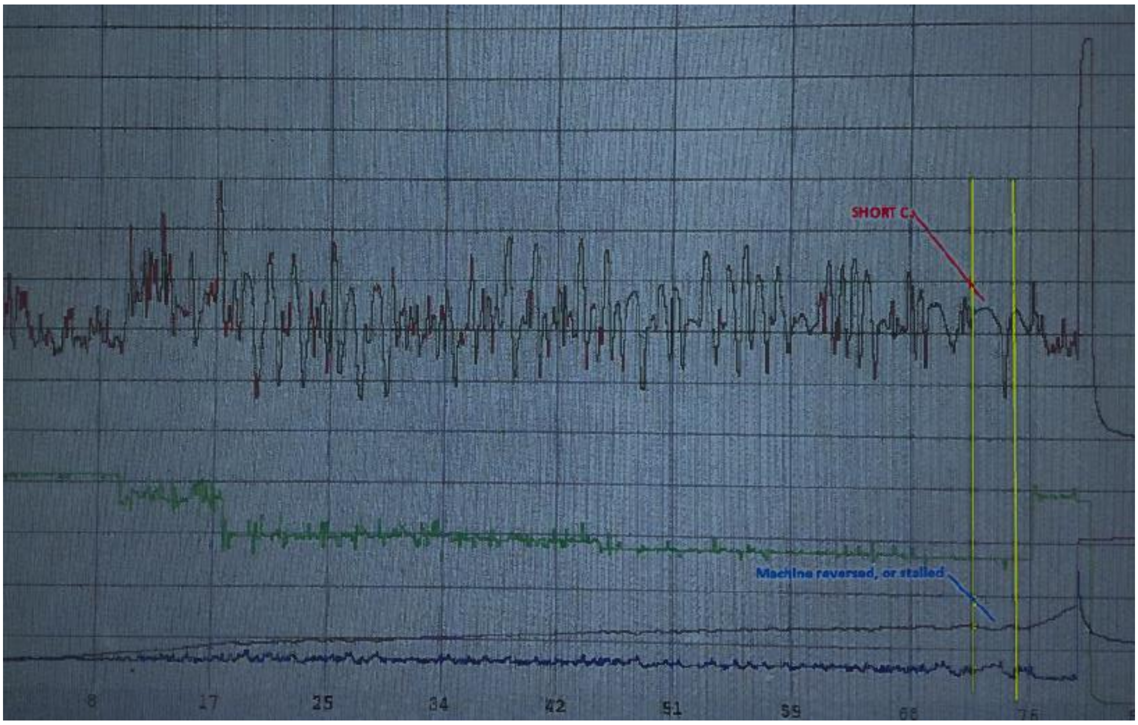

Figure 12 – Welding graphical output from welder

88 Geismar speculated that a small piece of the rail foot appeared to be missing or chipped prior to the rail welding procedure. Consequently they stated that “during the welding process in the area with the missing /chipped location would not have reached the required fusion temperature, thus generating a lack of upsetting material…. slag inclusions could be explained as there would have been insufficient quantity of material to be expelled in the upsetting sequence”.

RAIU consultant review

89 The consultant engaged by the RAIU to review the Serco Report and other evidence, confirmed the source and mode of the failure.

90 Also noting the alignment of the slag inclusions in the metal indicated these were likely to have originated from the flash butt welding process[8].

91 These slag inclusions may have originated from residual contaminants (e.g. corrosion, paint, etc) not removed by the rail end cleaner being included or these residues preventing effective flashing and causing oxidation of the molten metals to form slag which was not expelled from the joint.

92 In terms of the length of time of the initial crack was present prior to the rapid failure of the remainder of the rail section, this is difficult to be certain on as this would depend on multiple factors e.g. it could occur within a week in very damp conditions but take much longer in relatively dry conditions; thus the possibility that the crack formed on or around the time of rail delivery (January) or during installation (February) is plausible but not certain.

93 In terms of the Geismar Report, the potential “chip”/ “missing section” scenario, the consultant engaged by the RAIU noted that while plausible, it is unlikely slag inclusions would be found so far inwards[9].

---

[8] To note, the RAIU’s consultant found that it is unlikely that the slag inclusions were present in the rail during manufacture, as it is probable that the rail rolling process (where rail is manufactured into long lengths of a uniform section through passing through rollers that compress and deform the material whilst in malleable state) would have elongated any inclusions along the rail rather than causing inclusions that are perpendicular to the rail.

[9] The RAIU inspected a sample of new rails for squareness and for chips and markings on the rail ends; all rails were found to be within tolerance.

Events before, during and after the incident

Events before the incident

94 On the 13th October 2022, the section of rail that failed was welded to other sections of rail using the flash butt welding process (see paragraphs 67 to 71), with the records indicating that the weld was passed as "ok".

95 The rail was subsequently stored in the stacks at Portlaoise Rail Welding Plant.

96 On the 20th January 2023, the rail was transported to the relaying site on the long welded rail delivery train and delivered onto the Down line in advance of the relaying possession the following week.

97 It remained on situ on the Down line for eight days, until on the 28th January 2023 in an engineering possession for relaying and track renewal works, the rail was manipulated into position using *road rail vehicles* and clipped to the sleepers.

98 On the 30th January 2023 the track was *tamped* to level the track and consolidate the ballast below the sleepers. A follow up tamp took place on the 2nd February 2023.

99 Records supplied by IÉ-IM show that the rail was welded in-situ, using the *thermit process,* on the 8th February 2023.

100 On the 20th February 2023 the track was walked by a by a member of CCE staff during a routine track patrol (paragraph 79). At this point it is almost certain from corrosion evident that the foot of the rail was cracked, but it is highly unlikely it would have been visible.

Events during the incident

101 At 07:11 hrs on the 23rd February, Driver P402 reported an abnormal CAWS downgrade to the Mainline Signalman.

102 At 07:24 hrs the Driver A501 also reported a CAWS downgrade in the same area to the Mainline Signalman.

103 At 07:25 hrs the Mainline Signalman contacted another CTC staff member (the Traffic Regulator) who advised the SET Department to investigate the potential CAWS fault.

104 After 07:25 hrs, other drivers continued to report abnormal CAWS downgrades to the Mainline Signalman as they approached the affected area (twenty-eight passenger trains travelling over the broken rail). Drivers were advised to continue and obey lineside signals which were working normally.

105 At 10:52 hrs the SET member discovered the broken rail and made an emergency call to the Mainline Signalman to block the Up line to movements on approach to Signal HK180. The rail ends had completely parted by a short distance (approximately 10 mm) as the tension present in the rails was relieved, but the horizontal alignment was maintained. The gap at the broken rail prevented the transmission of the CAWS code down the running rail.

Events after the incident

106 Following the discovery of the broken rail at 10:52 hrs, the CCE Department were informed by the Mainline Signalman and mobilised to the location.

107 A PWI attended with support staff and attached a clamp (see Figure 13) to the rail to hold it in vertical and horizontal alignment.

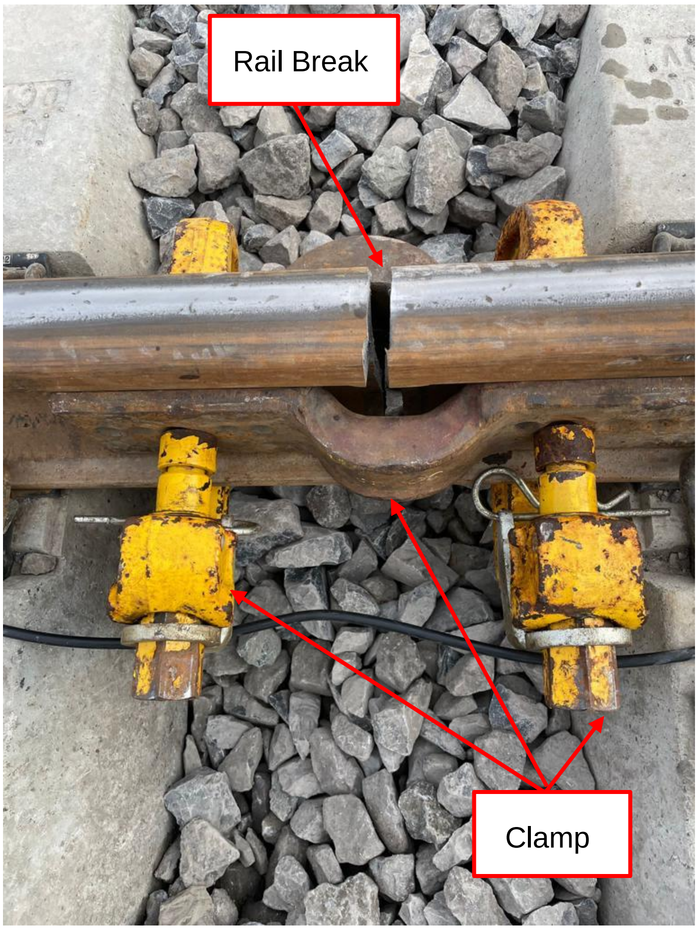

Figure 13 – Broken rail held by temporary rail clamps

108 A 25 mph (40 km/h) ESR was then imposed. ESR signage was subsequently erected by the CCE staff to advise drivers of the location. Traincrew depots were advised by a *shed notice* of the ESR having been imposed.

109 The first train to proceed over the temporarily repaired rail was advised to proceed at caution with CCE staff in attendance to observe the movement.

110 During a subsequent T3 Possession a 9 m section of rail was cut out and removed from site for analysis with a replacement section welded in.

111 Additionally, eighteen welds were tested either side of the broken rail using hand trolley mounted ultrasonic testing equipment which permitted testing of the full height of the rail profile. No defects were found.

Previous occurrences

112 The most recent recorded occurrence of a broken rail on the IÉ-IM network before this event was a broken rail on the Cork line on the preceding day (22nd February 2023). This also occurred at a weld joint, but in this case the weld was of the Thermit type. This is also subject to an investigation by the RAIU.

113 Prior to this there were no recorded broken rails in service since 2015.

114 There are no other recorded instances of flash butt weld failures on the IÉ network.

Analysis

Mechanism of failure of the broken rail

115 The supplier of the welding machine, found through interrogation of the machine, that during the welding of the affected rail, in October 2022, it was identified that there was a possible interruption (short circuiting and reversing or stalling) to the flashing process (paragraph 87, Figure 12). This would concur with Serco's findings that there was likely an "unknown flash butt welding process problem" (paragraph 85).

116 This "unknown flash butt welding process problem" resulted in a lack of fusion at the toe (paragraph 82 and 85) when the upset was trimmed, as evidenced by the lip profile, where excess material from upsetting had been trimmed/ sheared off when still hot (paragraph 84).

117 The metallographic examination found conclusive evidence of this lack of fusion along the surface including decarburisation, fissures and slag inclusions (paragraph 82). The slag inclusions may have been from contaminants not removed by the rail end cleaner (further discussed in paragraph 119) or these residues reducing the flashing and causing oxidation of the molten metals to then form slag which was not expelled from the joint (paragraph 92)[10].

118 Ultimately, the lack of fusion provided an initiation point for a crack to propagate rapidly across the foot on the gauge side until it reached the web/foot transition whereupon it arrested; likely occurring during movement of the rail string on site, as it is understood that the rail was manoeuvred several times until it was finally in position (paragraph 85). The rail then remained in the cracked condition for a period of time, estimated to be a small number of days until it failed completely by rapid overload (paragraph 85), possibly accelerated as a result of the weather conditions (paragraph 92)).

[10] The potential for a chip or small missing rail section to cause locally reduced flashing and rail heating process and oxidation of molten material which was allowed slag to form cannot also be excluded. However, there is insufficient evidence to conclude that this was the cause (paragraph 93).

Rail end cleaning

119 The design of the rail end cleaner and the safety barrier restricts effective visual inspection of the rail ends; as a result, it is possible that residual contamination (e.g. paint (paragraph 52)) could have gone undetected at this stage (paragraph 63). This risk was not identified in any risk assessments; and control measures to address this risk were not identified

120 It is noted that IÉ-IM have undertaken multiple risk assessments covering the rail welding plant and machines, however, these appear to be restricted to occupational health and safety for the operatives. The risk assessments do not address risks arising from the production process (e.g. contamination of the rail ends causing weld defects) which may impact the safe running of trains; and as such control measures to address these risks have not been identified (paragraph 64).

Conclusions

Causal, contributing, and systemic factors

121 The mechanism of failure for the broken rail was slag inclusion in the welding process causing a lack of fusion in the toe of the rail foot. The lack of fusion created a cracking initiation point which propagated from that location, probably starting from when the rail was handled or manoeuvred during delivery or installation; the crack then progressed through the remainder of the rail section in a single rapid event due to rapid overload (paragraphs 115 to 118). It is possible that the weather conditions accelerated the breaking of the rail.

122 The RAIU have identified the following possible causal factors which may have resulted in the lack of fusion:

- CaF-01 – An interruption to the flash butt welding process (paragraph 115);
- CaF-02 – Insufficient cleaning of the rail ends resulted in the inclusion of slag during the flash butt welding process (paragraph 91, 117 and 119).

123 The following contributory factor was identified, in terms of the cleaning of the rail ends:

- CoF-01 – The current design of the rail end cleaner and the safety barrier restricted effective visual inspection of the rail ends; as a result, it is possible that residual contamination could have gone undetected at this stage (paragraph 119).

124 A systemic factor related to the cleaning of the rail ends is as follows:

- SF-01 – This risk associated with not cleaning the rail ends adequately was not identified in any risk assessments at Portlaoise Rail Welding Plant; and as such control measures to address these risks have not been identified (paragraph 119).

Measures taken by IÉ-IM since the incident

125 After the discovery of the broken rail, IÉ-IM initiated ultrasonic testing of all the recently welded rails on site at Portlaoise in accordance with CCE-TRK-WKI-003. In addition a 10% sample check of the rails welded at Portlaoise on a weekly basis was initiated from the 20/03/2023 using the same method.

126 Following the incident, IÉ-IM identified an opportunity to enhance the arrangements for visual inspection of rail ends after cleaning by the rail cleaner in the Portlaoise Rail Welding Plant through the addition of a high-definition camera and monitor. At the time of this report being written, installation had yet to take place, as a result a safety recommendation is warranted, Safety Recommendation 2024001-01 (paragraph 128).

Safety Recommendations

Introduction to safety recommendations

127 In accordance with the European Union (Railway Safety) (Reporting and Investigation of Serious Accidents, Accidents and Incidents) Regulations 2020), RAIU safety recommendations are addressed to the NSA, the CRR, and directed to the party identified in each safety recommendation.

Safety recommendations as a result of this incident

128 Insufficient cleaning of the rail ends was identified as a possible cause of slag inclusion and lack of fusion. The RAIU makes the following safety recommendation to address CaF-02 (paragraph 122) to achieve greater assurance that rail cleaning has been achieved to the required standard:

Safety Recommendation 2024001-01

IÉ-IM should risk assess whether the existing rail end cleaning equipment and processes adequately control the risk of weld contamination and identify improvements where required.

129 The rail welding machine was identified as having potentially recorded an anomaly in the welding of the rail that subsequently failed. The RAIU makes the following safety recommendation to address CaF-01 (paragraph 122):

Safety Recommendation 2024001-02

IÉ-IM to investigate altering the monitoring and detection parameters of the rail welding machine to be able identify and highlight possible anomalies in the welding process.

130 The Portlaoise Rail Welding Plant risk assessments appear to be restricted to occupational health and safety risks and do not address risks arising from the production process which may result in a failed or broken rail; and as such control measures to address these risks have not been identified. Consequently, the RAIU make the following safety recommendation to address SF-01 (paragraph 124):

Safety Recommendation 2024001-03

IÉ-IM to revise the risk assessments for the Portlaoise Rail Welding Plant to ensure risks in the production process affecting the quality of rail welds are understood and control measures are identified.

Additional Information

List of abbreviations

AO	Additional Observations
CaF	Causal Factors
CAWS	Continuous Automatic Warning System
CCE	Chief Civil Engineer
CME	Chief Mechanical Engineer
CoF	Contributory Factors
CWR	Continuous Welded Rail
CRR	Commission for Railway Regulation
CTC	Centralised Traffic Control
EU	European Union
ESR	Emergency Speed Restriction
hr	hour
IÉ-IM	Iarnród Éireann Infrastructure Manager
IÉ-RU	Iarnród Éireann Railway Undertaking
km	kilometre
km/h	kilometres per hour
m	metre
MP	Milepost
mph	miles per hour
NSA	National safety authority
OB	Overbridge
OBC	Overbridge Cork
PTS	Personal Track Safety
RAIU	Railway Accident Investigation Unit
RA	Risk Assessment
RFI	Request For Information
SMS	Safety Management System
TCB	Track Circuit Block

Glossary of terms

Abnormal CAWS downgrade	If the in-cab display does not correspond with the lineside signal aspect at the relevant location and shows a more restrictive indication this is known as an abnormal downgrade e.g. in this case CAWS was displaying a red aspect instead of the proceed aspect shown by the signal.
Accident	An unwanted or unintended sudden event or a specific chain of such events which have harmful consequences. For heavy rail, the EU Agency for Railways divides accidents into the following categories: collisions, derailments, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others.
Article 20 of Directive (EU) 2016/798, Obligation to investigation	Article 20 (1) Member States shall ensure that an investigation is carried out by the investigating body referred to in Article 22 after any serious accident on the Union rail system. The objective of the investigation shall be to improve, where possible, railway safety and the prevention of accidents. Article 20 (2) The investigating body referred to in Article 22 may also investigate those accidents and incidents which under slightly different conditions might have led to serious accidents, including technical failures of the structural subsystems or of interoperability constituents of the Union rail system. The investigating body may decide whether or not an investigation of such an accident or incident is to be undertaken. In making its decision it shall take into account: (a) the seriousness of the accident or incident; (b) whether it forms part of a series of accidents or incidents relevant to the system as a whole; (c) its impact on railway safety; and (d) requests from infrastructure managers, railway undertakings, the national safety authority or the Member States.
Ballast	Graded stone which is used to hold the track in position (vertically and horizontally) and facilitate drainage.
Broken Rail	Broken rail is term used to describe where a rail suffers a defect that results in either part of the rail becoming detached or breaking into two sections and losing its mechanical strength.

Causal Factor	Any action, omission, event or condition, or a combination thereof that if corrected, eliminated, or avoided would have prevented the occurrence, in all likelihood.
Cess	The space along the running line
Continuous Automatic Warning System	An advisory train control system, AWS works by repeating the aspects shown by the lineside colour light signals on an Aspect Display Unit (ADU) inside the driver's cab. The ADU continuously displays the aspect that was shown by the previous signal until updated approximately 350 m before the next signal. The ADU then displays the aspect shown by that signal.
Continuous Automatic Warning System Downgrade	A change of the Aspect Display Unit display to a more restrictive aspect (e.g. single yellow to red), which is accompanied by a continuous audible tone and the illumination of the acknowledge switch that must be pressed by the driver within seven seconds to prevent an automatic brake application occurring.
Contributing Factor	Any action, omission, event or condition that affects an occurrence by increasing its likelihood, accelerating the effect in time or increasing the severity of the consequences, but the elimination of which would not have prevented the occurrence.
Cutting	An open passage excavated through higher ground for a road, railway or canal
CWR	This is rail that is laid in long sections which are welded together to minimise the number of joints to reduce maintenance and failures and improve the ride quality.
Decarburisation	This is the loss of carbon in the surface adjacent zone of the material. Carbon atoms react with Oxygen to form Carbon Dioxide or Carbon Monoxide.
Down Line	In this incident, trains travelling to Cork are travelling in the Down direction on the Down Line.
Down Side	Being located on the same side of the railway as the Down Line.
Eddy Current Testing	An electro-magnetic inductive testing process used to detect and characterize sub-surface flaws in conductive materials.

Embankment	A bank of earth or stone to carry a railway or road over a low lying area
Emergency Speed Restriction	An Emergency Speed Restriction is an unplanned speed restriction implemented at short notice which is advised to drivers through notices posted at traincrew depots and by signage on the lineside.
Five foot	The space between the rails.
Flash butt weld	Flash butt welding is a resistance welding process which is widely used in a static rail welding plants where the machinery is permanently installed. In the welding machine, electrical current is used to create an arc or flashing between the ends of two rails held in very close proximity. This heats the rails sufficiently to melt the surface of the rail, in the process expelling particles of contaminants. Following the flashing or heating phase, the rail ends are forged together by a mechanical force.
Incident	Any occurrence, other than an accident or serious accident, associated with the operation of trains and affecting the safety of operation. For heavy rail, the EU Agency for Railways divides incidents into the following categories: infrastructure; energy; control-command & signalling; rolling stock; traffic operations & management and others.
Investigation	A process conducted for the purpose of accident and incident prevention which includes the gathering and analysis of information, the drawing of conclusions, including the determination of causes and, when appropriate, the making of safety recommendations
Method Statement	A document that detail exactly how to carry out work safely; they describe the safety precautions to control risks identified in the risk assessment and detail the personal protective equipment, health and safety contacts and the control equipment required to keep workers and site visitors safe whilst tasks are ongoing.
Milepost	Marks distances.
Oxides	Chemical compounds with one or more oxygen atoms combined with another element.
Rail foot	Base of the rail, profiled to suit the fixing to the sleepers.
Road Rail Vehicle	A dual mode vehicle than can operate both on rail tracks and road mostly used for rail infrastructure maintenance.

Serious Accident	Any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact on railway safety regulation or the management of safety. For heavy rail, the EU Agency for Railways divides serious accidents into the following categories: collisions, derailments, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others.
Shed Notice	An operational notice issued to all drivers at a depot or shed advising them of operational issues, restrictions or changes to instructions.
Six foot	The space between one line and an adjacent line.
Slag	Non-metallic contamination in the weld consisting of oxides, environmental soiling and other residues.
Stressing	The tensioning of rail during installation to counteract the effect of expansion at higher temperatures to prevent buckling.
Systemic factor	Any causal or contributing factor of an organisational, managerial, societal or regulatory nature that is likely to affect similar and related occurrences in the future, including, in particular the regulatory framework conditions, the design and application of the safety management system, skills of the staff, procedures and maintenance.
Tamp	The process of packing the track ballast under railway tracks to make the tracks more durable and level.
T3 Possession	Absolute possession no operational train movements. Engineering trains On Track Machinery/ road rail vehicle movements are permitted. Planned Engineering Work.
Thermit welding	A type of rail welding used to weld rails in situ where heat generated from an exothermic reaction is used for the fusion.
Track Patrol	Patrol gangers carry out track patrols, which are continuous systematic examination of the track to locate conditions that are unsafe, potentially unsafe or likely to cause delay to trains.
Up Line	Up line is term used to describe the normal direction of traffic on railway routes. Each route has an “Up” and “Down” direction which are to or

	from a specified location - in this accident for Dublin Heuston station. Mileposts are measured from the same location.
Upset zone	The zone where the two parts being welded are forged together and material is extruded from the joint.
Upsetting	Basic deformation of the two pieces when compressed together resulting in increased width as the length is reduced.
Up Side	Being located on the same side of the railway as the Up Line.

References

EN13674-1:2011, Railway Applications – Track – Rail Part 1: Vignole Railway Rails 46Kg/m and Above.

EN14587-1 2007, Railway Applications – Track – Flash butt welding of rails – Part 1: New R220, R260, R260Mn and R350HT grade rails in a fixed plant

IÉ (2007), IÉ Rule Book (updated to July 2022)

IÉ-IM (2019), CCE Department, CCE-PLM-WKI-014 v2.0, Flashbutt Welding Process for New and 2nd Hand Rail.

IÉ-IM (2021), CCE Department, CCE-PLM-WKI-020 v1.0, Bend Test Process for New and 2nd Hand Rail

IÉ-IM (2019), CCE Department, CCE-PLM-WKI-066 v2.1, CWR Production at Portlaoise Rail and Sleeper Depot

IÉ-IM (2019), CCE Department, CCE-TMS-323 v2.1, Technical Standard for Stressing of Rail

IÉ-IM (2012), CCE Department, CCE-TMS-362 v1.2, Management of Rail Failures and Requirements for the Testing of Rails

IÉ-IM (2011), CCE Department, CCE-TRK-WKI-003 v1.0, Rail Test Work Instructions

Serco (2023), Investigation of Broken Flash Butt Weld", Issue 1, published 2nd March 2023.