SRT DERAILMENT-ELLESMERE STATION

FORENSIC ASSESSMENT REPORT

Rail Infrastructure Consultation
Toronto Transit Commission
Toronto, Ontario

2023-10-12

FIRM PROJECT NO.: 067065

Prepared for:

GANNETT FLEMING

DOCUMENT REVISIONS INDEX

Revision	Date	Description of Changes
0	July 26, 2023	Early Draft Issue
1	August 2, 2023	Draft Issue
2	September 8th, 2023	Final draft issue – incorporation of TTC comments and additions to Reenactment Procedure, and Findings and Conclusions sections
3	**October 12th, 2023**	**Final issue addressing TTC Rev. 2 comments**

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1 BACKGROUND

On July 25, 2023, TTC formally communicated that a train derailment incident on the Scarborough Rail Transit (SRT) south of Ellesmere Station, had occurred the evening of July 24, prompting the TTC to reach out to subject matter experts and third-party evaluators. Consequently, Gannett Fleming was engaged with the responsibility of completing a comprehensive forensic assessment of the rail infrastructure and providing post-incident investigative services for the SRT corridor, in the aftermath the derailment. This assessment encompasses an array of tasks, including an initial on-site inquiry, concrete core sampling, failure and metallurgical analysis, dynamic testing reenactment program, and localized track inspection. The central aim is to pinpoint the exact causal factors of the derailment, assess the condition of the rail infrastructure, and provide pragmatic recommendations to bolster safety measures and operational performance.

2 INTRODUCTION & OVERVIEW

2.1 Introduction

To address the recent derailment event to the south of Ellesmere Station along the SRT corridor, Gannett Fleming has initiated a comprehensive forensic assessment. This initiative comprises an array of investigative procedures designed to determine the fundamental factors that caused the derailment, scrutinize the conditions of both rail infrastructure and rolling stock, and the formulation of recommendations and best practices geared towards enhancing safety measures.

2.2 Overview

The forensic assessment program consists of several interconnected investigative tasks, each contributing to a thorough understanding of the incident's circumstances and underlying factors. Gannett Fleming has employed processes and methodologies as outlined by the Canadian Transportation Safety Board investigative process to comprehensively assess the derailment, integrating best practices from their published rail transportation safety investigations.

a) **Initial Derailment Site Inspection and Memo:** An on-site investigation was undertaken to gauge the extent of damage stemming from the derailment incident. The examination covered running rail, reaction rails, infrastructure, and the immediate surroundings, culminating in the identification of key contributory elements. The corresponding memo, presenting initial insights and observations, was delivered on Tuesday, August 23.
b) **SRT Detailed Investigation Program Workplan:** A comprehensive work plan was devised, outlining the various investigative actions required to assess the overall condition of the SRT corridor. This plan outlined strategies for core sampling, failure/metallurgical analysis, and vehicle dynamic testing (reenactment program). was presented to TTC on Tuesday, August 8. The plan delineated the methods, timelines, and coordination strategies employed throughout the investigation.
c) **Core Sampling Investigation:** This encompassed assessments of the structural integrity of the concrete invert slab, analyses of bolt assemblies and cross-sections, and rigorous concrete compressive strength tests. The collected data furnished essential insights for a thorough assessment. This assessment has been appended to this report.
d) **Failure/Metallurgical Analysis:** An in-depth metallurgical analysis was conducted, delving into the metal components implicated in the derailment. This analysis systematically identified material defects, fatigue, and signs of wear and tear. The results illuminated the performance and integrity of these components and their direct contribution to the incident.

e) **Dynamic Testing Program - Incident Reenactment:** To validate root cause theories and gain a deeper understanding of the incident's dynamics, a reenactment program was executed. This involved simulating load conditions between the linear induction motor and the reaction rail infrastructure to assess the system's response, vulnerabilities, and potential failure points. Collaboratively developed with TTC, the work plan accommodated a range of load scenarios.

3 THE INCIDENT

3.1 Investigation Background Information

The SRT Line 3 track services six stations over 6.4 km along the eastern district of Scarborough, connecting with the Line 2 Bloor Danforth line at Kennedy Station and terminating northeast at McCowan Station. The SRT consists of a direct fixation track on invert slab running on 115lb rail. The trains are powered by linear induction motors mounted on the cars' underside, inducing a current in the reaction rail, which runs in between the running rails on 1,435mm gauge tracks. Each trainset consists of four cars.

On Monday, July 24, at approximately 6:43 pm, an SRT Line 3 revenue train was travelling southbound from Ellesmere station at 40kph when it derailed at chainage 135+10. The trainset was carrying approximately 44 passengers. The rearmost car uncoupled from the trainset upon impact with a track obstruction and derailed. Preliminary investigations have focused on the track obstruction which resulted in the reaction rail lifting above the acceptable tolerance and contacting the underside of the trainset.

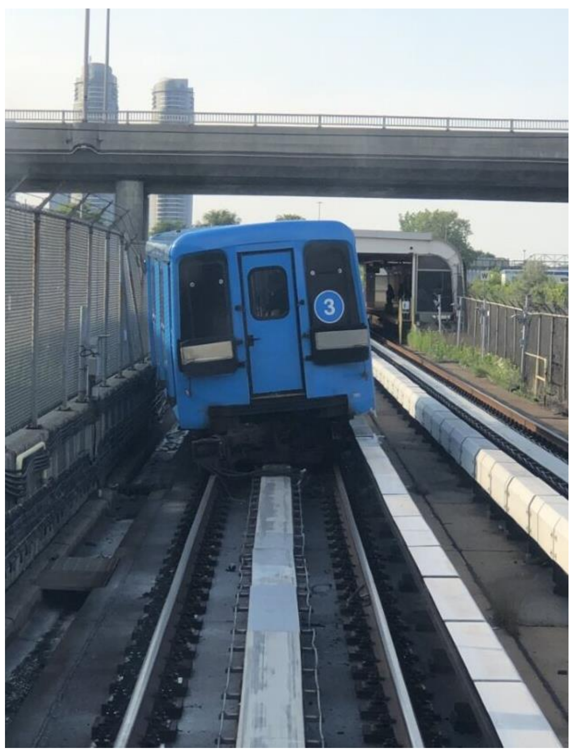


Figure 1: Derailed consist south of Ellesmere Station taken the evening of July 24th, 2023

The derailment occurred just south of Ellesmere Station (chainage 135+10) on the southbound track, as shown in Figure 2.

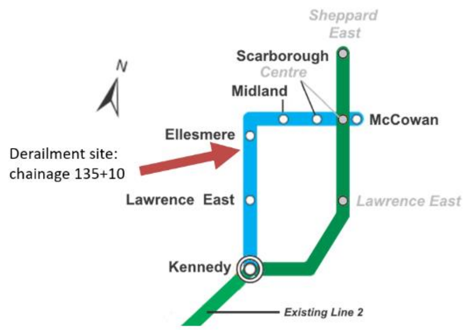


Figure 2: Derailment Site on SRT Line 3 Map

The day of the incident exhibited average July temperatures, with the external temperature recorded at a high of approximately 26 degrees Celsius. These warmer climatic conditions necessitated a precautionary measure wherein train speeds were reduced to approximately half of their optimal revenue speed—a protocol referred to as the 50/50 speed restriction. This reduction in speed is implemented to mitigate the risk of overheated rail infrastructure. At approximately 6:10 pm, 50/50 speed restriction was removed, allowing trains to operate at regular revenue speeds. The train preceding the incident train, Train 1 (consisting of cars 3026, 3027, 3006 and 3007, as shown in Figure 3), was travelling southbound at 6:37 pm when it came into contact with the reaction rail, resulting in minor damage on the Linear Induction Motor (LIM). Minutes later, at 6:43 pm, Train 2 (consisting of cars 3008, 3009, 3000 and 3001, as shown in Figure 5) was leaving Ellesmere Station at a speed of 40 km/h when the trailing Car (3001) hit the leading edge of the reaction rail. This contact caused car 3001 to decouple and derail due to the reaction rail pushing upwards, dislodging the car from the tracks after the initial impact.

Figure 3: Train prior to incident Train (Train 1 Overview)

Figure 4: Leading Edge Damage to Truck Fender on car 3006

It was observed that the leading edge of Truck 2 of car 3009 also experienced minor damage to its antenna bridge, as shown below in Figure 6.

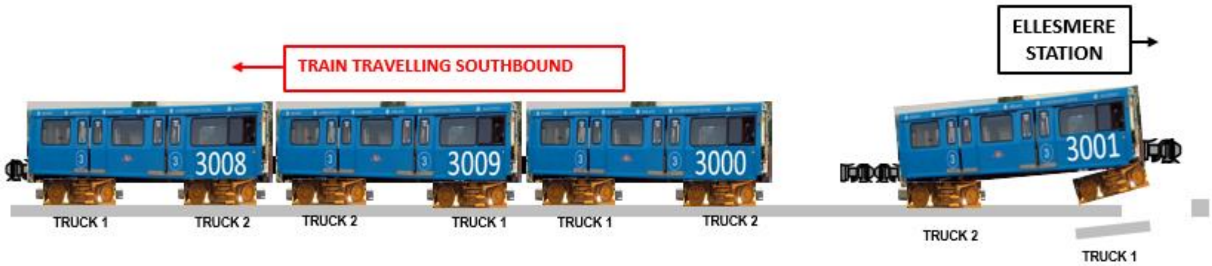


Figure 5: Incident Trains as provided by TTC RC&S

Figure 6: Leading Edge Damage to Antenna Bridge on car 3009

As expected, the most severe damage occurred on the leading edge of Truck 1 on car 3001 of the incident train. Figure 7 below depicts the damage sustained by the Linear Induction Motor mounted on the underside, which struck the reaction rail, causing the derailment.

Figure 7: Leading Edge Damage to LIM on car 3001

As a result, the front of the reaction rail was crumpled, with part of the top cap and rail itself torn off. The impact caused many of the anchor bolts, which hold the reaction rail in place, to fail and rip right out of the concrete slab (see Figure 8).

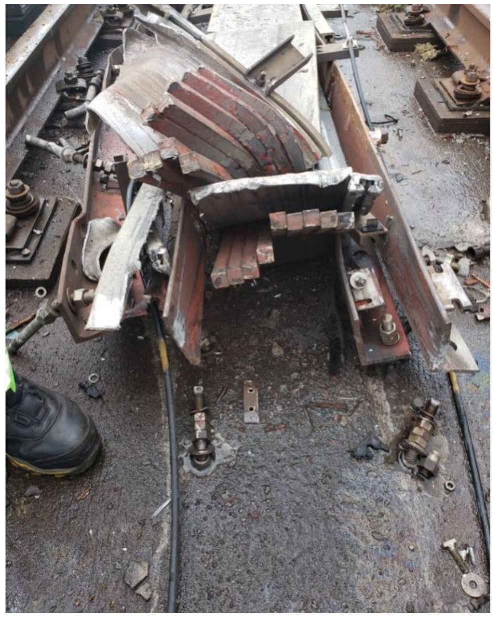


Figure 8: Front of Incident Reaction Rail Assembly

Following the decoupling of car 3001, the operator notified the TTC Operations Control Center. Shortly after notifying the TTC Operations Control Center, the power supply to the line was promptly disconnected, and emergency services were immediately dispatched to the scene.

Once passengers were evacuated and the site was secured, TTC personnel removed the derailed car 3001 via crane. The vehicle body of car 3001 was removed from the site and transported to McCowan Yard, and its accompanying wheel boogie was transported to Greenwood Yard for further investigation. The remainder of the trainset was also transported to McCowan Yard to be examined.

Passenger service, at the time, was temporarily suspended since the date of the derailment, and much of the derailment site was left untouched the day after to aid in the initial investigation assessment.

Upon Gannett Fleming's arrival to the derailment site on the afternoon of July 25, it was observed that a portion of the derailment had already been cleared, including the removal of car 3001.

4 INCIDENT ASSESSMENT OVERVIEW

4.1 Investigation Team

The investigation team consists of staff members from Gannett Fleming's Track, Structural, and System disciplines, all of whom will execute the investigation process highlighted in the following sections.

- Track Discipline Lead: Shane Arnold, Meng, P.Eng.
- Senior Track Technical Advisor: Mel White
- Structural Discipline Lead: William Van Ruyven, P.Eng., PMP.
- Senior Structural Engineer: Andrew Ward, P.Eng.
- Material Testing Lead: Abbas Haghbin, P.Eng., HAL Group Inc.
- Senior Vehicle Engineering Consultant: Steven Kraycar
- O&M Lead & Interface Manager: Pouyan Pourjam, P.Eng.

In addition to Gannett Fleming key staff members, Gannett Fleming has engaged the following subconsultants to aid in structural testing programs:

- Core Sample Testing & Evaluation – HAL Group Inc.
- Hardware Failure Analysis & Metallurgical Testing – Acuren Industrial Services

4.2 Gannett Fleming Investigation Process

4.2.1 Field Phase

The field phase involves a team of investigators dispatched to the incident site to examine the area, engage in conversations with relevant individuals, and gather necessary information to begin the investigation process. Throughout this phase, members of the investigation team undertook tasks including, but not restricted to:

- Examinations of the derailment site and other areas along the SRT Corridor.
- Examination and photography of any equipment, infrastructure, and rail vehicles pertinent to the occurrence.
- Conversations with TTC personnel to collect witness accounts of initial observations on the night of the incident.
- Identify elements involved in the derailment for further examination.
- Review and collect applicable documentation such as standards and inspection records.

4.2.2 Examination & Analysis Phase

The Gannett Fleming investigation team will collect pertinent information as required in the Field Phase, complete the Examination and Analysis Phase by conducting appropriate tests and determining an accurate sequence of events that lead to the incident. Elements reviewed in this phase of the investigation include but are not limited to:

- Examination and review of TTC vehicle, inspection, and related records.
- Examination of incident equipment components in laboratories as required.
- Testing of salvaged components, systems, machinery, infrastructure.
- Review and analyze any recorded data.

- Create and review simulations and reconstruct a sequence of events.
- Determine the sequence of events that lead to the event in question.
- Production of periodic reports and memorandum outlining status of laboratory investigations, testing, applicable theories as the investigative process continues.

4.2.3 Report Phase

Upon execution of all major actions in the Examination & Analysis Phase, this report has been drafted summarizing all activities and methodologies undertaken to determine and explain the root cause of the event in question.

5 FIELD PHASE

5.1 Initial Site Examination

An initial track inspection was conducted of the running rails, track profile and running surface to determine detailed information on the base infrastructure and allow the investigation team to focus on the root cause of the derailment. Track geometry measurements were taken north and south of the derailment site, with no anomalies found. The track gauge was observed to be 56-3/4" (1441 mm), which is within TTC standard TS-0603-02. Cross-level measurements were observed to be within 0" to 1/8" (3.18mm) of cross-level, which again is within TTC Standard TS-0603-04.

Secondly, a visual inspection was conducted on the track's fastener, grout pad, and surface/profile conditions. It was noted that no concerns were observed with any of the running rail conditions. However, "rub" marks on the top cap of the reaction rail were observed South of Ellesmere Station up to the derailment site. Evidence showed that these marks were present well before the incident.

Within the section of the reaction rail that was struck, it was observed that newer anchor bolts had been installed, indicating that some maintenance work had been performed in the area. It was observed that existing reaction rail cover joints did not overlap the reaction rail, which could contribute to vehicle equipment striking the reaction rail system. Additional initial observations are provided in Section 5.25.2 below. A copy of the track inspection report is provided in **Appendix A**.

5.2 Initial Infrastructure Observations

Immediately south of Ellesmere Station and to the north of the derailment site, noticeable abrasions on the reaction rail's top cap suggest that contact between the top cap and linear induction motor was a common occurrence along this track segment. However, the presence of oxidation in the area indicates that these abrasions were not recent (see Figure 9).

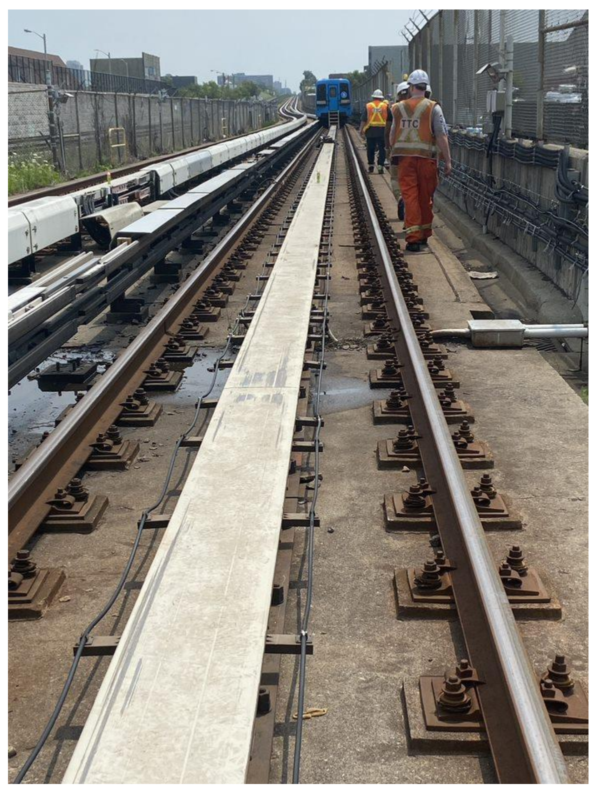


Figure 9: Top cap abrasion on reaction rail north of derailment site

At the derailment site, as noted in the previous section, it was observed that mounting bolts had been replaced. This replacement occurred at a jointed section of the reaction rail despite the typical TTC requirement at these locations being that the top cap be continuous and overlap the reaction rail joint. However, it was noted that the reaction rail was cut at the joint to install the anchor bolts, leaving a gap and a non-continuous surface at this location. The conditions here would mirror Figure 10 taken 70m south of the point of derailment.

As seen in Figure 10, the gap and non-level surface have the potential to create a scenario where the linear induction motor could make severe contact with the top cap. As discussed with TTC personnel, typical practice is for the top cap to be continuous at the reaction rail joints, with top cap joints staggered as opposed to coinciding.

After reviewing this scenario, Gannett Fleming took additional measurements at jointed locations north and south of the derailment site to determine whether the top of the running rail and top of the reaction rail were at the same elevations . The recorded measurements between the reaction rail and top of running rail ranged from -8mm to +5.2mm preceding and immediately after the derailment site location.

Figure 10: Maintenance activity at similar jointed reaction rail location south of derailment site

From reviewing TTC DM0804-13, Section 3.3.5, the tolerance for levelling between the reaction rail assembly and Top of Rail (TOR) is + 0/ +4.5mm. It should be noted that the new tolerances followed by TTC were confirmed to be -1mm and +5mm (elevation difference between TOR and top cap).

Additional site inspection photos have been provided in Appendix B. A few select photos have been highlighted below, along with initial observations.

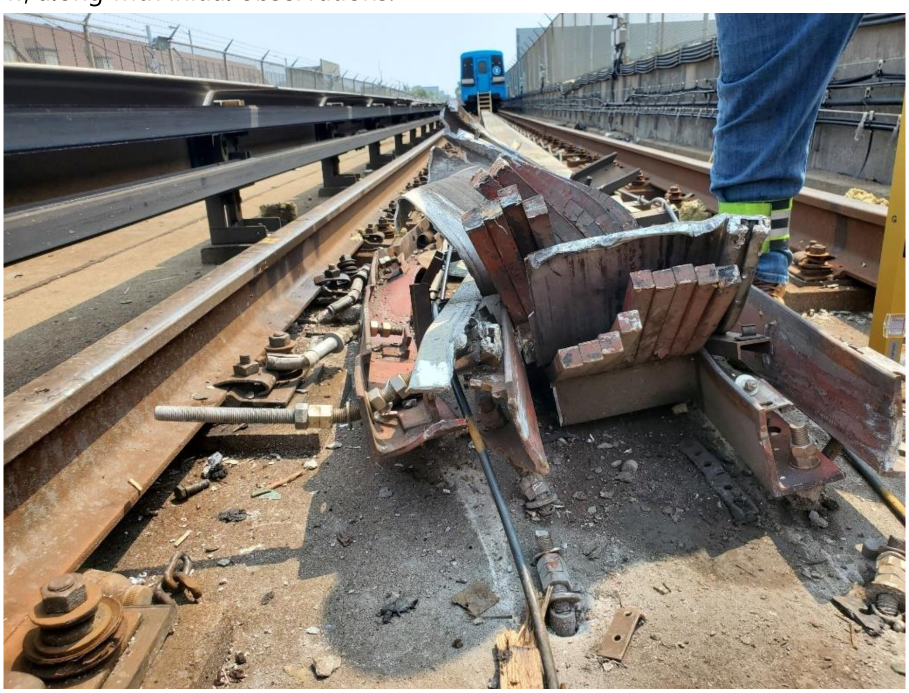


Figure 11: Section of reaction rail which came into contact with the linear induction motor.

5.3 Vehicle Dynamics - Initial Observations

Based on the dynamics and interaction between the car body and reaction rail, the undercarriage of the remaining vehicles in the derailment needed to be thoroughly observed. This was essential to assess Gannett Fleming's initial theory that the impact between the last car's linear induction motor and the reaction rail system was propagated by a preceding impact made by the other vehicles, in this case, cars 3006 and 3009. This, in theory, would have caused the reaction rail to rise further above allowable tolerances, after which the final induction motor could make a substantial enough impact to remove the assembly.

Gannett Fleming provided further expertise through their Senior Vehicle Engineering consultant to assess the vehicles and record damage. This gave a holistic picture of the vehicle-rail dynamics that might have contributed to the incident.

Further discussion on vehicle observations and dynamics can be found in Section 6.3 of the report.

5.3.1 Rail Vehicle Assessment – Initial Maintenance Record Review

Due to the scope split and the pace of the investigation, Gannett Fleming's assessment of the vehicle is limited to the documentation and material provided by TTC and visits to McCowan and Greenwood yards where photos (incident reaction rail, LIM motor, other bogie components) and measurements were recorded. Additionally, scheduled inspection and applied maintenance activities for the year 2023 until the date of the incident have been provided to the Gannett Fleming team.

The Gannett Fleming Team reviewed the maintenance files and reports for car 3001 and determined that there was nothing to indicate that this vehicle had any issues that were not rectified as part of the regular inspections and maintenance. Maintenance records of all the individual equipment groupings pertaining to the vehicle, such as vehicle, trucks, coupler, propulsion and brakes, were also inspected. It can be noted that no anomalies resulted from the review of the Safety Wheel Inspection findings from the inspection conducted on June 29, 2023. The Gannett Fleming Vehicle Group was also involved in all Gannett Fleming efforts looking into the derailment of car 3001 as well as all other aspects of the railroad, such as Track, System Operations, Environmental Conditions and Railroad Maintenance as of August 15, 2023.

Taking the inspection and maintenance records at face value, all inspection points were within acceptable operational limits and indicated car 3001 was fit for service at the time of its last inspection.

5.4 Additional Background Data

To properly assess the cause of the derailment, Gannett Fleming requested additional information to determine how the potential issue escalated. Additional information requested includes:

- Record drawings of the system
- CCTV footage of area where the derailment occurred, if available
- Track Inspection logs over the past year
- Vehicle Inspection logs over the past year
- Photos of the derailment immediately after the incident occurrence
- Standard Operating procedure for Reaction Rail Anchorage Assembly Installation
- Current Standards & Tolerances

At the time of publishing of this report, Track Inspection Logs were not provided. It is Gannett Fleming's understanding that these logs have been reviewed by another consultant participating in this investigation. Findings on the historical state of tracks in this area will need to be reviewed in parallel to this report.

6 EXAMINATION & ANALYSIS

6.1 Rail Infrastructure Inspection

6.1.1 Track Geometry and Surface Profile

An initial field investigation was conducted on July 28, 2023, to assist TTC in determining the root cause of the derailment. Completion of the initial investigation ruled out track infrastructure running rails, track geometry and surface profile. This inspection was conducted through visual assessment of track infrastructure, complemented by track geometry measurements utilizing a combined track gauge and level apparatus as shown in Figure 12.

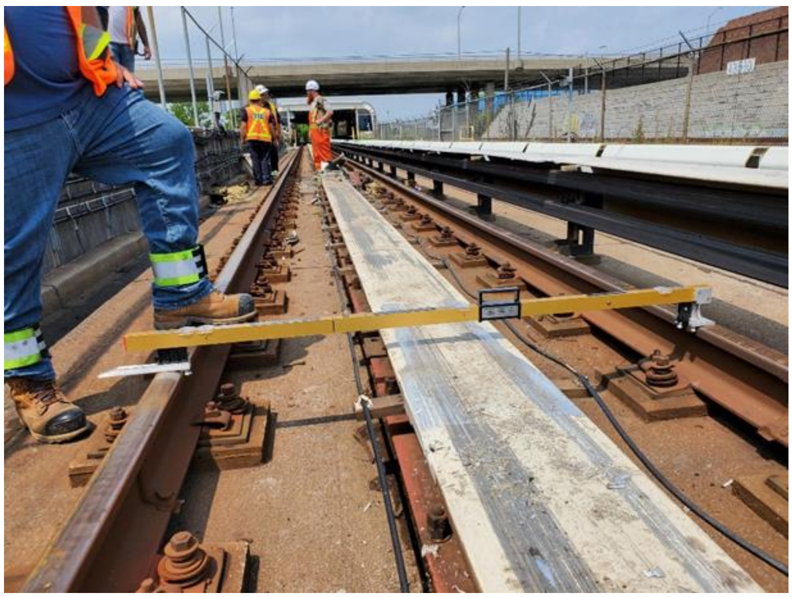


Figure 12: Cross-level, combination track gauge used for track inspection, and TOR-Reaction rail elevation measurements taken at a joint south (southbound) of derailment site.

6.1.2 Reaction Rail

Upon confirming that the rail profile and geometry were within the established TTC standards, eliminating them as potential causes for the derailment, the inspection team redirected their attention to the reaction rail. This pivotal component plays a central role in the propulsion of trains on the SRT network.

6.1.2.1 Overview

The reaction rail comprises a laminated back iron of nine soft steel bars. The number of laminations is a trade-off between thrust reduction and reaction rail cost. Laminated back iron is used in high-thrust areas. Low thrust areas such as yards have a reaction rail with solid back iron. An aluminum top cap (with a resistivity of 3.5 micro-ohms per meter) is a secondary winding. A mechanical assembly allows the transmission of forces to the guideway. The Top Cap is fastened to the reaction rail frame by using T-Bolts (Carriage Bolts) inserted in a channel of the top cap and attached to the frame of the reaction rail (Figure 13).

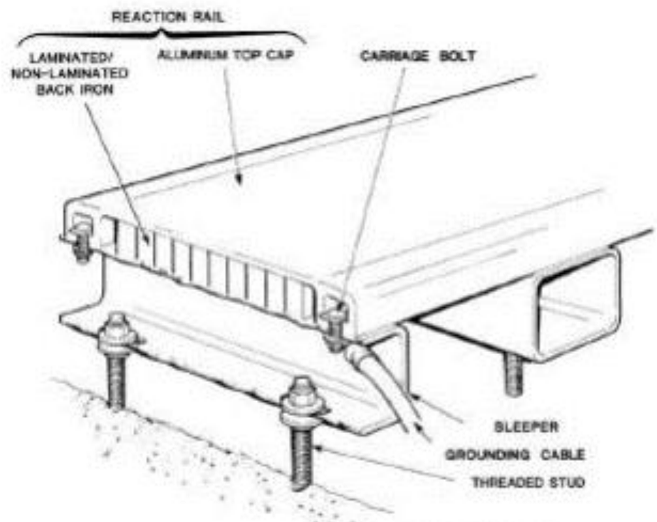


Figure 13: Typical Reaction Rail

6.1.2.2 Reaction Rail Standard Placement-Adjustment

The reaction rail is set in the center of the running rails at a height that allows the vehicle linear induction motor (LIM) to safely pass and still provide the magnetic forces required for proper operation of the LIM. As noted in Figure 14, the permissible tolerance range between the uppermost point of the reaction rail and the uppermost point of the running rail is -1mm to +5mm. In the context of this specific section, the measurement of reaction rail height is taken from the top of the running rail to the top of the reaction rail.

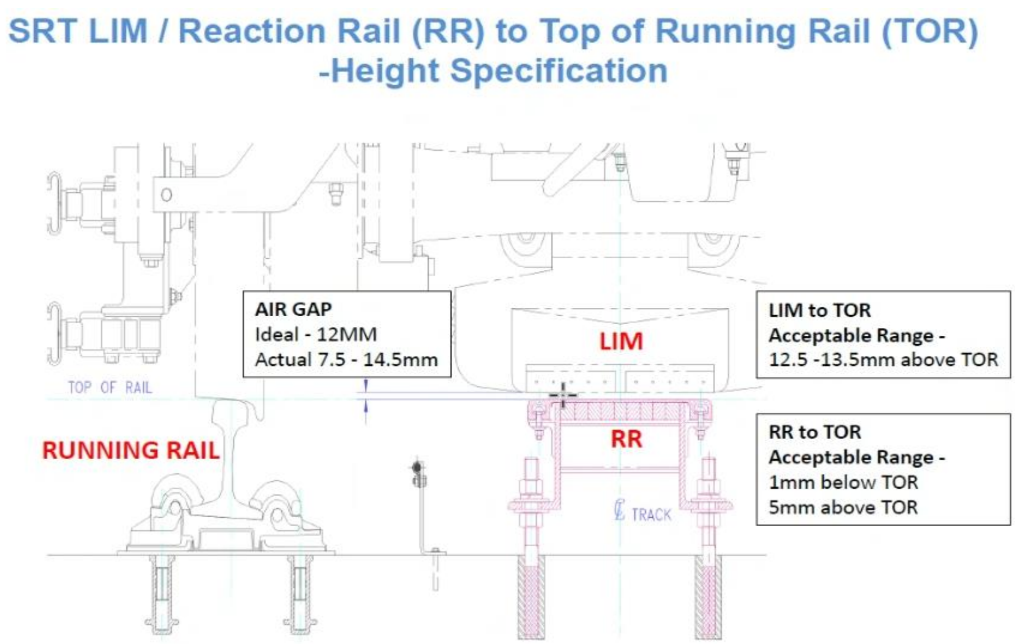


Figure 14: Reaction Rail to Top of Running Rail

6.1.2.3 Reaction Rail Height Investigation at Point of Derailment

The reaction rail height was measured immediately north of the point of derailment at a height of 5.2mm above top of running rail (see Figure 14 for reference). This is slightly above TTC's recommended value but within safe operating values. Reaction rail heights south of the point of derailment and where the derailed vehicle came to rest measured between -8mm to + 1.5mm, which is also within the safe operating values. It is assumed that the reaction rail anchor bolts at the point of derailment had fractured, allowing the reaction rail to lift and contact the LIM bumper of car 3006 in the preceding train before the incident train. Subsequently there was suspected contact with multiple cars between Train 1 and Train 2. This is assumed to have caused further lift of the reaction rail and ultimately derailed the incident train. Further investigation into failed anchor bolts is described in Section 0.

6.1.2.4 Reaction rail inspection

The primary root cause for the derailment is assumed to be failed components of the reaction rail system. It is known that the train struck an elevated reaction rail, which caused the derailment. The actual root cause is discussed in further detail in Section 7.3 of this report.

It was noted within the derailment site that numerous newer stainless steel anchor bolts secured the reaction rail frame to the invert slab, and some of the stainless steel bolts showed signs of fracture prior to the derailment. Figure 15 shows a similar fractured and misaligned anchor bolt found approximately 70 m south of the derailment site.

Figure 15: Fractured anchor bolt located approximately 70m south of the derailment site

6.2 Structural Assessment

A typical segment of reaction rail near the derailment site consists of a 2.48 m long assembly with nine (9) - 25 mm x 25 mm laminated back iron rods (inductor), seated on C75x9 channels and twin L125x90x10 steel angles, covered by an extruded aluminum cap, as depicted in Figure 16. Each 2.48 m long segment of reaction rail is typically secured by eight (8) anchor rods cast into the concrete guideway track slab.

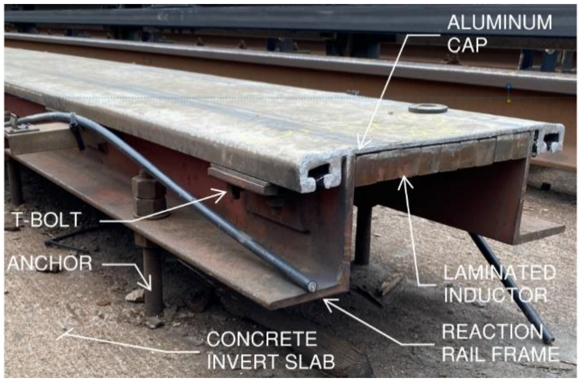


Figure 16: Typical Reaction Rail Components

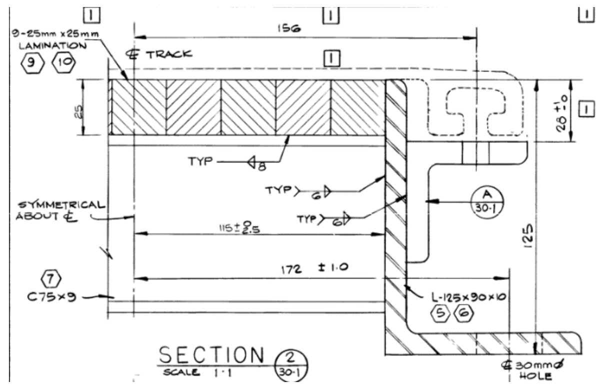


Figure 17: Typical Reaction Rail Drawing - Section

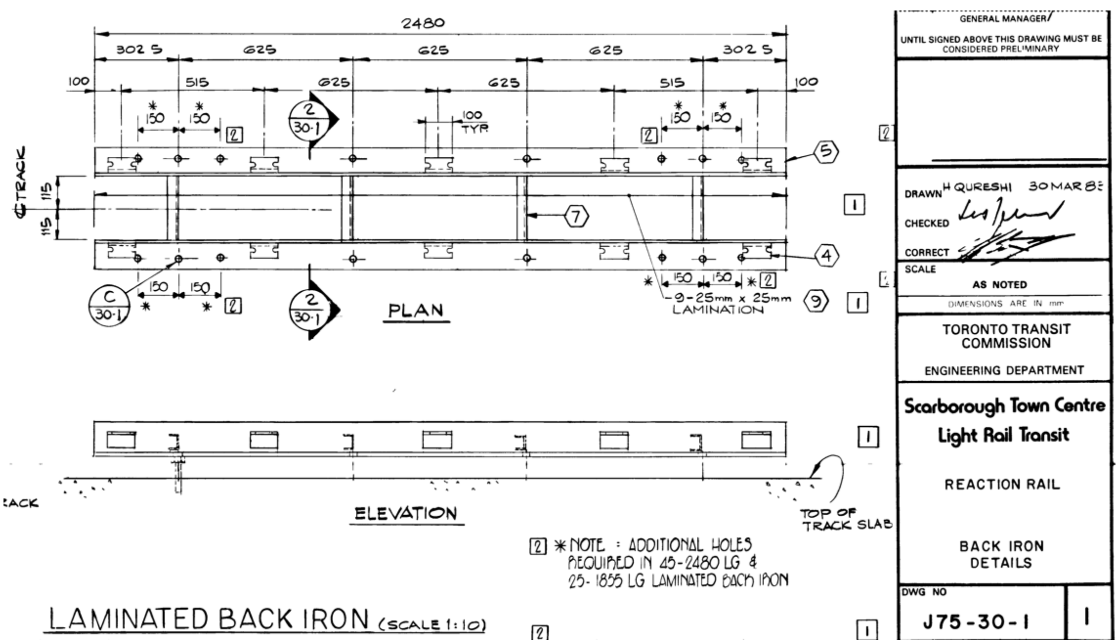


Figure 18: Typical Reaction Drawing - Plan and Elevation

The reaction rail at the derailment location had been impacted by the undercarriage of the train, causing distortion of the laminated inductors and resulting in a longitudinal translation of the reaction rail by several meters, where it became wedged under an adjacent section.

The impacted reaction rail assembly had been retrofitted, including modifications to the assembly and replacing the anchors using post-installed torque-controlled expansion anchors (Hilti HSL-GR stainless steel heavy-duty anchors, M20/30). Figure 20 shows an existing post-installed anchor found south of the derailment site. At the original sections of the reaction rail, the joints in the aluminum cap are offset from the joints in the lower frame, whereas at the retrofit sections, the joints in the aluminum cap and lower frame coincide at the same location (see Figure 19). The lapping of the aluminum cap over the lower frame joints found in the original sections mitigates the effect of any vertical variation in the reaction rail segments, making the original sections less likely to snag the train induction motor in the event of a loose or high reaction rail segment.

The aluminum cap plate on top of the reaction rail exhibits scars, likely from contact with train components, along the entire section of track. Many of these marks were tarnished with oxidation, suggesting that contact between the reaction rail and the trains had occurred for some time. Many T-bolts (holding the aluminum cap to the induction plate frame on the reaction rail) were loose or missing.

Figure 19: Retrofit south of the derailment site, short segment with coincident joints in aluminum cap and inductor

Figure 20: HSL-GR M20 anchors at retrofit south of the derailment site

The post-installed mechanical anchor assembly is shown below in Figure 21 to Figure 24.

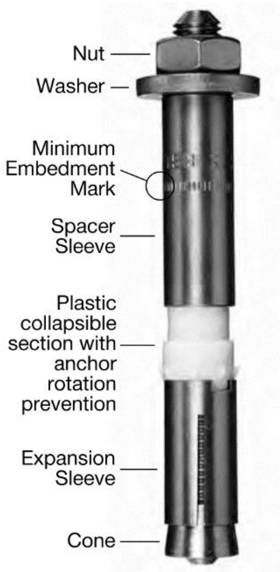


Figure 21: HSL-GR Stainless Steel Anchor (Hilti Manual)

Figure 22: Typical Assembly (SRT)

Figure 23: Partial Anchor Assembly Found at Derailment Site

Figure 24: Anchor Assembly (pullout failure)

According to TTC SOP SI-T-0007 - Anchor Bolt Replacement - SRT, the threaded rod supplied by Hilti is discarded and replaced by a longer stainless steel threaded rod of the same diameter. Grade A4 stainless steel is used for both the Hilti HSL-GR rods and the longer replacement rods, as confirmed by chemical analysis (**Appendix E**).

As part of the background information for this review, the TTC provided the following photographs showing testing of the anchors.

Figure 25: Post-Installed Anchor Test

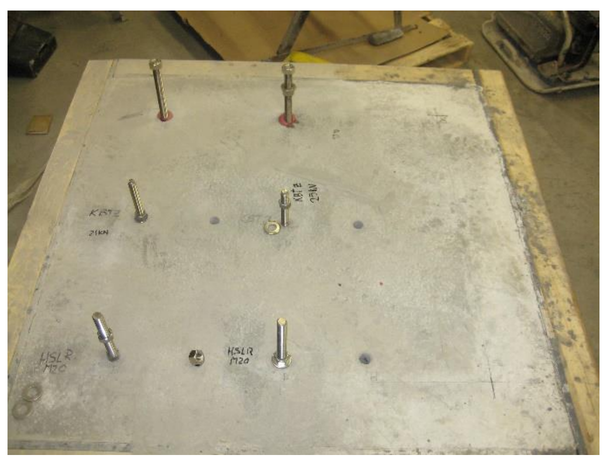


Figure 26: Post-Installed Anchor Test

The anchors secure the reaction rail in place, keeping it from lifting in response to forces applied by the LIM. TTC DM-0301-02 (3.2.4.8) stipulates the following design loads, which must be resisted by proper fastening methods to the guideway slab:

- Upward force on reaction rail 26 kN/LIM
- Lateral force on the reaction rail 3.5 kN/LIM
- Downward force on the LIM primary 26 kN/LIM
- Longitudinal force (braking) 15 kN/LIM

Since the LIM length is shorter than the 2.48 m reaction rail segment length, the forces listed above would typically be resisted by a single reaction rail segment and distributed over the eight supporting anchors. Assuming the properties of the stainless steel rod used are the same as the Hilti-supplied rod, the strength of properly installed rods and anchors is sufficient to resist the applied loading at ultimate limit states, including consideration of bending of the portion of rod above the concrete. However, it should be noted that bending of the rods in response to the applied longitudinal and lateral forces causes significant bending stresses in the rods, and there is potential for fatigue crack growth under this cyclic loading. The combined bending and tensile stress in the rods under the unfactored loads noted above is estimated to be 245 MPa. It is unknown whether the full force is applied at each cycle while the train is in service, or a fraction thereof.

Figure 27 below outlines the numbering convention for the anchors at the segment of reaction rail impacted during the derailment, with views looking north and south at the concrete invert slab following the derailment. Additional photos are provided in **Appendix B**.

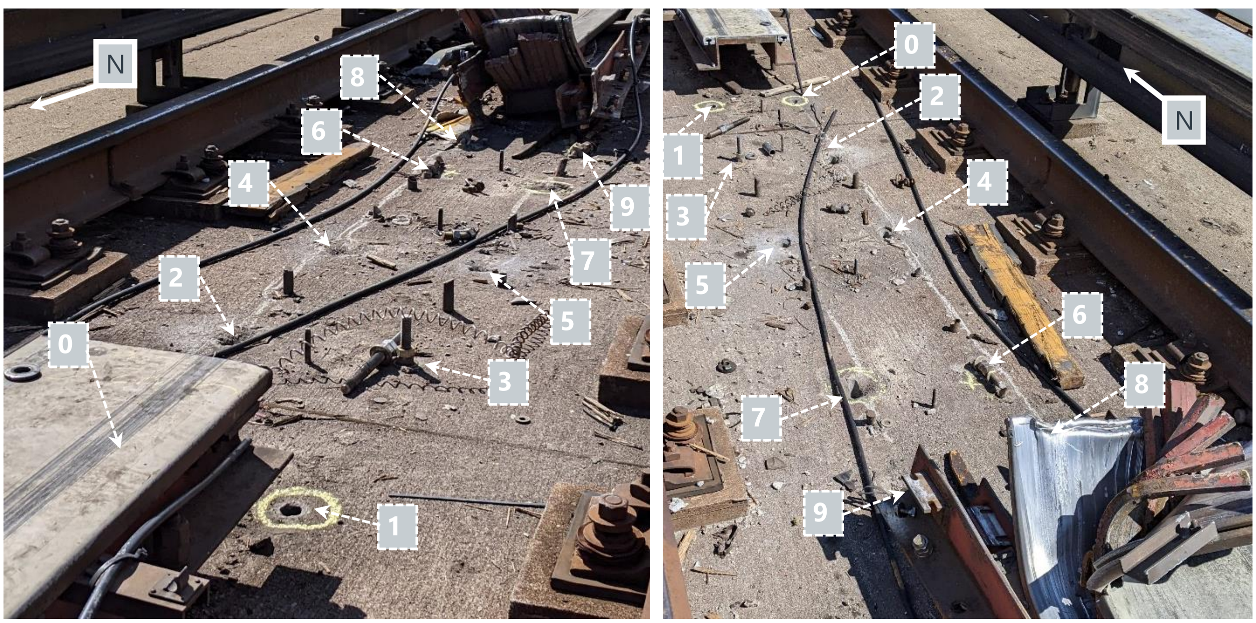


Figure 27: Anchor Layout Sketch

Coring of the concrete guideway invert slab was completed on Tuesday, August 1, 2023. A summary of relevant observations for each anchor from the site and the extracted cores is included below in Table 1, along with commentary regarding the observed failure mode for each anchor. Refer to **Appendix C** for the photographs and findings of the core sampling investigation.

Table 1. Anchor Summary

No.	Description
0	**Findings:** The rod was still connected to the reaction rail frame, with the expansion sleeve and cone remaining in the hole. No portion of the rod remained in the hole or connected to the cone or sleeve. The expansion sleeve and cone fell out of the hole once the core sample was removed, indicating that the expansion sleeve may not have been fully engaged with the concrete. Some bending deformation of the rod was noted near the top of rod, but the lower portion was not bent. Within the expansion sleeve, indentations from the threads of the rod were noted. Core sample C1 was taken at this location.
	Failure mode: As there is no evidence that the cone or expansion sleeve were lifted during the incident, it is suspected that the rod was disconnected from the cone prior to the incident. The bending deformation of the rod likely occurred following the train's contact with the reaction rail. The thread indentations found within the sleeve indicate that rod was likely in repeated contact with the sleeve prior to the failure.
1	**Findings:** The rod was fractured at the top, directly below the lower nut at the reaction rail frame connection. The rod was found to be loosely connected to the cone, which remained in the hole and engaged in the expansion sleeve. The rod was unthreaded by hand from the cone following the incident. Slight bending deformation of the rod was noted (Appendix E, Section 2.1.iv). Within the expansion sleeve, indentations from the threads of the rod were noted. Core sample C2 was taken at this location.
	Failure mode: The fracture in the rod directly below the reaction rail frame, with only slight bending deformation, indicates that the rod was fractured at this location prior to the incident. The thread indentations found within the sleeve indicate that rod was likely in repeated contact with the sleeve prior to the failure.
2 & 4	**Findings:** The entire anchor assembly, including rod, sleeves, and cone, was found intact and still attached to the reaction rail frame. Severe bending deformation of the rod was noted. A shallow cone-shaped spall was noted at the surface of the concrete.
	Failure mode: The anchor pulled out of the concrete. Bending deformation of the rod occurred prior to and during the pull-out failure during the incident, with the spalling damage to the concrete appearing to have occurred during the pull-out.
3	**Findings:** Rod was fractured at the top, directly below the lower nut below the reaction rail frame. The remainder of the anchor was still intact and secured in the concrete. Slight bending deformation of the rod was noted (Appendix E, Section 2.1.vii). The top of the rod appeared to have a hammered texture (Appendix B, Figure 11). Core sample C5 was taken at this location.
	Failure mode: The fracture in the rod directly below the reaction rail frame, without any bending deformation, indicates that the rod was fractured at this location prior to the incident. The hammered texture at the location of the fracture in the rod may have been a result of repeated lifting and dropping of the loose reaction rail, prior to the incident.
5	**Findings:** The rod and spacer sleeve were found connected to the reaction rail frame. It is suspected that the cone and expansion sleeve remain in the hole. Severe bending deformation of the rod was noted.
	Failure mode: The rod was disconnected from the cone and expansion sleeve. This condition may have been present prior to the incident.
6	**Findings:** The rod and anchor assembly were in the hole, with the spacer sleeve partially protruding above top of concrete. The rod was fractured, with deformation at the fracture location. Core sample C4 was taken at this location.

	Failure mode: During the incident, the anchor partially pulled out of the concrete, followed by fracture of the rod.
7	**Findings:** The rod and spacer sleeve were found connected to the reaction rail frame. The cone and expansion sleeve remained in the hole, with no portion of the rod attached to the cone or sleeve. Severe bending deformation of the rod was noted. Core sample C3 was taken at this location.
	Failure mode: The rod was disconnected from the cone and expansion sleeve. This condition may have been present prior to the incident.
8 & 9	**Findings:** The rod and anchor assembly were in the hole, with the spacer sleeve partially protruding above top of concrete. The rod was fractured, with deformation at the fracture location.
	Failure mode: During the incident, the anchor partially pulled out of the concrete, followed by fracture of the rod.

As noted above, there is evidence that anchors 1 and 3 were broken prior to the incident, and anchors 0, 1, 5, and 7 were loose prior to the incident.

According to the TTC SOP and the Hilti documentation, holes are to be drilled in the concrete to a depth of at least 155 mm using a 28 mm carbide hammer drill bit or diamond core bit, and fully cleaned using a vacuum or compressed air. At each of the core samples, the hole depth was at least as deep as the minimum specified hole depth of 155 mm. Some of the holes were deeper than required, which would not have a detrimental effect on the anchor performance. The measured hole diameters ranged from 28.2 mm to 30.2 mm. There is some variance in the measured diameters as compared to the expected 28.55 mm cutting diameter for a nominal 28 mm diameter drill bit, but the difference is not sufficiently large to indicate that an incorrect bit size was used for the drilling. Drilling powder was present at the bottom of some of the holes, indicating that the hole may not have been fully cleaned prior to anchor installation.

A failure analysis of the broken anchor bolts has been carried out, to provide additional insights into the potential causes of the anchor failures. This includes detailed visual examination, examination at low magnification and using a scanning electron microscope, metallographic sampling and examination, chemical analysis, hardness testing, and tensile testing. Comparison with and testing of unused anchor assemblies of the same type was also carried out. The results of the failure analysis indicate that anchors 1 and 3 fractured as a result of fatigue crack initiation and propagation. The thread roots of the fractured rods were found to have sharp corners, along with folds and micro-cracks, which contributed to the fatigue crack initiation. Refer to **Appendix E** for the Failure Analysis Report.

Anchors 0, 5, and 7 appear to have been loose prior to the incident but were not found to be fractured. It is possible that the rod gradually became disengaged from the cone and expansion sleeve due to cyclic loading. With each loosened anchor, the applied stresses on the remaining intact anchors would increase, possibly contributing to the observed fatigue crack formation and propagation at anchors 1 and 3. The precise cause of the rods becoming disengaged from the cone cannot be definitively established, but the following considerations are relevant and are likely to have contributed:

- **Installation:** No records of the anchor installation were provided, and it is not known whether the specified torque was applied to the nut during installation. The initial applied torque and pre-load in the rod could not be ascertained from the components retrieved from the site. The presence of drilling powder at the bottom of the hole indicates that the hole may not have been fully cleaned during installation. Furthermore, the TTC SOP requires that a torque seal be applied to the anchor bolt/nut, with a 6-month follow-up inspection to verify the torque seal condition (and thereby also verify that the nuts have not loosened). Torque seal was not found on the anchors and no records of follow-up torque inspection were provided.

- **Design:** Although Hilti's documentation states that this type of anchor is suitable for dynamic loading, it is unlikely that it was tested for the loading condition applied by the reaction rail. The torquing of the anchor induces a tensile pre-load in the rod between the cone and nut, and a corresponding clamping force between the nut/washer and the concrete. It is unlikely that the clamping force at this interface created enough frictional resistance to resist the applied horizontal loads, and therefore the connection would not be considered slip-critical. The height of the load application above the concrete surface (approximately 125 mm) increases the load at this interface by creating a lever effect. Once the frictional resistance is exceeded, a small slip would occur, and the anchor would continue to resist loads. However, over thousands of load cycles, the repeated slip between anchor components and concrete could result in loosening and/or unthreading of the anchor components.

It should also be noted that another segment of the reaction rail was found to be loose, approximately 70 m south of the derailment site. The anchors used at this location appear to be of the same type as those used at the derailment site. It is suspected that prior to the incident, support of the reaction rail at the derailment site was in a similar condition as this location, and that the failure of the bolts at this location has occurred in a similar manner as occurred at the derailment site. Within one reaction rail segment which is supported by 10 anchors, the following was noted:

- 2 anchors were fractured, with the fracture occurring directly below the lower nut of the reaction rail frame.
- 4 anchors were loose, and the rod could be moved within the hole.
- 3 anchors had loose nuts (the lower nut at surface of concrete is loose).
- 1 anchor appeared to be secure.

6.3 Rail Vehicle Assessment

In the investigation of the derailment incident, a comprehensive review of the provided data was conducted, focusing on key aspects, including vehicle inspection frequency, details of the derailed train (Assembly: car 3008-3009-3000-3001), the preceding train's information, and the Linear Induction Motor (LIM) involved in the incident. These observations aim to shed light on the factors contributing to the derailment and subsequent infrastructure failure.

The assessment of SRT "Mark I" vehicles are based on two distinctive sets of information:

1. Inspection logs and maintenance records of the fleet for the year 2023
2. Inspection of car 3001 after the derailment. The train wheel set from car 3001 was moved to Greenwood, while the remainder of the incident train was moved to McCowan yard.

6.3.1 Vehicle Observations – Post Accident Review

Initial findings reveal a comprehensive vehicle inspection routine, with major inspections carried out in accordance with standards every 60-70 days and safety inspections performed every 36-37 days.

After the trainset derailment, a post-incident review was conducted. It was found that car 3001 had detached from car 3000 due to the derailment forces. The shear bolts at the coupler cleanly separated, leading to the need for an assessment of the forces and dynamics involved in the incident. Notably, the impact markings indicate that the reaction rail came into contact with both car 3009 and the derailed car 3001. The resulting damage, extending up to 48/49mm above the Top of Rail (TOR) on car 3009, indicates that the vertical force exerted by car 3008's LIM onto the reaction rail caused severe lift; for the rail to have lifted this high indicates failure of the anchorage assembly of the reaction rail. This elevated reaction rail subsequently impacted car 3001. A detailed assessment of the derailed car 3001 uncovered a pronounced impact on the front antenna bridge of the rear bogie, evidenced by a three inch (3") high indentation.

A similar damage pattern was observed on car 3006 of the preceding train, suggesting a recurring issue with the infrastructure. car 3006 of the preceding train displayed damage consistent with the reaction rail rising to 57.15mm Above Track Reference (ATR) as measured at McCowan Yard. The deformation of the bumper suggested that both the aluminum top cap and laminated inductors both made impact with the undercarriage. Notably, no additional significant abrasions or impacts were identified along the rest of the train assembly, indicating localized effects.

TTC RC&S indicated that the LIM, weighing approximately 2000 lbs., is height adjustable through a teethed mechanism on the car's underside. Clearances were spot-checked for the remainder of the trainset involved in the derailment and were found to be within the required tolerances of 12.5 to 13.5mm (TOR to LIM). These gaps supersede TTC DM-0804-13, section 3.3.6, which initially indicated a gap tolerance from the top of the reaction rail assembly to the bottom of the linear induction motor on the vehicle to be 11 ± 3mm.

The recurrent damage patterns on car 3006 and car 3009 raise concerns about the LIM's dynamic interaction with the reaction rail and indicates continued progressive failure of the reaction rail anchorage assembly. The SRT system differs substantially from TTC's subway network given the LIM's behavior, interplay with the reaction rail, and influence on assembly components. In summation, these observations emphasize the need for a meticulous examination of multiple factors underpinning the derailment incident.

Although maintenance records indicate that the wheels were inspected and were within operational tolerance, the post-incident pictures show damage markings likely due to derailment and transportation off the site. No data regarding the wheel and flange wear prior to the incident were available.

The LIM height adjustment assembly pictures indicate the adjustment was made, and bolts were locked and marked (sealed) per standard procedure. This reduces the chance of LIM height adjustment negligence.

6.3.2 Maintenance Record Review

The review of inspection and maintenance records going back to January of 2023 regarding car 3001 provides the following summary:

- January inspection for Battery and LVPS
- February annual inspection of Smoke Detection system
- March overall HVAC inspection
- No inspection was recorded for the months of April and May
- During the month of June, a series of truck and vehicle safety inspections were performed.
- During the month of July, a series of standard inspections, cleaning and semi-annual axle bearing lubrication were performed.

The Vehicle Safety Inspection June 29th log for car 3001 confirms the following:

- Wheels and Flanges are within acceptable tolerance.
- LIM height gauge is within tolerance.
- Power distribution systems such as collectors and shoes were inspected.

- Truck's various components were inspected and passed.
- Couplers components were inspected and passed.

The maintenance logs correspond to inspection records as similar issues raised during the inspection were addressed and recorded in the maintenance activities. Considering the nature of the accident, a notable maintenance activity recorded on March 19 and June 5 is the LIM height adjustments.

Taking the available records at face value, there is no indication of vehicle maintenance-related defects leading to the derailment incident on July 24, 2023.

6.4 Reenactment Procedure

6.4.1 Workplan Summary

In collaboration with TTC, a detailed work plan was prepared to test the failure sequence and conditions that would have led to the lifting of the reaction rail and subsequent contact with the LIM or undercarriage of vehicles on different cars before the significant collision to car 3001. The purpose of the work plan was to conduct a reenactment to determine the narrative of the conditions that escalated the deterioration of reaction rail components leading to the derailment.

Given it is difficult to determine whether rods 2 and 4 were properly engaged as the entire anchor assembly of both were found intact and still attached to the reaction rail frame, this reenactment procedure served to confirm the conditions required for the reaction rail to rise above tolerances.

It must be noted that the procedure and parameters for such a test were to remain within the allowable gap tolerances between LIM and the reaction motor to avoid a collision and causing further damage to the equipment. Details of the Reenactment test can be found in **Appendix D.** The summary of the test procedure is as follows:

- Installation of GO PRO cameras on both sides of the reaction rail at the selected testing section at Lawrence East Station.
- Installation of a Tailor Square to measure and compare the approximate reaction rail lift in different test scenarios. Note, Tailor Square was installed only on the left side of the reaction rail.
- As per the test plan, all bolts on the selected reaction rails were sequentially numbered by paint stick to document the stages of the test and loosening of the bolts.
- The recordings were made individually per each pass to ensure individual recordings.
- With all rail fasteners intact, conduct a first pass of the consist at approximately 65% power to establish the baseline of SRT operating as intended and record the vehicle-infrastructure interface.
- Beginning sequential loosening of anchor bolts as described in the workplan.
- The test runs were conducted per scenario for both the forward direction (Southbound) and reverse direction (Northbound); however, considering the position of loosened bolts, the southbound tests were the primary intention of the procedure.
- A total of seven (7) bolt configurations were tested, and the movements were observed and recorded. Below are the seven (7) scenarios that were tested:
    - Scenario 1: Baseline conditions, all bolts intact
    - Scenario 2: Assume failure in bolt/anchor 0.
    - Scenario 3: Assumed bolts/anchors 0 and 2 failure.
    - Scenario 4: Assumed bolt/anchor 1 failure.

- Scenario 5: Assumed bolts/anchors 1 and 3 failure.
- Scenario 6: Assumed bolts/anchors 0 and 1 failure.
- Scenario 7: Assumed failure in bolts/anchors 0 to 3.

Figure 28: Go Pro Set Up on either side of the Reaction Rail

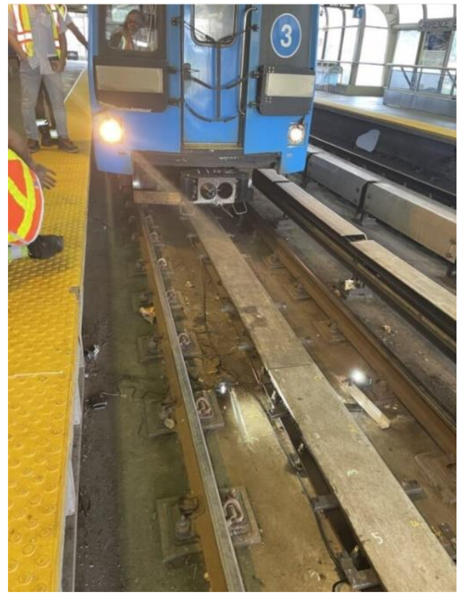


Figure 29: Overview of Test Set Up

6.4.2 Reenactment Observations

Recordings were taken during the reenactment procedure to understand the behaviour of the reaction rail and vertical movement in relation to various bolt failure scenarios in response to LIM magnetic force. Both vertical and longitudinal movements of the reaction rail were observed, highlighting the force exhibited by the LIM on the reaction rail and associated components. Table 2 below describes the reaction rail movement per pass per direction per side of rail.

Table 2: Reenactment Test Observations

Scenario #	Approx. Deflection – Right Side of Reaction Rail (even bolt #s)	Approx. Deflection - Left Side of Reaction Rail (odd bolt #s)
1	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No footage recorded.	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No footage recorded.
2	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No footage recorded.	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No footage recorded.
3	Forward Pass:	Forward Pass:

	• Minimal vertical deflection observed; mostly at bolt 0. Reverse Pass: • No movement observed in both vertical and horizontal directions.	• Slight horizontal displacement observed when train first meets the reaction rail. Reverse Pass: • No movement observed in both vertical and horizontal directions.
4	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No movement observed in both vertical and horizontal directions.	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No movement observed in both vertical and horizontal directions.
5	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No movement observed in both vertical and horizontal directions.	Forward Pass: • Minimal vertical deflection of 1/16" observed; mostly at bolt 1. Reverse Pass: • Vertical deflection of 1/8" observed; mostly at bolt 1. • Deflection occurred when train first meets the reaction rail. As the remaining cars transverse over the reaction rail, the movement is almost none.
6	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • No footage recorded.	Forward Pass: • No movement observed in both vertical and horizontal directions. Reverse Pass: • Minimal vertical deflection of 1/16" observed; mostly at bolt 1. • Deflection occurred when train first meets the reaction rail.
7	Forward Pass: • Vertical deflection observed; mostly at bolt 0. Reverse Pass: • Minimal vertical deflection observed when first two cars passed over the loosened bolts. • No movement observed when rear cars transverse over the reaction rail.	Forward Pass: • Vertical deflection of 8mm (5/16") observed. • Cyclical vertical movement. Reverse Pass: • Vertical deflection of 8mm (5/16") observed. • Cyclical vertical movement.

Figure 30: Go Pro View of Reaction Rail (Left Side)

Figure 31: Go Pro View of Reaction Rail (Right Side)

Upon careful review of the reenactment procedure's video footage, a discernible conclusion emerges: the elevation of the reaction rail beyond the maximum permissible tolerances necessitated the failure of a minimum of two rows of bolts. This alignment corresponds with the structural insights garnered from the fractured bolts and failed anchors. Analysis of the structural components reveals that bolt/anchors 0, 1, and 3 exhibited signs of breakage and potential loosening preceding the incident. Scenario 7 indicated that a minimum of two rows of anchor bolts were required for the reaction rail to begin to bend upward and behave like a hinge; however, with only two rows of bolts failing, the reaction rail would not rise beyond tolerances as demonstrated in the videos.

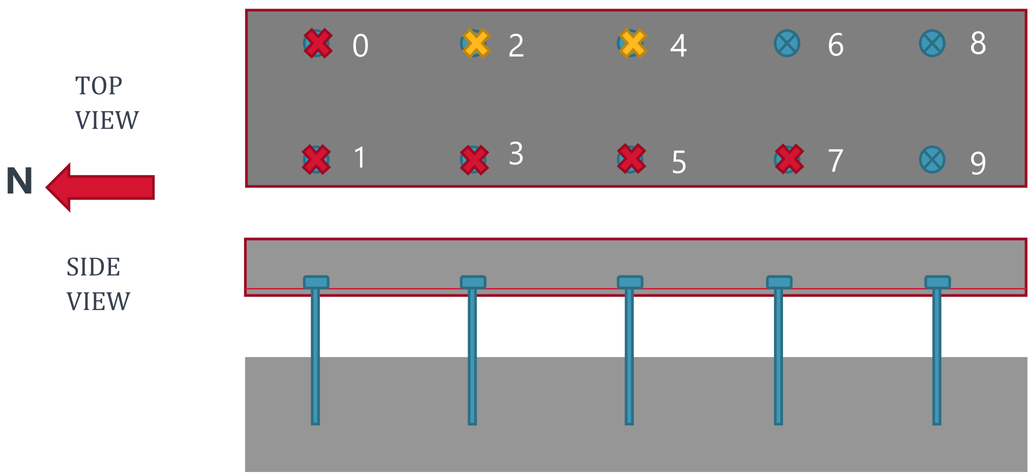


Figure 32: Bolt Failure configuration diagram. Red represents confirmed failed anchor bolts, and yellow represents suspected loose anchor bolts

Anchor bolts 5 and 7 are also suspected to have been loose prior to the incident. Noteworthy is the clean removal of anchors 2 and 4 during the derailment, implying a potential lack of secure anchoring into the invert slab. This collective evidence strongly points to a failure spanning over four rows of bolts/anchors per Figure 32, indicating a significant breakdown in component integrity at the time of derailment.

The reenactment procedure was key in determining the behaviour of the reaction rail and the failure required to necessitate the "hinge" type movement suspected to have caused the derailment.

6.4.3 Limitations

In the assessment process, certain limitations arose. The absence of numeric indicators prevented the SRT driver from confirming the sustained operation power level throughout the test duration.

The reenactment test imposed a maximum allowable elevation of 8mm for the reaction rail. This restriction was established to ensure test safety and preserve safety clearances between the reaction rail and the LIM (Linear Induction Motor) of the vehicles.

Furthermore, the test itself was conducted at an approximate speed of 25km/h, constrained by the availability of the allocated test track. Notably, the incident transpired at a higher speed of 40km/h. It should be noted that although test speeds were lower, the force induced on the reaction rail by the LIM was within the range of that experienced on the day of the derailment, as indicated by the level of thrust being applied. The varying speed is a factor to determine the rate of oscillation (lifting and dropping) of the reaction rail in between consists.

Regarding data collection, despite the installation of a measuring device in proximity to the reaction rail, the attainment of an accurate vertical movement reading was hindered by prevailing site conditions. Factors such as lighting conditions, camera quality, and the inherent precision of measurements collectively contributed to the challenges in achieving a precise measurement of vertical movement.

7 FINDINGS & CONCLUSIONS

7.1 Incident Narrative

Based on thorough infrastructure and vehicle inspections, comprehensive discussions with TTC personnel, and structural assessments, it is evident that the derailment's root cause lies in the collision between the undercarriage of car 3001 and the reaction rail. Gannett Fleming collaborated with Acuren and HAL to unravel the sequence and type of hardware failures that collectively led to this derailment incident.

The prevailing working hypothesis suggests that bolts 1 and 3 (see Figure 34 for reference) were fractured prior to the derailment, as indicated by their fracture surfaces and lack of severe bending deformation. As detailed in Section 0 of the report, the failure of these two bolts resulted from fatigue crack initiation and propagation. This supposition gains further support from the distortion evident on the preceding segment of the reaction rail's top cap, seemingly resulting from contact with the following reaction rail, which made contact with the undercarriage of car 3001 (see Figure 33). This sort of deformation could only occur from recurrent impact with the downstream top cap as it is lifted while a train passes.

Figure 33: Preceding top cap deformation at reaction rail/top cap joint

This proposed scenario finds additional reinforcement in similar observations, as Figure 15 shows another instance of premature bolt failure 70 m south of the derailment site. With bolt assemblies 0, 1, 3, 5 and 7 failing prematurely, the remaining bolts would have borne heightened loads, particularly at the leading edge of the reaction rail with a higher moment arm.

Both bolts 2 and 4 were removed cleanly from the invert slab during the derailment; while it is possible that the anchors were not secure, there is insufficient evidence to substantiate this inference, as the entire assembly was removed during the derailment. The reenactment procedure was critical in determining whether anchor bolts 2 and 4 could have failed. The footage and observations revealed that a minimum of two rows of anchor bolts needed to fail for the rail to begin to lift to the levels that could cause a derailment, confirming the likelihood that bolt 2 was most likely not properly engaged. The movement during the reenacted two rows of failure resulted in the movement of the reaction rail to the 8mm limit.

With this understanding from the reenactment procedure, it can be presumed that with up to four rows of bolt/anchor failure per Figure 34 below, the reaction rail would have risen to levels above tolerances, making impact with the underside of cars 3006, 3009, and ultimately derailing car 3001. The initial impact between the reaction rail and car 3006 is suspected to have raised the reaction rail further above tolerances, propagating in further worsened impact with car 3009 and then finally with car 3001.

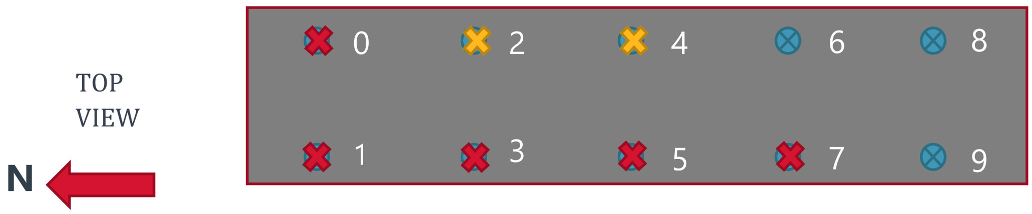


Figure 34: Plan view of suspected bolt failures. Red represents confirmed failed anchor bolts, and yellow represents suspected loose anchor bolts

While there is sufficient evidence to infer the behavior of the reaction rail, it is challenging to definitively determine its response following the impact with car 3006. This uncertainty arises from the inability to assess any deformation due to the preceding collision with derailed car 3001, and lack of footage of the reaction rail before the derailment. Consequently, Gannett Fleming cannot ascertain the precise settling of the reaction rail subsequent to its initial encounter with car 3006, but it is reasonable to presume that both the top cap and the laminated rods likely contributed to the bumper's deformation shown in Figure 4. The extent of separation between the top cap and laminated rods remains undetermined. In summary, the behavior of the reaction rail following the impact with car 3006 remains unpredictable, primarily due to the altered response resulting from damage incurred during the first incident, which subsequently led to sporadic impacts with car 3009 and the more severe collision with car 3001.

While the progressive behaviour of the reaction rail cannot be vetted, the reason for the reaction rail rising and the root cause of the incident can be attributed to the failure sequence of the bolts as described in Section 0 and inferred in this section of the report.

7.1.1 Limitations

- Due to damage to the reaction rail during the derailment, evidence of historical recent contact with other cars could not be definitively identified.

7.2 Rail Infrastructure Findings & Conclusion

In the zone directly surrounding the derailment site, no running rail infrastructure or track profile issues were identified as contributing factors for the incident cause, apart from the reaction rail and its corresponding infrastructure, as outlined in Section 7.3.1

7.3 Forensic Assessment Conclusion & Safety Actions

7.3.1 Conclusion – Cause & Contributing Factors

As previously noted, the rise in the reaction rail can be attributed to the failure sequence of the bolts, as detailed in Section 6.2 and further confirmed in section 7.1. The following summarizes potential contributing factors based on the observations made:

- **Failure of anchor bolts** – Findings indicate that several anchor bolts were loose and/or broken prior to the incident. Two anchors failed due to fatigue crack initiation and propagation prior to the incident, and three anchors were unbroken but disengaged prior to the incident based on the evidence presented. It should also be noted that failure of the anchor bolts likely occurred progressively, with each anchor failure resulting in an increase in loading on the remaining anchors and hastening their failure. With several anchors loose and broken, the reaction rail was sufficiently loose to be lifted high enough by the LIM to make contact with the train.
- **Location of the aluminum cap joint with respect to laminated inductor joints** – The aluminum top cap is designed to overlap the joints in the reaction rail for additional support of the reaction rail infrastructure per DM-0804-13, or bonded for continuity as noted in section 3.2.5 of the DM. At the location of the reaction rail retrofits, the joints with the aluminum cap are coincident with joints in the reaction rail frame. This results in a more severe difference between adjacent segments and exposes the ends of the laminated inductors, making it more likely that the train would snag on a loose or high segment of reaction rail.
- **Loose and missing T-Bolts** – At critical locations, specifically at coincident joints, the T-bolts hold the aluminum cap down on the reaction rail. Several T-bolts along this corridor were found to be missing or loose, which could permit the aluminum cap to sit higher and be exposed to more contact with the train.

7.3.2 Recommendations and Safety Actions

Based on the investigations and analysis detailed in this report, the following conclusions can be drawn, and the subsequent recommendations should be considered.

- All post-installed anchors should be tested to verify proper installation and capacity, particularly in areas of reaction rail retrofits.
  - Review and adjust procedure for post-installed anchors. Consider incorporating grouting as part of the anchor installation process to improve overall stability and load-bearing capacity. The use of grout can be beneficial in avoiding the loosening failure mode discussed in this report.
  - Attention should also be focused on areas exhibiting misalignment between the bolt holes in the reaction rail frame and the invert slab, as this misalignment has the potential to induce avoidable stress on the bolts.
- Joints in the aluminum panel above the laminated inductors should not coincide with joints in the inductors/frame.
  - It's important to highlight that the derailment site's location underwent a retrofit, resulting in the top cap joint coinciding with the LIM rail (reaction rail frame) joint. According to TTC DM0804-13 Section 3.2.5, these overlaps should typically be staggered. Adhering to this practice would have inhibited the elevation of the reaction rail at this

specific point. Moreover, it would have distributed both the lateral and lifting loads from the LIM across two separate reaction rail frames and anchorage assemblies.

- All loose or broken reaction rail anchor bolts should be immediately addressed and corrected to mitigate further deterioration of localized reaction rail infrastructure.
- All aluminum panels should be tightly secured (with T-bolts) and within tolerance to limit potential conflicts.
- Consideration should be made to installing lock nuts/double nutting T-bolts to prevent loosening/detachment.
- Consider integrating inspection training with a comprehensive understanding of vehicle and train dynamics. This fusion of knowledge empowers inspection personnel with technical proficiency and a nuanced grasp of the risks, forces, and stresses imparted on components by passing trains.

7.3.3 Additional Considerations

Education: In the instance of this derailment, the dynamics between the reaction rail and the LIM of the vehicle is a unique scenario in TTC's network. Understanding the forces applied on the reaction rail, and the risks associated with the failure of the components would benefit inspectors.

Through integrated knowledge sharing between equipment and engineering teams, track inspectors gain the ability to discern high-risk failure points and critical locations that demand heightened vigilance. This informed approach enables timely interventions, targeted maintenance, and a proactive stance toward averting catastrophic failures. To implement this lesson, it is recommended to design training modules that encompass theoretical and practical aspects of train dynamics and foster continuous learning to adapt to evolving train technologies. Ultimately, this integration augments infrastructure assessment efficacy and fortifies overall network safety and dependability.

APPENDIX A: TRACK INSPECTION REPORT

1.1 Record of Inspection

TRACK INSPECTION REPORT

ENGINEERING **Line:** SRT **Inspection Date:** 7/25/23

Yards or Other Tracks: Southbound Track

Main tracks, sidings and/or yard tracks inspected (see notes 1 & 2) (Mileage's of all tracks inspected)	Type of Inspection
Southbound Track (Chainage 135+73.80 to 135+10.00)	Walking

Turnouts & railway crossings at grade inspected (Location - station and/or mileage. (See note 4)

RECORD OF INSPECTION

- Track gauge was within standard (56-3/4")
- Cross level within standard (0" - 1/8")
- No visual surface irregularities
- Reaction Rail was struck
- Numerous sections of Reaction Rail covers show evidence of previous rub marks
- Newer lag bolts were installed in area that was struck

Track Inspector Ryan Fell [signature] Sr. Track Inspector

Name **Signature** **Title**

APPENDIX B: SITE PHOTOS

1.1 Derailment Site Photos

Figure 1: Derailment Site Looking South from Ellesmere Station

Figure 2: Section of Reaction Rail which came in contact with Linear Induction Motor

Figure 3: Damaged Reaction Rail and Bent Anchor Bolts

Figure 4: Derailment Site

Figure 5: Bent Anchor Bolts immediately South of Derailment Site

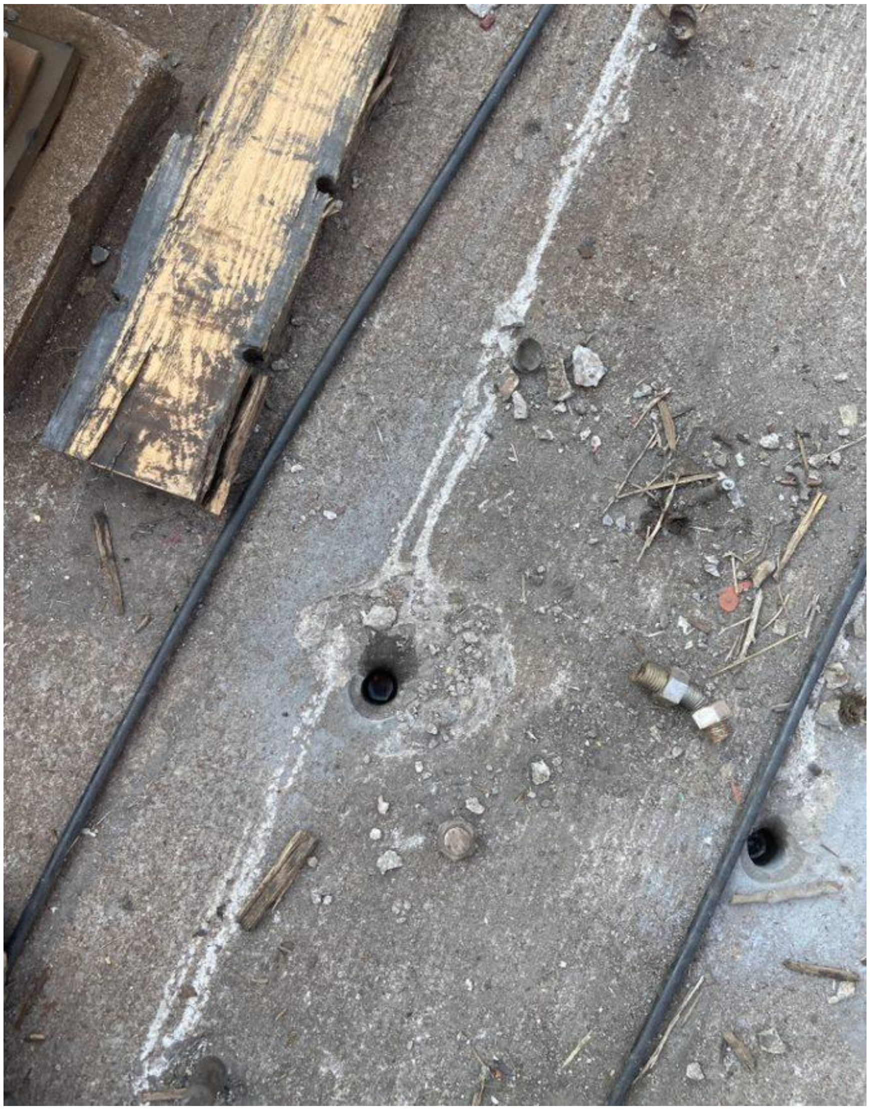


Figure 6: Anchor Bolts pulled out of Concrete Slab

Figure 7: Anchor Bolts zero (0) and one (1) at point of impact. Top cap abrasion

Figure 8: Bent Anchor Bolts South End of Derailment Site

Figure 9: Loose Anchor Bolts near Derailment Site (South end)

Figure 10: Fractured Anchor Bolt Approximately 70 m South of Derailment Site

Figure 11: Fractured Anchor Bolt (Anchor No. 3)

Figure 12: Impacted Reaction Rail Frame, pushed below the Adjacent Reaction Rail Frame. Note the upper portions of Anchor Nos. 1, 3, and 5 attached to the frame.

Figure 13: Upper Portion of Anchor Bolt Attached to Reaction Rail Frame (Anchor No. 1)

Figure 14: Upper Portion of Anchor Bolt Attached to Reaction Rail Frame (Anchor No. 3)

Figure 15: Upper Portion of Anchor Bolt Attached to Reaction Rail Frame (Anchor No. 7). Note that the spacer sleeve remains attached to rod, while cone and expansion sleeve remained within the concrete.

APPENDIX C: HAL CONCRETE REPORT

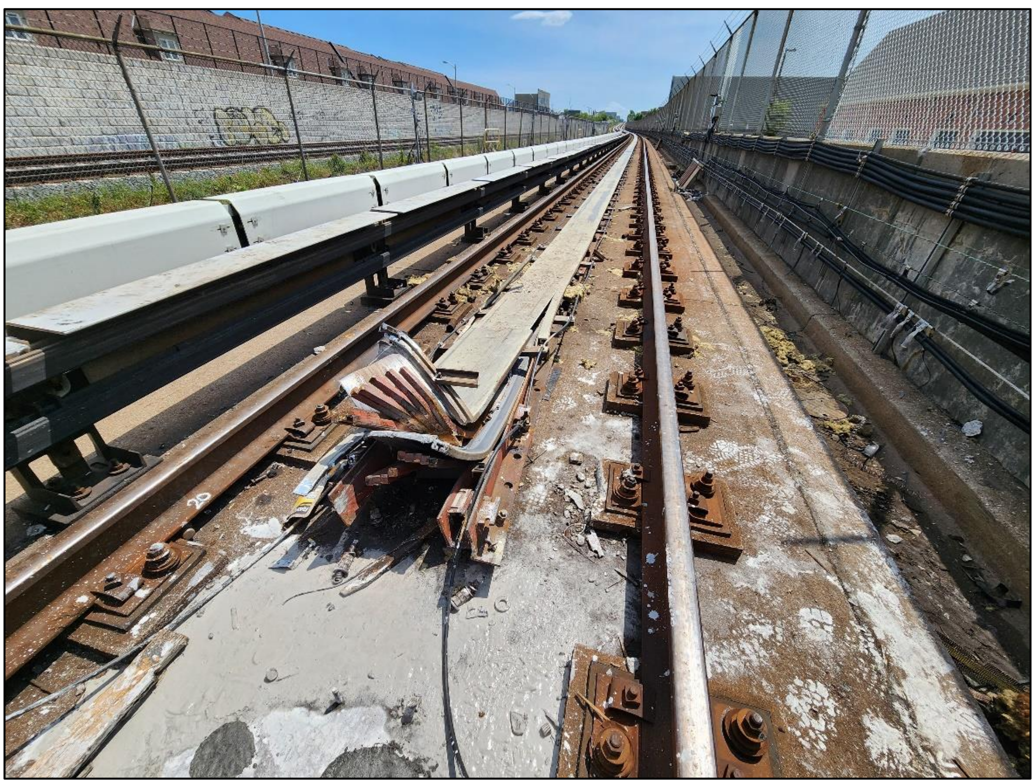
TORONTO TRANSIT COMMISSION

SCARBOROUGH RAPID TRANSIT, SCARBOROUGH, ONTARIO

LIMITED INVESTIGATION

October 2023

Project No.: 20230801



HAL

HAL

SCARBOROUGH RAPID TRANSIT, SCARBOROUGH, ONTARIO

LIMITED INVESTIGATION

TORONTO TRANSIT COMMISSION

PROJECT NO.: 20230801
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1 INTRODUCTION

HAL Group Inc. was retained by Gannett Fleming Canada ULC on behalf of The Toronto Transit Commission to extract five (5) concrete cores from a section of the invert slab where Scarborough train derailed around Ellesmere Station in Scarborough, Ontario. The cores were extracted from the invert slab where the bolts were dislodged, which mounts the Reaction Rail assembly to the slab.

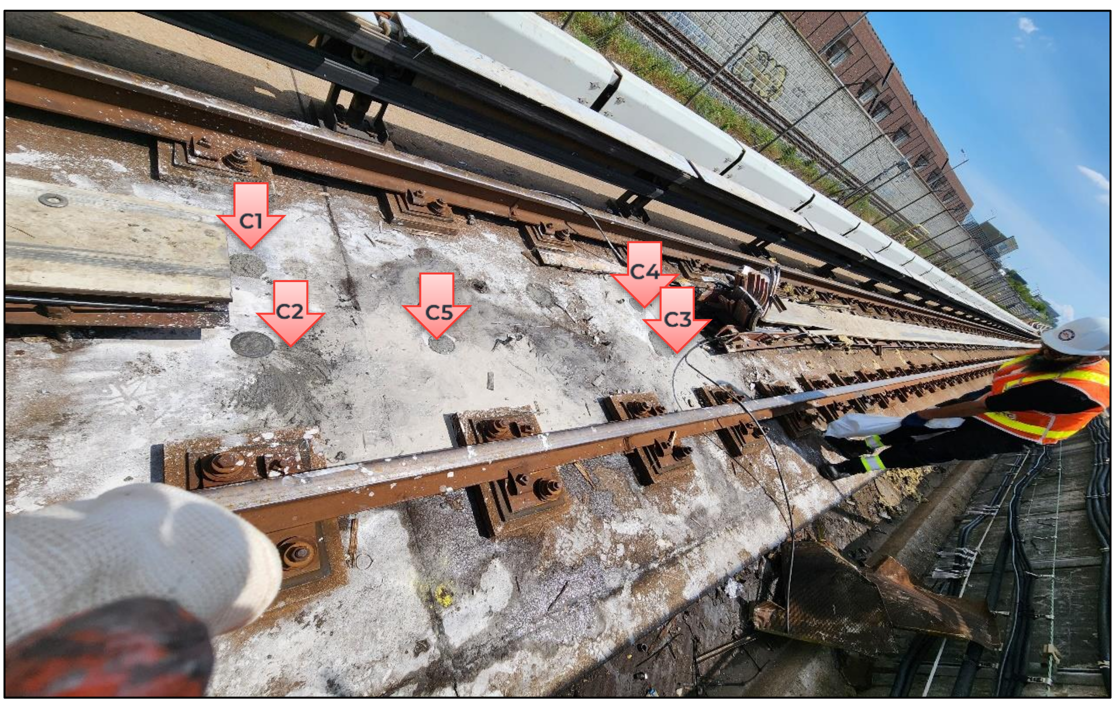
This report presents HAL's findings, through visual examination of the extracted cores. Field investigation was carried out by HAL on August 1, 2023.

2 METHODOLOGY

The following laboratory testing program was carried out to document the condition of the core samples.

1. Each core sample was photographed to show the as received condition of the cores.
2. A core log was prepared to describe the as received condition of the core samples.
3. Upon completion of the initial finding, each core sample was sawn across its diameter for the full length of the core, and additional core sample description were added to the initially prepared core log after visual examination.
4. One sawn sample from each core was tested for depth of carbonation, using a Phenolphthalein 0.5% solution to determine the depth of carbonation if any. Upon completion of the carbonation tests, photographs were taken of the tested faces of the core.

The core locations are shown in picture below.



3 FINDINGS

3.1 CORE NO. 1

The core sample length was 190 mm to 207 mm.

Core Sample Description:

- Core was taken directly over an anchor bolt installation.
- Some chipping damage to the top surface of the concrete was noted on one side of the core hole to a depth of approximately 20mm, likely due to anchor bolt impact damage.
- Anchor bolt hole was seen through the entire depth of the core submitted.
- Anchor bolt hole was ~29.5mm diameter, as measured at the top of core.
- Anchor bolt hole was ~28.2mm diameter, as measured at the bottom of core.
- Anchor bolt hole was noted to be full depth of the drilled core.
- Upon receipt of the core, we noted the expansion sleeve and cone fell out of the core hole. Bottom portion of the anchor assembly (expansion sleeve and cone), approximately 27.6mm diameter by 57.5mm length. The depth to the top of the expansion sleeve appears to be 100mm down from the top of the core, as evidenced by the sleeve imprint on the inside of the hole. No anchor bolt or other parts of the anchor assembly were provided.
- Core was terminated in sound concrete, due to intentional drilling break.
- Visual quality of the concrete and compaction was good. No visible cracks were seen in the concrete.
- Carbonation test showed slight carbonation of the top surface was noted to a depth less than 0.5mm.
- It was noted that the sleeve of C1 has indentations (photo P24).

3.2 CORE NO. 2

The core sample length was 228 mm to 224mm.

Core Sample Description:

- Core was taken directly over an anchor bolt installation, through the full thickness of the slab concrete.
- Anchor bolt hole was drilled to depth of approximately 197mm, with drilling powder visible from a depth of approximately 150 to 197mm.
- Anchor bolt hole was ~30.2mm diameter, as measured at the top of core.
- Anchor bolt hole diameter deeper into the hole was not measurable.
- Bottom portion of the anchor assembly (expansion sleeve and cone), approximately 27.6mm diameter by 57.5mm length, was still in drilled hole, at a depth of approximately 76mm down from the top of the core, to top of sleeve. Two white plastic spacers (~15mm in depth) compressed together were noted just above the top of the sleeve. No anchor bolt or other parts of the anchor assembly were provided.
- In general, visual quality of the concrete and compaction was good. Apart from the spalling damage seen at the top of the core, no cracking or other damage seen in the concrete.
- Carbonation test showed no visible carbonation of the top surface of the concrete.
- It was noted that the sleeve of C2 has indentations (photo P25).

3.3 CORE NO. 3

The core sample length was 230 mm to 240 mm.

Core Sample Description:

- Core was taken directly over an anchor bolt installation, through the full thickness of the slab concrete.
- Top of core had spalled away likely due to anchorage impact damage. Depth of spalling damage is not known from core examination and should be determined in the field prior to or after coring.
- Anchor bolt hole was drilled to depth of approximately 200mm, with drilling powder visible from a depth of approximately 197 to 200mm.
- Anchor bolt hole was ~28.5mm diameter, as measured at the top of core.
- Anchor bolt hole diameter deeper into the hole was not measurable.
- Bottom portion of the anchor assembly (expansion sleeve and cone), approximately 27.6mm diameter by 57.5mm length, was still in drilled hole, at a depth of approximately 120mm down from the top of the core, to top of sleeve. No anchor bolt or other parts of the anchor assembly were provided.
- Core was drilled through the entire thickness of the slab concrete.
- In general, visual quality of the concrete and compaction was good.
- Two vertically oriented cracks were seen on the outside faces of the core; one in line with the anchor hole to a depth of ~40mm, and the second crack on the opposite side of the core, to a depth of ~90mm. Also noted, on the same side as this crack was evidence of another drill hole that appear to be patched with grout.
- Carbonation test showed slight carbonation of the top surface was noted to a depth less than 0.5mm.
- No indentations were observed in the sleeve of C3 (photo P26).

3.4 CORE NO. 4

The core sample length was 242 mm.

Core Sample Description:

- Core was taken directly over an anchor bolt installation.
- Core was retrieved in two pieces; one piece 0 to 130mm in depth, and the second piece ~112mm in depth.
- Spalling damage to the top surface of the concrete was noted around the anchor bolt sleeve, to a depth of approximately 20mm, due to anchor bolt impact damage, as evidenced by the bent condition and sheared condition of the anchor bolt. Also noted, the due to the impact damage, the sleeve and anchor bolt pulled out of the concrete for a length of approximately 20mm.
- Anchor bolt hole was drilled to a depth of ~210mm.
- Anchor bolt hole diameter at the top of core was not measurable, due to spalling damage of concrete.
- Anchor bolt assembly present was a bent ~20mm diameter anchor bolt sheared at the top due to impact damage, a section of spacer metal sleeve ~70mm in depth, then two white plastic spacers (~15mm in depth), compressed together were noted just above the top of the spacer sleeve, then the expansion sleeve ~57mm in length and cone ~22mm in length assembly.
- Core was drilled through the entire thickness of the slab concrete.
- Visual quality of the concrete and compaction was good.
- Vertical crack in the concrete was noted in line with the anchor bolt to a depth of ~120mm. In addition, horizontal cracking was observed in the concrete at a depth of ~120mm seen in the concrete.
- Carbonation test showed slight carbonation of the top surface was noted to a depth less than 0.5mm.
- Could not observe the indentations in the sleeve of C4.

3.5 CORE NO. 5

The core sample length was 175 mm to 180 mm.

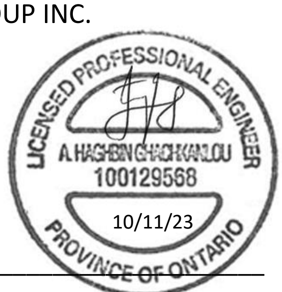
Core Sample Description:

- Core was taken directly over an intact anchor bolt installation.
- Core was terminated in sound concrete, likely due to an intentional drilling break.
- No damage to the concrete or anchor bolt installation was noted.
- Anchor bolt hole diameter at the top of core was not measurable, due to intact anchor bolt installation.
- Anchor hole was drilled the entire depth of the retrieved core.
- Intact anchor bolt assembly present with a ~20mm diameter anchor bolt, two nuts and washer, a section of spacer metal sleeve ~70mm in depth, then two white plastic spacers (~23mm in depth), partially compressed together were noted just above the top of the spacer sleeve, then the expansion sleeve ~57mm in length and cone ~22mm in length assembly.
- Total length of anchor bolt was ~255mm, and the anchor bolt depth into the concrete was ~155mm.
- Drilling powder was in the anchor drill hole noted at a depth of ~155 to 180mm.
- Visual quality of the concrete and compaction was good. No cracking was seen in the concrete.
- Carbonation test showed slight carbonation of the top surface was noted to a depth less than 0.5mm.
- It was noted that the sleeve of C5 has very minor indentations (photo P27).

4 CLOSURE

We trust that this limited investigation report is complete. Should you have any questions or comments, please do not hesitate to contact this office.

Yours very truly,
HAL GROUP INC.



Abbas Haghbin, P. Eng
President / Principal Engineer

Photo P1 – Core C1

Photo P2 – Core C1 Sawn Sample Faces

Photo P3 –Core C1 Sawn Sample Faces
(The expansion sleeve and cone placed in the imprinted anchor position on the interior of the core hole likely due to the expansion force applied during the installation and tightening of the bolts; left side core half was tested for depth of carbonation)

Photo P4 –Core C1 Top View

(The expansion sleeve and cone assembly fell out of core when handled)

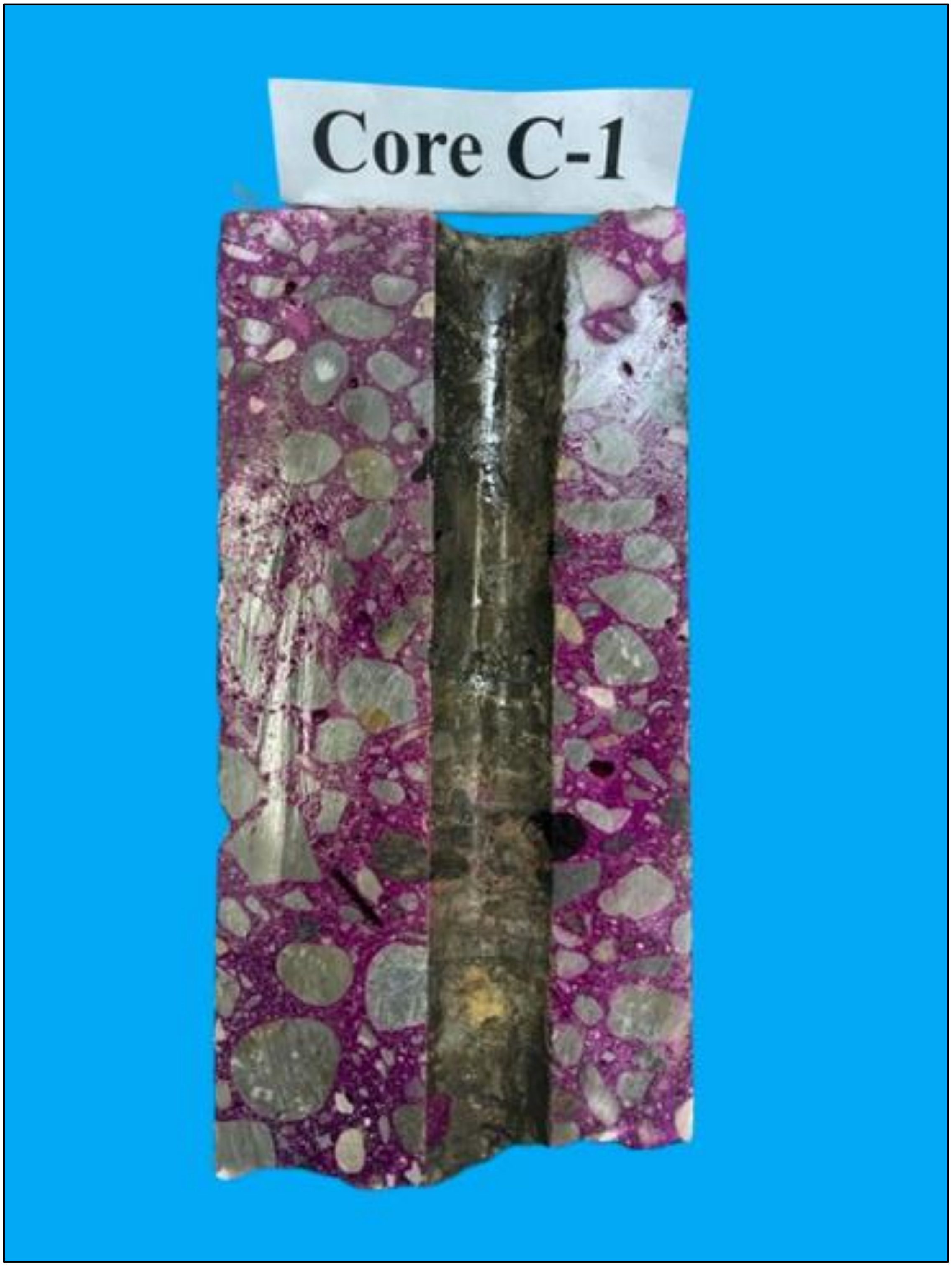


Photo P5 – Core C1

(Showing carbonation tested surface; Carbonation depth was determined to be less than 0.5mm)

Photo P6 – Core C2

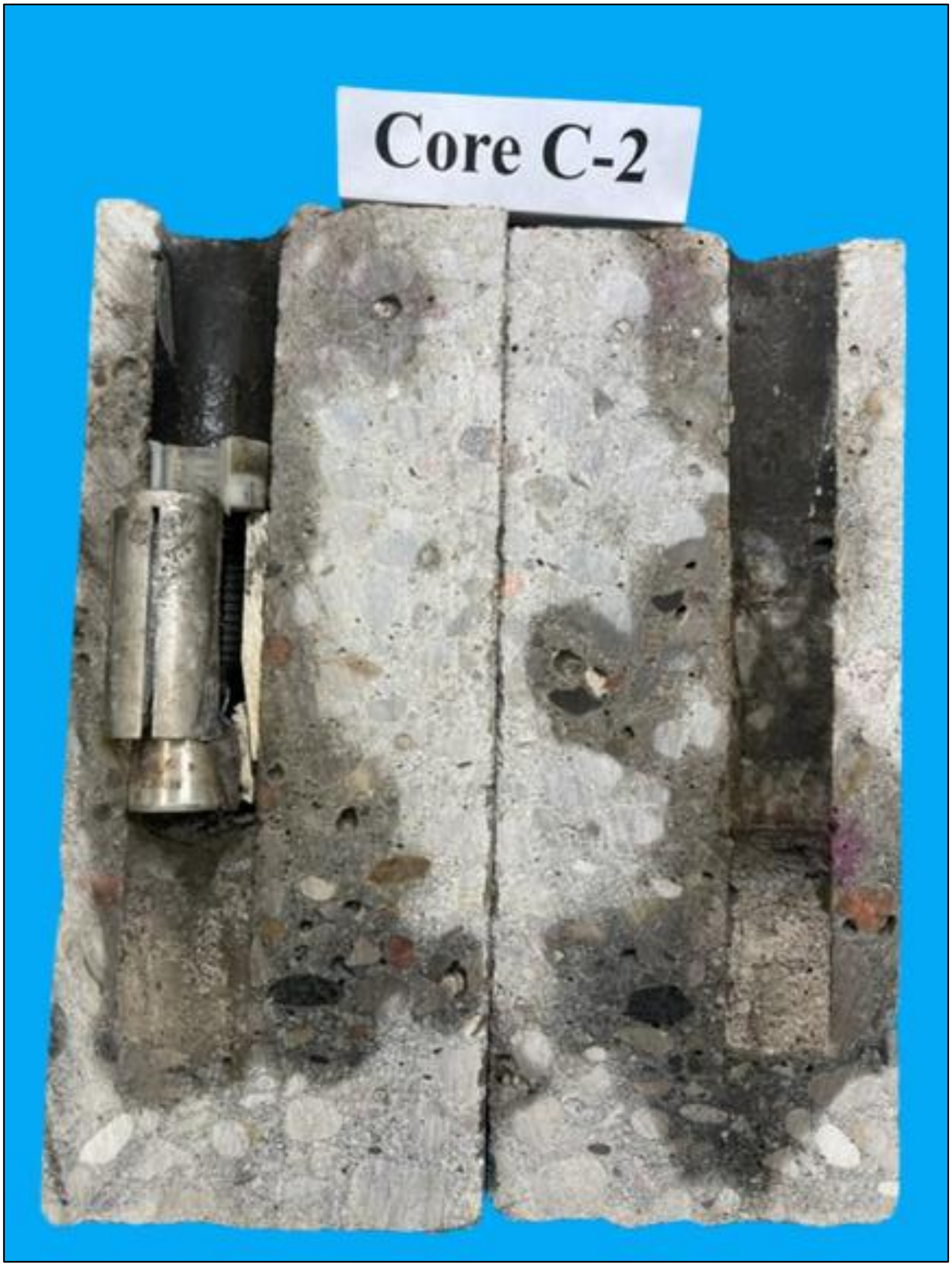


Photo P7 – Core C2 Sawn Sample Faces

(Note: the position of the expansion sleeve/cone and plastic spacers, and the drilling powder at the bottom of the drill hole)

Photo P8 – Core C2 Sawn Sample Face

(Showing sawn expansion sleeve and cone, and plastic spacers; note the position of the expansion sleeve/cone and plastic spacers, and the drilling powder at the bottom of the drill hole.)

Photo P9 – Core C2 Sawn Sample Face

(Showing close-up view of sawn expansion sleeve and cone, and plastic spacers; note the visible threading seen in the cone, and sleeve, and the drilling powder at the bottom of the drill hole.)

Photo P10 – Core C2 Top View

(Note :the visible crack adjacent to the core hole, across the diameter of the core)

Photo P11 – Core C2

(Showing carbonation tested surface; no visible depth of carbonation was noted.)

Photo P12 – Core C3

Photo P13 – Core C3 Sawn Sample Faces

(Note :the position of the expansion sleeve and cone)

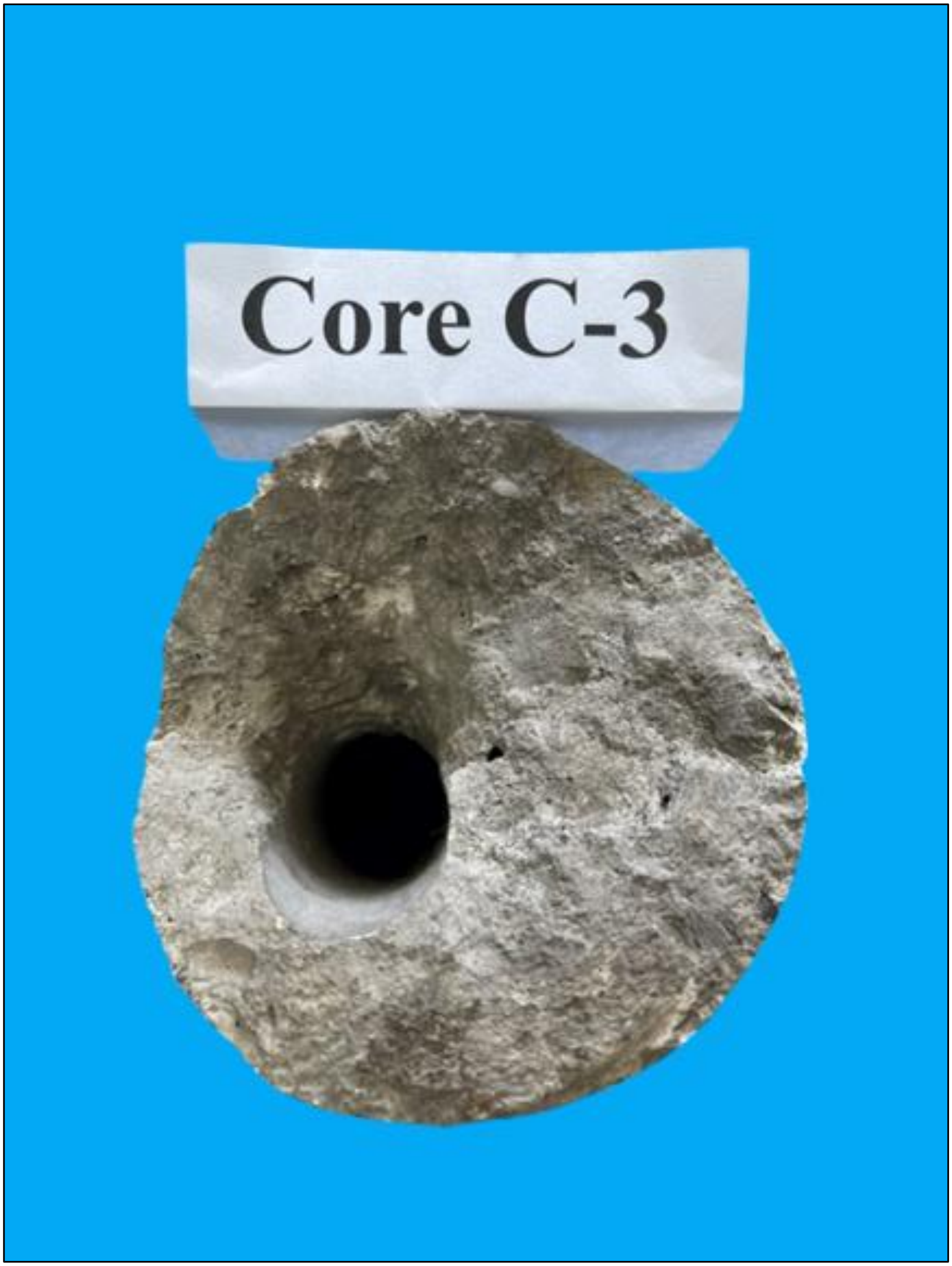


Photo P14 – Core C3 Top View

(Note : the spalled damaged concrete surface at the top of the core)

Photo P15 – Core C3

(Showing carbonation tested surface; carbonation depth was determined to be less than 0.5mm.)

Photo P16 – Core C4

(Note : that the core was retrieved in two pieces, with visible horizontal cracks adjacent to the interface of the pieces)

Photo P17 – Core C4 Sawn Sample Faces

(Note :the position of the expansion sleeve and cone, which appears to have been pulled out due to impact damage to the anchor bolt)

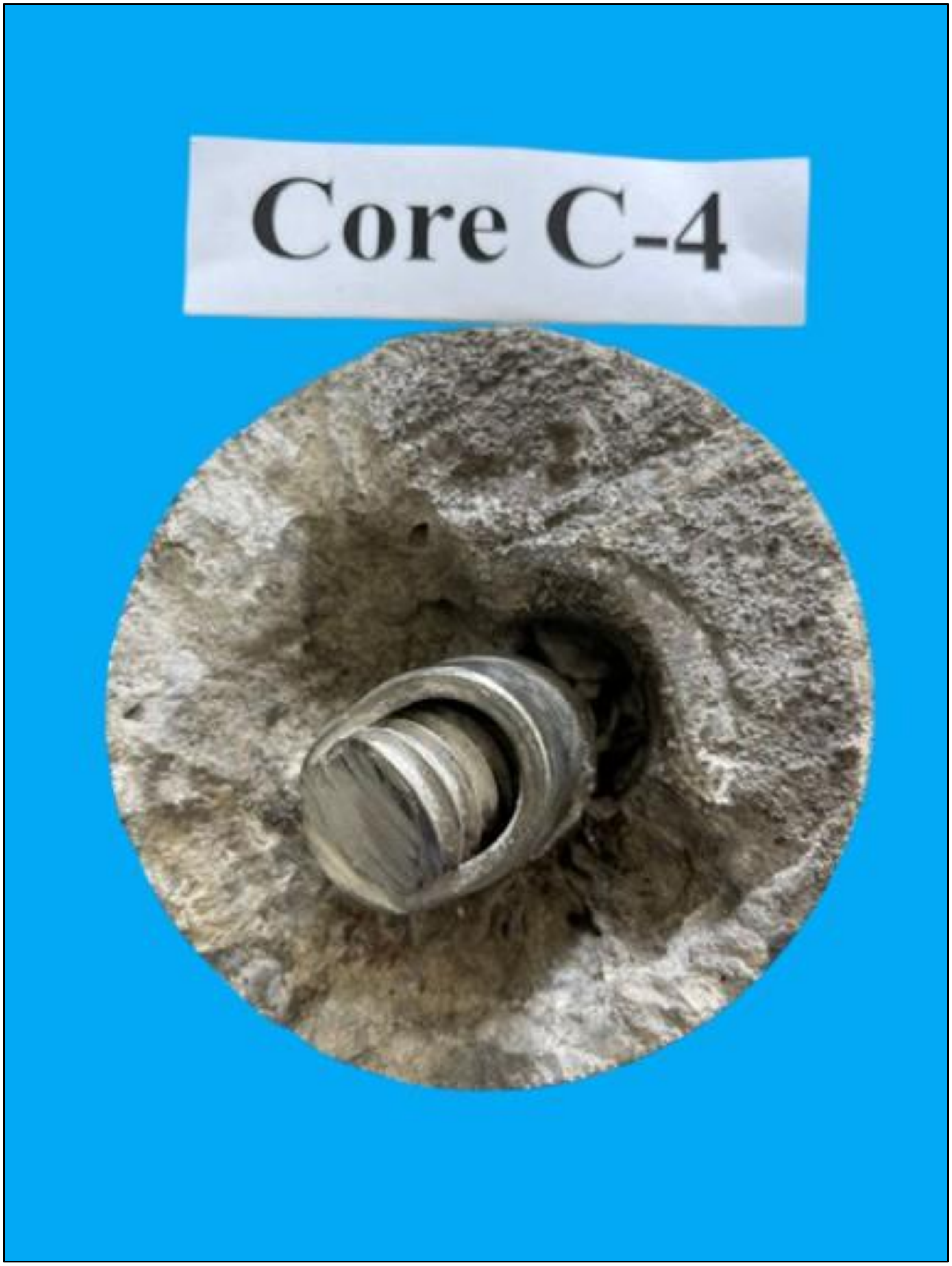


Photo P18 – Core C4 Top View

(Note: the spalled damaged concrete and sheared and bent anchor bolt assembly, due to impact damage.)

Photo P19 – Core C4

(Showing carbonation tested surface; carbonation depth was determined to be less than 0.5mm)

Photo P20 – Core C5

Photo P21 – Core C5 Sawn Sample Faces

(Note : the position of the spacer sleeve, plastic spacers, expansion sleeve and cone, and drilling powder at the bottom of the core hole)

Photo P22 – Core 5 Top View

(Note: the intact concrete and anchor bolt condition)

Photo P23 – Core C5

(Showing carbonation tested surface; carbonation depth was determined to be less than 0.5mm.)

Photo P24– Core C1

(It was noted that the sleeve of C1 has indentations)

Photo P25 – Core C2

(It was noted that the sleeve of C2 has indentations)

Photo P26 – Core C3
(Sleeve)

Photo P27 – Core C5

(It was noted that the sleeve of C5 has very minor indentations)

APPENDIX D: REENACTMENT WORKPLAN

Purpose

This work plan outlines additional testing programs proposed for TTC's SRT Line 3 following the July 24, 2023 derailment. It includes a Structural Testing Program, Dynamic Testing, and SRT Equipment Testing Program aiming to gather essential information on the root cause of the derailment.

Background

The SRT Line 3 track services six stations over 6.4 km along the eastern district of Scarborough. The trains are powered by linear induction motors mounted on the cars' underside and contact the reaction rail, which runs in between the running rails on 1,435mm gauge tracks.

On Monday, July 24, at approximately 6:43 pm, the SRT Line 3 subway was travelling southbound from Ellesmere station at 40kph when it derailed from the tracks. The trainset carried 44 passengers, five of whom were injured from the derailment. The rearmost car uncoupled from the trainset upon impact with the track obstruction and derailed.

To further examine the safety of the entire SRT line and determine additional risks or mitigation measures, Gannett Fleming (GF) will conduct a series of tests to assess infrastructure performance in both static (structural) and dynamic scenarios (vehicle/LIM loading testing).

Dynamic Testing Program – Reenactment

Infrastructure Assessment (Gannett Fleming)

A dynamic testing program is proposed below to determine the narrative of the conditions that escalated the deterioration of reaction rail components, leading to the derailment incident. This incident reenactment aims to provide observations on the performance of reaction rail components under a consistent load conditions.

The investigation into the derailment indicates that the root cause lies in a sequence of failed hardware, specifically bolts, anchors, or T-bolts. Based on the evidence collected, it appears that the anchor bolts may have sheared first, leading to increased loads on the remaining bolts and anchors in the system. As a result of the anchor bolts failing, it is plausible that the reaction rail assembly rose to levels above acceptable tolerances. This hypothesis is supported by the presence of hammering on portions of the bolts, which appear to have sheared first and mushrooming on segments of the preceding reaction rail top cap, which would likely have occurred before the derailment incident via repeated loading.

- The dynamic testing program will subject the reaction rail components to simulated load conditions similar to those encountered during the incident to validate this theory and gain further insights into the reaction rail's behavior. By doing so, we can assess the system's response and identify potential vulnerabilities and failure points.
- The dynamic test site has been determined to be at the southern end of Lawrence East station, on the southbound track.
- The testing program will commence with all reaction rail hardware intact to establish baseline performance and gather initial observations. By doing so, we can better understand the behavior of the reaction rail system under normal operating conditions.
- Upon completing baseline conditions testing, hardware will be adjusted to observe the height that the reaction rail rises, commencing with a single bolt failure at the LIM rail joint, and progressing as noted:
    - Scenario 1: Baseline conditions, all bolts intact
    - Scenario 2: Assume failure in bolt 0
    - Scenario 3: Assumed bolts 0 and 2 failure
    - Scenario 4: Assumed bolts 1 and 3 failure
    - Scenario 5: Assumed bolt 0 and 1 failure

- Scenario 6: Assumed failure in bolts 0 to 3
- Scenario 7 (if needed): Assume bolt/anchor failure in bolts 0 to 5

- The execution of the test modified the scenarios as noted below:
  - Scenario 1: Baseline conditions, all bolts intact
  - Scenario 2: Assume failure in bolt 0
  - Scenario 3: Assumed bolts 0 and 2 failure
  - Scenario 4: Assumed bolts 1 failure
  - Scenario 5: Assumed bolts 1 and 3 failure
  - Scenario 6: Assumed bolt 0 and 1 failure
  - Scenario 7: Assumed failure in bolts 0 to 3

Reaction Rail Lift

In conjunction with failing anchor bolts, it is plausible that the reaction rail assembly rose above acceptable tolerances. This test aims to measure the vertical displacement of the reaction rail upon contact with the LIM. It can be noted that max displacement will occur during the period where the vehicle increases acceleration from a stationary position. Gannett Fleming has reviewed the mainline and determined an optimal location for testing similar to the track's conditions at the derailment site.

Upon completing the dynamic testing program, Gannett Fleming will analyze the data and observations gathered to formulate actionable recommendations and corrective measures as part of the forensic assessment draft report to be submitted on August 22nd. These recommendations will aim to enhance the integrity and reliability of the reaction rail components, ensuring they can withstand the expected loads and operational conditions without compromising safety.

Program Logistics & Test Location Overview

- Test Location:
  - Lawrence West Station southbound track (chainage 117+03) has been determined as the optimal testing location
  - Before commencing this series of tests, TTC Track Team must verify that the track through the derailment site is safe.
  - Loop cable and derailment site must be cleared for safe passage to operate the vehicle under the proposed conditions.
- Equipment:
  - Wayside (GO Pro) cameras will be anchored to the concrete invert slabs via mounting plates. 60fps cameras will be utilized to capture details at higher speeds.
  - Cameras are to be placed on the inside of the running rails on both sides of the reaction rail, secured on a bracket affixed to the invert slab, and drilled in place with tapcons
  - TTC to review the feasibility of having cameras on both the east and west sides of the reaction rail
  - Displacement measurements of the reaction rail will be taken directly from the camera photos. Gannett Fleming and TTC to review the use of a Stadiometer to scale reaction rail height levels
- Transportation:
  - TTC will organize a work car to transport the SRT to the testing location.
  - The train will travel in the southbound direction. The contact between the trailing LIM and the leading edge of the selected reaction rail will be observed for both horizontal and vertical movement (objective is to see movement up to 8mm).

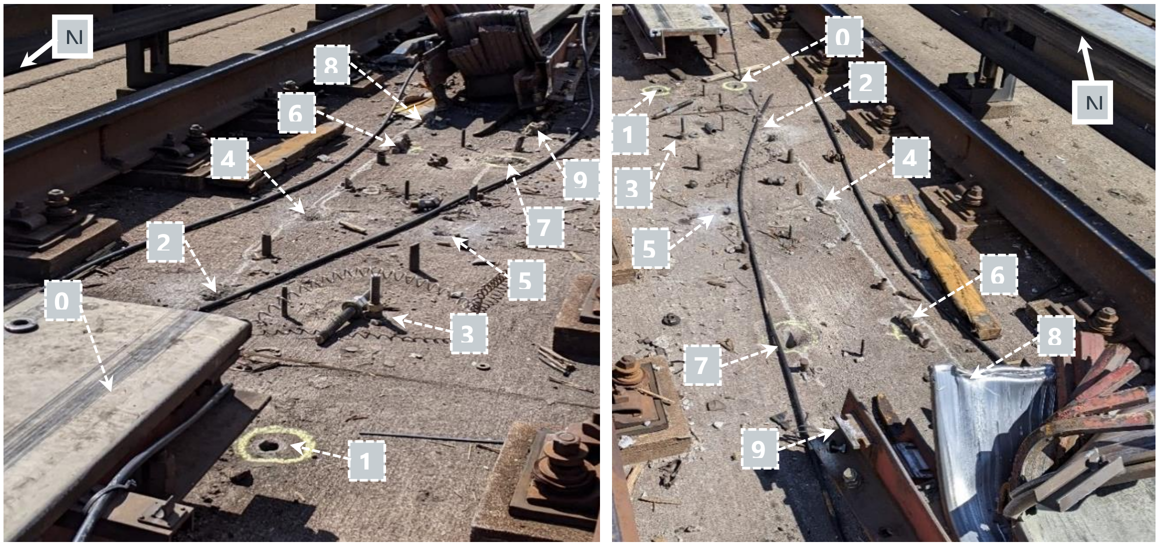


Figure 1: Anchor Bolt Layout

Assignee Abbreviations:

- RC&S: Rail Car & Shops
- TM: Subway Track Maintenance
- ME: Subway Maintenance Engineering
- GF: Gannett Fleming (Consultant)
- WAC: Work Area Coordinator
- OTC: Operations Training Centre

Re-enactment Procedure

The procedure for the re-enactment has been divided into two areas of responsibility: (a) safe movement of the workcar and switches and (b) actions by investigators and observers. Note, any deviations which occurred during the test day will be noted in red text.

Table 1: Re-enactment Procedure Sequence

#	Time August 16th, 2023 (24 hr. clock)	Duration (minutes)	Task	Location	Assignee	Required Personnel
1			Assembly test train revenue cars at McCowan Yard shop	McCowan Yard shop	RC&S	
2			Measure LIM height on all test train cars in relation to top of rail and record car numbering for test train consist. Recorded measurements and car numbering are to be provided to investigators and observers (GF) on test day.	McCowan Yard shop	RC&S	
3			Orient ST-1 work car with heavy end (no.1 end) facing west.	McCowan Yard	TM	
4			Perform track inspection of mainline track.	Mainline - McCowan - 500 feet south of Lawrence East- west/southbound track	TM	
5			Schedule O.T.C operators for tomorrow (2)		Yeeman Chen	
6			Schedule WAC for tomorrow		TM	
7			Schedule Work Zone for DOB		Bryan Callaghan	
8			Request Power Restoration			
9			Prepare job briefing for Track Access	all of mainline	WAC	
10			Prepare job briefing for test execution		Gordon Webster	
11			Install plates for camera mounting	Track level test location - Lawrence East Station - southbound track - 117+03	TM	
12			Check anchor bolts on test panel to ensure they are adjustable	Lawrence East station - southbound track	TM	

13			Remove ground straps to permit passage of test train & restore power.		Electrical	
14			Check all equipment (cameras, measuring equipment) to ensure all is charged and ready for test tomorrow		RC&S/ME/GF	
15	10:00		WAC takes control of existing work zone		TM	WAC
16	10:15		Conduct initial job briefing for movement of test train from McCowan Yard to Lawrence East station and pretrip inspections.	McCowan Yard	WAC	WAC ST-1 operator OTC operators (2) Rail vehicle analyzers (2) Work car mechanic for ST-1
17	10:30		Install cameras at track level - communicate with WAC before going to track	Lawrence East station 117+03	RC&S/GF	RC&S (2), GF (2), ME (1)
18	10:40		Torque of all 10 anchor bolts of the reaction rail to be measured and recorded.	Lawrence East station 117+03 - southbound track		
19	10:50		~~Set up stadiometer; ensure clear view of the camera.~~ Set up Tailor Square so that it is in clear view of the camera.	Lawrence East station 117+03 - southbound track		
20	10:40		Mobilize test train to Lawrence East station (work car operator, two OTC operators) with ST-1 shoving train	McCowan to Lawrence East stations on westbound/southbound track	TM/OTC	ST-1 operator OTC operators (2) Rail vehicle analyzers (2) Work car mechanic for ST-1
21	11:00		Uncouple ST-1 work car from revenue train – position ST-1 work car at Ellesmere station on the southbound track.	Lawrence East Station - southbound track	RC&S/TM	ST-1 operator OTC operators (2) Rail vehicle analyzers (2) Work car mechanic for ST-1
22	11:20		Tie ST-1 down - leave operator on the vehicle	Ellesmere Station - southbound track	TM	ST-1 operator Work car mechanic for ST-1
23	11:20		Back revenue-car train to the north of the station platform so that vehicle is clear of test reaction rail location (117+03) and	north end of Lawrence East	OTC	OTC operators (2)

			with a door on the platform so operators can disembark for job rebriefing *This will be considered the 'Starting Position' of the test.*	Station - southbound track		Rail vehicle analyzers (2)
24	11:30	0:30:00	Conduct job rebriefing/answer questions/job discussion	Lawrence East Station - southbound platform	WAC/ME/GF	WAC Corp/Safety/Heads (4) TM crew (4) TM management (1) RC&S management (2) RC&S - video equipment (2) ME management (2) GF (3) LTK (2-3) OTC operators (2) Rail vehicle analyzers (2)
25	12:00		**Start Test Sequence**			
26		0:10:00	Anchor bolts will be numbered on the concrete slab with paint/chalk in accordance with the Figure 1 numbering.	McCowan Yard shop	ME/GF	GF (2) TM crew
27			~~Torque of all 10 anchor bolts of the reaction rail to be measured and recorded per SOPs.~~ All 10 anchor bolts (bottom nuts – closest to concrete) were torqued to 150lbft, as per the SOPs	Lawrence East station 117+03	ME/GF	
27			Position train with front of first LIM immediately north of the test reaction rail.	Lawrence East station 117+03	OTC	
29			Investigators and observers will begin video recording for Scenario 1.	Lawrence East station 117+03	TM/RC&S/ME/GF	
Scenario 1: Baseline conditions, all bolts intact						
30	12:15	0:05:00	Under emergency mode, train will be placed at its starting position - north of the station platform so that the vehicle is clear of the test reaction rail location (117+03).	Lawrence East station 117+03	OTC	
31			During emergency mode, the entire test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear	Lawrence East station 117+03	OTC	

			the reaction rail, at which point it will be brought to a controlled stop.			
32			The test train will be reversed over the reaction rail, continue travelling to the starting position, and remain stationary until Scenario 2.	Lawrence East station 117+03	OTC	
33			Investigators and observers will end video recording for Scenario 1.	Lawrence East station 117+03	RC&S	
Scenario 2: Assume failure in bolt 0 (Left side of reaction rail)						
34	12:30	0:05:00	At bolt 0 (left of reaction rail), loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 2.**	Lawrence East station 117+03	TM/ME/GF RC&S	
35		0:05:00	During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.	Lawrence East station 117+03	OTC	
36			Test train will be reversed over the reaction rail and will continue travelling to the Starting Position at the station platform and remain stationary till Scenario 3.	Lawrence East station 117+03	OTC	
37			Investigators and observers will end video recording for Scenario 2.	Lawrence East station 117+03	RC&S	
Scenario 3: Assumed failure in bolts 0 and 2 (right side)						
38	12:45	0:05:00	Measure and record torque of all 10 anchor bolts. At bolt 2 (left of reaction rail), loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 3.**	Lawrence East station 117+03	TM/ME/GF RC&S	
39		0:05:00	During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.	Lawrence East station 117+03	OTC	

40			Test train will be reversed over the reaction rail and will continue travelling to the Starting Position at the station platform and remain stationary till Scenario 4.	Lawrence East station 117+03	OTC	
41			Investigators and observers will end video recording for Scenario 3.	Lawrence East station 117+03	RC&S	
Scenario 4: Assumed failure in bolt 1						
42	13:00		At bolts 0 and 2, adjust nut back to original position. At bolts, loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 4.**			
43			During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.			
44			Test train will be reversed over the reaction rail and will continue travelling to the starting position at the station platform and remain stationary till Scenario 5.			
45			Investigators and observers will end video recording for Scenario 4.			
~~Scenario 4:~~ Scenario 5: Assumed failure in bolts 1 and 3 (bolt adjustment)						
46	13:15	0:10:00	At bolts 1 and 3, loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 5.**	Lawrence East station 117+03	TM/ME/GF RC&S	
47		0:05:00	During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.	Lawrence East station 117+03	OTC	
48			Test train will be reversed over the reaction rail and will continue travelling to the starting position at the station platform and remain stationary till Scenario 6.	Lawrence East station 117+03	OTC	
49			Investigators and observers will end video recording for Scenario 5.	Lawrence East station 117+03	RC&S	

~~Scenario 5~~ Scenario 6: Assumed bolt 0 and 1 failure						
50	13:30		At bolts 1 and 3, adjust nut back to original position. At bolts 0 and 1, loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 6.**	Lawrence East station 117+03	TM/ME/GF RC&S	
51		0:05:00	During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.	Lawrence East station 117+03	OTC	
52			Test train will be reversed over the reaction rail and will continue travelling to the starting position at the station platform and remain stationary till Scenario 7.	Lawrence East station 117+03	OTC	
53			Investigators and observers will end video recording for Scenario 6.	Lawrence East station 117+03	RC&S	
~~Scenario 6:~~ Scenario 7: Assumed failure from bolts 0 to 3						
54	14:00	0:10:00	At bolts 2 and 3, loosen nut sitting directly above reaction rail so that it is 8mm (measured using taper gauge) above original location. **Investigators and observers will begin video recording for Scenario 6.**	Lawrence East station 117+03	TM/ME/GF RC&S	
55		0:05:00	During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail (not confirmed if 65% power level was maintained, train travelled at a speed of approximately 25km/hr). The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.	Lawrence East station 117+03	OTC	
56			Test train will be reversed over the reaction rail and will continue travelling to the starting position at the station platform and remain stationary.	Lawrence East station 117+03	OTC	
57			Investigators and observers will end video recording for Scenario 7.	Lawrence East station 117+03	RC&S	
~~Scenario 7 (if needed): Assumed failure from bolts 0 to 5~~						
58	~~12:50~~	~~0:10:00~~	~~At bolts 4 and 5, loosen nut sitting directly above reaction rail so that it is 8mm above original location.~~	~~Lawrence East station 117+03~~	~~TM/ME/GF/RC &S~~	

			~~**Investigators and observers will begin video recording for Scenario 7.**~~			
59	~~13:00~~	~~0:05:00~~	~~During emergency mode, the test train will be propelled with a power level not exceeding 65% along the reaction rail. The train will proceed until the rearmost car is observed to completely clear the reaction rail, at which point it will be brought to a controlled stop.~~	~~Lawrence East station 117+03~~	~~OTC~~	
60			~~Test train will be reversed over the reaction rail and will continue travelling to the starting position at the station platform and remain stationary.~~	~~Lawrence East station 117+03~~	~~OTC~~	
61			~~Investigators and observers will end video recording for Scenario 7.~~	~~Lawrence East station 117+03~~	~~RC&S~~	
62	~~13:05~~	~~0:10:00~~	~~At bolts 0 to 5, nuts sitting directly above reaction rail will be adjusted to the original location, such that the top of the reaction rail matches the top of rail.~~	~~Lawrence East station 117+03~~	~~TM/ME/GF~~	
63	~~13:15~~	~~0:10:00~~	~~Uninstall cameras at track level~~	~~Lawrence East station 117+03~~	~~RC&S/TM~~	
			Re-enactment Program – Scenario Review Complete			
64		0:20:00	Job rebriefing (for train return to McCowan)/debriefing (for test)	Lawrence East Station platform	WAC/ME	
65		0:30:00	Couple ST-1 to test train - remove track protection	Lawrence East Station - southbound track	RC&S/OTC	
66		0:10:00	Remove red lights/PTS to move test train into McCowan Yard	east/north McCowan station	TM	WAC + TM
67		0:30:00	Test train returns to McCowan Yard (work car operator, two OTC operators) with ST-1 pulling train	Lawrence East station to McCowan Yard - west/southbound track	WAC ST-1 operator OTC operators (2) Rail vehicle analyzers (2) Work car mechanic for ST-1	
68		0:10:00	Replace red lights/PTS to protect work zone	east/north McCowan station	TM	WAC + TM
69			Disassemble train as necessary	McCowan Yard	RC&S	

70		0:30:00	Remove Plate mounting for test cameras	Lawrence East Station track	TM	TM (4)
71			Give up control of work zone		WAC	

APPENDIX E: ACUREN REPORT

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A Higher Level of Reliability

FAILURE ANALYSIS EXAMINATION ON BROKEN ANCHOR BOLTS

Prepared for

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August 25, 2023
Acuren Project No.: 128-23-HAG003-J03831

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1.0 INTRODUCTION

Acuren Group received eight anchor bolts for examination. Two of the bolts had fractured during service and the remaining six were reference bolts sent for materials testing. The failed anchor bolts were found at the site of a SRT train derailment earlier this year. The bolts had fractured between the reaction rail and support to the guideway slab between the running rails (Figure 1). On-site inspection by third party groups found that other anchor bolts within the area appeared in good condition. Limited damage was also observed within the concrete where the bolts were installed (Figure 2). It was requested to determine the cause of failure on the two fractured anchor bolts and conduct materials testing on the remaining bolts.

1.1 SCOPE OF WORK

The following work was conducted on the fractured bolts submitted for examination:

- i) Visual Examination
- ii) Low magnification examination
- iii) SEM examination
- iv) Metallographic examination
- v) Tensile testing
- vi) Chemical analysis
- vii) Vickers Hardness Testing

The following work was conducted on the remaining six bolts submitted:

- i) Metallographic examination
- ii) Tensile testing
- iii) Chemical analysis
- iv) Charpy Impact testing (reference bolts only)

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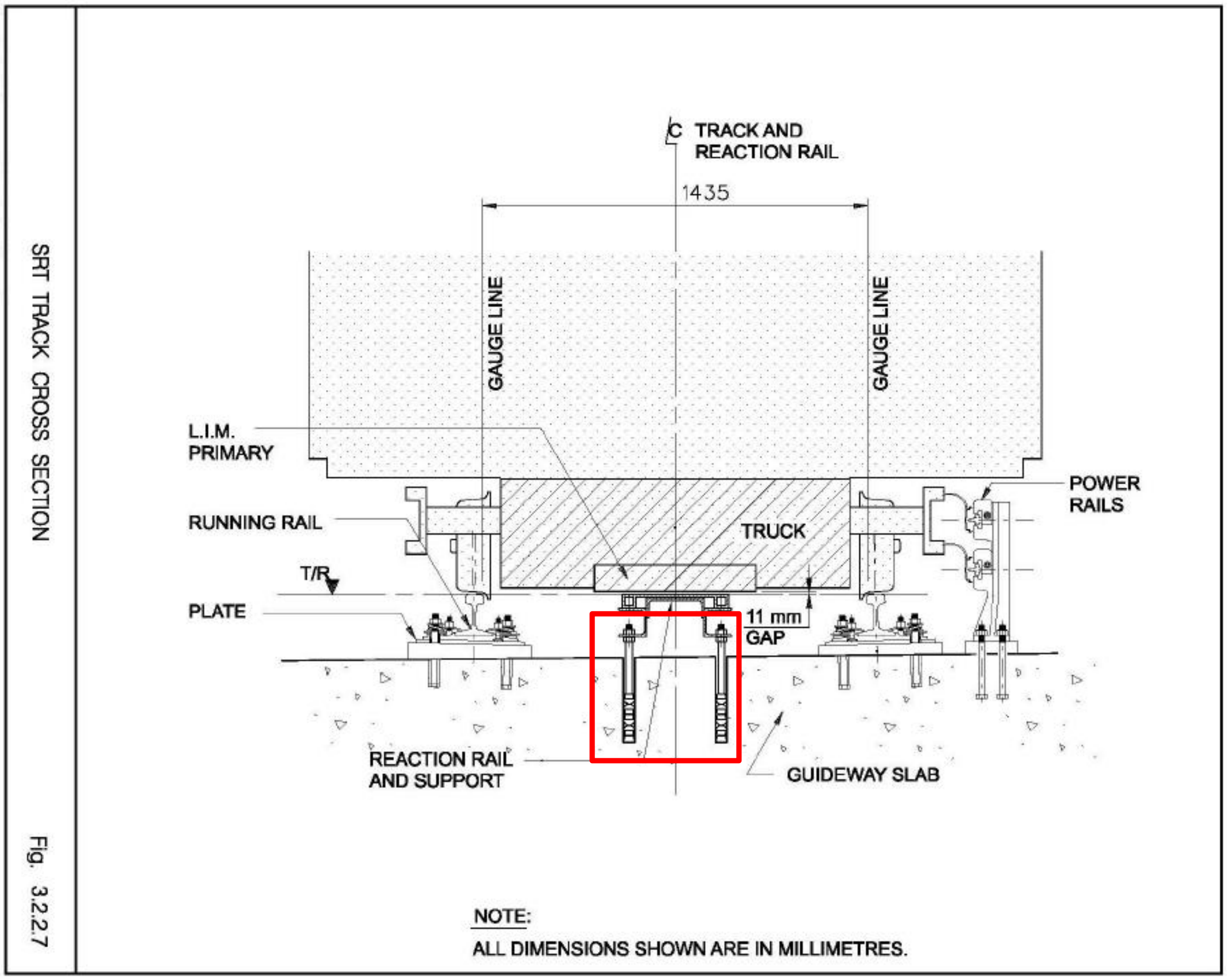


FIGURE 1. SCHEMATIC OF SRT TRACK CROSS SECTION AND FAILED BOLTS OUTLINED IN RED.

FIGURE 2. IMAGE PROVIDED BY CLIENT OF DERAILMENT DAMAGE.

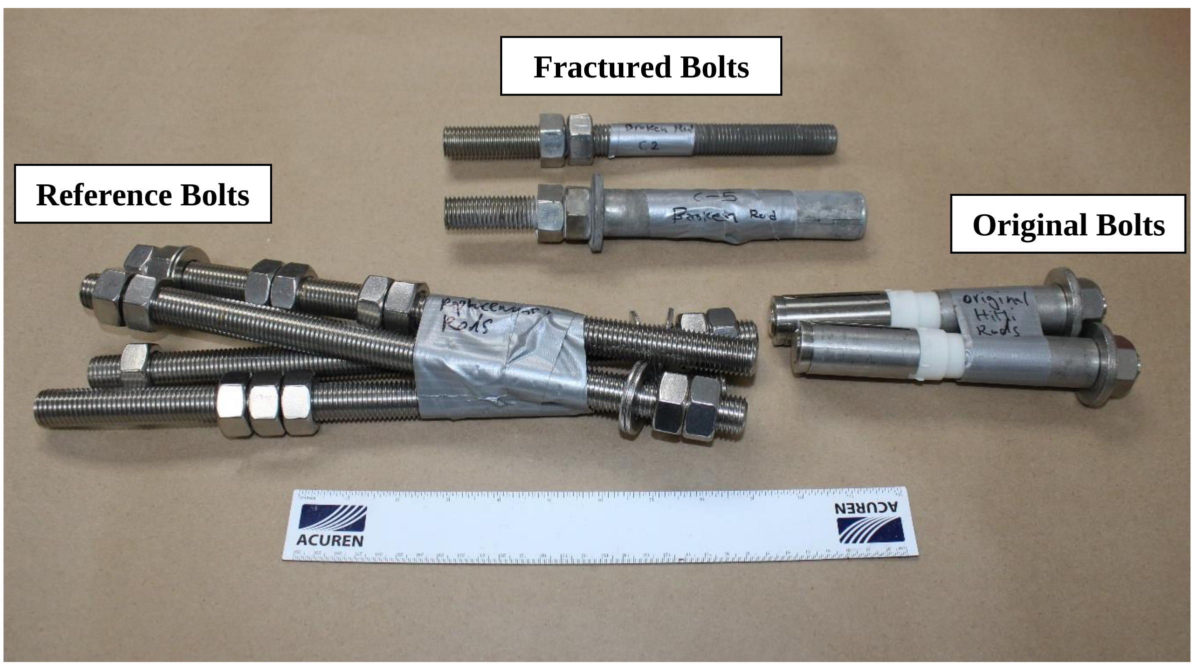


FIGURE 3. PHOTO OF BOLTS SUBMITTED FOR EXAMINATION.

2.0 INVESTIGATION

2.1 VISUAL EXAMINATION

The following observations were made on the submitted anchor bolts:

i) The submitted bolts can be seen in Figure 3. The fractured bolts can be seen in Figure 4. The fractured bolt C2 had two nuts attached to the bolt. One was fixed in place, the other was free to move up and down the threads of the bolt (Figure 5).

ii) Bolt C2 had a damaged fracture surface at one end and the other end was of original manufacture.

iii) Upon trying to remove the first nut, the threads remote the fracture had been stripped and flattened (Figure 6). It appeared as if something had been caught in the threads and mechanically dragged along them to flatten them (Figure 7). Some threads still had their shape, then flattened, then were of their original shape.

iv) Further examination found bolt C2 to have a slight curve to it. When placed next to a ruler, it was not parallel along the entire length to the ruler (Figure 8).

v) The fractured bolt C5 had its anchoring fixtures attached with visible cut marks along the length. It appeared as if it cut to try and free the anchor bolt from the fixturing (Figure 9).

vi) On bolt C5 one end was of original manufacture, the other end appeared to have been cut or ground that damaged most of the fracture features. Some heat tinting was also observed along the outer surface.

vii) Further examination found bolt C5 to exhibit the same slight curvature along its length. When placed next to a ruler, it was not parallel along the entire length of the ruler (Figure 10).

viii) Comparison of C5 to their original manufactured and assembled anchor bolts found the bottom pin was inserted further than on the original samples (Figure 11). An additional nut was present on top of the fixturing. The nuts on this bolt could not be moved and were fixed in place.

ix) After extracting the bolt from the sleeve, the inner surfaces of the sleeve exhibited indents from the threads of bolt C5 (Figure 12).

x) The original anchor bolts were arbitrarily labeled as O1 and O2 (Figure 13). Each had a nut near one slitted bolt end, followed by a washer, sleeves and pin at the bottom.

xi) The reference bolts had varying amounts of nuts and washers on them (Figure 14). Each reference bolt was arbitrarily labeled R1, R2, R3 and R4. The nuts and washers were removed and the bolts were examined further (Figure 15).

xii) After removing the nuts and washers, R1, R2 and R4 exhibited intermittent areas of rusting within the thread roots (Figure 16, Figure 17, Figure 18).

FIGURE 4. PHOTO OF SUBMITTED FRACTURED BOLTS.

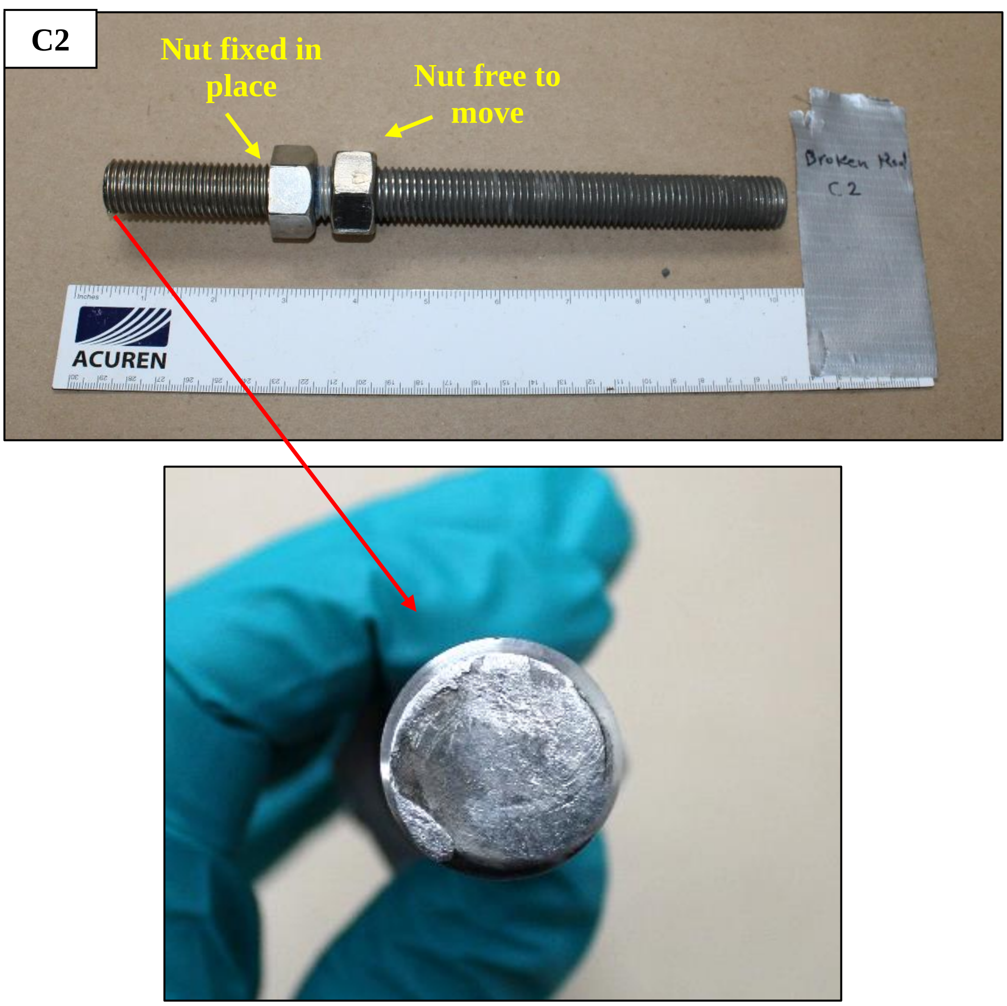
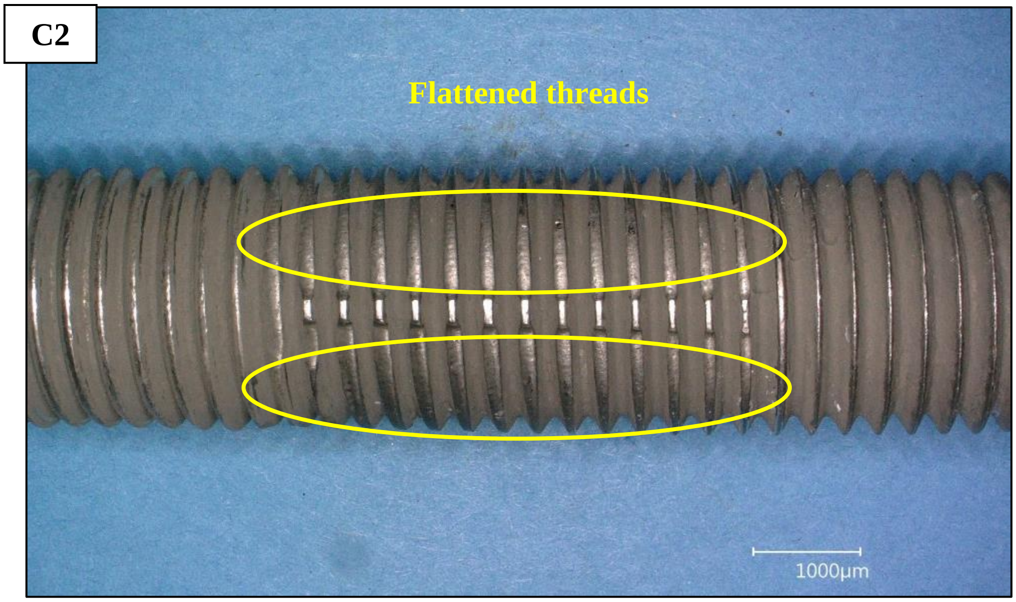


FIGURE 5. PHOTOS OF BOLT C2 AND THE FRACTURE SURFACE AT ONE END.



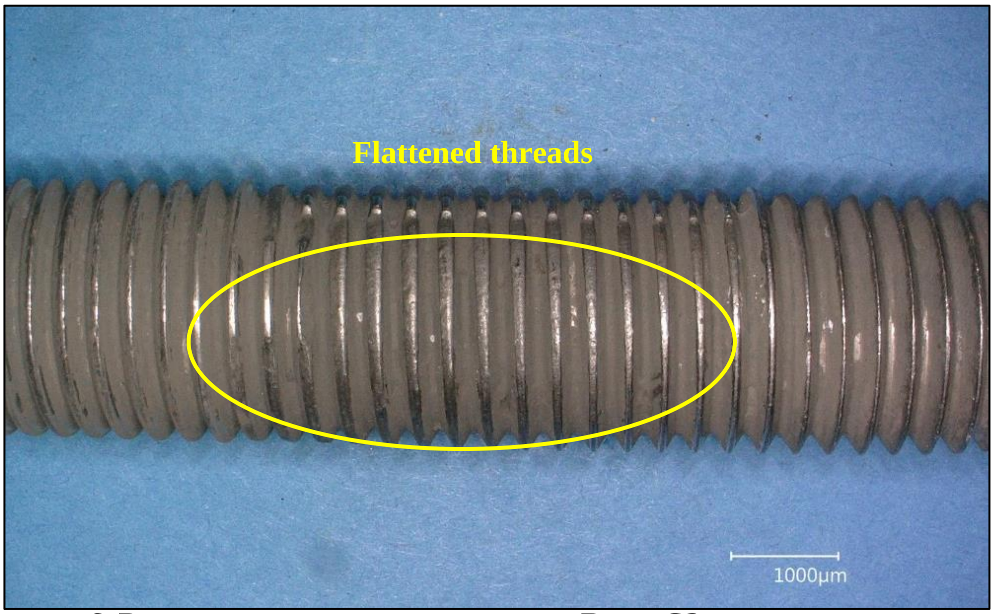


FIGURE 6. PHOTOS OF STRIPPED THREADS ON BOLT C2 REMOTE THE FRACTURE.

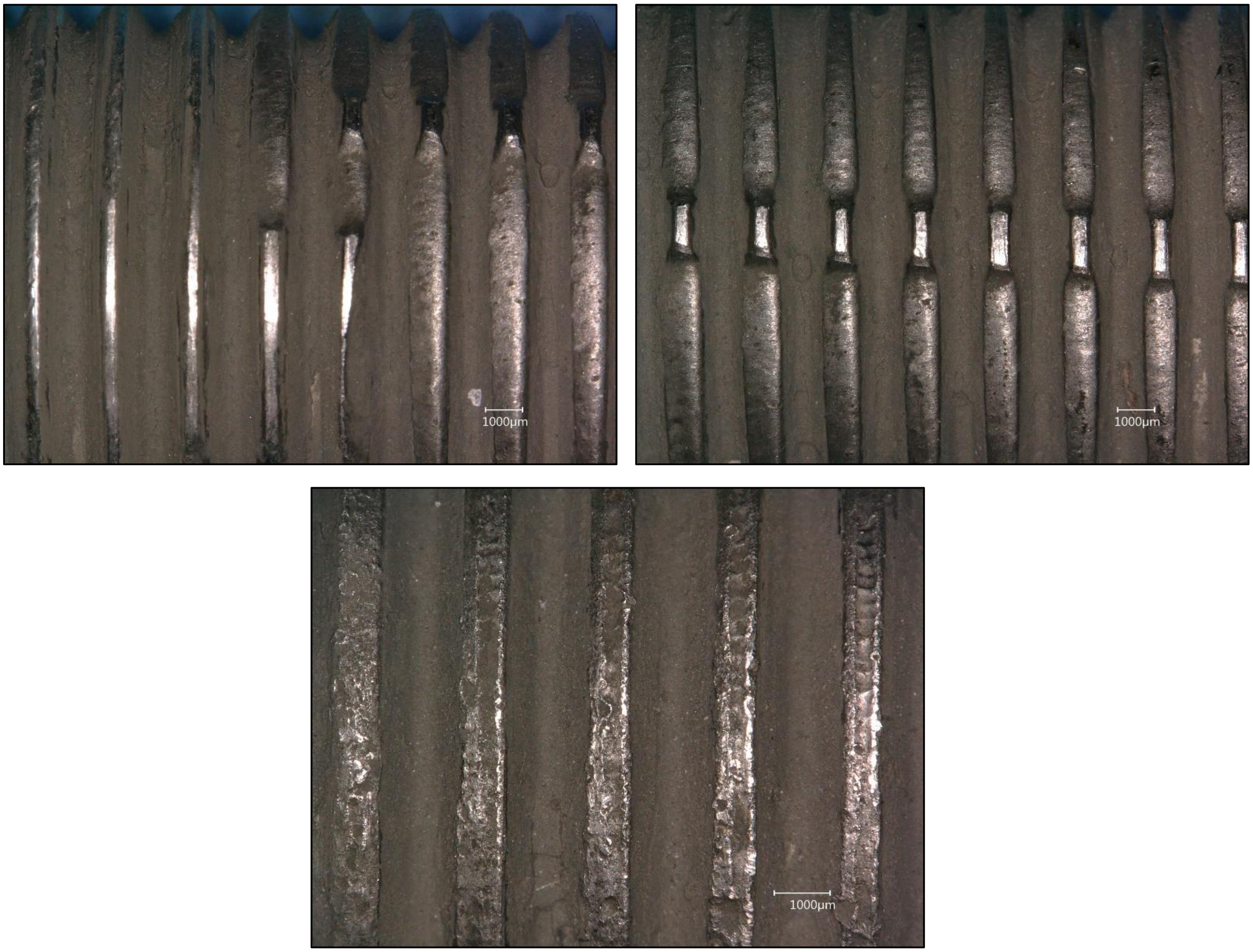


FIGURE 7. IMAGES SHOWING FEATURES OBSERVED AT AREAS OF STRIPPED THREADS ON BOLT C2.

FIGURE 8. PHOTO DISPLAYING A SLIGHT CURVE IN BOLT C2 UPON INITIAL EXAMINATION.

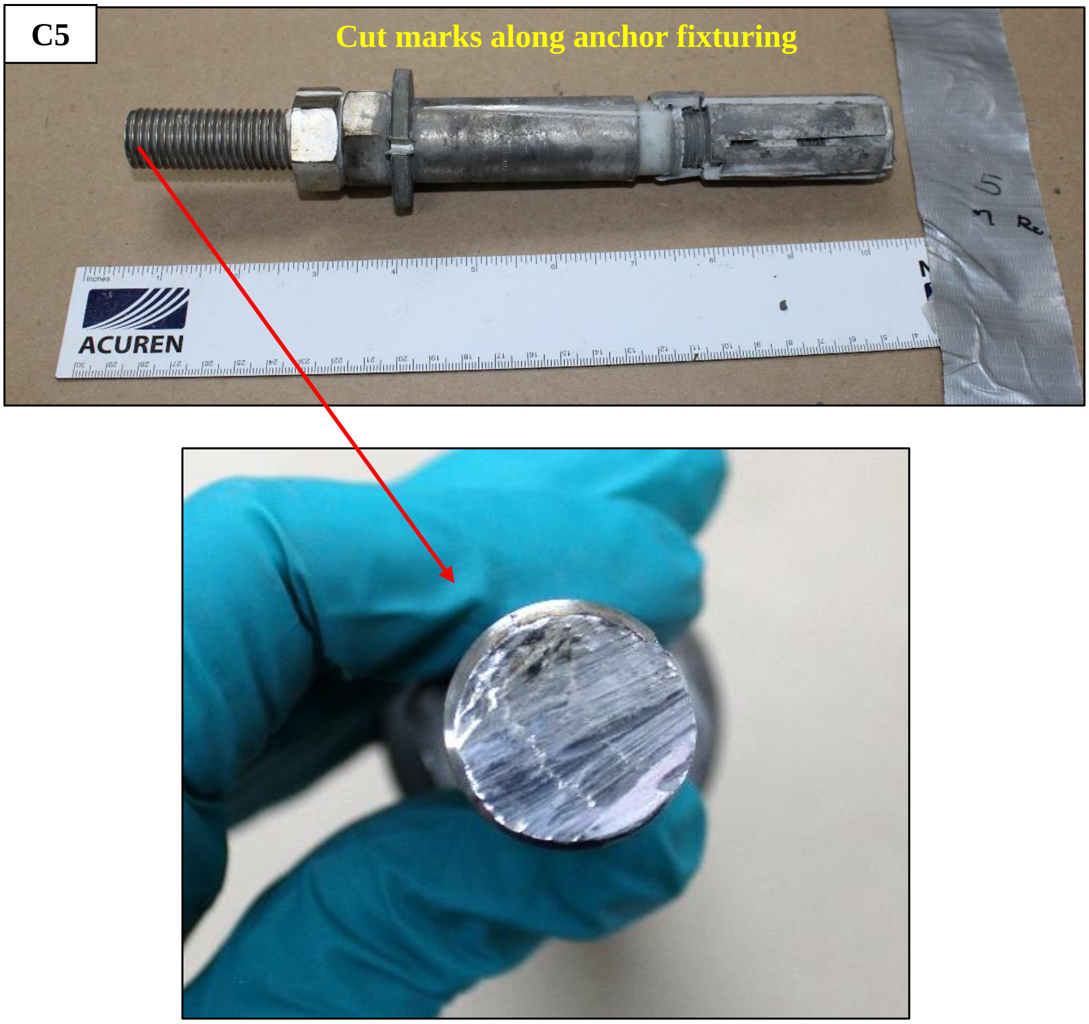


FIGURE 9. PHOTOS OF BOLT C5 AND THE CUT MARKS AND HEAT TINTING OBSERVED ON ONE END. NO FRACTURE SURFACE WAS VISIBLE.

FIGURE 10. PHOTOS DISPLAYING THE SLIGHT CURVE OBSERVED IN BOLT C5 COMPARED TO THE ORIGINAL BOLTS. THE INSERTS AT THE BOTTOM OF THE ANCHOR FIXTURING WAS DIFFERENT BETWEEN THE ORIGINAL BOLTS AND BOLT C5.

FIGURE 11. PHOTOS SHOWING THE BOTTOM OF THE ANCHOR FIXTURING ON THE ORIGINAL BOLTS AND BOLT C5.

FIGURE 12. PHOTO OF THE INNER SURFACE OF THE SLEEVE AFTER REMOVING BOLT C5.

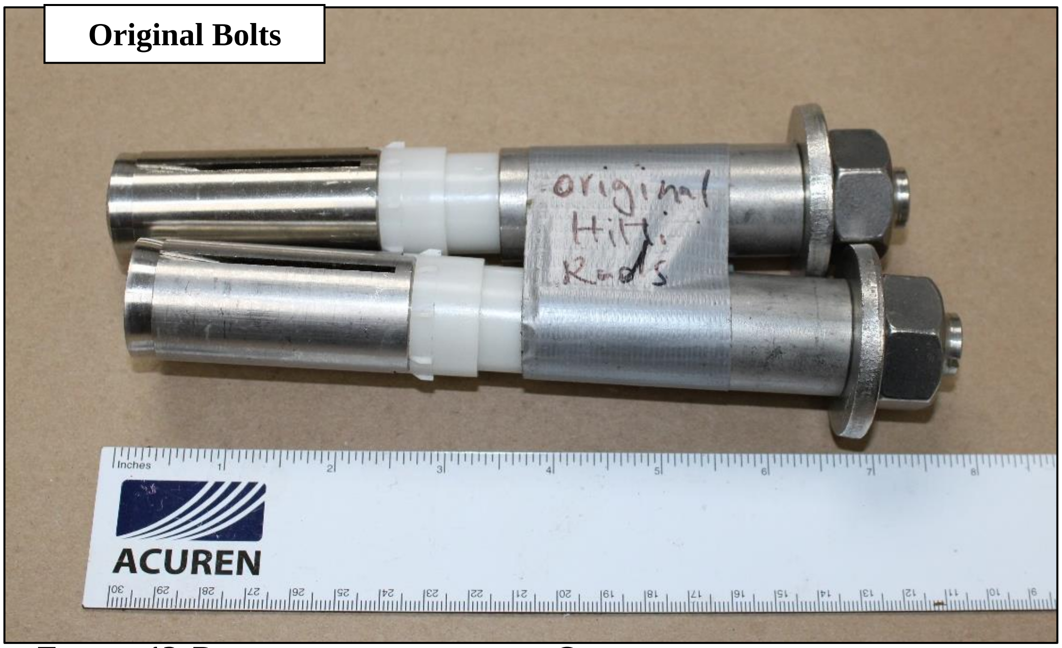


FIGURE 13. PHOTO OF THE SUBMITTED ORIGINAL BOLTS FOR EXAMINATION.

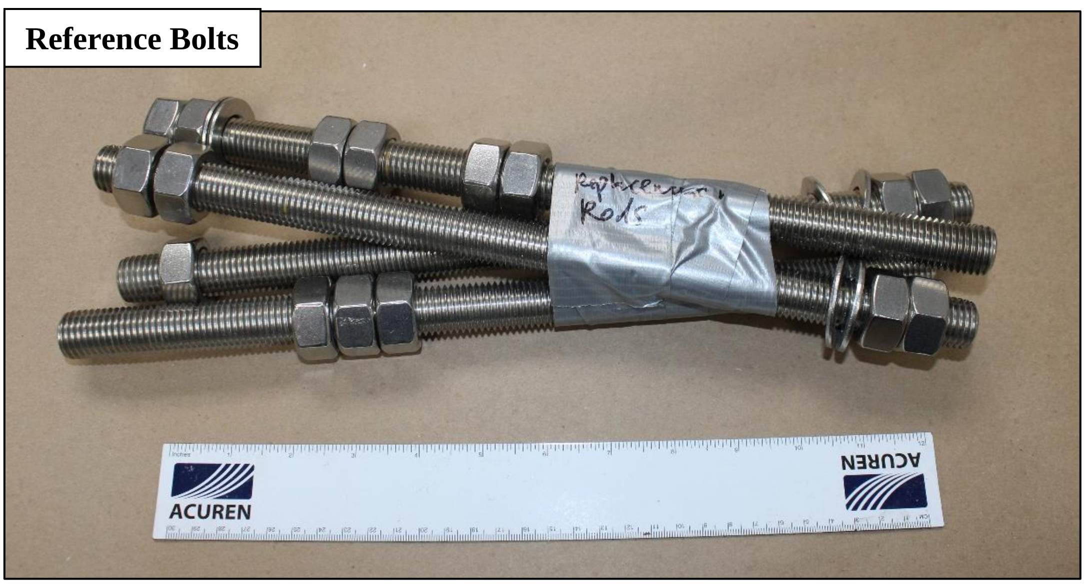


FIGURE 14. PHOTO OF THE SUBMITTED REFERENCE BOLTS FOR EXAMINATION.

FIGURE 15. PHOTO OF THE REFERENCE BOLTS AFTER REMOVING HARDWARE.

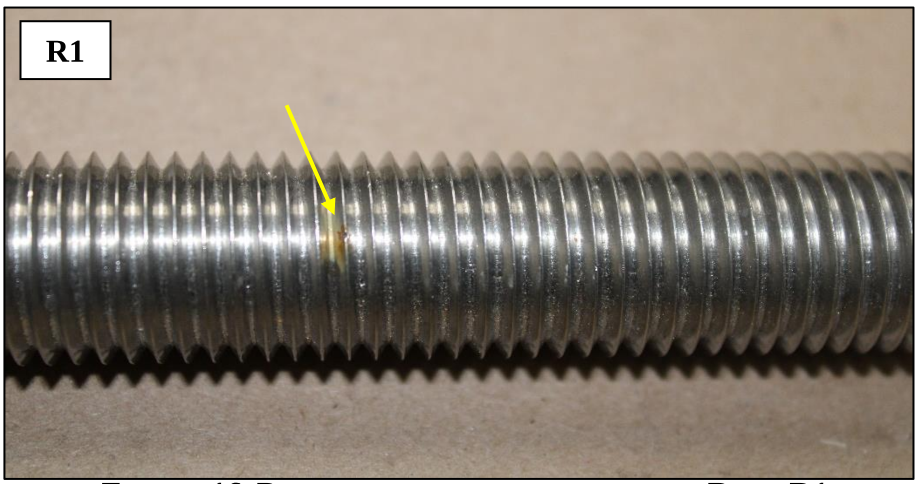


FIGURE 16. PHOTO SHOWING RUST STAINS ON BOLT R1.

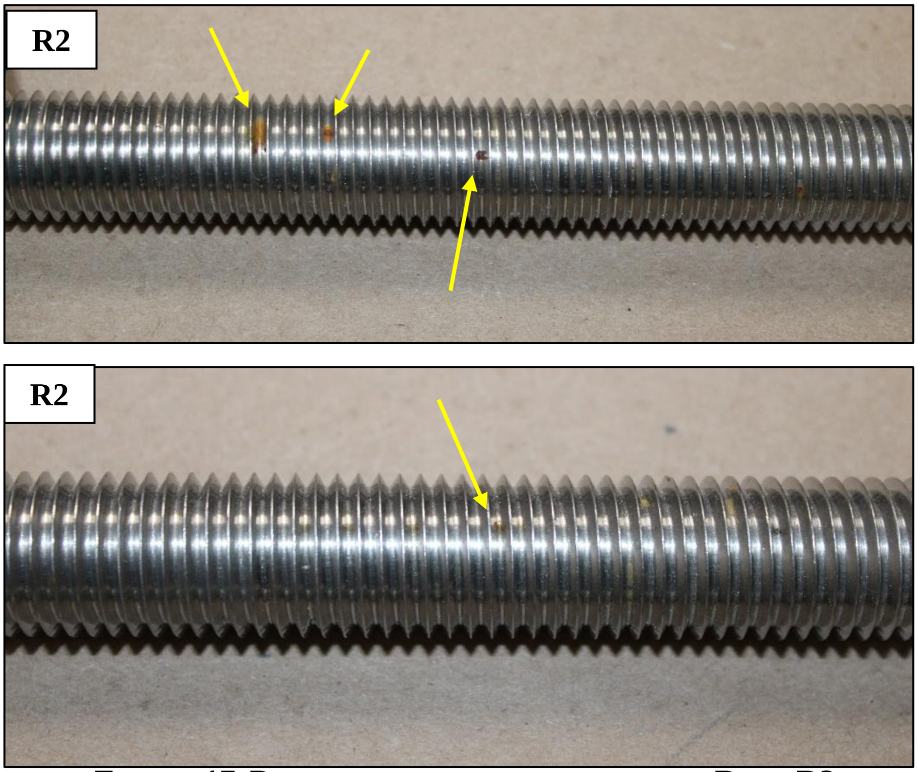


FIGURE 17. PHOTOS SHOWING RUST STAINS ON BOLT R2.

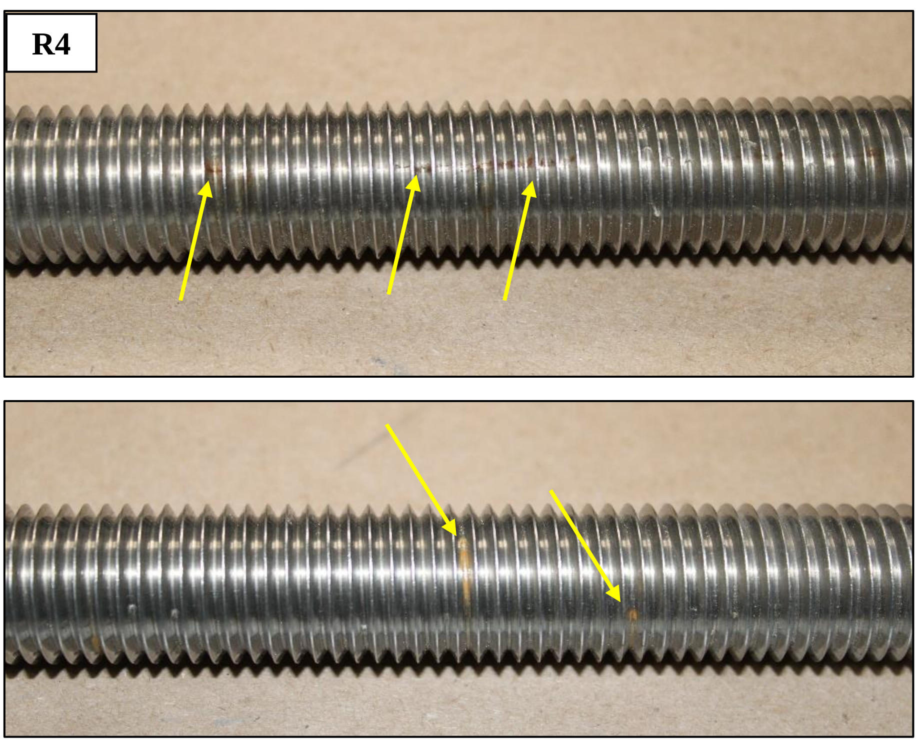


FIGURE 18. PHOTOS SHOWING RUST STAINS ON BOLT R4.

2.2 Low Magnification

We have removed the fracture surfaces of the broken bolts and examined them by means of a Keyence microscope at low magnification.
Following observations were made.

i) Figure 19 shows the fracture surface of Bolt C2.

ii) Most of the fracture surface was covered with scratch marks possibly due to the relative motion of mating face during crack propagation and after complete separation.

iii) Despite the scratch marks covering the fracture surface, some areas showed fracture features.

iv) Figure 20 shows close view of the fracture surface (6 o’clock area in Figure 19). We observed beach marks in that area. We arbitrarily marked that area as 6 o’clock. Appearance of the beach marks indicated that there were multiple crack initiations. Figure 19 and Figure 20 show two of the crack initiation sites. Centre of 6 o’clock region was also scratched removing fracture features and possibly more fracture initiation sites.

v) Figure 21 show close view of beach marks at left of 6 o’clock. We did not observe any marks/features on the thread face of 6 o’clock region.

vi) Crack (beach marks) propagated towards 12 o'clock. We observed beach marks at 12 – 03 o'clock region. Figure 19, Figure 22, and Figure 23 show those beach marks. Beach marks were rougher on the 12 – 03 o’clock region.

vii) Appearance of beach marks suggested.
  a) Stress concentration was severe.
  b) Nominal stresses were low.
  c) Applied stresses were tensile-tensile or unidirectional bending.

viii) Final fracture area was not visible at low magnification. A raised area around 1 o’clock was damaged removing fracture features in that area. That damaged area could possibly be the final fracture area, however, it could not be confirmed as it is damaged. SEM examination was conducted later revealed some final fractured areas.

ix) Figure 24 show thread roots at 6 o’clock region. A crack was observed at the root of the thread adjacent to the fracture surface. No other threads showed cracks.

x) A crack like indication, longitudinal in direction, was observed on the threads of the bolt, Figure 25. The indication was observed on the crests, flanks and the root of the thread.

xi) No deformation (other than a small damage that formed after crack initiation and crack propagation) was observed in the vicinity of fracture area.

xii) Figure 26 show the fracture surface of Bolt C5. The fracture surface was completely damaged, covered with scratch marks, removing all fracture features. Some pink foreign residues were also observed.

xiii) We did not observe any secondary crack at the thread roots in the vicinity of the fracture. Figure 28 shows some of the threads in the vicinity of the fracture surface.

xiv) Crack like longitudinal indications were observed on bolt C5 as well. Figure 29 shows on of those longitudinal indications.

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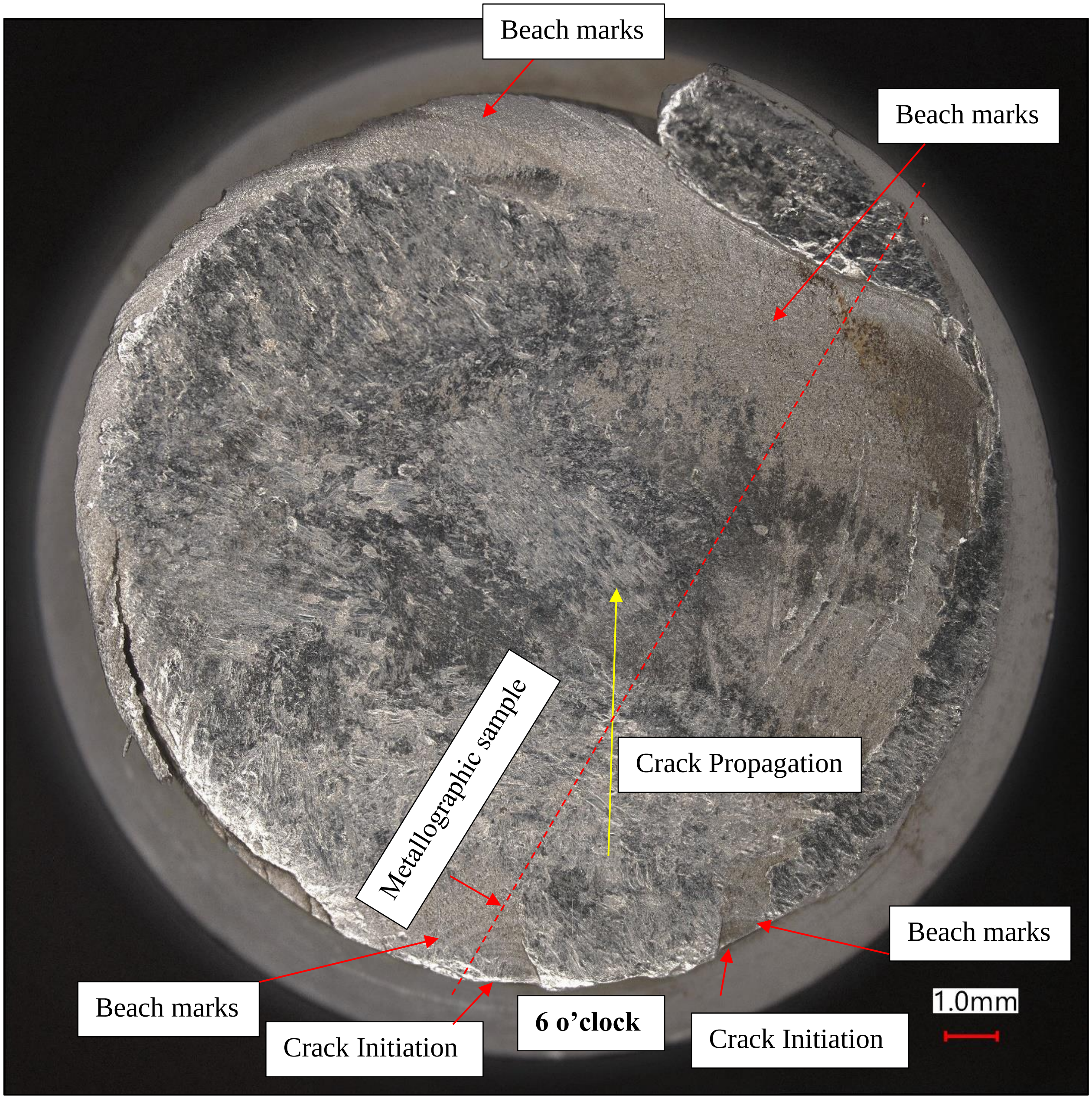

FIGURE 19. FRACTURE SURFACE, BOLT C2

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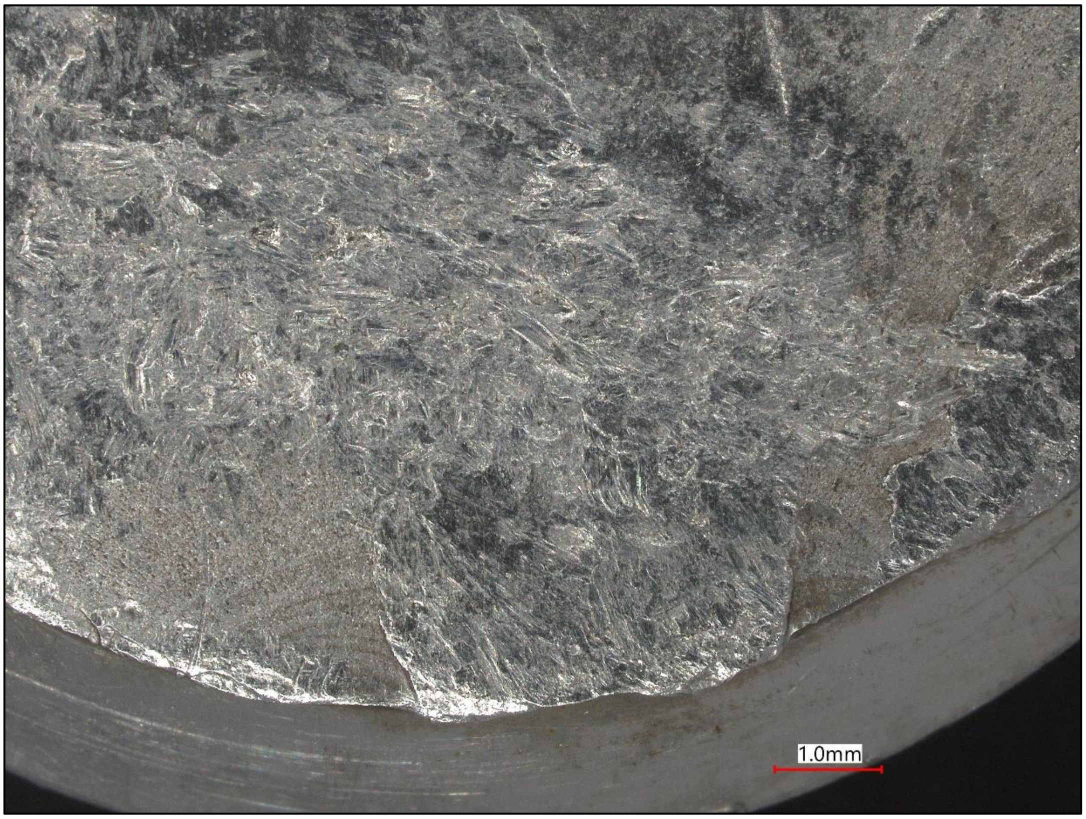

FIGURE 20. MULTIPLE CRACK INITIATION AREA, 6 O'CLOCK, BOLT C2

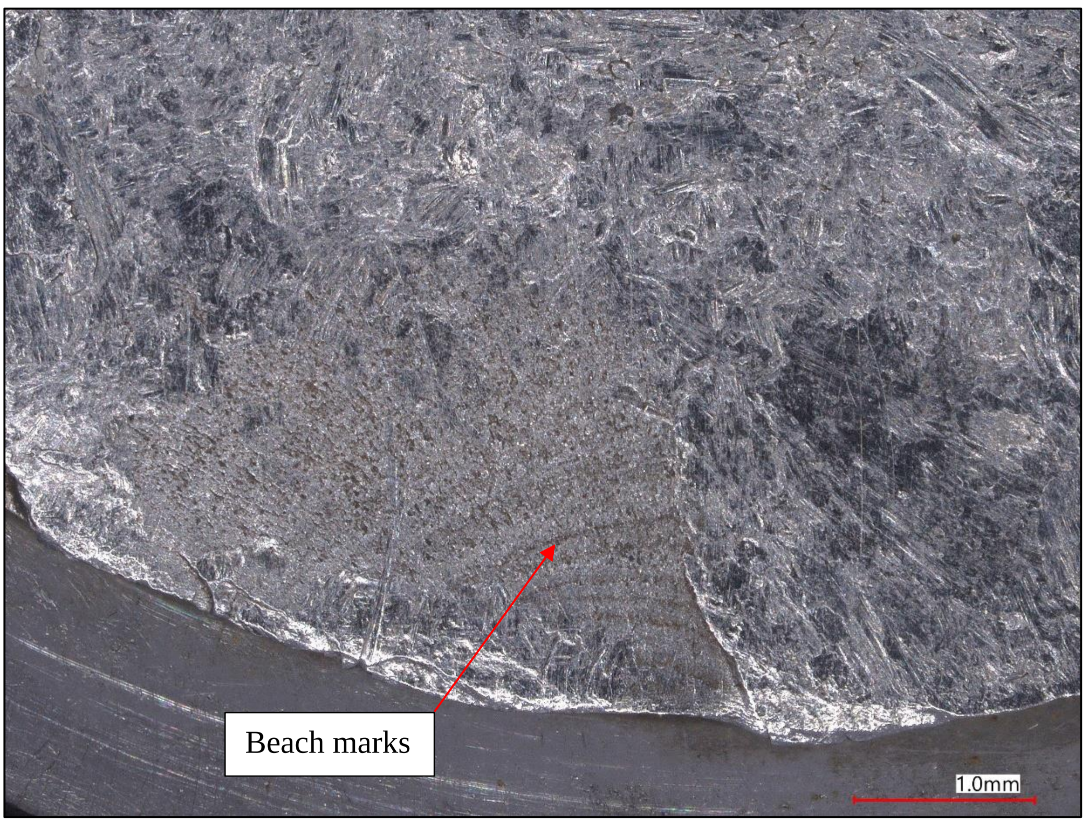

FIGURE 21. CLOSE VIEW OF BEACH MARKS. LEFT OF 6 O'CLOCK, BOLT C2

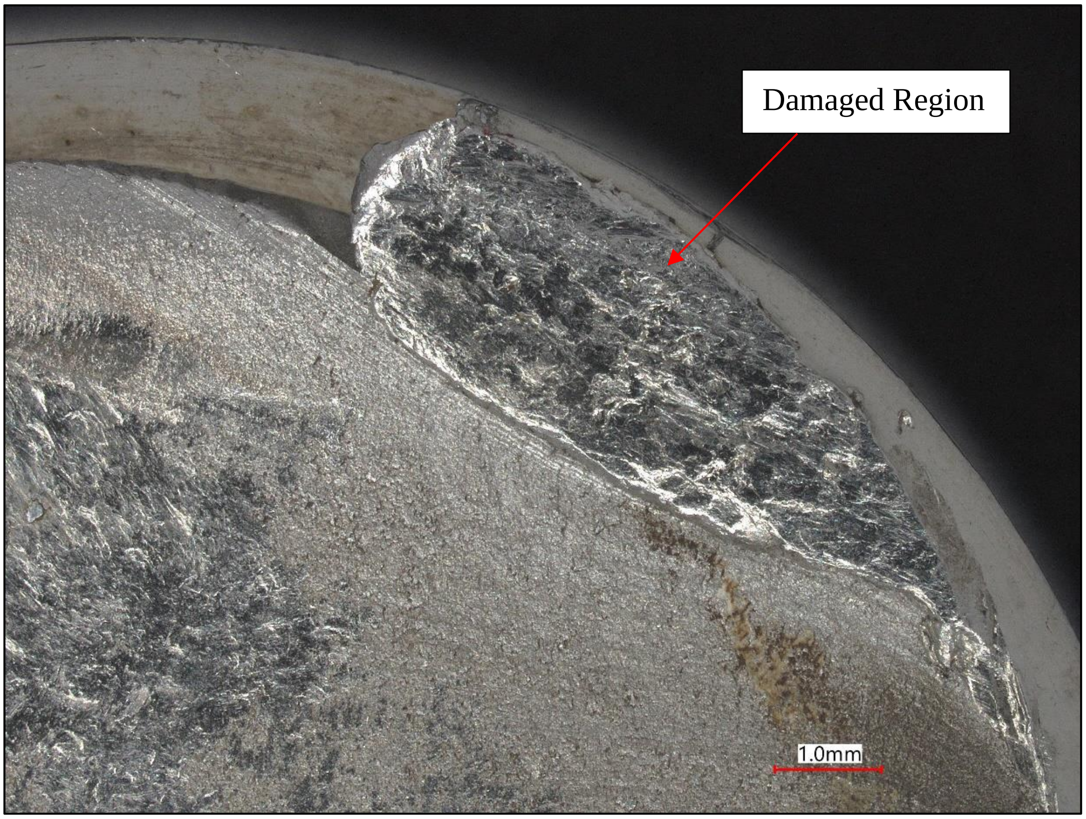

FIGURE 22. BEACH MARKS AROUND 12 – 01 O'CLOCK, BOLT C2

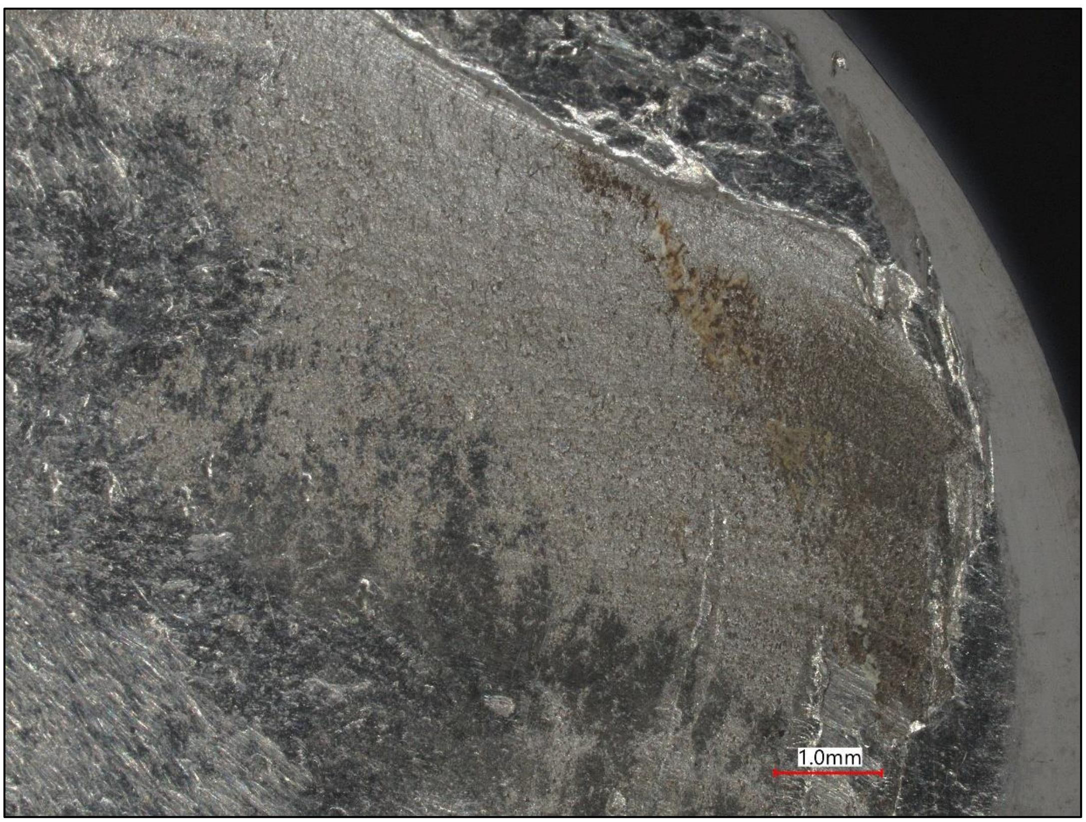

FIGURE 23. BEACH MARKS AROUND 3 O'CLOCK, BOLT C2

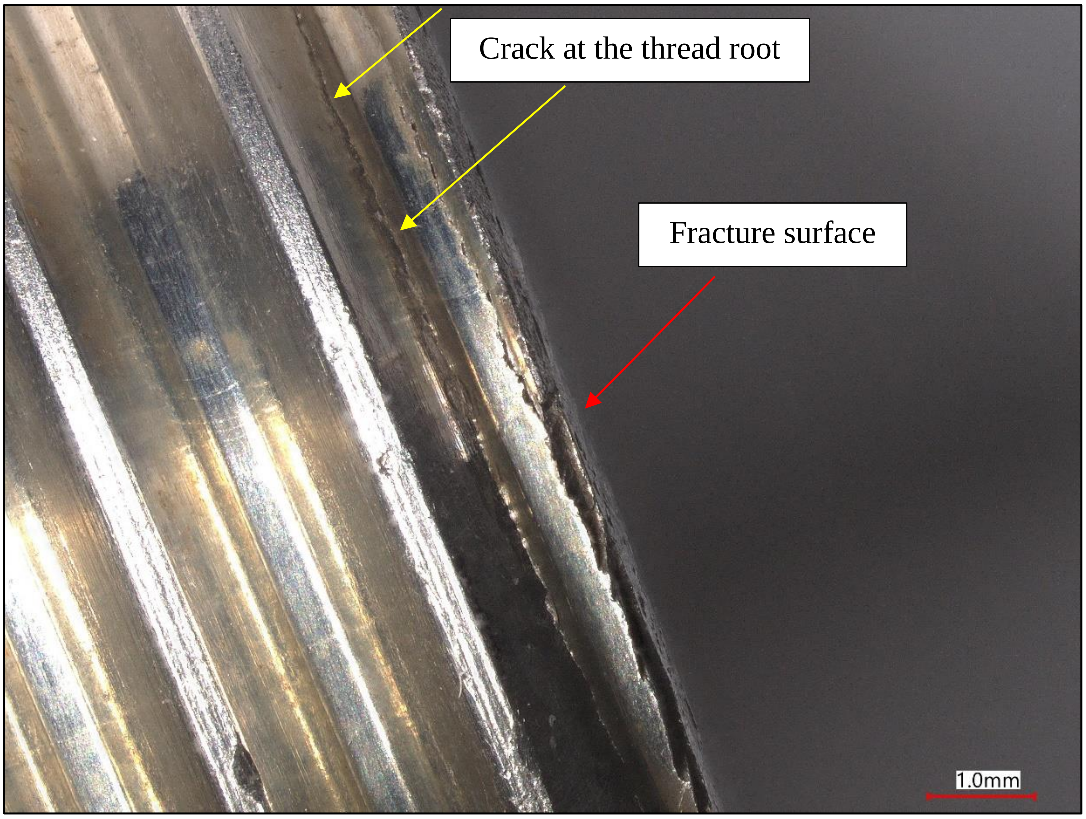

FIGURE 24. CRACK INITIATION AREA. ADJACENT THREAD ROOTS, BOLT C2

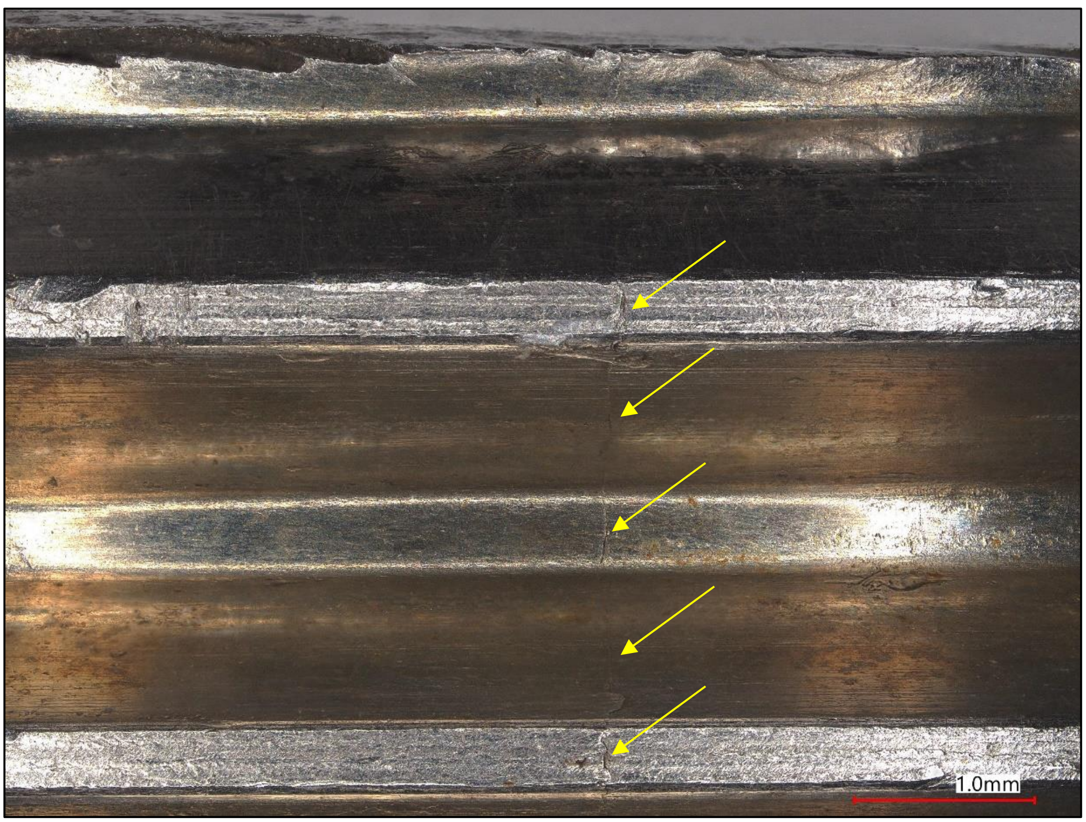

FIGURE 25. LONGITUDINAL CRACK LIKE INDICATION, BOLT C2

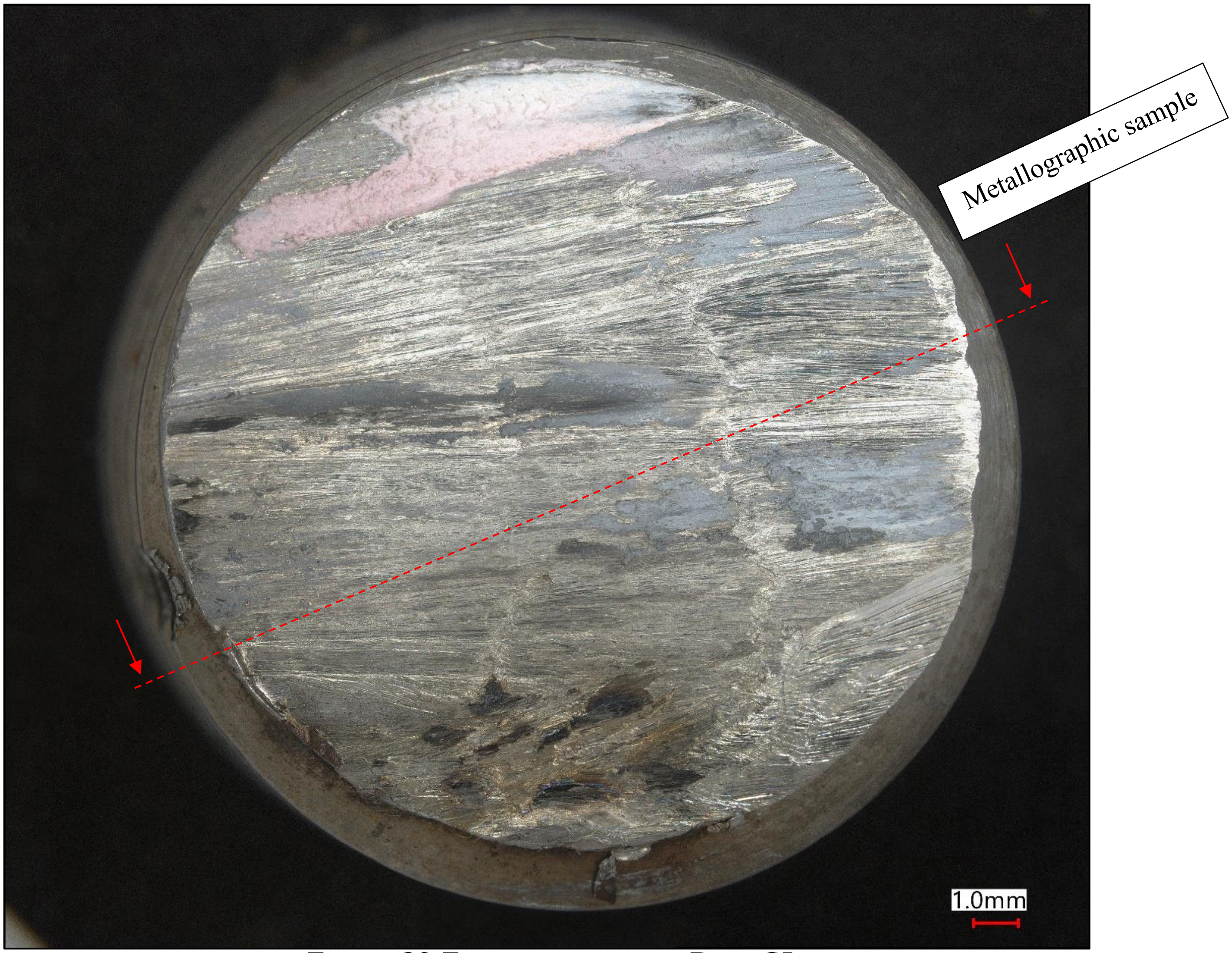

FIGURE 26. FRACTURE SURFACE, BOLT C5

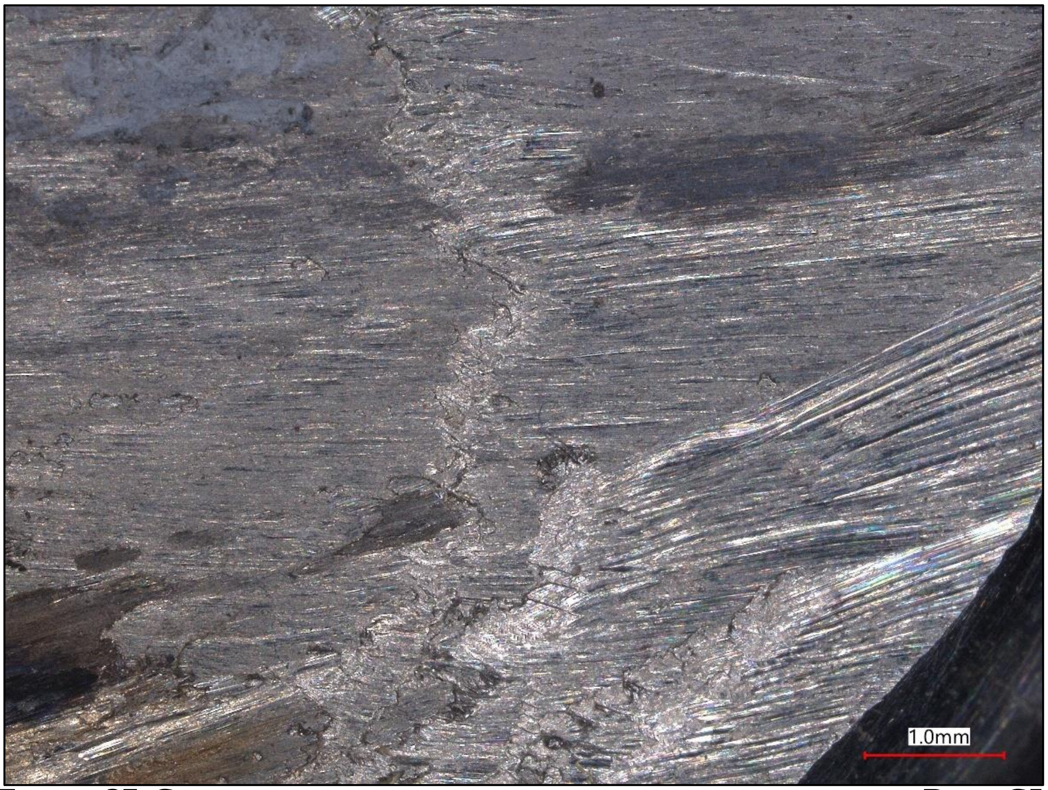

FIGURE 27. CLOSE VIEW OF SCRATCH MARKS ON FRACTURE SURFACE, BOLT C5

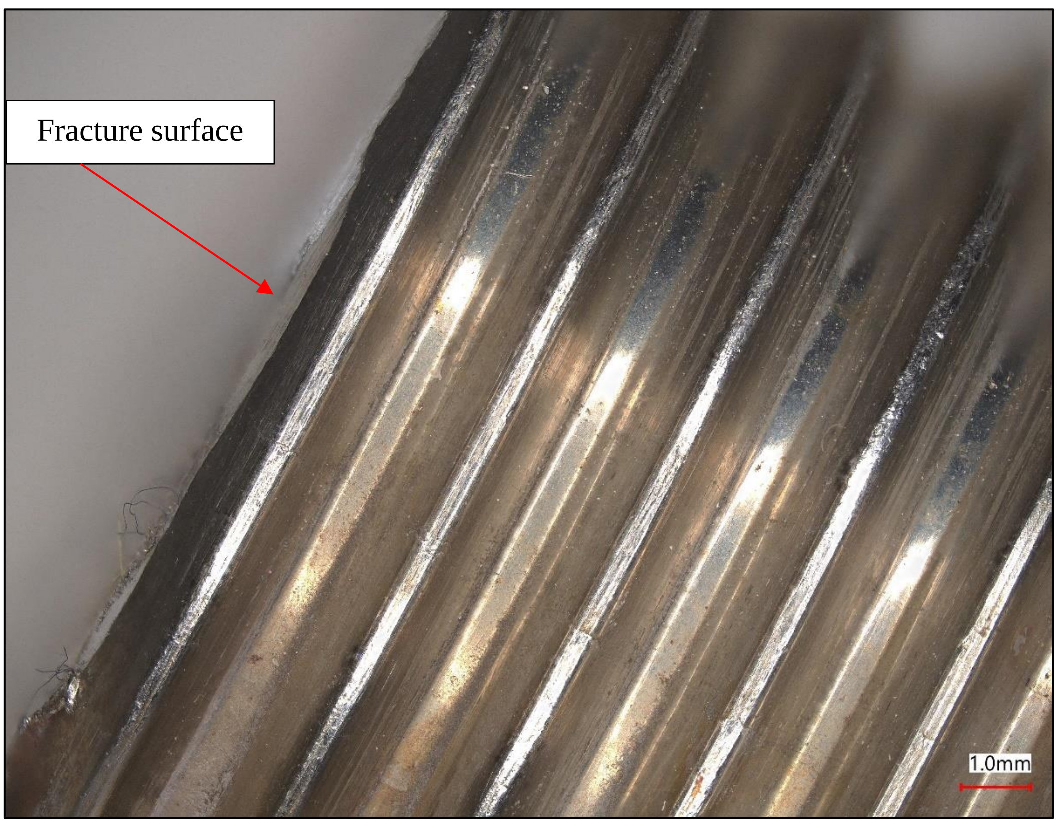

FIGURE 28. THREADS IN THE VICINITY OF THE FRACTURE SURFACE, BOLT C5

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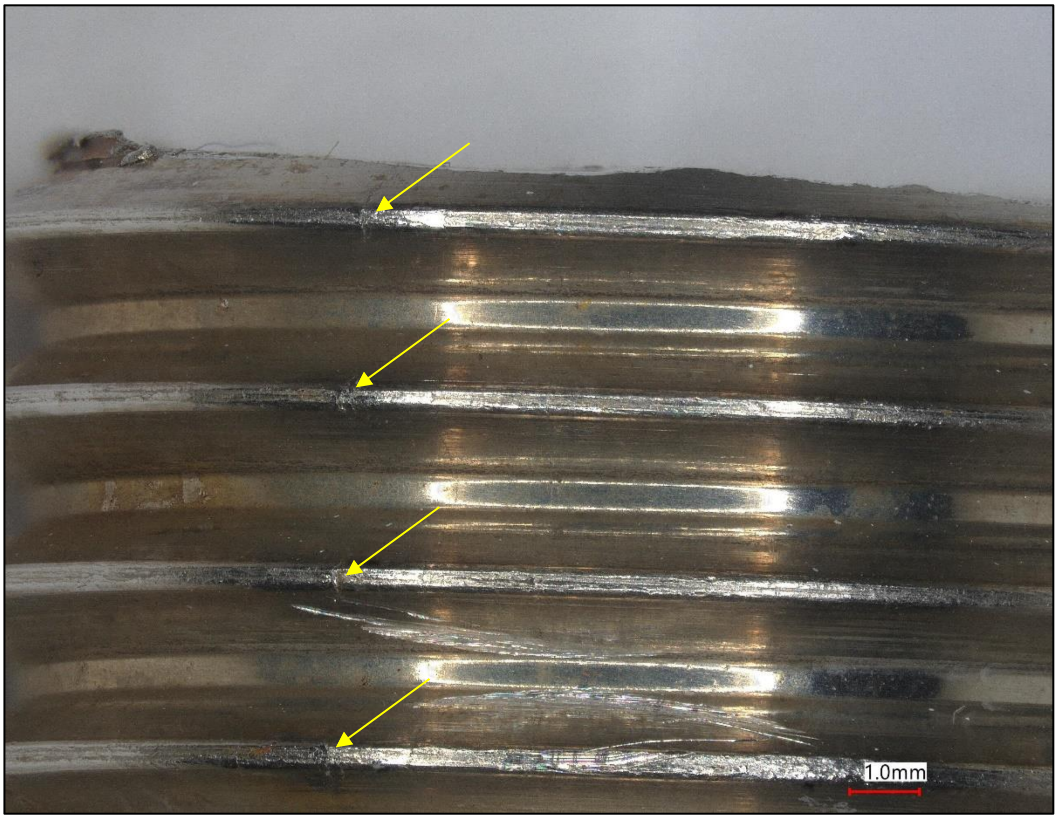

FIGURE 29. CRACK LIKE LONGITUDINAL INDICATION ON THE THREADS, BOLT C5

2.3 SCANNING ELECTRON MICROSCOPY

We removed the fracture surface of both bolts C2 and C5 and examined them by means of a scanning electron microscope (SEM). Following observations were made.

i) Figure 30 shows an area at 6 o’clock region (where cracks initiated) of Bolt C2. Fracture surface was burnished removing fine features in that area. Figure 31 and Figure 32 show the area in the vicinity of the ratchet marks. Rubbing marks were observed in that area.

ii) Figure 31 and Figure 32 show close view of radial crack like feature. Appearance of the feature suggested it was a small ratchet mark flattened because of rubbing of mating faces, however, one side (on the right) still showed beach marks suggesting fatigue cracks initiation.

iii) Figure 31 and Figure 32 show some indications on the thread face that were associated with the ratchet marks.

iv) Figure 33 shows closer view of the lower part of the small ratchet mark, with burnished beach marks on the right.

v) Figure 34 shows part of burnished/damaged region at 12 - 02 o’clock area. Beach marks were vaguely visible under the burnished surface, Figure 35.

vi) Beach marks were still visible at the end of the fracture surface at 12 o’clock, Figure 36.

vii) Figure 37 and Figure 38 show beach marks at 12 o'clock region. Surface was burnished even where beach marks were visible. Figure 39 shows the burnished beach marks. Figure 40 shows the same area at a higher magnification. It is clear how burnishing removed fine features.

viii) We were able to detect striations at 12 o’clock region in some area where burnishing did not remove the fine fracture features completely. Figure 41 and Figure 42shows tow areas where striations were observed.

ix) Figure 43 shows the top end of the fracture surface at 12 o’clock (see Figure 19), This area followed the beach marks (see Figure 43). Area above the beach marks showed dimples, evidence of transgranular ductile fracture. Figure 44 and Figure 45 show the dimples observed at two different magnifications. This is the area with final fracture.

x) Observation of dimples next to the raised and damaged area also suggests the damaged region was part of the final fracture area.

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xi) We had observed crack like indications on the threads during low magnification examination (see Figure 25). Figure 47 shows one of these indications. Appearance suggests these are deformed, moved and flattened material creating overlaps, Figure 46, Figure 47, Figure 48. These indications formed during manufacturing of the bolts.

xii) Figure 49 show thread face and portion of fracture surface of bolt C5. Fracture surface was heavily scratched leaving no features of the fracture. Figure 50 shows another area with heavy scratch marks.

xiii) Figure 51 shows a pocket between the thread face and fracture surface. This area showed dimples (See Figure 52), ductile transgranular fracture. Appearance suggests the pocket area was not part of the main fracture. It could be part of the final fracture area.

xiv) No deformation was observed in the vicinity of the fracture surfaces of both bolts, C2 and C5, suggesting the crack initiated and propagated in a brittle manner.

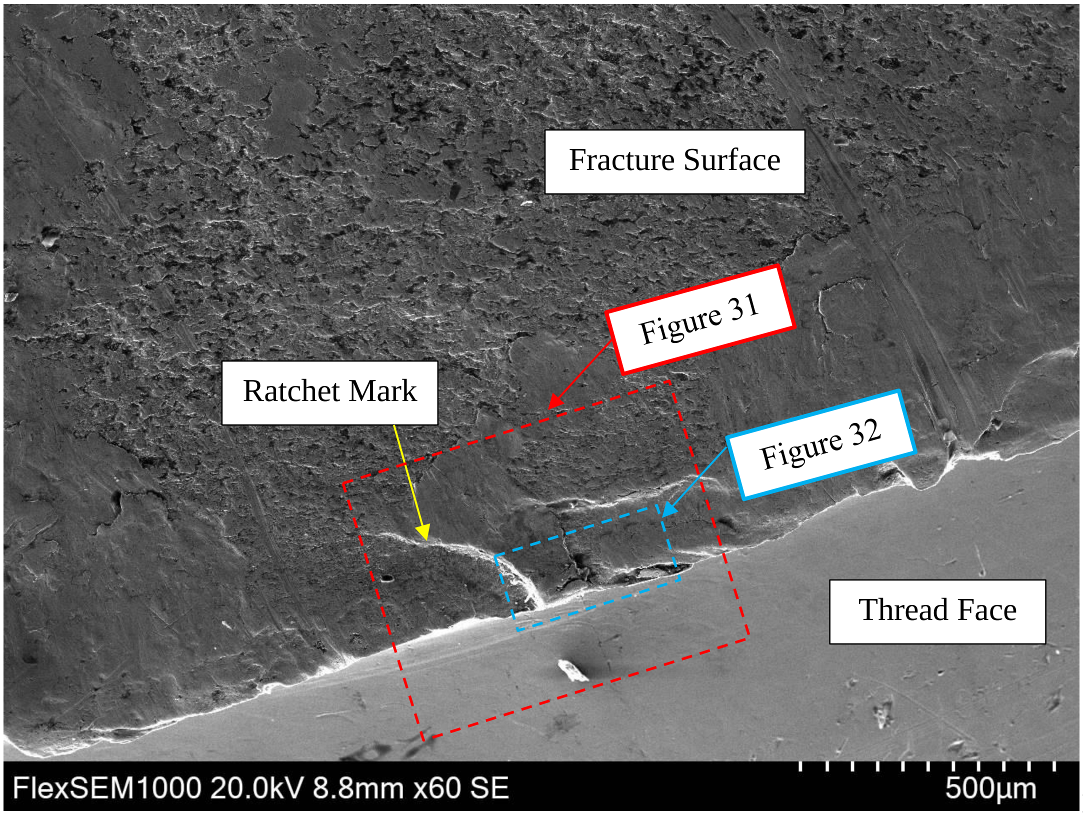

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FIGURE 30. FRACTURE SURFACE/THREAD FACE. 6 O'CLOCK BOLT C2

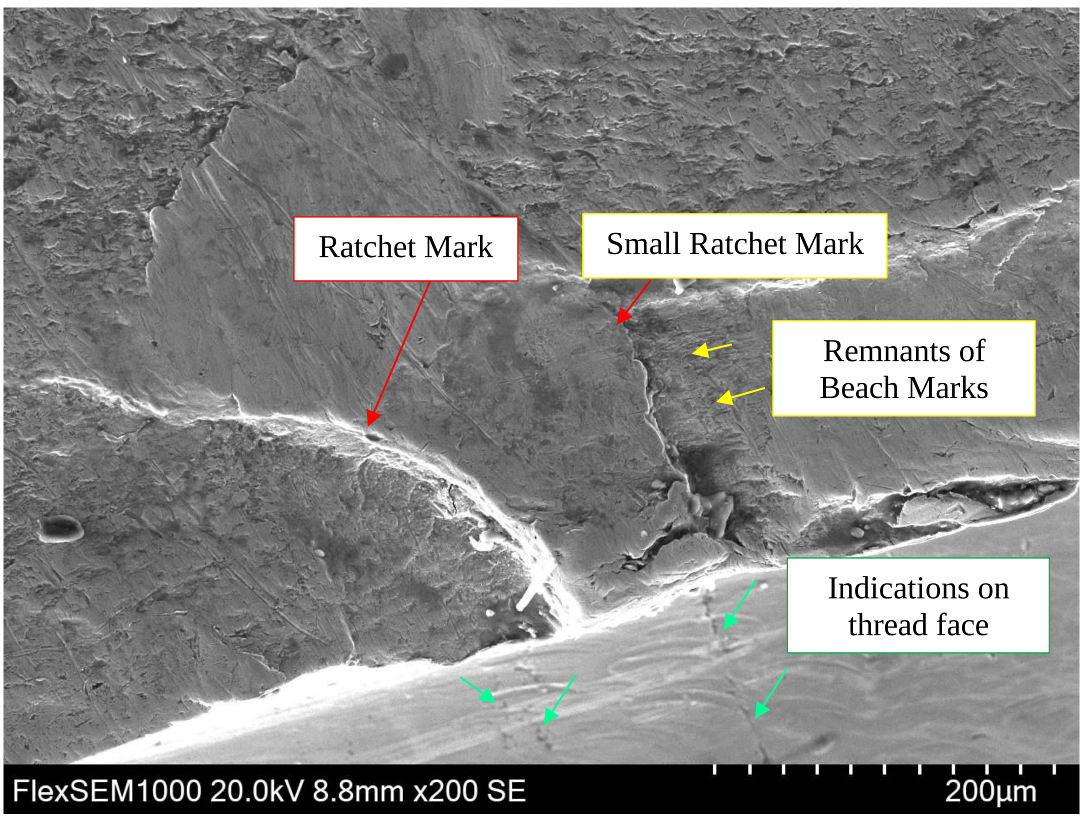

FIGURE 31. CLOSE VIEW OF THE RATCHET MARKS, BOLT C2

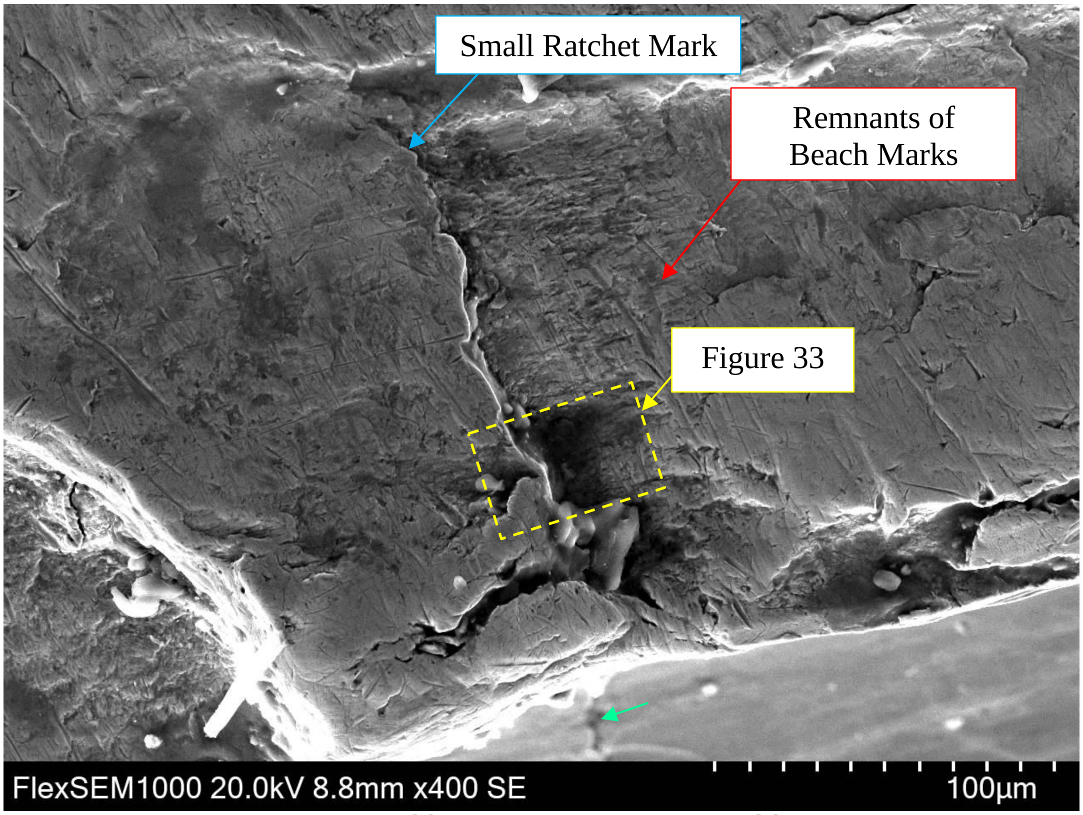

FIGURE 32. BEACH MARKS, BOLT C2

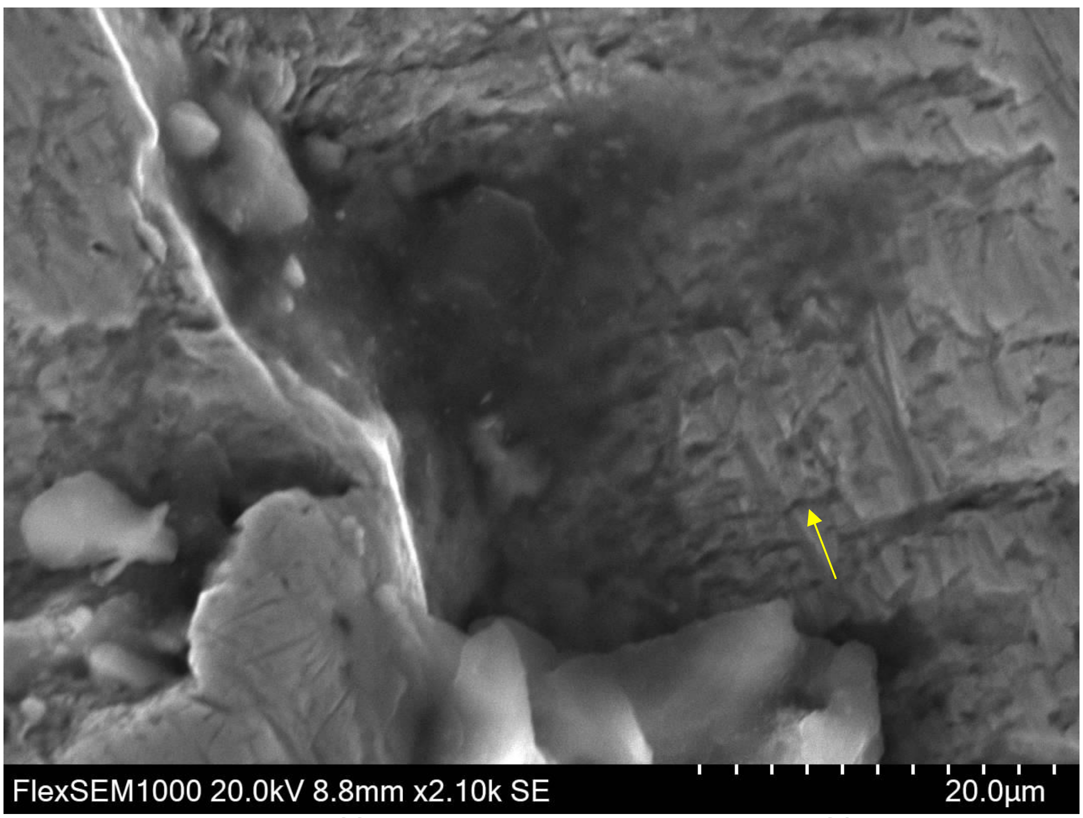

FIGURE 33. BURNISHED BEACH MARK, BOLT C2

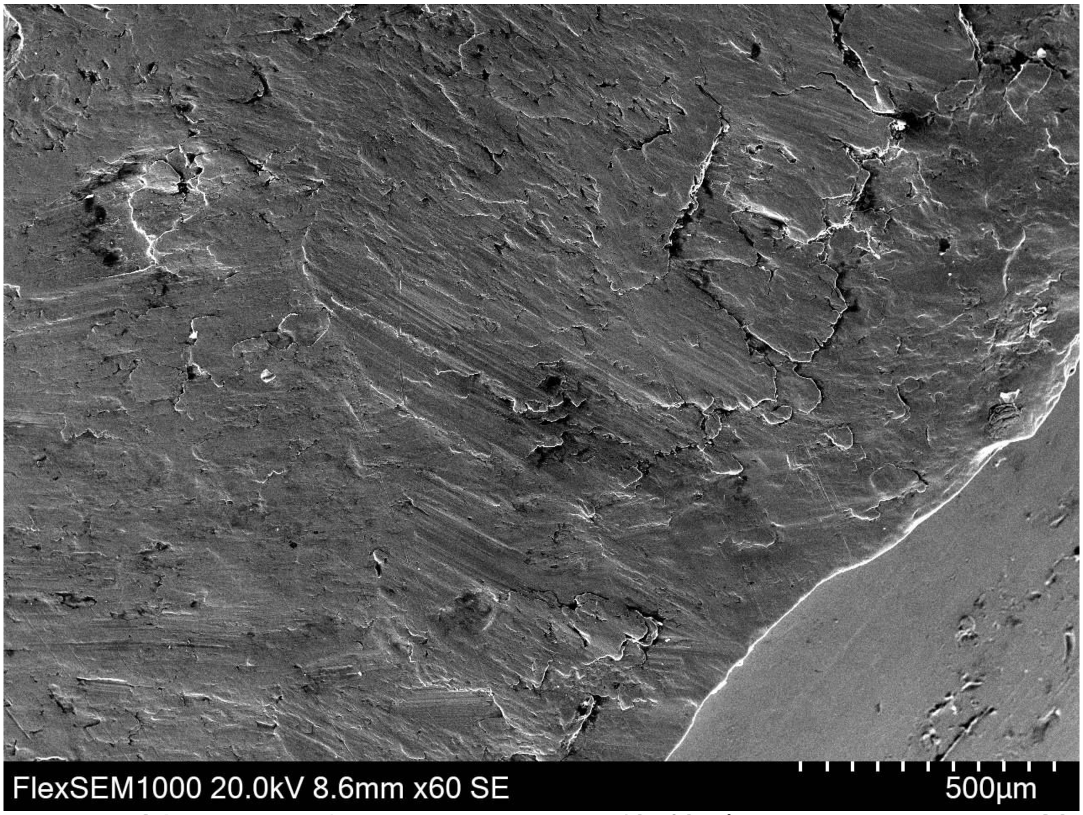

FIGURE 34. DAMAGED/BURNISHED AREA ON 12 -02 O'CLOCK REGION, BOLT C2

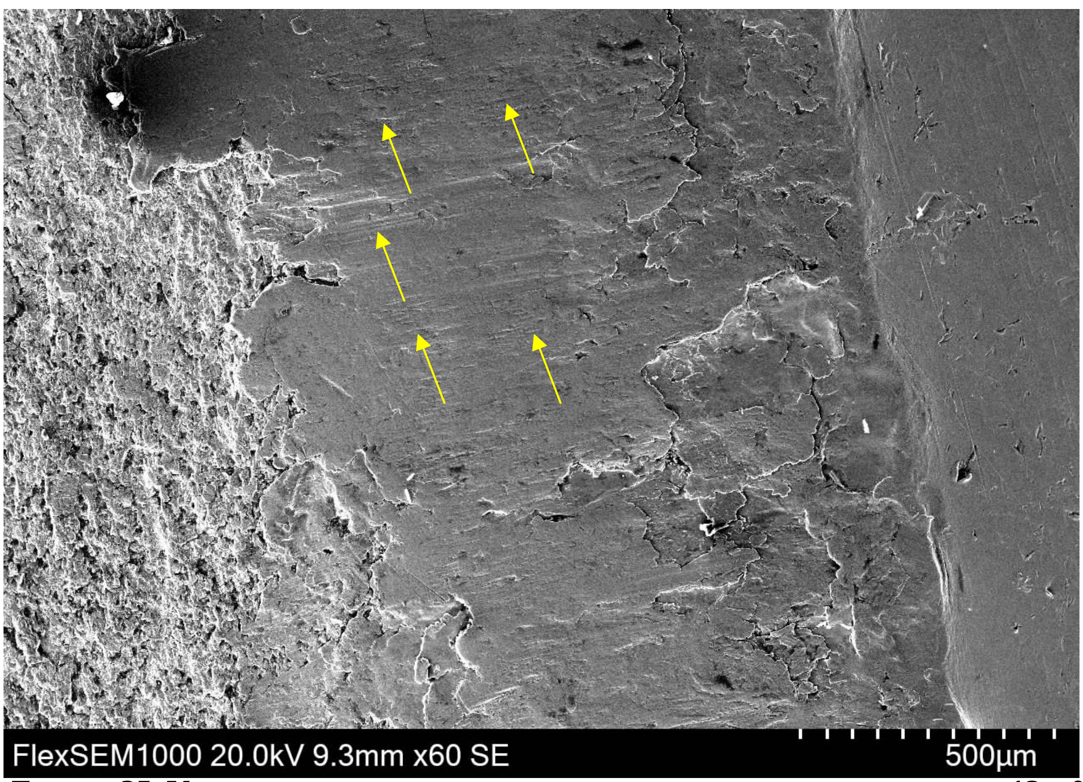

FIGURE 35. VAGUE BEACH MARKS ON THE BURNISHED FRACTURE SURFACE. 12 – 02 O'CLOCK REGION, BOLT C2

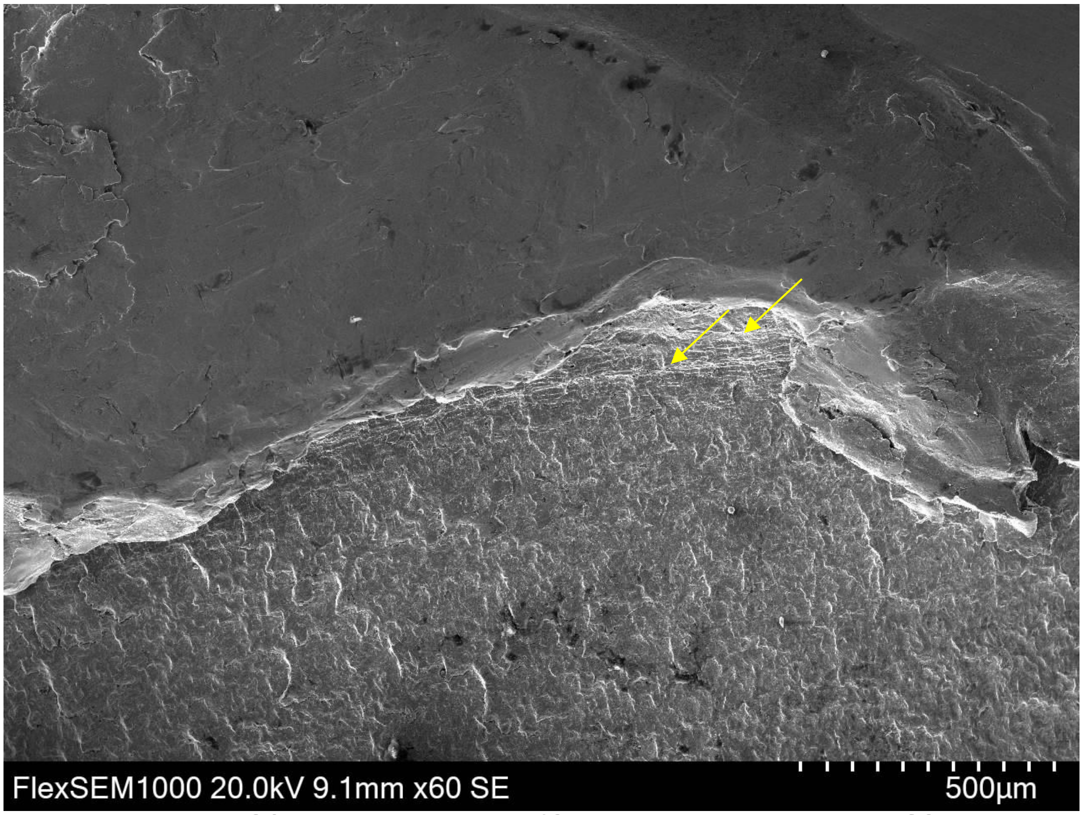

FIGURE 36. BEACH MARKS AT 12 O'CLOCK REGION, BOLT C2

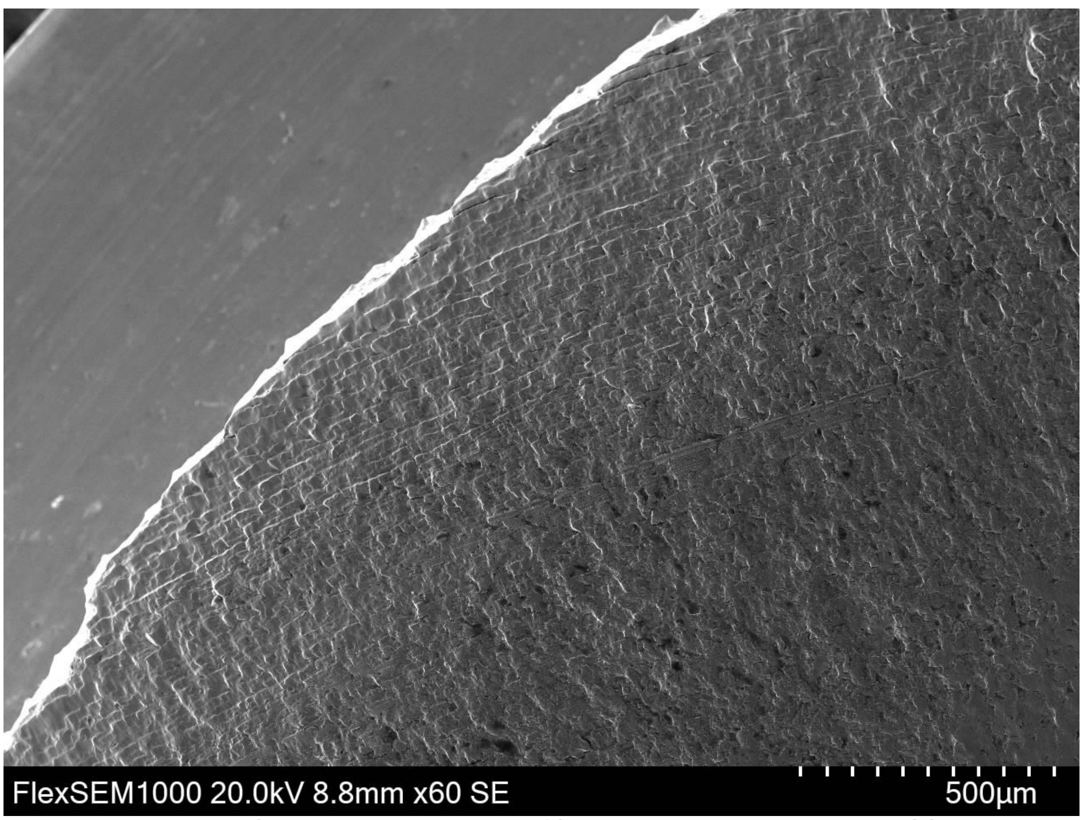

FIGURE 37. BEACH MARKS AT 12 O'CLOCK REGION, BOLT C2

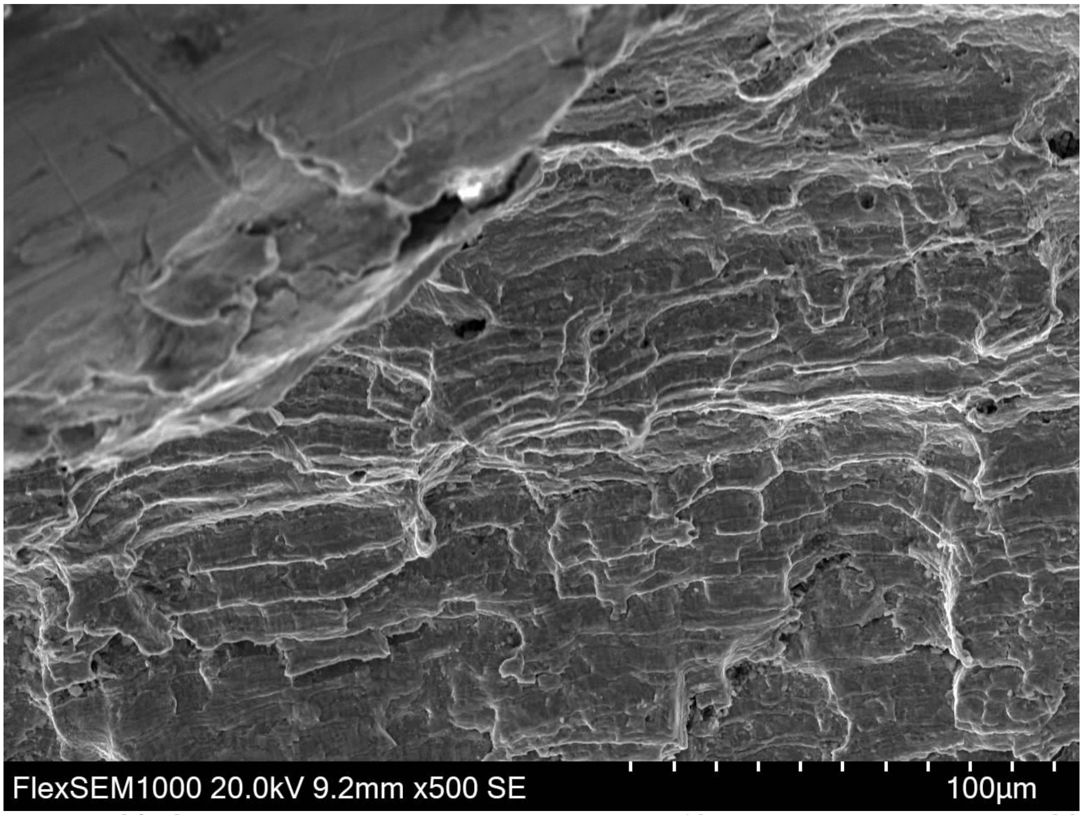

FIGURE 38. CLOSE VIEW OF THE BEACH MARKS AT 12 O'CLOCK REGION, BOLT C2

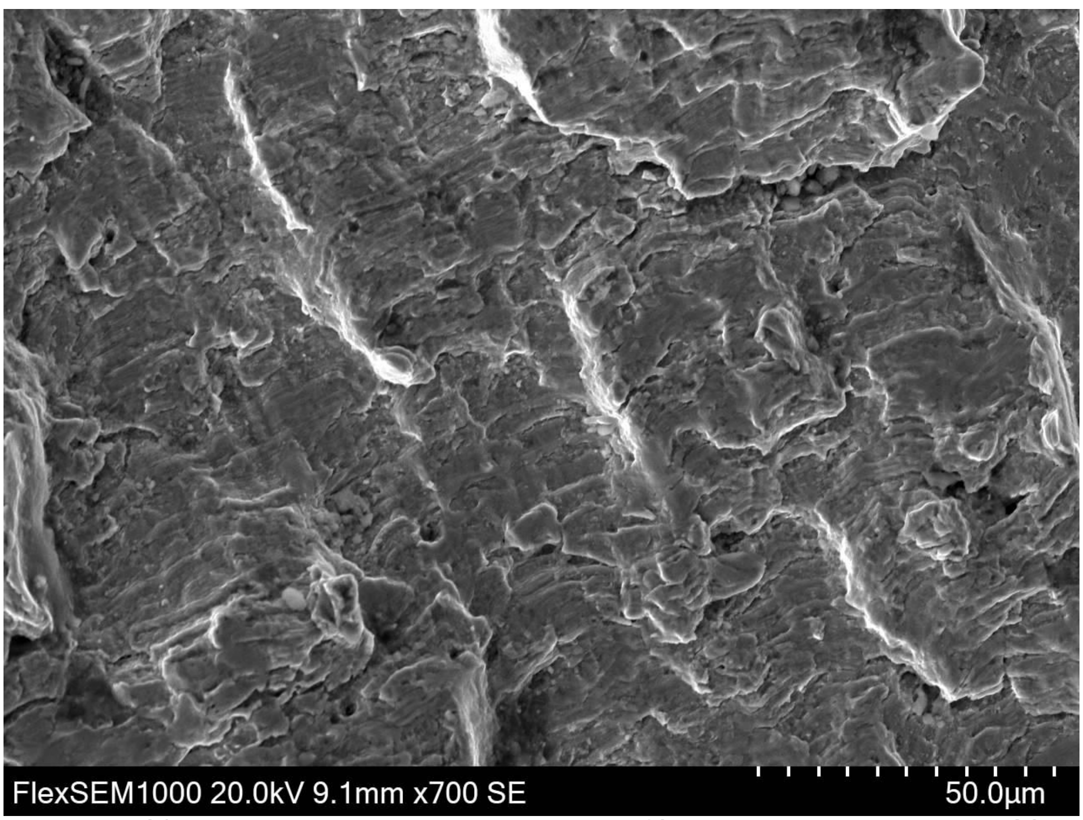

FIGURE 39. BURNISHED FRACTURE FEATURES 12 O'CLOCK REGION, BOLT C2

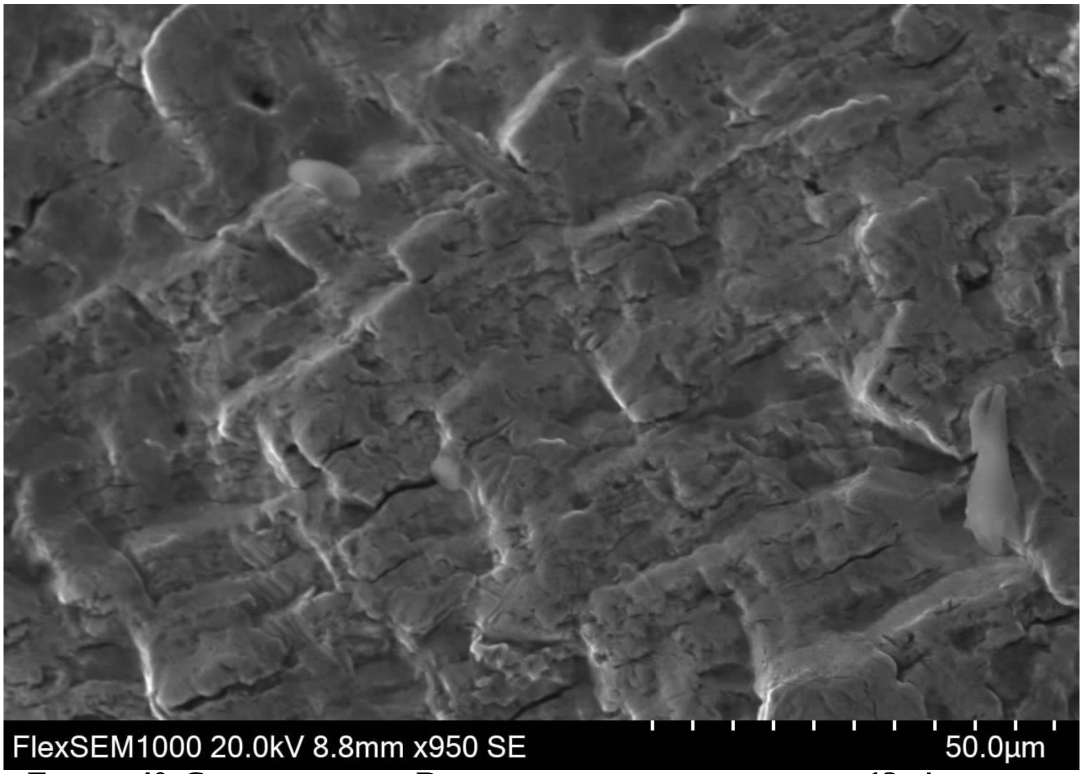

FIGURE 40. CLOSER VIEW OF BURNISHED FRACTURE FEATURES 12 O'CLOCK REGION, BOLT C2

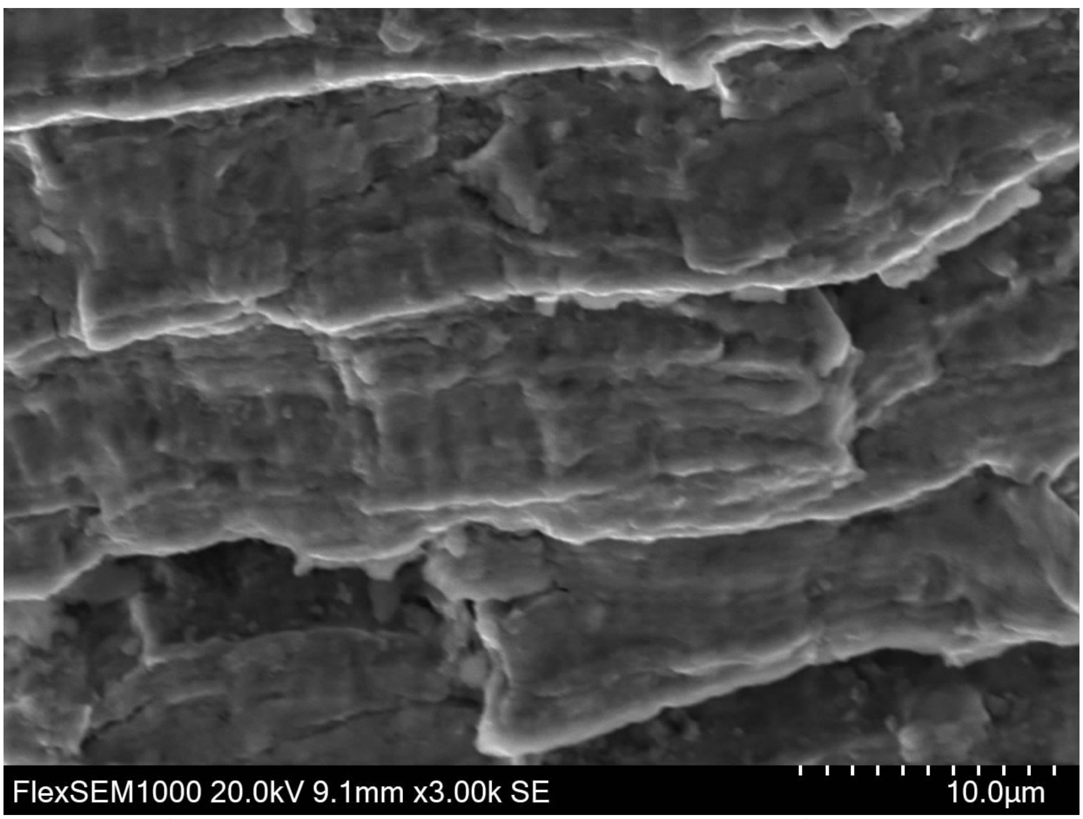

FIGURE 41. STRIATIONS IN THE AREA WITH BEACH MARKS. 12 O'CLOCK REGION, BOLT C2

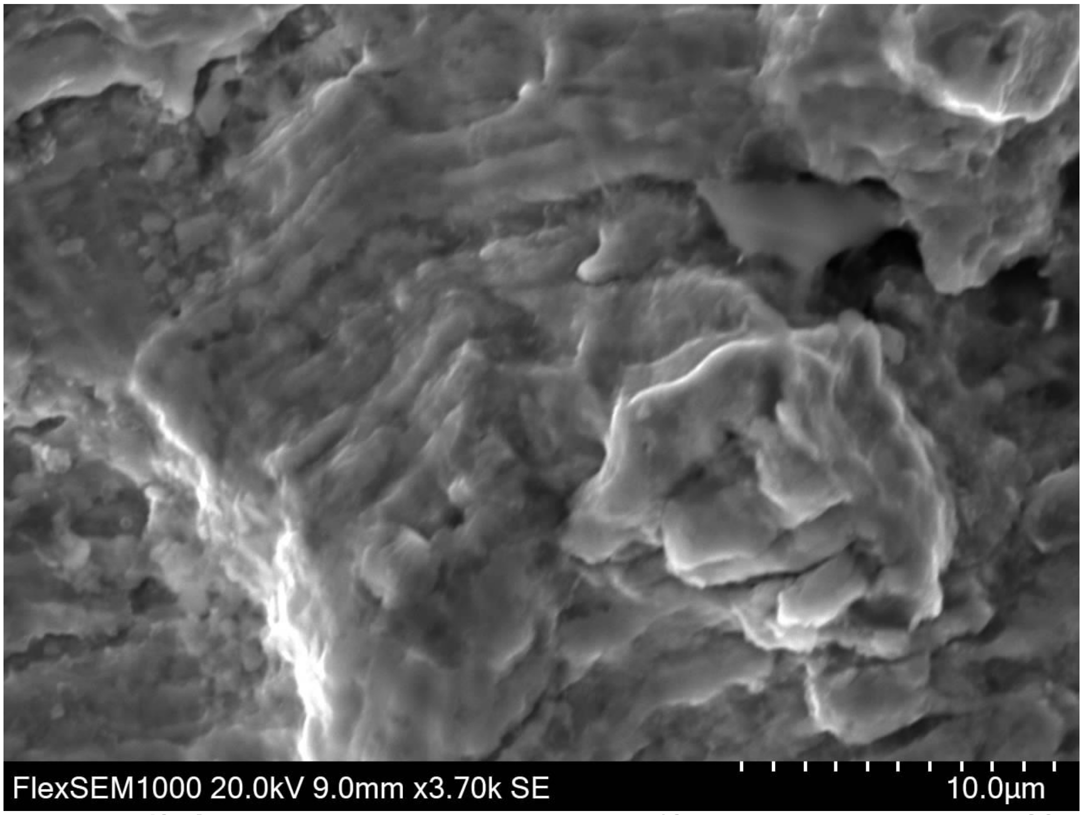

FIGURE 42. ANOTHER AREA WITH STRIATIONS, 12 O'CLOCK REGION, BOLT C2

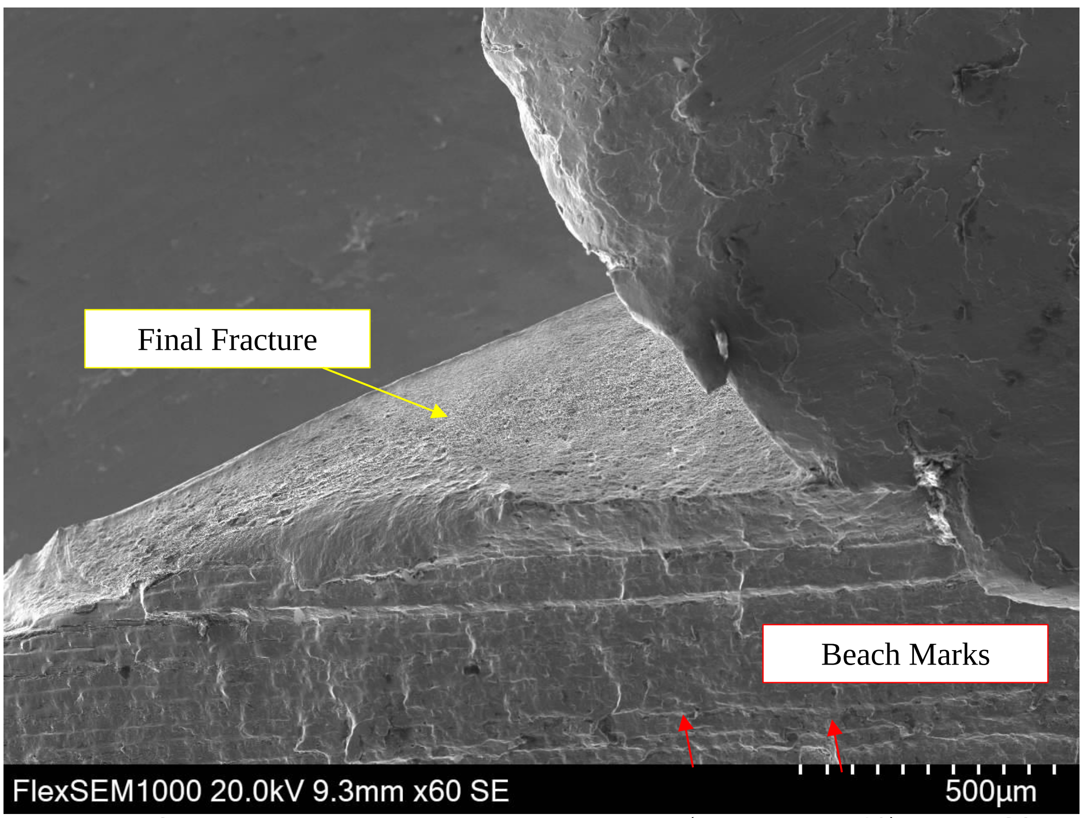

FIGURE 43. TOP END OF THE FRACTURE SURFACE (SEE FIGURE 19), BOLT C2

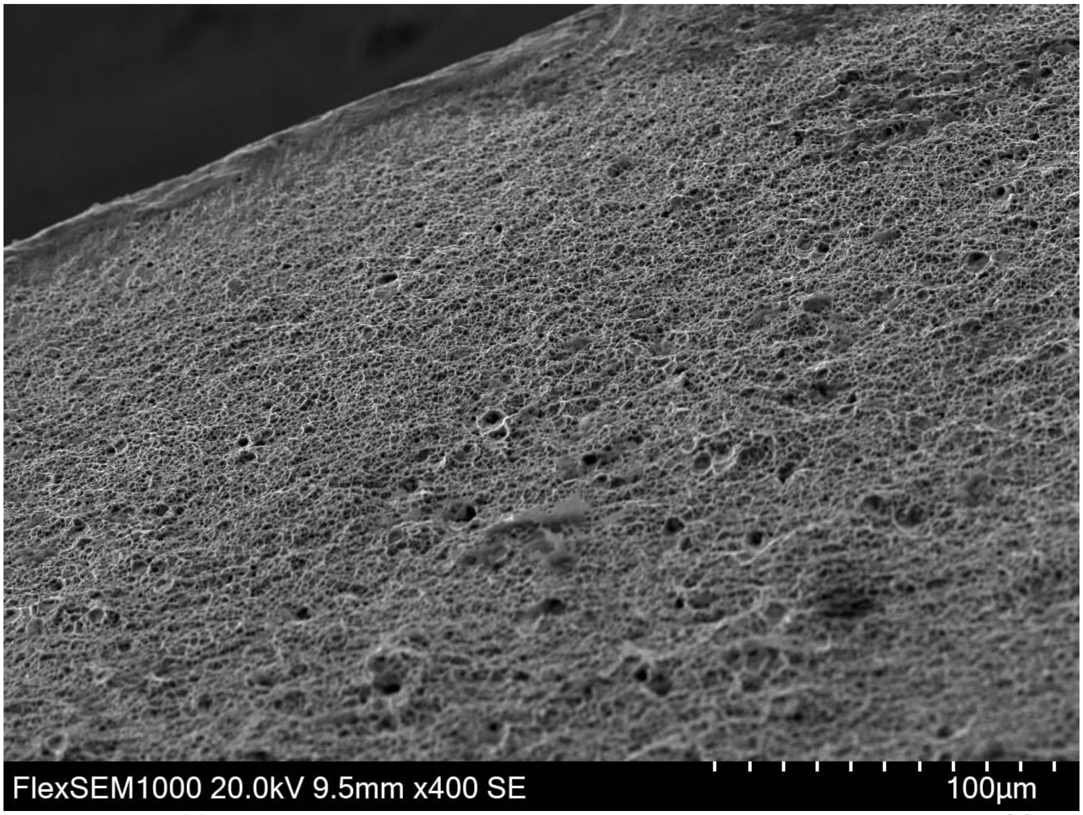

FIGURE 44. DIMPLES OBSERVED ON THE FINAL FRACTURE AREA, BOLT C2

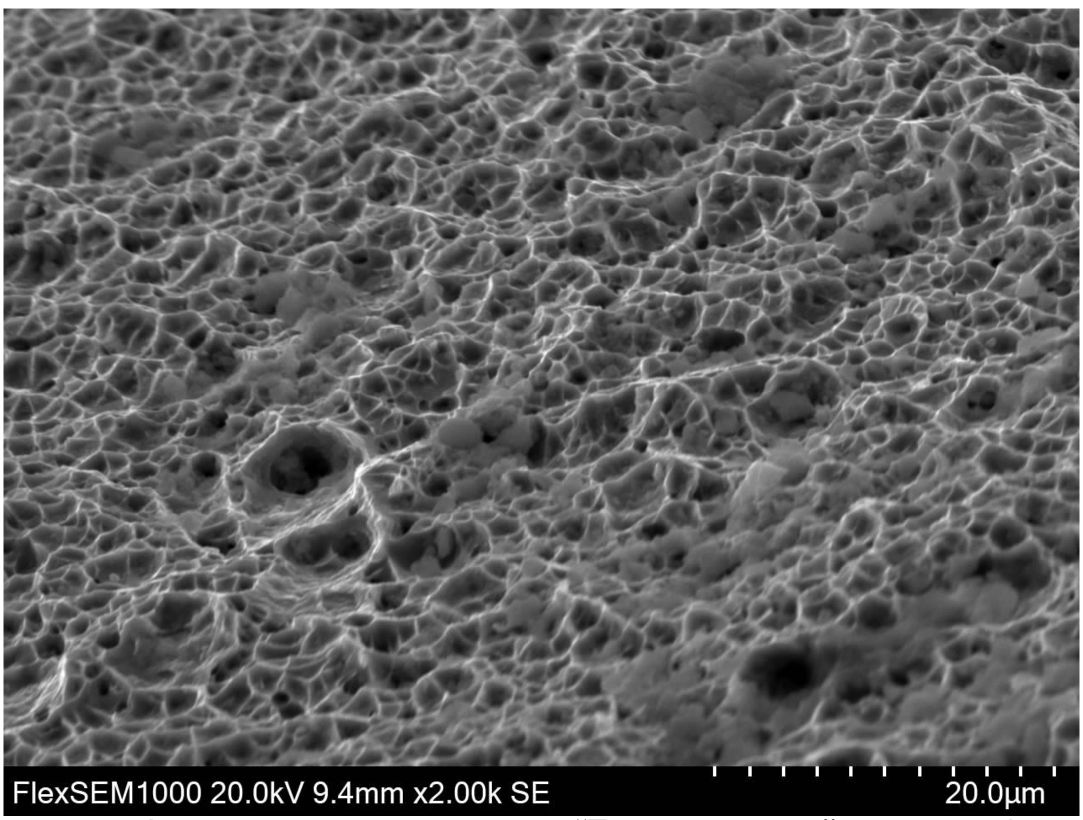

FIGURE 45. CLOSER VIEW OF AREA MARKED "FINAL FRACTURE" IN FIGURE 43, BOLT C2

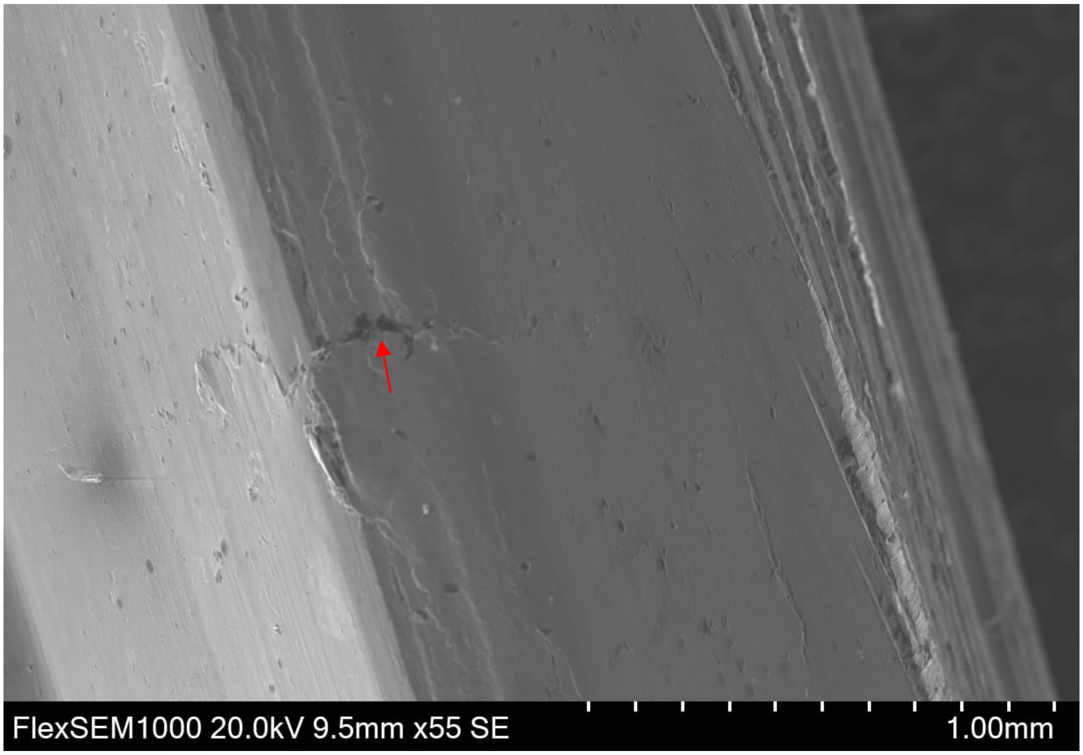

FIGURE 46. ONE OF THE CRACKS LIKE INDICATIONS OBSERVED DURING VISUAL EXAMINATION, BOLT C2

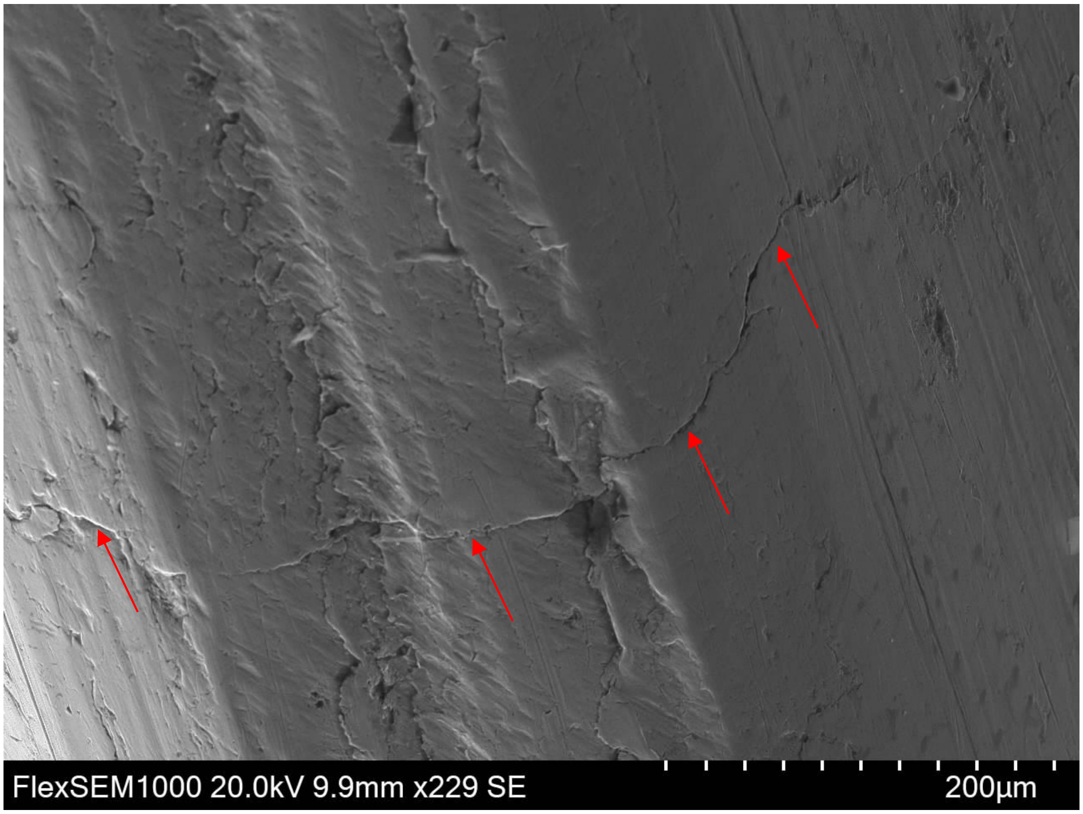

FIGURE 47. CLOSE VIEW OF ONE OF THE CRACK LIKE INDICATIONS, BOLT C2.

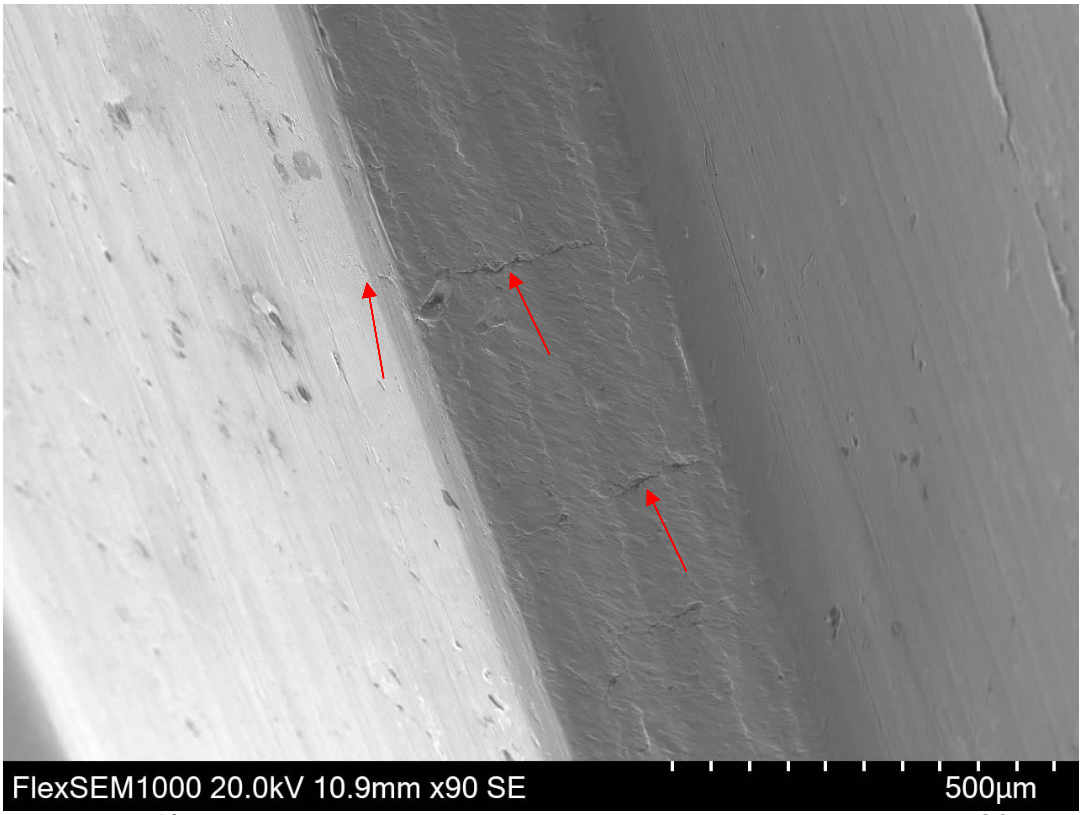

FIGURE 48. MICRO-CRACK LIKE INDICATIONS ON THE THREADS, BOLT C2

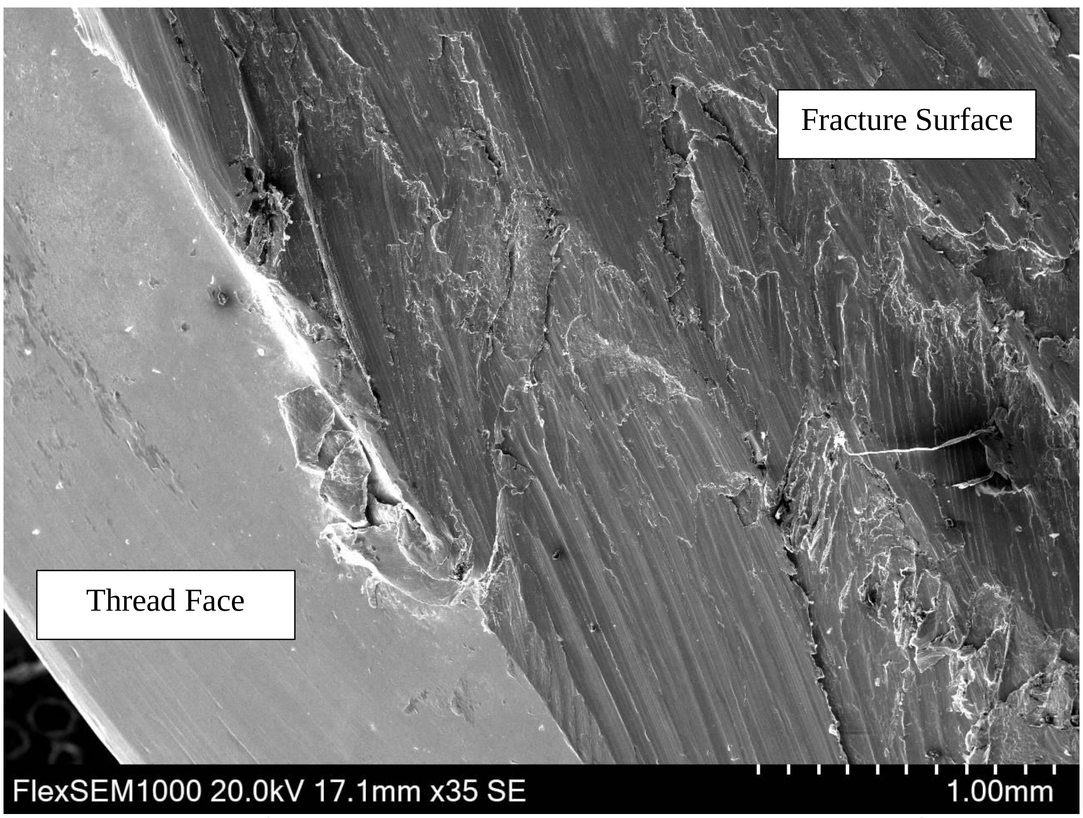

FIGURE 49. FRACTURE SURFACE AND THREAD FACE, BOLT C5

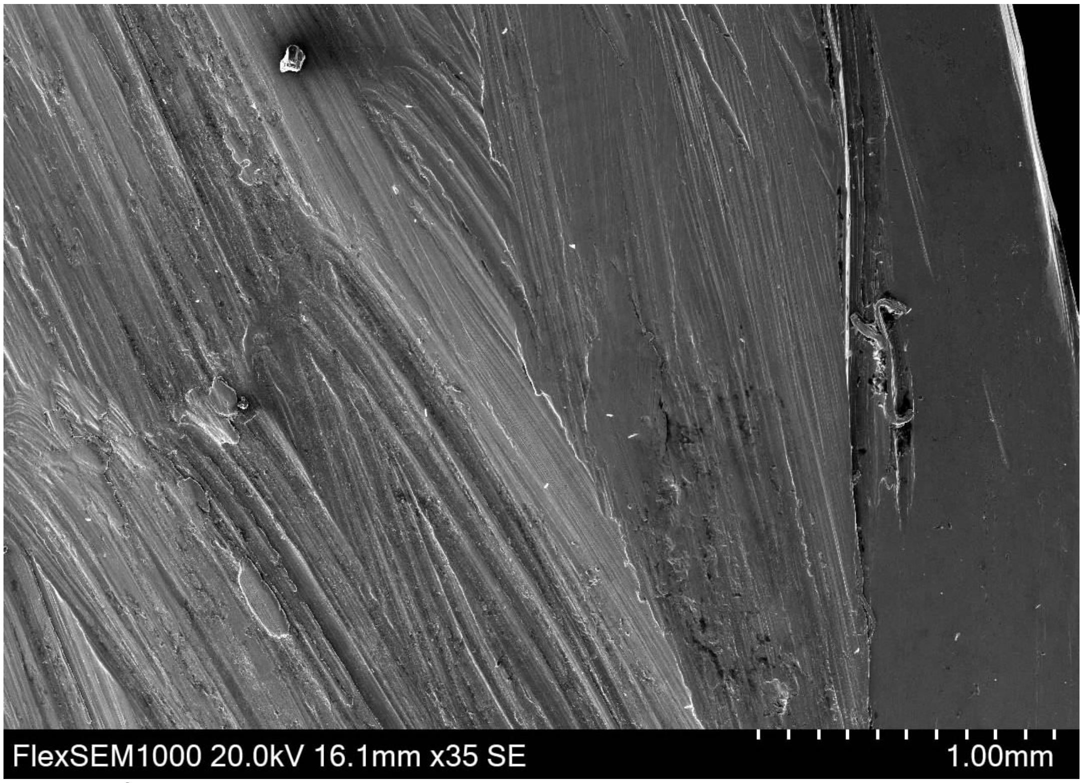

FIGURE 50. HEAVY SCRATCH MARKS ON THE FRACTURE SURFACE, ANOTHER AREA, BOLT C5

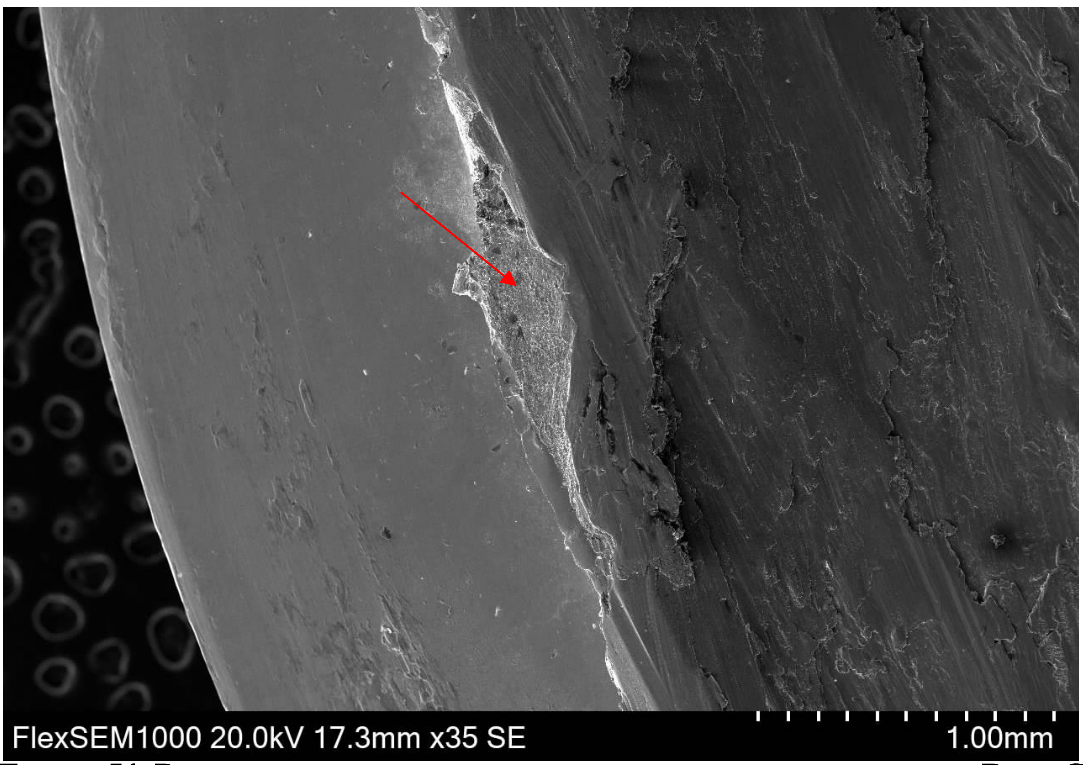

FIGURE 51. POCKET OF THE THREAD FACE – FRACTURE SURFACE BORDER, BOLT C5

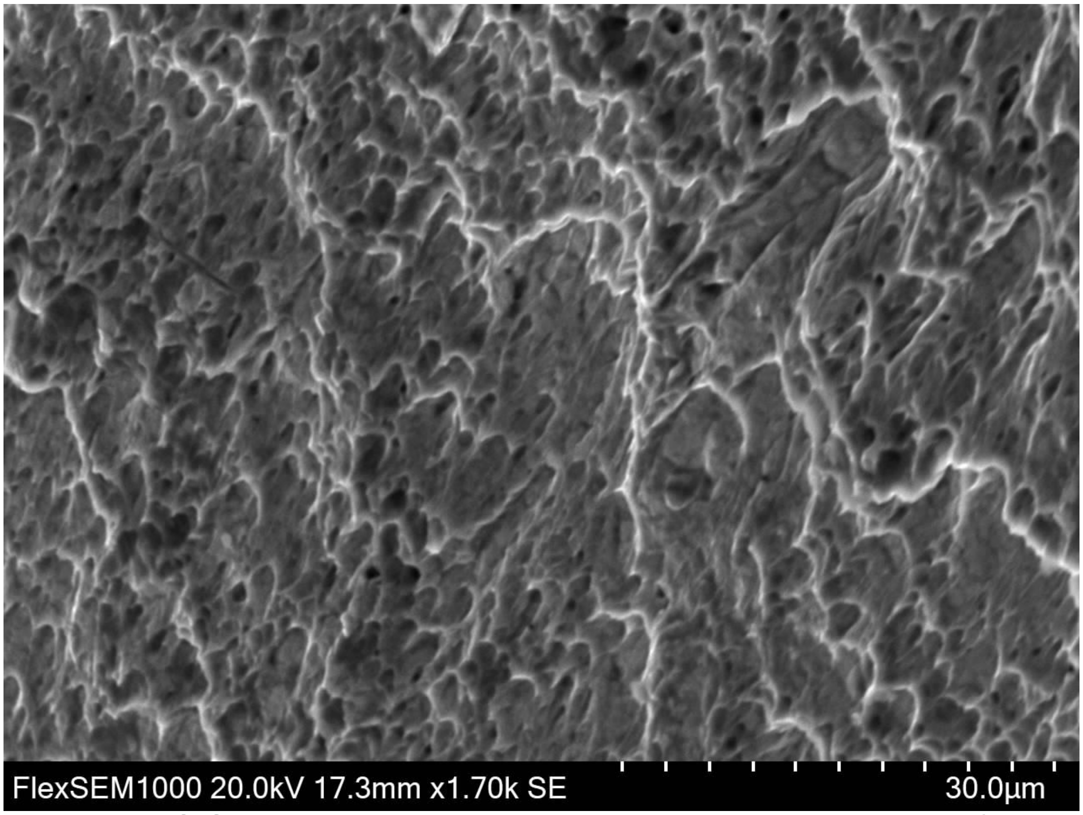

FIGURE 52. SHEARED DIMPLES OBSERVED IN THE POCKET IN FIGURE 51

2.4 METALLOGRAPHIC EXAMINATION

Two sections were removed, one from bolt C2 and one from bolt C5, for metallographic examination. The sections were cut perpendicular to the fracture surfaces for cross-sectional observations (see Figure 19 and Figure 26). The samples were mounted in Bakelite, ground, and polished in accordance with ASTM E3-11. After examination in the as-polished condition, we etched the samples using 10 oxalic acid solution in accordance with ASTM E407-07(2015) e1 to reveal their microstructure. The following observations were made.

i) Figure 53 shows a general image of the metallographic sample prepared from bolt C2 in as-polished condition. Figure 54 shows a low magnification of bolt core and the threads close to fracture surface in etched condition. Micro-segregation formed during manufacturing was observed.

ii) Close view of the area near the 6 o'clock region on the fracture surface where crack initiated did not show any abnormalities in the microstructure. We observed deformed grains close to the fracture surface that likely occurred during crack propagation or after complete separation due to relative motion of the mating faces.

iii) Appearance of flow lines on the threads suggested that the threads created by a rolling process, Figure 56.

iv) Some rolling defects/folds were observed at the crest, Figure 57. Cracking was observed at root of threads, Figure 58.

v) The microstructure of the bolt's core (bolt C2) showed austenitic grains with a small volume fraction of delta ferrite grains, Figure 59.

vi) A general image of the metallographic sample prepared from bolt C5 in as-polished condition is presented in Figure 60.

vii) Appearance of the flow lines at the threads indicated that the threads were made by a rolling process, Figure 61.

viii) Microstructure of the core (bolt C5) consisted of mostly austenitic structure with some elongated delta ferrite grains, Figure 62.

In addition to the broken samples, all the intact bolts were also sectioned in a logitudinal section for metallographic examinations. The samples were mounted in Bakelite, ground, and polished in accordance with ASTM E3-11. After examination in the as-polished condition, we etched the samples using 10 oxalic acid solution in accordance with ASTM E407-07(2015) e1 to reveal their microstructure. The following observations were made on each bolt.

2.4.1 Bolt O1

i) Figure 63 shows a general image of the metallographic sample prepared from bolt O1 in as-polished condition. Figure 64 shows the microstructure of the bolt at the threaded section that consisted of austenitic structure. The flow lines observed on the threads suggested that the threads were made by a rolling process.

ii) The core microstructure showed mostly austenite grains with some delta ferrite, Figure 65.

2.4.2 Bolt O2

i) Figure 66 shows a general image of the metallographic sample prepared from bolt O2 in as-polished condition. Figure 67 shows the microstructure of the bolt at the threaded section that consisted of austenite grains. The flow lines observed on the threads suggested that the threads were made by a rolling process.

ii) The core microstructure showed mostly austenite grains with some delta ferrite, Figure 68.

2.4.3 Bolt R1

i) Figure 69 shows a general image of the metallographic sample prepared from bolt R1 in as-polished condition. The thread shape at the root was different in reference bolts compared to intact anchor bolts (Bot O1 and O2). As shown in Figure 70 the root shape is not completely curved, and it showed sharp corners at the border of the root and flank.

ii) The flow lines appearance suggested that the threads were made by a rolling process, Figure 70. Microstructure of bolt in the threaded section was an austenitic structure. We observed some folds formed during manufacturing root of the threads as exhibited in Figure 71. The core microstructure showed mostly austenitic structure with some delta ferrite, Figure 72.

ACUREN

2.4.4 Bolt R2

i) Figure 73 shows a general image of the metallographic sample prepared from bolt R1 in as-polished condition. The root shape at the threaded section was not completely curved, and it showed sharp corners, similar to what we observed in Bolt R1, Figure 74.

ii) Flow lines appearance on the threads suggested that the threads were made by a rolling process, Figure 74. We observed some folds formed during manufacturing at the crest and flank of the threads as exhibited in Figure 75. The microstructure of threaded section showed an austenitic structure, Figure 75. The core microstructure exhibited mostly austenite grains with some delta ferrite, Figure 76.

2.4.5 Bolt R3

i) Figure 77 shows a general image of the metallographic sample prepared from bolt R3 in as-polished condition. The root shape at the threaded section was not completely curved, and it showed sharp corners, similar to what we observed in Bolt R1 and R2, Figure 78.

ii) Flow lines appearance on the threads suggested that the threads were made by a rolling process, Figure 78. We observed some folds at the crest of the threads, Figure 79. The microstructure of threaded section showed an austenitic structure. The core microstructure exhibited mostly austenite grains with some delta ferrite, Figure 80.

2.4.6 Bolt R4

i) Figure 81 shows a general image of the metallographic sample prepared from bolt R4 in as-polished condition. The root shape at the threaded section was not completely curved, and it showed sharp corners, similar to what we observed in Bolt R1, R2, and R3, Figure 82.

ii) The flow line shape on the threads suggested that the threads were made by a rolling process, Figure 82. The microstructure of threaded section showed an austenitic structure. The core microstructure exhibited mostly austenite grains with some delta ferrite, Figure 83.

ACUREN

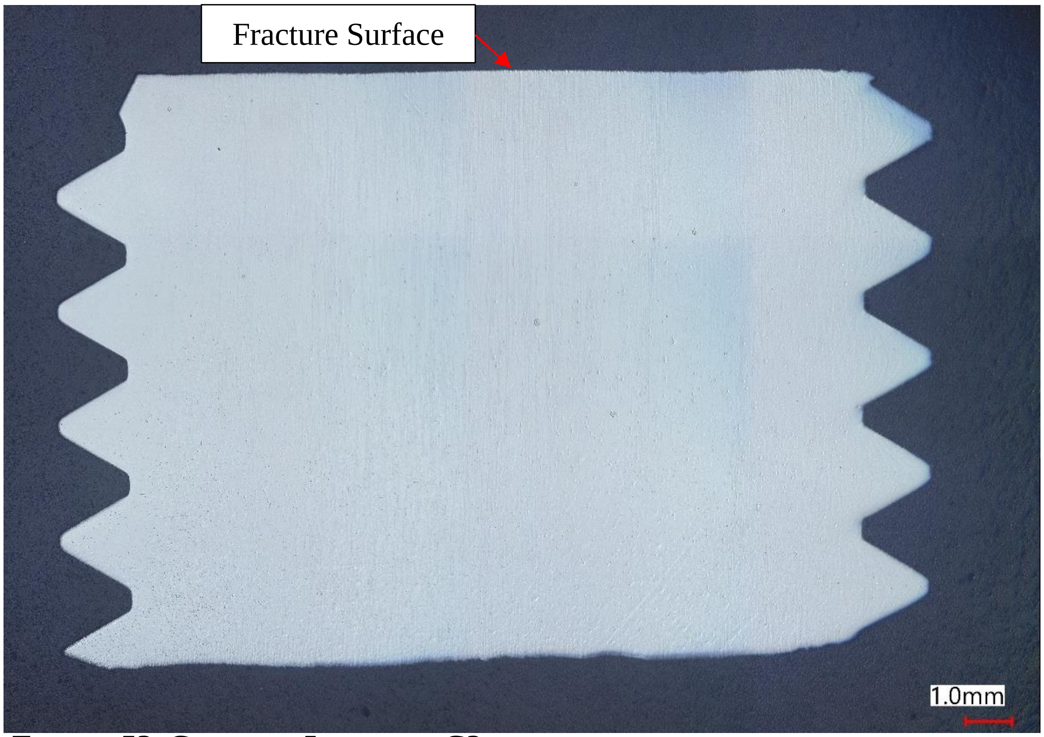

FIGURE 53. GENERAL IMAGE OF C2 METALLOGRAPHIC SAMPLE, AS-POLISHED

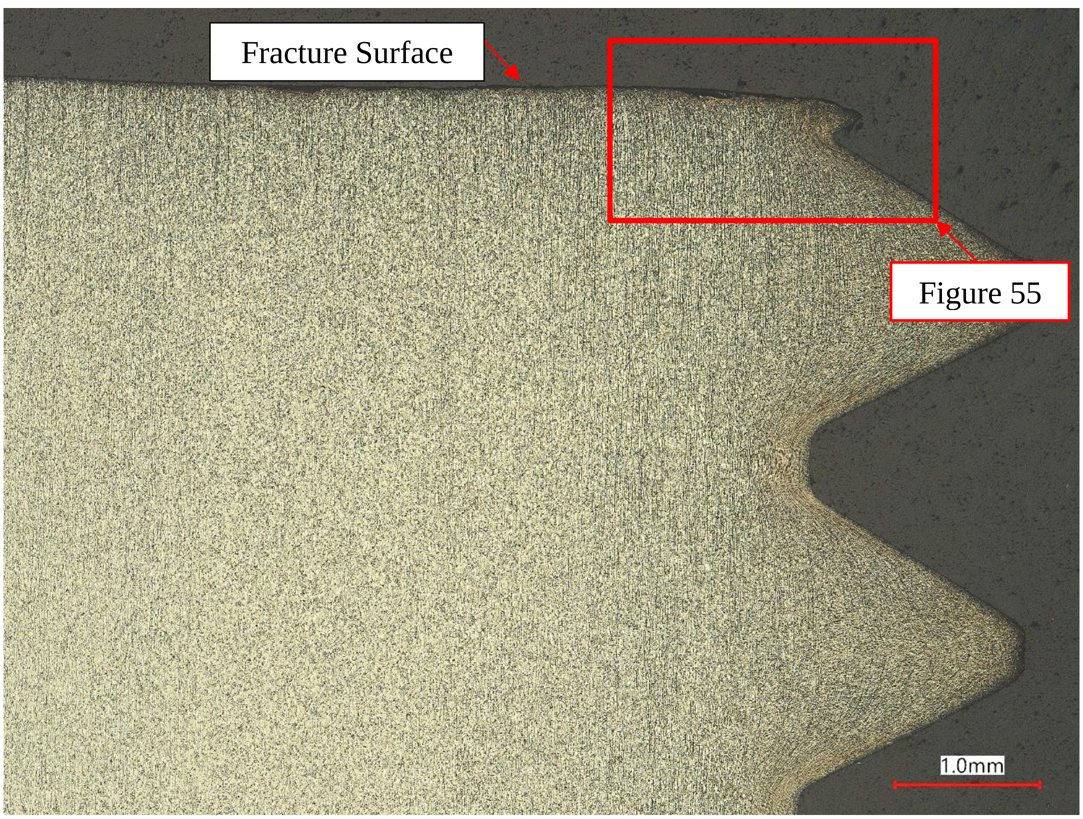

FIGURE 54. LOW MAGNIFICATION OF THREADS CLOSE TO CRACK INITIATION AREA AT 6 O'CLOCK REGION, BOLT C2

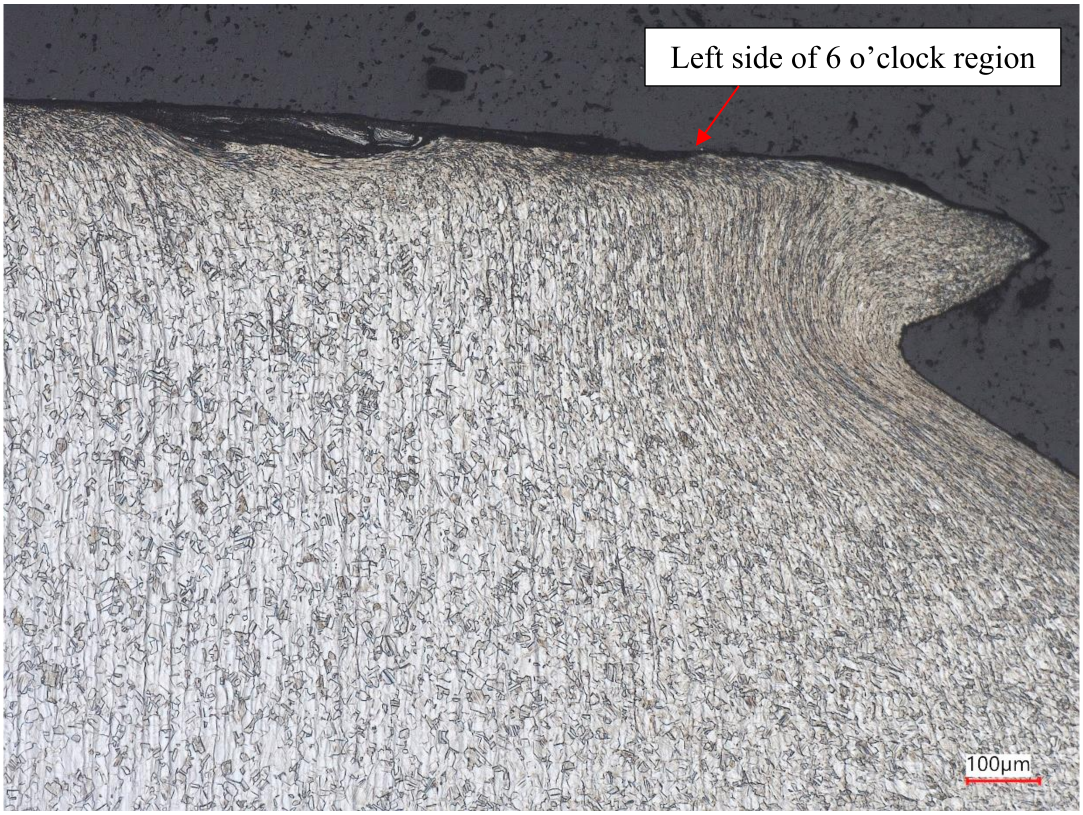

FIGURE 55. DEFORMATION OBSERVED IN AREAS CLOSE TO THE FRACTURE SURFACE, BOLT C2

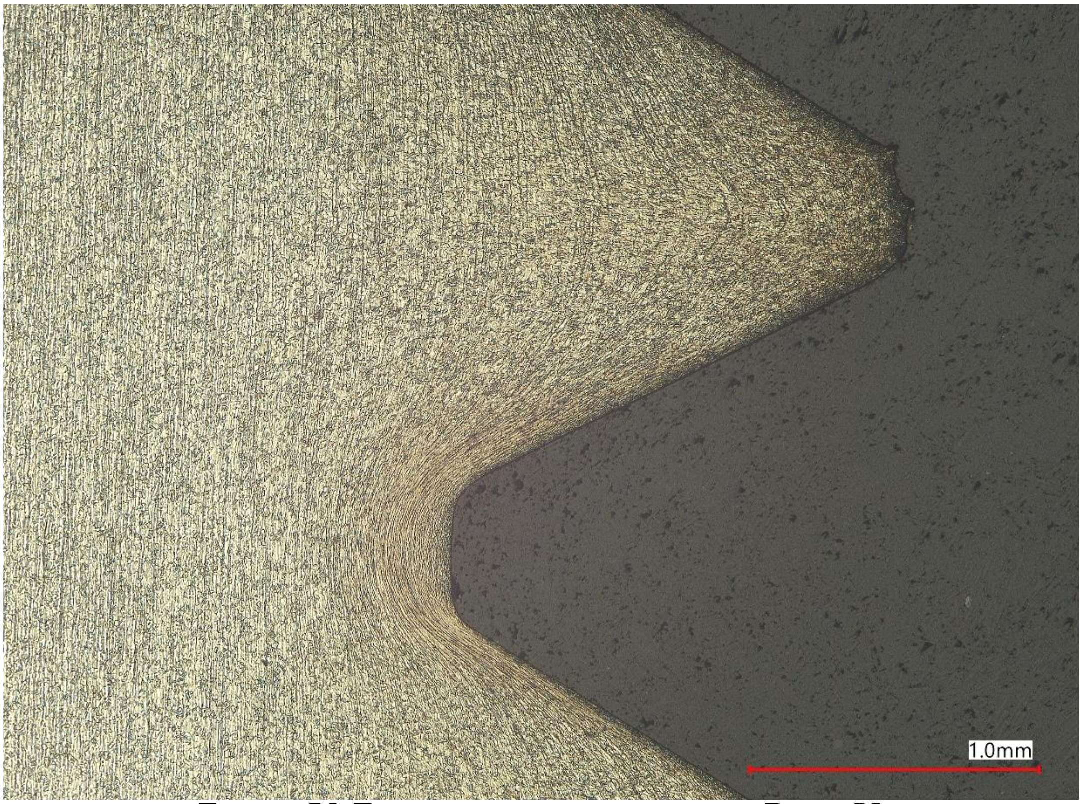

FIGURE 56. FLOW LINES ON THE THREADS, BOLT C2

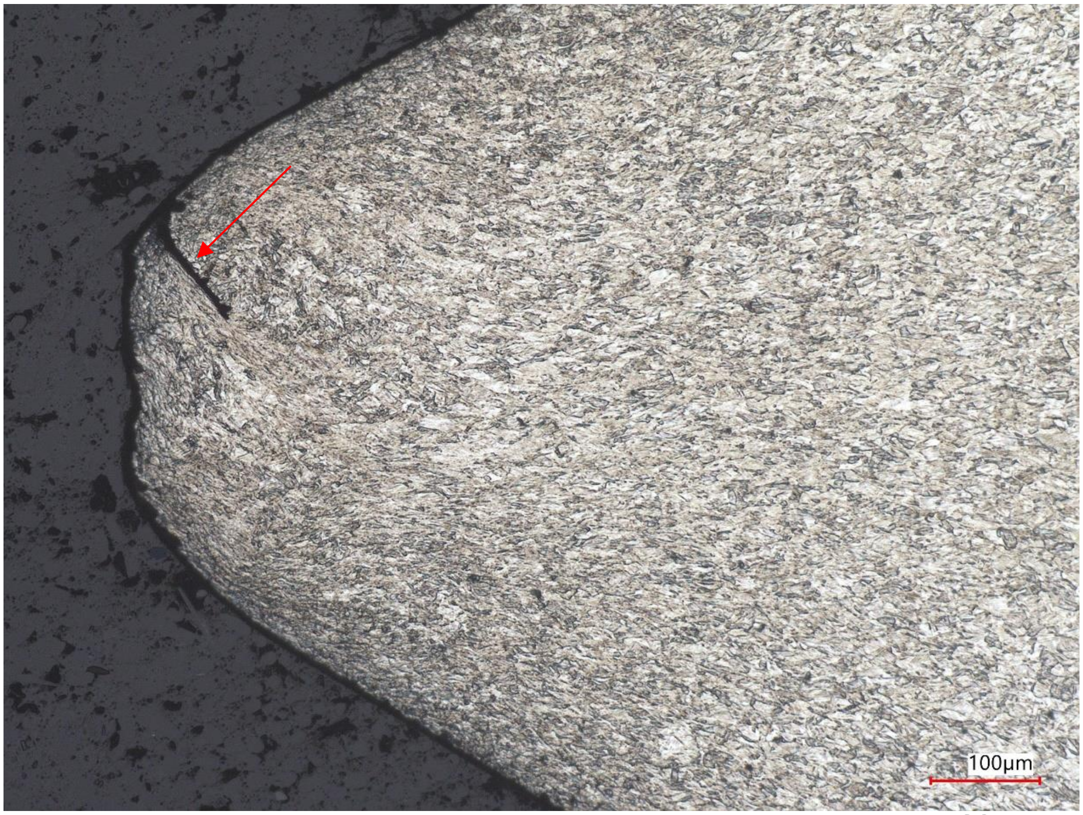

FIGURE 57. FOLDS OBSERVED AT THE CREST OF THE THREAD, BOLT C2

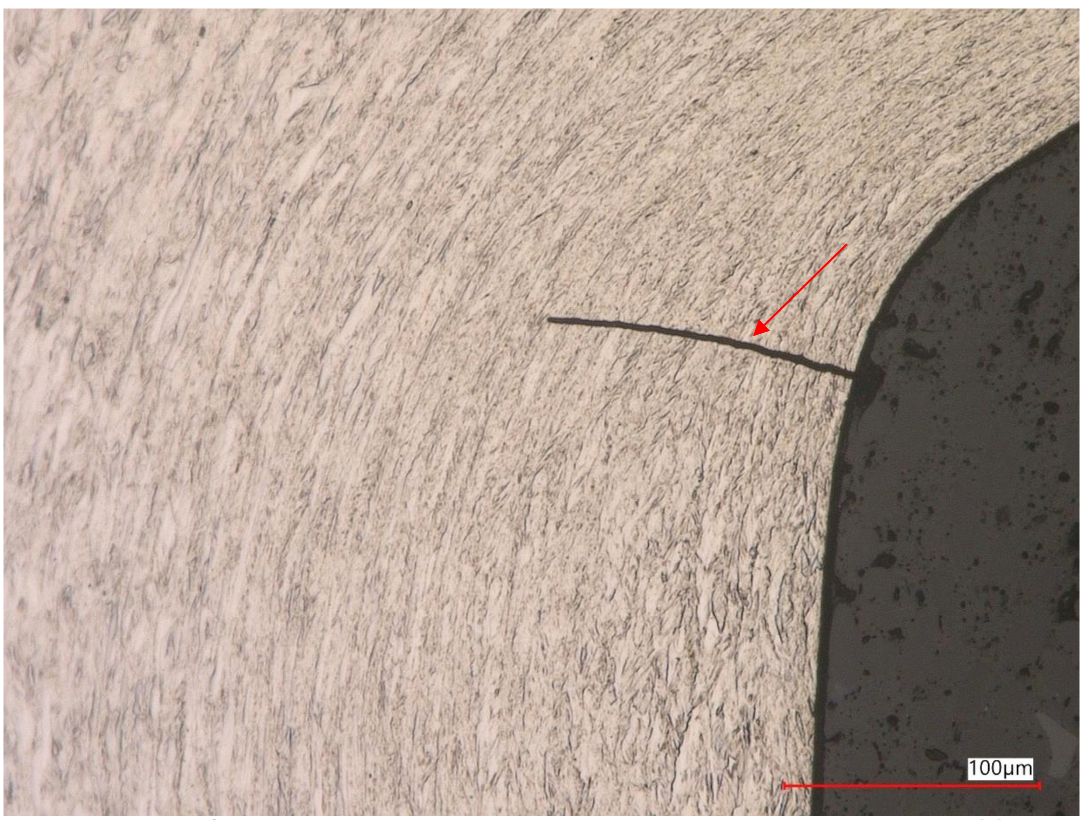

FIGURE 58. CRACK OBSERVED AT THE ROOT OF THE THREAD, BOLT C2

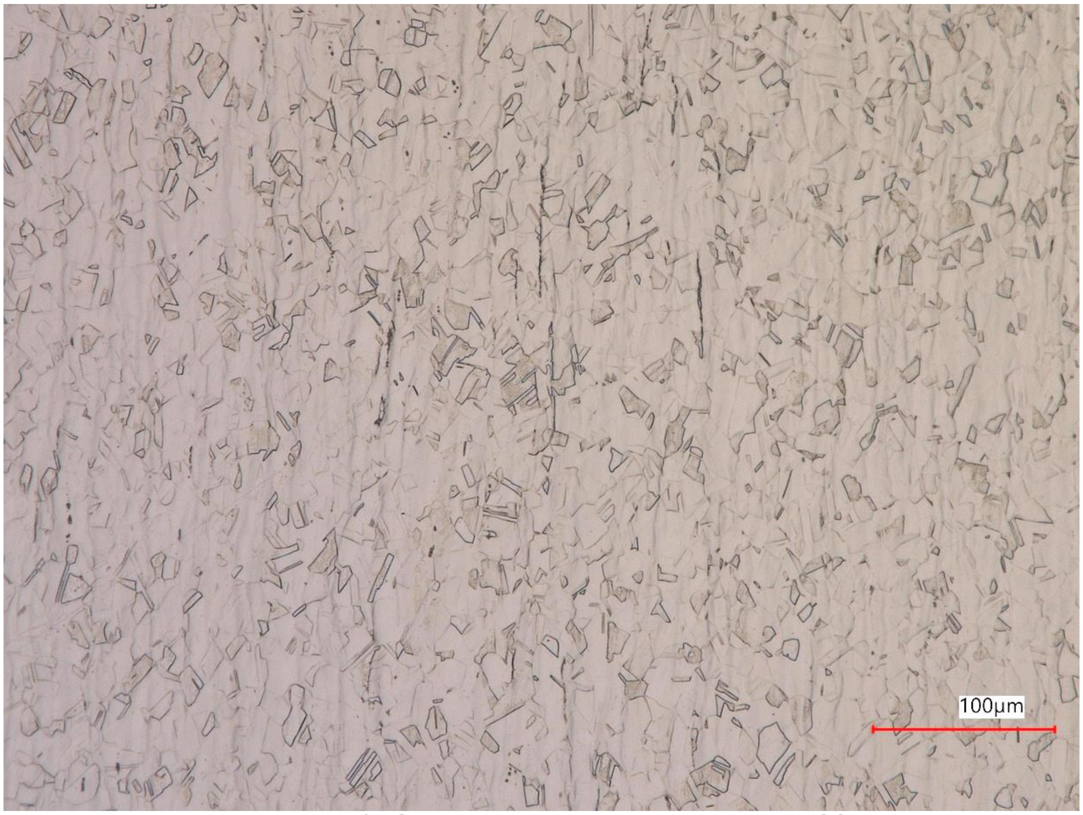

FIGURE 59. CORE MICROSTRUCTURE, BOLT C2

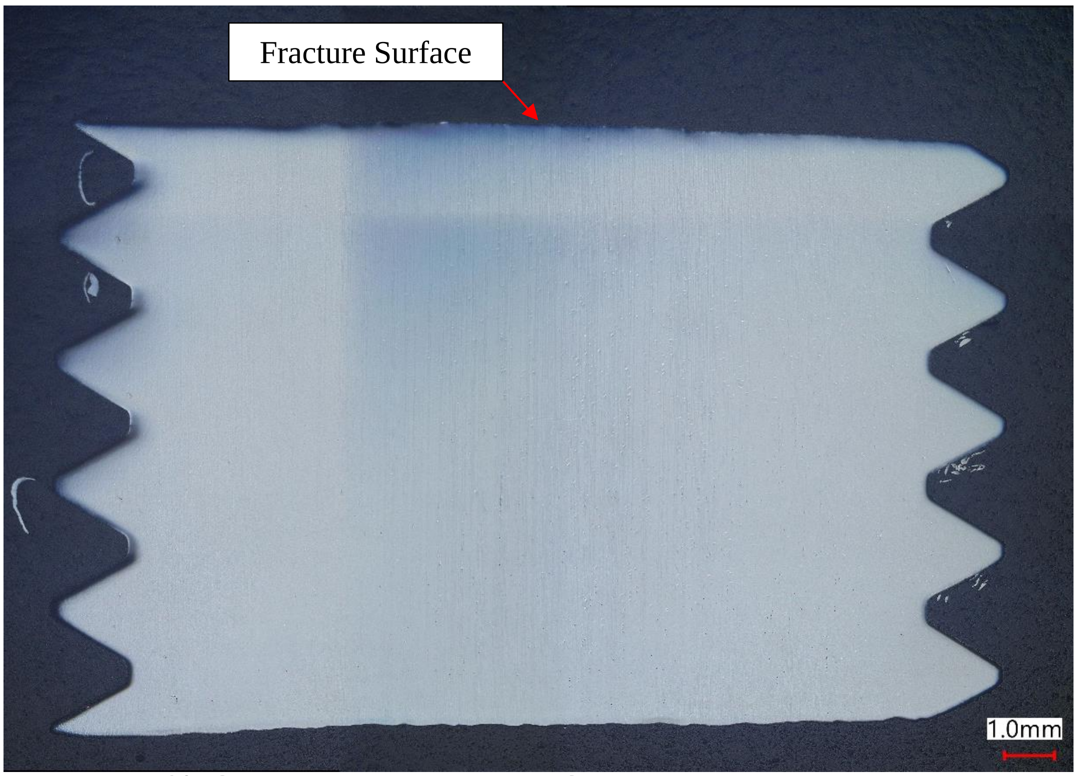

FIGURE 60. GENERAL IMAGE OF BOLT C5 IN AS-POLISHED CONDITION

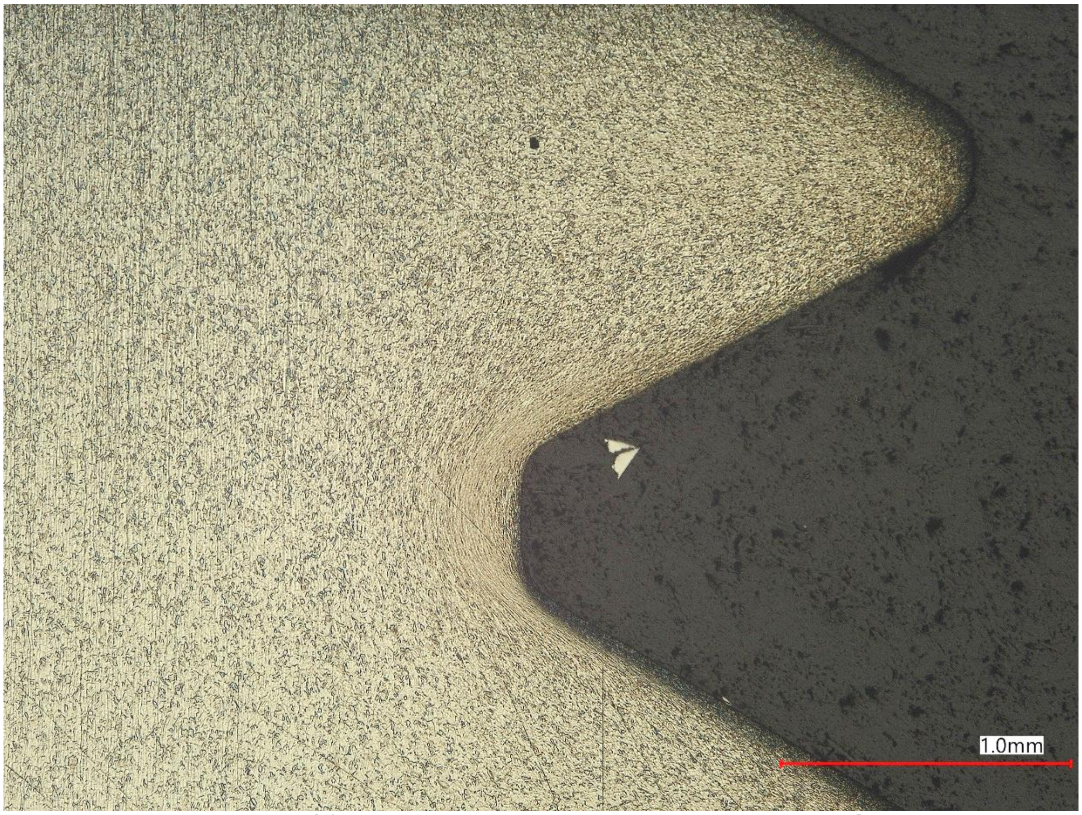

FIGURE 61. FLOW LINES ON THE THREADS, BOLT C5

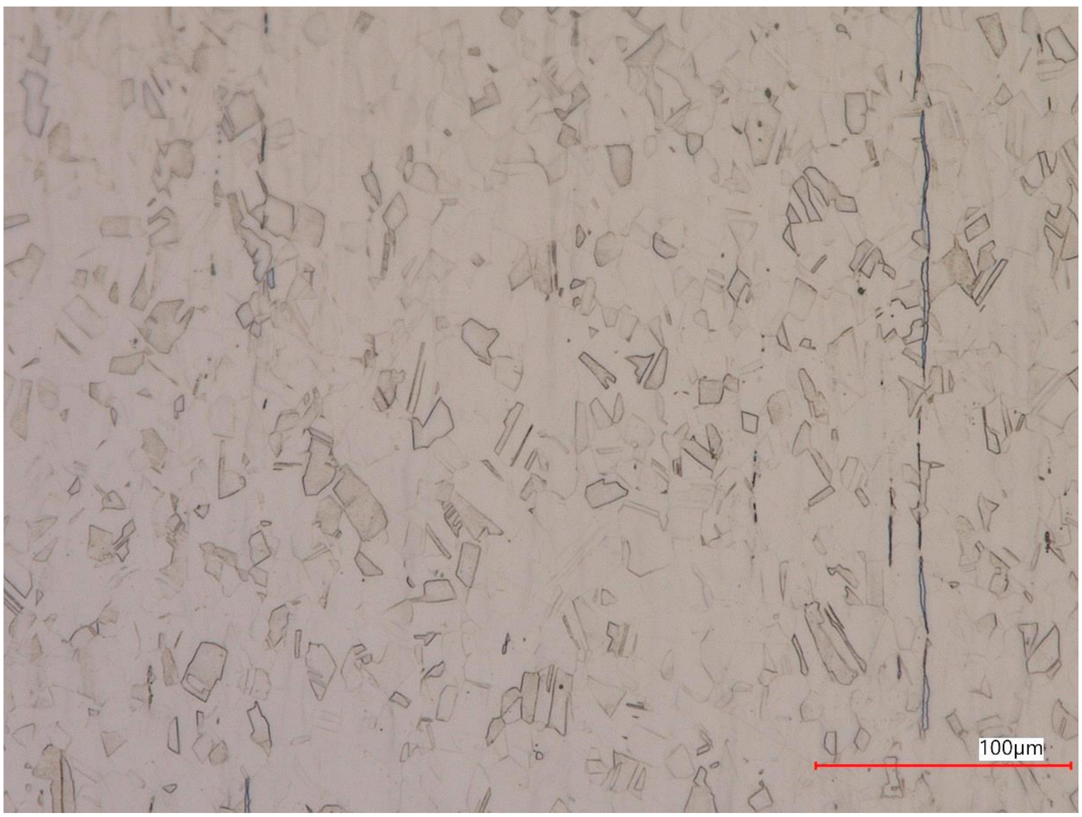

FIGURE 62. CORE MICROSTRUCTURE OF BOLT C5

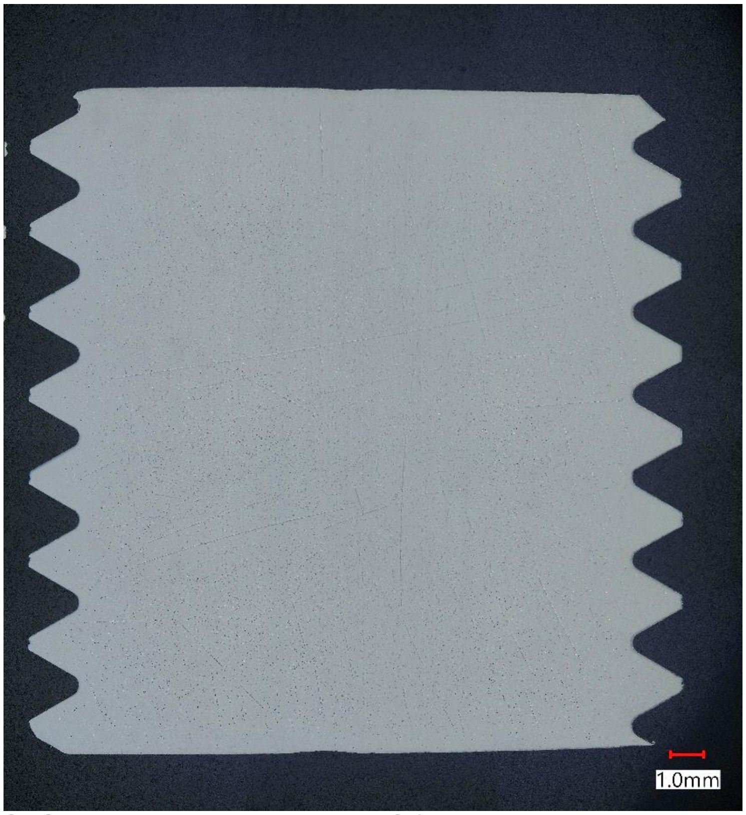

FIGURE 63. GENERAL IMAGE OF BOLT O1 IN AS-POLISHED CONDITION

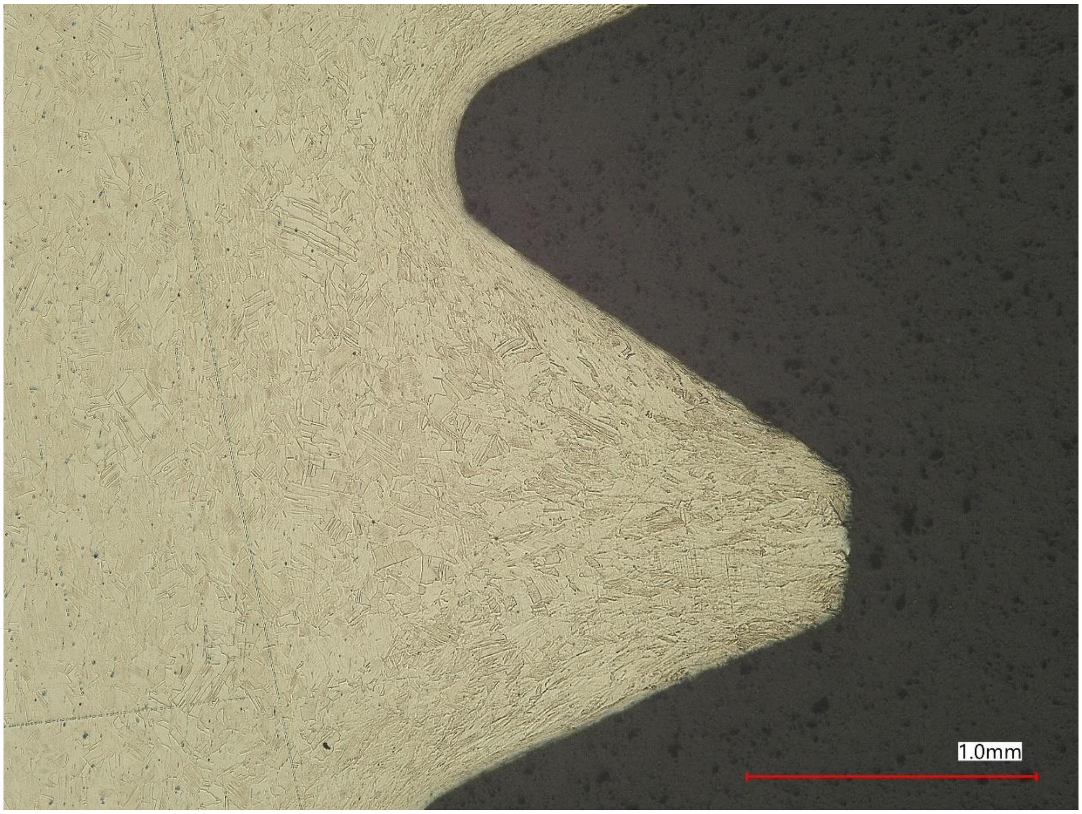

FIGURE 64. MICROSTRUCTURE OF THREADS, BOLT O1

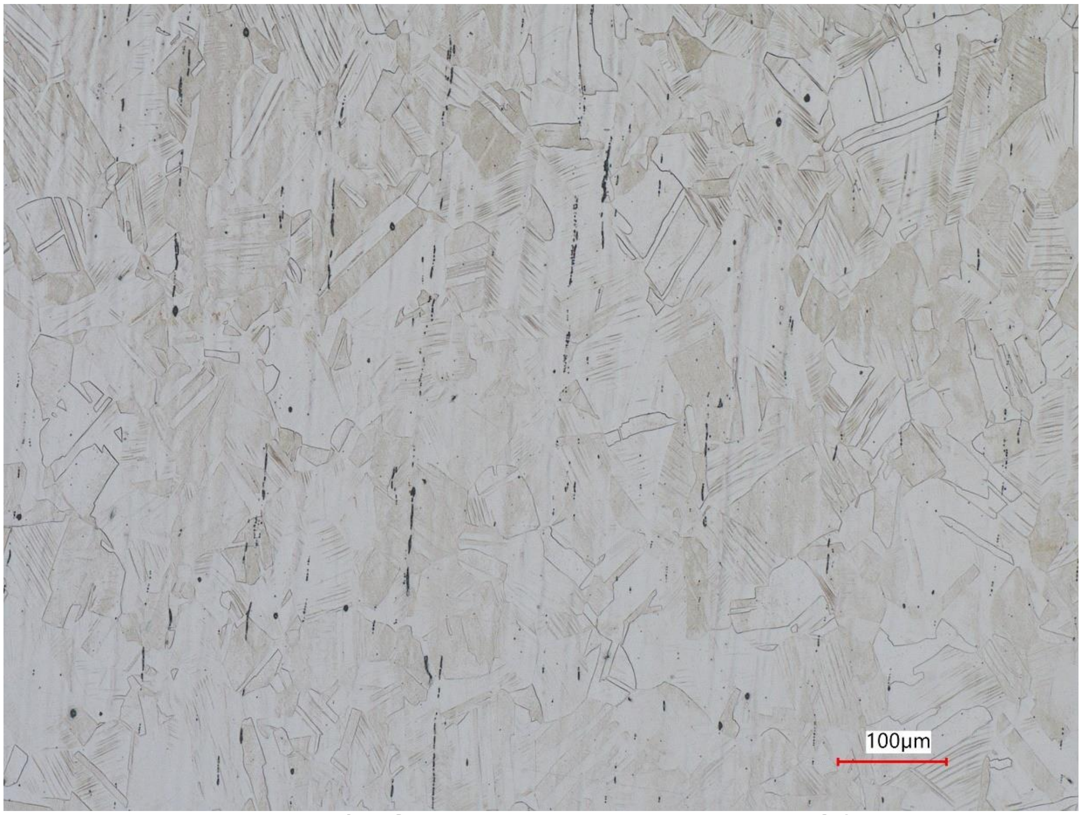

FIGURE 65. CORE MICROSTRUCTURE, BOLT O1

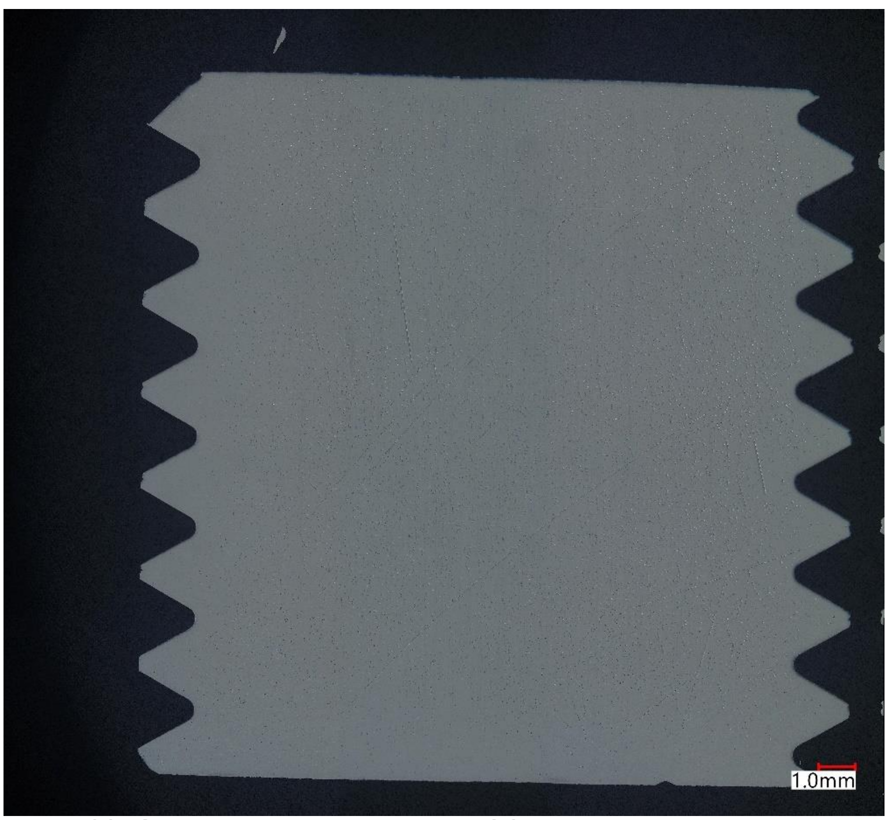

FIGURE 66. GENERAL IMAGE OF BOLT O2 IN AS-POLISHED CONDITION

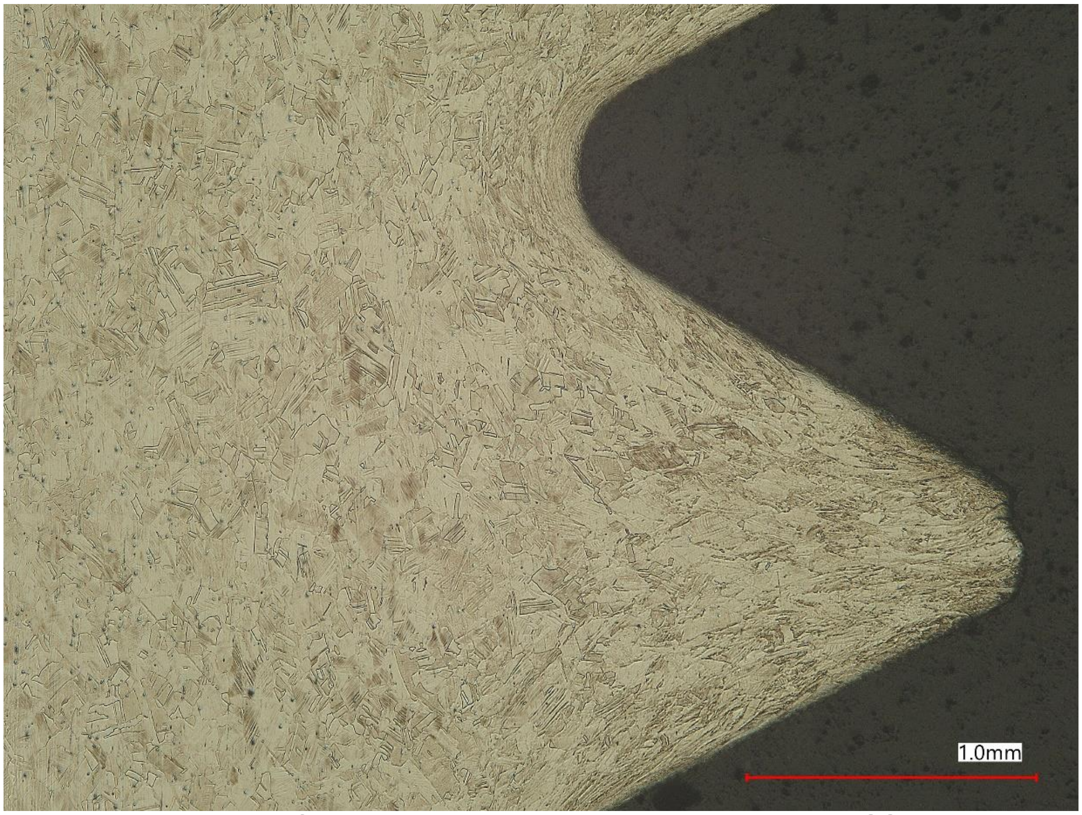

FIGURE 67. MICROSTRUCTURE OF THREADS, BOLT O2

FIGURE 68. CORE MICROSTRUCTURE OF BOLT O2

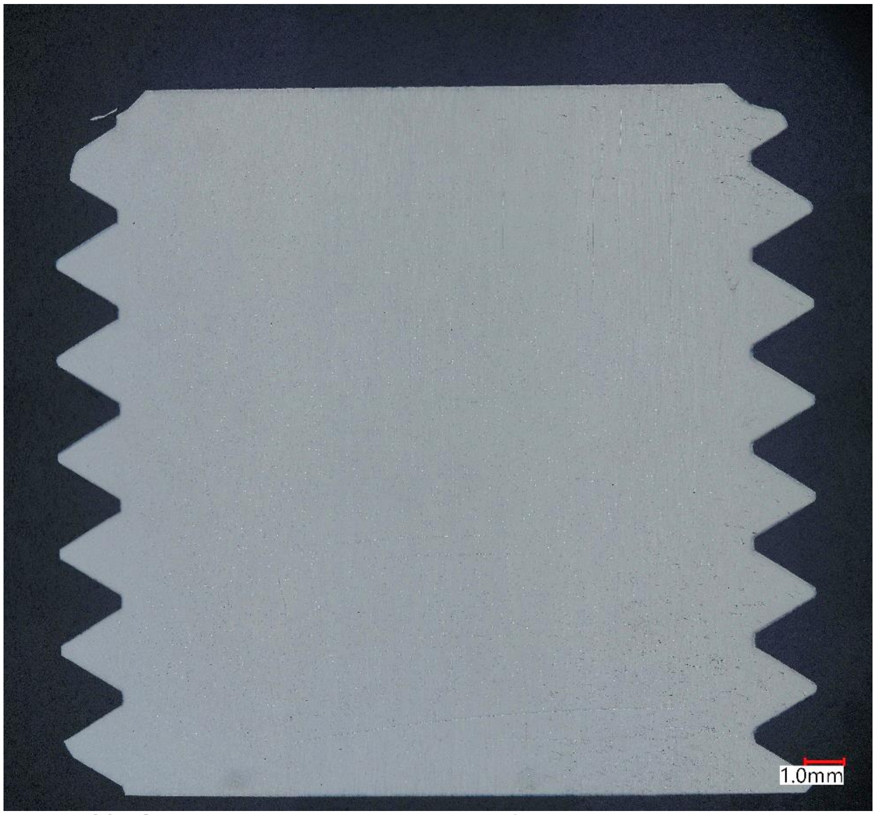

FIGURE 69. GENERAL IMAGE OF BOLT R1 IN AS-POLISHED CONDITION

FIGURE 70. ROOT SHAPE OF THREADS IN BOLT R1, SHARP CORNER

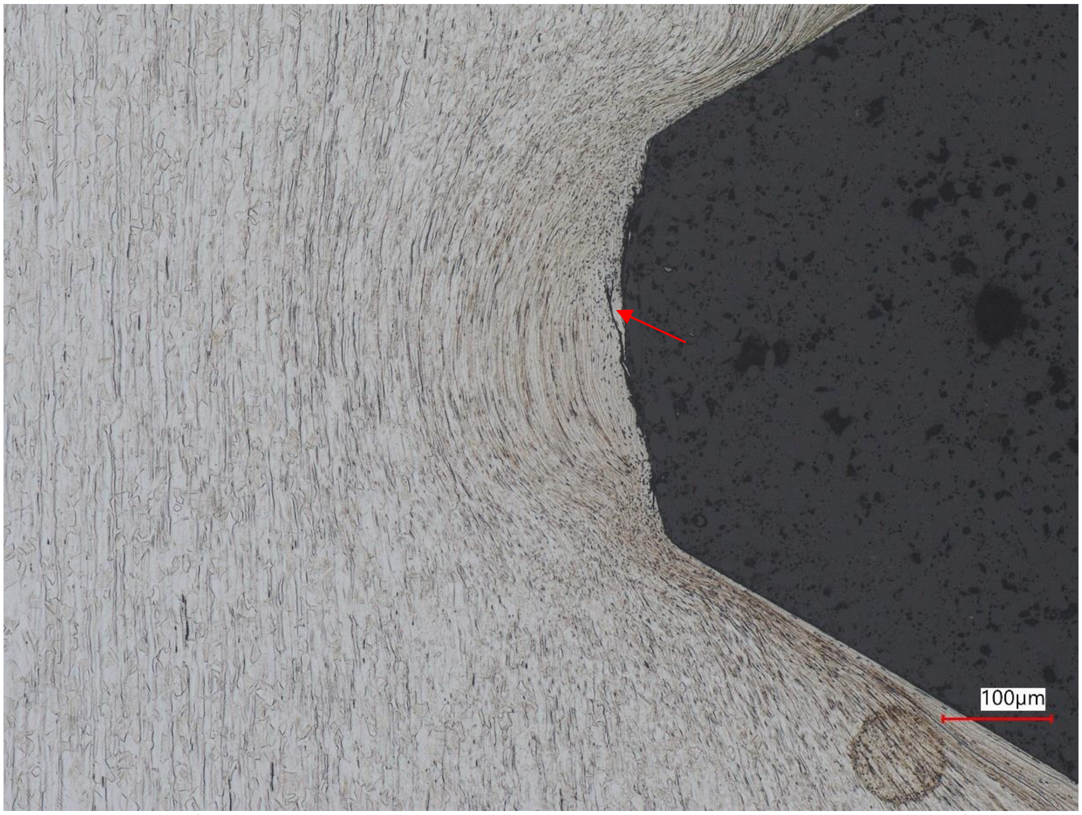

FIGURE 71. FOLD OBSERVED AT THE ROOT OF THE THREAD, BOLT R1

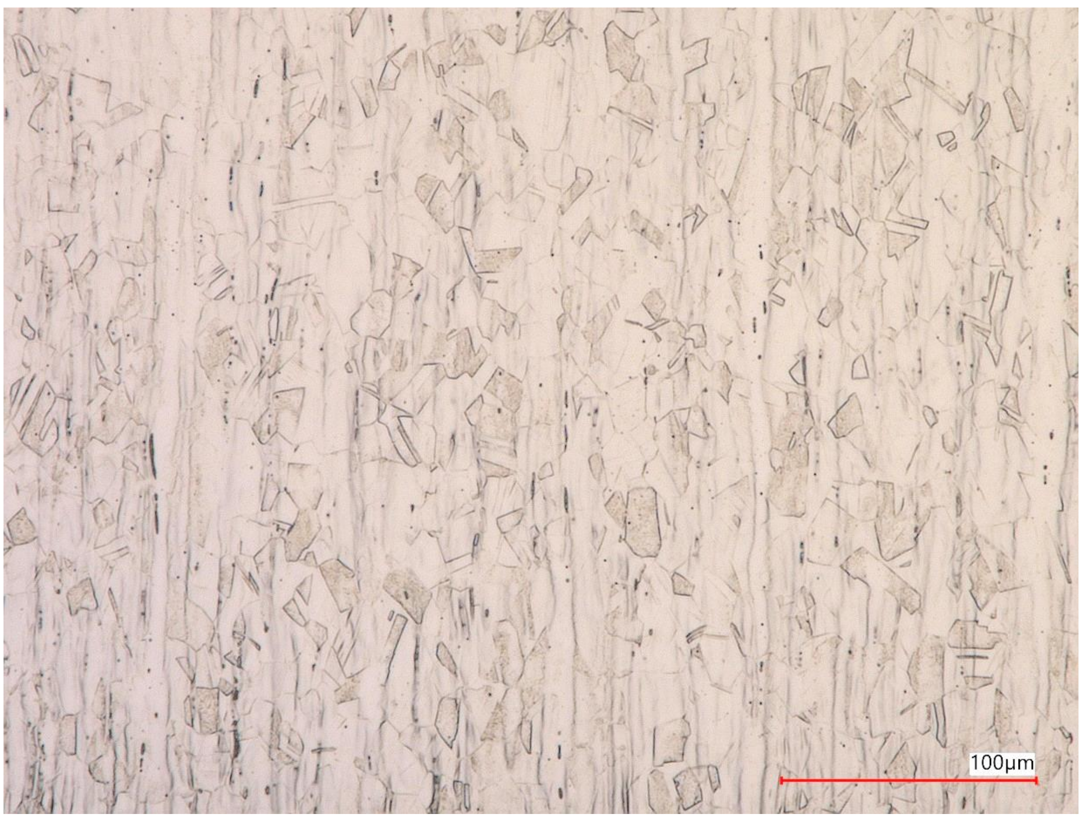

FIGURE 72. CORE MICROSTRUCTURE OF BOLT R1

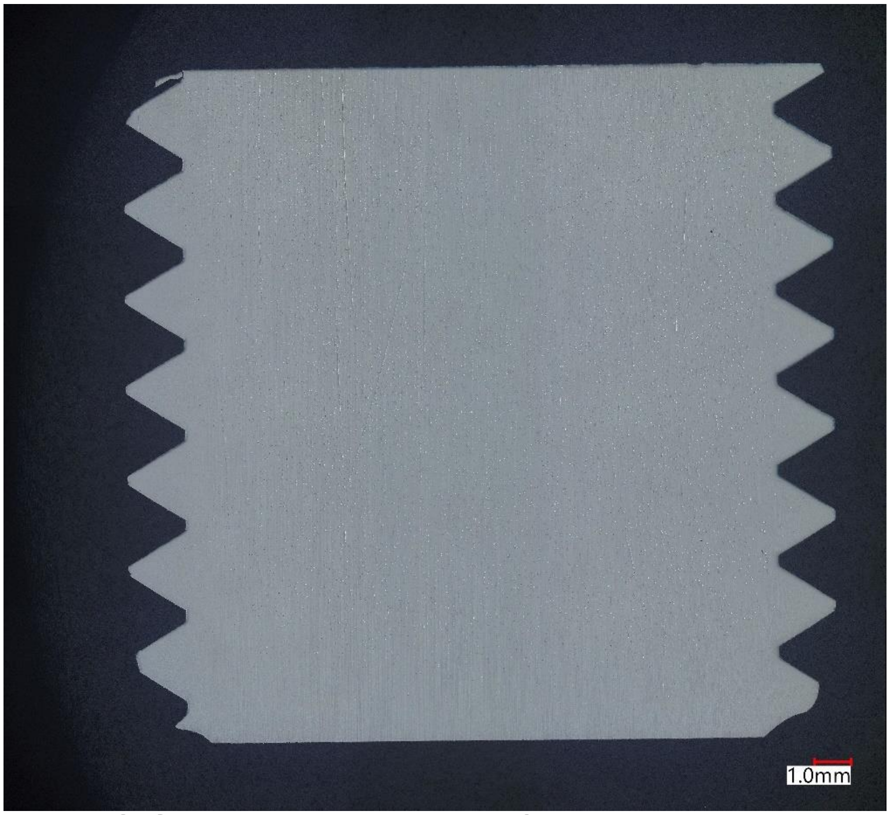

FIGURE 73. GENERAL IMAGE OF BOLT R2 IN AS-POLISHED CONDITION

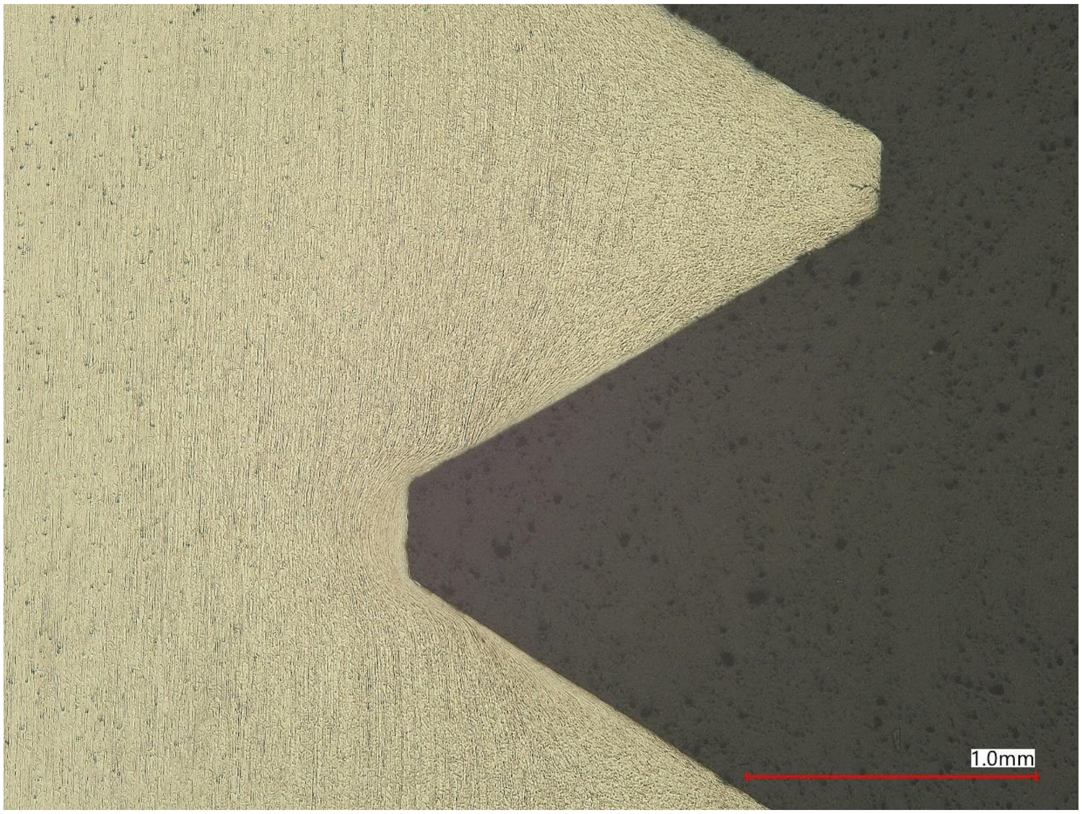

FIGURE 74. FLOW LINES ON THREADS, BOLT R2

FIGURE 75. FOLDS OBSERVED AT THE CREST AND FLANK OF THREADS, BOLT R2

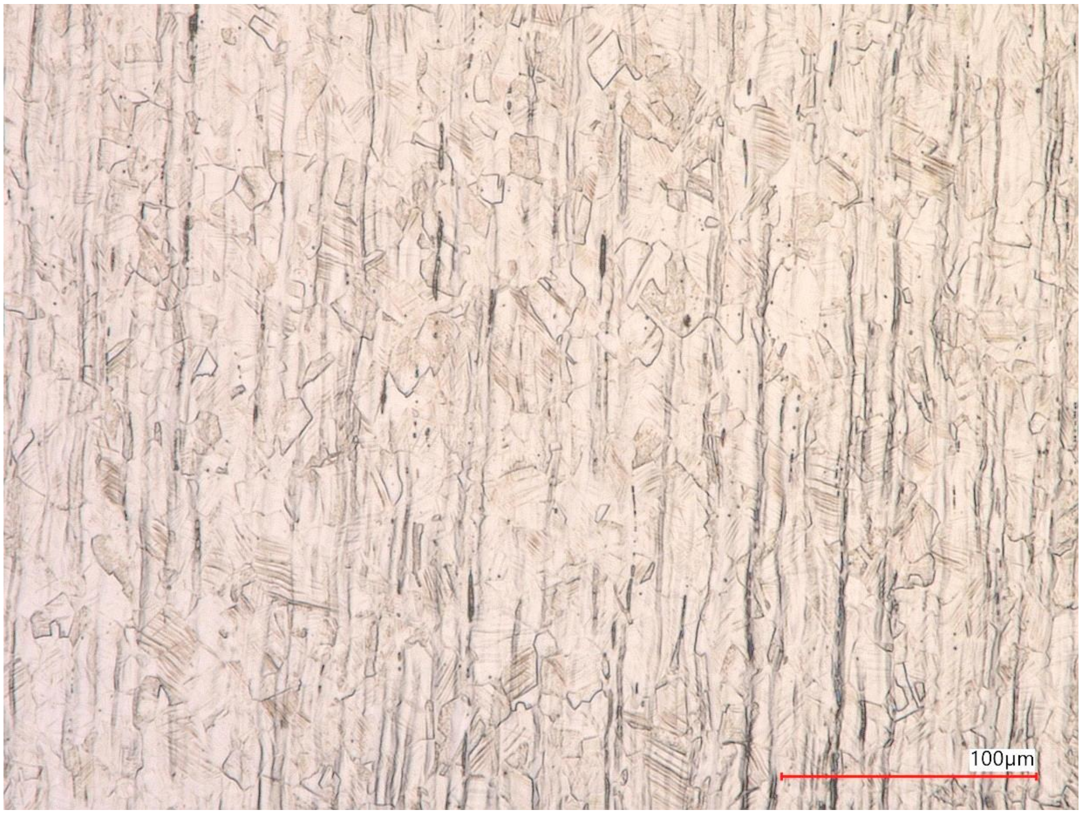

FIGURE 76. CORE MICROSTRUCTURE OF BOLT R2

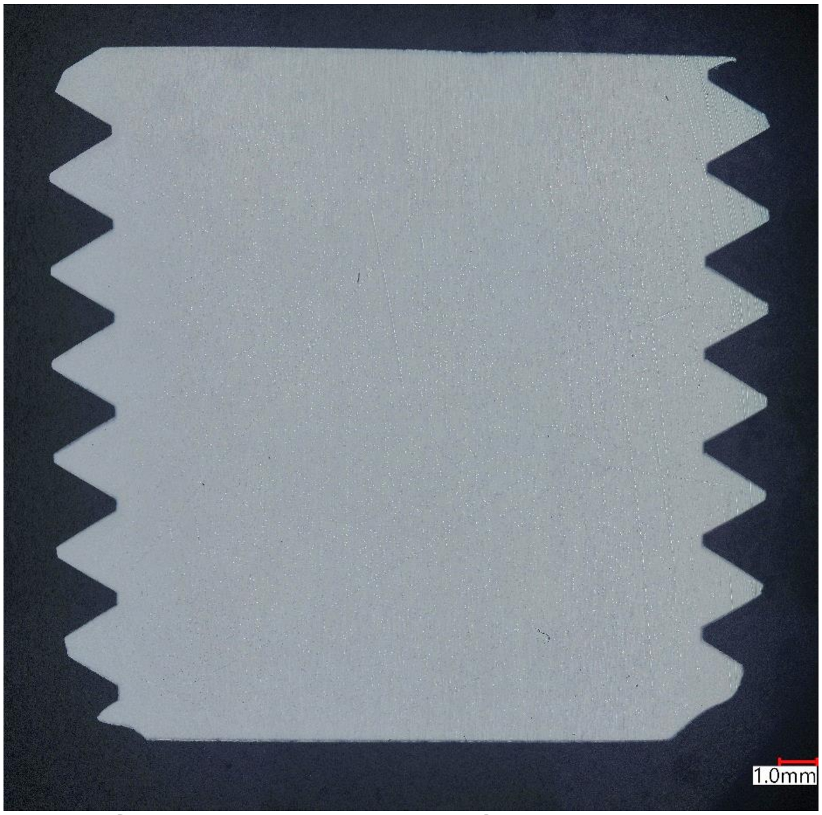

FIGURE 77. GENERAL IMAGE OF BOLT R3 IN AS-POLISHED CONDITION

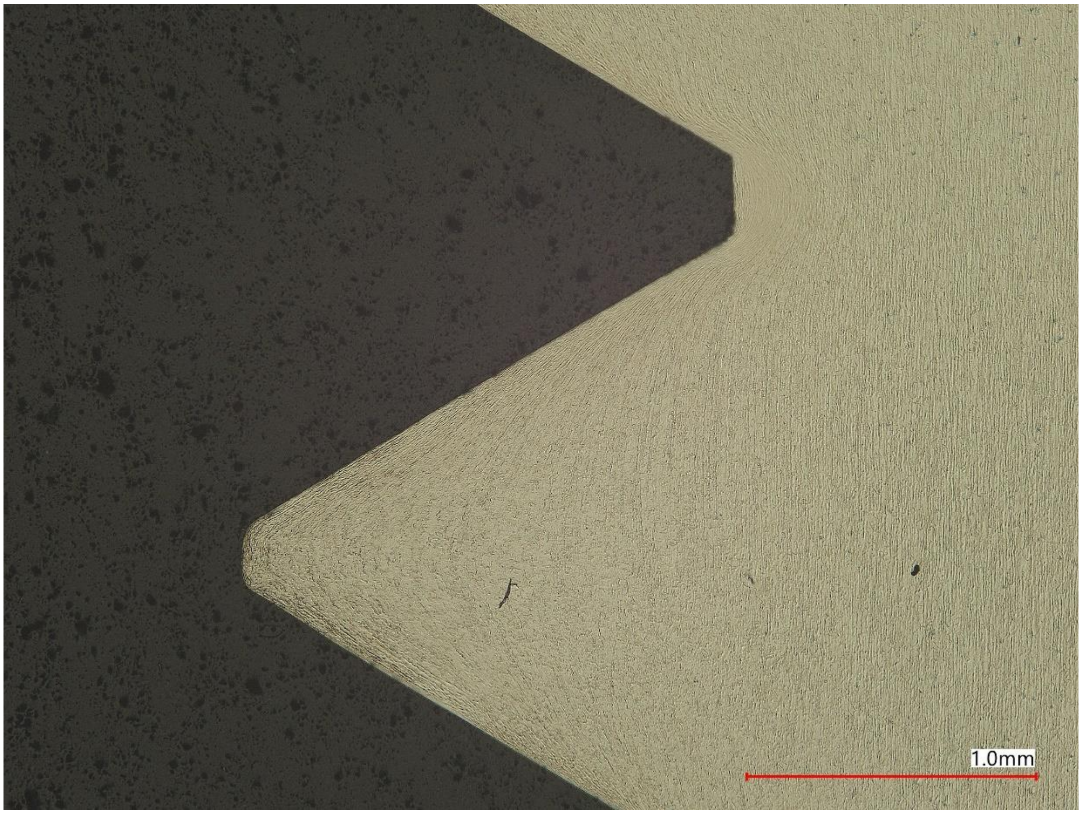

FIGURE 78. FLOW LINES ON THREADS, BOLT R3

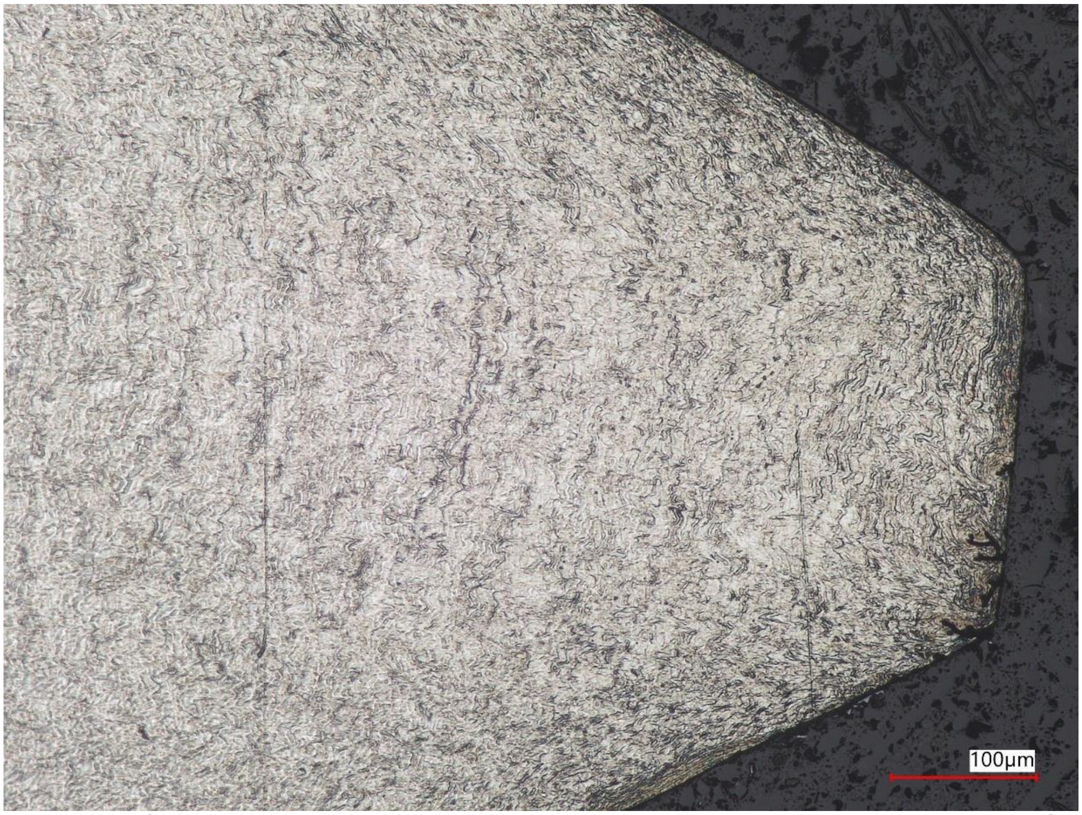

FIGURE 79. FOLDS OBSERVED AT THE CREST AND FLANK OF THREADS, BOLT R3

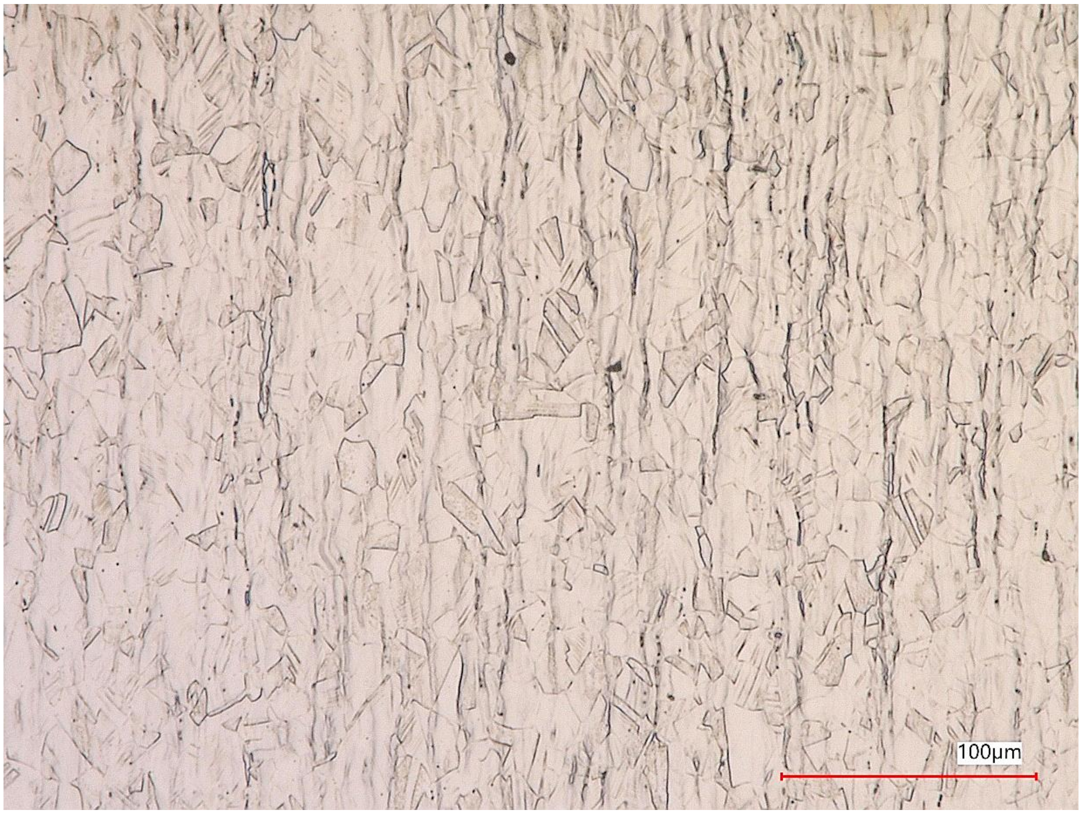

FIGURE 80. CORE MICROSTRUCTURE OF BOLT R3

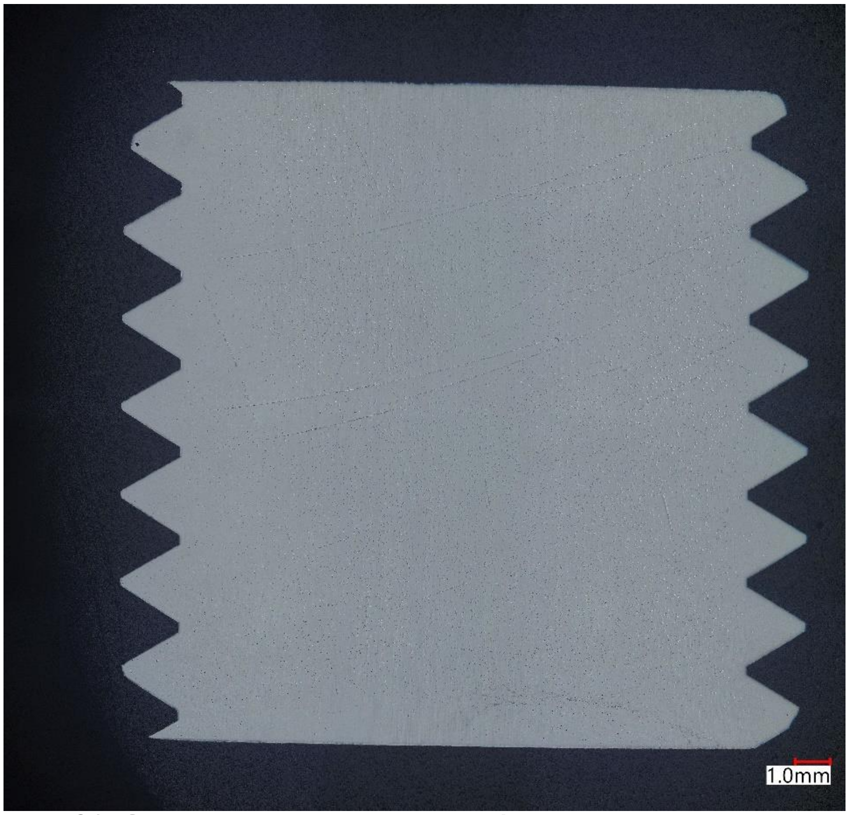

FIGURE 81. GENERAL IMAGE OF BOLT R4 IN AS-POLISHED CONDITION

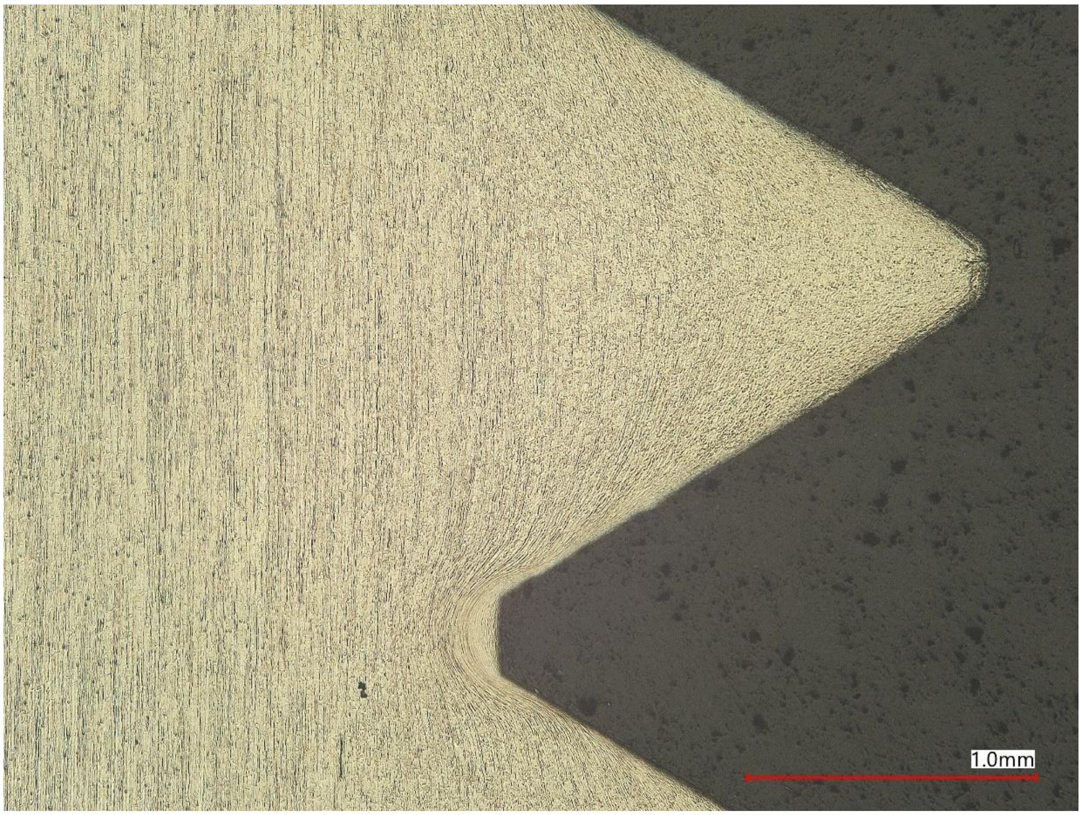

FIGURE 82. FLOW LINES ON THREADS, BOLT R4

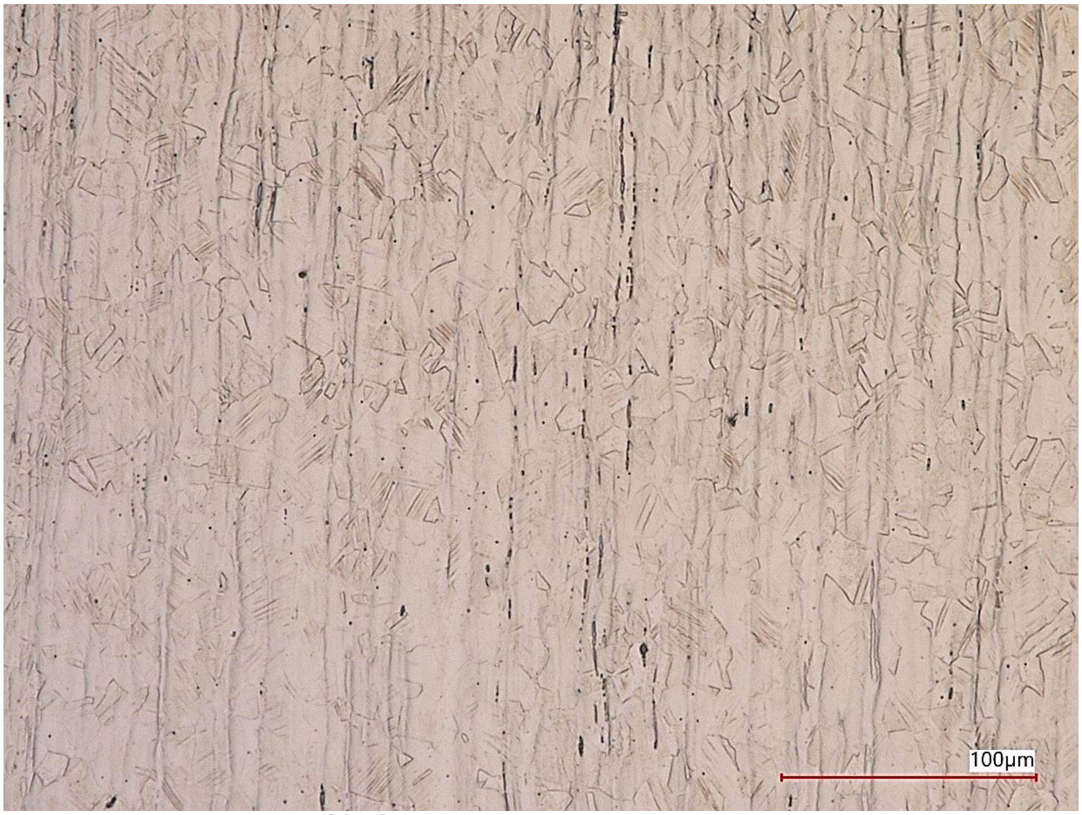

FIGURE 83. CORE MICROSTRUCTURE OF BOLT R4

2.5 TENSILE TESTING

Each submitted anchor bolt was subjected to a full-size stud tensile test in accordance with ISO 898-1. The exposed length between grips measured 2” in length during the test for C5 and for all other bolts, the exposed length between measured 2.5” in length. The nominal stress area of M20 x 2.5” thread used for tensile strength was 245mm^2. The results can be found in Table 1 below.

TABLE 1. TENSILE TEST RESULTS

Sample ID	Max Load (N)	Tensile Strength (MPa)	Fracture Location
C2	188 605	770	Exposed threads
C5	188 160	768	
O1	202 839	828	Exposed threads
O2	202839	828	
R1	208 622	852	Exposed threads
R2	217 963	890	
R3	222 856	910	
R4	218 408	891	

According to the Hilti data sheet for HSL-GR stainless steel heavy duty anchors, the nominal tensile strength for M20 anchor size should be 700 MPa. The UTS of the original and reference bolts conformed to the mechanical requirements of Hilti data sheet for HSL-GR stainless steel heavy duty anchors. Even after service, the fractured bolts met the strength requirements for M20 anchor bolts.

2.6 HARDNESS

Each submitted bolt was subjected to Rockwell hardness testing according to ISO 898-1:2013(E) and ISO 6508-1(2016). A transverse section was cut at one diameter length from the end of each bolt and prepared by grinding at 320 grit. Hardness readings were taken at four locations at the half radius position on the prepared surface. The results can be found in Table 2 below.

TABLE 2. HARDNESS TEST RESULTS

Sample ID	Hardness (HRC)	Average (HRC)
C2	25, 25, 23, 24	24
C5	24, 24, 24, 22	24
O1	25, 26, 27, 28	26
O2	29, 28, 26, 26	27
R1	30, 28, 28, 27	28
R2	29, 31, 32, 30	30
R3	32, 32, 31, 31	32
R4	29, 31, 31, 30	30

2.7 IMPACT TESTING

A longitudinal section was cut from each Reference bolt and three charpy impact specimens were machined for testing in accordance with ASTM E23-23a. The dimensions of the impact specimens measured 10 mm x 10 mm x 55 mm. Testing was conducted at -25ºC. The results can be found in Table 3 below.

TABLE 3. IMPACT TESTING RESULTS

Sample ID	Absorbed Energy	Specimen Number			Average
		1	2	3	
R1	(ft·lbf)	149	148	158	152
	(Joule) (1)	202	201	214	206
R2	(ft·lbf)	151	135	141	142
	(Joule) (1)	205	183	191	193
R3	(ft·lbf)	137	139	129	135
	(Joule) (1)	186	188	175	183
R4	(ft·lbf)	132	147	129	136
	(Joule) (1)	179	199	175	184

Note 1: Absorbed energy values in Joules were converted from values in ft.lbf

We have observed very high absorption energy values, which is typical for this type bolts.

2.8 CHEMICAL ANALYSIS

The specimens used for hardness testing were also subjected to chemical analysis using optical emission spectroscopy (OES). Testing was conducted according to ASTM E415-21 and the results were compared to ASTM F593-22[1], Alloy 316L material and ISO 3506-1:2009[2], Grade A4. The results can be observed in Table 4 and Table 5.

The chemical analysis of broken bolts (C2 and C5) conformed to the chemical requirements of ASTM F593-22, Alloy 316L material and ISO 3506-1:2009, Grade A4. Also, chemical analysis of reference bolts conformed to the chemical requirements of both standards. The chemical composition of original bolts (O1 and O2) was close but did not meet the chemical requirements of ASTM F593-22, Alloy 316L material and ISO 3506-1:2009, Grade A4.

TABLE 4. CHEMICAL ANALYSIS RESULTS

Element	Results (wt%)				ASTM F593-22 Alloy 316L	ISO 3506-1:2009 Grade A4
	C2	C5	O1	O2		
Fe	68.40	68.50	68.20	68.30	Remainder	Remainder
C	0.027	0.025	0.029	0.030	0.03 Max	0.08 Max
Si	0.37	0.35	0.38	0.40	1.00 Max	1 Max
Mn	1.10	1.09	1.77	1.76	2.00 Max	2 Max
P	0.034	0.038	0.027	0.026	0.045 Max	0.045 Max
S	< 0.00050	< 0.00050	0.020	0.019	0.030 Max	0.03 Max
Cr	16.58	16.50	16.77	16.72	16.0-18.0	16 – 18.5
Mo	2.08	2.08	2.05	2.05	2.00-3.00	2 – 3
Ni	10.13	10.21	9.91	9.92	10.0-14.0	10 – 15
Al	0.002	0.001	0.008	0.008	--	--
Co	0.21	0.22	0.13	0.13	--	--
Cu	0.80	0.78	0.41	0.41	--	4 Max
Nb	0.02	0.02	0.02	0.02	--	--
Ti	0.003	0.003	0.003	0.003	--	--
V	0.08	0.07	0.08	0.08	--	--

[1] Standard specification for stainless steel bolts, Hex cap Screws, and Studs
[2] Mechanical properties of corrosion-resistant stainless steel fasteners, Part1: Bolts, screws and studs

TABLE 5. CHEMICAL ANALYSIS RESULTS

Element	Results (wt%)				ASTM F593-22 Alloy 316L	ISO 3506-1:2009 Grade A4
	R1	R2	R3	R4		
Fe	69.50	69.40	Remainder	69.40	Remainder	Remainder
C	0.022	0.024	0.08 Max	0.023	0.03 Max	0.08 Max
Si	0.38	0.38	1 Max	0.37	1.00 Max	1 Max
Mn	0.94	0.95	2 Max	0.96	2.00 Max	2 Max
P	0.036	0.038	0.045 Max	0.038	0.045 Max	0.045 Max
S	0.008	0.009	0.03 Max	0.009	0.030 Max	0.03 Max
Cr	16.13	16.23	16 – 18.5	16.25	16.0-18.0	16 – 18.5
Mo	2.05	2.03	2 – 3	2.02	2.00-3.00	2 – 3
Ni	10.08	10.09	10 – 15	10.03	10.0-14.0	10 – 15
Al	< 0.0010	< 0.0010	--	< 0.0010	--	--
Co	0.27	0.27	--	0.27	--	--
Cu	0.36	0.36	4 Max	0.36	--	4 Max
Nb	0.01	0.01	--	0.01	--	--
Ti	0.002	0.002	--	0.002	--	--
V	0.07	0.08	--	0.08	--	

3.0 DISCUSSION

Fracture surface of Bolt C5 was completely compromised, due to relative motion of the mating faces removing all the crack features. However, macro appearance of the bolt fracture surface was similar to Bolt C2. Fracture surface of Bolt C2 was also compromised, however, it was possible to gather information from the areas with fracture features. Bolts fractured as a result of fatigue crack initiation and propagation. Fatigue crack initiated at the thread roots. Loading exerted on the bolts were tension-tension or unidirectional, or both. Crack propagated through the cross section. Appearance of the remnants of fracture features suggested there was severe stress concentration, and the applied nominal stresses were low.

Threads will simply act as stress concentrators. In addition, the folds and microcracks observed on the threads also acted as additional stress concentration sites. Ratchet marks corresponded with these folds/microcracks in some crack initiation sites (see Figure 31 and Figure 32). Those observations suggest, even though the nominal stresses were low, stress concentration at roots, created stresses above the design stress. Of course, folds/microcracks contributed highly intensifying the stress concentration on the thread roots.

We observed two different types of thread roots, round thread roots, and thread roots with sharp corners. Sharp corners are additional stress concentrators. Figure 58 is an example of fatigue crack initiation at the corner of the thread root.

Each submitted anchor bolt was subjected to a full-size stud tensile test in accordance with ISO 898-1. All the bolts including the broken bolts and the reference bolts met the requirement for nominal tensile strength for M20 anchor size in accordance with Hilti data sheet for HSL-GR stainless steel heavy duty anchors (provided by the client). Also, the results met the tensile strength requirement of steel grade A4, property class 70 as per BS EN ISO 3506-1:2009 standard.

Broken bolts as well as reference/original bolts were subjected to the chemical analysis testing using an Optical Emission Spectroscopy (OES). The broken bolts, C2 and C5, chemical composition results conformed to the chemical requirements of ASTM F593-22, Alloy 316L material and ISO 3506-1:2009, Grade A4. Also, chemical analysis of intact reference bolts (R1, R2, R3 and R4) conformed to the chemical requirements of grade 316L as per ASTM F593-22, and grade A4 in accordance with ISO 3506-1:2009. The results of original bolts (O1 and O2) were close to the requirement, however, did not conform to the chemical requirements of ASTM F593-22, Alloy 316L material and ISO 3506-1:2009, Grade A4.

Samples removed from broken bolts (C2 and C5) for metallographic examination. The results did not show any abnormalities in the microstructure. The microstructure was an austenitic structure at the threads. The core microstructure showed mostly austenite grains and some delta ferrite. This is a normal microstructure for the stainless-steel bolts. The appearance of the flow lines on the threads suggested that the threads were made by a rolling process and they are not machined. We also observed some rolling defects/folds created during the manufacturing process at the crest and root of the threads.

Metallographic examinations were also conducted on the intact reference bolts. The results showed austenitic structure in the threaded section of the bolts. The core microstructure consisted of mostly austenite grains with some delta ferrite in areas with micro-segregation. The flow lines observed on the threads suggested the threads were created by a rolling process. Some folds/defects were observed at the crest/root/flank of the bolts formed during the manufacturing process.

4.0 CONCLUSIONS

It was concluded that:

1) Bolts C2 and C5 cracked as a result of fatigue crack initiation and propagation.
2) Appearance of the fracture surface of Bolt C2 suggested that the
   i) Nominal stresses (applied) were low.
   ii) Stress concentration was severe due to
      a) Thread roots
      b) Sharp corners of the thread roots
      c) Folds, micro-cracks, etc. created on the threads during manufacturing
   iii) Applied stresses were tensile/tensile and/or unidirectional bending. Visual observations showed bending along the length of bolts suggesting unidirectional bending stresses were more influential on the results.
3) Observation of the bolts with round thread roots and the thread roots with sharp corners suggested either the threads were not specified or a breach of quality control.
4) Formation of micro-cracks and folds, of the threads further contributed to the fatigue crack initiation.
5) Observation of fatigue crack initiation and propagation suggest a revisit of the design stresses.

We trust that this report provides the information that you require. Please contact me if you require any further information, or if we can be of assistance in any other way.

Yours Sincerely,

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Please note that unless we are notified in writing, samples from this investigation will be disposed of after 60 days.

NOTES:

A) Any tests subcontracted to an approved subcontractor are highlighted above (*)

B) The Client will be notified if completion of test will exceed the time specified as a result of the volume of work or the complexity of the test

C) The Client should specify the standards used for testing/comparison purpose. We have a comprehensive library and online subscription of commonly used standards, however, we may ask the client to supply the standards if not common or the Client requests to purchase standard(s) on his behalf.

D) Please provide all the necessary information/documents (MSDS) pertaining to any Toxic / Dangerous materials prior to their arrival in the Laboratory.