Failure Analysis of Segmented Loop Diamond Wire:

Fracture Causes and Mechanisms

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Abstract

This report presents a systematic failure analysis of segmented loop diamond wire that fractured during service. Macroscopic examination and optical microscopy were employed to characterize the fracture morphology, matrix wear behavior, diamond grit retention, and steel core integrity. The investigation identifies bending fatigue of the steel wire core as the primary failure mechanism, compounded by advanced matrix wear, thermal damage, torsional stress, weld joint stress concentration, and corrosion-assisted crack propagation. Practical recommendations are provided to extend service life and mitigate premature fracture.

1. Introduction

Segmented loop diamond wire is widely used in precision cutting of hard and brittle materials, including semiconductors, optical glass, stone, and advanced ceramics. The wire consists of a multi-strand high-tensile steel core onto which diamond-bearing metal-matrix segments are sintered or brazed at regular intervals. During operation, the endless loop circulates continuously over guide pulleys and across the workpiece, subjecting the steel core to millions of cyclic bending events per hour.

Wire fracture is a critical failure mode that results in machine downtime, material waste, and potential equipment damage. Understanding the root causes of fracture is therefore of significant practical importance. The present investigation analyzes a batch of fractured loop diamond wires through macroscopic inspection and optical microscopy, with the aim of identifying the dominant failure mechanisms and contributing factors.

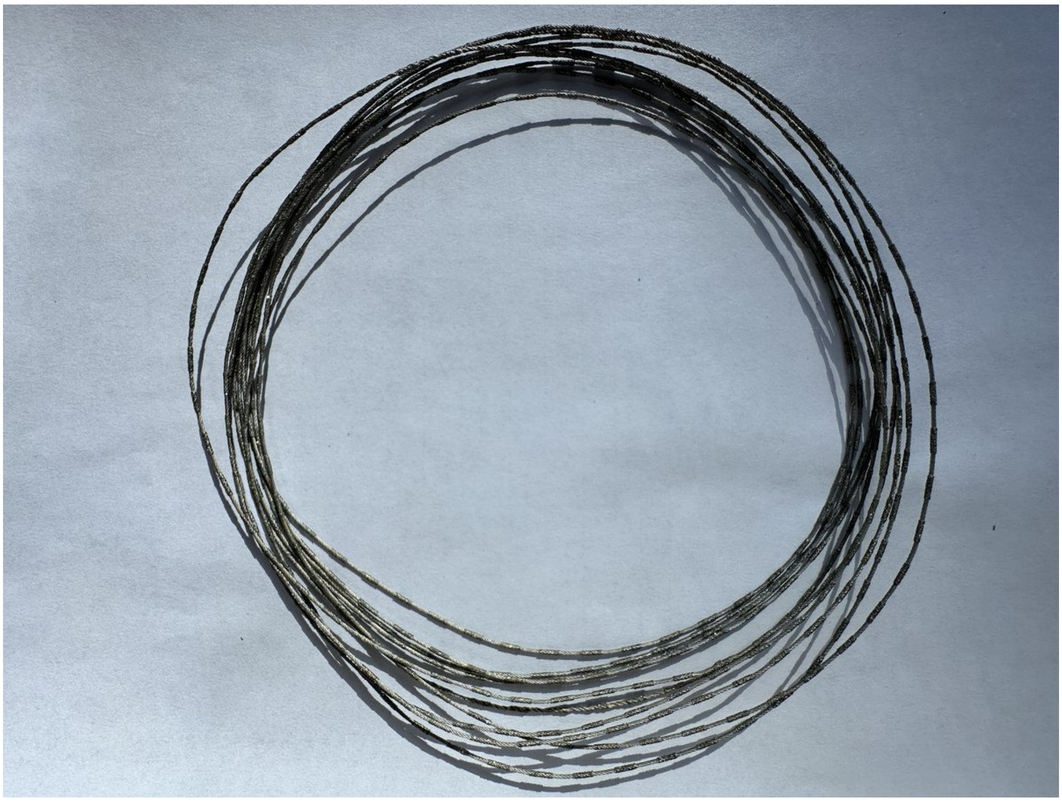


Fig. 1 — Reference specimen: intact segmented loop diamond wire in its as-received condition, showing the characteristic multi-turn loop geometry.

2. Sample Description

Two sets of specimens were examined: (a) fractured wires retrieved after service failure, and (b) an intact reference loop wire of nominally identical construction. Both sets consist of multi-strand twisted steel cores coated with a diamond-impregnated metallic matrix. No detailed manufacturing specifications were available at the time of analysis; observations are therefore based exclusively on visual and microscopic evidence.

3. Macroscopic Examination

3.1 Overall Condition of the Fractured Wire

The fractured specimens have entirely lost their original loop geometry. The wire segments are disordered and entangled, forming a characteristic figure-eight pile (Fig. 2). This pattern indicates that fracture did not occur instantaneously at a single cross-section; rather, the wire lost structural integrity progressively, allowing the released elastic energy to redistribute and coil the wire into a tangled mass.

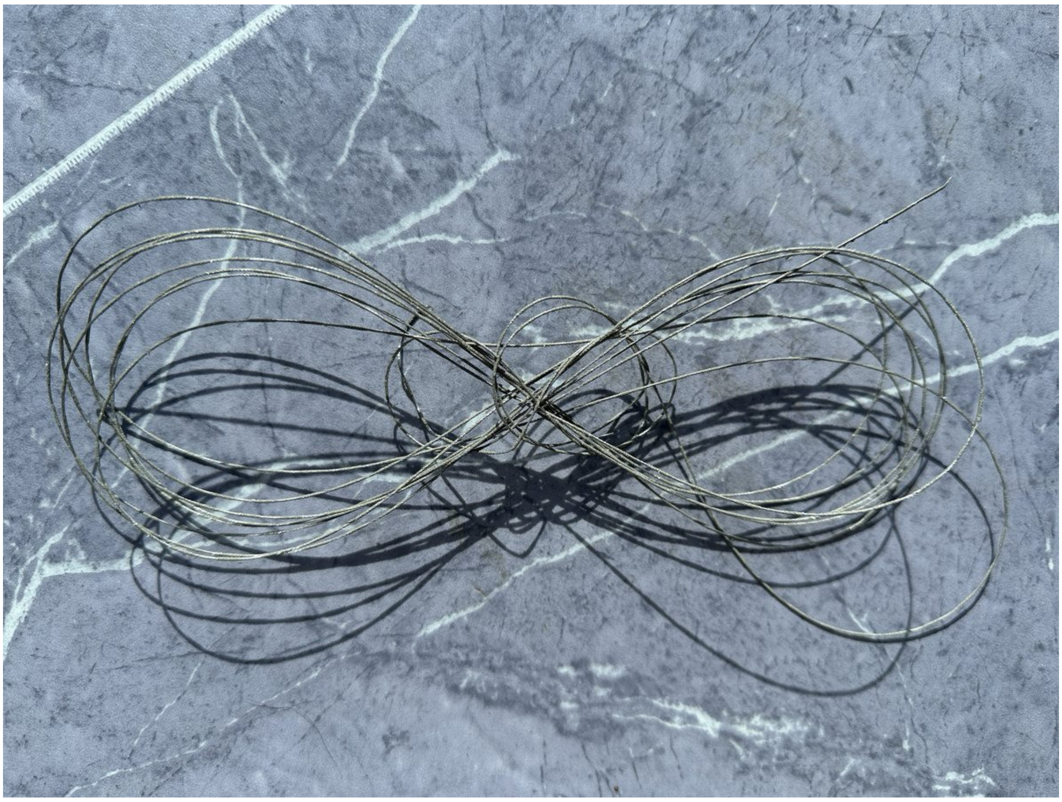


Fig. 2 — Macroscopic overview of the failed wire assembly. The complete loss of loop geometry and the characteristic tangled configuration are indicative of a progressive, energy-releasing fracture event.

3.2 Fracture-End Morphology

Close inspection of fracture ends reveals that individual wire strands are spread apart and bent into hook or curl shapes at the terminus (Fig. 3). This morphology is fundamentally inconsistent with a single-event static overload fracture, which would produce a flush, planar break across all strands simultaneously. Instead, the progressive strand separation and curvature are classical indicators of fatigue fracture, in which individual strands fail sequentially as fatigue cracks propagate independently through each sub-wire.

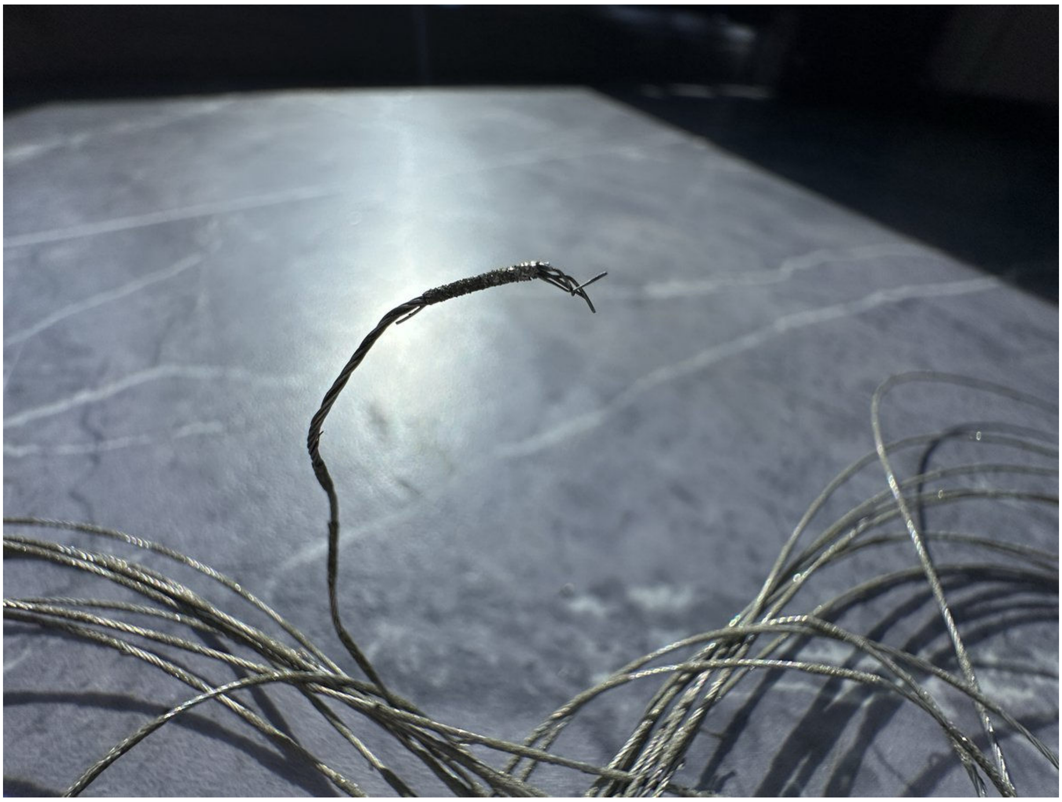


Fig. 3 — Fracture-end detail showing individual strands splayed apart and curled into hook configurations. This progressive strand-by-strand separation is diagnostic of fatigue failure rather than brittle or overload fracture.

3.3 Weld Joint — A Structural Weak Point

A distinct nodular protrusion was identified on one of the fractured wire segments (Fig. 4). This feature is consistent with the weld joint used to close the diamond wire into a continuous loop. The joint region constitutes a geometric discontinuity that concentrates stress during cyclic loading, making it the highest-risk initiation site for fatigue cracking. In addition, the metallurgical properties of the heat-affected zone adjacent to the weld are generally inferior to the base wire, further reducing local fatigue resistance.

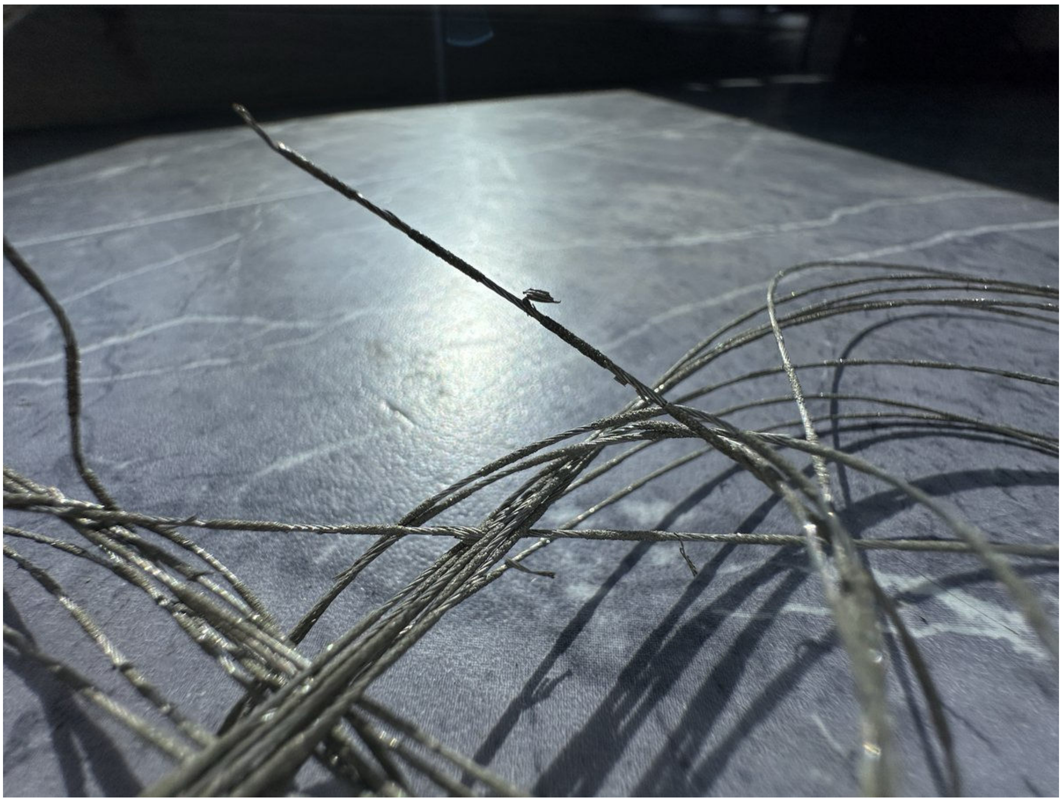
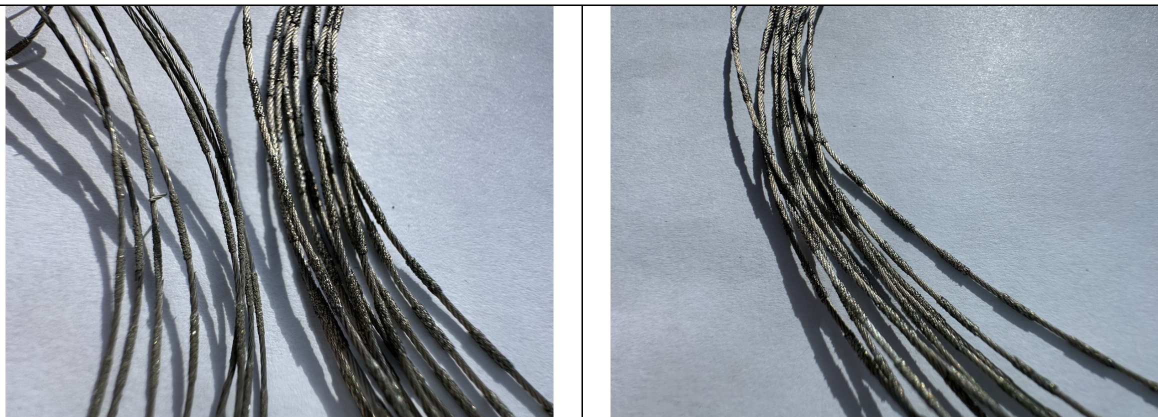


Fig. 4 — A nodular protrusion (arrowed) consistent with the loop weld joint. Geometric and metallurgical discontinuities at this location promote preferential fatigue crack initiation.

3.4 Comparative Wear Analysis

A side-by-side comparison of the failed wire and the reference specimen reveals dramatically different surface textures (Fig. 5). The failed wire exhibits a dull, rough surface with poorly defined strand geometry, indicating advanced matrix erosion. In contrast, the reference wire retains a bright, well-defined helical strand pattern. This differential wear confirms that the failed wire had been operated well beyond its effective service life before fracture occurred.



(a) Failed wire — severe surface wear *(b) Reference wire — normal condition*

Fig. 5 — Comparative macroscopic appearance. (a) Failed specimen showing heavily eroded matrix and loss of surface detail. (b) Reference specimen with intact diamond segments and defined strand geometry.

4. Microscopic Analysis

4.1 Corrosion and Oxidation at the Fracture Zone

Optical microscopy at the fracture zone reveals reddish-brown deposits concentrated within the matrix and at grain boundaries (Fig. 6). These deposits are characteristic of iron oxide (Fe_2O_3/Fe_3O_4) corrosion products resulting from oxidation of the steel core and metallic matrix. Corrosion damage reduces the effective load-bearing cross-section of the steel core and introduces stress-corrosion cracking susceptibility, both of which significantly accelerate fatigue crack propagation.

Fig. 6 — Optical micrograph of the fracture zone showing reddish-brown iron oxide deposits (indicated by arrow) within the damaged matrix, consistent with corrosion-assisted degradation of the steel core.

4.2 Severe Matrix Wear and Diamond Grit Pullout

Examination of the matrix surface in a mid-body region of the failed wire reveals extensive diamond grit loss (Fig. 7). Numerous circular and elliptical voids are present where diamond abrasives have been detached from the matrix. The surrounding matrix material appears thermally darkened (brown to black), consistent with oxidative heating above ~400 °C. This thermal discoloration indicates that insufficient coolant flow or excessive cutting speed led to localized overheating, which softens the metallic matrix and dramatically weakens the mechanical grip on diamond grains. Once grit is lost, the remaining matrix is rapidly ground away, exposing the bare steel core to direct abrasive loading.

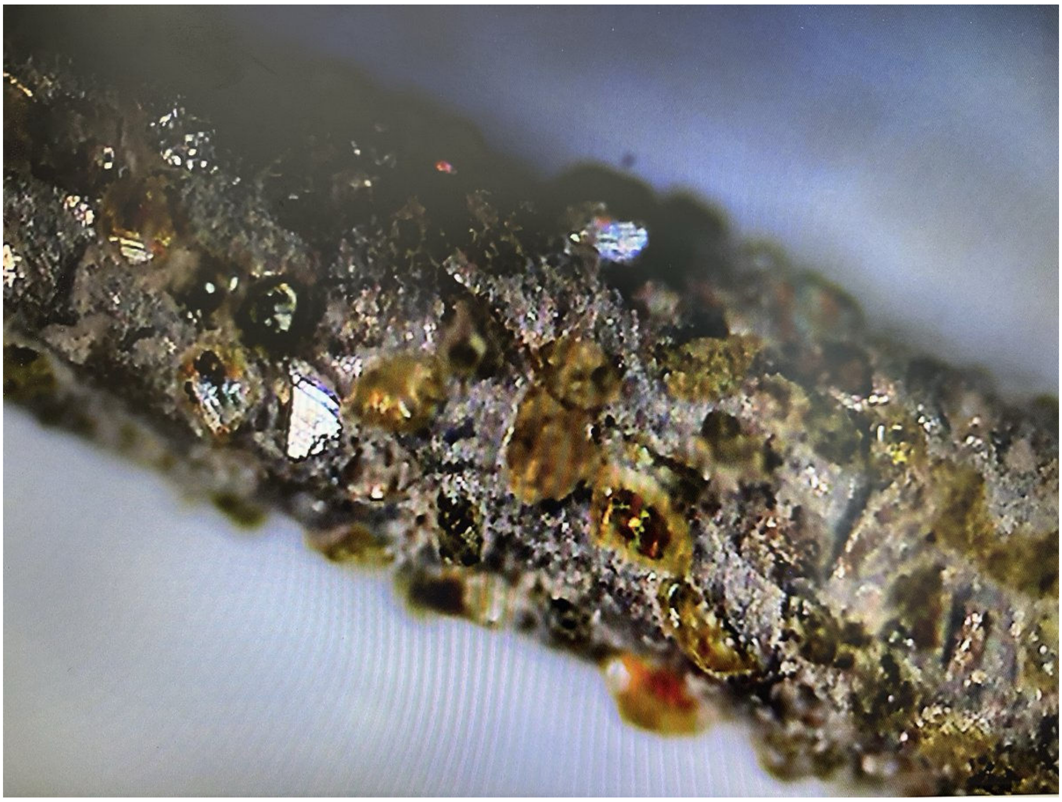


Fig. 7 — Optical micrograph showing the matrix of the failed wire with extensive diamond pullout voids (dark circular pockets) and thermally darkened matrix material, indicative of localized overheating and accelerated abrasive wear.

4.3 Reference Area: Normal Diamond Distribution

For comparison, a section of wire exhibiting relatively normal wear was examined (Fig. 8). Diamond grains are well-retained, display angular morphology consistent with minimal thermal alteration, and are distributed throughout a dense metallic matrix. The contrast with the failed region (Section 4.2) clearly demonstrates the role of thermal and mechanical overloading in destabilizing the matrix and triggering accelerated grit loss.

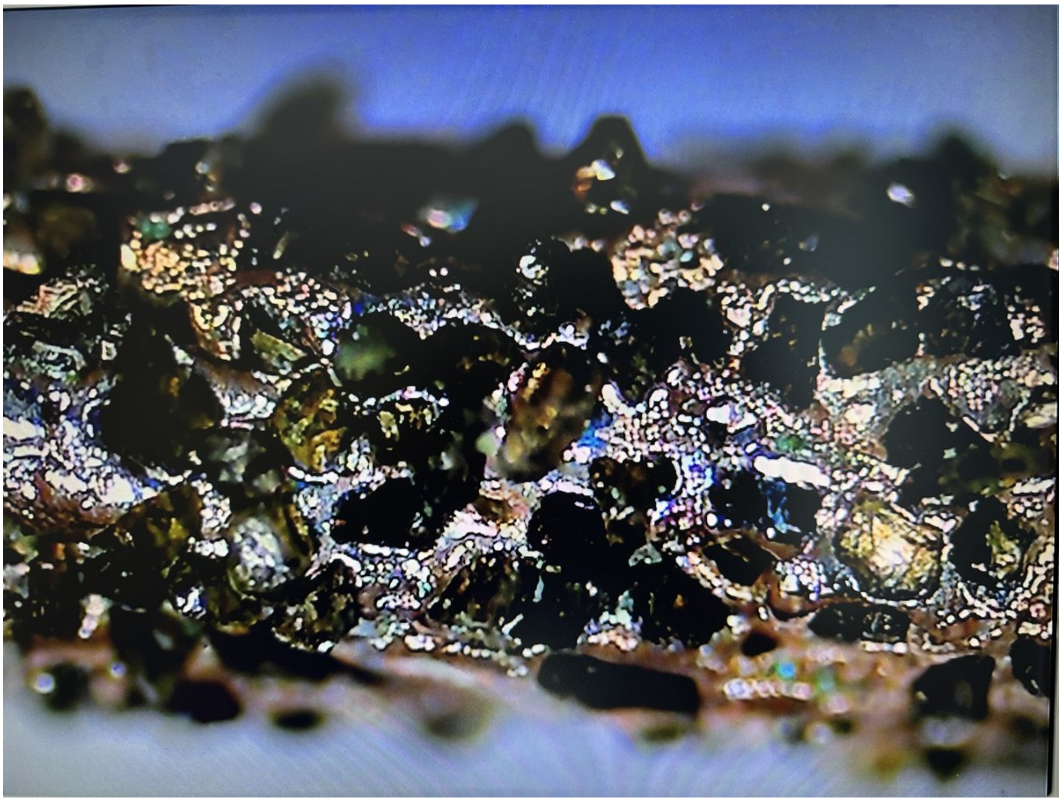


Fig. 8 — Optical micrograph of a reference section showing well-retained diamond grains with intact angular morphology, embedded in a dense metallic matrix. This represents normal, serviceable wire condition.

4.4 Axial Fatigue Cracks in the Steel Core — Primary Evidence

The most critical microscopic evidence is found on the exposed steel core strands near the fracture zone (Fig. 9). Multiple continuous cracks oriented parallel to the wire axis are clearly visible on strand surfaces. These axial cracks are the hallmark of rotary bending fatigue: as the wire repeatedly bends around guide pulleys, alternating tensile and compressive stresses are generated on the outer fibers of each strand. Fatigue damage initiates at surface stress risers (corrosion pits, micro-notches at matrix-core interfaces) and propagates axially along the strand until the remaining ligament is insufficient to sustain the applied load, resulting in sudden final fracture.

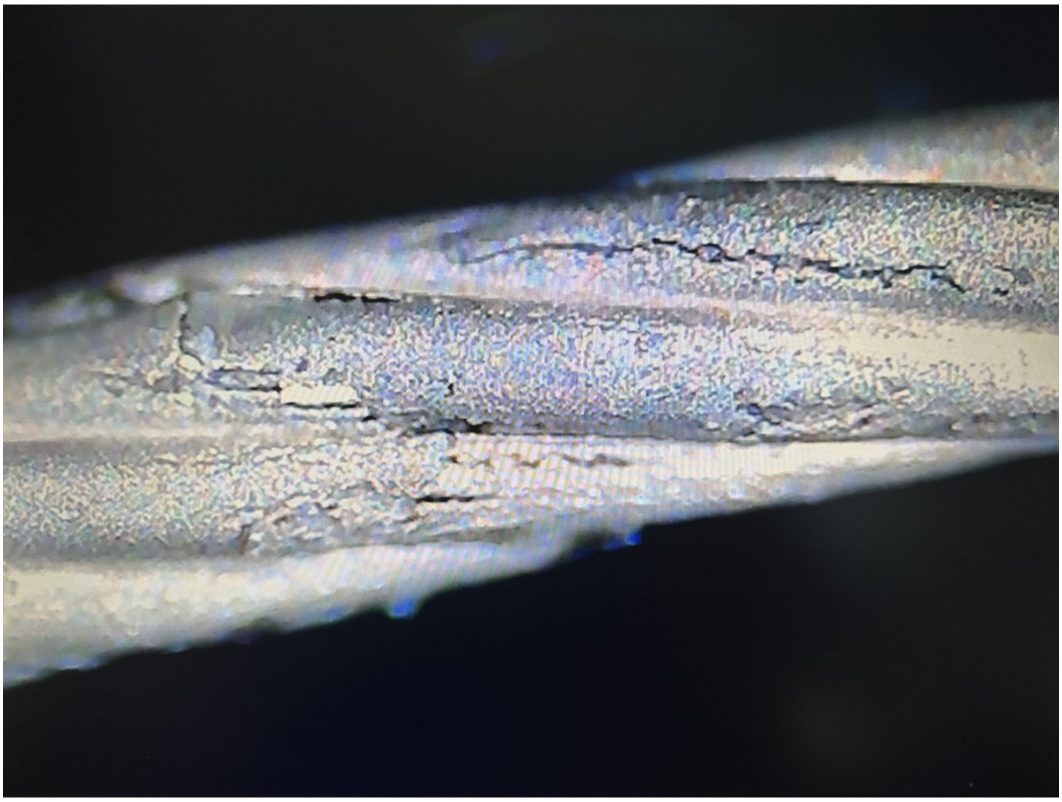
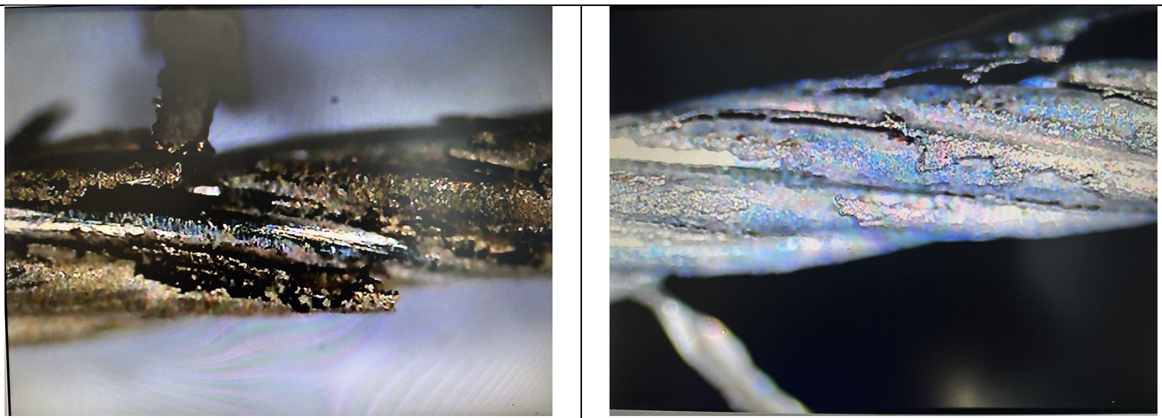


Fig. 9 — Optical micrograph of the exposed steel core, showing multiple axially oriented fatigue cracks propagating along the strand surface. This evidence constitutes the primary proof of rotary bending fatigue as the dominant failure mechanism.

4.5 Strand Delamination and Layer Separation at the Fracture Zone

Cross-sectional and oblique views of the fracture zone reveal a distinctive fish-scale layering pattern, with individual strands peeled apart and separated in a stepwise manner (Figs. 10 and 11). This delamination morphology arises when fatigue cracks propagate in each strand independently and at slightly different rates; the final overload fracture then propagates across strands sequentially rather than simultaneously, producing the observed stepped fracture surface. The absence of a flat, featureless fracture plane definitively excludes instantaneous overload or embrittlement as the primary cause.



(a) Fracture zone — strand delamination | *(b) Fracture zone — layered separation*

Fig. 10 — Optical micrographs illustrating the stepped, fish-scale fracture morphology at the failure zone. Sequential strand separation is consistent with independent fatigue crack propagation in each sub-wire.

5. Discussion: Failure Mechanism

The totality of macroscopic and microscopic evidence supports a compound failure scenario in which bending fatigue of the steel core is the primary mechanism, accelerated and preceded by a cascade of contributory degradation processes. The proposed failure sequence is summarized below.

1	**Advanced Matrix Wear and Thermal Overloading** Aggressive cutting parameters (excessive wire speed or feed rate) combined with inadequate coolant delivery generated localized thermal spikes. Matrix softening above ~400 °C weakened the mechanical retention of diamond abrasives.
2	**Diamond Grit Loss and Exposure of Steel Core** Progressive diamond pullout stripped the wire of its abrasive capability, forcing increased applied load to maintain cutting rate. The bare steel core was thereby exposed to direct abrasive and compressive forces, dramatically increasing the bending stress amplitude experienced by each strand.
3	**Corrosion-Assisted Crack Initiation** Moisture ingress through the degraded matrix promoted oxidation of the steel core. Corrosion pits and oxide-induced surface notches acted as preferential fatigue crack initiation sites, reducing the endurance limit of the wire significantly.
4	**Rotary Bending Fatigue — Primary Failure Mechanism** The steel core underwent millions of bending cycles as the loop circulated over guide pulleys. Fatigue cracks nucleated at surface defects, propagated axially along individual strands (Fig. 9), and caused progressive strand failure in a sequential manner (Figs. 10, 11), ultimately reducing load-bearing capacity to zero.
5	**Weld Joint Stress Concentration and Final Fracture** The weld joint (Fig. 4) represents a geometric and metallurgical stress concentration. In the context of already-degraded wire, this location was most susceptible to fatigue crack initiation, likely serving as the final fracture trigger that caused complete loop failure.

In summary, the wire fracture was not caused by a single catastrophic event. It represents the terminal stage of a progressive deterioration chain that began with excessive thermal and mechanical loading in service. Had the wire been withdrawn from service at early signs of matrix degradation (surface blackening, loss of cutting efficiency), fatigue fracture could likely have been averted.

6. Conclusions

Based on the macroscopic and microscopic evidence presented, the following conclusions are drawn regarding the fracture of the segmented loop diamond wire:

- The dominant failure mechanism is rotary bending fatigue of the multi-strand steel wire core, evidenced by axially oriented fatigue cracks on strand surfaces and sequential strand separation at the fracture zone.
- Advanced matrix wear and thermal overloading accelerated diamond grit loss, increasing the mechanical stress on the bare steel core and hastening fatigue damage accumulation.
- Corrosion products (iron oxides) at the fracture zone contributed to stress-corrosion crack initiation, lowering the effective fatigue threshold of the wire.
- The weld joint acted as a stress concentrator and likely served as the preferred site for fatigue crack initiation and final fracture.
- The fractured wire had been operated significantly beyond its effective service life, as demonstrated by severe surface wear relative to the reference specimen.

7. Recommendations

To mitigate premature fracture and extend the service life of loop diamond wire, the following measures are recommended:

- **Optimize cutting parameters** — Reduce wire speed and/or workpiece feed rate to keep the cutting zone temperature below the matrix softening threshold. Verify that coolant flow is directed precisely at the cut interface.
- **Implement condition-based wire retirement** — Establish surface inspection intervals; retire wire at the first signs of significant matrix blackening or diamond grit depletion, before the onset of fatigue cracking in the steel core.
- **Improve weld joint quality** — Audit the weld joint for geometric conformity and hardness. Consider post-weld heat treatment or mechanical dressing to reduce the stress concentration factor at the joint.
- **Prevent corrosion** — Store unused wire in a dry, sealed environment. Use a corrosion-inhibiting coolant formulation during operation to retard oxidation of the steel core.
- **Review pulley geometry** — Verify that guide pulley diameters are consistent with the wire's minimum bend radius specification. Excessively small pulleys increase the bending stress amplitude per cycle and dramatically shorten fatigue life.

— End of Report —