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Examination of Failed Threaded Bar Material

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Introduction

Sheffield Metallurgical Services was commissioned by [redacted] of North Tyneside Council to determine the root cause of failure of a threaded M20 316 stainless steel bar section from a sculpture fixing.

The M20 section formed part of an armature assembly securing the sculpture to the dome of a building and was used as a complete 3000mm length with no cutting or bending performed as part of the fabrication. The assembly was used to support a sculpture weighing approximately 65Kg with a height of approximately 180cm. The assembly was situated in an external coastal environment.

In agreement with the client, the following metallurgical examinations were conducted to determine the root cause of the failure:

- Visual / Binocular microscopic examination
- Scanning Electron Microscopy (SEM) Examination
- Energy-dispersive X-ray spectroscopy (EDS) analysis
- Hardness Testing
- Metallographic examination
- Chemical Analysis

Metallurgical Analysis

Visual / Macro Examination *

Two sections were received for examination measuring approximately 600mm long which were extracted from a lower part of the armature assembly where the sculpture was secured to the dome of the building. The as-received failed part is shown in Figure 1 to Figure 8, and a second part which was removed before failure from the building is shown in Figure 9 to Figure 11.

Initial visual examination of the failed part showed a fracture face sited in the central region of the resin statue section. The resin around the fracture showed a discoloured / burnt appearance. (Figure 3 & Figure 4).

The threaded bar was removed from the resin for further visual examination, which showed a fracture face with prominent beach marks and multiple ratchet marks at the site of initiation on the root of a threaded region. (Figure 5 & Figure 6). The beach marks were consistent with a bending fatigue mode of failure.

There was no mechanical damage present on the outer diameter of the threaded bar with exemption of the fracture face.

The 20mm threaded bar had small supports / cross sections welded on which showed evidence of excessive heat and melted regions on the outer diameter. (Figure 7 & Figure 8)

The threaded bar had been attached to a dome base plate by welding. The dome section was not available for examination on the failed part; however, this region was visible on the statue which had not failed. The comparison dome showed evidence of welds used to attach the dome base plate to the base of the statue and the threaded bar (Figure 10 & Figure 11). The weld showed a burnt appearance and was sited in a region close to where the failed material had fractured.

Macro Photographs

Figure 1: Failed Section as-received

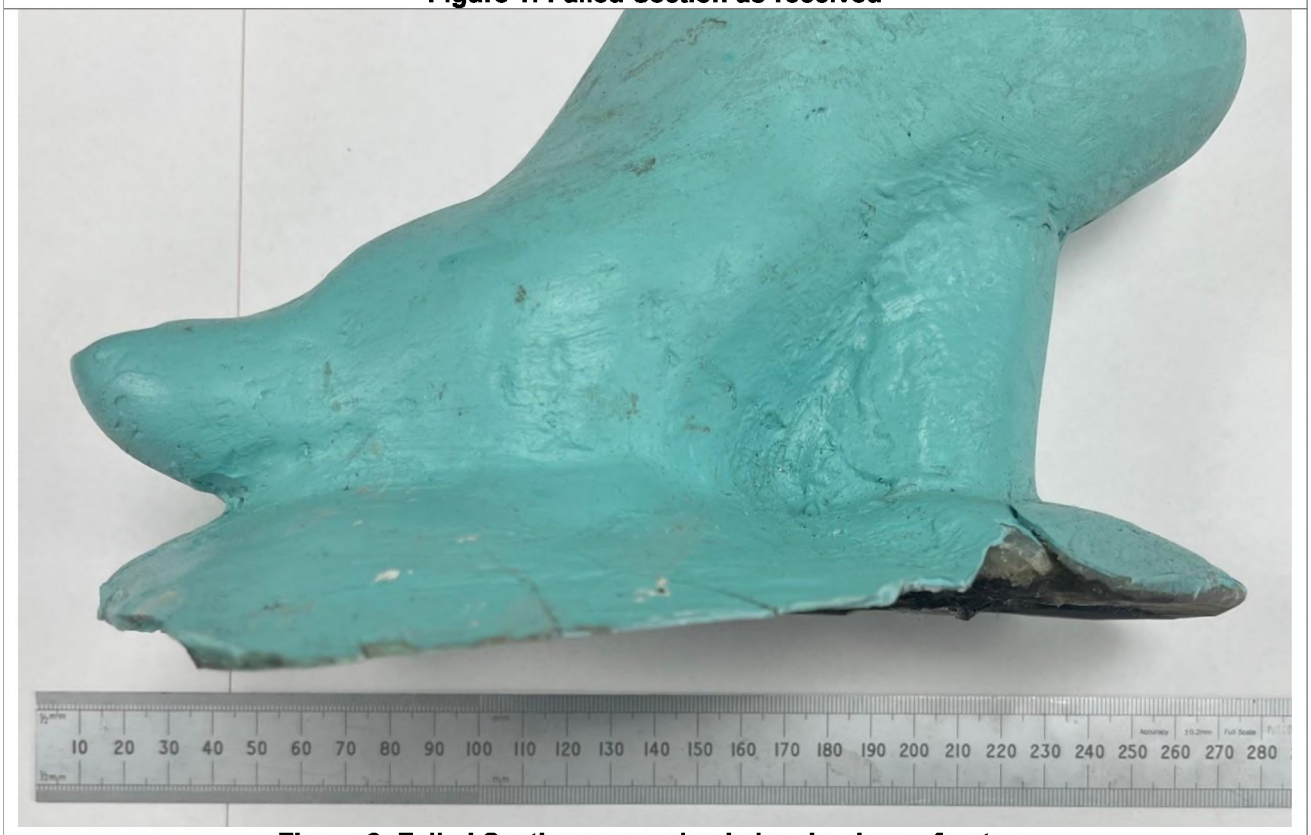

Figure 2: Failed Section as-received showing lower fracture

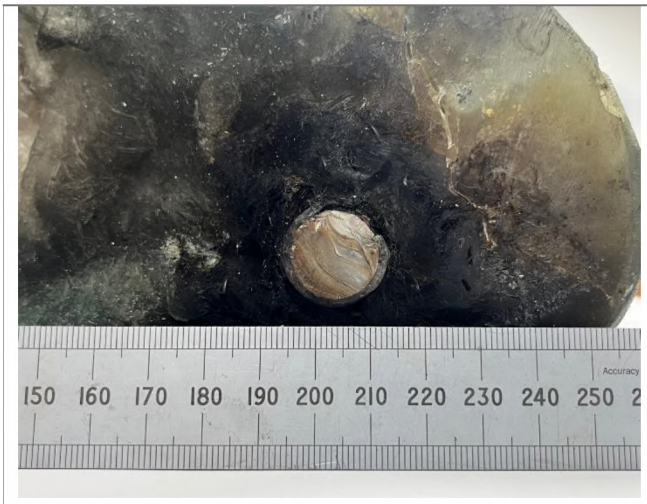

Figure 3: Fracture face of threaded bar and surrounding discolourisation

Figure 4: Fracture face of threaded bar, higher magnification showing fatigue beach marks

Figure 5: Fracture face of threaded bar showing multiple ratchet marks for crack initiation at the root of a thread

Figure 6: Fracture face of threaded bar, higher magnification

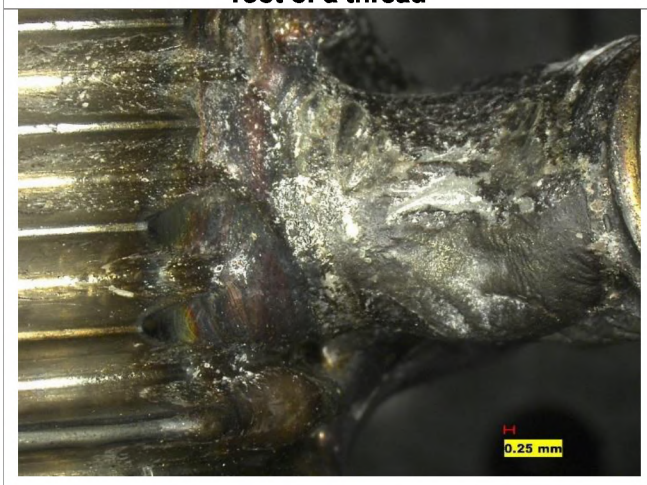

Figure 7: Welded section

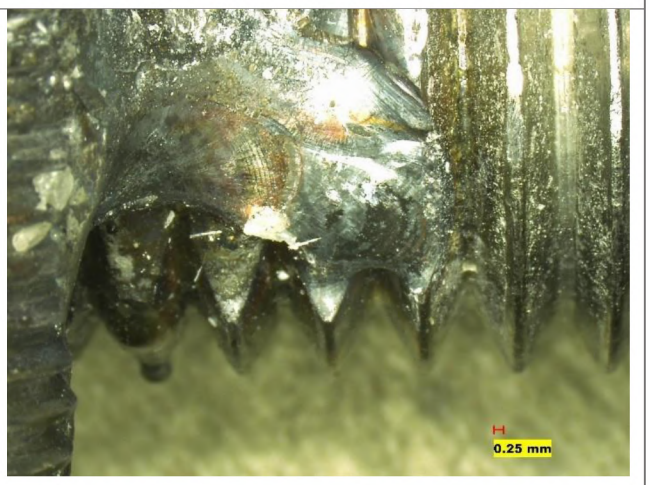

Figure 8: Welded section showing melted regions due to excessinve heat input

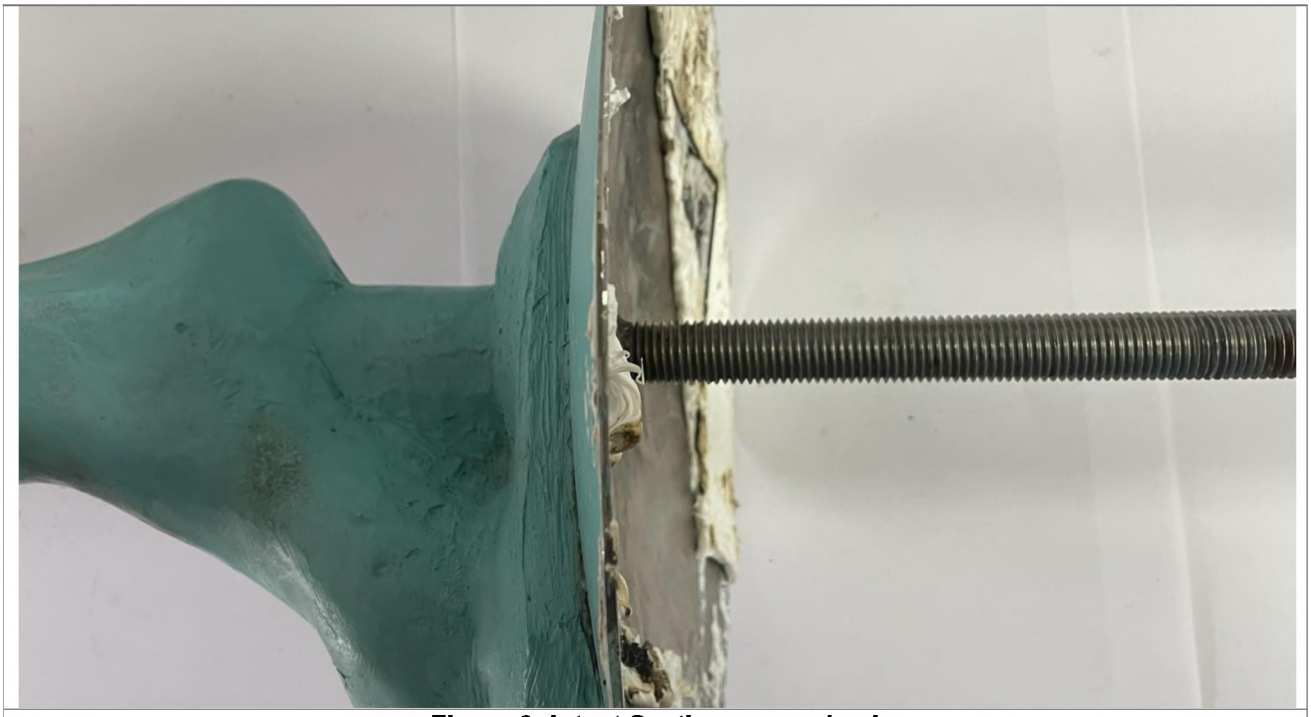

Figure 9: Intact Section as-received

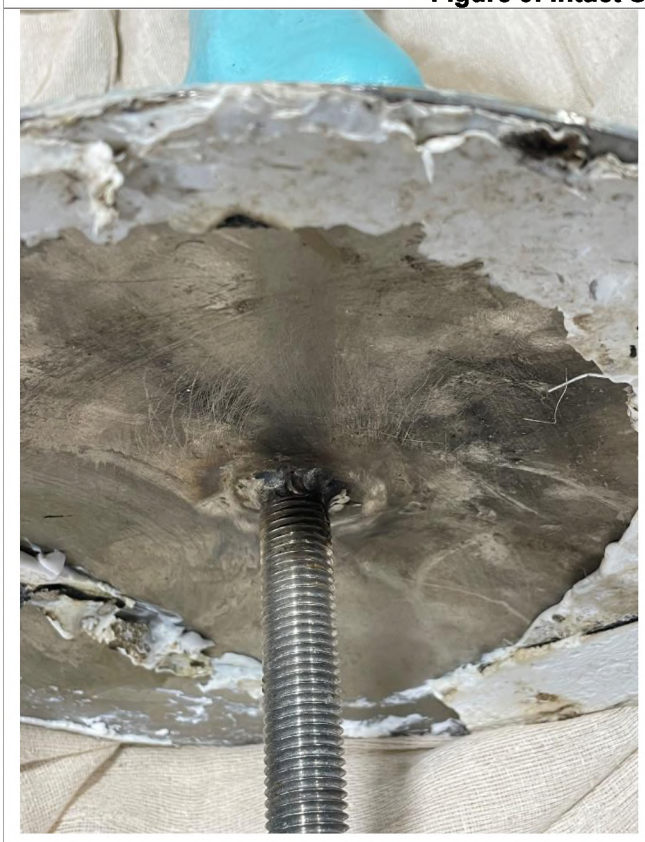

Figure 10: Intact Section as-received showing threaded bar welded to the base

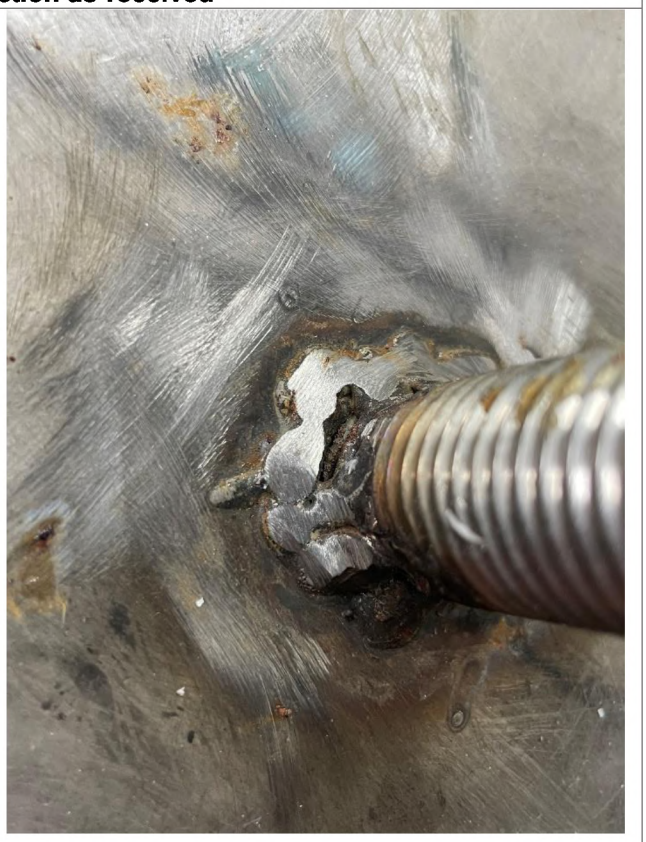

Figure 11: Intact Section as-received showing discolouration due to heat input from welding

SEM ANALYSIS

The fracture face from the failed part was extracted and examined in an unprepared as-received condition and examined in a Hitachi TM3000 Scanning Electron Microscope.

Initial low magnification showed evidence of an initiation site which propagated from the surface of the threaded bar at a thread root. There was evidence of multiple ratchet marks and beach marks indicative of a gradual fatigue mode of failure. (Figure 12& Figure 13).

High magnification in the centre of the bar revealed a ductile fracture face, which was deformed and had a flattened appearance which had most likely occurred post failure.

A micro section was prepared through the fracture face for further investigation in the SEM.

Initial low magnification revealed evidence of pre-existing material supply defects, which were consistent with a thread rolling origin. (Figure 14 to Figure 17)

SEM Analysis

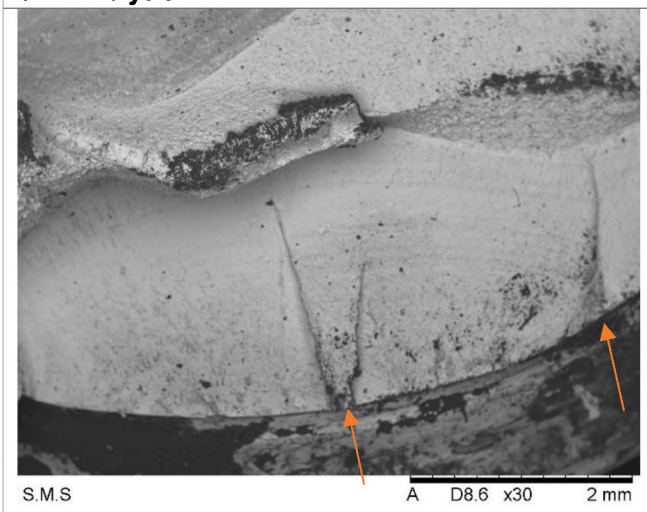

Figure 12: SEM Image showing initiation from the surface at a root thread.

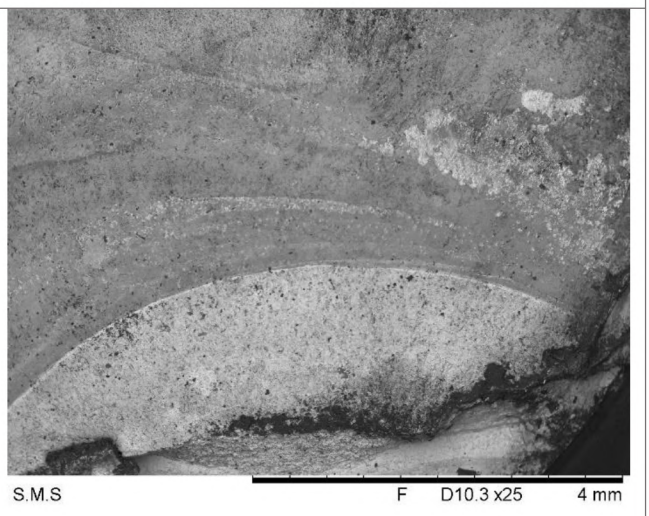

Figure 13: SEM Image showing mechanical damage / smearing and fatigue beach marks.

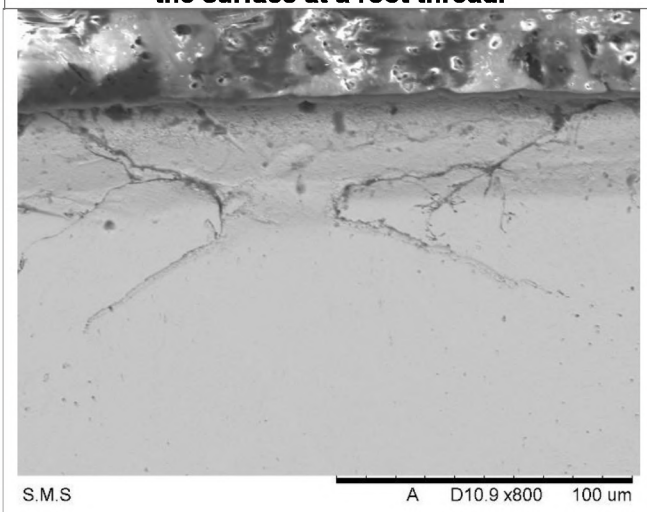

Figure 14: Surface thread rolling defects

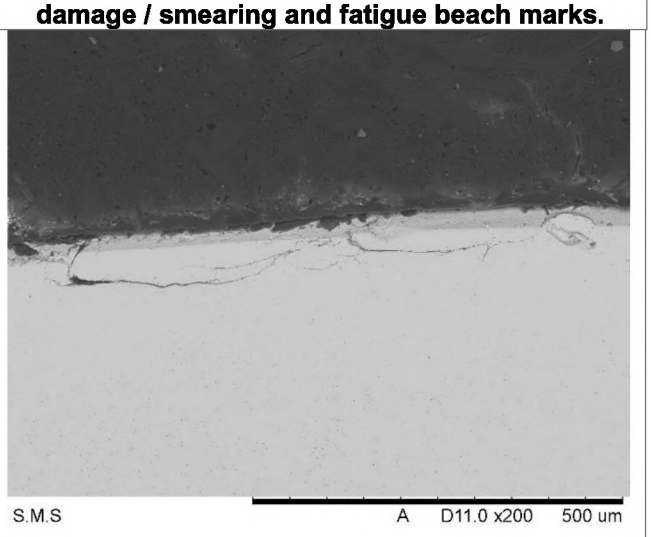

Figure 15: Surface thread rolling defects

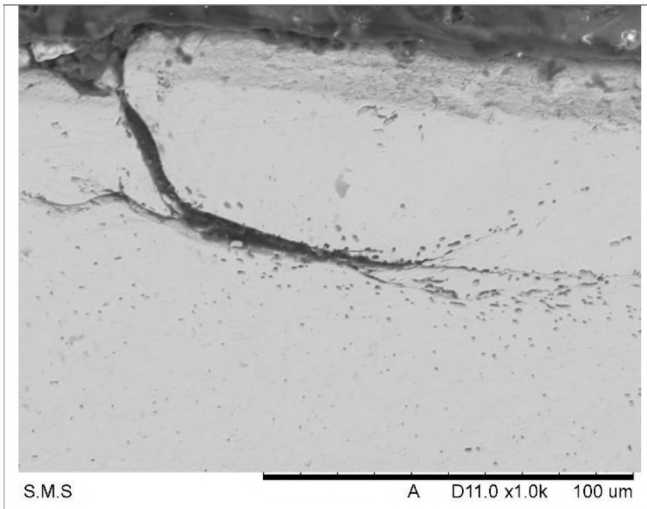

Figure 16: Surface thread rolling defects

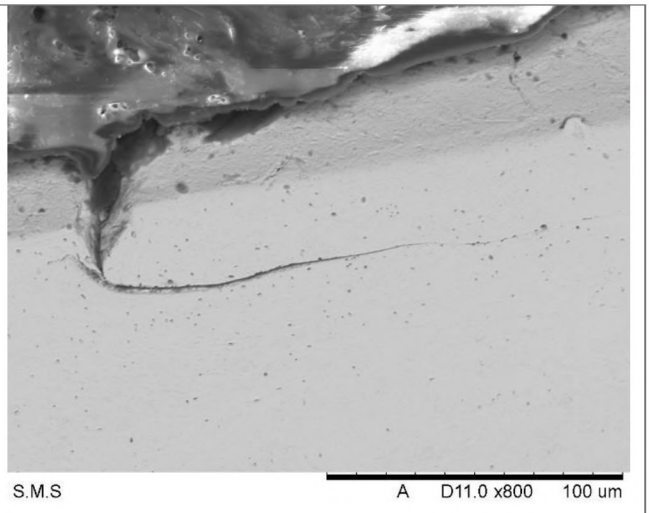

Figure 17: Surface thread rolling defect away from fracture

Metallurgical Analysis

Energy Dispersive X-Ray Analysis

Semi-quantitative chemical analysis was conducted in a Hitachi TM3000 Scanning electron microscope (SEM) with the aid of an in-situ Bruker EDS system. The assessment was performed in backscatter mode with an accelerating voltage of 15 KeV. The EDS method detects only elements with atomic number greater than 4 and so cannot detect hydrogen.

EDS analysis failed to highlight any corrosion products or detrimental phases on the fracture face that could have contributed to the failure.

Metallurgical Analysis

Metallographic Examination

Failed Section

The fracture face was sectioned longitudinally and was ground and polished to a 1-micron finish in accordance with ASTM E3 / E407 and examined in both the as-polished and etched conditions.

The opposite side of the of the fracture face was not available for examination, therefore cracking in this region cannot be ruled out.

Photomicrographs failed to highlight any cracking in the bulk of the material, but did show some evidence of microcracks at the surface near the fracture face. (Figure 18 & Figure 19)

Etching the section in Kallings No2 Reagent revealed a general microstructure of twinned austenitic grains typical of a 316 stainless steel with sulphides strung out along the rolling direction. The level of sulphides observed was thought to be high for a 316 stainless grade of material. (Figure 20 & Figure 21).

There was evidence of cracking at the thread root following the structural flow (figure 22).

There was no evidence of any other non-metallic inclusions or oxides that would aid failure.

Microphotographs – Failed Section

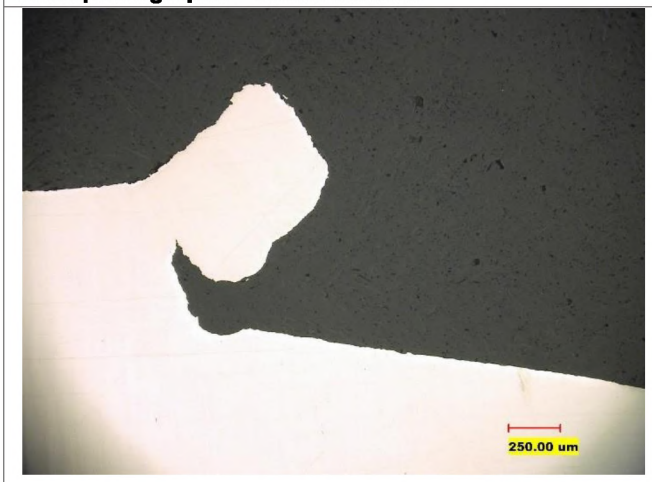

Figure 18: Microsectrion taken along fracture face
Unetched

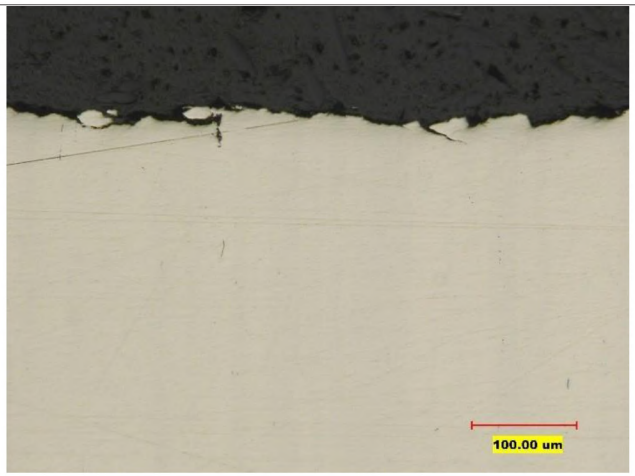

Figure 19: Surface secondary cracking
Unetched

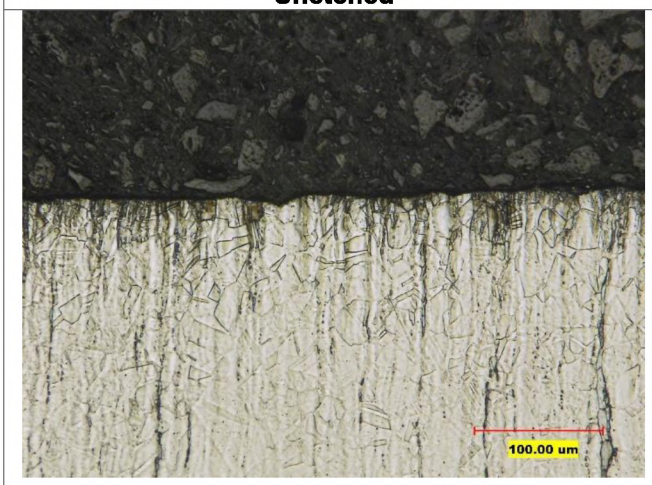

Figure 20: General microstructure
Etchant: Kallings No 2
Magnification: x100

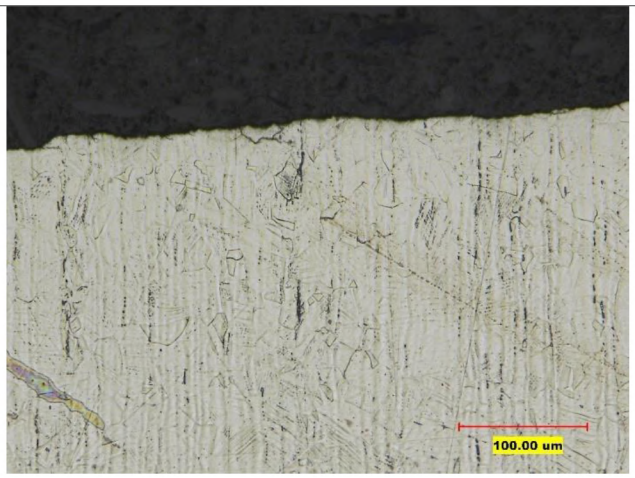

Figure 21: Surface microstructure
Etchant: Kallings No 2
Magnification: x100

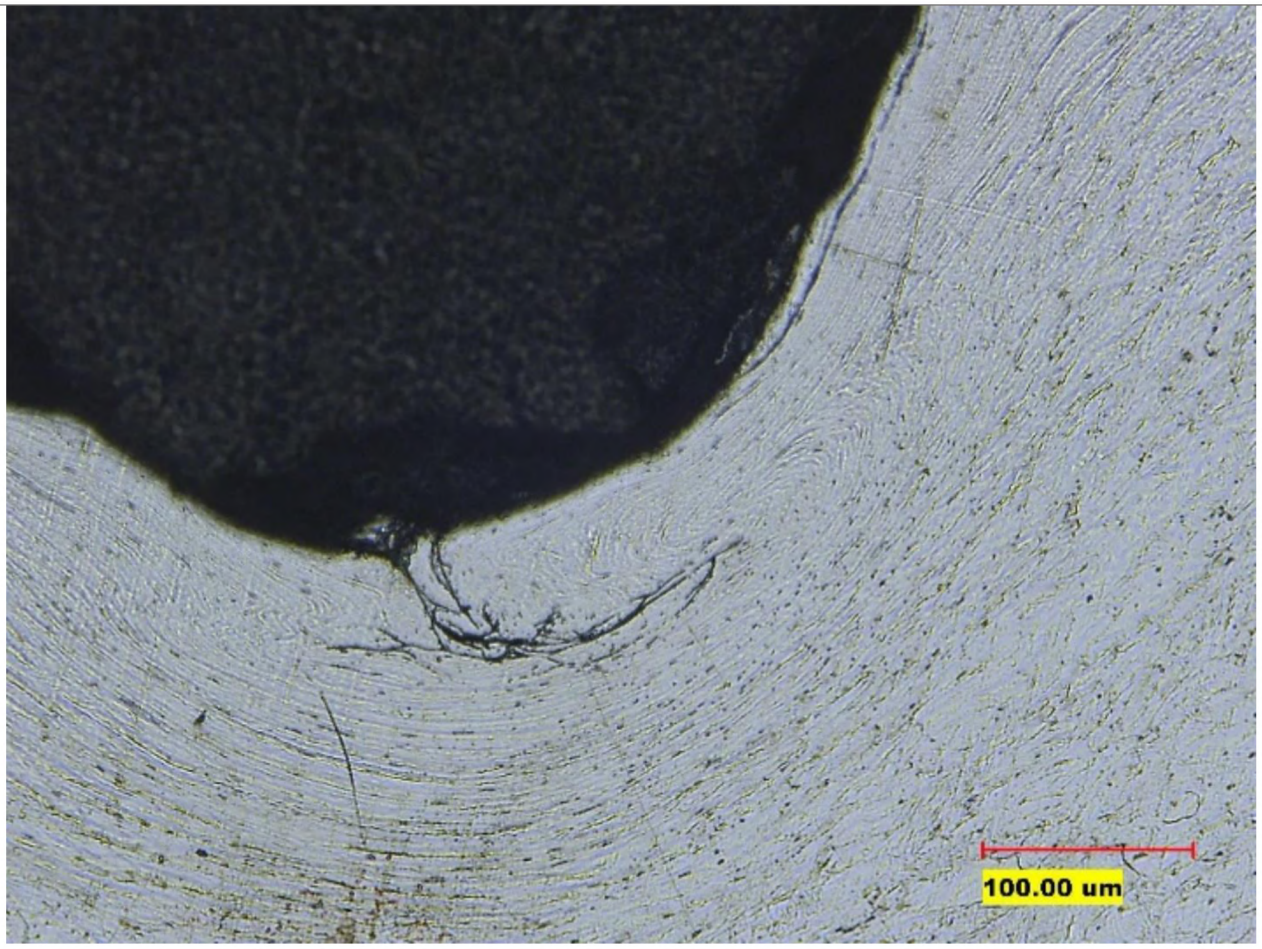

Figure 22: Microphotograph showing cracking at the thread root following the structural flow.
Etchant: Kallings No 2
Magnification: x500

Intact Section

Sectioning through the dome welded region in a longitudinal orientation revealed that the welding process had caused a large heat affected zone (HAZ) extending approximately 1.05mm into the base threaded bar (Figure 23). Cracking was observed in the root of the weld (Figure 24). There was no evidence of cracking extending into the bulk material from the weld. The change in the microstructure at the HAZ (Figure 25) would alter the mechanical properties of the bar and lead to structural weakness in this area. Some of the threads were also not present due to melting. There was evidence of cracking sited in the root of the threads, following the structural flow (Figure 26).

Microphotographs – Intact Section

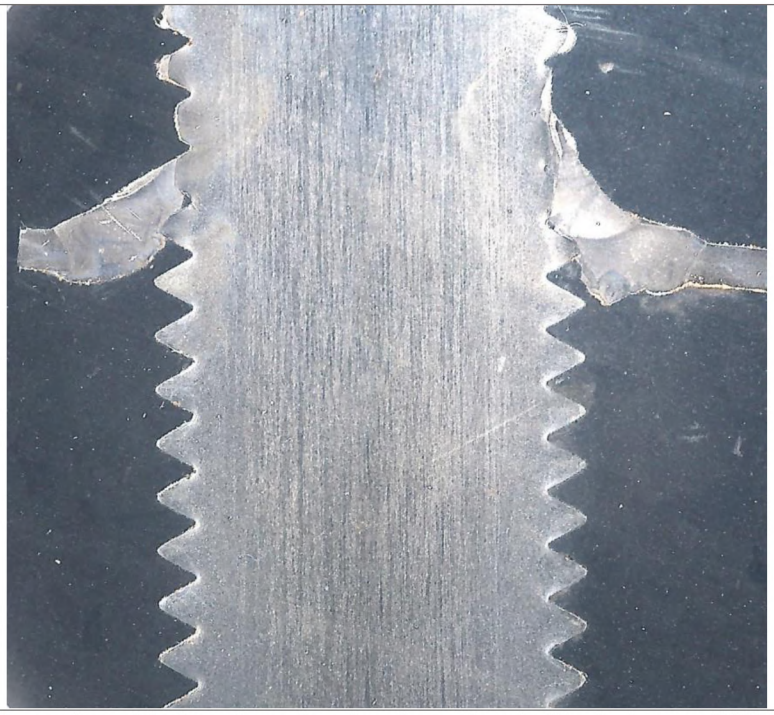

Figure 23: Section through welded region showing large heat affected zone (HAZ) and destruction of threads due to weld heat input

Figure 24: Microphotograph showing weld root crack.
Etchant: Kallings No 2
Magnification: x100

Figure 25: Microphotograph showing weld onto threads and change in microstructure at HAZ.
Etchant: Kallings No 2
Magnification: x100

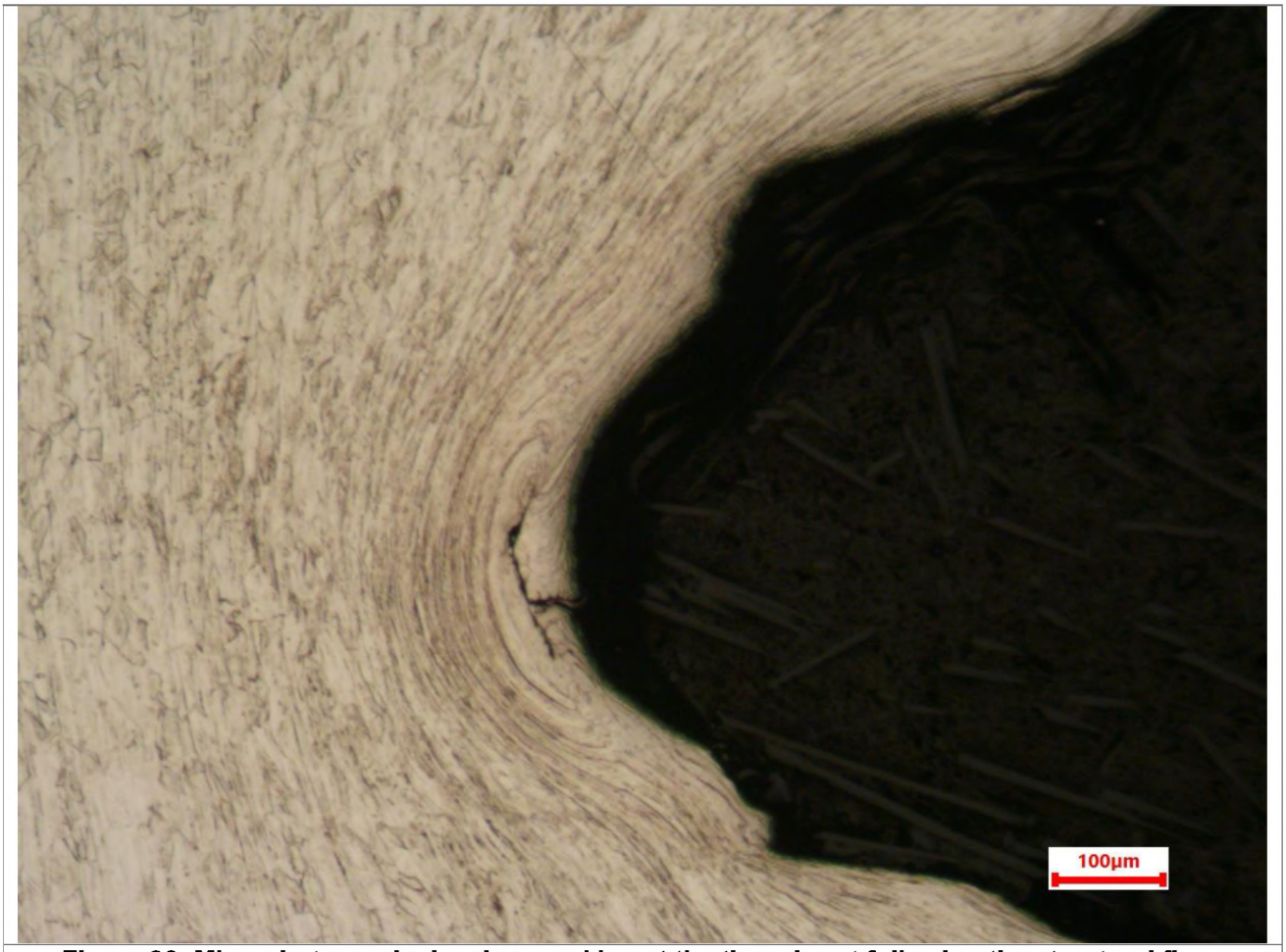

Figure 26: Microphotograph showing cracking at the thread root following the structural flow.
Etchant: Kallings No 2
Magnification: x100

Metallurgical Analysis

Hardness (ASTM E384-16)

Vickers hardness testing was conducted in accordance with ASTM E384 and a 0.3kg load was applied.

Failed Sample
Hardness values of 235 HV0.3 were noted in the fracture region and values of ~ 240HV0.3 were noted in the bulk material.

Intact Sample
Hardness values of 212 HV0.3 were noted in the weld regio, values of ~ 175HV0.3 were noted in the heat affected zone and values of 263 HV0.3 were noted in the bulk of the material.

The lower hardness in the intact sample is likely due to the change in microstructure observed caused by the high heat input from the weld. No significant difference was observed in the failed sample, but it is suspected that the section opposite the fracture face that was not removed from the building would also show a lower hardness at the welded region extending into the base 316 threaded bar.

Chemical Analysis

Detailed chemical analysis was conducted by spark optical emission spectroscopy (OES) and confirmed the material was comparable to that of 316 stainless steel.

C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %	Co %	Cu %	Nb %	Ti %
0.0447	0.43	1.51	0.0052	0.0205	16.5	2.05	10.2	<0.0020	0.125	<0.656	0.0335	0.0057

V %	W %	Pb %	Sn %	B %	Ca %	Zr %	Zn %	B %	As %	Se %	Sb %	Fe
0.0789	0.045	0.0055	0.0132	0.0032	0.00	0.013	0.00	0.0032	0.00	0.0101	0.0212	Bal-ance

Discussion

Detailed examination of the fracture face revealed multiple beach marks indicative of a gradual bending fatigue failure which had initiated from the surface of threaded bar. The failure was likely to have occurred due to a combination of excessive heat applied during the welding procedure coupled with the presence of pre-existing material supply defects, i.e. pre-existing cracking in the root of the threads.

The fatigue crack was likely to have propagated from a pre-existing root defect and gradually propagated over time. Windy conditions would have increased the bending moment of the bar and accelerated the failure.

The fracture face did not show any evidence of intergranular features or oxides and EDS analysis failed to highlight any corrosion products what would have aided failure.

The threaded bar did not exhibit any mechanical damage on the outer diameter; therefore, impact / installation damage can be ruled out as a mode of failure.

Sectioning of the threaded bar revealed a presence of manufacturing defects, which followed the structural flow lines in the rolling direction.

The intact threaded bar showed a reduction in hardness at the HAZ near where the bar was welded to the dome. The lower hardness due to heat input will have reduced the structural capability of the bar.

Conclusion

The results of the examinations conducted indicate that that the threaded bars failed due to bending fatigue caused by a combination of material supply defects and fabrication induced overheating during installation/manufacture.

The laboratory has tested the materials / items supplied by the client 'as sampled' in accordance with the customer's own requirements. Opinions and interpretations expressed herein are outside the scope of the UKAS, GE AVIATION, SAFRAN and NADCAP accreditations. Samples will be stored for a period of 1 month following completion of analysis after which the items will be disposed of.

END OF TEXT –

Report Signatories and Approval

Author	[redacted] [redacted] Metallurgist (For and on behalf of Sheffield Metallurgical Services)
Approval	[redacted] (For and on behalf of Sheffield Metallurgical Services)