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Failure Investigation of a Duplex Stainless Steel Flange: Role of Improper Heat Treatment and Sigma Phase Embrittlement

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INTRODUCTION & AIM

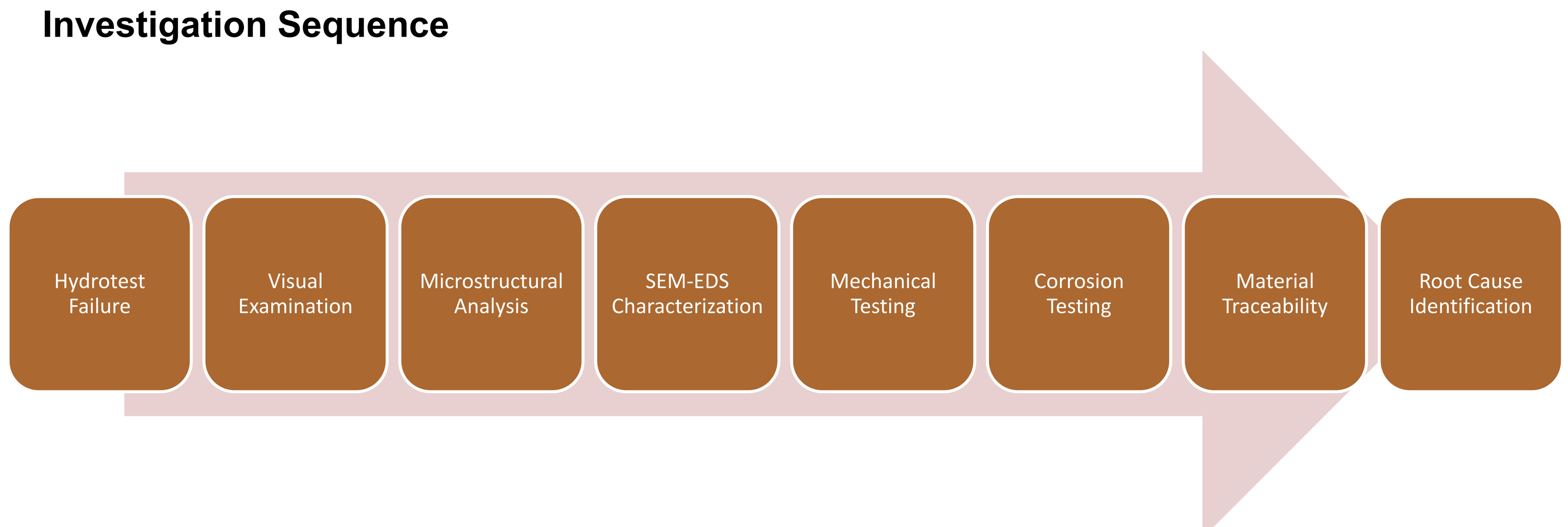
Background
Duplex Stainless Steels (DSS) are widely used in pressure-retaining components due to their high strength, toughness, and corrosion resistance. Their performance depends on maintaining a balanced ferrite-austenite microstructure. However, inappropriate thermal exposure during fabrication or heat treatment can promote precipitation of sigma (σ) phase, an intermetallic phase that severely degrades mechanical properties and corrosion resistance.

Aim
To investigate the root cause of a DSS flange failure that occurred during hydrostatic pressure testing using a multidisciplinary failure analysis approach.

METHODOLOGY

Failure Investigation Workflow
The investigation consisted of:
- Visual examination
- Fractographic analysis
- Optical microscopy
- SEM with EDS
- Hardness mapping
- Ferrite content measurements
- Charpy V-notch impact testing
- ASTM G48 corrosion testing
- Heat number traceability review

Investigation Sequence



RESULTS, METALLURGICAL EVIDENCE & ROOT CAUSE ANALYSIS

1. Metallurgical Analysis
Metallographic examination revealed extensive intermetallic (σ) phase precipitation throughout the flange material, indicating significant deviation from the intended duplex ferrite-austenite microstructure. Ferrite measurements performed using Ferritescope and ASTM E562 point-count methods showed substantially lower ferrite content, further confirming extensive intermetallic phase formation. The combined metallographic evidence indicates that the flange had not been adequately solution heat treated.

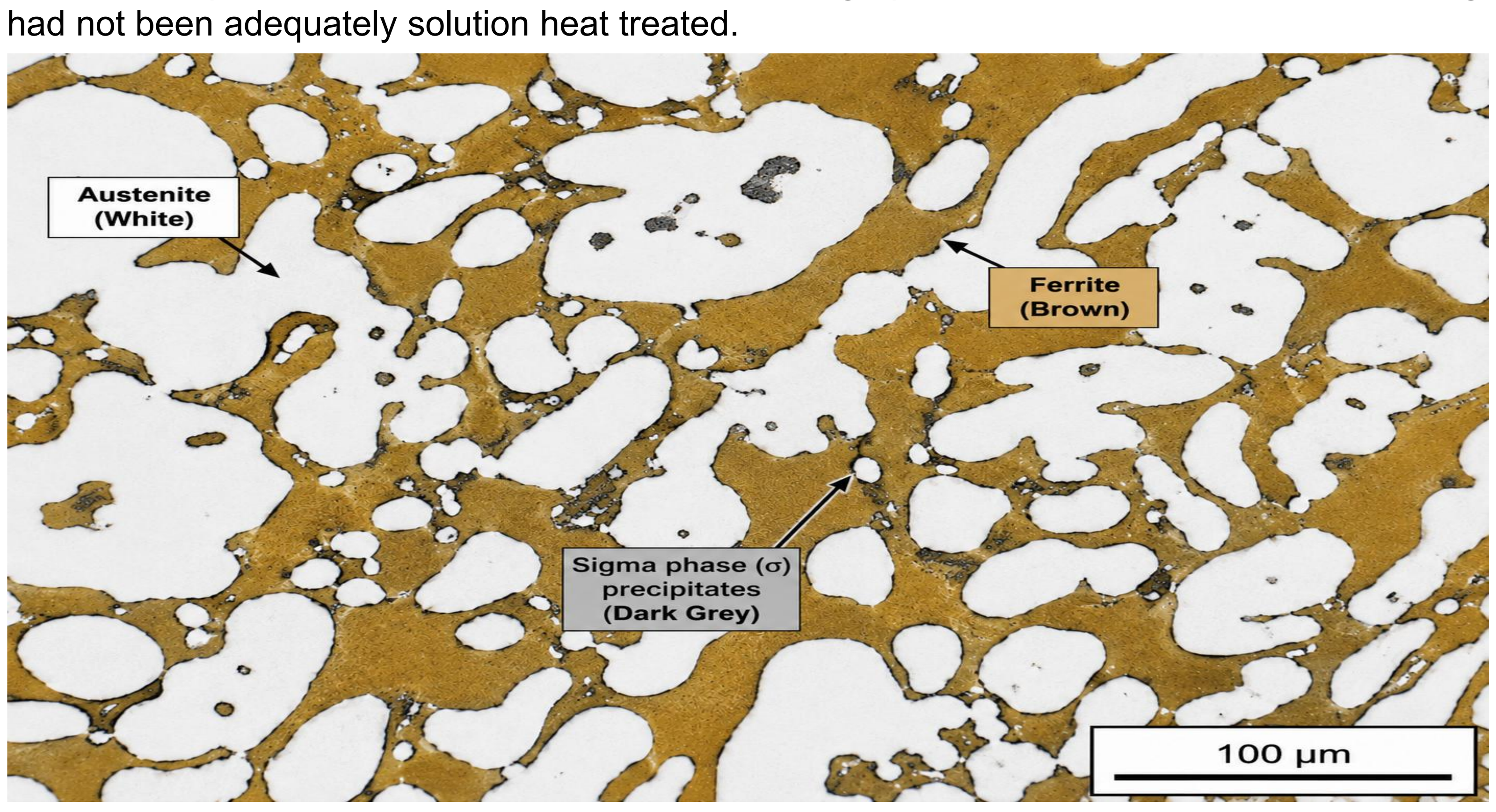


Figure 2. Extensive intermetallic (σ) phase precipitation observed throughout the failed flange material.

2. Mechanical and Corrosion Evidence
Mechanical testing revealed significant reductions in ductility and toughness, confirming severe embrittlement of the material. ASTM G48 corrosion testing demonstrated increased susceptibility to localized corrosion due to chromium-depleted regions adjacent to sigma-rich areas. These results collectively confirm the detrimental impact of intermetallic phase precipitation on both mechanical and corrosion performance.

3. Fractographic Analysis
Fractographic examination revealed a predominantly brittle fracture surface with unstable crack propagation through the weld-neck region. Distinct chevron patterns observed under SEM confirmed rapid brittle fracture propagation associated with severe embrittlement. The reduced load-bearing capacity of the embrittled material facilitated crack initiation during hydrostatic loading.

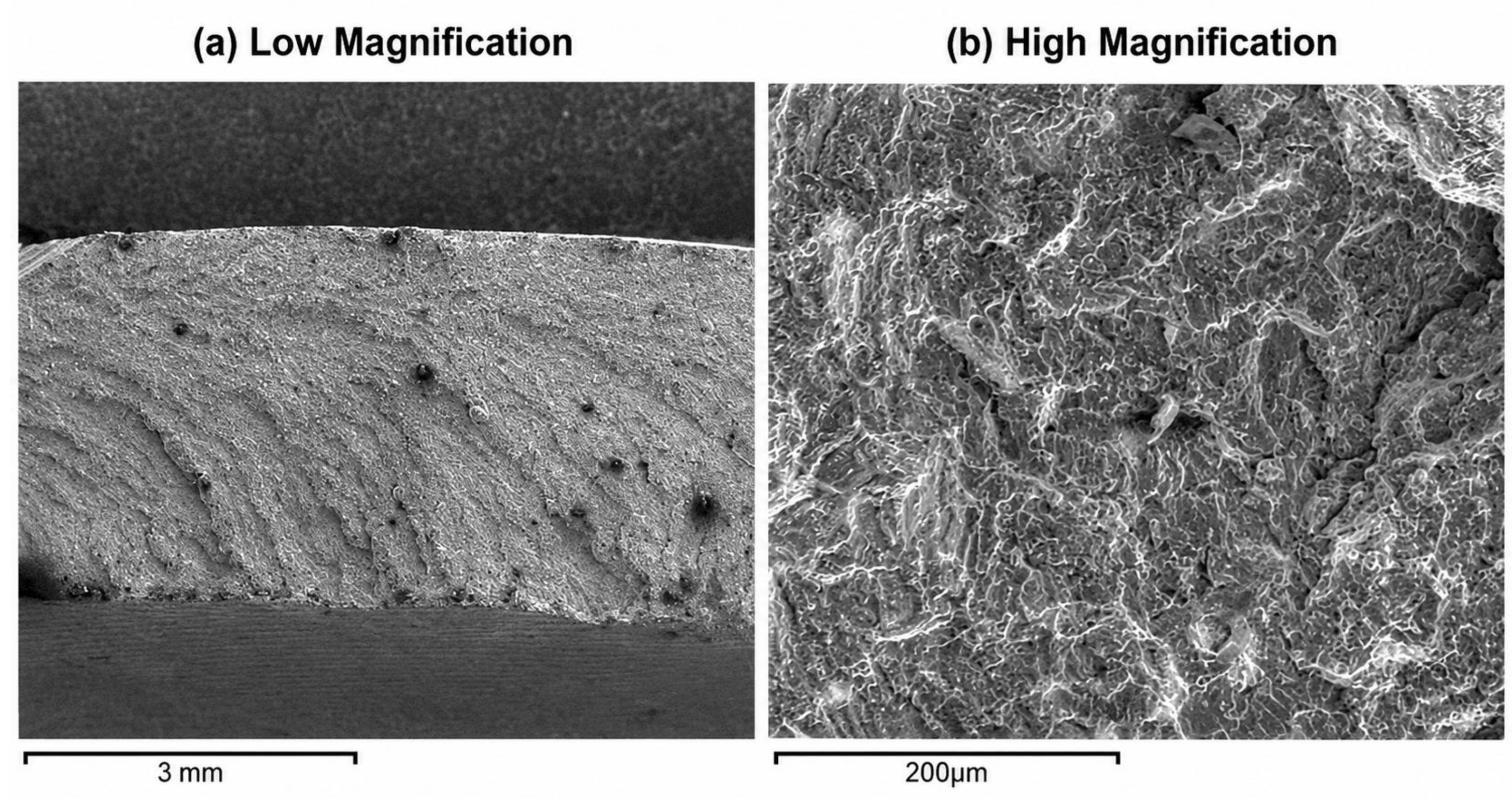


Figure 3. (a) Low-magnification SEM image showing circumferential brittle crack propagation through the weld-neck region; (b) High-magnification SEM image showing chevron patterns characteristic of unstable brittle fracture propagation.

Root Cause Statement
Inadequate solution heat treatment promoted extensive intermetallic (σ) phase precipitation, causing reduced ferrite content, severe embrittlement, and brittle fracture during hydrostatic testing.

CONCLUSION

- The DSS flange failed by brittle fracture during hydrostatic testing.
- Extensive sigma phase precipitation caused severe embrittlement.
- Chromium and molybdenum segregation confirmed intermetallic phase formation.
- Chromium-depleted regions increased susceptibility to localized corrosion.
- Material degradation was confined to a single heat number.
- Improper thermal exposure during heat treatment was identified as the root cause.
- Strict thermal process control and heat number traceability are essential to prevent recurrence.

A single improper heat treatment cycle transformed a high-performance duplex stainless steel into a brittle component that catastrophically failed during hydrostatic loading.

FUTURE WORK/ REFERENCES/ACKNOWLEDGMENT

Future Work
- Develop rapid screening methods for early sigma phase detection.
- Integrate metallurgical risk factors into integrity management programs.
- Establish predictive models linking thermal exposure and sigma phase precipitation.

References
- ASTM A240/A240M – Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet and Strip.
- ASTM G48 – Standard Test Methods for Pitting and Crevice Corrosion Resistance.
- ASTM A923 – Detecting Detrimental Intermetallic Phase in Duplex Stainless Steels.

Acknowledgement
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