

Journal of **Failure Analysis** — *and* **Prevention**



**Failure Analysis of
Alloy Steel Shaft with**

**Worm-Gearing System
Subjected to Dynamic
External Loading**

**Cracking Failures Due
to Sub-Surface Notch
Chipping**



Springer
JOURNAL OF FAILURE ANALYSIS
AND PREVENTION

ASIM
ASIAN SOCIETY OF
INTEGRATED MECHANICAL
ENGINEERING

Volume 38 Number 2 February 2020

ISSN 1056-4601
CODEN JFAPDH

Journal of Failure Analysis and Prevention



**Failure Analysis of
Long Service Life Steel**

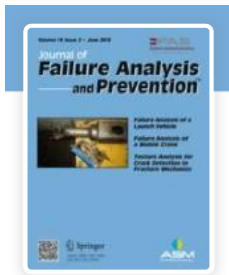
**Investigating the Role
of Hydrogen in the
Failure of Steel**

**Failure Analysis of
Steel in the Presence of
Hydrogen**



Taylor & Francis
Taylor & Francis Group
Taylor & Francis Group





Journal of Failure Analysis and Prevention

[Journal of Failure Analysis and Prevention](#) > [Volumes and issues](#) > Volume 19, issue 2

Search within journal

Volume 19, issue 2, April 2019

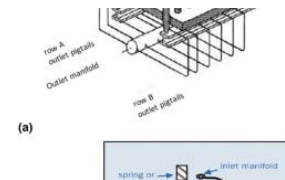
36 articles in this issue

[Failure Analysis of Incoloy 800HT and HP-Modified Alloy Materials in a Reformer](#)

Chris Maharaj, Andres Marquez & Riza Khan

Case History---Peer-Reviewed |

Published: 20 March 2019 | Pages: 291 - 300

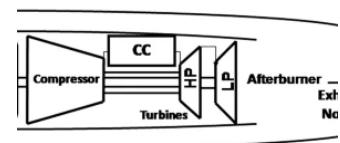


[Thermal Fatigue Failure of Low-Pressure Turbine Blade in a Low-Bypass Turbofan Engine](#)

R. K. Mishra & S. K. Jha

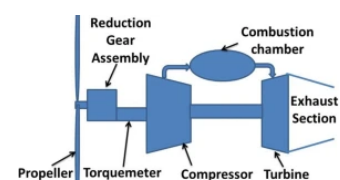
Case History---Peer-Reviewed |

Published: 18 March 2019 | Pages: 301 - 307



[Failure Analysis of a Cam Gear in the Torquemeter Assembly of a Turboprop Engine](#)

R. K. Mishra, D. Arul Kumaresan ... Vinay Kumar



Case History---Peer-Reviewed |

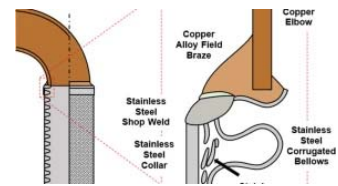
Published: 19 March 2019 | Pages: 308 - 313

[Failure of a Dissimilar Metal Braze in an Expansion Joint](#)

Brett A. Miller, Phillip D. Swartzentruber & Justin T. Barnes

Case History---Peer-Reviewed |

Published: 22 March 2019 | Pages: 314 - 319

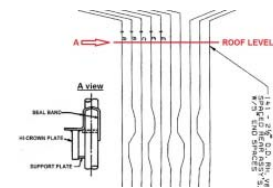


[Cracking of AISI T22 Reheater Pendant Assembly Tubing of Steam Boiler](#)

B. Erenburg, A. Zilberberg & E. Iskevitch

Case-History---Peer-Reviewed |

Published: 25 March 2019 | Pages: 320 - 327



[Product News](#)

News | Published: 27 March 2019 | Pages: 328 - 330



[Industry Updates](#)

News | Published: 27 March 2019 | Pages: 331 - 336



[Professional Resources](#)

News | Published: 27 March 2019 | Pages: 337 - 342



[Training](#)

Calendar | Published: 27 March 2019 | Pages: 343 - 346

Events

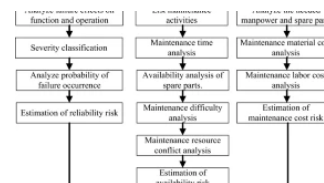
Calendar | Published: 01 April 2019 | Pages: 347 - 349

[An Extended FMECA Method and Its Fuzzy Assessment Model for Equipment Maintenance Management Optimization](#)

Ling Wang, Yangfen Gao ... Xiai Chen

Technical Article---Peer-Reviewed |

Published: 08 February 2019 | Pages: 350 - 360

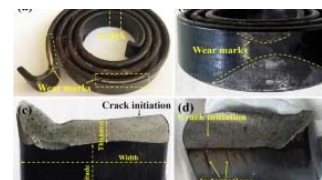


[Failure Analysis of an Automobile Coil Spring in High-Stress State](#)

Shuaijiang Yan, Qingxiang Wang ... Guodong Cui

Technical Article---Peer-Reviewed |

Published: 01 February 2019 | Pages: 361 - 368

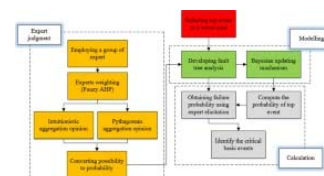


[Acquiring and Sharing Tacit Knowledge in Failure Diagnosis Analysis Using Intuitionistic and Pythagorean Assessments](#)

Mohammad Yazdi

Technical Article---Peer-Reviewed |

Published: 01 February 2019 | Pages: 369 - 386

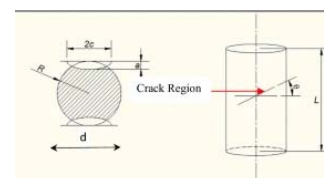


[Mixed-Mode Stress Intensity Factor Estimation of Inclined Cracks in an Unnotched Round Bar](#)

S. Suresh Kumar & M. E. Aniruthan

Technical Article---Peer-Reviewed |

Published: 12 February 2019 | Pages: 387 - 393

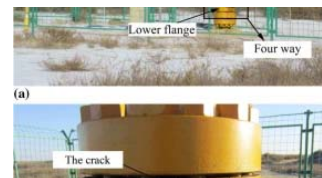


[Failure Analysis of a Four-Way Flange Cracking in a KQ65 Wellhead Christmas Tree](#)

Ji-ming Zhang, Xiqiang Wang ... Ping Du

Technical Article---Peer-Reviewed

Published: 04 February 2019 | Pages: 394 - 401

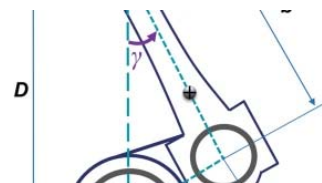


[Stress Analysis and Fatigue Life Assessment of a Piston in an Upgraded Engine](#)

Mohsen Najafi, Hadi Dastani ... Salim Pirani

Technical Article---Peer-Reviewed

Published: 05 March 2019 | Pages: 402 - 411



[Leakage on Water Cooling Distribution Pipe in a Hydroelectric Power Plant](#)

M. Nurbanasari, T. S. Purwanto ... Y. Irwan

Technical Article---Peer-Reviewed

Published: 30 January 2019 | Pages: 412 - 417

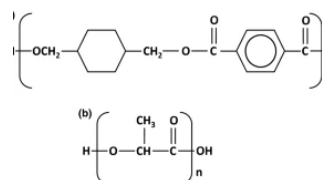


[Failure Analysis of Additively Manufactured Polyester Test Specimens Exposed to Various Liquid Media](#)

Israel A. Carrete, Diego Bermudez ... David A. Roberson

Technical Article---Peer-Reviewed

Published: 04 February 2019 | Pages: 418 - 430



[Application of Casting Simulation in Failure Analysis of Impeller](#)

Yudha Pratesa, Badrul Munir & Suryadi Najamuddin

Technical Article---Peer-Reviewed

Published: 08 February 2019 | Pages: 431 - 437



[Failure Analysis of the Tubes in a Methanol Synthesis Tower](#)

S. W. Liu, W. Z. Wang ... L. P. Guan

Technical Article---Peer-Reviewed

Published: 19 February 2019 | Pages: 438 - 444

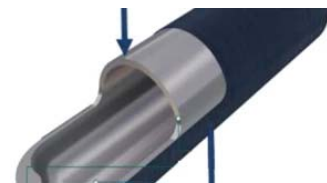


[Reliability Analysis of Type III Gas Storage Vessel Under Pressure Loading](#)

A. Ghouaoula, A. Hocine ... Rami Suleiman

Technical Article---Peer-Reviewed

Published: 22 March 2019 | Pages: 445 - 452



[Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant](#)

M. Nurbanasari, H. Abdurrachim & M. M. Prihadi

Technical Article---Peer-Reviewed

Published: 18 March 2019 | Pages: 453 - 460

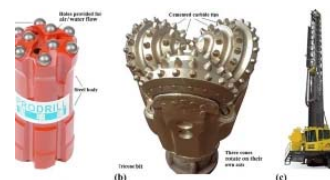


[On the Critical Assessment into Damage Behavior of a WC-Co Hard Metal Alloy Used in the Form of Rock Drill Bits](#)

Saurabh Dewangan

Technical Article---Peer-Reviewed

Published: 18 March 2019 | Pages: 461 - 470

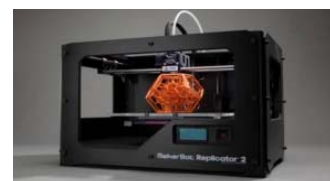


[Failure Analysis of Additive Manufactured Fiber-Reinforced Thermoplastics](#)

Siddharth M. Nayak, P. Balachandra Shetty ... G. R. Viraj

Technical Article---Peer-Reviewed

Published: 18 March 2019 | Pages: 471 - 475

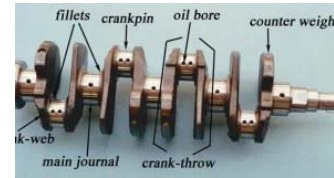


[Photoelastic Stress Analysis of Crankpin Fillets of a Crankshaft](#)

Riad Ahmad, Ahmad O. Hasan & Hani Al-Rawashdeh

Technical Article---Peer-Reviewed |

Published: 18 March 2019 | Pages: 476 - 487



[Evaluation of Failure and Repair of the Jebba and the Shiroro Hydroelectric Power Stations](#)

C. T. Thomas, O. Ogunbiyi ... B. J. Olufeagba

Technical Article---Peer-Reviewed |

Published: 21 March 2019 | Pages: 488 - 495

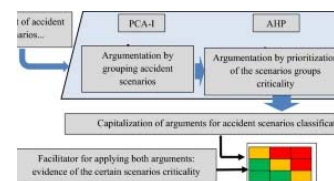


[PCA-I and AHP Methods: Unavoidable Arguments in Accident Scenario Classification](#)

Hefaidh Hadeef & Mébarek Djebabra

Technical Article---Peer-Reviewed |

Published: 21 March 2019 | Pages: 496 - 503

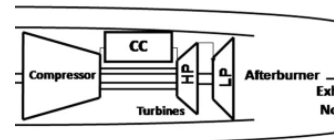


[Analysis of Low-Pressure Turbine Nozzle Guide Vane Failure in an Aero Gas Turbine Engine: A Computational Approach](#)

D. Arul Kumaresan & R. K. Mishra

Technical Article---Peer-Reviewed |

Published: 19 March 2019 | Pages: 504 - 510

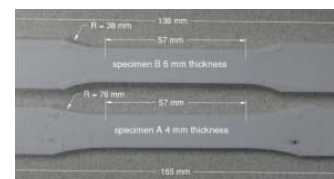


[Tensile and Fatigue Analysis of 3D-Printed Polyethylene Terephthalate Glycol](#)

Grzegorz Dolzyk & Sungmoon Jung

Technical Article---Peer-Reviewed |

Published: 26 March 2019 | Pages: 511 - 518

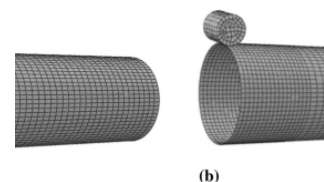


[Mechanical Behavior and Evaluation of Dented Pipe Caused by Cylindrical Indenter](#)

Chunyu Yu, Binqun Qiu ... Jie Zhang

Technical Article---Peer-Reviewed

Published: 25 March 2019 | Pages: 519 - 535

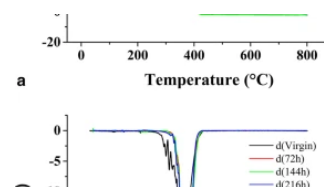


[Degradation of Polycarbonate Properties Under Thermal Aging](#)

Sonya Redjala, Rabah Ferhoum ... Said Azem

Technical Article---Peer-Reviewed

Published: 20 March 2019 | Pages: 536 - 542

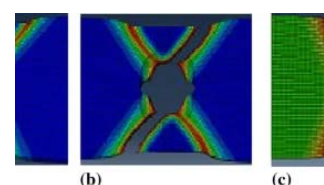


[Finite Element Failure Analyses of Structural Steel Solid and Perforated Tension Coupons](#)

K. K. Adewole & F. A. Olutoge

Technical Article---Peer-Reviewed

Published: 25 March 2019 | Pages: 543 - 550

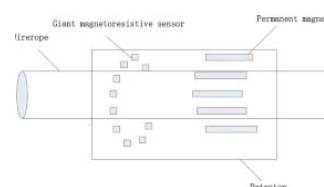


[Nondestructive Testing of Wire Ropes Based on Image Fusion of Leakage Flux and Visible Light](#)

Juwei Zhang & Shilei Wang

Technical Article---Peer-Reviewed

Published: 28 March 2019 | Pages: 551 - 560

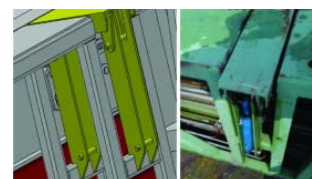


[Buckling Failure Analysis of Hydraulic Cylinder Rod on the Flap Institutions for Power Catwalk](#)

Qiaolei Sun, Zheng Chen ... Yiliu Tu

Technical Article---Peer-Reviewed

Published: 28 March 2019 | Pages: 561 - 569



[Erosion of an Arrow-Type Check Valve Duo to Liquid–Solid Flow Based on Computational Fluid Dynamics](#)

Xiaodong Zhang, Yongsen Chen & Wenwu Yang

Technical Article---Peer-Reviewed |

Published: 27 March 2019 | Pages: 570 - 580



[Ultimate Failure of Defective Pipelines Reinforced with Composite Repair Systems](#)

Rumu Chen, Jinshui Qiu ... Ganglu Ren

Technical Article---Peer-Reviewed |

Published: 29 March 2019 | Pages: 581 - 589



For authors

[Submission guidelines](#)

[Manuscript editing services](#)

[Ethics & disclosures](#)

[Open Access fees and funding](#)

[Contact the journal](#)

Submit manuscript 



Working on a manuscript?

Avoid the most common mistakes and prepare your manuscript for journal editors.

[Learn more](#) →

Explore

[Online first articles](#)

[Volumes and issues](#)

[Sign up for alerts](#)

Not logged in - 103.147.9.231

Not affiliated

SPRINGER NATURE

© 2023 Springer Nature Switzerland AG. Part of [Springer Nature](#).



Journal of Failure Analysis and Prevention

[Journal of Failure Analysis and Prevention](#) > Editors

Editors

Editor-in-Chief

Elvin Beach, The Ohio State University, Columbus, OH, USA

Associate Editors

Adam Boesenberg, Danfoss Power Solutions, Ames, IA, USA

Ryan Haase, Materials Evaluation and Engineering, Minneapolis, MN, USA

Joseph Maciejewski, Novelis, Inc., Kennesaw, GA, USA

Vir Nirankari, Exponent, Inc., Natick, MA, USA

Editorial Board

Milo Kral, Board Liaison, University of Canterbury, Christchurch, New Zealand; **Mark Barkey**, The University of Alabama, Tuscaloosa, AL, USA; **Daniel Benac**, Baker Risk Engineering, San Antonio, TX, USA; **Pierre Dupont**, Schaeffler Belgium Sprl/bvba, Dour, Belgium; **Margaret Flury**, Medtronic, Minneapolis, MN, USA; **Brad James**, Exponent Inc., Menlo Park, CA, USA; **Richard McSwain**, McSwain Engineering, Inc., Pensacola, FL, USA; **Brett Miller**, IMR Test Labs, Louisville, KY, USA; **David Moore**, Unified Engineering, Aurora, IL, USA; **George Pantazopoulos**, Elkeme SA, Athens, Greece; **Craig Schroeder**, Briggs & Stratton, New Berlin, WI, USA; **Roch Shipley**, Professional Analysis Consulting, Inc., Lisle, IL, USA; **Daniel Thomas**, Infinity Space, Cambridge, United Kingdom; **Dustin Turnquist**, Engineering Systems Inc., Englewood, CO, USA; **Mary Anne Fleming**, Staff Liaison, Senior Content Developer, Journals, ASM International, Materials Park, OH, USA

For authors

[Submission guidelines](#)

[Manuscript editing services](#)

[Ethics & disclosures](#)

[Open Access fees and funding](#)

[Contact the journal](#)

Submit manuscript 



Working on a manuscript?

Avoid the most common mistakes and prepare your manuscript for journal editors.

[Learn more](#) →

Explore

[Online first articles](#)

[Volumes and issues](#)

Sign up for alerts



Publish with us

[Authors & Editors](#)

[Journal authors](#)

[Publishing ethics](#)

[Open Access & Springer](#)

Discover content

[SpringerLink](#)

[Books A-Z](#)

[Journals A-Z](#)

[Video](#)

Other services

[Instructors](#)

[Librarians \(Springer Nature\)](#)

[Societies and Publishing Partners](#)

[Advertisers](#)

[Shop on Springer.com](#)

About Springer

[About us](#)

[Help & Support](#)

[Contact us](#)

[Press releases](#)

[Impressum](#)

Legal

[General term & conditions](#)

[California Privacy Statement](#)

[Rights & permissions](#)

[Privacy](#)

[How we use cookies](#)

[Manage cookies/Do not sell my data](#)

[Accessibility](#)

Not logged in - 103.147.9.231

Not affiliated

SPRINGER NATURE

© 2023 Springer Nature Switzerland AG. Part of [Springer Nature](#).

Journal of Failure Analysis and Prevention

COUNTRY	SUBJECT AREA AND CATEGORY	PUBLISHER	H-INDEX
<div>United States</div> <div><div>Universities and research institutions in United States</div><div>Media Ranking in United States</div></div>	<div>Engineering</div> <div><div>Mechanical Engineering</div><div>Mechanics of Materials</div><div>Safety, Risk, Reliability and Quality</div></div> <div>Materials Science</div> <div><div>Materials Science (miscellaneous)</div></div>	<div>Springer New York</div>	<div>29</div>
PUBLICATION TYPE	ISSN	COVERAGE	INFORMATION
<div>Journals</div>	<div>15477029, 18641245</div>	<div>2001-2021</div>	<div><div>Homepage</div><div>How to publish in this journal</div></div>

SCOPE

The Journal of Failure Analysis and Prevention (JFAP) is written for and read by individuals involved in failure analysis, materials scientists, and mechanical, manufacturing, aeronautical, civil, chemical, corrosion, and design engineers. The publication is unique in that it contains current news and technical articles, as well as archival peer-reviewed papers and reviews. JFAP provides information gathering techniques, technical analysis, and emerging tools that will assist failure analysis professionals in determining the cause of failures and eliminating failures in the future. Articles demonstrate the importance of failure analysis to product/performance improvements and industrial problem solving. JFAP is intended to be of interest to both the experienced and less experienced failure analysis practitioner with a focus on shared interest across the industries.

Join the conversation about this journal

FIND SIMILAR JOURNALS ?

1

Engineering Failure Analysis

NLD

58%

similarity

2

Corrosion Reviews

DEU

30%

similarity

3

Frattura ed Integrita Strutturale

ITA

28%

similarity

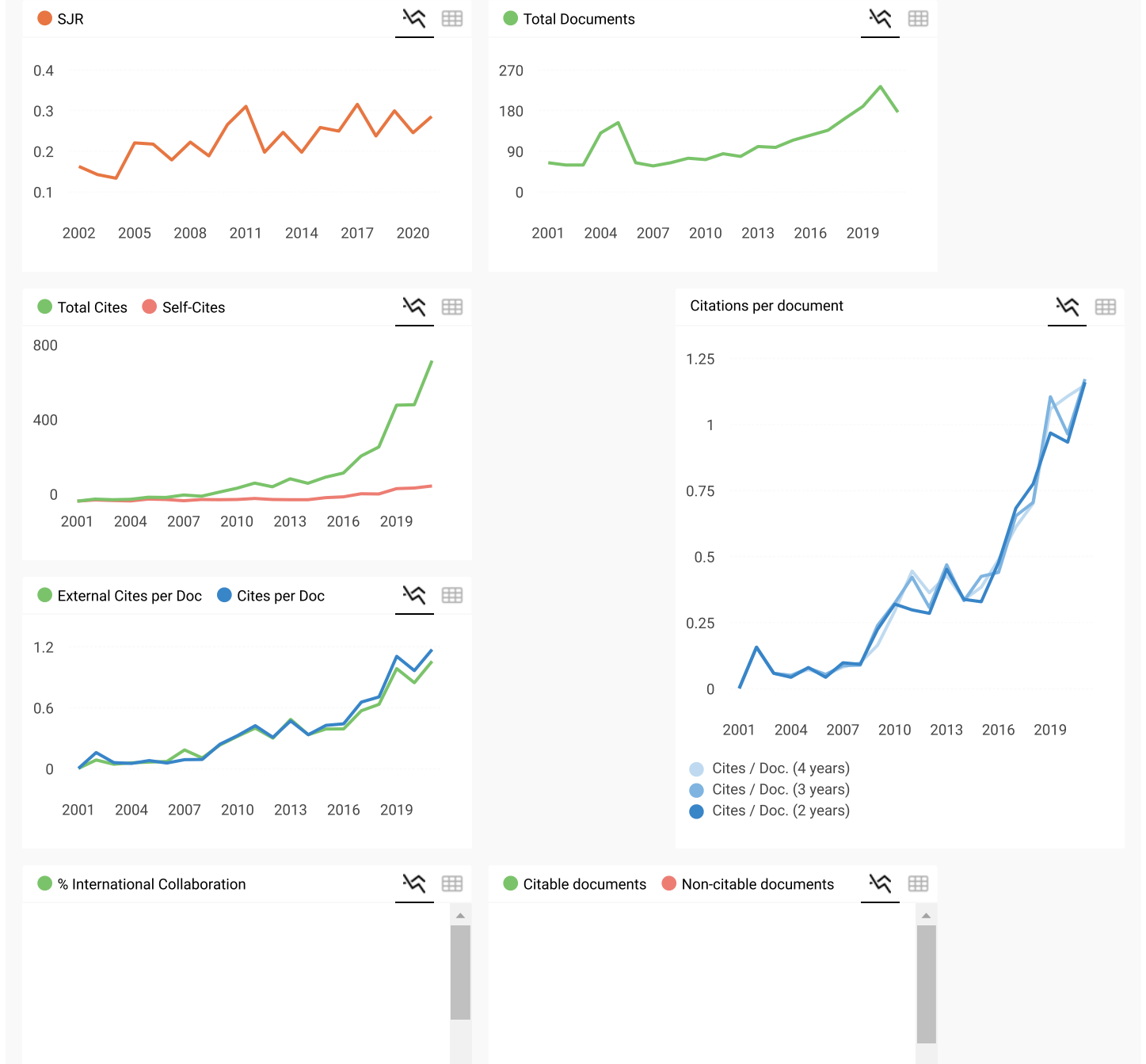
4

Journal of S Engineering

GBR

2

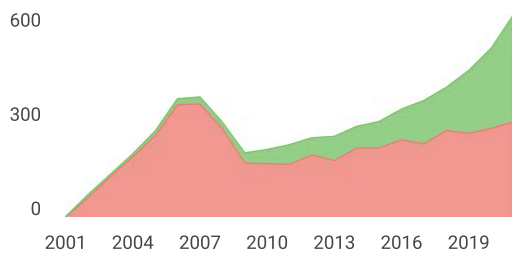
s



22.5

600

● Cited documents ● Uncited documents



Journal of Failure Analysis and Prevention

Q3

Materials Science (miscellaneous)

best quartile

SJIR 2021

0.29

powered by scimagojr.com

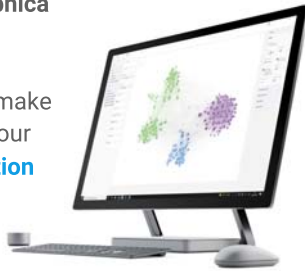
← Show this widget in your own website

Just copy the code below and paste within your html code:

```
<a href="https://www.scimaç
```

SCImago Graphica

Explore, visually communicate and make sense of data with our [new data visualization tool](#).



Metrics based on Scopus® data as of April 2022

A

Amin Suhadi 3 years ago

Dear Publisher,

could you tell me, how much do I have to pay if I want to publish my article in this journal (failure analysis and prevention).

thank you

sincerely

Amin Suhadi

Senior Researcher

BPPT-Indonesia

← reply

M

molly edward 2 years ago

nothing, it is free only if you need to activate the open access option

best regards



Melanie Ortiz 3 years ago

SCImago Team

Dear Amin,

thank you for contacting us.

We are sorry to tell you that SCImago Journal & Country Rank is not a journal. SJR is a portal with scientometric indicators of journals indexed in Elsevier/Scopus.

Unfortunately, we cannot help you with your request, we suggest you visit the journal's homepage (See submission/author guidelines and fees, if there are any) or contact the journal's editorial staff , so they could inform you more deeply.

Best Regards, SCImago Team

Leave a comment

Name

Email

(will not be published)



I'm not a robot

reCAPTCHA
Privacy - Terms

Submit

The users of Scimago Journal & Country Rank have the possibility to dialogue through comments linked to a specific journal. The purpose is to have a forum in which general doubts about the processes of publication in the journal, experiences and other issues derived from the publication of papers are resolved. For topics on particular articles, maintain the dialogue through the usual channels with your editor.

Developed by:



Powered by:



Follow us on @ScimagoJR

Scimago Lab, Copyright 2007-2022. Data Source: Scopus®

EST MODUS IN REBUS

Horatio (Satire 1,1,106)

[Cookie settings](#)

[Cookie policy](#)

[Home](#) > [Journal of Failure Analysis and Prevention](#) > [Article](#)

Technical Article---Peer-Reviewed |

[Published: 18 March 2019](#)

Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant

[M. Nurbanasari](#) , [H. Abdurrachim](#) & [M. M. Prihadi](#)[Journal of Failure Analysis and Prevention](#) **19**, 453–460 (2019)**205** Accesses | **1** Citations | [Metrics](#)

Abstract

A failure analysis was carried out on an A213 T91 secondary superheater tube after 4 months of overhaul. The failure caused the 600-MW coal power plant was shut down. The investigation consisted of visual inspections, microstructure analysis, Vickers hardness test, x-ray diffraction, and ash fusion temperature test and ash content analysis. The failed tube had a thin-lip rupture with sharp edges and experienced a decrease in hardness in the area of lip rupture. The microstructure analysis shows the coarse carbide and some isolated voids. Corrosion products were detected in slag deposits, and nonuniform thin oxide layer in the inner wall of the tube was observed. It is concluded that the main failure of the failed tube was due to the formation of slag deposits on the

outer surface of the tube wall. This formation has resulted in simultaneously occurring phenomena, which was the localized flue gas erosion followed by the rapid overheating of the tube. The formation of slag deposits was in consequence of the use of coal with lower ash fusion temperature than required coal ash fusion temperature for the power plant.

This is a preview of subscription content, [access via your institution](#).

Access options

Buy article PDF

39,95 €

Price includes VAT (Indonesia)

Instant access to the full article PDF.

[Rent this article via DeepDyve.](#)

[Learn more about Institutional subscriptions](#)

References

1. G.K. Gupta, S. Chattopadhyaya, Critical failure analysis of superheater tubes of coal-based boiler. *Strojniški vestnik J. Mech. Eng.* **63**(5), 287–299 (2017)

2. D.R.H. Jones, Creep failures of overheated boiler, superheater and reformer tubes. Eng. Fail. Anal. **11**(6), 873–893 (2014)

3. A. Saha, H. Roy, Failure investigation of a secondary super heater tube in a 140MW thermal power plant. Case Stud. Eng. Fail Anal. **8**, 57–60 (2017)

4. A.K. Pramanick et al., Failure investigation of super heater tubes of coal fired power plant. Case Stud. Eng. Fail. Anal. **9**, 17–26 (2017)

5. G.A. Lamping, R.M.J. Arrowood, Manual for investigation and correction of boiler tube failures. Final report. Southwest Research Institute, San Antonio, USA, 331 (1985)

6. Z.-F. Hu, D.-H. He, X.-M. Wu, Failure analysis of T12 boiler re-heater tubes during short-term service. J. Fail. Anal. Prev. **14**(5), 637–644 (2014)

7. S. Srikanth et al., Analysis of failures in boiler tubes due to fireside corrosion in a waste heat recovery boiler. Eng. Fail. Anal. **10**(1), 59–66 (2003)

8. S. Chaudhuri, Some aspects of metallurgical assessment of boiler tubes-Basic principles and

case studies. Mater. Sci. Eng. A **432**(1–2), 90–99 (2006)

9. F. Masuyama, Creep rupture life and design factors for high-strength ferritic steels. Int. J. Press. Vessels Pip. **84**(1), 53–61 (2007)

10. I.J. Perrin, J.D. Fishburn, A perspective on the design of high-temperature boiler components. Int. J. Press. Vessels Pip. **85**(1), 14–21 (2008)

11. R.K. Roy et al., Analysis of superheater boiler tubes failed through non-linear heating. Procedia Eng. **86**, 926–932 (2014)

12. R.W. Bryers, Fireside slagging, fouling and high temperature corrosion of heat transfer surface due to impurities in steam-raising fuels. Prog. Energy Combust. Sci. **22**(1), 29–120 (1996)

13. A. Movahedi-Rad, S.S. Plasseyed, M. Attarian, Failure analysis of superheater tube. Eng. Fail. Anal. **48**, 94–104 (2015)

14. S. Chaudhuri, R. Singh, High temperature boiler tube failures, Case studies, in *Proceeding: COFA*. 1997 (Jamshedpur, India), pp. 107–120

15. J.H. Swisher, S. Shankarnarayan, Inhibiting vanadium induced corrosion. Mater. Perform. **33**(9), 49 (1994)

16. D. Young, *High Temperature Oxidation and Corrosion of Metals*, 2nd edn. (Elsevier, Amsterdam, 2016)

Author information

Authors and Affiliations

**Department of Mechanical Engineering,
Institut Teknologi Nasional, Jl. PHH.
Mustapha 23, Bandung, 40124, Indonesia**
M. Nurbanasari & M. M. Prihadi

**Department of Mechanical Engineering,
University of Pasundan, Jl. Dr. Setiabudi
No. 193, Bandung, 40132, Indonesia**
H. Abdurrachim

Corresponding author

Correspondence to [M. Nurbanasari](#).

Additional information

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Rights and permissions

[Reprints and Permissions](#)

About this article

Cite this article

Nurbanasari, M., Abdurrachim, H. & Prihadi, M.M. Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant. *J Fail. Anal. and Preven.* **19**, 453–460 (2019). <https://doi.org/10.1007/s11668-019-00619-9>

Received	Published	Issue Date
07 November 2018	18 March 2019	15 April 2019

DOI

<https://doi.org/10.1007/s11668-019-00619-9>

Keywords

Superheater tube

Flue gas

Overheating

Erosion

Not logged in - 103.147.9.231

Not affiliated

SPRINGER NATURE

© 2023 Springer Nature Switzerland AG. Part of [Springer Nature](#).

Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant

M. Nurbanasari, H. Abdurrachim & M. M. Prihadi

Journal of Failure Analysis and Prevention

ISSN 1547-7029

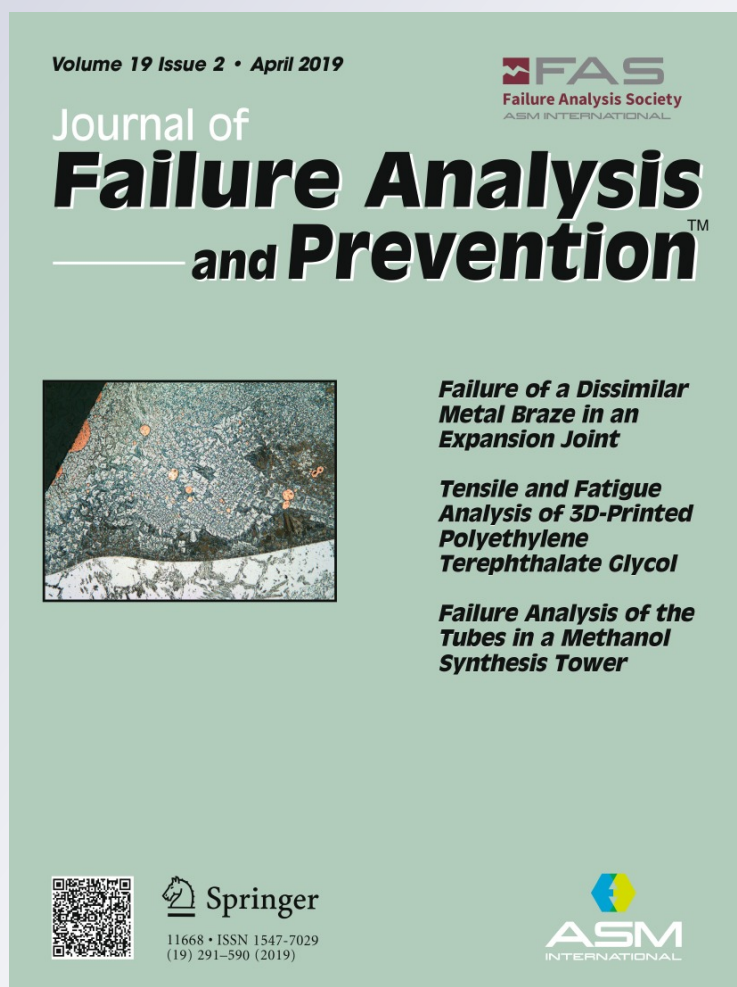
Volume 19

Number 2

J Fail. Anal. and Preven. (2019)

19:453-460

DOI 10.1007/s11668-019-00619-9



Your article is protected by copyright and all rights are held exclusively by ASM International. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com".



TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant

M. Nurbanasari · H. Abdurrachim · M. M. Prihadi

Submitted: 7 November 2018 / Published online: 18 March 2019
 © ASM International 2019

Abstract A failure analysis was carried out on an A213 T91 secondary superheater tube after 4 months of overhaul. The failure caused the 600-MW coal power plant was shut down. The investigation consisted of visual inspections, microstructure analysis, Vickers hardness test, x-ray diffraction, and ash fusion temperature test and ash content analysis. The failed tube had a thin-lip rupture with sharp edges and experienced a decrease in hardness in the area of lip rupture. The microstructure analysis shows the coarse carbide and some isolated voids. Corrosion products were detected in slag deposits, and nonuniform thin oxide layer in the inner wall of the tube was observed. It is concluded that the main failure of the failed tube was due to the formation of slag deposits on the outer surface of the tube wall. This formation has resulted in simultaneously occurring phenomena, which was the localized flue gas erosion followed by the rapid overheating of the tube. The formation of slag deposits was in consequence of the use of coal with lower ash fusion temperature than required coal ash fusion temperature for the power plant.

Keywords Superheater tube · Flue gas · Overheating · Erosion

Introduction

A boiler plays a vital element in coal-fired power plants. It consists of important components to maintain the power supply such as boiler tubes, superheater, economizer and air heater. One of the crucial components of pressure parts is the superheater tube that is basically a heat exchanger in which heat is transferred from furnace gas to steam. The superheater tubes experience high pressure and are located in the radiation zone of boiler. The temperature of flue gas (hot gas) in this zone is around 700 °C, and the temperature of steam coming out of the superheater tubes is around 540 °C [1]. Although the tubes usually are used for 20 years and some have been in use for much longer, tube failure often occurs. Improper heat transfer between steam and furnace gas in the superheater tube creates serious problems, which leads to shut down the whole power plant. It has been reported that creep damage [1–4], fatigue [5, 6], excessive thermal stresses, water/steam corrosion [7], short-term overheating [8] are general mode failures of superheater tubes. This paper reports a failure analysis on secondary superheater tubes in a 600-MW coal power plant that has operated for 22 years to prevent the same failures in the future. The power plant was shut down after operating for 4 months since overhaul maintenance in December 2017. It seems that during overhaul maintenance, the cleaning process was done poorly as the tubes were covered with thick slag deposits (see Fig. 1). The power plant was designed for coal with ash fusion temperature of 1300 °C. The design temperature and the operating pressure of the tube were 540 °C and 17 MPa, respectively. The original outside diameter of the failed tube was 60.3 mm, and wall thickness was 8.0 mm. The

M. Nurbanasari (✉) · M. M. Prihadi
 Department of Mechanical Engineering, Institut Teknologi Nasional, Jl. PHH. Mustapha 23, Bandung 40124, Indonesia
 e-mail: meilinda@itenas.ac.id

M. M. Prihadi
 e-mail: marzuqiprihadi@gmail.com

H. Abdurrachim
 Department of Mechanical Engineering, University of Pasundan, Jl. Dr. Setiabudi No. 193, Bandung 40132, Indonesia
 e-mail: halim.ar@unpas.ac.id

leaked tubes were removed and then replaced. One piece of failed tube was received for conducting the investigation.

Methodology

Failure analysis was performed on the failed (leaked) tube. The investigated tube is shown in Fig. 2, and visual inspection was carried out around the lip rupture. For detailed analysis, the failed tube was cut along the cross section and some microstructure/hardness samples were collected from different locations (numbers 1, 2 and 3 in Fig. 2).

The metallographic samples were prepared by using standard metallographic techniques, and the samples were etched with 3% nital solution to reveal the microstructures.



Fig. 1 Secondary superheater tubes in installed condition taken from the manhole

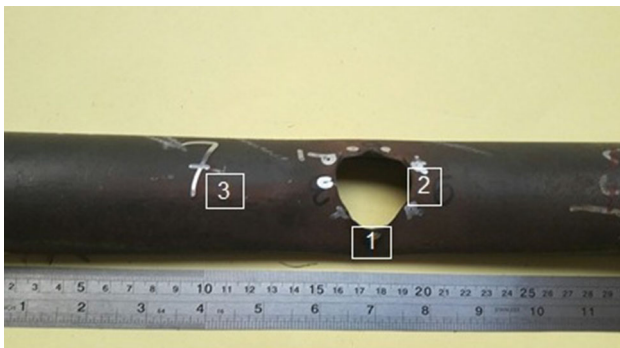


Fig. 2 Cross section of the failed tube (the numbers indicate the location of samples)

The microstructure was analyzed by optical and scanning electron microscope (SEM) equipped with an energy-dispersive x-ray (EDX) analysis facility. Average hardness data were taken from six times measurement on the microstructure samples conducted on Vickers hardness tester with a 500 g load and dwelling time of 15 s. X-ray diffraction was also conducted to identify the slag deposits of fly ash on the outer wall of the tube. The International Centre for Diffraction Data (ICDD) database from 2002 was applied to identify the phases present. In addition, the samples for chemical composition and microstructure analysis for material verification of the failed tube were taken 500 mm away from the lip rupture. The bulk chemical composition of slag was analyzed by optical emission spectrometer, and the wall thickness was measured by a micrometer. Ash fusion temperature test and coal fly ash analysis of the slag deposits were also performed to evaluate the melting and slagging behavior using the standard method of ASTM D1857-2017 and ASTM D3682-2013, respectively.

Results and Discussion

Material Verification of the Failed Tube

The optical emission spectrometer result shows that the chemical composition of the failed tube consists of 0.12% C, 0.48% Mn, 8.89% Cr, 1% Mo, 0.39% Si, 0.2% V, 0.02% P, 0.004% S (in wt.%) and the remainder is iron. Microstructure analysis in Fig. 3 (the location of sample number 3 in Fig. 2) exhibits that the failed tube had carbides along the grain boundaries with ferrite matrix and the average hardness is 196 HV.

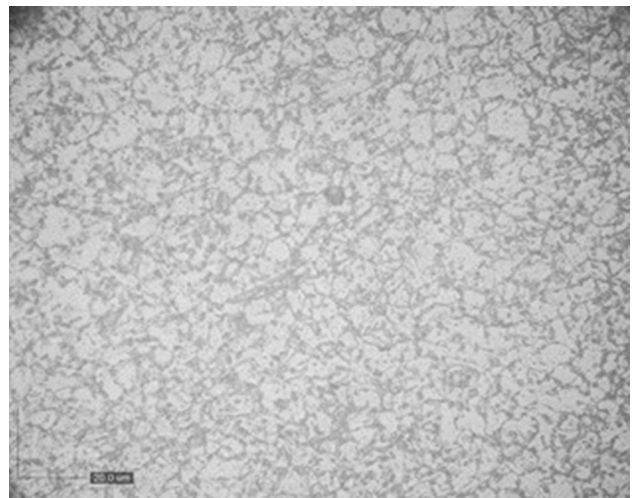


Fig. 3 An optical image of microstructure taken 500 mm away from the thin-lip rupture

Based on the aforementioned data, it can be concluded that the steel of the failed tube is in good agreement with the standard of ASTM A213 T91. The steel has been used widely for power plant application and has very good creep strength and good resistance to oxidation [9, 10]. Hence, failure owing to faulty chemistry of the steel is ignored.

Failure Analysis of Failed Tube

Visual Inspection

Visual inspection on the failed secondary superheater tube in Fig. 4a exhibits that the tube had a sharp edges and thin-lip rupture in the dimension around of 35 mm length and 36 mm width. The wall thickness measurement on the edge rupture shows the thickness reduction did not occur uniformly and the wall thickness was in the range 0.90–2.89 mm or 65–88% of the original wall thickness. The color around the lip rupture was light brown pertaining to superficial iron oxides. There is a change in color because during the operation the tube interacted with an extreme environment where steam flowed inside of the tube and the outside of the tube was exposed to flue gas (hot gas). No material loss was observed at the inner surface of the tube in Fig. 4b, which indicated that the thinning of the failed

tube took place at outer surface. Visual inspection also reveals that the tube was bent or exhibited a bowed shape as shown in Fig. 5.

Microscopic Examinations

A SEM micrograph of inner surface of the tube wall in the opposite side of the lip rupture is shown in Fig. 6. As can be seen, the tube had adherent nonuniform oxide scale layer with the thickness ranging from 0.223 to 0.272 mm that formed during the long-term operation. As the oxide layer is very thin, it will not block the flow of steam; hence, it is believed that the tube failure occurred due to factors outside of the tube wall.

A SEM image in Fig. 7a (the location of sample number 3 in Fig. 2) shows dispersed carbides and the presence of some isolated voids, which indicate creep damage. Furthermore, the microstructure on the lip rupture in Fig. 7b (the location of sample number 2 in Fig. 2) reveals that the long-term service in high temperature caused the carbide appearance to become spherical particles in a ferrite matrix and the void had been interconnected and formed a crack. The presence of some isolated voids and coarse carbides is related to overheating [1, 11] and creep damage. In addition, ductile fracture was also observed in the failed zone as seen in Fig. 7c (the location of sample number 1 in Fig. 2), which strengthens the evidence that the material had experienced softening and overheating.

To support the data, SEM-EDS analysis was carried out on the outer surface of the tube wall near the lip rupture. The result of SEM EDS in Fig. 8a shows the EDS spectra of inorganic elements, i.e., Si, Ca, Al, Fe, Ti and V, which contributed to the formation of slag deposits [12]. The presence of those inorganic elements is also supported by fly ash content analysis which evidences the content of TiO_2 as 0.58%, Al_2O_3 as 15.43% and Fe_2O_3 as 12.64%. Fly ash content analysis also detected the presence of Na_2O with the amount of 1.84%. It could be determined that those elements came from the fuel and coal being used in the combustion [13], which might relate to poor and incomplete fuel combustion conditions. It must be noted that the existence of certain inorganic elements in coal such as Si, Ti, V and Na would decrease the ash fusion temperature. SEM-EDS quantitative data of Fig. 8a in Table 1 show the

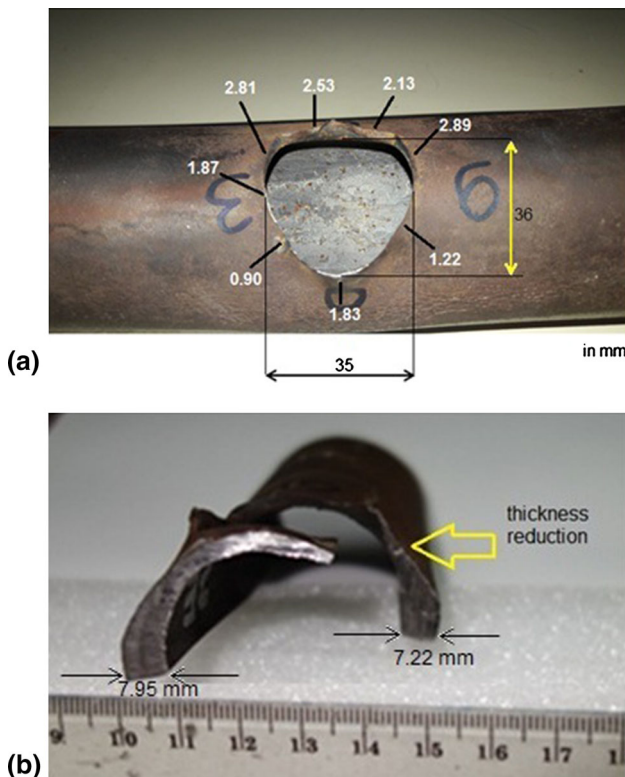
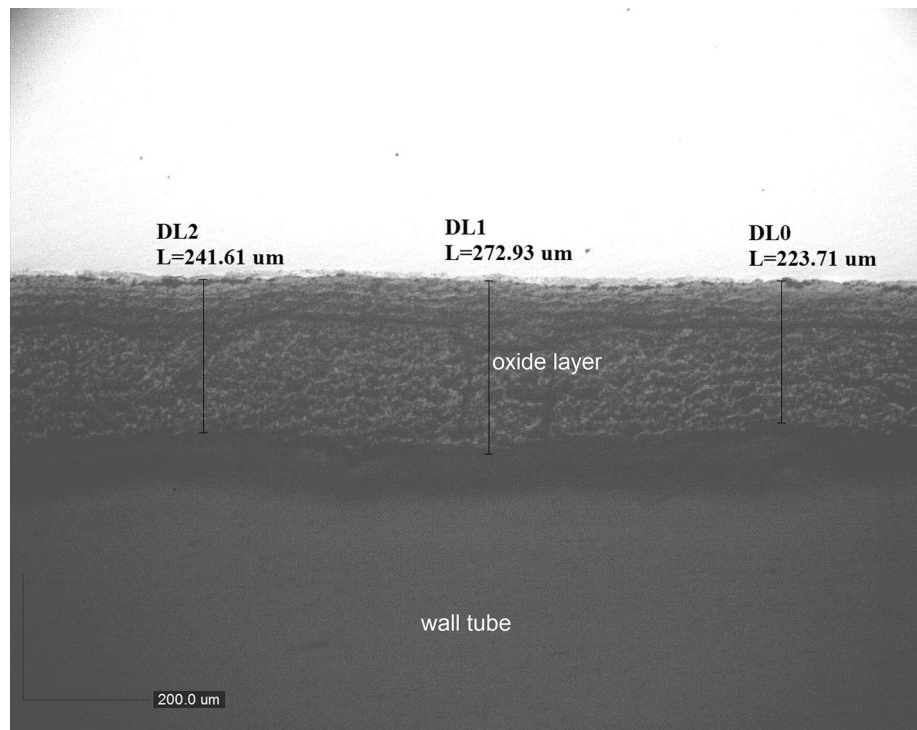


Fig. 4 (a) Failed tube suffered a thin-lip rupture (white numbers indicate the thickness). (b) Cross-sectional cutting of the failed tube shows that reduction in wall thickness started from the outer wall



Fig. 5 Failed tube experienced plastic deformation (bowed shaped)

Fig. 6 Thickness of the thin adherent oxide scale layer at the inner surface in the opposite side of the lip rupture



presence of corrosive elements (Si and Ca) is below 20% mass (see Table 1) which suggested that the corrosion attack had occurred and was caused by the fusion of ash particles [14]. The spectrum of vanadium was also detected by SEM-EDS analysis as shown in Fig. 8b. The presence of vanadium with the amount of 0.75% mass (see Table 2) caused corrosion due to the formation of V_2O_5 which has a melting point of 690 °C [15, 16].

X-ray Diffraction Study

Slag deposits identification taken from outer wall of the tube was conducted using x-ray diffraction, and the results are presented in Fig. 9. The results obtained from XRD in Fig. 9 identified that deposits consist of alkali sulfate compound ($CaSO_4$) and corrosion products (iron oxides), which evidence the failed tube had suffered corrosion attack. The compound $CaSO_4$ caused coal/fly ash corrosion on the interface of scale/metal tube with a temperature range of 566–732 °C. The compound with low melting point formed molten flux at operating temperature and eliminated oxide layer which led to the tube being exposed. Overtime, metal tube continued to be consumed and a reduction in wall thickness caused it to be nonuniform and damaged. Therefore, it is evident that coal/fly ash corrosion occurred and started with an

accumulation of fly ash on the surface of a tube that operated at a temperature of 540–705 °C [12].

Microhardness Results

The hardness test on the failed tube in Table 3 shows variation in hardness on the lip rupture (the location of sample numbers 1 and 2 in Fig. 2) compared to the area away from the lip rupture (the location of sample number 3 in Fig. 2). With respect to the material hardness of ASTM A213 T91, the significant decrease in hardness near the lip rupture indicates that the creep damage and material softening during service had occurred.

Discussions

From the evidence, failure mechanism in secondary superheater tube can be explained further using the following illustration of superheater tube with slag deposits on the outer wall of the tube as shown in Fig. 10.

Flue gas flow upward between the two tubes with slag deposits in the outer wall (see Fig. 10). Slag deposits caused the flue gas flow to be nonuniform where the flow which went through the slag deposits was slower. As the volume of the flue gas stayed the same, the flow

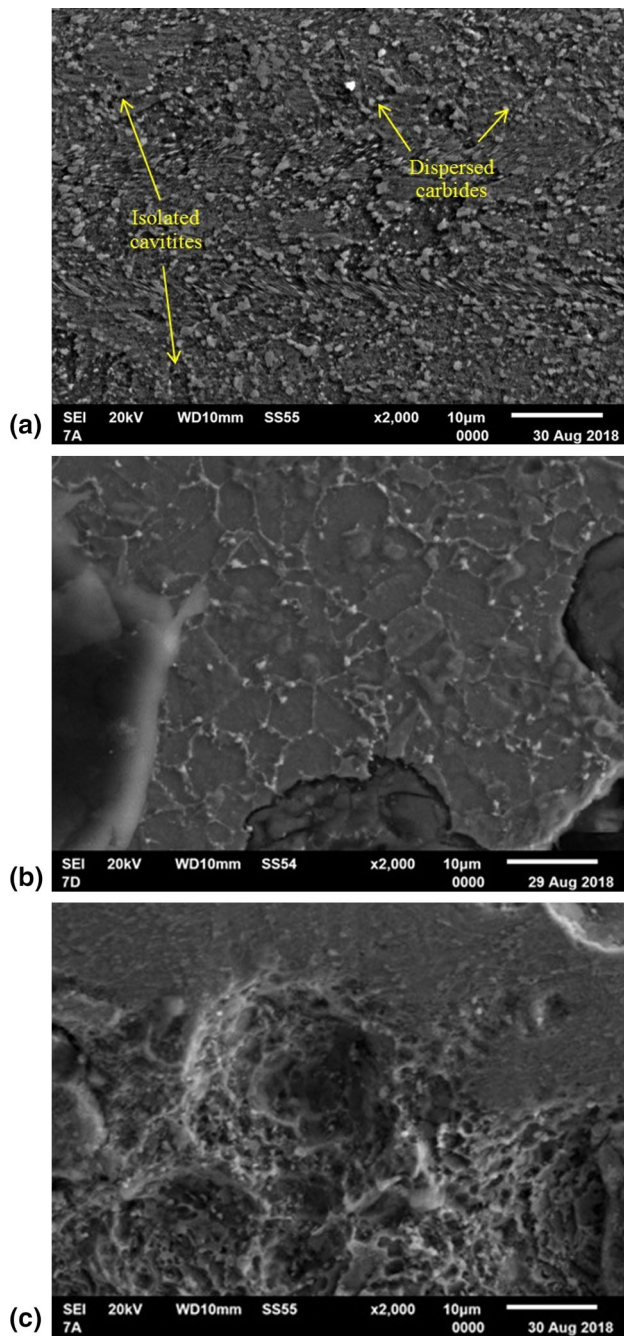


Fig. 7 (a) A secondary electron of the SEM image shows dispersed carbides and isolated cavities. (b) A secondary electron of the SEM image shows coarse carbides near the lip rupture. (c) A secondary electron of the SEM image shows a typical dimpled-rupture fracture surface

which went through areas free of slag deposits became faster and led to turbulence. This then caused localized erosion on the outer wall surface and decrease in thickness nonuniformly in the affected area significantly.

The turbulence that occurred in the localized erosion area resulted in the accumulation of heat and led to overheating. It must be noted that the rate of heat transfer in the outer wall with slag deposits was lower than the area which was not covered with slag deposits. This condition caused the outer surface of the tube wall temperature on the area covered by slag deposits to be decreased and the outer surface of the tube wall that was not covered by slag deposits to be increased. The localized rapid overheating beyond the operating temperature drove the flow of material and softened the tube wall. Due to the localized wall thinning and softening of the tube, the tube was unable to withstand the hoop stress with the result that the tube was bent or had a bowed shape (see Fig. 5) leading to a failure due to overloading [1] and resulting in ductile fractures as shown by dimple rupture (see Fig. 7c).

In this case, although corrosion attack had occurred and creep damage was observed, they did not contribute significantly to the main failure of the tube. Hence, it is concluded that the tube failed because of slag deposit formation on the outer surface of the tube wall, which resulted in two simultaneous mechanisms: localized flue gas erosion followed by rapid overheating.

It is clearly evident that the formation of slag deposits on the outer surface of the tube wall is the main cause of the tube failure. It was mentioned previously that the power plant was designed for coal with fly ash temperature of 1300 °C; however, the result of ash fusion temperature test shows that the power plant used coal with fly ash temperature of 1100 °C. The low ash fusion temperature of the used coal was due to the presence of inorganic trace elements as proven by SEM EDS analysis and fly ash content analysis of the slag deposits. If ash fusion temperature is low, ash particles can easily fuse and adhere to the outer surface of the tube wall, forming larger particles and finally causing the slag layer to grow thicker.

Conclusions

Based on the aforementioned data and discussions, the following conclusions are drawn:

- (a) The material of the failed tube is satisfied with the specification of ASTM A213 T91 grade steel and suitable for secondary superheater application.
- (b) The main cause of failure in the secondary superheater tube was due to the formation of slag deposits on the outer wall of the tube causing two

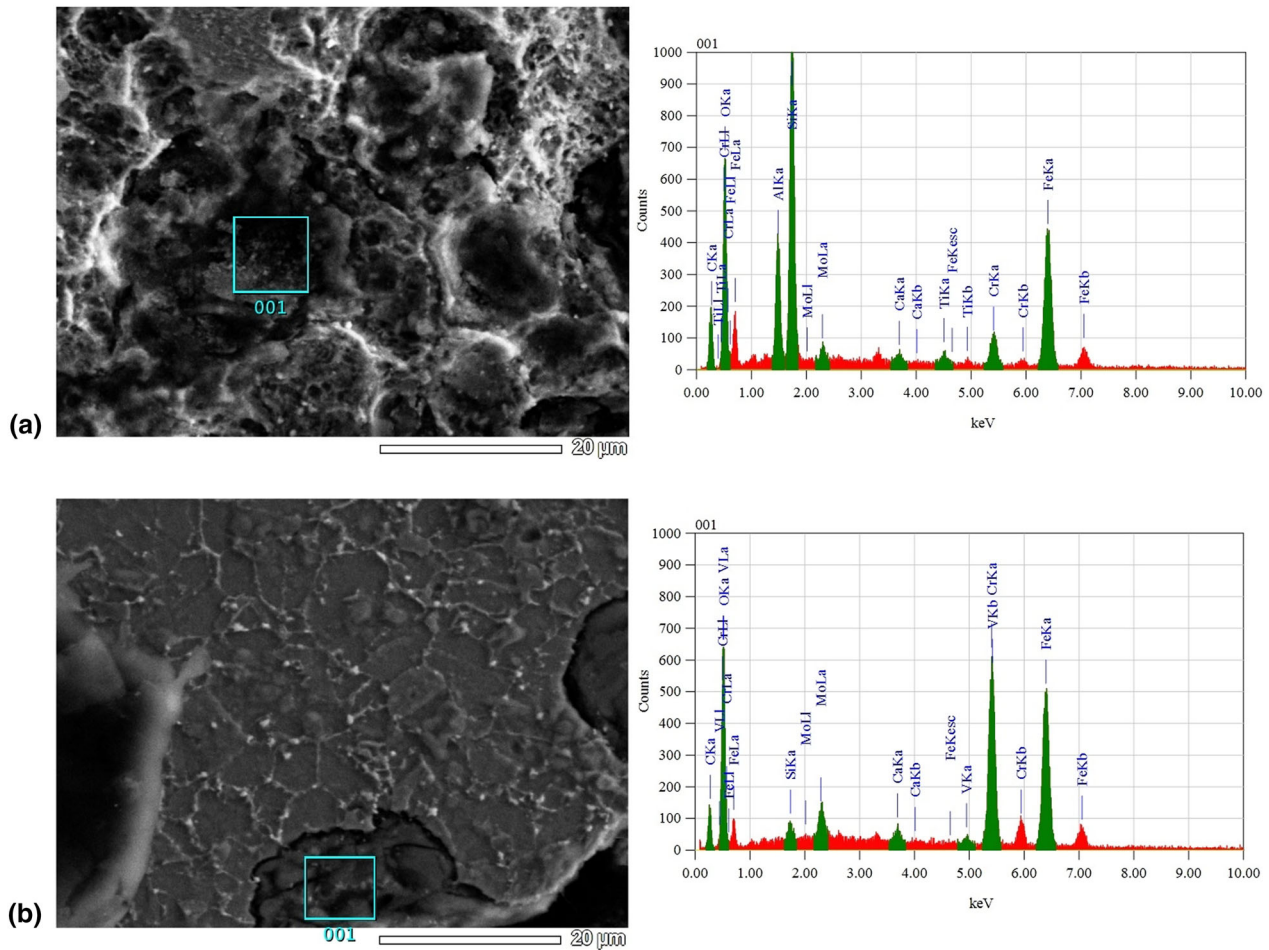


Fig. 8 (a) EDS spectrum taken near lip rupture (the location of sample number 1 in Fig. 2). (b) EDS spectrum taken near lip rupture (the location of sample number 2 in Fig. 2)

Table 1 SEM-EDS quantitative data on the lip rupture in mass % (the location of sample number 1 in Fig. 2)

Element	% mass
C	18.35
O	30.75
Al	5.48
Si	14.79
Ca	0.45
Ti	0.88
Cr	3.31
Fe	23.80

Table 2 SEM-EDS quantitative data on the lip rupture in mass % (the location of sample number 1 in Fig. 2)

Element	% mass
C	10.51
O	25.10
Si	0.75
Ca	0.77
V	0.75
Cr	24.43
Fe	33.24

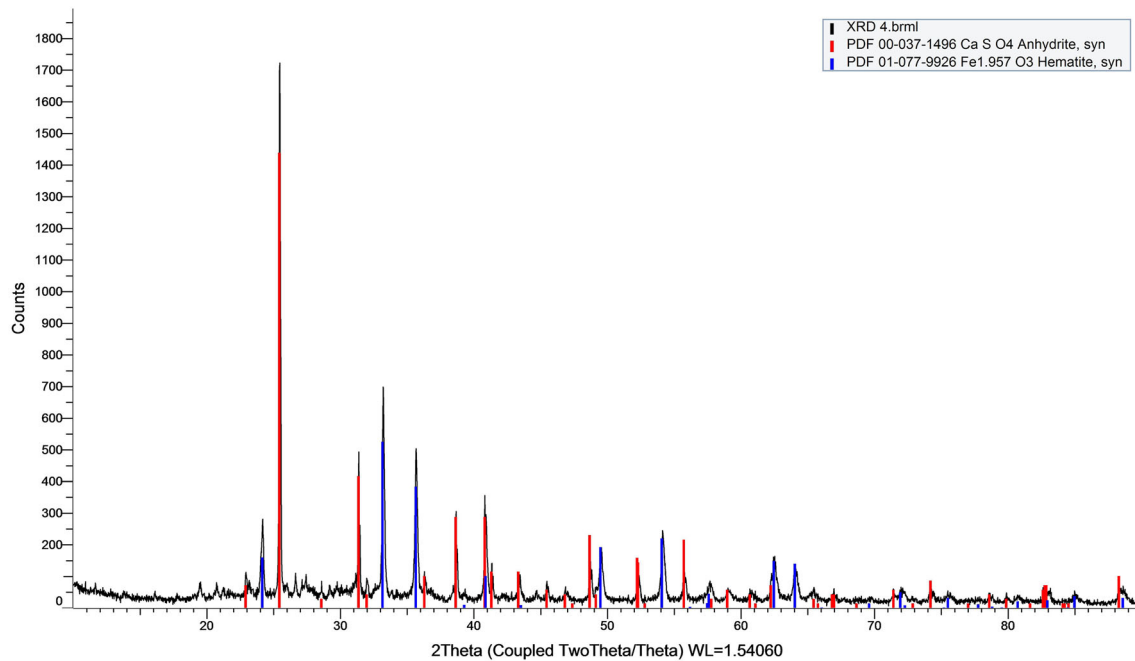


Fig. 9 Characteristic of x-ray diffraction spectrum from slag deposits shows the presence of CaSO_4 and iron oxides

Table 3 Hardness data of the failed tube in different locations (for the location, see Fig. 2)

Location	1	2	3
Hardness (HV)	154.0	155.7	191.1

- (c) The formation of the slag on the outer surface of the tube wall owing to the ash fusion temperature of the used coal was lower than required coal ash fusion temperature.

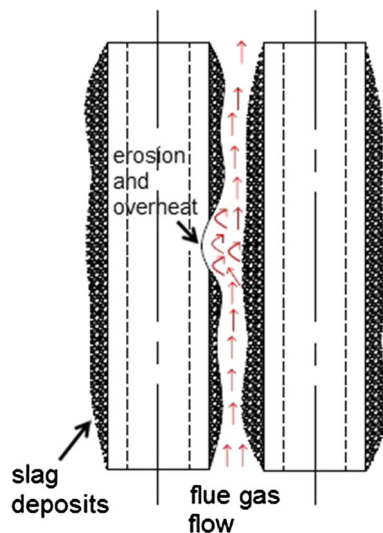


Fig. 10 Illustration of failure mechanism on superheater tube with scale on the outer wall of the tube

simultaneous phenomena that came into play, namely localized flue gas erosion and followed by rapid overheating.

Recommendations

Future actions to prevent failures are as follows:

- Carry out regular check on air-to-fuel ratio in order to avoid any excess air which can cause incomplete combustion in the superheater.
- Use coal with the required ash fusion temperature.
- Soot blowing must be carried out periodically and properly according to the manual procedure to remove slag deposits from the tubes.

References

- G.K. Gupta, S. Chattopadhyaya, Critical failure analysis of superheater tubes of coal-based boiler. *Strojniški vestnik J. Mech. Eng.* **63**(5), 287–299 (2017)
- D.R.H. Jones, Creep failures of overheated boiler, superheater and reformer tubes. *Eng. Fail. Anal.* **11**(6), 873–893 (2014)
- A. Saha, H. Roy, Failure investigation of a secondary super heater tube in a 140MW thermal power plant. *Case Stud. Eng. Fail. Anal.* **8**, 57–60 (2017)
- A.K. Pramanick et al., Failure investigation of super heater tubes of coal fired power plant. *Case Stud. Eng. Fail. Anal.* **9**, 17–26 (2017)

5. G.A. Lamping, R.M.J. Arrowood, Manual for investigation and correction of boiler tube failures. Final report. Southwest Research Institute, San Antonio, USA, 331 (1985)
6. Z.-F. Hu, D.-H. He, X.-M. Wu, Failure analysis of T12 boiler reheater tubes during short-term service. *J. Fail. Anal. Prev.* **14**(5), 637–644 (2014)
7. S. Srikanth et al., Analysis of failures in boiler tubes due to fireside corrosion in a waste heat recovery boiler. *Eng. Fail. Anal.* **10**(1), 59–66 (2003)
8. S. Chaudhuri, Some aspects of metallurgical assessment of boiler tubes-Basic principles and case studies. *Mater. Sci. Eng. A* **432**(1–2), 90–99 (2006)
9. F. Masuyama, Creep rupture life and design factors for high-strength ferritic steels. *Int. J. Press. Vessels Pip.* **84**(1), 53–61 (2007)
10. I.J. Perrin, J.D. Fishburn, A perspective on the design of high-temperature boiler components. *Int. J. Press. Vessels Pip.* **85**(1), 14–21 (2008)
11. R.K. Roy et al., Analysis of superheater boiler tubes failed through non-linear heating. *Procedia Eng.* **86**, 926–932 (2014)
12. R.W. Bryers, Fireside slagging, fouling and high temperature corrosion of heat transfer surface due to impurities in steam-raising fuels. *Prog. Energy Combust. Sci.* **22**(1), 29–120 (1996)
13. A. Movahedi-Rad, S.S. Plasseyed, M. Attarian, Failure analysis of superheater tube. *Eng. Fail. Anal.* **48**, 94–104 (2015)
14. S. Chaudhuri, R. Singh, High temperature boiler tube failures, Case studies, in *Proceeding: COFA. 1997* (Jamshedpur, India), pp. 107–120
15. J.H. Swisher, S. Shankarnarayan, Inhibiting vanadium induced corrosion. *Mater. Perform.* **33**(9), 49 (1994)
16. D. Young, *High Temperature Oxidation and Corrosion of Metals*, 2nd edn. (Elsevier, Amsterdam, 2016)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.