Central Power Research Institute

Vol. 21(2)/89-97, December 2025
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v21i2.1216

Power Research

Failure Analysis of Intermediate Pressure Control Valve (IPCV) Stud Bolts in a 625MW Supercritical Thermal Power Unit

R. K. Kumar* and D. Laxman Rao

Materials Technology Division, Central Power Research Institute, Bangalore - 560080, Karnataka, India; rkkumar@cpri.in

Abstract

The failure of several Intermediate Pressure Turbine Control Valve (IPCV) stud bolts used in a 625MW supercritical thermal power plant was investigated to identify the root cause and mechanism of failure. The bolts, made of 20Cr1Mo1VNbTiB alloy steel, fractured during operation after approximately 64,700 hrs of service and 92 start-up–shutdown cycles. Visual examination revealed that cracks consistently initiated near the first threaded region adjacent to the valve body–flange parting plane. Fractographic analysis indicated fatigue crack growth covering nearly 70–80% of the fracture area, followed by a sudden brittle overload fracture. Hardness and residual stress analyses indicated thermal softening and stress relaxation during long-term exposure. Charpy impact tests demonstrated a severe drop in impact energy (from ~182 Joules in new bolts to ~38 Joules in failed ones), indicating embrittlement. Scanning Electron Microscopy Energy Dispersive X-ray Spectroscopy (SEM-EDX) observations showed a bainitic matrix with Molybdenum Monocarbide (MoC) and Titanium Carbide (TiC), with the failed bolts exhibiting excessive MoC precipitation along grain boundaries. The combined effects of cyclic loading, microstructural embrittlement, and stress concentration led to fatigue-controlled failure.

Keywords: Carbide Precipitation, Embrittlement, Failure Analysis, Fatigue Fracture, High-Temperature Service, Steam Turbine Valve, Stud Bolts, 20Cr1Mo1VNbTiB Steel

1. Introduction

Steam turbines in thermal power plants operate under high-temperature and high-pressure environments, where components are subjected to complex thermal, mechanical, and vibrational stresses. Bolted joints play a vital role in maintaining steam-tight integrity between valve or casing sections, sustaining substantial pre-tension loads under fluctuating thermo-mechanical conditions. The failure of such bolts can lead to steam leakage, turbine shutdown, and severe economic losses[1,2].

Several researchers have reported that turbine bolt failures often result from a combination of creep, stress relaxation, fatigue, and temper embrittlement processes. During long-term exposure at elevated temperatures, low-alloy Cr–Mo–V steels used in turbine bolts experience microstructural degradation by carbide precipitation, impurity segregation, and temper embrittlement. To mitigate these effects, 20Cr1Mo1VNbTiB steel has been developed as a modified variant, offering improved creep strength and thermal stability through the fine dispersion of MoC, NbC, and TiC carbides[3]. However, extended exposure at high temperatures can promote carbide coarsening and the formation of continuous networks along grain boundaries, leading to a reduction in ductility and impact toughness. Moreover, the increasing frequency of start-up and shutdown cycles in modern power plants has intensified fatigue and thermal loading on such components, accelerating crack initiation at thread roots where stress concentration is maximum[4].

Moshayedi *et al.*[5] studied early failure in Cr–Mo–V turbine bolts, attributing it primarily to Reversible Temper

*Author for correspondence

© Power Research

Embrittlement (RTE) caused by phosphorus segregation and carbide precipitation at grain boundaries. Their work demonstrated that appropriate heat treatment, including optimised austenitising and tempering, can enhance impact toughness and reduce embrittlement. Zhang *et al.*[6] investigated the fracture of high-temperature 20Cr1Mo1VNbTiB steel stud bolts used in steam turbines and identified a coarse-grained zone at the root of the first thread, where microstructural transformation from tempered bainite to martensite reduced ductility and promoted intergranular cracking under cyclic thermal stresses.

Similarly, Kang *et al*[7]., analysed a 25Cr–2MoVA steel bolt that fractured after 23 years of service in a high-pressure steam turbine, revealing that long-term exposure caused grain coarsening and ferrite formation along grain boundaries, which triggered brittle fracture during startup.

Given these operational and metallurgical challenges, failure analysis of turbine bolting systems remains essential for assessing material degradation and preventing recurrence. The present investigation focuses on the failure of Intermediate Pressure Control Valve (IPCV) stud bolts from a 625MW supercritical thermal power unit. The bolts, manufactured from 20Cr1Mo1VNbTiB alloy steel, fractured prematurely after approximately 64,700 hours of service and 92 start-up–shutdown cycles under operating steam pressure conditions of approximately 35 bar. A comprehensive investigation involving visual inspection, chemical composition analysis, hardness measurement, residual stress evaluation, impact toughness testing, and microstructural and fractographic examination using SEM–EDX was carried out to determine the root cause and mechanism of failure.

2. Experimental Procedure

Failed and unfailed stud bolts were collected from the IPCV assembly of a 625MW supercritical thermal power unit. The bolts, made of 20Cr1Mo1VNbTiB alloy steel with dimensions of M33 × 273mm, were examined to determine the cause of failure.

Visual and fractographic examinations were performed on the cleaned fracture surfaces to identify the fracture mode and crack initiation regions. The chemical composition of the bolt material was determined using Optical Emission Spectroscopy (OES). Hardness measurements were carried out along the longitudinal direction using a Leeb hardness tester (Make-Accuplus, Model TH110A), and the values were converted to Brinell hardness numbers for comparison.

Residual stress measurements were conducted at the thread root and shank regions using the X-Ray Diffraction (XRD) technique (Make-Rigaku, Model Micro Area Analyser). Standard Charpy impact tests were performed on V-notched specimens machined from failed, in-service, and new bolts in accordance with ASTM E23 to evaluate the loss of toughness.

The fracture surfaces of the impact specimens were examined using a scanning electron microscope (Model-ZEISS EVO 18) equipped with energy-dispersive X-ray spectroscopy (Make-AMETEK) to identify fracture features. Metallographic samples were prepared by conventional grinding, polishing, and etching, followed by SEM examination to assess microstructural degradation near the fracture regions.

3. Results and Discussion

3.1 Visual Examination

The failed IPCV stud bolts were cleaned with inhibited hydrochloric acid solution to remove corrosion products and surface contaminants before examination. The view of the cleaned fracture surfaces is shown in Figure 1. Visual inspection of all fractured bolts revealed two distinct regions on the fracture surface: A smooth region representing the crack initiation and propagation zone, and a rough region corresponding to the catastrophic final fracture. The smooth region, typically covering about 70–80% of the bolt cross-section, exhibited a relatively flat morphology with well-defined beach marks, indicating progressive crack growth under cyclic loading. The remaining rough region showed irregular topography, signifying sudden final rupture once the remaining portion could no longer support the applied load. In all the examined bolts, crack initiation occurred from the threaded end near the parting plane between the valve body and flange, consistent with the region of maximum stress concentration.

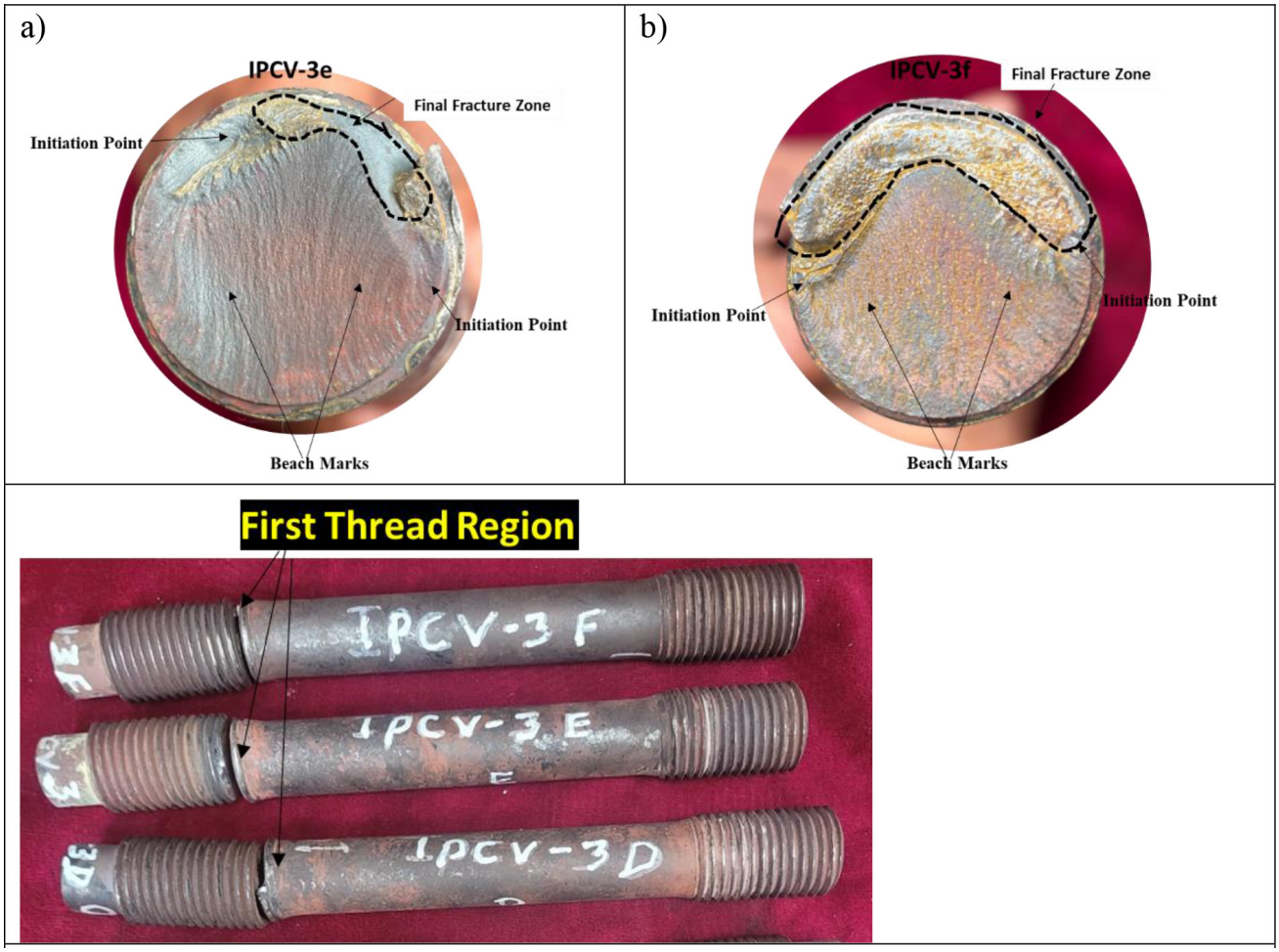


Figure 1. Close-up views of the cleaned fracture surfaces of stud bolts showing **(a)** fracture surface of failed bolt 1, **(b)** fracture surface of failed bolt 2, and **(c)** failure location at the first thread region.

3.2 Chemical Composition

The chemical composition of the failed and New IPCV stud bolt was determined using an Optical Emission Spectrometer (OES) at multiple locations near the fracture region. The average elemental concentrations are presented in Table 1, along with the specified composition range for 20Cr1Mo1VNbTiB low-alloy steel. The results confirm that the composition of the failed bolt conforms well to the standard limits for 20Cr1Mo1VNbTiB alloy steel.

Table 1. Chemical composition of the failed stud bolt compared with the standard range for 20Cr1Mo1VNbTiB alloy steel (wt.%).

Element	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Ti
Failed Stud Bolt	0.175	0.56	0.50	0.024	0.020	0.91	0.82	0.08	0.55	0.13	0.07
New Stud Bolt	0.145	0.48	0.30	0.019	0.016	0.82	0.67	0.07	0.56	0.04	0.25
(Reference Values)	0.17-0.23	0.40–0.60	0.40–0.65	0.025 max	0.025 max	0.90–1.30	0.75–1.00	≤0.30	0.50–0.70	0.11-0.22	0.05-0.14

3.3 Hardness Measurement

The hardness of the IPCV stud bolts was measured using a portable hardness tester based on the rebound principle. Measurements were performed on several failed studs, one in-service (non-failed) stud, and one unused (new) stud. The average hardness of the failed studs ranged between 204 and 232BHN, while the in-service stud exhibited an average hardness of 229BHN, and the new stud showed a higher value of 246BHN. All readings lie within the typical range for 20Cr1Mo1VNbTiB alloy steel (≈ 200–260BHN).

3.4 Residual Stress Analysis

Residual stress measurements were carried out on selected failed, in-service, and new IPCV stud bolts to evaluate the influence of pre-existing stresses on crack initiation and propagation. Measurements were taken at the thread root region, as these are the most stress-concentrated locations in bolted components. The surface residual stress results are summarised in Table 2. The new stud bolt exhibited a high compressive residual stress of approximately –372MPa at the inner thread region, which is beneficial for fatigue resistance. In contrast, the in-service (unfailed) and failed bolts showed significantly reduced compressive or even slightly tensile residual stress values, indicating substantial stress relaxation during service exposure at elevated temperatures (540–550°C for ~60,000h).

Table 2. Residual stress values measured by X-ray diffraction (XRD) at the thread regions of IPCV stud bolts

Stud Sample	Measurement Location	Residual Stress (MPa)
Failed Bolt -1	Thread region	+82 ± 12
In-service (unfailed) Bolt	Inner thread region	–44 ± 27
New Bolt		–372 ± 21

This relaxation is attributed to creep deformation under sustained load, leading to a redistribution of stresses. Since compressive residual stresses enhance fatigue life, their relaxation and conversion toward tensile stress increase the likelihood of crack initiation at the thread roots—consistent with the observed fracture locations in the failed bolts.

3.5 Impact Toughness Evaluation

Charpy impact tests were conducted on the new, failed, and in-service (unfailed) IPCV stud bolt samples to evaluate their impact toughness and resistance to brittle fracture under dynamic loading conditions. V-notched specimens were machined longitudinally from the bolts, and tests were performed as per ASTM E23.

The results, summarised in Table 3, show a substantial reduction in toughness for the failed bolts compared to the new ones. The new stud bolt exhibited an average impact energy of 181.7J, indicating high ductility and good resistance to impact loading. In contrast, the failed bolts displayed drastically lower impact energies of 38J and 34J, respectively. The in-service unfailed bolt showed an intermediate toughness of 76J, approximately 41% of the new sample's value, suggesting partial embrittlement during service. The photographs of the fractured surfaces of the impact-tested specimens for the new and failed bolts are shown in Figure 2.

Table 3. Charpy impact energy values for IPCV stud bolts

Sample Description	Impact Energy (in Joules)	Average Impact Energy (in Joules)
New Bolt	186, 168	181.7
Failed Bolt	38,34	36
Unfailed (In-service) Bolt	74, 78	76

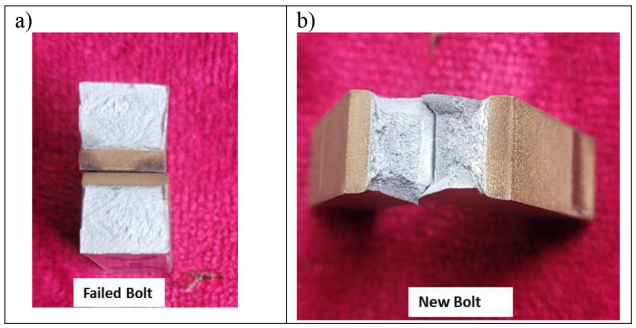


Figure 2. Photographs of impact-tested stud bolt samples **(a)** failed bolt and **(b)** new bolt.

3.6 Fractography Analysis

After the Charpy impact tests, the fractured surfaces of the new, in-service (unfailed), and failed stud bolt specimens were examined using SEM to study their fracture behaviour and correlate it with the measured impact toughness.

The SEM fractographs of the impact-tested specimens from new bolt samples are shown in Figure 3. The new bolt specimens, which exhibited high impact energy, revealed a ductile fracture morphology characterised by numerous deep, equiaxed dimples, indicative of extensive plastic deformation before failure.

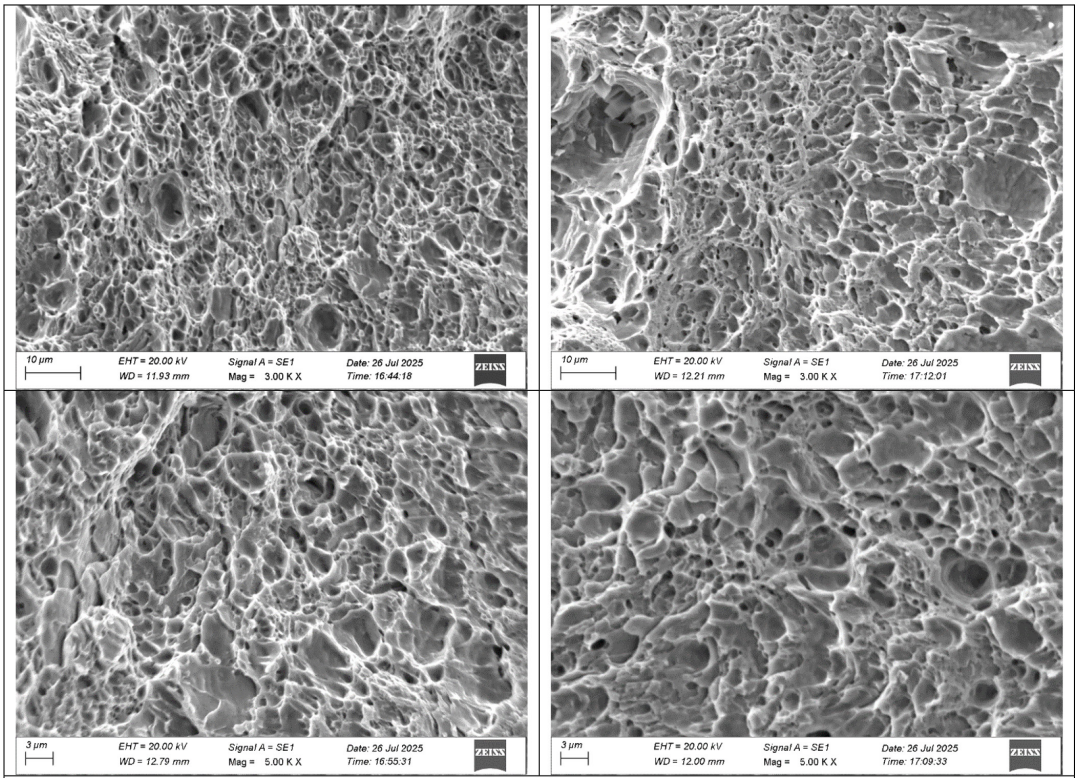


Figure 3. SEM fractographs of impact tested specimens (New stud bolt) showing ductile fracture morphology.

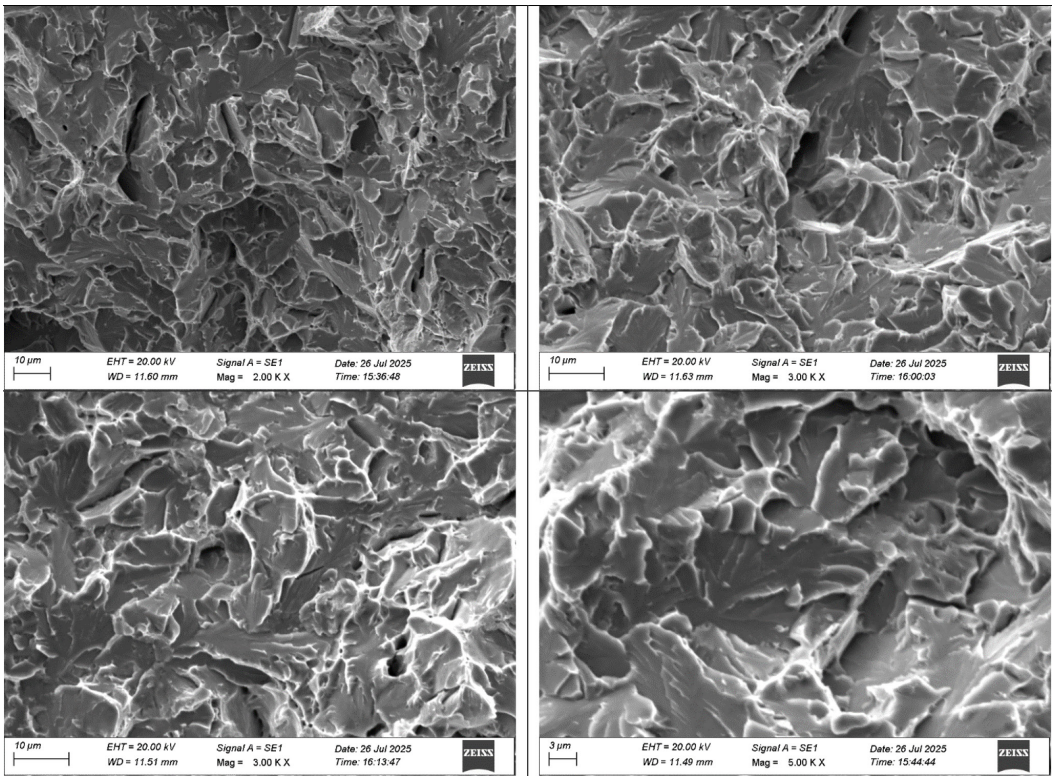


Figure 4. SEM fractographs of impact tested specimens (Failed stud bolt) exhibiting intergranular and cleavage fracture features with secondary cracking.

In contrast, the failed bolt specimens, which recorded much lower impact energies, displayed predominantly brittle cleavage fracture features such as flat facets, river patterns, and occasional secondary cracking along grain boundaries. The SEM fractographs of the impact-tested specimens from failed bolt samples are shown in Figure 4. These microstructural features are consistent with temper embrittlement and long-term thermal degradation developed during prolonged service exposure.

The fractured surface of the service-failed IPCV stud bolt was further examined under SEM to identify the crack initiation sites and understand the crack propagation

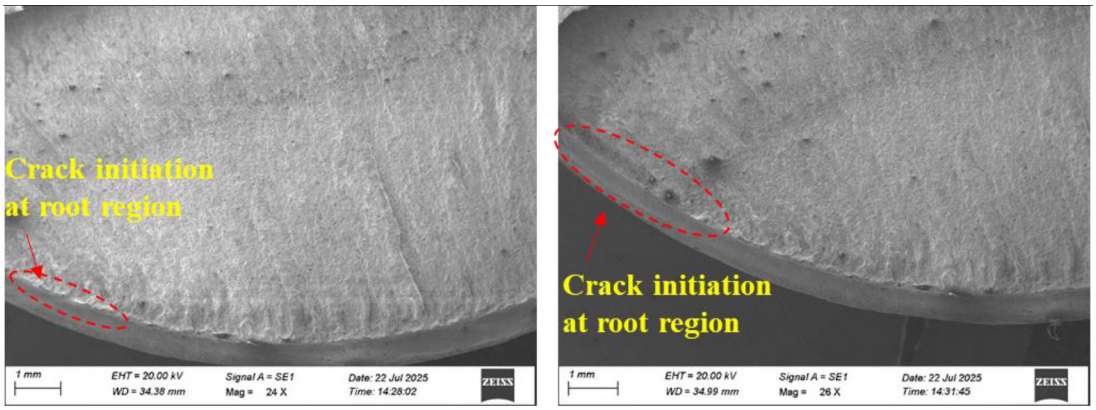


Figure 5. SEM fractographs of the failed IPCV stud bolt.

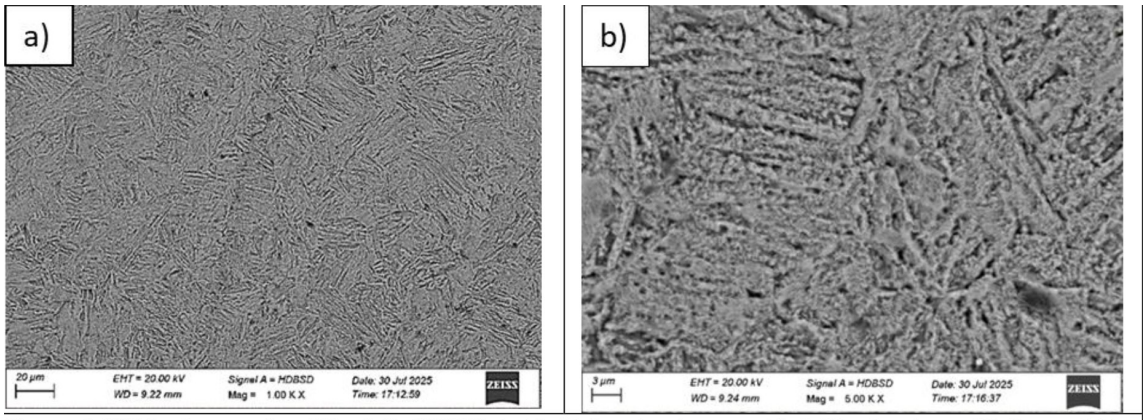


Figure 6. SEM micrographs of the failed IPCV stud bolt showing tempered bainitic structure with fine carbide precipitates uniformly distributed within the grain matrix: **(a)** 1000X; **(b)** 5000X

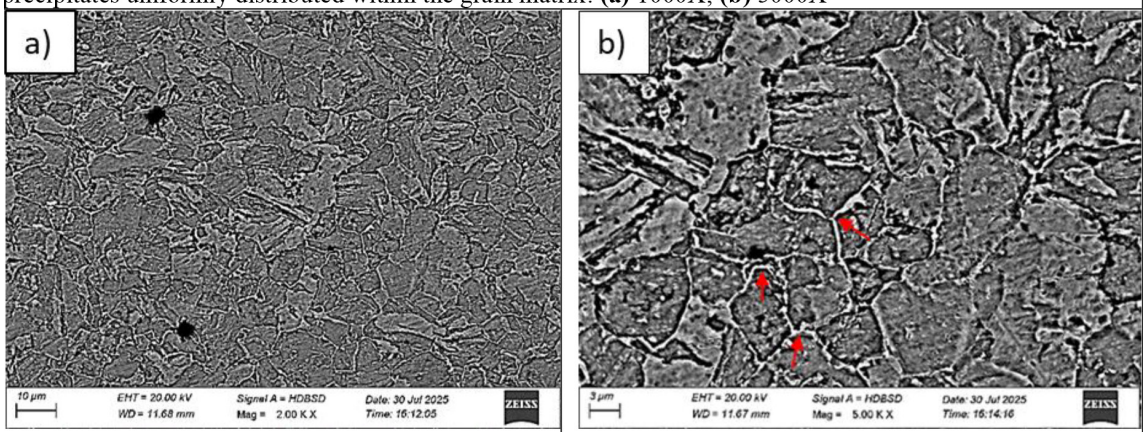


Figure 7. SEM micrographs of the failed IPCV stud bolt showing coarse carbide precipitation and continuous film-like networks along grain boundaries: **(a)** 2000X; **(b)** 5000X.

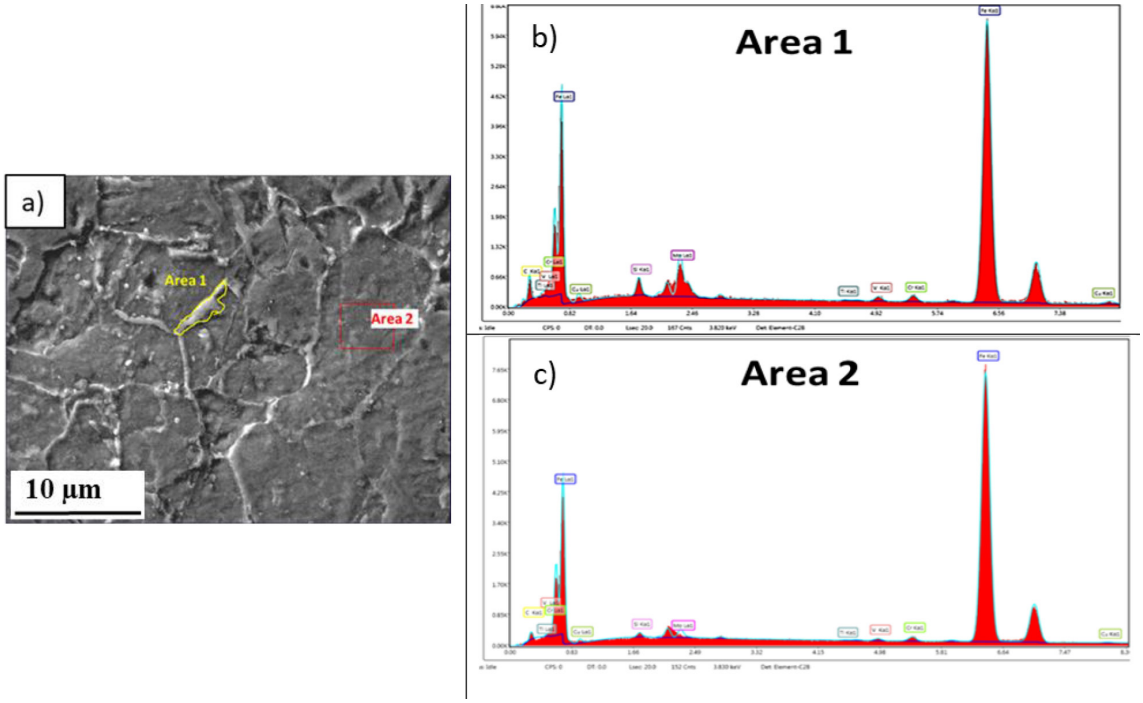


Figure 8. **(a)** SEM image showing EDS locations: ***Area 1***—grain boundary precipitate, ***Area 2*** -grain interior. **(b)** EDS spectrum of ***Area 1*** showing Mo enrichment. **(c)** EDS spectrum of ***Area 2*** showing lower Mo content.

Table 4. Elemental composition (in wt.%) of grain boundary precipitate (Area 1) and grain interior (Area 2) obtained from EDS analysis

Element	Area 1 (Grain Boundary Precipitate) (wt.%)	Area 2 (Grain Interior) (wt.%)
Carbon	7.21	2.50
Silicon	1.50	0.42
Molybdenum	6.77	1.67
Titanium	0.14	0.08
Vanadium	0.71	0.37
Chromium	0.92	0.67
Iron	81.25	93.93
Copper	1.49	0.36

mechanism. The observations revealed that multiple cracks had originated from the thread root region, which is known to experience maximum stress concentration. Detailed fractographic examination showed the presence of fatigue striations and beach marks, indicating progressive crack growth under cyclic thermo-mechanical loading. The SEM micrographs are shown in Figure 5.

3.7 Microstructural Analysis

The microstructure of the failed, in-service, and new IPCV stud bolts was examined at various locations to assess possible metallurgical degradation due to prolonged high-temperature service. The new bolt exhibited a tempered bainitic microstructure with uniformly distributed fine precipitates within the matrix, typical of properly heat-treated 20Cr1Mo1VNbTiB steel (Figure 6).

In contrast, the failed bolts revealed a tempered bainitic structure with coarse carbide precipitation and the formation of a film-like network of carbides along prior austenite grain boundaries (Figure 7). Such boundary carbide films are indicative of long-term thermal exposure and are often associated with temper embrittlement and loss of grain boundary cohesion. These microstructural degradations correlate well with the ~80% reduction in impact energy observed for the failed studs compared to the new bolts, confirming that prolonged exposure to high temperature and embrittlement are the dominant factors in the observed failure.

4. Results of Analysis

The failure of 20Cr1Mo1VNbTiB stud bolts used in the IPCV assembly of a 625MW supercritical thermal power unit was systematically investigated through mechanical, microstructural, and fractographic analyses. The results indicate that the premature failure resulted from a combined effect of cyclic fatigue and microstructural

degradation associated with long-term high-temperature service.

Fractographic observations confirmed that cracks consistently initiated at the first engaged thread region, where stress concentration and preload are the highest. The presence of fatigue striations and beach marks under SEM revealed that the cracks propagated progressively under cyclic thermo-mechanical stresses during repeated turbine start-up and shutdown cycles. With 92 recorded operating cycles over seven years, such fluctuating stresses would have accelerated fatigue crack growth. Residual stress relaxation due to creep deformation at elevated temperatures further reduced the fatigue endurance strength of the bolts. Overtightening during maintenance to mitigate steam leakage may have further increased local stress intensity near the thread roots, promoting crack initiation. Exposure to steam and moisture could also have facilitated environment-assisted cracking, as suggested by the localised oxide deposits observed near the fracture regions.

Microstructural examination revealed that the new bolts exhibited a tempered bainitic matrix with fine and uniformly distributed carbides, while the failed bolts showed coarse carbide precipitation and the formation of continuous carbide films along grain boundaries. These microstructural features are typical of long-term exposure at ~540–550°C and correspond to temper embrittlement and loss of grain boundary cohesion. Energy Dispersive X-ray Spectroscopy (EDS) analysis was performed on the grain boundary regions to identify the nature of the precipitates formed after heat treatment.

The corresponding EDS spectra are presented in Figure 8, and the composition is given in Table 4, which confirms the enrichment of molybdenum along the grain boundaries. EDS analysis of the grain boundaries confirmed the enrichment of Mo, Cr, and V, indicative of the presence of MoC carbides. While these carbides contribute to strength when finely dispersed, their coarsening and alignment along grain boundaries significantly lower toughness and facilitate intergranular fracture. The present findings indicate the formation of coarse molybdenum-rich carbides at the grain boundaries, which are known to contribute to the degradation of mechanical properties by promoting creep cavity formation and intergranular cracking. This observation is consistent with previous research on 20Cr1Mo1VNbTiB bolts used in supercritical thermal power units, where the precipitation and growth of Mo-rich carbides during long-term service were identified as a primary cause of material ageing and failure[8-10]. The impact toughness of the failed bolts decreased by nearly 80% compared to the new bolts, indicating significant embrittlement. Additionally, residual stress measurements revealed a reduction in compressive residual stress from –372MPa in new bolts to –44MPa in service-exposed ones, suggesting substantial stress relaxation due to creep deformation.

5. Conclusions

The failed IPCV stud bolts made of 20Cr1Mo1VNbTiB steel exhibited tempered bainitic microstructure with coarse carbide precipitation and film-like MoC carbides along grain boundaries, confirming temper embrittlement after long-term service at ~540°C.

Charpy impact testing revealed a significant reduction (~80%) in impact energy for the failed bolts compared to new bolts, indicating severe loss of toughness due to microstructural degradation.

Residual stress measurements demonstrated stress relaxation in the failed bolts, likely caused by creep deformation during prolonged service, thereby reducing the fatigue resistance of the threads.

Fractographic analysis confirmed crack initiation at the thread root and progressive fatigue crack propagation, followed by brittle intergranular fracture, consistent with embrittlement and stress concentration.

EDS analysis confirmed Mo- and Cr-rich carbide segregation along grain boundaries, correlating with intergranular fracture features and supporting the observed embrittlement mechanism.

The premature failure was thus caused by the synergistic effect of cyclic fatigue, residual stress relaxation, and thermal embrittlement due to long-term service exposure and operational practices such as frequent tightening and thermal cycling.

6. Acknowledgements

The authors acknowledge the Central Power Research Institute (CPRI), Bangalore, for its continuous support in conducting this study.

7. References

1. Cheng Y, Wang S. Failure analysis of exhaust valve bolt of ultra supercritical unit. J Phys Conf Ser. 2021; 2030:012071. https://doi.org/10.1088/1742-6596/2030/1/012071
2. High-temperature bolting life prediction and life assessment. [Online]. Available: www.epri.com
3. Si J, Lv H, Ren F, Ren B. Failure analysis on the bolt fracture of the pressure control valve in a power plant. in Proceedings - 2020 5th International Conference on Mechanical, Control

and Computer Engineering, ICMCCE 2020, Institute of Electrical and Electronics Engineers Inc; 2020. p. 792-795. https://doi.org/10.1109/ICMCCE51767.2020.00174

4. Li N, Li L, Zhang, Luo Z. Fracture failure analysis on ultra supercritical turbine bolts. In IOP Conf Ser: Mater Sci Eng. Institute of Physics Publishing, Apr; 2019. https://doi.org/10.1088/1757-899X/490/2/022002
5. Moshayedi H, Moattari M, Azizpour K. Failure analysis of outer casing bolts of a 325 MW steam turbine. Eng Fail Anal. 2019; 97:189-200. https://doi.org/10.1016/j.engfailanal.2019.01.044
6. Zhang T *et al*. Fracture analysis of 600 MW steam turbine valve bolts based on ultrasonic technology for coarse-grain detection. Eng Fail Anal. 2020; 118. https://doi.org/10.1016/j.engfailanal.2020.104933
7. Qin Kang X. Failure analysis of a bolt in a high-pressure steam turbine. J Fail Anal Prev. 2016; 16(5):842-848. https://doi.org/10.1007/s11668-016-0160-8
8. Jianjun Z, Ziming F, Xiao L, Xin Q, Yunpeng G. Failure analysis of fastening bolts of one steam turbine valve cover. Heat Treat Met. 2021; 46(10):262-266.
9. Kawashima F *et al*. Prediction of crack growth in CrMoV cast steel after long-term service at high temperature. Mater Sci Eng. 2009; A(510-511):149-153. https://doi.org/10.1016/j.msea.2008.04.093
10. Zhang J *et al*. Failure analysis and service properties of 20Cr1Mo1VNbTiB Bolt in 660 MW supercritical thermal power unit. J Fail Anal Prev. 2022; 22(4):1744-1752. https://doi.org/10.1007/s11668-022-01453-2