were performed following sectioning through the perforation on the tee. The stratified corrosion deposits on the inside surface of the tee primarily contained oxygen and iron, with significant traces of carbon, sulfur, and silicon, and minor traces of copper, manganese, sodium, calcium, and chlorine. Similar analyses were performed on the pipe nipple following sectioning through the consumed threads. The pipe nipple corrosion deposits primarily contained oxygen, carbon, and iron, with traces of aluminum, calcium, sulfur, silicon, sodium, barium, and chlorine. The SEM images and EDS dot maps are available in our NACE conference publication.[3]

X-Ray Diffraction Analysis

The deposits/corrosion products removed from the inside surface of the tee were analyzed using EDS and x-ray diffraction (XRD). The former method identifies the elements present; the latter identifies crystalline compounds, but does not detect non-crystalline organic sludges. EDS analysis confirmed that the predominant elements present in the deposits were carbon, oxygen, sulfur, and iron. XRD analysis indicated that the primary crystalline phases present were siderite—52 wt%, quartz (SiO_2)—22 wt%, mackinawite (FeS)—7 wt%, greigite (Fe_3S_4)—11 wt%, troilite (FeS)—3 wt%, and sulfur—5 wt%. Siderite is formed from carbonic acid corrosion (CO_2 corrosion) of steel, while mackinawite, greigite, and troilite are iron sulfides formed from hydrogen sulfide (H_2S) corrosion of steel.

Similar analyses were performed on the deposits/corrosion products removed from the inside surface of the pipe nipple. EDS analysis confirmed that the predominant elements present in the deposits were carbon, oxygen, barium, sulfur, and iron. XRD analysis indicated that the primary crystalline phases present were barite ($BaSO_4$)—9 wt%, siderite ($FeCO_3$)—21 wt%, mackinawite (FeS)—4 wt%, calcite ($CaCO_3$)—36 wt%, and akaganeite—30 wt%. Siderite and mackinawite are formed during CO_2 and H_2S corrosion, respectively. Calcite and barite scales typically form from produced water. Akaganeite forms only in environments containing high concentrations of chlorides, such as produced water.

Vickers Hardness Test

Vickers hardness tests were performed on the metallographic mounts taken across the perforations on the tee and the pipe nipple cross sections. The average hardness for the tee was 163.5 HV, which converts to 84 HRB per ASTM A370.[4] These hardness values are below the 92 HRB maximum specified for ASTM A234[5] Grade WPB fittings. The average hardness for the pipe nipple was 140 HV (77 HRB), which is typical for these CS fittings.

Chemical Analysis

Elemental composition of the tee and pipe nipple determined using optical emission spectroscopy (OES) indicated that the tee material met the requirements for ASTM A234 Grade WPB steel, while the pipe nipple material met the requirements for ASTM A106[6] Grade B specification.

Discussion

The corrosion product in the tee was primarily iron carbonate, which is commonly formed during carbonic acid corrosion of steel. The presence of iron sulfides indicates that dissolved H_2S also contributed to the corrosion. The presence of greigite is indicative of periodic ingress of oxygen into the system, which can significantly increase the corrosion rate of CS equipment.[7] The tee perforation was located at a turbulent zone where the fluid from the connection line intermingled with the fluid from the main line, which led to significant material thinning adjacent to the perforation. The corrosion deposits away from the perforation were of uniform thickness. OES analysis indicated that the tee met the chemical composition requirements for ASTM A234 Grade WPB steel. The microstructure was characterized by Widmanstatten ferrite, blocky ferrite, and pearlite, which is typical of CS. The investigation did not detect any metallurgical defects or deficiencies that could have contributed to the perforation.

The pipe nipple perforation occurred at the root of a thread, which corresponds to a location with the least wall thickness. The corrosion product was primarily iron carbonate, which indicates CO_2 corrosion. The presence of iron sulfides indicates that dissolved H_2S also contributed to the corrosion. The pipe nipple chemical composition met the requirements for ASTM A106 Grade B steel. The microstructure was characterized by ferrite and pearlite, which is typical of CS. The investigation on the pipe nipple did not detect metallurgical defects or deficiencies that could have contributed to the corrosion damage.

Conclusions

1. The tee perforated due to localized corrosion and fluid turbulence. Corrosion was from carbonic acid and hydrogen sulfide. The deposits contained iron carbonate, and two forms of iron sulfide, one of which (Fe_3S_4) typically forms in oxygenated environments implying oxygen ingress. The perforation occurred at a location where fluids intermingled and caused turbulent conditions.
2. The pipe nipple corroded at the inside surface due to carbonic acid and hydrogen sulfide. The deposits contained iron carbonate and iron sulfide. The location of the perforation was at a thread root, where the wall thickness is at a minimum.
3. The best mitigation strategies against CO_2 corrosion tie back to having robust corrosion control programs, which includes corrosion test coupon installation, monitoring field water chemistry, corrosion inhibitor development and inhibitor residual monitoring, as well as corrosion rate monitoring using ultrasonic or in-line inspection tools.[8-9]

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SUDHAKAR MAHAJANAM is an associate II for the materials practice at Stress Engineering Services, Inc., Houston, Texas, USA, email: Sudhakar.Mahajanam@stress.com. In this role, he performs damage mechanism assessment, failure analyses, and provides materials/corrosion guidance to various external clients. Sudhakar has 27 years of experience in the field of metallurgy and corrosion, with 14 years in oil and gas. He is a Licensed Professional Engineer in the State of Texas, and holds certifications in API 571 and API 580. He has a bachelor's degree in metallurgical engineering from the Indian Institute of Technology Roorkee; M.S. and Ph.D. degrees in materials science and engineering from The Ohio State University; and an MBA from the University of Texas at Austin. Sudhakar has published over 45 technical papers, presented at acclaimed national/international conferences, and is a technical editor for several peer-reviewed journals. He has been a member of NACE International (now AMPP) for over 15 years.

SRI KRISHNA CHIMBLI is a senior associate at Stress Engineering Services, Inc., email: Sri.Chimbli@stress.com. Sri has over 15 years of experience in failure analysis, welding, metallurgical evaluation, manufacturing, and material selection. He has spent most of his career working in the oil and gas industry supporting upstream, midstream, and downstream assets. He also has experience in heat treatment, fabrication, and inspection. Sri has participated in numerous field inspections, fire damage assessments, root cause failure analysis, surveys, and process audits for the industry. He holds certifications in API 577–Welding Inspection and Metallurgy and API 571—Corrosion and Materials. He is also an AWS Certified Welding Engineer and a Certified Welding Inspector and is a Professional Metallurgical Engineer in the State of Texas. Sri has been a member of NACE International (now AMPP) for five years. MP