Hydrogen Embrittlement Prevention in High Strength Steels by Application of Various Surface Coatings-A Review

Sandeep Kumar Dwivedi and Manish Vishwakarma

Abstract The applicability of various coatings such as graphene, reduced graphene, al, cu, zn, carbon, nitrogen, oxygen, niobium, boron nitride, and TiAlN as a protective barrier to high strength steel for hydrogen embrittlement was studied. These all coatings were applied by different coating techniques such as(chemical vapor deposition (CVD), electroplating discharge (EPD), electrolysis, gas diffusion, plasma diffusion, high velocity oxygen fuel (HVOF), magnetically enhanced plasma ion plating system, plasma vapor deposition, and ion beam sputter.) on the high strength steel substrate followed by characterization of applied coating and mechanical testing. Reduction in life cycle due to the hydrogen embrittlement was analyzed.

Keywords Hydrogen embrittlement · Graphene coating · Scanning electron microscopy

1 Introduction

The phenomenon of hydrogen embrittlement (HE) will occur when metal surfaces are exposed to hydrogen environment which leads to catastrophic failure. It was found that HE considered as an important problem in several application areas, such as nuclear plant reactor vessel [1, 2], high-pressure gaseous hydrogen storage tanks [3, 4], petroleum and natural gas pipelines [5, 6].

Generally, when metal comes to contact with the hydrogen or working in hydrogen atmosphere, then some common ways by metals failed are hydrogen embrittlement (HE), hydrogen-induced-blistering, hydrogen attack, cracking due to precipitation of internal hydrogen, and hydride-formation cracking [7]. Generally, there are two mechanisms which responsible for the HE in steels. First one is that at cracks or crack tip, hydrogen atoms are accumulated, and decreases the fracture energy while inspiring cleavage-like failure [8, 9]. The second mechanism includes mobility of

S. K. Dwivedi (✉) · M. Vishwakarma
Department of Mechanical Engineering, Maulana Azad National Institute of Technology, Bhopal, M.P. 462003, India
e-mail: Sandeep0183@gmail.com

R. M. Singari et al. (eds.), *Advances in Manufacturing and Industrial Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-8542-5_58

dislocations increased due to effect of hydrogen at crack tip through shielding effect, reducing the shear strength, and ultimately responsible for local plasticity enhancement [10]. In order to protect the equipment from the hydrogen diffusion, it is necessary to measure how much concentration of hydrogen has been diffused into the material at the time of failure, but thrush hold concentration of hydrogen which is causing the equipment failure is not found clearly. And the basic mechanism which is responsible for the HE is also not found clearly still some discussion is going on this [11].

It was found that hydrogen diffusion causes mechanical properties broadly tensile strength and fatigue strength are reduced with and without changes in yield strength. Temperature, source of hydrogen, and surface condition are responsible for HE [12]. Various methods which were responsible for hydrogen entrance in the material are cathodic reaction or charging, electroplating, during welding, etc. [13]. Literature said that the cathodic charging plays a very significant role for hydrogen diffusion and current density considered as an important factor for hydrogen absorption and propagation in steel. For hydrogen diffusion and embrittlement occurrence in steel, current density must be in range of 0.02–40 mA/cm^2 [14, 15]. It was concluded that at higher current density, hydrogen absorption and propagation are faster than the lower current density, so more hydrogen is diffused at higher current density.

In this paper, the prevention of HE in high strength steels by application of different surface coatings such as graphene, reduced graphene, al, cu, zn, carbon, nitrogen, oxygen, niobium, boron nitride, and TiAlN, etc., is discussed and selection of suitable coatings is given to reduce the HE phenomena.

2 Hydrogen Embrittlement in Steel

High strength steels are mostly subjected to hydrogen embrittlement effect. The embrittlement refers to change from ductile phase to brittle phase. Hydrogen caused the embrittlement is termed as "hydrogen embrittlement." HE can be noticeable in different ways. HE causes reduction in the following

- Ultimate-tensile strength and braking strain or ductility
- Fracture strength and toughness.

Furthermore, there is a case where unstressed components are subjected to failure. However, there is a case in which ductility will decrease with no change in tensile strength [16]. Examples of internal hydrogen embrittlement is solutions used during fabrication like acid cleaning, electroplating, pickling, and providing protective coatings, phosphating, etching, paint stripping, etc. Second way of HE is external hydrogen embrittlement which occurs during the working condition of equipment. The following mechanisms by which hydrogen is entering and tapped in the lattice are

- Hydrogen-enhanced decohesion mechnaism (HEDE),

- Hydrogen-enhanced local plasticity model (HELP), and
- Adsorption-induced dislocation emission (AIDE) [7, 17, 18].

After entering into the metal lattice hydrogen will be tapped in different regions. Examples of hydrogen taps are dislocations, grain boundaries, voids, and phase boundaries, micro cracks, precipitates, interfaces, solutes, surface cracks, surface oxides, and 0D, 1D, 2D lattice defects. In last 50 years, various authors focus on research related to hydrogen diffusion and hydrogen embrittlement (HE) [19–21]. Hydrogen causes slip localization [22–24], softening and hardening [24–32], interaction between hydrogen–dislocation [32–35] and creep [36] have been also reported, and apart from all these effects, HE has severely effect fatigue crack rate behavior as well as tensile properties.

3 Hydrogen Embrittlement Prevention

Complete prevention of HE in high strength steels is laborious but we can prevent some extent so that we can save the life of the equipment. To reduce the hydrogen diffusion from metal surface, sharp and very steady variation, notches must be prevented or avoided and removal of residual stresses are performed before the processing step [37, 38]. Sometimes, baking operation is performed to remove hydrogen which was available in lattice or surface during the processing. In broad view, baking is considered as a heat-treatment-process and processing temperature is depending on the process material [39]. Prevention from HE can also be achieved by adding specific alloying material to the base or parent material [7].

Our main focus on prevention of HE by surface coatings, surface coatings can be done by different ways. Very well-known methods are chemical vapor deposition, physical vapor deposition, electroplating, plasma vapor deposition, gas diffusion, etc.

3.1 HE Prevention by Reduced Graphene Oxide (RGO) Coating

Graphene is most suitable element to reduce the HE from high strength steel materials. It has a thin film of carbon atom which has some unique properties [40–42]. Its chemical inertness properties make him to use at various operating condition. It is also stable in atmosphere condition temperature to 400 °C and reduce the oxidation of the substrate material because of hydrophobic characteristic or property [43], and that is due to its non-polar covalent double bonds, which is responsible for prevention of hydrogen atom bonding with the water [44, 45]. That is the reason, we are selected the graphene material as a coating due to its light weight and halt charge transmit at the metal–electrolyte interface. Thus, most of the researchers have studied and selected

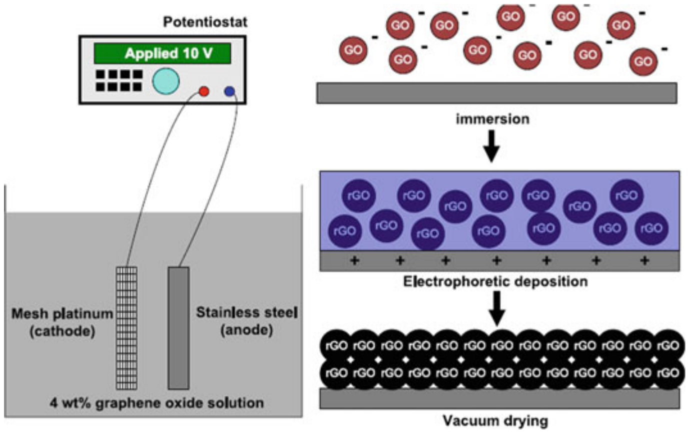

Fig. 1 rGO deposition in the stainless-steel substrate by using EPD technique [47]

the graphene as the coating material [46]. However, graphene coating can diminish corrosion properties of stainless steel as it is coated by CVD. Graphene has been replaced by reduced graphene oxide (rGO) because of its high-volume, low in cost, and processing capabilities at room temperature. One of the economical methods to develop rGO on stainless steel is electrophoretic-deposition method (EPD).

Kim and Kim [47] explained the effect of reduced graphene oxide coating to reduce HE in stainless-steel material. They used the electrophoretic-decomposition technique to coat the rGO above the substrate material. Evaluation of mechanical properties was done by slow strain rate test (SSRT) during hydrogen charging condition [47].

Synthetization of purified graphene to graphene oxide (GO) was done by modified-hammers method [48]. After this synthetization, GO was spreaded out in water and sonicated at room temperature for 4 h in 4 mg/ml concentration solution. After preparation of GO solution, electrophoretic-deposition technique was used at 10 V DC current supply to deposit rGO. For achieving required thickness of rGO above the substrate material time required to be 8 min. After completion of deposition process, samples were taken in vacuum for drying to prevent from oxidation [47].

A below representation showing electrophoretic-deposition process for the establishment of reduced graphene oxide on the stainless-steel substrate material is illustrated in Fig. 1.

3.1.1 Characterization of Sample

The investigation of the rGO in surface and cross-section of substrate material (stainless steel) was done by scanning electron microscopy (SEM).

3.1.2 Electro Chemical Measurements

Electro chemical behavior of rGO on stainless-steel specimen was analyzed using the conventional three electrode cell. Cathodic-polarization experiment or examination and electrochemical-impedance spectroscopy were conducted on rGO. Initially, 0.5 M sulfuric acid solution (H_2SO_4) with 250 mg/L arsenic trioxide (As_2O_3) (pH = 1.0) was prepared and samples were kept in that solution for 2 h. So that hydrogen diffusion and penetration were taken place easily. Nitrogen gas flows through the solution to remove the dissolved oxygen for 2 h and then measurement was done [47].

3.1.3 Slow Strain Rate Tests (SSRT)

SSRT have been widely applied to environmental induced cracking like corrosion cracking and HE. In this case, SSRT testing was performed at strain rate of 1.0×10^{-6}/s to evaluate the effect of rGO deposit or coating to reduce the hydrogen embrittlement effect in stainless-steel material. Here, HC was done at a negative current (-0.5 A/cm^2) for investigation of behavior or effect of HE in coated and bare samples by SSRT testing.

During the testing, it was found that the mechanical properties like the yield, tensile stresses, and strain, of stainless-steel specimen in hydrogen charging condition are reduced. After applying the rGO coating to stainless steel specimen, it was found that the mechanical properties of coated sample return back to initial value of uncharged specimen. Elongation behavior of hydrogen-charged specimen was also affected and reduced from percentage elongation of 40.1% to the value of 23.5% for uncharged to hydrogen-charged specimen. While elongation percentage of rGO-coated hydrogen-charged specimen comes around 35.6%. So, effect of HE in coated sample was reduced and these coating acts a barrier for hydrogen diffusion in stainless steel [47].

3.2 Coating of Zn, Ni, Cu, Al, PVD-Ti-DLC, Carbon, Nitrogen, and Oxygen Diffusion Layers

Electroplating of Zinc (Zn), Nickel (Ni), Copper (Cu), Aluminum (Al), PVD-Ti-DLC, various diffusion layers such as oxygen, nitrogen, and carbon, and electroless NiP coatings are examined and evaluated to reduce the effect of HE in 304 austenitic stainless-steel material. SSRT testing was performed for mechanical properties estimation [17].

Metastable grades like AISI 304 material rigorously experience the HE effects because of austenite to ferrite phase transformation at the time of operation [49–51].

Table 1 Overview of various coatings [62]

Coating material	Coating type	Deposition technique	Thickness μm	Hardness	Adhesion acc [HF]	Remarks
Al	On top	Elecrtroplating	22	15–25 HB	4	Globular structure
Cu	On top	Elecrtroplating	2	50–110 HB	1	Thin coating with pin load
Ni	On top	Elecrtroplating	12	510 HV	1	Ni adhesion coating
Zn	On top	Elecrtroplating	11	92 HV	2	Ductile zinc coating
NiP	On top	Electroless	10	550 HV	2	Amorphous NIP type coating
Ti-DLC	On top	PVD	3	1440 HV	1	Ti adhesion coating
Carbon	Diffusion	Gas diffusion	25	1225 HV	1	Long term gas diffusion
Nitrogen	Diffusion	Gas diffusion	500	300 HV	1	Small term gas diffusion
Oxygen	Diffusion	Plasma diffusion	1	1200 HV	2	Oxidizing at −550 °C

Calculation of HV was done by some formula HB = 0.95 HV

Zn, Ti-DLC, Al, Cu, and the oxygen diffusion layers as well as amorphous Nip coatings were examined because of their unique quality of low hydrogen diffusion coefficient [52–61].

Two AISI 304 stainless steel of internal heat number 40, 4 were used as a substrate material for testing various coatings and diffusion layers. The coatings properties were illustrated by metallo-graphic cross sections, Vickers and Rockwell testing, and X-ray diffraction (XRD) technique was used for internal stresses and phase analysis [62]. A simple coating and some diffusion layer properties are given in Table 1.

Cylindrical specimen is having an outer diameter 8 mm, notch diameter 6 mm, radius on notch is 0.2 mm, and angle of notch is 35^0. Stress concentration factor is 3.4. Fatigue testing was performed in that specimen and operated in atmosphere of hydrogen (10 MPa) until the specimen has broken or failure occurs.

3.3 Niobium Coating on API 5CT P110 Steel

In gas and oil industry, the components are subjected to extreme conditions and aggressive environment. The corrosion phenomena in API 5CT P110 steels is very

Table 2 Niobium coatings spraying parameter [83]

Parameters used	
Flow rate of oxygen (L/min)	164
Flow of propane (L/min)	144
Compressed air flow (L/min)	181
Nitrogen flow—carrier gas (L/min)	290
Gun to substrate distance (mm)	300
Power feed rate (g/min)	41
Speed of Gun transverse (m/s)	0.2
Number of passes	5

fast [63] and HE occurs in that steel due to working in aggressive condition [64]. By application of coating in P110 steel, they exhibit a good corrosion resistance and also work effectively in hydrogen environment as they show resistance for, HE [65].

Thermal spray coatings have received very good attention for protection of oil and gas industry components against HE [66–69]. These kinds of coatings have growing and expanding application in protection against fatigue operation [70] and oxidation process [71–73] and economical and very efficient choice to meet all requirement [74]. Recently, various authors are working in development of nanostructured coating which have better and superior properties [75, 76]. Other coating techniques such as high velocity oxygen fuel (HVOF) is also very efficient in case of corrosion in API 5CT P110 steel [77].

Niobium has very good corrosion resistant in various media [78, 79], and refractory properties [80, 81]. HVOF coating technique was used to deposit niobium in API 5CT P110 steel as it acts as a protective film over the base material against the corrosion.

The parameters which are responsible for spraying process are depicted in Table 2. The surface roughness of coating substrate was measured by contact profilometer in which by Ry values were obtained. The microhardness of both materials was obtained by microhardness tests and this hardness test was performed at the 3 N load and 15 s holding or processing time, as specified and given in the ASTM standard [82].

4 Conclusions

i. Hydrogen embrittlement resistance of rGO coating in stainless steel was examined and investigated by Kim and Kim. Their results showed that rGO-coated samples have less tendency to absorb the hydrogen than the uncoated sample.
ii. Resistance for hydrogen was increased by rGO coating because of C-H bond formation and increase the diffusion length, during the charging condition. So

it is clear that rGO can act as a barrier for hydrogen penetration and acts as a resistance for, HE.

iii. During hydrogen charging condition in coated samples, some surface irregularities, defects such as pores, coating and surface interface act as a hydrogen accumulator and hydrogen adsorbed sites. So, these sides inhibiting the entry of hydrogen from coated sample APT CT P110 steel. It is concluded that hydrogen-trapping capacity of coated sample was 7.5 time more than the normal steel specimen.

iv. Thermal spraying coating of niobium using HVOF also reduces the susceptibility of hydrogen embrittlement and act as barrier for hydrogen diffusion.

v. Electroplating of Zn, Cu, Ni, Al, PVD-Ti-DLC and electrolysis NiP coatings along with oxygen, nitrogen, and carbon diffusion layers was examined for reducing the susceptibility of HE. It was found that carbon and nitrogen diffusion layers work effectively to reduce hydrogen diffusion.

vi. It was found that very little work is carried out for tensile and ductility improvement when worked on hydrogen atmosphere. The Ni and C diffusion layers reduced crack propagation in hydrogen atmosphere.

References

1. Harries DR, Broomfield GH (1963) Hydrogen embrittlement of steel pressure vessels in pressurized water reactor systems. J Nucl Mater 9:327–338
2. Lucas GE (2010) An evolution of understanding of reactor pressure vessel steel embrittlement. J Nucl Mater 407:59–69
3. Zheng J, Liu X, Xu P, Liu P, Zhao Y, Yang J (2012) Development of high pressure gaseous hydrogen storage technologies. Int J Hydrogen Energy 37:1048–1057
4. Takasawa K, Wada Y, Ishigaki R, Kayano R (2010) Effects of grain size on hydrogen environment embrittlement of high strength low alloy steel in 45 MPa gaseous hydrogen. Mater Trans 51:347–353
5. Capelle J, Gilgert J, Dmytrakh I, Pluvinage G (2008) Sensitivity of pipeline steel API X52 to hydrogen embrittlement. Int J Hydrogen Energy 33:7630–7641
6. Hadianfard MJ (2010) Failure in a high pressure feeding line of an oil refinery due to hydrogen effect. Eng Fail Anal 17:873–881
7. Dwivedi SK, Vishwakarma M (2018) Hydrogen embrittlement in different materials: A review. Int J Hydrogen Energy 43(46):21603–21616
8. Troiano AR (1960) The role of hydrogen and other interstitials in the mechanical behavior of metals. Trans ASM 52:54–80
9. Song J, Curtin WA (2013) Atomic mechanism and prediction of hydrogen embrittlement in iron. Nat Mater 12:145–151
10. Devanathan MAV, Stachurski Z (1962) The absorption and diffusion of electrolytic hydrogen in palladium. Proc R Soc A270:90–102
11. Dwivedi SK, Vishwakarma M, Ahmed S (2018) Experimental investigation of hydrogen embrittlement during coating process and effect on mechanical properties of high strength steel used for fasteners. Mater Today: Proc 5(9):18707–18715
12. Grabke HJ, Gehrmann F, Riecke E (2001) Hydrogen in microalloyed steels. Steel Res Int 72:225–235

13. Birnbaum HK, Sofronis P (1994) Hydrogen-enhanced localized plasticity-mechanism for hydrogen-related fracture. Mater Sci Eng A 176:191–202
14. Robertson IM, Sofronis P, Nagao A, Martin ML, Wang S, Gross DW et al (2015) Hydrogen embrittlement understood. Metall Mater Trans 46(6):2323–2341
15. Vergani L, Colombo C, Gobbi G, Bolzoni FM, Fumagalli G (2014) Hydrogen effect on fatigue behavior of a quenched & tempered steel. Procedia Eng 1(74):468–471
16. Dong CF, Liu ZY, Li XG, Cheng YF (2009) Effects of hydrogen charging on the susceptibility of X100 pipeline steel to hydrogen-induced cracking. Int J Hydrogen Energy 34(24):9879–9884
17. Dwivedi SK, Vishwakarma M (2019) Effect of hydrogen in advanced high strength steel materials. Int J Hydrogen Energy 44(51):28007–28030
18. Pradhan A, Vishwakarma M, Dwivedi SK (2020) A review: The impact of hydrogen embrittlement on the fatigue strength of high strength steel. Materials Today: Proceedings, Mar 12
19. Mertens G, Duprez L, De Cooman BC, Verhaege M (2007) Hydrogen absorption and desorption in steel by electrolytic charging. Adv Mat Res 15:816–821. Trans Tech Publications
20. Danford MD (1987) Hydrogen trapping and the interaction of hydrogen with metals. NASA; Technical Paper 2744
21. A review of hydrogen embrittlement of martensitic advanced high-strength steels
22. Farrell K, Quarrell AG (1964) Hydrogen embrittlement of an ultra-high-tensile steel. J Iron Steel Ins 1002–1011
23. Shih DS, Robertson IM, Birnbaum HK (1988) Hydrogen embrittlement of alpha titanium: in situ TEM studies. Acta Metall 36(1):111–124
24. Brass AM, Chene J (1998) Influence of deformation on the hydrogen behavior in iron and nickel base alloys: a review of experimental data. Mater Sci Engng A 242:210–211
25. Birnbaum HK, Sofronis P (1994) Hydrogen-enhanced localized plasticity: a mechanism for hydrogen-related fracture. Mater Sci Engng A 176:191–202
26. Heller WR (1961) Quantum effects in diffusion: internal friction due to hydrogen and deuterium dissolved in/cap alpha/-iron. Acta Metall 9:600–613
27. Matsui H, Kimura H, Kimura A (1979) The effect of hydrogen on the mechanical properties of high-purity iron. III.—the dependence of softening on specimen size and charging current density. Mater Sci Engng 40(22):227–234
28. Kimura H, Matsui H (1979) Reply to "further discussion on the lattice hardening due to dissolved hydrogen in iron and steel" by Asano and Otsuka. Scripta Metall 13:221–223
29. Hirth JP (1980) Effects of hydrogen on the properties of iron and steel. Metall Mater Trans A 11(6):861–890
30. Dufresne F, Seeger A, Groh P, Moser P (1976) Hydrogen relaxation in a-iron. Phys Stat Sol A 36:579–589
31. Senkov ON, Jonas JJ (1996) Dynamic strain aging and hydrogen-induced softening in alpha titanium. Metall Mater Trans A 27:1877–1887
32. Au JJ, Birnbaum HK (1973) Magnetic relaxation studies of hydrogen in iron: relaxation spectra. Scripta Metall 7:595–604
33. Magnin T, Bosch C, Wolski K, Delafosse D (2001) Cyclic plastic deformation behaviour of Ni single crystals oriented for single slip as a function of hydrogen content. Mater Sci Engng A 314:7–11
34. Clum JA (1975) The role of hydrogen in dislocation generation in iron alloys. Scripta Metall 9:51–58
35. Birnbaum HK, Robertson IM, Sofronis P (2000) Hydrogen effects on plasticity. In: Lepinoux J (ed) Multiscale phenomena in plasticity. Kluwer Academic Publishers, Dordrecht
36. Mignot F, Doquet V, Sarrazin-Baudoux C (2004) Contributions of internal hydrogen and room-temperature creep to the abnormal fatigue cracking of Ti6246 at high Kmax. Mater Sci Engng A 380:308–319
37. _Cwiek J (2010) Prevention methods against hydrogen degradation of steel. J Achiev Mater Manuf Eng 43(1):214–221
38. Timmins PF. Solutions to hydrogen attack in steels

39. Grobin AW Jr (1988) Other ASTM committees and ISO committees involved in hydrogen embrittlement test methods. Hydrogen Embrittlement: Prev Contr 962:46
40. Geim AK, Novoselv KS (2007) The raise of graphene. Nat Mater 6:183–191
41. Zou C, Yang B, Bin D, Wang J, Li S, Yang P et al (2017) Electrochemical synthesis of gold nanoparticles decorated flower-like graphene for high sensitivity detection of nitrite. J Colloid Interface Sci 488:135–141
42. Zhang K, Xiong Z, Li S, Yan B, Wang J, Du Y (2017) Cu3P/RGO promoted Pd catalysts for alcohol electro-oxidation. J Alloys Compd 706:89–96
43. Bunch JS, Verbridge SS, Alden JS, van der Zande AM, Parpia JM, Craighead HG et al (2008) Impermeable atomic membranes from graphene sheets. Nano Lett 8:2458–2462
44. Leenaerts O, Partoens B, Peeters FM (2009) Water on graphene: hydrophobicity and dipole moment using density functional theory. Phys Rev B 79:235–244
45. Chen S, Brown L, Levendorf M, Cai W, Ju YS, Edge-worth J et al (2011) ACS Nano 5:1321–1327
46. Liu Y, Zhang J, Li S, Wang Y, Han Z, Ren L (2014) Fabrication of a super hydrophobic graphene surface with excellent mechanical abrasion and corrosion resistance on aluminium alloy substrate. RSC Adv 4:45389–45396
47. Kim Y-S, Kim J-G (2017) Electroplating of reduced-graphene oxide on austenitic stainless steel to prevent hydrogen embrittlement. Int J Hydrogen Energy 1–10
48. Hummers WS, Offeman RE (1958) Preparation of graphitic oxide. J Am Chem Soc 80:1339–1339
49. Hecker SS, Stout MG, Stauidhammer KP, Smith JL (1982) Metal Trans 13A:619
50. Han G, He S, Fukuyama S, Yokogawa K (1998) Acta Mater 46(13):4559
51. Maksimovich GG, Tret'yak IY, Ivas'kevich LM, Slipchenko TV (1985) Fiz.-Khim. Mekh. Mater 21(4):29
52. Mindyuk AK, Svist EI, Koval VP (1974), Vasilenko II, Babei YuI (1974) Mater Sci 8(1):98
53. Chen CL, Lee PY, Wu JK, Chiou DJ, Chu CY, Lin JY (1993) Corros Prev Control 40(3):71
54. Vainonen E, Likonen J, Ahlgren T, Haussalo P, Wu CH (1997) J Appl Phys 82(8):3791
55. Scully JR, Young GA, Smith SW (2000) Mat Sci Forum 331–337:1583
56. Young GA, Scully JR (1998) Acta Mater 46:6337
57. Hashimoto E, Kino T (1983) J Phys F Met Phys 13:1157
58. Caskey GR, Dexter AH, Holzworth ML, Louthan MR, Derrick RG (1976) Corrosion 32:370
59. Rudd DW, Vose DW, Johnson S (1961) J. Phys. Chem. 65:1018
60. Begeal DB (1978) J Vac Sci Technol 15:1146
61. Luu WC, Kuo HS, Wu JK (1997) Corros Sci 39(6):1051
62. Michler T, Naumann J (2009) Coatings to reduce hydrogen environment embrittlement of 304 austenitic stainless steel. Surface & Coatings Technology 203:1819–1828
63. Zhu SD, Wei JF, Bai ZQ, Zhou GS, Miao J, Cai R (2011) Failure analysis of P110 tubing string in the ultra-deep oil well. Eng Fail Anal 18:950–962
64. Covered T Analysis of high-collapse grade P110 coupling failures—a case study by element materials technology
65. Lin N, Guo J, Xie F, Zou J, Tian W, Yao X, Zhang H, Tang B (2014) Comparison of surface fractal dimensions of chromizing coating and P110 steel for corrosion resistance estimation. Appl Surf Sci 311:330–338. https://doi.org/10.1016/j.apsusc.2014.05.062
66. El Rayes MM, Abdo HS, Khalil KA (2013) Erosion—corrosion of cermet coating. Int J Electrochem Sci 8:1117–1137
67. Pombo Rodriguez RMH, Paredes RSC, Wido SH, Calixto A (2007) Comparison of aluminum coatings deposited by flame spray and by electric arc spray. Surf Coatings Technol 202:172–179. http://dx.doi.org/10.1016/j.surfcoat.2007.05.067
68. Guilemany JM, Miguel JM, Armada S, Vizcaino S, Climent F (2001) Use of scanning white light interferometry in the characterization ofwear mechanisms in thermal-sprayed coatings. Mater Charact 47:307–314. https://doi.org/10.1016/S1044-5803(02)00180-8
69. Motta FP (2011) Propriedades de revestimentos de nióbio obtidos por aspersão térmica a plasma sobre aço API 5L X65. Universidade Federal do Rio Grande do Sul

70. Ibrahim A, Berndt CC (2007) Fatigue and deformation of HVOF sprayed WC–Co coatings and hard chrome plating. Mater Sci Eng A 456:114–119
71. Cha SC, Gudenau HW, Bayer GT (2002) Comparison of corrosion behavior of thermal sprayed and diffusion-coated materials. Mater Corros 53:195–205
72. Gu L, Zou B, Fan X, Zeng S, Chen X, Wang Y, Cao X (2012) Oxidation behavior of plasma sprayed Al @ NiCr with cyclic thermal treatment at different temperatures. Corros Sci 55:164–171. https://doi.org/10.1016/j.corsci.2011.10.017
73. Matthews S, James B, Hyland M (2013) High temperature erosion—oxidation of Cr_3C_2—NiCr thermal spray coatings under simulated turbine conditions. Corros Sci 70:203–211
74. Tan JC, Looney L, Hashmi MSJ (1999) Component repair using HVOF thermal spraying. Mater Process Technol 93:203–208
75. Wang Y, Bai Y, Liu K, Wang JW, Kang YX, Li JR, Chen HY, Li BQ (2015) Microstructural Evolution of Plasma Sprayed Submicron-/nano-zirconia-based thermal barrier coatings
76. Xu K, Wang A, Wang Y, Dong X, Zhang X, Huang Z (2009) Surface nano crystallization mechanism of a rare earth magnesium alloy induced by HVOF supersonic micro particles bombarding. Appl Surf Sci 256:619–626. https://doi.org/10.1016/j.apsusc.2009.06.098
77. de Brandolt CS, Ortega-Vega MR, Menezes TL, Schroeder RM, de Malfatti CF (2016) Corrosion behavior of nickel and cobalt coatings obtained by high-velocity oxyfuel (HVOF) thermal spraying on API 5CT P110 steel. Mater Corros 67:368–377
78. Kouřil M, Christensen E, Eriksen S, Gillesberg B (2012) Corrosion rate of construction materials in hot phosphoric acid with the contribution of anodic polarization. Mater Corros 63:310–316
79. Wang W, Mohammadi F, Alfantazi A (2012) Corrosion behaviour of niobium in phosphate buffered saline solutions with different concentrations of bovine serum albumin. Corros Sci 57:11–21
80. Tommaselli MAG, Mariano NA, Pallone EMJA, Kuri SE (2004) Oxidation of niobium particles embedded in a sintered ceramic matrix. Mater Corros 55:531–535
81. Galetz MC, Rammer B, Schutze M (2015) Refractory metals and nickel in high temperature chlorine containing environments—thermodynamic prediction of volatile corrosion products and surface reaction mechanisms: a review. Mater Corros 66:1206–1214
82. Mathieu S, Knittel S, Berthod P, Mathieu S, Vilasi M (2012) On the oxidation mechanism of niobium-base in situ composites. Corros Sci 60:181–192
83. de Souza Brandolt C, Noronha LC, Hidalgo GEN, Takimi AS et al (2017) Niobium coating applied by HVOF as protection against hydrogen embrittlement of API 5CT P110 steel. Surf Coat Technol