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Glossary of Words [165-167]

Activation energy (Q): The energy required to initiate a reaction, such as diffusion.

Anion: A negatively charged, nonmetallic ion

Anode: The electrode in an electrochemical cell or galvanic couple that experiences oxidation, or gives up electrons.

Capacitance (C): The charge-storing ability of a capacitor, defined as the magnitude of charge stored on either plate divided by the applied voltage

Carburizing. The process by which the surface carbon concentration of a ferrous alloy is increased by diffusion from the surrounding environment.

Cathode. The electrode in an electrochemical cell or galvanic couple at which a reduction reaction occurs.

Cation. A positively charged metallic ion

Corrosion. Deteriorative loss of a metal as a result of dissolution environmental reactions

Corrosion rate (CR). Thickness loss of material per unit of time as a result of corrosion; usually expressed in terms of mils per year or millimeters per year.

Diffraction (x-ray). Constructive interference of x-ray beams that are scattered by atoms of a crystal.

Diffusion. Mass transport by atomic motion.

Diffusion coefficient (*D*). The constant of proportionality between the diffusion flux and the concentration gradient in Fick's first law. Its magnitude is indicative of the rate of atomic diffusion.

Dislocation. A linear crystalline defect around which there is atomic misalignment. Plastic deformation corresponds to the motion of dislocations in response to an applied shear stress.

Ductile-to-brittle transition. The transition from ductile to brittle behavior with a decrease in temperature exhibited by some low-strength steel (BCC) alloys; the temperature range over which the transition occurs is determined by Charpy and Izod impact tests

Ductility. A measure of a material's ability to undergo appreciable plastic deformation before fracture; it may be expressed as percent elongation (%EL) or percent reduction in area (%RA) from a tensile test.

Erosion–corrosion. A form of corrosion that arises from the combined action of chemical attack and mechanical wear.

Ferrite (iron). Body-centered cubic iron; also, iron and steel alloys that have the BCC crystal structure.

Grain. An individual crystal in a polycrystalline metal or ceramic.

Grain boundary. The interface separating two adjoining grains having different crystallographic orientations

Grain size. The average grain diameter as determined from a random cross section

Hardness. The measure of a material's resistance to deformation by surface indentation or by abrasion

Hexagonal close-packed (HCP). A crystal structure found for some metals. The HCP unit cell is of hexagonal geometry and is generated by the stacking of close-packed planes of atoms.

Intergranular corrosion. Preferential corrosion along grain-boundary regions of polycrystalline materials

Isothermal transformation (*T–T–T*) diagram. A plot of temperature versus the logarithm of time for a steel alloy of definite composition. Used to determine when transformations begin and end for an isothermal (constant-temperature) heat treatment of a previously austenitized alloy.

Kinetics. The study of reaction rates and the factors that affect them.

Lattice. The regular geometrical arrangement of points in crystal space.

Metallic bond. A primary interatomic bond involving the nondirectional sharing of nonlocalized valence electrons ("sea of electrons") that are mutually shared by all the atoms in the metallic solid.

Microstructure. The structural features of an alloy (e.g., grain and phase structure) that are subject to observation under a microscope.

Octahedral position. The void space among close-packed, hardsphere atoms or ions for which there are six nearest neighbors. An octahedron (double pyramid) is circumscribed by lines constructed from centers of adjacent spheres.

Oxidation. The removal of one or more electrons from an atom, ion, or molecule.

Passivity. The loss of chemical reactivity, under particular environmental conditions, by some active metals and alloys, often due to the formation of a protective film

Phase. A homogeneous portion of a system that has uniform physical and chemical characteristics

Pitting. A form of very localized corrosion wherein small pits or holes form, usually in a vertical direction.

Plastic deformation. Deformation that is permanent or nonrecoverable after release of the applied load. It is accompanied by permanent atomic displacements

Polarization (corrosion). The displacement of an electrode potential from its equilibrium value as a result of current flow

Reduction. The addition of one or more electrons to an atom, ion, or molecule

Slip. Plastic deformation as the result of dislocation motion; also, the shear displacement of two adjacent planes of atoms.

Solid-solution strengthening. Hardening and strengthening of metals that result from alloying in which a solid solution is formed. The presence of impurity atoms restricts dislocation mobility

Strain hardening. The increase in hardness and strength of a ductile metal as it is plastically deformed below its recrystallization temperature.

Tetrahedral position. The void space among close-packed, hardsphere atoms or ions for which there are four nearest neighbors.

Thermal stress. A residual stress introduced within a body resulting from a change in temperature

Toughness. The ability of a material to absorb energy and plastically deform before fracturing;

Yield strength (*y*). The stress required to produce a very slight yet specified amount of plastic strain; a strain offset of 0.002 is commonly used.

Appendices

Appendix A: A brief literature survey on high temperature oxidation of austenitic stainless steels.

S.No.	Alloy	Temperature	Environment	Findings	References
1.	17.8Mn, 9.5 Cr, 1.0 Ni, 0.27 C, and 0.03 N	700-1000 °C	Air Oxidation 1500 min	Three layered structures. No internal oxidation up to 700°C	Douglas et al. [34]
2.	Mn-containing Fe-28% Cr alloys	800-1000°C	O_2, 100 h	$MnCr_2O_4$ at the interface Depletion of Mn at surface.	FH Scott et al.[100]
3.	Fe–18Cr–18Mn stainless steels	525, 625, and 725°C	Air Oxidation 500 h	Interstitials (N) does not affect the oxidation. Two layered structure of oxide layer.	James Rawers. [35]
4.	304L steel	500–800°C	Humid air 0.02–13 cm/sec flow rate 168 h	Cr evaporation in 500-800°C High flow rate early breakdown (800°C).	H Asteman et al. [168]
5.	Fe-Cr-Mn-N (Ni-free)	800°C	Ageing/oxidation 200 h	Precipitation of Cr2N σ phase above 850°C Mn, Fe and Cr oxide layer Mn-depleted ferrite zone	B Kartik et al [13]
6.	Low Nickel austenitic stainless steel	600-700°C	Dry air 500 cycles of 1 h	Oxide layer shows good adhesion to surface. FCC to BCC transition at the surface reduces the thermal stresses	FJ Preez et al. [97]
7.	Fe-Cr18-Mn16-N0.83-Nb0.15	950-1150°C	Static air for 10 h	Parabolic rate law was followed and Mn_3O_4 oxide layer was formed	Xianli Liu et al.[157]
8.	Nitronic 32	800-1000°C	Static air for 24 h	Presence of Mn deteriorates the oxidation resistance.	F.Gesmundo et al.[169]
9.	Fe-9Cr, Fe-17Cr and Fe-25Cr	700°C	500 Cycle of 1 hr Ar-20O_2, Ar-20O_2-5H_2O and Ar-5O_2-20H_2O	Cr vaporization was observed with increasing Cr content in steels. Water vapor presence increases the formation of Chromium oxide.	N.K. Othman et al. [170]
10.	Cr_2O_3 and $MnCr_2O_4$	850-1050°C	50-1000 h Synthetic air with 10% H_2O (5 l/h)	Cr_2O_3 shows higher Cr volatilization compared to $MnCr_2O_4$ in humid air environments.	Alexander Stenzel et al. [171]

Appendix B: Metal dusting of behavior of various austenitic stainless steels.

S.No.	Alloy	Temperature	Environment	Findings	References
1.	304L	650°C	25%CO + 3%H_2O +H_2 1000 h	Carbide's formation followed by oxidation.	P. Szakalos et al. [49]
2.	Fe and Ni based alloys	550-650°C	H_2O (0-21 wt%), CO (31-43 wt%), H_2 (31-59wt%), CO_2 (2-6 wt%) 500 h	Beneficial effect of the H_2O for low alloyed steels. Do not prevent pitting. Thick oxide layer was formed.	A. Rouaix-Vande Put et al.[62]
3.	Ni based alloys	550-750°C	20 vol%H_2 and 80 vol% CO 100-1000 h	Experimental Setup affects initiation and damage Sample holder affects the process	F. Di Gabriele et al.[172]
4.	Fe–Ni–Cr–Al based alloys	650°C	50%CO–49%H_2–1%H_2O 325 cycles of 1 h	Thermal and Mechanical stress causes spallation and initiation of metal dusting.	Jianqiang Zhang et al.[173]
5.	Fe–Cr–C and Fe–Ni–Cr–C systems	680°C	68% CO–26% H_2–6% H_2O 200 h	Spallation of Cr_2O_3 due to thermal cycle. Internal Carburization (Fe containing).	C. H. Toh et al.[59]
6.	$MnCr_2O_4$ and Cr_2O_3 spinel	1050°C	2%CH4 + 98%H2 at a flow rate of 55.4 mL/min 100 h	Better performance of $MnCr_2O_4$ than Cr_2O_3 due to anti coking property of manganese.	Hao Li et al. [109]
7.	Inconel 601 (substrate) NiCrAlY.	650°C	50CO:50H2 gas 160 h and 1000 h	Defects in coating in NiCrAlY leads to carburization and metal dusting.	C.M. Chun et al. [174]
8.	800HT	570 °C and atmospheric pressure	47.25CO-47.25H_2-5.5H_2O gas mixture for 4000 h.	Initial carburization and subsequent oxidation were the primary mechanism of metal dusting	Aurélien Fabas et al.[83]
9.	Fe and Ni foils of 99.99%	350°C to 1050°C.	H_2:CO ratio ranging from 2:98 to 90:10 for 500 h	Highest metal dusting rate with 1:1 ratio. Metal disintegration through graphite tubes.	C.M. Chun et al.[175]
10.	304 Stainless steels	700°C	CO/H_2/H_2O for 300 h.	Internal carbide precipitation and volume expansion was primary mechanism	Jianqiang Zhang et al. [55]

11.	Ni based Inconel 601	550 ºC	10% CO in Ar (a_C>>1) gas mixture for 20 h	The higher carbon formation appears to be associated with inclusion of Ni and/or Fe species in the surface oxide layer.	P.V.D.S. Gunawardana et al[176]
12.	Austenitic stainless and nickel-based superalloys.	593°C	53.4H2-5.7CO$_2$-18.4CO-22.5H$_2$O for 1000 h	Ni based alloys performs better than Fe base alloys. High humidity can reduce the susceptibility of the alloys to metal dusting attack.	Z. Zeng [177]
13.	Pure iron sample.	700°C	24.81–94.81 vol% H$_2$, 5–75 vol% CO and 0.19 vol% H$_2$O for 4 h	Heavy deposition of coke with iron carbide particle. Increasing CO increases the intensity of attack.	J Zhang[178]
14.	Alloy 800, 18Cr 8Ni steel, 10CrMo 9 10, P 91	600 °C	24vol %CO, 74vol %H$_2$, 2vol %H$_2$O	Surface finish influences the metal dusting attack. Easy Cr diffusion in ferritic stainless-steel leads to Cr$_2$O$_3$ formation.	HJ Grabke[110]
15.	304L, 321, 316, 316L type 430 and type 441	650°C	CO-18.9% H$_2$-79.1%, H$_2$O-2% for 30 days	Ferritic material (430&441) performed better than that of austenitic material.	GA Slabbert et al. [179]
16.	Austenitic SS 304	700ºC	Ar-75%CO$_2$ and Ar-75%CO$_2$-12%H$_2$O for 10, 20, 30, 40 and 50 h	Deterioration of oxide layer at higher temperature and it get enhances in the presence of water vapor.	Nurul atikah shariff et al.[180]
17.	Fe20%Cr32%Ni balanced.	600 ºC	24%CO-74%H$_2$-2%H$_2$O for 1500 h	Addition of W, Nb and Mo initially retard the metal dusting and after precipitation of carbides metal dusting increases.	S. Strauß* et al.[181]
18.	High chromium ferritic and austenitic steels	600°C	N$_2$-CO-CO$_2$-H$_2$O for 300 h	Internal carburization of the steel results in formation of (chromium) carbide precipitates.	L Niewolak et al.[182]
19.	MnCr$_2$O$_4$ and Cr$_2$O$_3$	1050°C	2%CH$_4$ + 98%H$_2$ for 100 h	MnCr$_2$O$_4$ spinel was found to be better than Cr$_2$O$_3$.	Hao Li et al.[109]
20.	Cr/Cr$_2$O$_3$ thin films deposited on 304L	800 °C	CH$_4$ + H$_2$ for 20 h	Improvement of metal dusting resistance due to Cr$_2$O$_3$ coating.	L. Melo-Máximo et al.[107]

Appendix C: Erosion Behavior of different stainless steels.

S.No.	Alloy	Temperature	Erodent & Parameter	Findings	References
1.	13/4 martensitic and 21-4-N nitronic steels	Room Temperature	SiC, 120 m/s, 30^o and 90^o, 120 min	12-4-N steel performed better than martensitic grade due to superior mechanical properties.	AK Chauhan et al. 2008[77]
2.	AISI 310S, AISI 316, AISI 1020	Room Temperature	Al_2O_3, 15^o-90^o with impact velocity of 30-100m/s	Erosion rate increases with decrease in hardness of material. Ductile mechanism of erosion.	J Malik et al. [74]
3.	AISI 316 and 304L	25,350,650℃	SiO_2, 15-45^o with impact velocity of 25 m/s	Erosion oxidation was prominent. Quick formation of thin oxide layer.	M Antovo et al.[130]
4.	Cast 13/4, Cast 21-4-N and hot rolled 21-4-N	Room Temperature	SiC, 30 and 90^o with impact velocity of 120m/s for 120 min	Erosion resistance of cast 13/4 was better while 21-4-N in hot rolled condition performed better.	A.K Chauhan et al. 2009[79]
5.	SUS 304	Room Temperature	Al_2O_3, 0-90^O with impact velocity of 200m/s	Micro-cutting and ploughing were the primary mechanism of erosion.	QB Nguyen et al.[183]
6.	316L and coated with WC-Cr_3C_2–Ni	500-650℃	Al_2O_3 at 30 and 90^o impact angle with impact velocity of 30 m/s for 10 min.	Uncoated samples performed better than coated samples owing to lower hardness of uncoated samples.	DG Bhosale et al. 2020[184]
7.	High Cr cast iron	900℃	Alumina at 30, 60 and 90^o with discharge rate of 26 g/sec.	Type of heat treatment influences the erosion rate. Better performance of as quenched samples.	Kazumichi Shimizu et al. [185]
8.	Borided X12CrNiMoV12-3 steel	Room temperature and 400℃	SiO_2 at 30, 60 and 90^o with 30 m/sec for 10 min	Coating of FeB and FeB_2 on steel increases the erosion resistance.	A. Ruiz-Rio et al.[186]
9.	AISI 304, 316 and 420 stainless steels	Room temperature	SiC at 30-90^o at impact velocity of 24 m/sec for 10 min.	AISI 420 shows best resistance to erosion and it shows ductile Behavior for erosion.	J.R. Laguna-Camacho et al.[187]
10.	SUS 304	Room temperature	Al_2O_3 at impact angle of 0-90^O at	Plastic deformation induced indentation, ploughing and cutting	QB Nguyen et al. 2019 [188]

			velocity of 30m/sec	was primary mechanism of erosion.	
11.	316L (Cr3C225 (Ni20Cr) coating)	Room temperature, 200, 400 and 600℃	Alumina at impact angle of 30, 60 and 90° with velocity of 100m/sec	For both coated and uncoated specimen ductile Behavior of erosion. Increase in temperature increases erosion rate.	Hemant Nautiyal et al.[138]
12.	SS 304	Room Temperature	Alumina at impact angle of 30 and 60° at velocity of 40m/sec	Highest metal removal was at 30° impingement angle and alloy exhibited ductile Behavior.	Mayank Patel et al.[189]
13.	304, 316 and 410 stainless steels	Room temperature	SiC with impact angle of 30, 60 and 90° at velocity of 100 m/sec	410 SS shows better erosion resistance. Soft zone formation beneath the eroded layer in 410 SS compared to 304 and 316.	Trilok Singh et al.[190]
14.	Martensitic and nitrogen alloyed austenitic stainless steels	Room temperature	Alumina at impact angle of 30, 45, 60 and 90° with impact velocity of 41m/sec	Mechanical properties affect the erosion rate. At oblique and normal angle of impingement lower erosion rate for nitrogen alloyed stainless steel.	Ashish Selokar et al.[191]
15.	AISI 444, AIS 439 and AISI 304	Room temperature	Silica sand with impact velocity of 40, 66 and 85 m/sec at impact angle of 15, 30, 45 and 90°	Peak erosion at 30° impingement angle. Hutching's normal model of erosion was followed.	A Aazad Hussian et al.[192]
16.	Nitrogen alloyed austenitic stainless steel and 316L	Room temperature	Alumina at 30, 60 and 90° impingement angle with impact velocity of 41m/sec	Nitrogen alloyed austenitic stainless steel performed better than 316L due its superior mechanical properties.	Ashish Shelokar et al. [139]
17.	AISI 446	550,650 and 750℃	Al_2O_3 with angle of 60, 75 and 90° at velocity of 100 m/sec	Erosion rate increases with increase in temperature.	A Mishra et al. [125]
18.	API X120	Room temperature	Al_2O_3 at 30-90 with velocity of 43-167 m/sec	With increase in impingement angle and velocity erosion rate increases.	Paul C. Okonkwo et al.[193]

Appendix D: Aqueous corrosion Behavior of high nitrogen austenitic stainless steels.

S.No.	Alloy	Ageing Temperature	Environment	Findings	References
1.	Fe-17Cr-21Mn-0.59N	700, 800 and 900°C for 14 h	0.5 M NaCl solution, Cyclic potentiodynamic Test	Precipitation of Cr_2N. Disc shape precipitates increase the pitting resistance.	K.Krishna Kumar et al.[80]
2.	Type 316L and Ni free high Mn austenitic stainless steel	650 C for 2 h	0.5% NaCl and acidic solution of 0.5 M NaCl + 0.5 M H_2SO_4	Solution treated Ni free austenitic stainless steel show high corrosion resistance compared to 316L in both the solutions.	Xinqiang Wu et al. [15]
3.	High nitrogen austenitic stainless steel	Solution treated condition	0.05 M H_2SO_4 + 0.5 M NaCl and 0.05 M H_2SO_4 + 0.5 M Na_2SO_4	Alloys exhibit self-passive Behavior in both solutions. Cl diffusion leads to passive film breakage.	Y.X. Qiao et al.[194]
4.	High manganese nickel free stainless steel with N variation	Room temperature	3.5% NaCl and 0.5 M H_2SO + 0.5 M NaCl solutions	Increase in N content enhances the dissolution resistance in both the solutions.	Yao Fu et al.[195]
5.	High nitrogen stainless steel Effect of cold work and Sensitization	650 ◦C for 2 h	0.5 M H_2SO_4 + 0.5 M NaCl, 3.5% NaCl and 0.5 M NaOH + 0.5 M NaCl	Increasing cold work increases the corrosion rate. Precipitation of Chi phase during the sensitization.	Yao Fu et al. 2009 [196]
6.	Fe-18.4Cr-15.8Mn-2.2Mo-0.66N-0.04C	Room temperature	3.5 % NaCl	Ultrafine grain size increases the ability of oxide film to re-passivate easily.	H. Zhang et al.[197]
7.	High nitrogen CrMn stainless steel.	875°C for 2 h	3.5 % NaCl solution at 30°C	Increasing amount of low angle grain boundary will increase in corrosion resistance.	Jianjun Qi et al.[198]
8.	High nitrogen nickel free austenitic stainless steel and 316L	Room temperature	0.9%NaCl solution (saline), phosphate-buffered saline, Hanks' solution	High nitrogen nickel free stainless steel shows lower corrosion rates and has advantage for re-passivation in all solutions	Daisuke Kuroda et al.[199]
9.	High nitrogen nickel free	Room temperature	3.5 % NaCl	Increase in applied potential leads to deterioration in passive film	H. Shi et al.[200]

	austenitic stainless steel				
10.	Fe-16Cr-Mn-Mo-N (Varying Mo and N)	Room Temperature	3.5 % NaCl	N content increases the passive Behavior of film while Mo addition enhances the pitting resistance.	KL Chao et al.[81]
11.	19Cr-18Mn-0.69N, Type 316L SS and 14Cr-8-Mn SS	Room Temperature	3.5% NaCl	Mn sulfide inclusions reduces the combined efficiency of Mo and N towards pitting corrosion.	P. Saravanan et al.[201]
12.	Fe-19% Cr-5% Ni-5% Mn-3% Mo-0.024% C-0.69% N	Ageing at 400-1000℃ for 0.1-1000 h of samples.	19.5 N H_2SO_4 + 0.01 M KSCN	Corrosion resistance decreases with ageing time and temperature owing to Cr_2N precipitation.	B.S. Covino et al.[202]
13.	Nickel free manganese bearing stainless steel	Room temperature	0.1 M NaOH solutions with 1–5 M NaCl	Passive film contains chromium oxy-hydroxides. Depletion of Mn below the passive film.	B. Elsener et al.[203]
14.	High nitrogen nickel free stainless steel.	Room temperature	0.1 M NaCl, 0.5 M NaCl, and 0.05 M H_2SO_4 + 0.5 M NaCl	High nitrogen nickel free stainless steel possesses excellent corrosion resistance in acidic chloride environment	Yanxin Qiao et al.[23]
15.	1Cr18Ni9Ti austenitic stainless steel	Room temperature	3% NaCl test aqueous solution	Two layered passive layer structure formed first with iron hydroxides followed by chromium oxides/hydroxides.	M. K. Lei et al.[204]
16.	Cr23N1.2 and 304 austenitic stainless steels.	20, 40, 60 and 80°C of electrolyte	3.5 % NaCl solution	Increasing temperature of solution leads to increase in corrosion rate. No re-passivation occurred at all temperature.	B. R. Tzaneva[205]
17.	High nitrogen nickel free and conventional austenitic stainless steel	Room temperature	3.5 wt.% NaCl solutions	NH_3 molecularly adsorbed on the Cr_2O_3 passive film improves resistance of film and initiation of pitting corrosion on high nitrogen steel.	Shicheng Sun et al.[151]
18.	Mn–Cu–C-N austenitic	Room temperature	0.5M H_2SO_4	Cu was shown to	M. Milititsky et al.[206]

	stainless steel and AISI 304		and 0.5M H_2SO_4 plus 0.4M NaCl solutions	be beneficial in decreasing the dissolution current values. Nitrogen enhances the re-passivation ability.	
19.	Fe-22Cr-1.9Ni-2.3Mo-0.2N-xMn	Ageing at 800℃ from 30-930 min	3.5 wt.% NaCl solutions	Precipitation of σ phase and increase in Mn content leads to deterioration of corrosion resistance.	Zaiqiang Feng et al.[207]

List of Publications

1. **Sharvan Kumar** and G. S. Mahobia. "Cyclic oxidation of Fe–18Cr–21Mn–0.65 N austenitic stainless steel at 400–700° C." *Transactions of the Indian Institute of Metals* 73.10 (2020): 2457-2470.
2. **Sharvan Kumar** and G. S. Mahobia. "The features of metal dusting process in the extremely low nickel austenitic stainless steel (18Cr-21Mn-0.65 N-Fe)." *Corrosion Science* 176 (2020): 108926.
3. **Sharvan Kumar**, Ankitendran Mishra, Sunil Mohan and G.S. Mahobia. "The solid particle erosion of pre oxidized high manganese nitrogen stabilized austenitic stainless steel (18Cr-21Mn-0.65 N-Fe) at 400 to 700° C." *Surface Topography: Metrology and Properties* 9.3 (2021): 035002.
4. **Sharvan Kumar**, Dheeraj Jaiswal, C.K. Behera and G.S. Mahobia Potentiodyanmic Corrosion of Fe-18Cr-21Mn-0.65N austenitic stainless steel at 400-700℃. (Communicated)