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Effect of heat treatment on microstructure, mechanical and corrosion characteristics of Duplex Stainless Steel 2205: A Review

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Abstract:
Duplex stainless steel 2205 has proven to be the most acceptable material for marine and saline applications because of its superior corrosion resistance with good erosion and wear resistance.. This review article focuses primarily on the morphology, mechanical properties, and corrosion resistance analysis of DSS 2205. Various microstructure characterization and corrosion testing techniques used by previous researchers are thoroughly overviewed and their results are discussed in the form of table. The effects of heat treatment and quenching time on corrosion resistance and mechanical properties of DSS 2205 are studied and critical observations are noted down. The examination of morphology carried out by previous researchers on heat treatment at several temperatures and different quenching media also comparison of with and without treated samples are studied and critical remarks have been presented. Mechanical features of DSS 2205 based on tensile test, micro-hardness test, etc. are discussed. This article includes exhaustive literature review of standard research articles which may become ready information for subsequent researchers to establish their line of action.

Keywords: 1. Microstructure, 2.Mechanical properties, 3.Corrosion resistance, 4.Heat treatment.

Introduction:
DSS 2205 is an intermediate grade between ferritic and austenitic stainless steels. DSS 2205 is more resistant to stress corrosion than austenitic types. They have better toughness than ferritic steels but not well for austenite [4]. On the other hand, the strength of DSS 2205 is greater than that of austenite. As a result of extensive research and development recently, a number of new forged alloys have been developed and relevant technical data obtained to verify the treatment of dual-phase steels as other types of steel [5]. Cr- Chromium and N- nickel are the main alloying elements having % of volume fraction is in between 18-28% and 4.5-8% respectively. Copper, molybdenum, tungsten, nitrogen, manganese, and silicon may be added to control morphological changes to balance and which is beneficial for corrosion resistance [6]. Mo-Molybdenum is typically added to improve the corrosion characteristics for crevice and pitting [7]. In the DSS 2205 the amount of the main phases is controlled by % of alloy elements and heat treatment. The ratio of the principal phases plays a crucial part for defining their properties.
The volume fraction of α-ferrite and γ-austenite varies with change in temperature and at high temperatures the morphology becomes more ferrite, less Ni and more Cr equivalents which changes the % of amount in structure α-ferrite and γ-austenite varies in between 40-60 or 30-70. Like the ferritic, they are ferro-magnetic, but have the good occurrence of the austenitics and have lower thermal expansion and higher heat conductivity than austenitic grades. For wrought alloys, austenite is lands in a ferrite matrix can be observed in the morphology due to which laths austenite formation in a ferrite matrix. The presence of α-ferrite with γ-austenite shows the better inter-granular corrosion resistance also improves SCC resistance compared to fully austenitic stainless steels. Also, improve the mechanical characteristics and localized corrosion resistance in the occurrence of austenite in the structure due to the presence stabilizing components like N and Ni.

Moreover, at higher temperature treatment volume % of ferrite phases in the DSSs 2205. Treatment below the recrystallization temperature uneven deformation of the ferrite phase, which contains large amounts of Cr and Mo, and has low solubility of N and C, may cause in the morphology, makes formation of intermetallic phases which have unpleasant effects on corrosion and mechanical characteristics. Figure 1 shows the precipitation of main and intermetallic phase at various temperatures in DSS and it is evident that most of these precipitates concern ferrite and ferrite promoting elements such as Cr, Mo and W. The Figure 1 also illustrates that almost all the formation of secondary phase in the temperature range of 300° - 1000°C [9].

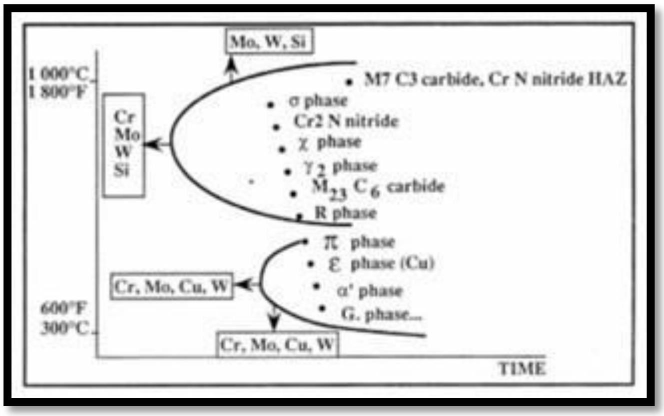

Figure 1. Possible formation of phases in DSS [9]

Summary of literatures

In the presented review, study is focus on the effect of heat treatment on morphology, mechanical and corrosion properties of duplex stainless steel.

Duplex stainless steel

Duplex stainless steel (DSS) is an alloy that having good mechanical and corrosion characteristics because of the in morphology it shows biphasic structure of austenite and ferrite with balance contain shown in figure 2 ferrite indicate in the dark section the than austenite and they combine the high strength of ferrite with the ductility and toughness of the austenite [4]. DSS is composed of alloying elements chromium (Cr), nickel (Ni), copper (Cu), molybdenum (Mo) and has a carbon content of 0.03% [9].

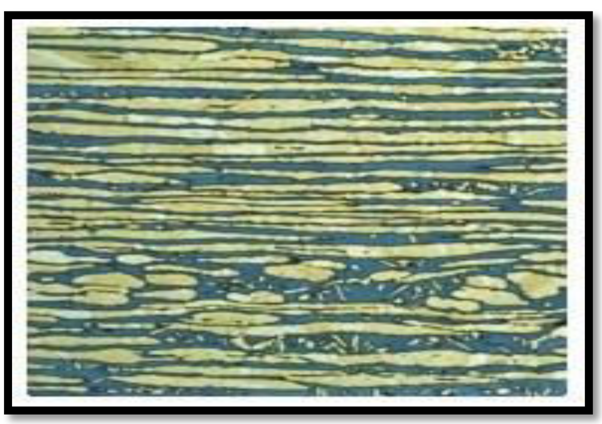

Figure 2. Austenite-ferrite phase structure of DSS

DSS is twice as strong and more resistant to crevice corrosion, pitting and stress corrosion cracking (SCC) than Austenite stainless steel [10]. Based on the corrosion resistance and pitting resistance equivalent number (PREN), DSS are classified into different grades such as lean duplex stainless steel (LDSS), standard duplex stainless steel, super duplex stainless steel (SDSS) and hyper duplex stainless steel as shown in Table 1.

Table 1. Chemical composition of DSS PREN: Pitting Resistance Equivalent Number [17].

Type	Composition (wt.%)								
	Fe	Cr	C+	Ni	Mo	N	Cu	Mn	PREN
Lean Duplex	Bal	20.0-24.0	0.03	1.0-5.0	0.10-0.30	0.10-0.22	-	1.5-4.5	24.0-28.0
Duplex	Bal	21.0-23.0	0.03	4.50-6.0	2.50-3.50	0.10-0.22	-	1	33.0-35.0
Superduplex	Bal	24.0-29.0	0.03	4.50-8.0	2.70-4.50	0.10-0.35	0.7	0.7-0.8	> 41.0
Hyper duplex	Bal	27.0	0.03	6.50	5.0	0.40	-	1.4	49

Various researchers have significantly contributed in this area for find the influence on morphology, mechanical and corrosion characteristics of duplex stainless steel due to treated at higher temperature and presence of intermetallic phases are thoroughly studied and discussed in the Table 2.

Table 2. Summary of Literature studied by various Researchers

Sr. No	Author & Year	Main Investigation	Material	Temperature	Method / Technique	Conclusion	Critical Observation(s)
1	Li et al., [1] (2020)	Effect of Heat Treatment on the Microstructure and Corrosion resistance	Stainless and carbon steel thickness (2 and 3 mm)	700 °C	SEM, EPMA, potentiodynamicpolarization	Due to diffusion more carbon to combine with chromium on the grain boundaries of stainless steel and more chromium-carbide formed in the stainless steel surface in bimetal plate.	In bimetal plate diffusion of carbon increases the % of carbon on stainless steel causes the poor corrosion resistance.
2	Jana et al., [2] (2020)	Effect of heat treatment on microstructure, mechanical, corrosion and biocompatibility	Mg-Zn-Zr-Gd-Nd alloy	250 °C	SEM, EDX, XRD, potentiodynamicpolarization	The corrosion potential of Mg alloy shifted from -1.51V to -1.49V and the corrosion current density decreased from 66.9mA/cm^2 to 31.6 mA/cm^{2}after heat treatment.	After heat treatment showed improvement in resistance to corrosion, hardness and decreases strength due to presence of the secondary phases.
3	Liu et al., [3] (2019)	Effect of heat treatment for significantly improved corrosion resistance	Mg-15Gd-2Zn-0.39 Zr alloys (20 X 20 X 10)	773 K for 35 h and 473 K for 8 h, 128 h and 300 h	SEM, EDS, XRD, Potentiodynamic polarization, scanning Kelvin probe force microscope analysis (SKPFM)	Mg matrix slightly improved due to the dispersive distributed precipitates causes improved the corrosion resistance for alloys Mg-Gd-Zn-Zr after reduction in the micro-galvanic effect.	The corrosion rate of as cast alloys were high due to micro-galvanic effect between eutectic phase and Mg matrix.
4	Papula et al,. [4] (2019)	Effect of Post-Processing Heat Treatment	Duplex Stainless Steel 2205 powder	950 °C, 1000 °C, 1050 °C and 1100 °C (10 X 10 X 10) and (11mm dia, 75 mm height)	SEM, XRD, Potentiodynamic polarization	Annealing treatment decreased the residualstresses in the material and 40-46 % ofaustenite phase was formed. The heat treatment improved the pitting corrosion resistance	Due to dual phase microstructure yield and tensile strength decreased with increase in the ductility also better corrosion resistance.

Sr. No	Author & Year	Main Investigation	Material	Temperature	Method / Technique	Conclusion	Critical Observation(s)
5	Haghdadi et al., [5](2019)	Microstructure dependence of impact toughness	Duplex stainless steels 2205 (10 X 10 X 55 mm)	600 °C for 60 min, 1370 °C for 40 min, water & air cooled	Charpy impact test V notch, EBSD	The ductile to brittle transition temperature was estimated to be ~ - 80 °C for microstructures W and E while microstructure R showed impact toughness values higher than 40 J even at-196 °C.	The positive effect on the toughness due to ferrite phase in the microstructure R showed significantly higher toughness compared to microstructures E and W.
6	Liu et al., [6] (2018)	Effect of High Concentrations of NaCl Solution on Pitting Corrosion	Duplex stainless steels 2205	Critical pitting temperature 40 and 45 °C (Rod dia. 16 mm)	SEM, potentiodynamic polarization	Above and below the CPT the corrosion current density, electrochemical impedance and corrosionmorphology of 2205 DSS were significantly changed.	Critical pitting temperatures were significantly affecting the corrosion behavior of 2205 DSS in NaCl.
7	Paulsen et al., [7] (2018)	Microstructure Evolution Sigma Phase Investigated at Low-temperature using In Situ SEM	Super Duplex stainless steels	850 °Cfor 12 min and 15 min	SEM, EBSD	Tensile test at - 40 °C ductility increased and reduced in without and with sigma phase respectively.Large amount of sigma and chi phase increase and reduce the tensile strength respectively.	Reduction of tensile strength related to chi phase precipitating at the grain boundaries, creating imperfections structure.Materials performance was low due to the effect of secondary phase'sat low temperature.
8	Pezzato et al., [8] (2018)	Effect of the Heat Treatment on the Corrosion Resistance	Duplex stainless steels (2101, 2304, 2205 and 2507)	Temp range 750 °C - 900 °C	SEM, Potentiodynamic polarization	The effect of secondary phases was less pronounced inthe chlorinated acid solution than in the 0.6M NaCl solution. 2205 and 2507 exhibited a strong corrosion resistance	Secondary phases precipitation was mainly influenced the resistance to corrosion of the lean duplex grades.

						after heat treatment.	
Sr. No	**Author & Year**	**Main Investigation**	**Material**	**Temperature**	**Method / Technique**	**Conclusion**	**Critical Observation(s)**
9	Sheu et al., [9] (2018)	Effect of Heat Treatment on the Corrosion Resistance, Mechanical Properties and Wear Resistance	Low Carbon Steel	Temp range 200 °C – 600 °C	SEM, XRDPotentiodynamic polarization, Nano-Indenter XP, Ball-on-disk tribometer	Hardness was increased after heat treatment on Cr-C coating and Cr-C/Al_2O_3 composite coating.Corrosion resistance will reduce with an increase of heating temperature.	Cr-C/Al_2O_3 composite coating reduces wear resistance; Micro hardness and wear resistance was improved in Cr-C coating and reduces the wear weight loss.
10	Sabzi et al., [10] (2018)	Effect of heat treatment on corrosion behavior	St37 steel sheet (2 × 5 cm)	200 °C - 400°C for 1 hr.	SEM, EDS, XRD, Potentiodynamic polarization , EIS	After heat treatment morphology changes due to P content reduction of the nano-composite coating also decreased corrosion resistance and formed different phases such as and CuP2 , Cu3P, Ni8P3, Ni5P2.	Secondary phases are formed and affecting on corrosion resistance due to reduction of element % in composite material.
11	Loto et al., [11] (2018)	Effect of heat treatment processes on the localized corrosion resistance	austenitic stainless steel 301	1000 °C for 30 min	Potentiodynamic polarization, optical microscopy analysis	Optical microscopic images showed a deteriorated morphology and the presence of different phases for the untreated sample and intergranular cracks and corrosion pits were observed on treated 301SS.	Variation of Cl ion no significant effect on corrosion resistance, cause the lowest corrosion rate values, as compare to annealed steel.

Sr. No	Author & Year	Main Investigation	Material	Temperature	Method / Technique	Conclusion	Critical Observation(s)
12	Feng et al., [12] (2018)	Effect of Heat Treatment Process on Hardness and CorrosionResistance	Nickel-based Superalloy GH4169	720 °C, 950 °C ,1050 ° C and untreated	SEM, Rockwell hardness	Sample heated at 1050 °C was high hardness value; lowest corrosion rate and microstructure was finest and uniform.	The corrosion rate and weight loss of the unheated specimens were about twice that of the treated specimens
Sr. No	**Author & Year**	**Main Investigation**	**Material**	**Temperature**	**Method / Technique**	**Conclusion**	**Critical Observation(s)**
13	Makhdoom et al., [13] (2017)	Microstructural and Electrochemical behavior	Duplex Stainless Steel 2205	Untreated	GTAW, SMAW, SEM, XRD,	GTAW weldment found more effective towards corrosion resistance presence of relatively larger amount of secondary austenite (γ).	Formation of large amount of ferrite and chromium nitride causes high corrosion rate in SMAW. Sigma and chi phases are not visible in both welding process.
14	Mohammed et al., [14](2017)	Effects of Heat Input on Microstructure, Corrosion and Mechanical Characteristics	Austenitic and Duplex Stainless Steels	500 °C – 750 °C	SEM, EDX, Potentiodynamic polarization	The number of thermal cycles was significantly associated criteria to evaluate the deleterious impact of sigma phase extension. DSS solidifies in the single-phase ferritic ASS solidifies in the austenitic or austenitic-ferritic mode.	Low heat inputs were harmfully affected mechanical and corrosion properties of DSS due to ferrite and severe precipitation of chromium nitrides.
15	Argandona et al., [15] (2017)	Effect of temperature on Austenite, Ferrite and Sigma Phases	UNS Super duplex stainless steel S32760	850 °C 0 min, 21 min , 25 min (10.97 mm X 20 mm)	SEM, XRD, Nanoindentation Techniques	High macrohardness value for the samples with a longer thermal aging. Macrohardness increase from 315 HV to 427 HV for sigma phase. Nanoindentation shows lower hardness value due to complexity of the sigma phase structureand	Hardness values were increased for longer heat treatment duration causes, formation of a higher percentage of the sigma phase.

						surface roughness	
16	Hammood et al., [16] (2017)	Effect of heat treatment on corrosion behavior in orthodontic applications	Super duplex stainless steel plates SAF 2205	800°C for (2, 4, 8 min), at 850°C for 2 min and at 900°C for 2 min and water quench	SEM, XRD, Vickers hardness, Potentiodynamic polarization	For secondary phase formation and phase balance aging temperature, aging time and chemical composition played important roles. Higher corrosion resistance treated at 900°C, 2min and treated at 800°C, 2min has least corrosion resistance.	2205 have excellent resistance to corrosion.The hardness values of the aged samples were changed with aging temperature and time in the range from 234 to 264 HV
Sr. No	**Author & Year**	**Main Investigation**	**Material**	**Temperature**	**Method / Technique**	**Conclusion**	**Critical Observation(s)**
17	Kahar [17] (2017)	Duplex Stainless Steels-An overview	Duplex Stainless Steels (S32304, S32205, S32750)	50 °C – 300 °C	SEM, TIG, Potentiodynamic polarization	High level of Cr, Mo, and N steels shows high pitting & stress corrosion cracking resistance in chloride-containing environments. Modern duplex stainless steels havegenerally good weld ability.	Too slow cooling can in the higher alloyed duplex grades cause formation of inter-metallic phases detrimental to corrosion resistance and toughness.
18	Zheng et al., [18] (2016)	Effect of Heat Treatment on Corrosion Resistance	6061 Aluminum Alloy	Single aging 440 °C - 560 °C, Dual aging 170 °C - 250 °C	SEM, Potentiodynamic polarization	Aging on 6061 aluminum alloys obtained higher hardness and reduces the corrosion resistance of materials. In dual aging at higher temperature hardness was decrease and improve the corrosion resistance	Material treated at higher temperature to avoid the secondary phases and improve the corrosion resistance and solution treatment increase the tensile fracture time.

19	Sivam et al., [19] (2016)	Investigation exploration outcome of heat treatment on corrosion resistance in marine application	Aluminum alloy 5083	up to 420°C for 90 min aging 150 °C and 200°C (50 x 25 x 6 mm)	weight loss test method, Immersion test	An intermetallic particle in aluminum alloy plays a major role in pitmorphology. Higher hardness value obtained (86 HV) after artificial aging at 200°C of 120 min.	In weight loss test alloy exhibit low corrosion rate values for heat treated specimens compared to untreated specimens but the hardness of specimens increased.
20	Byun et al., [20] (2016)	Effect of Heat Treatment on Corrosion Resistance and Adhesion Property	Zn-Mg-Zn Multi-layer Coated Steel	200 °C (20 X 10 mm)	PVD process, salt spray test	The red rust generation time was 624 hours in heat-treated sample for 360 sec.The delamination of coating layer was observed from heat-treated sample for 240 sec which were composed of 85% intermetallic.	The % of the intermetallic compound phasesgradually increased by increased in heating time for coated samples.
Sr. No	**Author & Year**	**Main Investigation**	**Material**	**Temperature**	**Method / Technique**	**Conclusion**	**Critical Observation(s)**
21	Li et al., [21] (2016)	Effect of heat treatment on corrosion behavior in 3.5 wt.% sodium chloride solution	AZ63 magnesium alloy	720 °C	SEM, EDS,Potentiodynamic polarization,Electrochemicaltest	The protective oxide layer on homogenized alloyretarded the highest corrosion rate.	The heat treatments exert an influence on the corrosionbehavior of AZ63 alloy through the morphological changes.
22	Davanageri, et al., [22] (2015)	Influence of Heat Treatment on Microstructure, Hardness and Wear Behavior	Super Duplex Stainless Steel AISI 2507	850°C for one hour followed by water and oil quenching	XRD, SEM, pin on disc wear testing equipment	The phase transformation of ferrite to σ phase show crystal structure and due to this increases the hardness and wear resistance in heat treated samples.	The sliding distance increases the wear volume lost, increased for the water quenched specimens and hardness were increased in oil quenched specimens.

23	Liu et al., [23] (2015)	Effects of Heat Treatment on Microstructure and Pitting Corrosion Resistance.	Duplex Stainless Steel 2205	Temperature of 590° for 10,24,48,72 and 96h. 650° for 2,5,10, 18 and 24h.	XRD, SEM, TEM, anodic polarization	The pitting resistance of samples was reduced both at aging temperatures. R phase found at 590°C and R phase and σ phase found at 650°C.	The precipitation of intermediate phase decreased the pitting corrosion resistance of 2205 duplex stainless steel.
24	Zheng et al., [24] (2015)	Effect of heat treatment on the structure, cavitation erosion and erosion-corrosion behavior	304 austenitic stainless steel	coating heat treated at 550 °C, 650 °C and 750 °C	EDS, SEM, XRD	Crystalline phases are exposed in the coatings after heat treatments at 650 °C and 750 °C and don't treat the coating at a temperature of 650 °C because loss the bonding between the coating and the substrate after the heat treatment	The cavitation erosion resistance of the coating treated at 750 °C was good in distilled water, exhibits hardness about 1000 Hv and degrades rapidly in 3.5 wt.% NaCl solution.
25	Zhong et al., [25] (2015)	Effect of heat treatment on microstructure evolution and erosion-corrosion behaviour	Nickel-aluminium bronze (NAB) alloy	675°C furnace cooled, 900°C air cooled	SEM, hardness,Potentiodynamic polarization	Strength and hardness of the alloy depending on microstructure, decrease slightly by annealing and increased remarkably by normalizing processes.	The increasing % of hard phases such as ß' improved the erosion-corrosion resistance of the NAB alloy.
Sr. No	**Author & Year**	**Main Investigation**	**Material**	**Temperature**	**Method / Technique**	**Conclusion**	**Critical Observation(s)**
26	Gholami et al., [26](2015)	Effect of annealing temperature on pitting corrosion resistance	2205 duplex stainless steel	Annealing temperatures 1050 °C, 1150 °C 1250 °C for 45 min. water quench.	SEM, EDS	Special pitting was occurred in ferritephase and cause for reduction in pitting resistanceat 1250°C annealing alloy.	Nucleation frequency and stability products of Metastable pits are increased with increasing annealing temperature.
27	Chan et al., [27] (2014)	Review Effect of Secondary Phase Precipitation on the Corrosion Behavior	2205 duplex stainless steel	-	-	Formation of secondary phases was due to fabrication, improper heat treatment and welding process, cooling	Intermetallic phase formed at 700–900 °C and Cr-rich α'-precipitates formed at

						temperature	350–550 °C
28	Jerzy et al.; [28] (2014)	Effect of microstructure on mechanical properties andcorrosion resistance	2205 duplex stainless steel	500 °C, 700 °C, 1050 °C	Microstructure, hardness	At 500°C even for short time cooling lowers resistance to stress corrosion and increase cooling time improve corrosion resistance.	Precipitation of s-phase as well as the secondary austenite in its structure at 700 °C reduces the corrosion resistance.

Critical Observations From Literature Review

1. The change in microstructure, due to heat treatment and secondary phase precipitation, shows asignificant part in the corrosion performance of the DSS 2205.
2. Precipitation of secondary parts in DSS led to a drastic reduction in its corrosion resistance and mechanical propeties.
3. Another factor which is responsible for the change in the ferrite/austenite ratio where the corrosion occurred preferentially in the ferrite phase of DSS 2205.
4. The austenite phase shows better corrosion resistance than the ferrite phase due to maximum Ni content than ferrite which was better for mechanical properties.
5. Cr is the most active element in the passive film to develop the resistance of DSS 2205 to localized corrosion.
6. The heat treatment about 1080°C to DSS 2205 improves the corrosion resistance of steel comparatively.

Conclusion:

The presented review focuses on the extensive efforts taken by previous researchers in the field of Duplex stainless steel grades. Theeffects of heat treatment at different temperature on microstructure, mechanical properties and corrosion resistance of DSS 2205 arediscussed It identifies future scope, applicability of DSS in the field of aerospace, automobile, marine, rail industries, etc. can define on the temperature range of heat treatment.

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