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A REVIEW ON: MECHANICAL, AND MICROSTRUCTURAL BEHAVIORS OF DUPLEX AND AUSTENITIC STAINLESS-STEEL REINFORCING REBAR AFTER EXPOSURE TO ELEVATED TEMPERATURES

Haitham Abdallah Khamis AL Adawani [1], Tuan Zaharinie Tuan Zahari [1, 2, *], and Muhammad Khairi Faiz bin Ahmad Hairuddin [1, 2]

[1] *Department of Mechanical Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*
[2] *Centre of Advanced Manufacturing and Material Processing, Universiti Malaya,50603 Kuala Lumpur, Malaysia*
** (Corresponding author: E-mail: tzaharinie@um.edu.my)*

ABSTRACT

The utilization of structural stainless steel has risen due to its attractive aesthetic and architectural features as well as its durability. This paper examines previous research on the use of duplex and austenitic stainless steel reinforcement bars in reinforced concrete structures, focusing on their material properties affected by prolonged exposure to high temperatures and different cooling methods. It is important to know that for duplex stainless steel reinforcing rebar, the manufacturing process plays a critical role in preventing the formation of excessively brittle phases, such as sigma phases, within the microstructure. Duplex stainless steel rebars exhibit a less stable microstructure, making them more susceptible to changes under similar conditions compared to austenitic rebars. This paper provides a comprehensive review of the literature on reinforcing bars comprised of duplex and austenitic stainless steel for use in reinforced concrete constructions.

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1. Introduction

In recent times, there has been a rise in the utilization of structural stainless steel, largely due to its attractive aesthetic and architectural features as well as its durability. Santonen et al. [1] classified stainless steels as iron alloys with a minimum of 10.5% chromium by weight and a maximum of 1.2% carbon. Mustapha Karkarna et al. [2] clarified that chromium content is crucial for the formation of a self-repairing oxide layer, referred to as a passive layer, which ensures the alloy's corrosion resistance. The metallurgical composition of stainless steel is significantly affected by various alloying elements, leading to the classification of stainless steels into four distinct categories, each possessing unique mechanical, chemical, and physical properties. The categories include martensitic, ferritic, duplex, and austenitic stainless steels as illustrated in Fig.1[3]. Therefore, the presence of additional alloying elements, such as titanium, molybdenum, nitrogen, and niobium can influence these stainless-steel groups. Two grades in the same category might show comparable mechanical strength, for instance, the presence of molybdenum improves the corrosion resistance of one stainless steel type compared to another that does not contain molybdenum [4].

Austenitic and duplex grades are the most used for structural purposes. Austenitic steels typically consist of a minimum of 18% chromium and 8% nickel. These varieties offer distinct benefits for reinforcing concrete due to their specific metallurgical composition and unique physical characteristics as illustrated by Muwila [5].

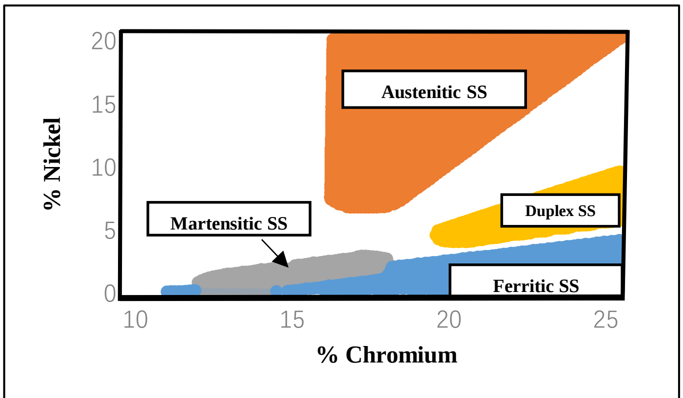

Fig. 1 Stainless steel types and their typical chemical compositions

The main two types of austenitic materials are 304 (designated by ASTM A240), sometimes referred to as UNS S30400 or 1.4301, and X5CrNi18-10 in Europe. The second classification is 316, designated by ASTM A240, known as UNS S31600 or 1.4401, and represented as X5CrNiMo17-12-2 [6].

Markeset [7] demonstrated that these varieties have specific benefits for reinforcing concrete because of their metallurgical composition and physical characteristics. Duplex stainless steels typically include 22-23% chromium and 4-5% nickel, resulting in a two-phase microstructure that comprises both austenitic and ferritic phases [8]. The three main types of duplex stainless steel are UNS S32101–1.4162/X2CrMnNiN21-5-1, UNS S32304–1.4362/X2CrNiN23-4 and UNS S32205–1.4462/X2CrNi-MoN22-5-3. Austenitic steels exhibit lower mechanical strength compared to duplex steels whereas, the higher chromium content and lower nickel and molybdenum levels in duplex steels enhance their attractiveness, providing a favorable balance of corrosion resistance, cost-effectiveness, and stable pricing [9].

Dainezi et al. [10] determined that in DSS, limitations related to operational temperature could lead in the formation of hard, chromium-rich intermetallic phases, affecting both mechanical and corrosion properties. The adjustment of the alloy elements such as (Cr, Mo, Ni, Mn, N, C) along with the alloy processing enables the development of a two-phase microstructure characteristic of DSS. This homogeneous microstructure comprises primary ferrite and austenite phases, which can be altered to redissolve undesirable substances through heat treatments, including dissolution and aging [10]. For instance, Cronemberger et al. [11], and Mohammed et al. [12] noted that elevating the temperature and extending the solubilization process resulted in a microstructure characterized by larger grains. However, the cooling rate, especially slow cooling in a furnace, affects the formation of intermetallic phases (sigma, chi, and alpha line), which subsequently influences mechanical properties, including reduced strength, increased hardness, decreased toughness, and increased susceptibility to corrosion. Therefore, analyzing the effect of secondary phase precipitation and various cooling methods on stainless steel reinforcing rebar after high-temperature exposure is important to understand its behavior in fire scenarios.

This paper provides a comprehensive analysis of prior research on the use of duplex and austenitic stainless steel reinforcement bars in reinforced concrete structures. It further explores the investigation of material properties that are influenced by extended exposure to elevated temperatures and various cooling methods. The objective is to improve understanding of how these conditions affect the mechanical and microstructural behavior of duplex and austenitic stainless steel reinforcement bars. The following is the structure of this paper: section 2 reviews a general background of stainless-steel reinforcement with its material property. Section 3 expresses the behavior of stainless-steel reinforcement under elevated temperatures, it gives a detailed scenario of post fire, secondary phase precipitation and thermal aging impact on duplex and austenitic stainless steel reinforcing bar. Finally, Section 4 expresses the current challenges, conclusion and future expectations.

2. Stainless steel reinforcing bars

Stainless steel is available in a variety of forms, including structural components, plates, bars, and sheets. M. Rabi et al. [13] have made significant research progress in recent years, as stainless steel rebars are becoming increasingly common in load-bearing constructions due to their properties. Structural elements subjected to corrosive conditions can benefit from stainless steel reinforcing bars, which minimize the frequency and expense of required maintenance [13] and compared to carbon steel, its chloride ion corrosion resistance reduces their need for concrete alkalinity and increases their design life beyond 100 years and they also reduce concrete cover, deck, and substructure weight [13].

3. Material property

3.1. Duplex and Austenitic stainless steel reinforcing rebar families

Stainless steels are classified into four types: ferritic, martensitic, austenitic, and duplex. This classification is defined by the steel's microstructure and allows for an easy examination of the physical and mechanical properties within each group, as explained by Rosso et al. [14]. The characteristics of one group may significantly differ from those of another. Austenitic stainless steels are non-magnetic, whereas ferritic and duplex stainless steels exhibit magnetic properties [14]. The following grades of austenitic and duplex reinforcing bars are commonly used, as clarified by Outokumpu [15]: where EN1.4301, 1.4307, and 1.4311 for austenitic, and 1.4362, 1.4462, and 1.4162 for duplex:

1- According to M. M. Rabi [16], grade EN 1.4162 is a type of duplex stainless steel with reinforcing properties. With a reduced nickel concentration, this material is less expensive while still providing great corrosion resistance and being nearly twice as strong as austenitic stainless steels.
2- Gardner [17] stated that EN 1.4362 is a duplex stainless steel, sometimes referred to as lean duplex, which has superior corrosion resistance compared to austenitic grades. The comparatively high nickel concentration and optimal metal composition make it particularly effective against localized corrosion and stress corrosion cracking.
3- Grade EN 1.4462 has better mechanical strength and comparable corrosion resistance to grade EN 1.4362 [13].
4- The most used stainless steel in structural applications is grade EN 1.4301, which contains 18% chromium and 8% nickel. This grade is widely used in a variety of applications due to its exceptional corrosion resistance, as well as its excellent strength, formability, and weldability [13].
5- The 1.4311 austenitic stainless steel has high tensile strength and increased toughness at low temperatures due to its high nickel, nitrogen content, and low carbon content [13].
6- Grade EN 1.4307 can be substituted for grade 1.4301 due to its reduced carbon content, which leads to enhanced weldability and increased resistance to intergranular corrosion [13].

3.2. Chemical composition

Stainless steel often contains iron as the primary metal, as well as chromium, nickel, and other alloying components. Covert et al. [18] concluded that the chemical composition of stainless steel may vary depending on the exact grade or type. The elemental composition of the stainless-steel alloy primarily affects the mechanical properties and corrosion resistance of each grade for example:

- Nickel promotes the production of austenite in stainless steel, preventing corrosion. Its presence enhances the alloy's ductile characteristics and adds to its strength [13].
- Chromium is known for its high corrosion resistance because of its self-repairing passive properties. This makes it an important component in various stainless-steel compositions. According to F.-U. Rehman [19], adding chromium increases the alloy's ductility and strength while also increasing the formation of a ferritic phase.
- Manganese is a key ingredient in stainless steel manufacture, acting as a deoxidizing agent and improving crack resistance. It enhances the production of a ferrite phase at higher temperatures and an austenite phase at lower temperatures [19].
- At temperatures as high as 500°C, molybdenum has fire-resistant properties and is a useful element for corrosion resistance. Similar to chromium, molybdenum greatly increases ferrite's strength [19].
- The addition of nitrogen (N) significantly enhances the mechanical properties of stainless steel, including its strength and ductility, as demonstrated by [20] and Markeset et al. [21].
- Stainless steel alloys frequently include additional elements such as phosphorus (P), copper (Cu), carbon (C), silicon (Si), and sulfur (S). Table 1 outlines the chemical composition of commonly utilized grades of stainless-steel reinforcement.

Table 1
Outlines the chemical composition of commonly utilized grades of stainless-steel reinforcement [22]

Stainless steel grade	Chemical composition (%)- Upper acceptable % limits for every component									
	C	Si	Mn	S	Cr	Ni	Mo	Cu	P	N
1.4162	0.04	1.0	4.0-6.0	0.015	21.0-22.0	1.35-1.70	0.10-0.80	0.10-0.80	0.040	0.20-0.25
1.4462	0.03	1.0	2.0	0.015	21.0-23.0	4.5-6.5	2.5-3.5	-	0.035	0.10-0.22
1.4311	0.03	1.0	2.0	0.030	17.5-19.5	8.5-11.5	-	-	0.045	0.12-0.22
1.4404	0.03	1.0	2.0	0.030	16.5-18.5	10.0-13.0	2.0-2.5	-	0.045	≤0.11
1.4362	0.03	1.0	2.0	0.015	22-24.5	3.5-5.5	0.10-0.60	0.10-0.60	0.035	0.05-0.20
1.4436	0.05	1.0	2.0	0.030	16.5-18.5	10.5-13.0	2.5-3.0	-	0.045	≤0.11

3.3. Mechanical property

The mechanical properties of stainless-steel reinforcement bars relate to the physical characteristics that affect their strength, durability, and resistance to external forces. The properties include tensile strength, yield strength, elongation, toughness, and impact resistance. Stainless steel reinforcement bars offer significant tensile strength, allowing them to support loads and withstand deformation [23].

3.3.1. Stress and strain characteristics of stainless-steel alloys

Stainless steel reinforcement has excellent mechanical properties, including high strength and stiffness, as well as exceptional ductility, toughness, and fatigue resistance. However, those properties may differ depending on the grade and production method. Duplex and austenitic stainless steels are frequently utilized in concrete construction projects due to their exceptional corrosion resistance, and widespread availability as demonstrated by Pardeshi et al. [24] and M. Rabi et al.[25].

Stainless steel grades of this nature generally provide enhanced strength, superior strain hardening, and greater ductility compared to carbon steel reinforcement. Furthermore, they demonstrate a unique constitutive response in comparison to carbon steel [13]. Unlike carbon steel, stainless steel does not display a distinct yield point at a typical room temperature. The stress-strain relationship is non-linear, exhibiting increased strength and reduced stiffness as demonstrated in Fig.2[25]. The yield strength is often assessed by measuring the 0.2% proof stress ($f_{0.2p}$). In contrast, carbon steel exhibits a behavior that is either elastic-plastic or elastic-linear hardening, defined by a distinct yield point and a moderate level of strain hardening [13]. Table 2 presents the mechanical properties of several widely used stainless steel reinforcements, providing the 0.2% proof strength ($\sigma_{0.2}$), ultimate strength (σ_u), Young's modulus (E), and ultimate strain (ε_u) as outlined by Medina et al. [26]. The ability of stainless steel to deform without fracture significantly improves its structural integrity, allowing it to withstand substantial damage and distortion under loading conditions, such as seismic environments. Investigations conducted by Pardeshi et al. [24], Di Sarno et al. [27], and Xu et al. [28] have demonstrated that this characteristic aids in the redistribution of loads and stresses across the structure.

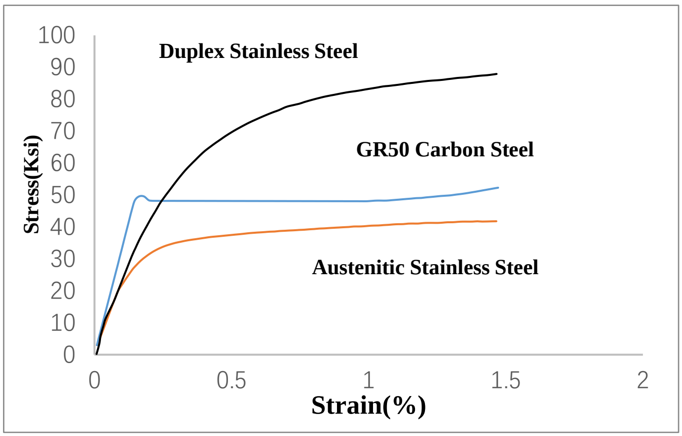

Fig. 2 An illustrative representation of stress-strain diagrams for Austenitic and Duplex stainless steel, alongside carbon steel. [25]

Table 2
Mechanical properties of Stainless steel and carbon steel reinforcement [26]

References	Grade	Dia mm	$\sigma_{0.2}$ (N/mm^2)	σ_u (N/mm^2)	E (kN/mm^2)	E_u (%)
Gardner et al. **[29]**	1.4162	12	682	874	199.1	32.4
	1.4162	16	646	844	195.2	32.9
	1.4311	12	480	764	202.6	48.3
	1.4311	16	528	717	199.9	47.9
	1.4307	12	562	796	210.2	39.9
	1.4307	16	537	751	211.1	42.4
	1.4362	16	608	834	171.4	35.1
M. Rabi et al. **[30]**	Carbon steel	10	525	627	196	20.1
	1.4301	8	720	888	156	44.6
	1.4301	10	668	799	148.6	38.3
	1.4301	12	670	795	186.8	26.7
	1.4436	8	614	823	178.5	36.5
	1.4436	10	661	793	179.3	25.6
	1.4436	12	645	803	198.6	25.3
Q. Li et al. **[31]**	Carbon steel	12	380	530	230	31
	1.4462	6.5	595	800	141	32.5
	1.4462	12	660	830	141	37.8
	1.4462	16	640	795	151	33.9
Q. Li et al. **[32]**	Carbon steel	16	477	654	202	26.8
	1.4362	12	637	872	156	33
	1.4362	16	532	768	156	36.4
	1.4362	25	543	761	202	31.1
	1.4362	32	527	748	139	36.9
	Carbon steel	10	589	661	201.4	12.49
M. Rabi et al. **[25]**	Carbon steel	12	554	635	211.8	9.21
	1.4301	10	515	790	200.9	32.4
	1.4301[grip-rib]	12	715	868	184.0	21.1

3.3.2. Modulus of Elasticity in Stainless Steel Alloys

Rehman et al. [33] recommended to select a Young's modulus in the range of 190-200 kN/mm^2 for various grades of stainless steel. Eurocode 2 specifies that the Young's modulus of carbon steel is around 200 kN/mm^2 [34]. The complex constitutive behavior of stainless-steel reinforcement requires further investigation, particularly related to evaluation of reliability in future uses. Recent academic literature indicated that a reduced value for the Young's modulus of stainless-steel reinforcement could be more suitable in design considerations as concluded by Medina et al. [26], M. Rabi et al. [30], and Rabi et al. [13]. The stress-strain characteristics of carbon steel are precisely represented using a simple bilinear model. The material behavior of stainless steel is characterized by the modified Ramberg-Osgood model, which defines a continuous and nonlinear relationship. The initial version of this model was introduced in 1943 by Giardina Jr et al. [35] to represent the elastic phase, and to include the inelastic phase which was subsequently revised by Jr et al. [36] and Mirambell et al. [37]. The modified Ramberg-Osgood material model is extensively utilized to characterize the behavior of stainless steel in design and simulation scenarios, with its parameters obtained from Equations 1 and 2.

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n} \qquad for \quad \sigma \le \sigma_{0.2} \tag{1}$$

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma-\sigma_{0.2}}{E_2} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u-\sigma_{0.2}}{E_2}\right)\left(\frac{\sigma-\sigma_{0.2}}{\sigma_u-\sigma_{0.2}}\right)^{m} \qquad for\ \sigma_{0.2} < \sigma \le \sigma_u \tag{2}$$

The equations contain variables for engineering strain (ε) and stress (σ), including a tangent modulus (E_2) at 0.2% proof stress, ultimate stress (σ_u), its associated strain (ε_u), and the strain at a 0.2% increase in stress ($\varepsilon_{0.2}$). The constants n and m relate to material hardening in response to strain. These parameters are generally obtained from tensile tests, as outlined in Eurocode 3 Part 1-4, which provides recommended values for structural stainless steel and their applicability may differ when used for stainless steel reinforcement.

4. Behavior of stainless-steel reinforcements subjected to elevated temperatures

4.1. Post-fire examination of stainless-steel reinforcement bars

The post-fire scenario regarding stainless steel reinforcing bars involves the properties and condition of these bars after exposure to fire conditions. Gardner et al. [29] determined that the fire intensity, heat exposure, and duration can affect the mechanical properties of stainless-steel reinforcing bars. F. U. Rehman et al. [33] identified that elements such as strength, malleability, and corrosion resistance are crucial and assessing the condition of stainless-steel reinforcing bars post-fire exposure is vital for verifying their structural integrity and functional performance for future uses [33]. Stainless steel reinforcement bars, commonly referred to as rebar, are utilized in construction to enhance the durability of concrete structures.

Stainless steel reinforcement bars exhibit exceptional resistance to corrosion, heat, and oxidation. This characteristic significantly reduces the effect of fire on its mechanical properties. A crucial element in creating fire-resistant structures is the material's ability to preserve its stiffness and strength even under elevated temperatures. Badoo [39] clarified that stainless steel maintains considerable strength and stiffness under elevated temperatures. Extensive research has been conducted on the behavior of structural stainless steel in fire conditions, as demonstrated in Table 3. For example, Tao et al. [40] found that EN 1.4462, 1.4362, 1.4307, 1.4404, and 1.4003 stainless steels, heated from 300 to 1200 °C for 20 minutes, exhibited negligible influence of thermal conditions on the stress-strain (σ-ε) characteristics at temperatures of 500 °C or below. However, the strength significantly decreases at temperatures above 600 °C. Austenitic alloys typically perform well, with mild steel and duplex alloys having similar efficacy. Ferritic alloys, on the other hand, have superior strength when compared to high-strength steels, but they are susceptible to embrittlement at temperatures above 800 °C.

Gao et al. [41] investigated both EN 1.4401 and 1.4301, which were heated from 200 to 1100 °C for durations of 30 and 180 minutes. The study concluded that initial findings indicate a modest decline in the post-fire mechanical characteristics of stainless steels S30408 and S31608 when exposed to temperatures below 1000 °C. Furthermore, the modulus of elasticity increases following fire exposure, peaking at a temperature of 800°C, with an approximate rise in the coefficient of 50%. On the other hand, exposure to fire results in a notable reduction in nominal yield strength, with decreases of around 30% for S30408 and 20% for S31608 at temperatures of 1100°C.

A further investigation conducted by Fan et al. [42] on EN 1.4301 involved heating the material at temperatures ranging from 100 to 900 °C for durations of 5 and 15 minutes. The analysis revealed significant discrepancies in the stress-strain curves of stainless steel at elevated temperatures, specifically between 600 and 800 °C, when contrasting steady-state and transient testing methodologies. The observed variances were notably reduced within the temperature range of 100–500 °C.

Table 3

Notable Results from Prior Research

Material Type	heating rate	Target Temperature (°C) & aging time	Cooling mode	Findings	Reference
EN 1.4462 1.4362 1.4307 1.4404 & 1.4003	20°C/min	Heated from 300 to 1200°C for 20 min	Slow cooling in air	Up to 500 °C, stainless steel exhibits stable stress-strain characteristics; however, above 600 °C, it begins to deteriorate. At high temperatures, different steel types behave differently in terms of strength and brittleness.	Z.Tao et al. **[40]**
EN 1.4401 & 1.4301	20° C/ min	Heated from 200 to 1100°C for 30 and 180 min	Rapid quenching in water and gradual ambient air cooling	The research indicated a reduction in the strength of stainless steels S30408 and S31608 at temperatures below 1000°C. Furthermore, exposure to fire led to notable decreases in yield strength, approximately 30% for S30408 and 20% for S31608, at temperatures reaching 1100°C..	Gao et al. **[41]**
EN 1.4301	10 &20° C/ min	Heated between 100 and 900°C for 5 and 15 min	n/a	Significant differences in the stress-strain curves of stainless steel were observed at elevated temperatures ranging from 600 to 800 °C when comparing steady-state and transient testing methods. The variances were lower within the temperature range of 100–500 °C.	Fan et al. **[42]**
EN 1.4301, 1.4436, B500B & 1.4401	10° C/ min	Heated from 100 & 900°C for 1 hour	Rapid quenching in water, gradual cooling in ambient air, and within a furnace environment	Stainless steel reinforcement bars preserved their mechanical properties after exposure to elevated temperatures, with the cooling rate exerting minimal influence. Notable alterations in behavior were observed at moderate temperature levels.	F.U. Rehman et al. **[33]**
EN 1.4301	10° C/ min	Heated from 300, 400 to 1000 °C for 20 min	Gradual air cooling	The material properties of austenitic stainless steel remain stable at elevated temperatures, with notable alterations occurring beyond 600 °C to 800 °C.	(A. He et al. **[43]**
EN 1.4162 & 1.4462	20° C/ min	Heated from 1 & 10 hours heated from 600 to 800 °C	Slow cooling in the furnace and fast cooling in water	The materials retain their strength and flexibility post-exposure to fire, demonstrating their capacity to withstand high pressures without affecting safety.	Maslak et al. **[44]**
EN 1.4462	n/a	For 30 min, heated at 1050°C	Rapid quenching within water, gradual cooling in ambient air, and internal furnace cooling.	The addition of particular components decreased the material's strength; however, high-temperature treatment followed by quenching improved its toughness without causing further phase formation.	Chaudhari et al. **[45]**
EN 1.4162	20° C/ min	For 0,60, 180 mins,heated from 200 till 1000°C	The material is heated in the furnace until 150°C and then cooled to room temperature.	The mechanical properties of lean duplex stainless steel specimens remained stable at elevated temperatures and across different exposure durations.	Y.et al.**[46]**
EN 1.4406	n/a	Within the temperature range of 250 to 850°C, utilizing increments of 50°C.	Rapid quenching in aqueous solution	The research investigated the influence of temperature and strain rate on the tensile characteristics of nitrogen-alloyed low carbon grade 316L(N) austenitic stainless steel. Increased temperatures led to enhanced ductility and reduced flow stress and work hardening rate due to dynamic recovery phenomena.	Choudhary **[47]**
EN 1.4372 & 1.4404	n/a	For one hour heated at 1050 °C	Rapid quenching in aqueous solution	The reduction in heat input enhanced tensile strength and microhardness. The morphology of ferrite was influenced by the level of heat applied, where low heat yielded both skeletal and lathy ferrites, while high heat resulted exclusively to the formation of skeletal ferrite.	Tandon et al. **[48]**
EN 1.4162, 1.4571& 1.4301	40-60°C/ min	For 5-10 mins heated at 350, 650 & 950°C	Gradual temperature reduction in an atmospheric environment	The research indicated that samples cooled at distinct temperatures exhibited differing impacts on ultimate strengths. Samples cooled at 350 and 650 °C demonstrated increased strength, whereas those cooled at 950 °C showed reduced strength. The failure mechanisms in stainless steel connections following fire exposure were similar to those seen in specimens tested under non-post-fire conditions.	Cai **[49]**
EN 1.4462 & RS	n/a	For 30,60,120,180,300 & 10080 min, heated for 500 °C	Rapid quenching within water	The research indicates that spinodal decomposition enhances the tensile strength while diminishing the ductility of 2205 Duplex Stainless Steel. It also preserves mechanical properties superior to rebar steel at temperatures below 500°C for short durations.	X. Li et al. [**50]**

S235JR & EN 1.4404	10° C/ min	For 15 mins, heated from 100 till 950 °C	n/a	The mechanical integrity of SC bimetallic steel can get weakened at elevated temperatures, and current predictive models for carbon-manganese or stainless steel are considered not sufficient.	Ban et al**. [51]**
EN 1.4410[LN]	n/a	For 1 hour, heated at 1100,1150 &1200 °C	Rapid quenching within water	Additive manufacturing can produce type 25Cr duplex stainless steel with enhanced mechanical properties, including strength and ductility. This makes it applicable to various applications.	J. He et al. **[52]**
EN 1.4959, 2.4663, 1.4841, 1.4404& 1.4990	10, 15 & 20° C/ min	For 30 & 180 min,heated between 400 till 700 °C	n/a	The materials demonstrated improved ductility at higher temperatures, correlated with an increase in nickel content.	Calmunger et al. **[53]**
EN 1.4301	20° C/ min	For 30 min heated at 200 & 300 °C, for 800 °C is heated for 45,90 & 135 min	Gradual temperature reduction within a furnace	The effect of duration of exposure to high temperatures on the mechanical characteristics of stainless steel after combustion seems limited. Nonetheless, a significant decrease in yield strength is noted for both flat and curved specimens when subjected to temperatures above 500 °C. When compared to carbon steel, stainless steel exhibits better durability and maintains superior strength after exposure to fire events.	Wang et al. **[54]**

4.2. Precipitation of secondary phases and thermal aging conditions in stainless steel reinforcement bars

Sathirachinda [55] clarified that the emergence of secondary phases requires the development of supplementary chemical compounds or structures within a stainless-steel substrate. This may occur as a result of thermal aging or exposure to specific environmental conditions. X. Li et al. [56] concluded that thermal aging may induce secondary phase precipitation in stainless steel reinforcing bars, potentially affecting their mechanical properties and overall performance. J. Li et al. [57] indicated that the existence of secondary phases can induce modifications in the material's microstructure, as illustrated by the formation of chromium carbides. This phenomenon may reduce corrosion resistance and increase brittleness in stainless steel. Moreover, the conditions of thermal aging significantly influence the formation of these secondary phases which are determined by factors such as temperature duration and the metal composition of the alloy as clarified by Byun et al. [58]. Table 4 summarizes the notable results from prior research for the secondary phases precipitations and thermal aging conditions.

Austenitic stainless steels are made up only of the austenitic phase, whereas duplex steels typically include both austenite and ferrite as their main phases, as illustrated in Fig. 3 which was done by Raha [59]. Li [60] noted that the microstructure of duplex steels typically displays a predominance of a ferritic matrix scattered with austenitic islands, which is due to initial precipitation and higher ferrite content. The ratios of ferrite to austenite significantly affect the corrosion resistance and mechanical properties of duplex Stainless Steels. Chromium, molybdenum, and nitrogen are all known for their important functions in reducing pitting corrosion, with higher concentrations linking to enhanced resistance [60]. Variations in properties arise from differences in chemical composition, which depend on the enrichment of ferrite or austenite with stabilizing elements like chromium and molybdenum for ferrite, and nitrogen (N) for austenite [60]. The temperature used in heat treatment can alter the ratio of ferrite to austenite, as well as its composition as shown in Fig. 4 which was done by Tan et al. [61].

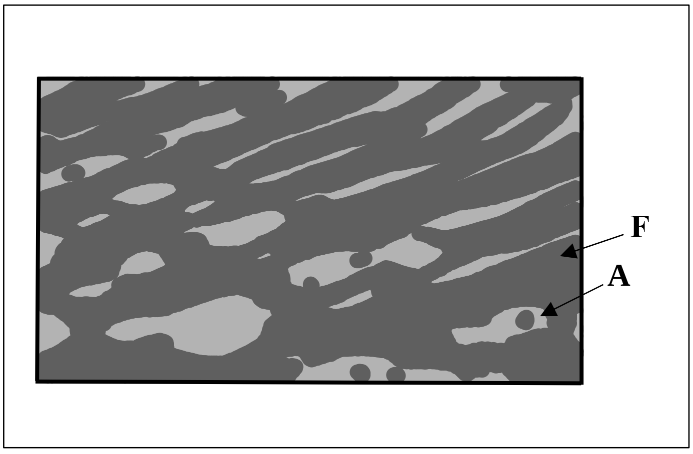

Fig. 3 Microstructure of Duplex stainless steel

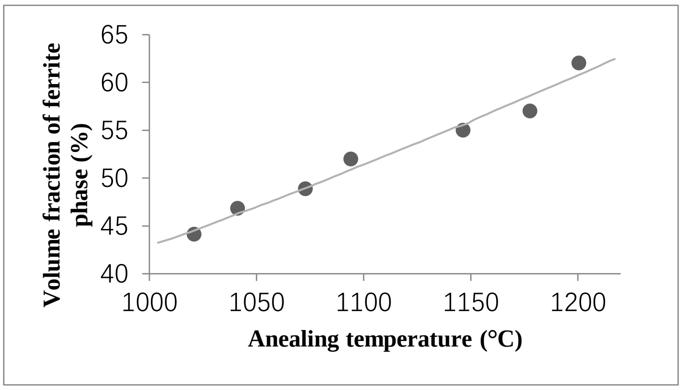

Fig. 4 Fractional volume of the ferrite phase after undergoing thermal treatment across different temperatures for a duration of 2 hours

Thermal aging involves exposing stainless steel rebars to high temperatures for an extended duration. H. Y. Huang et al. [62] concluded that prolonged exposure to elevated temperatures can result in additional microstructural alterations, including grain growth and the formation of new phases. Thus, variations in phase ratios and changes from thermal aging due to different heat treatments may lead to modifications in mechanical properties which are influenced by the amount of ferrite phase and its initial morphology at temperatures above 1000°C [63]. Furthermore, the increased concentration of alloying elements leads to the formation of various intermetallic phases, nitrides, and carbides, including sigma phase, chi phase, and $M_{23}C_6$, during heat treatment processes conducted at temperatures below 1000 °C [60]. For example, DSS undergoes phase changes via spinodal decomposition at temperatures lower than 525°C, with reactions occurring more rapidly around 475°C. This mechanism enables the transformation of the initial phase, x, into a chromium-deficient X phase and a chromium-enriched (x') phase, as explained by Chan et al. [64] and Tavares et al. [65] and the following points explain those phases:

σ (Sigma) phase: Shamanth et al.[66] found out a precipitate enriched with chromium and molybdenum, exhibits hardness and brittleness, typically forming in the temperature range of 650 to 1000°C. This formation is frequently linked to a decrease in both impact toughness and corrosion resistance. Ferrite has higher mobility and concentrations of molybdenum and chromium than austenite, so the **σ**-phase precipitates primarily in the ferritic phase. It can also develop in the heat affected zone during welding processes. This substance has a tetragonal crystal structure, with 32 atoms per unit cell and five distinct crystallographic sites for atom placement. The morphological characteristics of the **σ**-phase change with temperature. At 750°C, it has a structure similar to coral, however, at 950°C, its shape becomes larger and more densely packed.

The decrease in Mo content is significantly larger compared to that of Cr, indicating that Mo primarily influences the precipitation of the **σ**-phase. The σ-phase develops quickly, requiring a very rapid cooling rate to prevent its development during the quenching process from solutionizing temperatures. For EN 1.4462 duplex stainless steel, it is crucial to maintain a cooling rate of 0.23 Kelvin per second to ensure that the formation of **σ**-phase remains below 1% [67]. The addition of significant amounts of alloying elements into DSS results in the formation of various carbides, intermetallic compounds, and secondary phases. These constituents precipitate at varying kinetics within specific temperature ranges, as illustrated in Fig. 5[68].

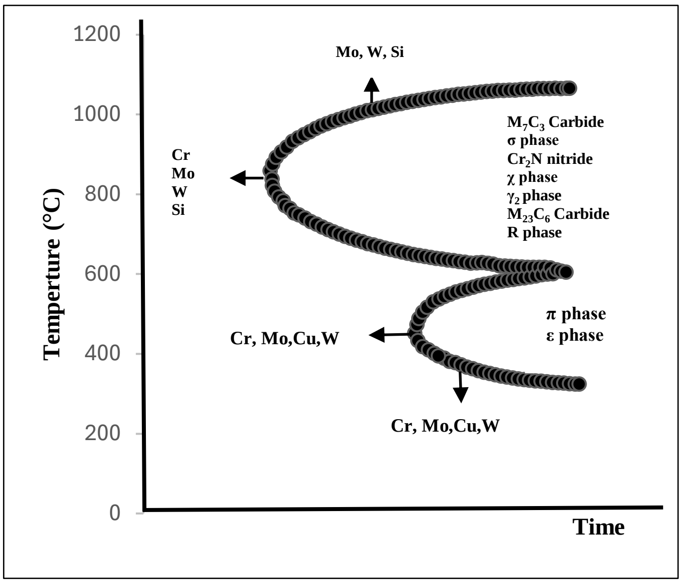

Fig. 5 Isothermal cooling curve for the ternary Fe-Cr-Ni system illustrating the impact of alloying additions on the precipitation of secondary phases during cooling

χ (Chi) phase:

The addition of ferrite with elements that can form intermetallic compounds during extended thermal exposure around 700°C allows the precipitation of the Chi (χ) phase. It generally begins at the δ/γ interface and extends into the δ matrix, and evaluating its influence on corrosion and toughness is difficult due to the common coexistence with the **σ** phase. An increase in aging duration leads to a higher concentration of Mo and a decrease of Fe in the χ-phase. During isothermal aging, the precipitation of the χ-phase consistently precedes that of the **σ**-phase, however, under continuous cooling conditions, the formation of the χ-phase occurs only at decreased cooling rates, as concluded by Redjaïmia [67].

α′ (alpha prime) phase:

The BCC crystal structure in this phase corresponds with the α phase, consisting of approximately 62-83 % of chromium. Within the temperature range of 300 to 550 °C, alpha prime mainly develops as the principal precipitation phase due to spinodal decomposition. This phenomenon is commonly referred to as 475 °C embrittlement, characterized by increased hardness, yield strength, and tensile strength, accompanied by reduced elongation and impact resistance [60]. For more than fifty years, researchers have systematically investigated the phenomenon of spinodal decomposition in stainless steels.

Epsilon phase:

A study by Shamanth et al. [66] found that in duplex alloys containing copper, reduced solubility at lower temperatures leads to the super-saturation of ferrite. This condition leads to the precipitation of very fine Cu-rich epsilon (ε) phase particles within the ferrite grains after 100 hours of exposure at 500°C. This significantly expands the lower temperature strengthening range for duplex stainless steels. ε-phase is often incorrectly identified as γ_2 due to similar formation temperatures.

R phase:

The isothermal treatment of duplex stainless steels at temperatures between 550 and 650°C results in a consistent and finely dispersed distribution of the R-phase within δ grains [67]. The R-phase, characterized by its enrichment in molybdenum, exhibits a trigonal crystal structure and its emergence reduces both the toughness and the critical pitting temperature in duplex stainless steels. Nilsson [69] clarified that R-phase precipitations can occur as either intergranular or intragranular, with the former potentially presenting a higher risk for pitting corrosion due to their capacity to contain up to 40% Mo. The extension of the aging process results in the conversion of R-phase into σ-phase, which is due to the diffusion of Mo from the former phase to the latter. As a result, there is a decrease in the volume fraction of R-phase, as concluded by S. Zhang et al. [70].

G, π and τ phases:

The G-phase forms at α/α′ interfaces within a temperature range of 300 to 400°C following extended exposure, due to the accumulation of Ni and Si at these particular locations [66]. The π-nitride precipitate, which has a cubic crystal structure and is enriched in chromium and molybdenum, appears at intergranular locations within duplex stainless-steel welds after undergoing isothermal treatment at 600°C for a prolonged duration [66]. The η-phase is a precipitate defined by significant faulting and needle-like morphology, formed as a result of heat treatment at temperatures between 550 and 650°C. This phase exhibits an orthorhombic crystal structure [67].

Table 4

Summarizes the notable results from prior research for the secondary phases precipitations and thermal aging conditions

Material type	Target Temperature (°C) ,aging time & cooling mode	Findings	Reference
EN1.4462	Within the temperature range of 600 to 1000 °C for a duration of 2600 minutes, followed by rapid quenching in water.	The effects of aging temperature on the corrosion resistance of duplex stainless steel were not significant; however, aging at temperatures ranging from 700 to 900°C results in a reduction in pitting corrosion resistance. W-substituted steel showed better pitting corrosion resistance compared to its Mo-only counterpart	Ahn et al. [71]
EN 1.4501	Within the temperature range of 900 to 1100 °C for a duration of 120 minutes, followed by rapid quenching in water	Sigma phase particles develop at the interfaces of ferrite and austenite grains, with the soaking temperature determining their dissolution and the ferrite-to-austenite ratio. Higher heat treatment temperatures increase ferrite content, preventing sigma phase formation above 1060°C for a balanced distribution of approximately 50% each - affecting material hardness inversely with heating temperature.	Martins et al. [72]
EN 1.4662	Subjected to heating at a temperature of 475°C for durations of 100, 300, 600, 1100, and 2000 hours followed by quenching in water.	After 1100 hours, chromium stabilizes at 5%, decreasing corrosion resistance and significantly influencing mechanical properties. Low Duplex Stainless Steel 2404 has lower corrosion resistance than Duplex Stainless Steel 2205 due to the division of α and α′ phases during spinodal decomposition.	Silva et al. [73]
EN 1.4462	The samples were subjected to heating at temperatures of 450°C, 475°C, 800°C, and up to 850°C for durations of 1 hour, 3 hours, and 12 hours followed by quenching in water	Exposure to high temperatures leads to phase precipitation in the ferrite matrix, reducing steel hardness and corrosion resistance. Prolonged aging reduced corrosion resistance and increased sensitization due to phase precipitates at higher temperatures.	Dainezi et al. [10]
EN 1.4162	Subjected to heating at 700 °C for durations of 3, 10, 30, 120, and 240 minutes followed by rapid quenching in water	After aging lean Duplex Stainless Steel 2101 at 700°C, intermetallic precipitates with higher chromium concentration formed between the α/γ and α/α boundaries. A secondary phase of austenite with lower chromium content was found near these precipitate regions.	L. Zhang et al. [74]

EN 1.4501	Subjected to a temperature of 300 °C for durations of 3,000, 6,000, and 12,000 hours.	Variations in Chromium concentration during aging affect the hardness of the ferrite phase and result in a reduction of impact toughness. Aging causes a change in fracture behavior from ductile to cleavage, with crack propagation mainly occurring through the ferrite phase along deformation twin interfaces, while delamination between austenite and ferrite phases becomes visible.	Pettersson et al.[75]
EN 1.4462	Heated from 700 to 1050 °C for intervals of 5, 30, 60, and 120 minutes	The alpha phase becomes more noticeable in 2205 Duplex Stainless Steel when the levels of nitrogen and carbon are low. It forms inside or on the edges of ferrite grains. After being aged at 850°C, it's most common. At first, the π-phase is seen, but between 700°C and 750°C, the χ-phase mostly forms because of stronger thermodynamic forces. This was proven with Thermo-Calc software, which also showed that sigma expands more quickly. But c-phase concentrations have a bigger effect on steel's impact toughness than χ-phase concentrations because π-phase does not occur as frequently.	Y. L. He et al. [76]
EN 1.4462	Subjected to heating at a temperature of 850 °C for durations of 6, 40, and 600 minutes followed by rapid quenching in water	The different phases of microstructure development in stainless steel, such as the formation of chromium nitrides and carbides and the evolution of the sigma phase, were examined using a variety of etching techniques. Sigma phase development and embrittlement from the precipitation of chromium carbides and nitrides were caused by aging heat treatments that were performed at temperatures higher than 850°C for longer than six minutes. Sigma phase emergence was not detected by the Charpy impact test.	Zucato et al. [77]
EN 1.4162	Heated to a temperature of 750°C for a duration of 3 and subsequently 480 hours, followed by quenching in water.	The study on EN 1.4162 lean duplex stainless steel shows that exposure to 750°C for a duration of up to 480 hours leads to the formation of precipitates at the phase boundaries and intersections of ferrite grains. Nitride formation was initially observed, whereas extended durations resulted in σ phase precipitation. The aging process affected mechanical properties, resulting in a decrease in ductility while improving yield strength and ultimate tensile strength.	Dandekar et al. [78]
EN 1.4462	Within a temperature spectrum of 450 to 1000 °C, for a duration of 10 minutes followed by rapid quenching in water.	Aging at temperatures ranging from 600 to 950 °C results in the formation of new phases, including Cr2N, σ, and χ. The most significant decrease in pitting corrosion resistance and impact energy occurs at 850 °C. Temperatures reaching 600 °C leads to a change of the pitting initiation site from austenite to an altered ferritic phase because of precipitation incidents.	Deng et al. [79]
EN 1.4462	Subjected to heating at 300 and 400°C for durations of 3,000; 5,000; and 7,000 hours.	When heating to 400 ºC, the ferrite phase in 2205 DSS steel exhibits an increase in hardness due to the formation of new phases. However, this does not occur when heated up to 300 ºC for up to 7000 hours. Furthermore, extended heating at 400 °C results in increased chromium loss in the material, with no noticeable self-repairing occurring despite prolonged exposure.	Rovere et al.[80]
EN 1.4410	Heated at 700-900 °C for varying durations with rapid water quenching.	The aging of the samples led to sigma-phase precipitation in both ferrite and austenite regions, resulting in decreased stability and resistance to pitting corrosion. Exposure to chloride-containing aggressive environments caused localized damage to previously ferritic regions that had transformed due to aging at temperatures above 700 ºC for more than 1 hour.	Angelini et al. [81]

5. Conclusion

Both duplex and austenitic stainless steel reinforcement bars have excellent strength and corrosion resistance which making them an ideal option for reinforced concrete structure. However, the absence of standardized practices and recommendations for employing duplex stainless-steel rebar may raise concerns about its effectiveness and long-term durability in concrete constructions. When evaluating duplex grade rebars, it is essential to understand the manufacturing process to avoid the development of highly brittle phases, such as sigma phases, within the microstructure. Additionally, duplex stainless steel rebars exhibit a less stable microstructure in comparison to austenitic rebars, making them more susceptible to changes under similar conditions. Consequently, this paper provides a comprehensive review of research on reinforcing bars made of duplex and austenitic stainless steel used in reinforced concrete structures. Furthermore, it examines the effects of prolonged high-temperature exposure on material characteristics, as well as various cooling methods. Sufficient information has been provided in the current literature to enable engineers to make well-informed decisions on the structural integrity of duplex and austenitic stainless steel reinforced concrete structures after being exposed to fire. A detailed analysis of various temperature exposure levels was conducted, covering a wide range of potential behaviors to maximize informative value. The examined cooling methods were analyzed to replicate real-world conditions that the rebar could experience.

In conclusion, the engineering research community has recognized the significant benefits that stainless steel reinforced concrete offers to the construction industry, especially when a durable, low-maintenance life cycle is required. In addition, this paper summarized the mechanical behavior of duplex and austenitic reinforcement rebars when subjected to static loads. Potential future investigations could include an assessment of material strength and resistance to fracture, alongside an examination of their behavior during repeated loading cycles.

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References

[1] Santonen, T., Stockmann-Juvala, H., & Zitting, A. (n.d.). Review on toxicity of stainless steel.
[2] Mustapha Karkarna, Y., Bahadori-Jahromi, A., Zolghadr Jahromi, H., Halliwell, E., & Mohammad Rabi, M. (2022). Reinforced Concrete Design with Stainless Steel. In Reinforced Concrete Structures - Innovations in Materials, Design and Analysis. IntechOpen. https://doi.org/10.5772/intechopen.106327 [3] Zhu S.Y. and Qiu C.X., "Performance-based plastic design of self-centering steel braced frame", Proceedings of the 2nd International Conference on Performance-based and Life-cycle Structural Engineering (PLSE 2015), Brisbane, QLD, Australia, 1259-1259, 2015.
[3] Stoica, M., Alexe, P., Dinica, R., & Carac, G. (2012). Electrochemical Behaviour of AISI 304 Stainless Steel Immersed in Mixtures Consisting by Biocide and Fungal Suspensions. In Food Industrial Processes - Methods and Equipment. InTech. https://doi.org/10.5772/30839.
[4] Stainless steel reinforcement bar the sustainable cost effective choice for concrete infrastructure knowledge for a brighter future. (n.d.).
[5] Muwila, A. (2006). The Effect of Manganese, Nitrogen and Molybdenum on the Corrosion Resistance of a Low Nickel (<2 wt%) Austenitic Stainless Steel.
[6] Steels, A. (n.d.). Atlas TechNotes. www.atlassteels.com.au
[7] Markeset, G. (2009). SINTEF Building and Infrastructure Gro Markeset Stainless steel reinforcement in con-crete structures-State of the art COIN Project report 4-2008. www.coinweb.no .
[8] Kahar, Dr. S. D. (2017). Duplex Stainless Steels-An overview. International Journal of Engineering Research and Application, 07(04), 27–36. https://doi.org/10.9790/9622-0704042736
[9] The Use of Stainless Steel for the Construction Industry. (2020).
[10] Dainezi, I., Borges, S. H., & Mariano, N. A. (2023). Effect of Precipitation of Alpha Line and Sigma Phases on the Microstructure and Corrosion Resistance of the Duplex Stainless Steel SAF 2205.
[11] Cronemberger, M. E. R., Nakamatsu, S., Rovere, C. A. Della, Kuri, S. E., & Mariano, N. A. (2015). Effect of cooling rate on the corrosion behavior of as-cast SAF 2205 duplex stainless steel after solution annealing treatment. *Materials Research*, *18*, 138–142. https://doi.org/10.1590/1516-1439.352114.
[12] Mohammed, A. M., Shrikrishna, K. A., & Sathiya, P. (2016). Effects of post weld heat treatment on friction welded duplex stainless-steel joints. Journal of Manufacturing Processes, 21, 196–200. https://doi.org/10.1016/J.JMAPRO.2015.10.005
[13] Rabi, M., Shamass, R., & Cashell, K. A. (2022). Structural performance of stainless steel reinforced concrete members: A review. In Construction and Building Materials (Vol. 325). Elsevier Ltd. https://doi.org/10.1016/j.conbuildmat.2022.126673.
[14] Rosso, M., Peter, I., & Suani, D. (2013). About heat treatment and properties of Duplex Stainless Steels. www.journalamme.org
[15] Outokumpu, ©. (n.d.). Handbook of Stainless Steel.
[16] Rabi, M. M. (2019). Analysis and design of stainless steel reinforced concrete structural elements.
[17] Gardner, L. (2005). The use of stainless steel in structures. In Progress in Structural Engineering and Materials (Vol. 7, Issue 2, pp. 45–55). https://doi.org/10.1002/pse.190.
[18] Covert, R. A., & Tuthill, A. H. (n.d.). Pages 506-517 Copyright© International Association for Food Protection, 6200 Aurora Ave (Vol. 20, Issue 7).
[19] Rehman, F.-U. (2022). Mechanical tensile testing and metallurgical investigation of the residual properties of stainless-steel reinforcing bar after exposure to elevated temperatures.
[20] Avesta Welding. (2009). The Avesta welding manual : practice and products for stainless steel welding. Avesta Welding.
[21] Markeset, G., Rostam, S., & Klinghoffer, O. (2006). Guide for the use of stain-less steel reinforcement in concrete structures.
[22] Version, E. (2014). Stainless steels-Part 1: List of stainless steels.
[23] Mcgurn, J. F. (n.d.). Stainless Steel Reinforcing Bars in Concrete.
[24] Pardeshi, R., Thakur, B., & Parghi, A. (2020). Seismic investigation of longitudinally aligned shape memory alloy-stainless steel reinforced concrete column. IOP Conference Series: Materials Science and Engineering, 814(1).
[25] Https://www.aisc.org/publications/steel-standards/stainless-steel- standards/?_gl=1*hkj6z9*_gcl_au*NzY2NDM5MTkxLjE3MzMxMDg3Njc.*_ga*MTczNjcyNzQzMC4xNzI5NjY0OTE2*_ga_97VGG712JL*MTczMzEwODc 2Ny4xLjEuMTczMzEwODk1NS4zNS4wLjA
[26] Medina, E., Medina, J. M., Cobo, A., & Bastidas, D. M. (2015). Evaluation of mechanical and structural behavior of austenitic and duplex stainless-steel reinforcements. Construction and Building Materials, 78, 1–7. https://doi.org/10.1016/j.conbuildmat.2015.01.008.
[27] Di Sarno, L., Elnashai, A. S., & Nethercot, D. A. (2003). Seismic performance assessment of stainless steel frames. Journal of Constructional Steel Research, 59(10), 1289–1319. https://doi.org/10.1016/S0143-974X(03)00067-1
[28] Xu, C., Nehdi, M. L., Youssef, M. A., Wang, T., & Zhang, L. V. (2021). Seismic performance of RC beam-column edge joints reinforced with austenite stainless steel. Engineering Structures, 232. https://doi.org/10.1016/j.engstruct.2020.111824.
[29] Gardner, L., Bu, Y., Francis, P., Baddoo, N. R., Cashell, K. A., & McCann, F. (2016). Elevated temperature material properties of stainless-steel reinforcing bar. Construction and Building Materials, 114, 977–997. https://doi.org/10.1016/j.conbuildmat.2016.04.009 .
[30] Rabi, M., Shamass, R., & Cashell, K. A. (n.d.). Experimental investigation on the flexural behaviour of stainless steel reinforced concrete beams.
[31] Li, Q., Guo, W., Liu, C., Kuang, Y., & Geng, H. (2020). Experimental and Theoretical Studies on Flexural Performance of Stainless Steel Reinforced Concrete Beams. Advances in Civil Engineering, 2020. https://doi.org/10.1155/2020/4048750.
[32] Li, Q., Cui, Y., & Wang, J. (2021). Basic mechanical properties of duplex stainless-steel bars and experimental study of bonding between duplex stainless-steel bars and concrete. Materials, 14(11). https://doi.org/10.3390/ma14112995.
[33] Rehman, F. U., Cashell, K. A., & Anguilano, L. (2022). Experimental Study of the Post-Fire Mechanical and Material Response of Cold-Worked Austenitic Stainless-Steel Reinforcing Bar. Materials, 15(4). https://doi.org/10.3390/ma15041564.
[34] EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. (2004).
[35] Giardina Jr, R., Wei, D., & Joseph Giardina, R. (2020). Ramberg-Osgood material behavior expression and large deflections of Euler beams Ramberg-Osgood material behavior expression and large deflections of Euler beams Journal Title XX(X):1-26. https://doi.org/10.1177/ToBeAssigned.
[36] Jr, K., & Msceng, R. (2001). Full-range Stress-strain Curves for Stainless Steel Alloys. http://www.civil.usyd.edu.au/.
[37] Mirambell, E., & Real, E. (2000). On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation. In Journal of Constructional Steel Research (Vol. 54). www.elsevier.com/locate/jcsr.
[38] EN 1993-1-4: Eurocode 3: Design of steel structures - Part 1-4: General rules – Supplementary rules for stainless steels. (2006).
[39] Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, *64*(11), 1199–1206. https://doi.org/10.1016/j.jcsr.2008.07.011
[40] Tao, Z., Wang, X. Q., Hassan, M. K., Song, T. Y., & Xie, L. A. (2019). Behaviour of three types of stainless steel after exposure to elevated temperatures. Journal of Constructional Steel Research, 152, 296–311. https://doi.org/10.1016/j.jcsr.2018.02.020.
[41] Gao, X., Zhang, X., Liu, H., Chen, Z., & Li, H. (2018). Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure. Construction and Building Materials, 165, 82–92. https://doi.org/10.1016/j.conbuildmat.2018.01.020.
[42] Fan, S., He, B., Xia, X., Gui, H., & Liu, M. (2016). Fire resistance of stainless-steel beams with rectangular hollow section: Experimental investigation. *Fire Safety Journal*, *81*, 17–31. https://doi.org/10.1016/j.firesaf.2016.01.013.
[43] He, A., Liang, Y., & Zhao, O. (2019). Experimental and numerical studies of austenitic stainless steel CHS stub columns after exposed to elevated temperatures. Journal of Constructional Steel Research, 154, 293–305. https://doi.org/10.1016/j.jcsr.2018.12.005.
[44] Maslak, M., Pancikiewicz, K., Pazdanowski, M., Stankiewicz, M., Wozniczka, P., & Zajdel, P. (2023). Quantification of the Post-Fire Strength Retention Factors for Selected Standard Duplex and Lean Duplex Stainless Steel Grades. https://doi.org/10.20944/preprints202312.0286.v1.
[45] Chaudhari, A., Diwakar, N., & Kalpande, S. (n.d.). Mechanical characteristics, morphology and corrosion behavior of duplex stainless steel 2205. In Eur. Chem. Bull (Vol. 2023).
[46] Huang, Y., & Young, B. (2018). Mechanical properties of lean duplex stainless steel at post-fire condition. *Thin-Walled Structures*, *130*, 564–576. https://doi.org/10.1016/j.tws.2018.06.018.
[47] Choudhary, B. K. (2014). Influence of strain rate and temperature on tensile deformation and fracture behavior of type 316L(N) austenitic stainless steel. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 45(1), 302–316.
[48] Tandon, V., Thombre, M. A., Patil, A. P., Taiwade, R. V., & Vashishtha, H. (2020). Effect of Heat Input on the Microstructural, Mechanical, and Corrosion Properties of Dissimilar Weldment of Conventional Austenitic Stainless Steel and Low-Nickel Stainless Steel. Metallography, Microstructure, and Analysis, 9(5), 668–677. https://doi.org/10.1007/s13632-020-00681-y
[49] Cai, Y., & Young, B. (2019). Structural behaviour of cold-formed stainless steel bolted connections at post-fire condition. *Journal of Constructional Steel Research*, *152*, 312–321. https://doi.org/10.1016/j.jcsr.2018.03.024
[50] Li, X., Lo, K. H., Kwok, C. T., Sun, Y. F., & Lai, K. K. (2018a). Post-fire mechanical and corrosion properties of duplex stainless steel: Comparison with ordinary reinforcing-bar steel. Construction and Building Materials, 174, 150–158. https://doi.org/10.1016/j.conbuildmat.2018.04.110.
[51] Ban, H., Bai, R., Yang, L., & Bai, Y. (2019). Mechanical properties of stainless-clad bimetallic steel at elevated temperatures. *Journal of Constructional Steel Research*, *162*. https://doi.org/10.1016/j.jcsr.2019.105704
[52] He, J., Lv, J., Song, Z., Wang, C., Feng, H., Wu, X., Zhu, Y., & Zheng, W. (2023). Maintaining Excellent Mechanical Properties via Additive Manufacturing of Low-N 25Cr-Type Duplex Stainless Steel. Materials, 16(22). https://doi.org/10.3390/ma16227125.
[53] Calmunger, M., Chai, G., Eriksson, R., Johansson, S., & Moverare, J. J. (2017). Characterization of Austenitic Stainless Steels Deformed at Elevated Temperature. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 48(10), 4525–4538. https://doi.org/10.1007/s11661-017-4212-9.
[54] Wang, X. Q., Tao, Z., Song, T. Y., & Han, L. H. (2014). Stress-strain model of austenitic stainless steel after exposure to elevated temperatures. Journal of Constructional Steel Research, 99, 129–139. https://doi.org/10.1016/j.jcsr.2014.04.020
[55] Sathirachinda, N. (2010). Relative nobility of precipitated phases in stainless steels Evaluation with a combination of local probing techniques. KTH Chemical Science and Engineering, Royal University of Technology.
[56] Li, X., Lo, K. H., Kwok, C. T., Sun, Y. F., & Lai, K. K. (2018b). Post-fire mechanical and corrosion properties of duplex stainless steel: Comparison with ordinary reinforcing-bar steel. Construction and Building Materials, 174, 150–158. https://doi.org/10.1016/j.conbuildmat.2018.04.110
[57] Li, J., Du, C. W., Liu, Z. Y., Li, X. G., & Liu, M. (2018). Effect of microstructure on the corrosion resistance of 2205 duplex stainless steel. Part 1: Microstructure evolution during isothermal aging at 850 °C and evaluation of anticorrosion properties by methods of cyclic potentiodynamic polarization and electrochemical impedance tests. Construction and Building Materials, 189, 1286–1293. https://doi.org/10.1016/j.conbuildmat.2018.08.186.
[58] Byun, T. S., Yang, Y., Overman, N. R., & Busby, J. T. (n.d.). Thermal Aging Phenomena in Cast Duplex Stainless Steels.
[59] Raha, B. (2024). Useful Steps Recommended for the Production of Thick-Walled Duplex Stainless Steel Casting. *International Journal of Metalcasting*, *18*(1), 505–511.
[60] Li. (1968). Microstructural development of duplex stainless steels during thermomechanical processing. https://doi.org/10.26190/unsworks/21479.
[61] Tan, H., Jiang, Y., Deng, B., Sun, T., Xu, J., & Li, J. (2009). Effect of annealing temperature on the pitting corrosion resistance of super duplex stainless steel UNS S32750. Materials Characterization, 60(9), 1049–1054. https://doi.org/10.1016/j.matchar.2009.04.009
[62] Huang, H. Y., Wang, Y., & Xie, J. X. (2014). Stress-induced phase transformation characteristics and its effect on the enhanced ductility in continuous columnar-grained polycrystalline Cu-12wt%Al alloy. *Materials Science and Engineering: A*, *596*, 103–111. https://doi.org/10.1016/j.msea.2013.12.041.
[63] Unnikrishnan, K., & Mallik, A. K. (1987). Microstructure—Strength relations in a duplex stainless steel. Materials Science and Engineering, 94(C), 175–181. https://doi.org/10.1016/0025-5416(87)90331-4.

[64] Chan KW, Tjong SC. Effect of Secondary Phase Precipitation on the Corrosion Behavior of Duplex Stainless Steels. Materials (Basel). 2014 Jul 22;7(7):5268-5304. doi: 10.3390/ma7075268. PMID: 28788129; PMCID: PMC5455814.

[65] Tavares, S. S. M., da Silva, M. R., Pardal, J. M., Abreu, H. F. G., & Gomes, A. M. (2006). Microstructural changes produced by plastic deformation in the UNS S31803 duplex stainless steel. Journal of Materials Processing Technology, 180(1–3), 318–322. https://doi.org/10.1016/j.jmatprotec.2006.07.008

[66] Shamanth, V., S. Ravishankar, K., & Hemanth, K. (2019a). Duplex Stainless Steels: Effect of Reversion Heat Treatment. In *Stainless Steels and Alloys*. IntechOpen. https://doi.org/10.5772/intechopen.80007.

[67] Redjaïmia, A. (1992). Decomposition of Delta Ferrite in a Fe-22Cr-5Ni-3Mo-0.03C Duplex Stainless Steel. A Morphological and Structural Study. https://www.researchgate.net/publication/262724866

[68] Vicente, A. D. A., Botelho Junior, A. B., Sartori Moreno, J. R., Abreu Santos, T. F., Romano Espinosa, D. C., & Soares Tenório, J. A. (2019). Micro-Structural Characterization and Semi Quantitative Chemical Analysis of Ferrite and Austenite Phases in Duplex Stainless Steels. Available at SSRN 3309760.

[69] Nilsson, J. O. (1992). Super duplex stainless steels. Materials Science and Technology (United Kingdom), 8(8), 685–700. https://doi.org/10.1179/mst.1992.8.8.685

[70] Zhang, S., Shi, X., Liang, Y., Xu, H., Yan, C., Yan, W., Rong, L., & Yang, K. (2023). χ phase and its effect on the mechanical properties of a Mo-bearing high–Si austenitic stainless steel after aging at 650 °C. Journal of Materials Research and Technology, 23, 4280–4292. https://doi.org/10.1016/j.jmrt.2023.02.069.

[71] Ahn, Y. S., Kim, J. M., & Jeong, B. H. (2002). Effect of aging treatments and microstructural evolution on corrosion resistance of tungsten substituted 2205 duplex stainless steel. Materials Science and Technology, 18(4), 383–388. https://doi.org/10.1179/026708302225001642.

[72] Martins, M., & Casteletti, L. C. (2005). Heat treatment temperature influence on ASTM A890 GR 6A super duplex stainless-steel microstructure. Materials Characterization, 55(3), 225–233. https://doi.org/10.1016/j.matchar.2005.05.008.

[73] Silva, R., Baroni, L. F. S., Kugelmeier, C. L., Silva, M. B. R., Kuri, S. E., & Rovere, C. A. D. (2017). Thermal aging at 475 °C of newly developed lean duplex stainless steel 2404: Mechanical properties and corrosion behavior. Corrosion Science, 116, 66–73. https://doi.org/10.1016/j.corsci.2016.12.014.

[74] Zhang, L., Jiang, Y., Deng, B., Zhang, W., Xu, J., & Li, J. (2009). Effect of aging on the corrosion resistance of 2101 lean duplex stainless steel. *Materials Characterization*, *60*(12), 1522–1528. https://doi.org/10.1016/j.matchar.2009.08.009.

[75] Pettersson, N., Wessman, S., Thuvander, M., Hedström, P., Odqvist, J., Pettersson, R. F. A., & Hertzman, S. (2015). Nanostructure evolution and mechanical property changes during aging of a super duplex stainless steel at 300°C. *Materials Science and Engineering: A*, *647*, 241–248. https://doi.org/10.1016/j.msea.2015.09.009.

[76] He, Y. L., Zhu, N. Q., Lu, X. G., & Li, L. (2010). Experimental and computational study on microstructural evolution in 2205 duplex stainless steel during high temperature aging. Materials Science and Engineering: A, 528(2), 721–729. https://doi.org/10.1016/j.msea.2010.09.067.

[77] Zucato, I., Moreira, M. C., Machado, I. F., & Giampietri Lebrão, S. M. (2002). 385 Microstructural Characterization and the Effect of Phase Transformations on Toughness of the UNS S31803 Duplex Stainless Steel Aged Treated at 850 °C Microstructural Characterization and the Effect of Phase Transformations on Toughness of the UNS S31803 Duplex Stainless Steel Aged Treated at 850 °C. In *Materials Research* (Vol. 5, Issue 3).

[78] Dandekar, T. R., Kumar, A., Khatirkar, R. K., Singh, J., & Kumar, D. (2021). Effect of isothermal aging at 750 °C on microstructure and mechanical properties of UNS S32101 lean duplex stainless steel. Materials Today Communications, 29. https://doi.org/10.1016/j.mtcomm.2021.102753.

[79] Deng, B., Wang, Z., Jiang, Y., Sun, T., Xu, J., & Li, J. (2009). Effect of thermal cycles on the corrosion and mechanical properties of UNS S31803 duplex stainless steel. Corrosion Science, 51(12), 2969–2975. https://doi.org/10.1016/j.corsci.2009.08.015.

[80] Rovere, C. A. D., Santos, F. S., Silva, R., Souza, C. A. C., & Kuri, S. E. (2013). Influence of long-term low-temperature aging on the microhardness and corrosion properties of duplex stainless steel. Corrosion Science, 68, 84–90. https://doi.org/10.1016/j.corsci.2012.10.038.

[81] Angelini, E., De Benedetti, B., & Rosalbino, F. (2004). Microstructural evolution and localized corrosion resistance of an aged superduplex stainless steel. Corrosion Science, 46(6), 1351–1367. https://doi.org/10.1016/j.corsci.2003.09.024.