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Manufacturing Duplex Steel by Using Induction Furnaces and Characterization

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by
Gülşah Uslu

ORCID 0009-0002-8950-5795

Thesis Advisor: Assoc. Prof. Dr. Gül YILMAZ ATAY

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APPROVED BY:

Advisor: **Prof. Dr. Gül Yılmaz Atay**
İzmir Kâtip Çelebi University

Committee Members:

Prof. Dr. M. Özgür Seydibeyoğlu
İzmir Kâtip Çelebi University

Prof. Dr. Mücahit Sütçü
Manisa Celal Bayar University

Date of Defense: January 10, 2024

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Manufacturing of Duplex Steel by Using Induction Furnaces and Characterization

Abstract

Duplex steels are materials that contain ferrite and austenite phases in their structure, have high resistance to corrosion, and also show improved mechanical values. While the austenite in its structure provides general corrosion resistance and ductility, ferrite provides resistance to stress corrosion cracking and mechanical strength. Duplex steels have widespread use, especially in shipping and petrochemistry. The current production method of duplex steels, which are in demand with a wide usage area, is generally argon oxygen decarburization furnaces (AOD). In addition to the production method of duplex steels, which contain elements with critical values in their chemical composition, the heat treatment process also has an important place. The ferrite and austenite phases in its structure are expected to be at 50% values, so that the desired mechanical strength can be achieved while providing corrosion resistance and ductility. In this study, the production of duplex steels, whose current production method is argon oxygen decarburization furnaces, was achieved using induction furnaces. Accordingly, it is aimed to provide new markets, reduce existing costs and reduce carbon emissions. After the duplex steels were produced in the induction furnace, heat treatment was applied to the produced parts. The obtained parts were examined structurally and morphologically, and ferrite and austenite phases were detected at a rate of 50% in the structure. Additionally, the mechanical properties of duplex steels produced in the induction furnace were evaluated.

Keywords: Duplex steel, induction furnaces, heat treatment

Dubleks Çeliklerin İndüksiyon Ocağı ile Üretilmesi ve Karakterizasyonu

Öz

Dubleks çelikleri yapısında ferrit ve östenit fazları bulunduran, korozyona karşı yüksek dayanıma sahip, ve bunun yanında gelişmiş mekanik değerler gösteren malzemelerdir. Yapısındaki östenit genel korozyon dayanımı ve süneklik sağlarken, ferrit sayesinde ise gerilmeli korozyon çatlağına karşı dayanım ve mekanik dayanım elde edilmektedir. Dubleks çelikleri gemicilik ve petrokimya başta olmak üzere yaygın bir kullanımına sahiptir. Geniş kullanım alanı ile talep gören dubleks çeliklerinin mevcut üretim yöntemi genellikle argon oksijen dekarbürizasyon ocaklarıdır (AOD). Kimyasal komposizyonunda kritik değerlere sahip elementler barındıran dupleks çeliklerinin üretim yönteminin yanı sıra ısıl işlem prosesi de önemli bir yer tutar. Yapısında bulunan ferrit ve östenit fazlarının %50 değerlerinde olması bekleni ki bu şekilde korozyon direnci ve süneklik sağlanırken istenen mekanik dayanım da elde edilebilmektedir. Bu çalışmada mevcut üretim yöntemi argon oksijen dekarbürizasyonu ocakları olan dubleks çeliklerinin indüksiyon ocakları ile üretiminin gerçekleşmesi sağlanmıştır. Buna bağlı olarak yeni pazar sağlanması, mevcut maliyetlerin azaltılması ve karbon emisyonunun düşürülmesi hedeflenmiştir. Dubleks çeliklerinin üretiminin indüksiyon ocağında yapılmasının ardından üretimi yapılan parçalara ısıl işlem uygulanmıştır. Elde edilen parçalar yapısal ve morfolojik olarak incelenmiş, yapıda ferrit ve östenit fazları %50 oranlarında tespit edilmiştir. Ayrıca indüksiyon ocağında üretilen dubleks çeliklerinin mekanik özellikleri değerlendirilmiştir.

Anahtar Kelimeler: Dubleks çelik, indüksiyon ocakları, ısıl işlem

To my Family

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List of Abbreviations

AOD	Argon Oxygen Decarburization
C	Carbon
Cr	Chromium
Cu	Copper
DSS	Duplex Stainless Steel
FCC	Face-centered cubic
HAZ	Heat-affectedZone
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Ni	Nickel
ORCID	Open Researcher and Contributor ID
PREN	Pitting Resistance Equivalent Number
TEM	Transmission Electron Microscopy
TTT	Time-temperature-transformation
W	Tungsten

List of Symbols

Δ	Ferrite phase
Γ	Austenite phase
σ_0	Initial stress [MPa]

Chapter 1

Introduction

Stainless steels are iron-based alloys that contain a minimum of 12% chromium (Cr) [1]. In addition to chromium, they are alloys that include elements such as iron, carbon, and nickel, among others. To achieve and support certain characteristic properties in stainless steels, elements like nickel, molybdenum, copper, manganese, titanium, aluminum, niobium, and silicon are added [2]. Stainless steels exhibit high corrosion resistance based on the amount of chromium present in them. The chromium oxide layer formed on the surface of stainless steels provides high resistance to corrosion.

The utilization of these steels in the global industry has been steadily increasing, leading to a growing variety of stainless steel types in recent years. One of the reasons for the increasing application of stainless steels, a subtype of iron alloys developed to enhance corrosion resistance, is their exceptional resistance to corrosion. Stainless steels are primarily produced in the form of flat products, bars, pipes, and castings [3]. They find extensive use in storing and transporting products in industries such as petroleum, chemicals, and food. Moreover, their longer lifespan compared to other steels has been cited as a cost-effective advantage [4].

Despite providing high corrosion resistance, stainless steels fall short when high mechanical properties are required in their application. The inability to meet the desired mechanical properties is a crucial limitation to the use of stainless steels. This challenge has been overcome by developing duplex stainless steels, which combine ferritic and austenitic phases. Duplex stainless steels containing ferrite and austenite phases offer both corrosion resistance and high mechanical properties. EN 1.4462 (SAF 2205) duplex stainless steel materials are among the most widely used within this group and find extensive application in defense industries, shipbuilding, and offshore operations.

This thesis aims to facilitate the production of 2205 duplex steels using induction furnaces, as opposed to the current production method involving argon oxygen decarburization furnaces. For small-scale companies that currently use induction furnaces, investing in an AOD furnace is significantly costly. Consequently, this not only requires machine investment but also acquiring sufficient space, optimizing energy resources, and hiring new personnel. One of the significant objectives of the thesis is to create new markets using the existing system for firms producing with induction furnaces. In addition to this, the thesis aims to increase capacity, reduce current costs, and lower carbon emissions with the existing system.

Within the scope of this thesis, the initial goal is to manufacture parts. Following the production of duplex steels in the induction furnace, heat treatment will be applied to the produced parts. The resulting parts will be examined structurally and morphologically, and the mechanical properties of duplex steels produced in the induction furnace will be evaluated.

Chapter 2

Stainless Steels

Stainless steels constitute a common class of materials used in various industries. As the industry develops, the need for stainless steels also increases. Stainless steels typically contain iron, chromium, and various other alloying elements such as titanium, molybdenum, and nickel. The addition of chromium, often in amounts above 10%, is fundamental as it forms a passive, protective oxide layer on the steel's surface, preventing corrosion. One of the primary attributes of stainless steels is their exceptional resistance to corrosion. This resistance is due to the chromium oxide layer, which acts as a barrier between the steel and the environment. Different grades of stainless steel offer varying levels of corrosion resistance, making them suitable for different applications.There are numerous types of stainless steels, classified into families based on their microstructure and properties. Common families include austenitic, ferritic, martensitic, and duplex stainless steels. Each family possesses specific characteristics that make them suitable for distinct applications.Stainless steels exhibit various mechanical properties, including high tensile strength, excellent ductility, and resistance to both high and low-temperature extremes. These properties make them suitable for challenging and diverse environments.While stainless steels offer unique advantages, they can be more challenging to work with compared to standard carbon steels. Proper fabrication and welding techniques are essential to maintain the material's mechanical properties and corrosion resistance. Stainless steel production and use can have environmental impacts, greenhouse gas emissions and including energy consumption. Sustainable practices and recycling of stainless steel are becoming increasingly important considerations.

2.1 Types of Stainless Steels

Stainless steels are a versatile family of alloys characterized by their resistance to corrosion, high-temperature strength, and a wide range of applications. They are widely employed in industries such as construction, automotive, aerospace, healthcare, and many others. Understanding the various types and characteristics of stainless steels is crucial for selecting the right material for specific applications. Types of stainless steel is given Table 2.1.

Table 2.1: Types of stainless steel

1	Austenitic Stainless Steel
2	Ferritic Stainless Steel
3	Martensitic Stainless Steel
4	Precipitation-Hardening Stainless Steel
5	Duplex Stainless Steel

2.1.1 Austenitic Stainless Steel

Austenitic stainless steels are a type of stainless steel characterized by their composition, which includes 12-25% chromium and 8-25% nickel. They are categorized as part of the AISI 300 series and possess a crystal structure known as face-centered cubic (FCC). Austenitic stainless steels are known for their non-magnetic properties and exhibit excellent ductility, formability, and resistance to corrosion [5,6]. Their strength can only be enhanced through cold working due to their FCC structure at room temperature. The melting point of these steels varies between 1400 to 1450°C, depending on the carbon content. Unlike ferritic stainless steels, which undergo a transition from ductile to brittle behavior at lower temperatures, this issue is not observed in austenitic stainless steels because of their austenitic microstructure. Their suitability for applications involving resistance to sub-zero (cryogenic) temperatures down to -270°C or resistance to high-temperature corrosion, along with their strong mechanical properties, has made this steel group widely applicable across various fields.

The characteristics drastically change when nickel is added. As illustrated in Figure 2.1, the atoms are rearranged to appear in the center of each face as well as on the cube's corners. In this way, it turns into what is known as austenitic stainless steel.

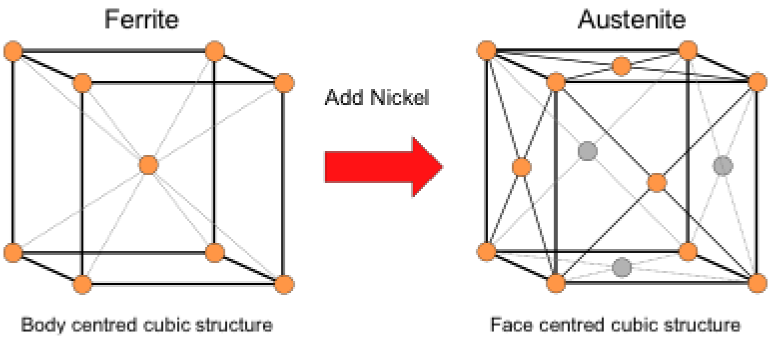


Figure 2.1: With the addition of nickel the atoms in austenitic stainless steels are arranged on the corners of the cube and also in the centre of each of the faces

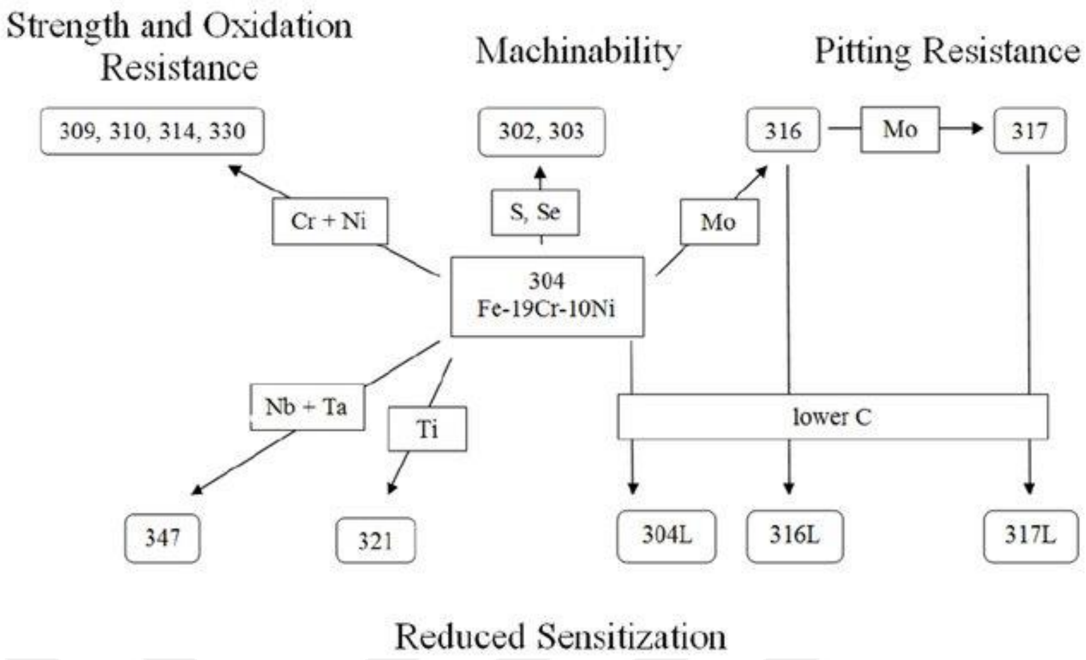


Figure 2.2: Family of austenitic chromium-nickel (300 series) stainless steel alloys, [7]

2.1.2 Ferritic Stainless Steel

These steels have compositions typically ranging from 16-30% chromium (Cr) and 0.05-0.25% carbon (C). Additionally, alloying elements like aluminum (Al), niobium (Nb), molybdenum (Mo), and titanium (Ti) can be added to these steels [8,9]. Due to their low carbon content, they cannot be hardened through heat treatment. The high resistance of these steels to corrosion and oxidation is primarily attributed to their significant chromium content. Ferritic stainless steels find wide applications in today's industry. They are characterized by their magnetic properties and can be shaped through rolling. Their corrosion resistance is higher compared to martensitic stainless steels. Ferritic stainless steels are used in various industries such as the automotive, chemical, petrochemical, and food industries [10,11]. In high-chromium variants of this steel, the annealing process at high temperatures can result in the formation of the sigma phase within the structure. While this may lead to an increase in hardness, it often results in a brittle structure and reduced corrosion resistance, making it generally undesirable. In certain varieties of ferritic stainless steels, specific amounts of chromium and other alloying elements are added to stabilize the ferrite phase completely [5,12].

The iron and chromium atoms in ferritic stainless steel are grouped in a form known as a body-centered cubic structure, with one atom in the center and the other atoms on the cube's corners (Figure 2.3). Ferritic stainless steel has a very strong stress corrosion cracking resistance in addition to being ferro-magnetic.

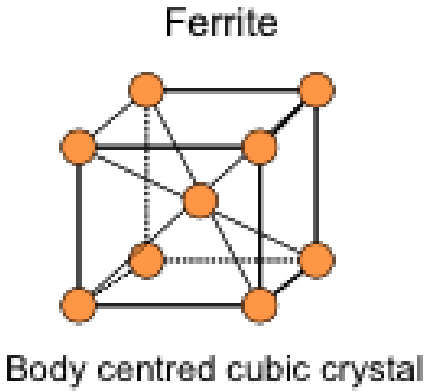
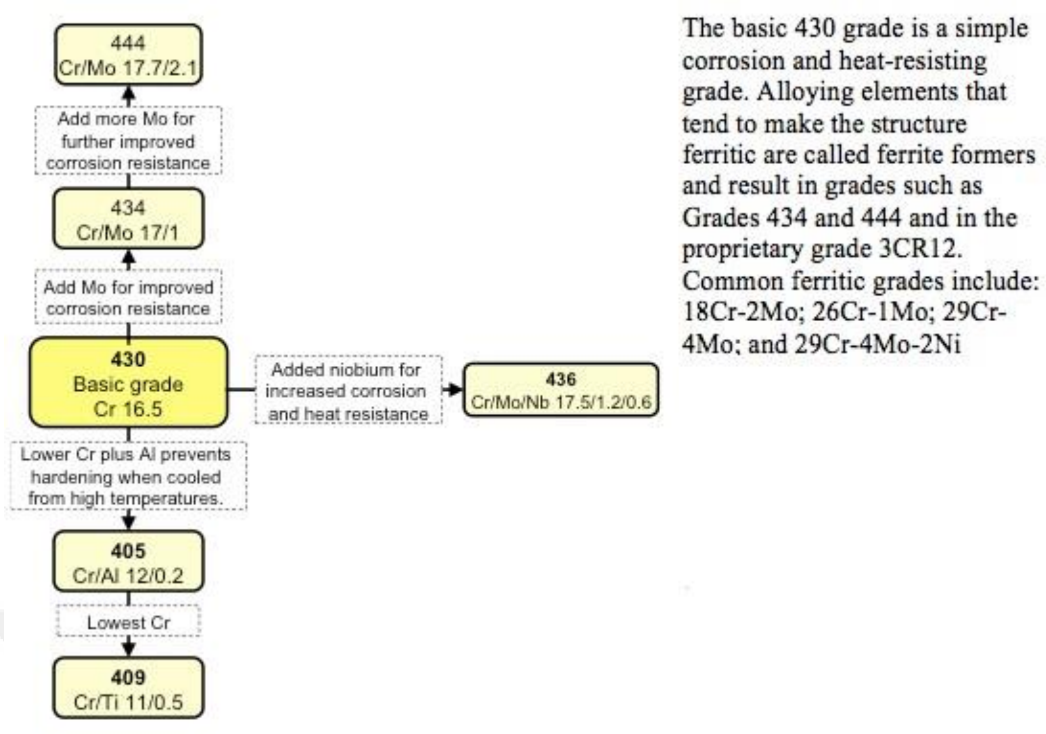


Figure 2.3: In ferritic stainless steel, the atoms are arranged in a body-centred cubic structure



The basic 430 grade is a simple corrosion and heat-resisting grade. Alloying elements that tend to make the structure ferritic are called ferrite formers and result in grades such as Grades 434 and 444 and in the proprietary grade 3CR12. Common ferritic grades include: 18Cr-2Mo; 26Cr-1Mo; 29Cr-4Mo; and 29Cr-4Mo-2Ni

Figure 2.4: Ferritic stainless-steel family

2.1.3 Martensitic Stainless Steel

Martensitic stainless steels typically contain 11-18% chromium (Cr) and can have carbon (C) content of up to 1.2% [13,14]. In addition, small amounts of alloying elements like manganese (Mn), nickel (Ni), niobium (Nb), molybdenum (Mo), and tungsten (W) can be added to tailor their microstructure. To achieve the desired properties in martensitic stainless steels, various heat treatment processes, similar to other alloyed steels, are applied to alter their internal structure. By subjecting the steel to a quenching process at austenitizing temperatures (950-1050°C), the internal structure transforms into martensite. The addition of alloying elements like Ni and Mo can enhance corrosion resistance and toughness in martensitic stainless steels [3,15]. Martensitic stainless steels are magnetic, can be cold-rolled, and exhibit high toughness. They also have high resistance to environmental and chemical influences. These steels find applications in a variety of fields, including valves, various connecting components, gears, pins, shafts, chains, dental tools, springs, and more.

Low-carbon martensitic steels are particularly used in turbine blades and wheels, including steam turbines [16,17].

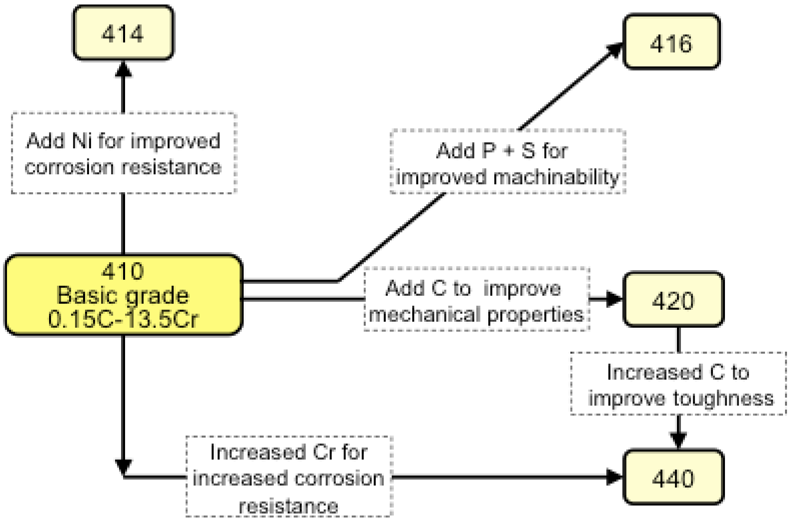


Figure 2.5: The martensitic Grade 400 series.

2.1.4 Precipitation-Hardening Stainless Steel

These are steels that undergo precipitation hardening due to the presence of alloying elements such as Ti, Cu, Mo, Nb, Al, and others [18]. When alloyed with Ti, Cu, Nb, and Al, these steels exhibit precipitation formation. They possess a high degree of ductility and toughness but have only moderate corrosion resistance [3]. Precipitation hardening is a process that, in principle, involves aging following a rapid quenching after solution treatment of the alloy. The mentioned alloying elements in the steel's structure dissolve during solution treatment and subsequently precipitate in small particles during aging, enhancing the hardness and strength of the matrix. As a result of this process, the steel can possess mechanical properties similar to martensitic stainless steels and corrosion resistance comparable to AISI 304-type austenitic stainless steel. One of the significant advantages of these steels in production is that, after easy processing and shaping in the normalized state, an additional heat treatment at 480-600°C can significantly enhance their mechanical properties. This process can increase their strength up to 1700 MPa, surpassing the strengths of martensitic stainless steels [18,19].

2.1.5 Duplex Stainless Steel

Duplex stainless steels are part of the stainless steel family and are distinguished by the coexistence of both ferrite and austenite phases in their structure. In contrast to austenitic and ferritic stainless steels, duplex stainless steels demonstrate enhanced mechanical properties, stress corrosion cracking resistance, weldability, and toughness. This superiority can be attributed to their well-balanced microstructure, comprising approximately equal proportions of ferrite and austenite phases [6,20].

The ferrite phase (δ) in the structure provides mechanical strength and corrosion resistance, while the austenite phase (γ) imparts ductility to the steel. These steels typically contain 18-28% chromium and 4.5-8% nickel. The creation of a dual-phase microstructure is achieved by subjecting the steel to high-temperature annealing followed by rapid cooling [21]. Duplex stainless steels incorporate elements like chromium (Cr), molybdenum (Mo), nickel (Ni) and nitrogen (N). Chromium and molybdenum balance the ferrite phase, whereas nitrogen and nickel balance the austenite phase. Some variations of duplex stainless steels also include elements such as manganese (Mn), copper (Cu), and tungsten (W) within the structure [22,23]. Molybdenum enhances mechanical properties, while nitrogen improves corrosion resistance. The presence of these phases within the structure leads to the formation of both chromium-rich and chromium-poor segregation zones within ferrite grains. However, a high cooling rate during processing may hinder the attainment of the desired austenite percentage and result in the unwanted formation of structures like nitrides [4,24].

2.2 Duplex Steels Properties

Stainless steels are commonly classified into four primary families: austenitic, ferritic, martensitic, and duplex. Among these, the duplex family stands out as a preferable option, offering an exceptional balance of cost-effectiveness, weldability, and toughness. This makes it the preferred choice when both strength and corrosion resistance are crucial [25]. Despite being more technically demanding than traditional austenitic stainless steel grades like type 304 and 316, duplex stainless steels (DSSs) provide superior corrosion resistance across a broader range of challenging conditions. It is crucial, especially during fabrication and welding processes, to prevent the formation of undesired secondary phases and to maintain the advantageous equilibrium between ferrite and austenite.

Originally, duplex stainless steels found their main use in components that demanded superior corrosion resistance. Nevertheless, there is a growing inclination to explore their application in structural contexts owing to their impressive mechanical characteristics. The evolution of duplex steel grades in contemporary times encompasses the production of steels with elevated alloy content to improve corrosion resistance [26,27] and concurrently, steels with reduced alloy content for construction applications and cost-effectiveness [28]. Table 1 outlines the standard chemical composition of four distinct grades of duplex stainless steels [28,13].

Table 2.2: Typical chemical composition (wt%) of important duplex grades[29]

	Cr	Ni	Mo	Mn	N
2304	21.5-24.5	3.0-5.5	0.05-0.6	2.5	0.05-0.2
LDX 2101	21.5	1.5	0.3	5	0.22
2205	22.0-23.0	4.5-6.5	3.0-3.5	2	0.14-0.22
2507	24.0-26.0	6.0-8.0	3.0-5.0	1.2	0.24-0.32

The characteristics of some duplex stainless steel grades:

- 2304(EN 1.4362, UNS S32304): This duplex stainless steel is characterized by a relatively low alloy content, known as lean duplex. Its corrosion resistance is comparable to standard austenitic stainless steels, yet it boasts higher strength and enhanced stress corrosion resistance [25].
- LDX 2101(EN 1.4162, UNS S32101): A recently developed lean duplex stainless steel, LDX 2101 features a reduced nickel content for cost-effectiveness. Compensating for the lower nickel levels, increased manganese and nitrogen levels are incorporated to maintain a high austenite fraction. Its strength is on par with DSS 2205, and its corrosion properties surpass those of austenitic 304 [28].
- 2205 (EN 1.4462, UNS S32205): Currently the most widely used duplex grade, 2205 is a moderately alloyed duplex stainless steel offering superior corrosion properties compared to standard austenitic stainless steels. It exhibits satisfactory fabrication, weldability, and economic properties [28].
- 2507 (EN 1.4410, UNS S32750): Recognized as a highly alloyed duplex stainless steel or super duplex, 2507 provides exceptional corrosion resistance in extremely aggressive environments and high strength [13]. However, caution is required during thermal treatments due to the rapid formation of secondary phases at high temperatures, stemming from its elevated chromium and molybdenum content.
- Sandvik SAFUREX (UNS S32906): Created as a contemporary super duplex stainless steel, SAFUREX has been engineered to endure the corrosion challenges present in the stamicarbon urea process [14]. It features elevated levels of chromium and nitrogen, coupled with moderate molybdenum content [30], yielding an unparalleled blend of superior strength, outstanding corrosion resistance, and effective weldability.

The microstructure of stainless steel weldments or castings can be predicted from the chemical composition using the Schaeffler-DeLong diagram [31], as shown in Fig. 2.6 [32]. The elements stabilizing the austenite are known as Ni-equivalents, and the alloying 10 elements stabilizing the ferrite are known as Cr-equivalents [31]:

Cr-equivalent = Cr + Mo +1.5Si +0.5 Nb [wt%]

Ni-equivalent = Ni +30(C+N) + 0.5Mn [wt%]

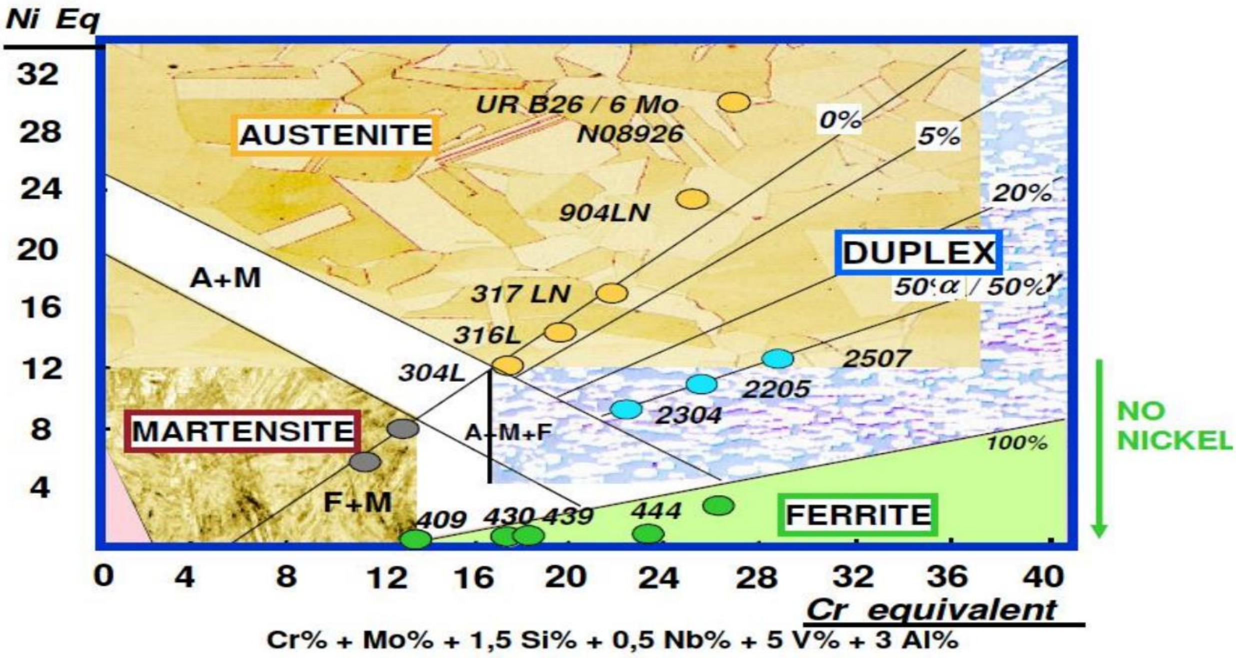


Figure 2.6: Schaeffler Diagram

Table 2.3: PRE, PREN, PRENW number acc. To material type

FAMILY	USA	EURONORM	Cr	Mo	Ni	Mn	Cu	N	Others	PRE	PREN	PRENW
300	304L	1.4307	18	0	9	1	0			18	18	18
	316L	1.4401	17	2	11	1	0			24	24	24
	904LN	1.4339	20	4	25	1	1,5	0,1		33	35	35
Standard DUPLEX (1996)	S 32304	1.4362	23	0	4	1		0,13		23	25	25
	S 32205	1.4462	22	3	6	1		0,17		32	35	35
	S 32750	1.4410	25	3,5	7	1		0,27		37	41	41
	S 32760	1.4501	25	3,8	7	1	0,7	0,27	0,7W	38	42	43
	S 32520	1.4507	25	3,5	7	1	1,5	0,25		37	41	41
New DUPLEX (EX)	S 31500		18,5	2,7	5	1		0,1		27	29	29
	S 32101	1.4162	21	0	1,5	5		0,2		21	24	24
	S 32001		20	0,3	1,7	5	0,3	0,15		21	23	23
	S 32003		20	1,7	3,5	2		0,15		26	28	28
	S 31260		27	3	7	1	0,5	0,16	0,3W	37	39	40
	S 39274		25	3	7	1	0,6	0,27	2W	35	39	42
	S 32906	1.4362	29	2	6	1		0,4		36	42	42
	S 32707		27	5	6,5	1		0,4		44	49	49

PRE = %Cr + 3.3%Mo ; PREN(W) = %Cr + 3.3%Mo + 16%N + (3.3(0.5%W)).

Duplex stainless steels are defined as steel types that contain equal proportions of austenite and ferrite phases. The first requirement for achieving the desired properties from the material is to establish a balance of austenite and ferrite in the microstructure. The material's ability to have the desired microstructure is achieved through the appropriate selection of composition and the correct application of heat treatments.

Figure 2.7: %50 Ferrite, %50 Austenite. (acc. to ASTM A890, Picture is taken from Key to Metals)

Table 2.4: Material Properties of 2205 Duplex Stainless Steel [33]

Yield Strength	448	Mpa
Ultimate Tensile	621	Mpa
Density	7820	Kg/m3
Elastic Modulus	190	Gpa

2.2.1 Corrosion Resistance

Corrosion is the process of material deterioration due to electrochemical reactions, resulting in damage to the material. In an aqueous environment, corrosion occurs through anodic and cathodic reactions, and the rates of these reactions determine the corrosion rate. Slowing down these reactions allows for the reduction of corrosion rates. The most common types of corrosion in duplex stainless steels are hydrogen embrittlement, pitting corrosion and stress corrosion cracking. Particularly, pitting corrosion and stress corrosion cracking in these types of corrosion do not form an oxide layer (rust) on the material surface, making detection challenging. Damage in these types of corrosion occurs without any warning. The risk of corrosion damage in duplex stainless steels is high, especially in the shipbuilding industry and offshore applications, where aggressive environments are present.

The mechanism of corrosion resistance in stainless steels differs from other types of steel. In general, in alloy-free and alloyed steels, an oxide layer forms on the material surface. The physical properties of the formed oxide layer vary depending on environmental conditions, and factors such as the adhesion of this layer to the material, its protectiveness determine the corrosion properties of the material. In stainless steels, the corrosion resistance of the material is provided by the passive film formed on the material surface. For the passive film to exhibit protective properties, it must completely cover the material surface, be free of pores, not dissolve in aggressive environments, and remain undamaged mechanically[34].

One of the most significant factors causing damage in stainless steels is the presence of hydrogen. The presence of hydrogen leads to two different types of damage in the material. The first is the embrittlement of the structure and the occurrence of damage due to the presence of hydrogen, and the second is the formation of stress corrosion cracking due to internal stresses caused by hydrogen presence.

Hydrogen embrittlement bears resemblance to stress corrosion cracking. In both scenarios, the ductile metal experiences brittle fracture, and the interaction of a corrosive environment with tensile stress results in corrosion-induced damage.

Pitting corrosion is a type of corrosion that occurs regionally on the metal surface and progresses into the material. It typically starts in defective areas on the material surface or places with compositional differences. The key alloying elements that enhance the pitting corrosion resistance of stainless steels are Mo, Cr and N. As the ratio of these alloying elements increases within the alloy, the resistance to pitting corrosion also increases. In particular, the amount of Cr has a significant impact on achieving a more homogeneous structure of the passive film formed on the metal surface and reducing defects within the passive film[35,36,37].

To characterize the resistance of stainless steels to pitting corrosion, the concept of Pitting Resistance Equivalent Number (PREN) has been developed based on the presence of these alloying elements. As the PREN value increases, the resistance to pitting corrosion also increases[38].There are two equations for PREN, namely PREN16 and PREN30 (2.4 and 2.5), which evaluate nitrogen in different proportions. PREN16 is more widely used in contemporary applications.

$$\mathrm{PREN16} = \%\mathrm{Cr} + 3{,}3\times \%\mathrm{Mo} + 16 \times \%\mathrm{N} \tag{2.4}$$

$$\mathrm{PREN30} = \%\mathrm{Ct} + 3{,}3\times \%\mathrm{Mo} + 30 \times \%\mathrm{N} \tag{2.5}$$

One of the most important alloying elements that enhances pitting corrosion resistance in stainless steels is Mo. Nitrogen (N) also has a significant effect on the increase in pitting corrosion resistance when combined with molybdenum [39,40]. Additionally, copper (Cu) is mentioned to have a significant impact on the increase in corrosion resistance [40]. However, some studies suggest that copper has no effect on pitting corrosion resistance [41].

In duplex stainless steels, one of the crucial variables for achieving the desired corrosion resistance is ensuring an appropriate balance of ferrite-austenite phases. A high ferrite ratio leads to the formation of Cr2N intermetallics, reducing pitting corrosion resistance, while a high austenite ratio decreases N concentration and leads to Cr-Mo segregation, resulting in a decrease in pitting corrosion resistance [37].

2.3 Historical Development of Duplex Stainless Steels

Duplex stainless steels are materials that combine corrosion resistance, high mechanical properties, and ease of production. These steels have become more preferred over austenitic and other stainless steels, starting from the 1980s, due to factors such as cost-effectiveness, improved metallurgical techniques, welding and corrosion properties, and a wide range of applications. Through extensive research into the history of duplex stainless steels, their historical development can be divided into two periods.

- 1930-1960: The initial duplex stainless steels emerged in Switzerland around 1930. Termed as "First-Generation Duplex Stainless Steels," these alloys featured Cr, Ni, and Mo as their sole alloying elements. They were specifically developed to address intergranular corrosion challenges observed in high-carbon austenitic stainless steels. The inaugural duplex casting was achieved in Finland in 1930, and the first patent for duplex casting, identified as Uranus 50, was officially granted in France in 1936. These pioneering duplex stainless steels exhibited enhanced resistance to hot cracking compared to austenitic stainless steels. This made it easier to cast complex-shaped parts. Pioneering companies like Avesta, Creusot-Loire, and Sandvik developed duplex stainless steel types with higher mechanical properties compared to austenitic stainless steels, without requiring very low carbon content, which was challenging to achieve at the time. However, the high carbon content resulted in the dominance of ferritic HAZ during the welding process and reduced corrosion properties at ferritic-ferritic grain boundaries, limiting their use. As a result, the inability to precisely adjust metallurgical variables and the fact that it was a single-company product meant that the desired mechanical and microstructural properties could not be achieved, and its use did not become widespread [42].
- 1960 and Beyond: While the first-generation duplex stainless steels had advantages in some aspects, their use was limited due to their welding characteristics. In 1968, the development of refining techniques in electric arc

furnaces (Argon Oxygen Decarburization - AOD), low-carbon material production, better controllable heat, and reduced impurity levels in the structure resulted in a significant increase in final product quality. This situation provided a wide range of options for duplex stainless steels. With the AOD technique, it became possible to add nitrogen as an alloying element to the structure. Nitrogen in duplex stainless steels provides an increase in HAZ toughness and corrosion properties. Besides enhancing the stability of austenite, nitrogen also reduces harmful intermetallic ratios [42].

Second-generation duplex stainless steels are defined by the presence of nitrogen as an alloying element. However, the most significant advancement in duplex stainless steel metallurgy occurred in the 1970s with the development of the 2205 class. Today, the majority of duplex stainless steels available on the market belong to this class.

2.4 The Physical Metallurgy of Duplex Stainless Steels

Duplex stainless steels primarily solidify as ferritic alloys and then undergo a solid-state transformation to austenite at lower temperatures. As a result, the balance between austenite and ferrite is adjusted at temperatures above 1000 °C, ideally achieving a ratio of 60-50% austenite. The presence of a high level of alloying elements in duplex stainless steels leads to a complex precipitation behavior. Various precipitations can have a significant impact on both mechanical and corrosion properties. This complexity is further compounded by the uneven distribution of alloying elements between the austenitic and ferritic phases.

Due to the faster diffusion rate of the ferritic phase, most of the technically relevant precipitations occur in this phase. The most critical precipitations that can lead to potential embrittlement include the formation of hexagonal nitrides (Cr_2N) within a temperature range of 700-900 °C, the α' precipitation (associated with 475 °C embrittlement), as well as the intermetallic sigma and χ phases. These intermetallic precipitations not only affect the mechanical properties but also have a significant impact on corrosion properties [43].

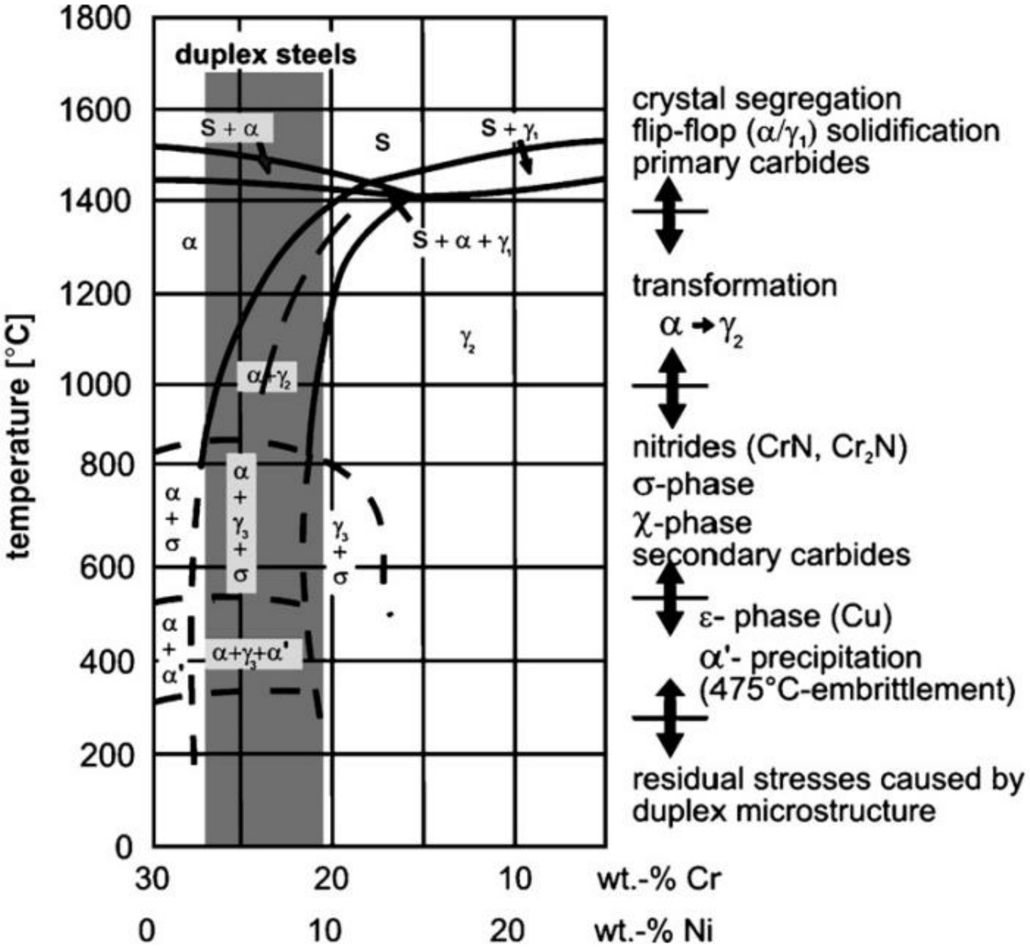


Figure 2.8: Pseudo-binary Fe–Cr–Ni phase diagram at a 70% Fe section[43]

The solubility of alloying elements such as Cr and Mo in the ferrite phase is higher than their solubility in the austenite phase. As the temperature decreases, the solubility of these alloying elements in the ferrite phase decreases, increasing the tendency for the formation of secondary phases in the microstructure of duplex stainless steels.

In duplex stainless steels, the phases formed during cooling from high temperatures to room temperature are determined using time-temperature-transformation (TTT) diagrams. Figure 2.9 shows the TTT diagram for the EN 1.4462 alloy. In duplex stainless steels, the temperature ranges of 600°C to 1000°C and 300°C to 600°C are particularly important regarding the transformations that occur in the microstructure [44].

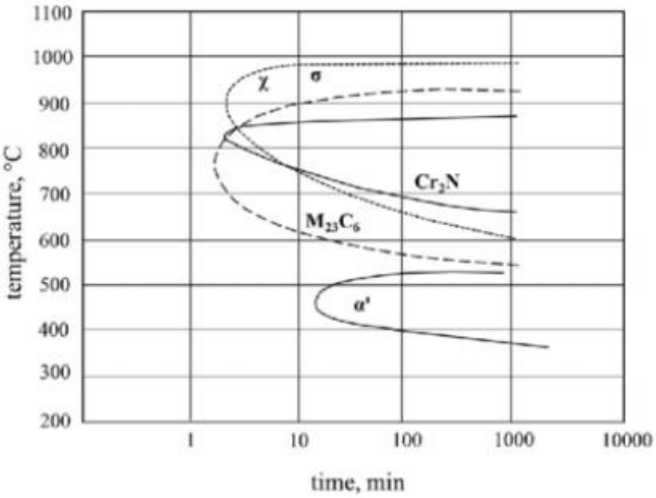


Figure 2.9: Schematic TTT Diagram of DSS 1.4462 [45]

At temperatures above 1000°C, austenite transforms into ferrite in duplex stainless steels. Especially between 1050°C and 1300°C, the structure becomes entirely ferritic, and the ferrite phase becomes enriched in alloying elements like C and N.

The temperature span from 600°C to 1000°C is notably sensitive because it facilitates the creation of secondary phases, posing a potential detriment to both the mechanical characteristics and corrosion resilience of the material. The pace of secondary phase development escalates with elevated concentrations of Cr, Mo, and W in the steel. Consequently, to eradicate secondary phases within the microstructure of duplex stainless steels, it is imperative to administer heat treatment exceeding 1050°C, succeeded by swift cooling (quenching).The range of 300°C to 600°C is especially important because Cr tends to segregate in specific regions within the ferrite phase during this temperature range (see Figure 2.9). In duplex stainless steels with balanced cooling in this temperature range, different ferrite phases with varying Cr content may emerge, negatively affecting the material's mechanical properties and corrosion resistance [46,21].

2.5 Duplex Stainless Steels Usage Areas

Duplex stainless steels are a special material class that offers a wide range of applications due to their unique combination of mechanical and corrosion resistance properties.

- **Oil and Gas Industry**: Duplex stainless steels are used in harsh conditions within the gas and oil industry, including offshore platforms, subsea equipment, oil refineries, and pipelines. Their high corrosion resistance and strength make them ideal for these applications.

- **Chemical Industry**: Chemical facilities involve handling acids, alkalis, and aggressive chemicals. Duplex steels provide high durability and corrosion resistance in such environments.

- **Maritime and Marine Industry**: Due to their resistance to the corrosive effects of seawater, duplex stainless steels are commonly used in maritime applications. They are suitable for submarine equipment, ship hulls, and seawater purification systems.

- **Energy Generation**: Duplex steels find applications in power plants, nuclear energy facilities, and wind energy installations. Their ability to withstand high temperatures and pressure is crucial for these constructions.

- **Chemical Transportation**: Duplex stainless steels are a reliable choice for applications involving the transportation and storage of chemical substances, such as chemical tankers, storage tanks, and conveyance systems.

- **Water Treatment and Wastewater Processing**: Water treatment and wastewater processing plants require materials that can withstand aggressive environments, making duplex stainless steels an ideal choice for corrosion resistance.

- **Structural Applications**: The high strength of duplex steels allows their use in structural applications. They are preferred for projects like bridges, lighthouses, and underwater structures.

- **Automotive Industry**: Duplex stainless steels are used in automotive exhaust systems and components. Their ability to handle high temperatures and corrosion resistance is valuable in these applications.

Duplex stainless steels have become a preferred material in various industries and applications due to their high corrosion resistance, superior strength, good weldability, and adaptability to a range of temperature conditions. They offer reliability and durability for applications where these qualities are essential.

2.6 Effect of Alloying Elements

The alloying elements in duplex stainless steels can be broadly categorized into two groups: ferrite-forming and austenite-forming alloying elements. Chromium (Cr) is the fundamental alloying element that stabilizes the ferrite phase, while Nickel (Ni) is the primary alloying element that stabilizes the austenite phase. Other alloying elements in addition to these two include Carbon (C), Nitrogen (N), Molybdenum (Mo), Manganese (Mn), and Copper (Cu). The influence of these alloying elements on the formation of the austenite and ferrite phases can be observed in Figure 2.6. Together with Chromium and Nickel, the effect of alloying elements on the formation of ferrite and austenite phases is expressed using the Chromium Equivalent (Cr eq) and Nickel Equivalent (Ni eq). [47,48]

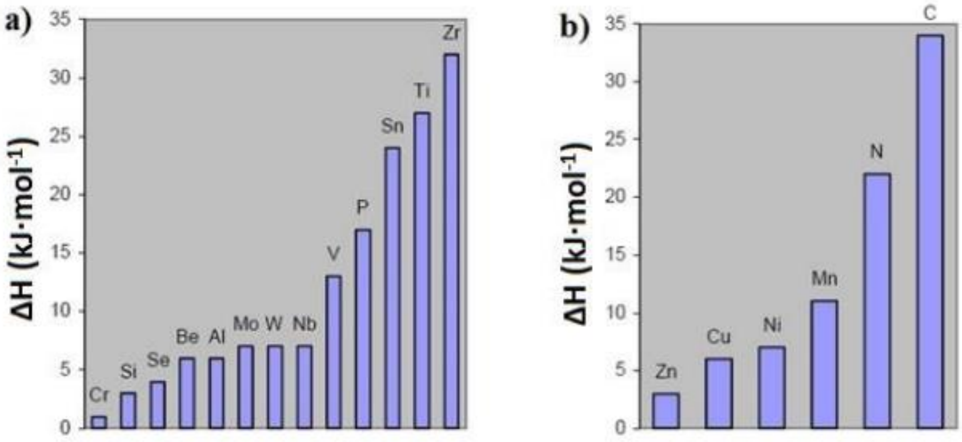


Figure 2.10: The effect of alloying elements on the formation of the ferrite and austenite phases is as follows:a) Alloying elements that stabilize the ferrite phase.b) Alloying elements that stabilize the austenite phase [37]

2.6.1 Chromium (Cr)

Chromium (Cr) is the primary alloying element in stainless steels, and its most important role is to enhance localized corrosion resistance. Localized corrosion resistance is achieved due to the formation of a Cr-rich (Fe, Cr)2O3 layer on the surface.

Chromium is the most crucial alloying element that stabilizes the ferrite phase. It also acts as a carbide-forming alloying element. In stainless steels, the carbides formed by Cr include (Fe, Cr)23C6 and (Fe, Cr)7C3 carbides. In duplex stainless steel, the presence of nitrogen (N) can also lead to the formation of the Cr2N phase [47,35, 37].

Chromium provides several advantages in duplex stainless steels, such as ensuring corrosion resistance and achieving the desired proportion of the ferrite phase. However, it can also contribute to the formation and growth of intermetallic phases.

2.6.2 Nickel (Ni)

Nickel (Ni) is an alloying element that stabilizes the austenite phase. The use of Ni as an alloying element expands the austenite phase field in the phase diagram, making the austenite phase stable at room temperature. Nickel is not a carbide-forming alloying element. However, it has a significant impact on the precipitation kinetics of intermetallic phases, especially in duplex stainless steels.

The required amount of Ni in the composition of duplex stainless steels depends on the ratio of Cr in the material. To achieve the desired proportion of the dual-phase structure consisting of ferrite and austenite, attention should be paid to the Cr and Ni ratios used in alloy design. As the Cr ratio in the alloy composition increases, the Ni ratio also increases [47,49].

2.6.3 Molybdenum (Mo)

The purpose of molybdenum (Mo) in stainless steels varies depending on the type of stainless steel:

- Ferritic Stainless Steels: In ferritic stainless steels, molybdenum acts as an alloying element that stabilizes the ferrite phase. Its presence ensures ferritic solidification and maintains the structure of the resulting phase.
- Austenitic Stainless Steels: The use of molybdenum in austenitic stainless steels enhances corrosion resistance and also improves the material's high-temperature strength. Mo is particularly effective in preventing pitting and crevice corrosion in chloride solutions.

Both chromium (Cr) and molybdenum (Mo) broaden the passivation range and reduce corrosion current density. This leads to an increase in corrosion resistance. Molybdenum's positive impact on pitting and crevice corrosion in chloride solutions is particularly noteworthy, and it plays a crucial role in improving the overall corrosion resistance of stainless steels [47,49].

2.6.4 Carbon (C)

Carbon is the fundamental alloying element in steels. In stainless steels, low levels of carbon content (typically between 0.03% and 0.08%) are desired to achieve the property of corrosion resistance. In stainless steel, carbon, in conjunction with chromium (Cr), can form M23C6 carbides, which can lead to intergranular corrosion.

Additionally, carbon is an alloying element that stabilizes the austenite phase and needs to be considered when achieving the desired microstructure. Therefore, the carbon content should be carefully taken into account to ensure the desired microstructure and properties [47,49].

2.6.5 Nitrogen (N)

Nitrogen is used in stainless steels to enhance corrosion resistance, increase the austenite fraction, and improve mechanical properties. In the case of duplex stainless steels, its use is becoming more common as a replacement for nickel (Ni). The addition of nitrogen (N) in duplex stainless steel reduces the reliance on nickel, allowing for the achievement of the desired austenite fraction, and results in improved mechanical properties and corrosion resistance.

Furthermore, the reduced use of nickel leads to cost savings. Another significant feature of nitrogen is that it stabilizes the steel against the formation of intermetallic phases in duplex stainless steels, reducing the likelihood of such phases forming [47,50].

2.7 Literature

Nickel is a significant alloying component in stainless steel, primarily used to stabilize the austenite phase. However, due to the increasing cost of nickel, there is a shift towards substituting it with nitrogen. Nitrogen can be introduced into the molten steel in several ways. It can be added as a master alloy in electric arc and air induction furnaces, or it can be incorporated into the melt by exposing it to a nitrogen gas atmosphere. The total amount of nitrogen absorbed by the molten steel is influenced by mass transfer laws. To facilitate the interaction between gas and metal, various methods can be employed in mini steel plants. These methods include stirring the melt while exposing it to gas in an induction furnace with a vacuum system, bubbling gas through the melt in a ladle or AOD converter, and subjecting the melt to ionized gas exposure using a plasma arc. Gupta and friends colleagues conducted various experiments on introducing nitrogen into liquid metal. The authors detailed their experimentation involving the introduction of nitrogen into a 1.5 kg laboratory air induction furnace. In this process, the metal was initially melted in a crucible, and then a nitrogen cloud was applied to the surface of the melt for a duration of 22 minutes[51].

It is evident that, following a 22-minute exposure of the gas to the molten metal, only 0.0453 wt.% nitrogen was incorporated into the melt, in contrast to the equilibrium value of 0.2128 wt%. This notable discrepancy between the calculated and observed values may be attributed to the relatively high oxygen content (0.073 wt%) present in the melt, which could not be entirely eliminated during the melting process in the presence of air[51].

Nitrogen could be added to stainless steel in a few different ways. The operator's decision will be based on the availability of a particular facility within the plant, the size of the melting process, the amount of nitrogen needed in the alloy, and the precision limit for the steel's nitrogen content[51].

In a study conducted by Hättestrand and colleagues, the effects of cold deformation on the ferrite decomposition in duplex stainless steels during heat treatment in the range of 450-500 °C were investigated. This was done through microhardness measurements and transmission electron microscopy (TEM). It was observed that cold deformation could change the α→α+α` phase separation mechanism from nucleation and growth to a spinodal decomposition. These findings were discussed in terms of increased dislocation density and the effects of stable creep [52].

In a study conducted by Karahan and colleagues, the effects of static deformation aging on commercially available solution-treated duplex phase stainless steels were thoroughly examined. Some of the duplex phase stainless steel test specimens were pre-deformed up to 5% strain. Then, they were heat-treated at 30 °C intervals in a furnace at 100-200-300-400-500-600 °C. Some other test specimens were solution-treated at 1050 °C for 30 minutes and rapidly quenched in water. After solution treatment, they were subjected to a short-duration 5% strain deformation. Hardness, elongation, tensile strength, and deformation were tested to determine the effects of static deformation aging on mechanical properties due to heat treatment. The test results showed that mechanical properties are influenced by static deformation aging when applied at different temperatures within the same time frame [53].

Lopez and colleagues examined the behavior of duplex phase stainless steels to enhance the effect of sigma phase. They investigated two test specimens. The first was the double-cycle electrochemical potentiodynamic reactivation test, which indicates a degree of sensitivity to intergranular corrosion. The second specimen was the low strain rate test, providing a relative degree of sensitivity for stress corrosion cracking. This sensitivity was achieved through several heat treatments at 675 °C or 900 °C. The effect of the sigma phase was clearly observed on corrosion resistance and mechanical properties [54].

Pohl and colleagues investigated the impact of intermetallic precipitates on the properties of duplex stainless steels. Rather than complex precipitation and transformation behavior that affects mechanical and corrosive properties, it reveals the corrosion resistance group of ferritic-austenitic duplex phase steels. Most critical property changes were associated with precipitates in the range of 650-950 °C [55].

Chapter 3

Experimental Process

The foundry industry is known for its high energy consumption and significant emissions of pollutants. Studies indicate that the melting process within foundries is responsible for a major portion of the energy consumption, waste generation, and pollution release. Consequently, enhancing the overall energy efficiency and environmental sustainability of the industry requires the development of more effective and efficient melting processes. The primary goal of this thesis is to streamline the production of 2205 duplex steels through the utilization of induction furnaces, as opposed to the current and more expensive method that relies on argon oxygen decarburization (AOD) furnaces. Small-scale companies, currently reliant on induction furnaces, face substantial financial burdens when considering the investment in AOD furnaces. This transition not only entails the cost of new machinery but also necessitates the acquisition of additional space, optimization of energy resources, and the recruitment of new personnel. Another significant objective of this thesis is to identify new market opportunities for companies that use induction furnaces for their production processes. Furthermore, the thesis seeks to enhance production capacity, reduce existing costs, and minimize carbon emissions within the current operational framework. Within the scope of this project, work will be carried out by casting into sand molds. The schematic image of sand mold casting is shared below.

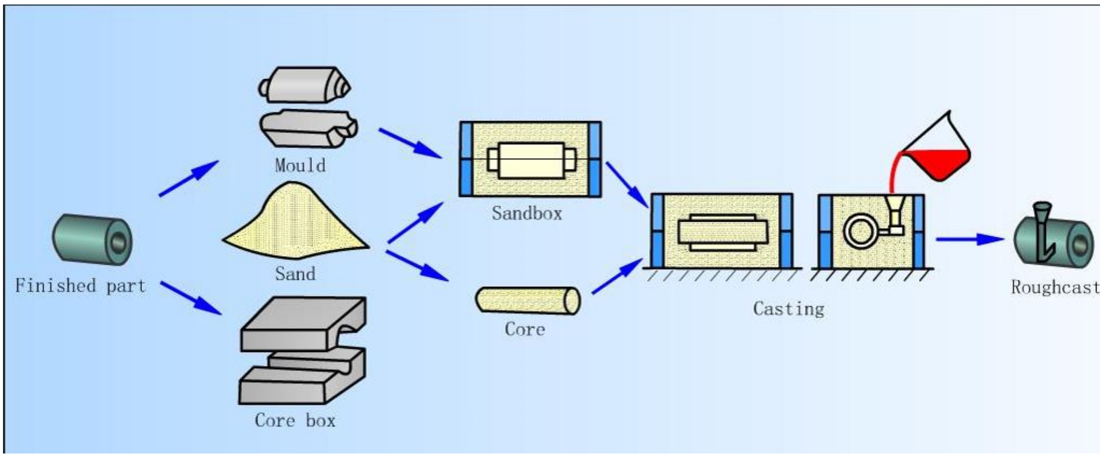


Figure 3.1: The production process flow of sand casting

3.1 Molding

The first stage of the study involved molding operations with a tension chrod model and thermal sand during the molding process. Thermal sand is a recycled form of silica sand. After molding the cope and drag, the model was removed, and they were coated with zircon paint. Once the drag and cope were dried, they were sealed to complete the molding process. Below, the model and drag and cope used in the molding are presented.

Figure 3.2: The molding process of tension chord

3.2 Casting

An induction furnace with a capacity of 350 kg was used for the melting process. During the melting process, samples were taken from the furnace and the chemical composition was examined with a spectrometer. Production approval was given when it was seen that the chemical composition was between the specifications. Below is the chemical result seen on the spectrometer.

A spectrometer is an instrument used to measure certain properties of light as a function of the electromagnetic spectrum. Spectrometers are employed in spectroscopic analyses to describe materials by measuring certain characteristics of light. To determine the chemical composition of the sample taken during melting, a spectrometer has been utilized, as shown in Figure 3.3.

Figure 3.3: OBLF Model Spectrometer

Figure 3.4: 350 kg Induction Furnace

After the confirmation of the chemical composition, the casting process was carried out. Casting was performed into a mold containing 4 tension chrod.

Figure 3.5: Casting Process

3.3 Heat Treatment

Heat treatment was applied to the unmachined tensile samples prepared by cutting after casting. Annealing was done at 1150 degrees. In order to provide rapid cooling to the samples, a bath was prepared and water cooling was performed.

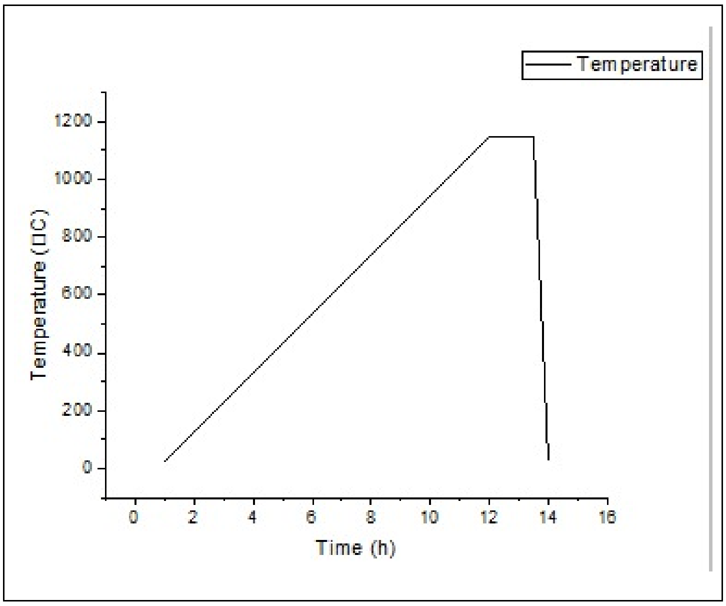


Figure 3.6: Graphic of Heat Treatment

3.4 Examination To Mechanical Properties

According to ASTM E8M, samples prepared to tensile test and charpy test. 3 tension chord samples prepared to tensile test, one tension chord prepared to charpy test.

3.4.1 Charpy Test

According to the TSE 6892-1 standard, the notch-impact samples given in Figure 3.7 were prepared according to the dimensions of the technical drawing.

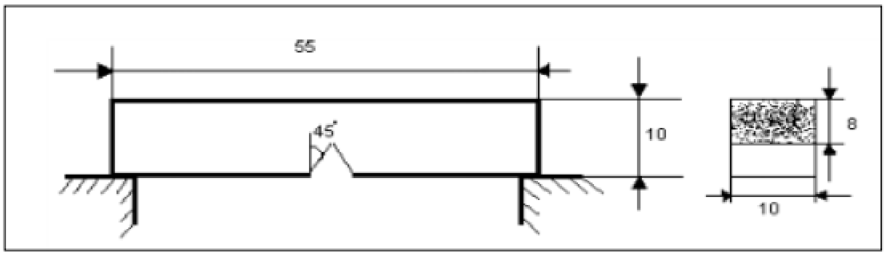


Figure 3.7: Measurements of charpy test samples

2 mm deep notch was cut on the samples prepared for notch-impact at a 45° angle on a notching machine. Charpy notch-impact tests of the samples were carried out with a Alşa Model test device (Figure 3.8).

Figure 3.8: Alşa model Charpy Test Machine

The device breaks the samples by free oscillating with the weight of the striking head. The results are given in Joules via the indicator on the device. The notched samples were placed respectively in the Charpy notch impact test device and the experiments were carried out and the results were obtained.

Figure 3.9: Charpy test samples

According to this project, this company have a customer who is want to receive duplex steel. This customer requirements is duplex steels works in -70 ℃degrees situtation. 3 samples charpy test performed room temperature, 3 samples charpy test performed -70 ℃.

For -70 ℃, charpy test samples was freezed in box using nitrojen.

Figure 3.10: Charpy test samples in -70 ℃

3.4.2 Tensile Test

According to the TS EN 6892 standard, the tensile samples were prepared according to the dimensions of the specimen 2 technical drawing.

Tensile test is the process of pulling test samples prepared according to standards on a single axis, at an absolute speed and at a constant temperature, until they break. During the test, a constantly increasing tensile force is applied to the standard size sample. Meanwhile, the elongation of the sample is also recorded. It is a method used to examine the behavior of materials under a uniaxial tensile stress that spreads homogeneously over the cross-section and to obtain information about their mechanical properties. In addition, tensile testing is widely used to obtain information about the strength of materials. As a result of the tensile test, it provides information about the important properties of the materials such as tensile and yield strength, elasticity limit.

Figure 3.11: Alşa Model Tensile Test Machine

3.4 Microstructure Analysis

Cross-sections were taken from each pull rod. The surfaces of the samples underwent various metallographic processes. To perform metallographic processes, a Struers brand Citopress-10 Model hot mounting press device was used (Figure 3.12).

Figure 3.12: Struers brand Citopress-10 Model Hot Mounting Press Machine

After obtaining Bakelite samples, they were subjected to metallographic processes using a Struers brand Tegramin-30 Model automatic grinding and polishing machine (Figure) for the grinding process. The grinding process is divided into two stages, rough grinding, and fine grinding. The purpose of the rough grinding stage is to achieve the initial flat surface for the fine grinding and polishing stages. This device can perform grinding and polishing processes with two movable discs, and the rotation speed can be adjusted.

Figure 3.13: Struers brand Tegramin-30 Model

The samples were sequentially ground with 220, 500, 1200, 2000, and 4000 grit abrasive papers for an average of 3 minutes each. After the grinding process, the samples were held on polishing discs for fine polishing. The discs are covered with polishing cloths. Initially, the samples were polished with a 6 µ and then a 3 µ diamond suspension for an average of 4 minutes each on polishing cloths, resulting in a mirror-like polished surface on the samples.

The microstructures were examined with an optical microscope. Gliseregia was used as an etching agent. The phases in the microstructure were determined as percentages with the Clemex software created on the optical microscope.

Figure 3.14: Micro-structer samples

Chapter 4

Results and Discussion

4.1 Chemical Composition

The obtained chemical results exhibit a notable conformity with established material standards, affirming the efficacy of the manufacturing process. The adherence of the chemical composition to industry standards underscores the precision and reliability of the production method. This alignment further emphasizes the suitability of the material for its intended applications, meeting the stringent criteria outlined in the relevant material standards. The consistent correlation between the chemical analysis outcomes and the specified material standards provides a robust foundation for the reliability and quality of the produced duplex steel. It is evident that the manufacturing process effectively maintains the chemical integrity required by industry benchmarks, thereby ensuring the material's suitability for its designated use.

4.2 Charpy Test Results

Charpy test results shown Table 4.1 According to TS EN 10213-2010(values taken from Key to Metals) impact value higher or equal to 30 j for 2205 duplex steels.

Table 4.1: Charpy Test Results

Samples Number	Test Temperature	Test Results	Avr.	Standard Deviation	Requested Values	Related Standard /Spec
1	RT	182 J	185,66 J	4,04	Min 30 J	TS EN 10213
2	RT	185 J			Min 30 J	TS EN 10213
3	RT	190 J			Min 30 J	TS EN 10213
4	-70 ℃	31 J	32,33 J	1,52	Min 27 J	TS EN 10213
5	-70 ℃	34 J			Min 27 J	TS EN 10213
6	-70 ℃	32 J			Min 27 J	TS EN 10213

Figure 4.1: RT Test Temperature Samples

Figure 4.2: -70 ℃ Test Temperature Samples

The obtained Charpy impact test results indicate a robust performance of the duplex steel samples. The energy absorption values, with an average of 185,66 J, surpass the minimum requirements for TS EN 10213, highlighting the excellent impact toughness of the material.

The consistency in the impact energy values across the test specimens underscores the homogeneity and reliability of the duplex steel's microstructure. This uniformity is crucial for applications where resistance to sudden impact or shock loading is a critical consideration.

Moreover, the observed high impact energy absorption values suggest that the duplex steel maintains its structural integrity and toughness even at room temperature. This is a favorable characteristic for applications in various industries, including mining sector, oil, gas sector, sea water sector, where the material may be subjected to dynamic loading conditions.

In conclusion, the Charpy impact test results affirm the superior impact toughness of the duplex steel under room temperature conditions, validating its potential for use in demanding environments where resistance to sudden loading is paramount. These findings contribute valuable insights into the mechanical properties of duplex steel, emphasizing its suitability for applications requiring exceptional impact performance.

Topalska and Labanowski investigates the impact of heat treatments and ensuing microstructural changes on the mechanical properties, particularly impact toughness, of commercial 2205 duplex stainless steel and the higher alloy superduplex 2507 grade. Ageing treatments were applied to both steels in the temperature range of 500-900 °C, with exposure times of 6 minutes, 1 hour, and 10 hours. Microstructural examinations using a light microscope, hardness measurements, and impact toughness tests were conducted to analyze the microstructure and changes in mechanical properties. The findings confirm that high-temperature service of duplex stainless steels should be approached cautiously. The precipitation of secondary phases, predominantly the σ phase, significantly degrades the mechanical properties of the steels. However, acceptable levels of these phases in the microstructure depend on the steel's application[56].

This charpy test results and Topalska and Labanowski studies, it is evident that thermal cycles can impact the microstructure and mechanical properties of duplex stainless steel. Specifically, the study notes that duplex 2205 steel, affected by thermal cycles and containing approximately 10% sigma phase, still exhibits acceptable mechanical properties. In my own microstructure analysis, I observed the absence of the sigma phase, contributing to high impact values exceeding 40 J, consistent with the study's findings[56].

This study underscores the importance of considering the presence of secondary phases in duplex stainless steel microstructures, highlighting the need for careful evaluation and control of thermal conditions for the safe operation of the steel. The information presented fills a gap in the literature, providing clarity on the acceptable levels of secondary phases in duplex stainless steel microstructures.

In the second Charpy test conducted at -70 degrees Celsius, aiming to meet the specific customer requirement of a minimum 27 J, the obtained values were 31 J, 34 J, and 32 J for the respective test samples. These results signify that the duplex steel samples not only meet but exceed the minimum threshold specified by the existing customer's demand, emphasizing the capability of small-scale firms to promptly address and fulfill pending customer requests.

This outcome holds significant implications for smaller enterprises, highlighting their capacity to cater to existing customer demands effectively. The achieved impact toughness values at -70 degrees Celsius showcase the adaptability and responsiveness of small-scale firms to meet stringent customer specifications. This not only strengthens the current business relationships but also positions these firms as reliable partners capable of addressing a diverse range of customer needs.

The ability to fulfill the -70 degrees Celsius, 27 J requirement underscores the practicality of these duplex steel samples in real-world applications, especially in environments requiring exceptional low-temperature performance. Small-scale firms, by demonstrating their competence in meeting such specific demands, position themselves as viable and competitive players in the market.

In conclusion, the results of the second Charpy test affirm the suitability of the duplex steel samples for demanding applications, showcasing their resilience and reliability even under extreme conditions. Small-scale firms, by successfully responding to existing customer requirements, not only meet expectations but also pave the way for expanded opportunities and strengthened client relationships. This adaptability positions them as valuable contributors in the industry, capable of meeting diverse challenges and fulfilling customer expectations.

4.3 Tensile Test Results

Tensile test results and TS EN 10213 values shown Table 4.2 Results showed that experimental results compared to TS EN 10213 values, this results was successful in tensile test.

Table 4.2: Tensile Test Results

Samples Number	Ultimate Tensile-Rm (MPa)	Yield Strength Rp02 (Mpa)	Elongation (%)
1	714,62	558,81	34,9
2	711,65	572,19	35,1
3	670,03	526,10	35,6
Avr	698,766	552,366	35,2
Standard Deviation	24,93	23,71	0,36

Table 4.3: According To TS EN 10213 Material Values

Ultimate Tensile-Rm (MPa)	≥ 600 Mpa
Yield Strenght Rp02 (Mpa)	≥ 420 Mpa
Elongation (%)	≥ 20 %

Following the tensile testing conducted at room temperature, the ultimate tensile strength (UTS) values for the three test specimens were recorded in sequence as 714,62 MPa, 711,65 MPa, and 670,03 MPa. The corresponding yield strength values were 558,81 MPa, 572,19 MPa, and 526,1 MPa, while the elongation values stood at 34,9%, 35,1%, and 35,6%, respectively. It is noteworthy that these results align within the specified tolerance range according to TS EN 10213 standards.

The observed ultimate tensile and yield strength values fall within the specified spectrum outlined by TS EN 10213, affirming the compliance of the duplex steel samples with the industry-accepted standards. This adherence underscores the robust mechanical properties of the material and its suitability for various engineering applications.

The consistent and satisfactory mechanical performance, as evidenced by the tensile test results, validates the duplex steel's structural integrity and load-bearing capabilities. These properties are crucial for ensuring the material's reliability under different stress conditions, demonstrating its resilience in practical applications.

The conformity of the duplex steel samples to TS EN 10213 standards enhances their significance for diverse industrial applications. The material's ability to meet and even exceed the specified standards establishes it as a reliable and high-performance option for engineering and construction projects.

In conclusion, the tensile test results underscore the robust mechanical characteristics of the duplex steel samples. Their alignment with TS EN 10213 standards not only validates their suitability for a range of industrial applications but also positions them as materials of choice that meet stringent quality benchmarks. The consistent mechanical properties, particularly the ultimate tensile and yield strengths, highlight the material's reliability and make it a valuable resource for engineering solutions demanding structural integrity and high-performance standards.

Images of the parts resulting from the tensile test are shared below.

Figure 4.3: 1. Sample

Figure 4.4: 2. Sample

Figure 4.5: 3. Sample

4.3 Microstructure Results

Microstructure samples were prepared to tensile test samples. The phases in the microstructure were determined as percentages with the Clemex software. This program showed that ferrite phases area in total microstructure area. Since Clemex calculates at 100x, the samples were examined at 100x. Microsture and percentages value was shown in figures.

According to Clemex phases results, first sample was contain to %49,54 ferrite, second sample was %44,24 and third sample was %51,42 ferrite ratio in total area. In duplex steel, we would like to see %40-60 ratio ferrite in microstructure.

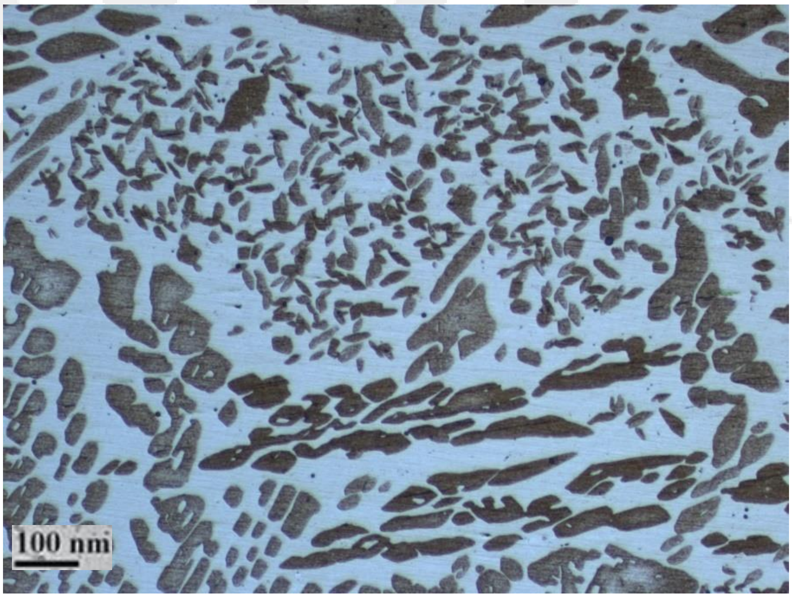
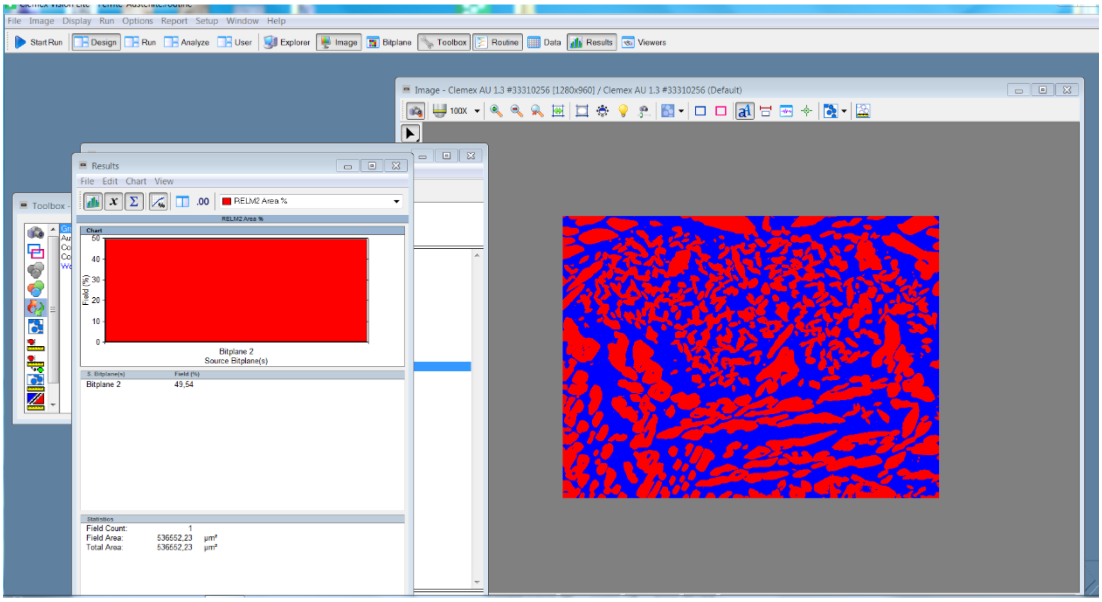


Figure 4.6: 1. Sample 100X



RELM2 Area %

S. Bitplane(s)	Field (%)
Bitplane 2	49,54

Statistics

Field Count:	1	
Field Area:	536552,23	µm²
Total Area:	536552,23	µm²

Figure 4.7: 1. Sample 100X Clemex Results

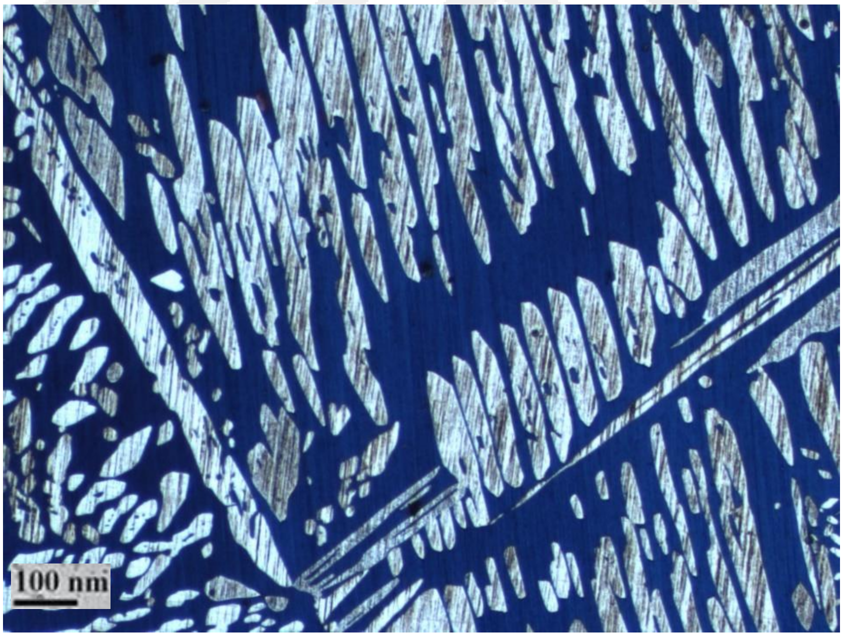
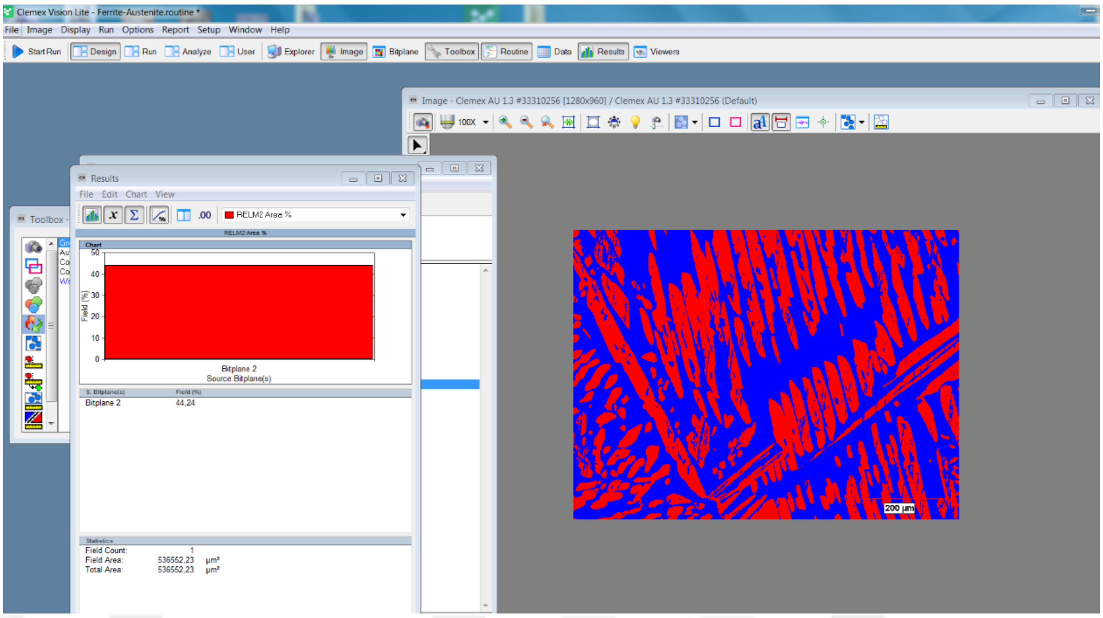


Figure 4.8: 2. Sample 100X



RELM2 Area %

Bitplane 2
Source Bitplane(s)

S. Bitplane(s)	Field (%)
Bitplane 2	44,24

Statistics
Field Count: 1
Field Area: 536552,23 µm²
Total Area: 536552,23 µm²

Figure 4.9: 2. Sample 100X Clemex Results

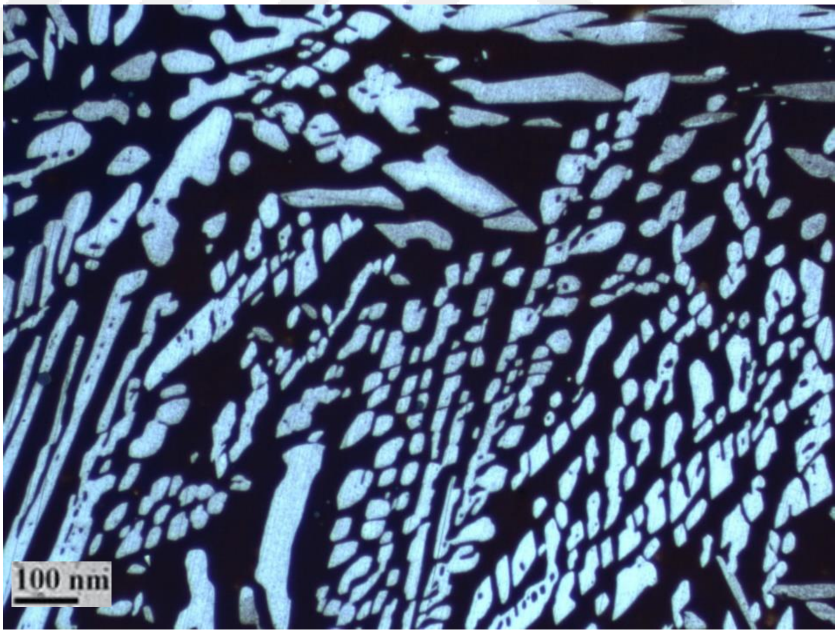
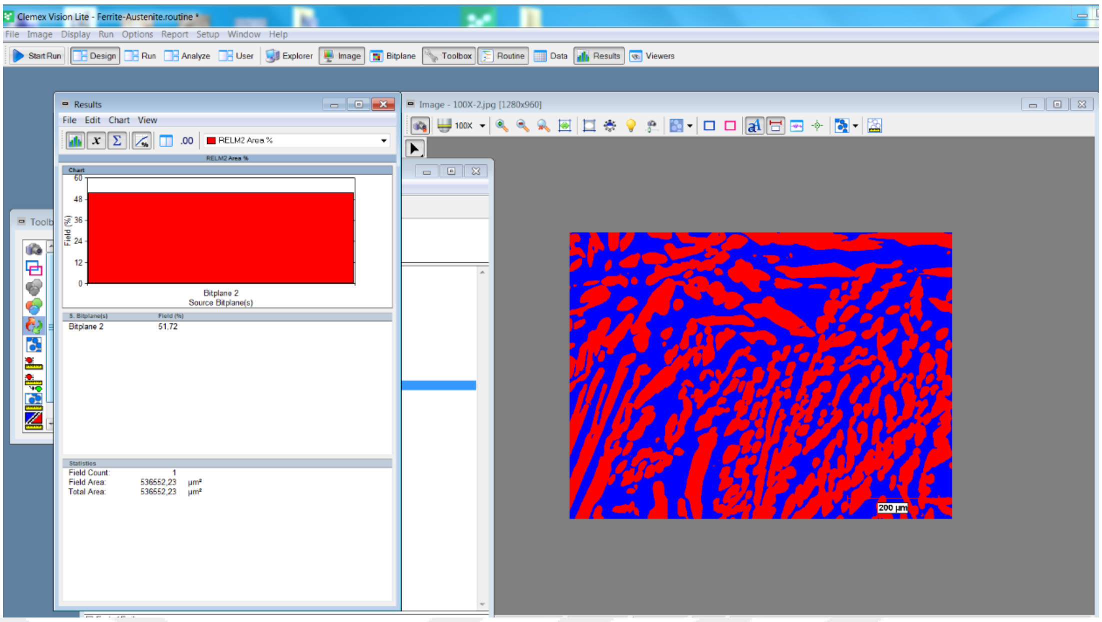


Figure 4.10: 3. Sample 100X



S. Bitplane(s)	Field (%)
Bitplane 2	51,72

Statistics

Field Count:	1	
Field Area:	536552,23	µm²
Total Area:	536552,23	µm²

Figure 4.11: 3. Sample 100X Clemex Results

The examination of three samples under an optical microscope, coupled with the analysis using Clemex software, yielded the following ferrite phase ratios: 49.0%, 54.2%, and 51.4%, respectively. These findings contribute valuable insights into the microstructural composition of the samples, which are integral to understanding the material's properties and behavior.

The determined ferrite phase ratios reveal variations in the microstructure of the examined samples. The observed percentages signify the proportion of ferrite present in each sample, indicating the distribution of this phase within the duplex steel matrix. These insights are critical for comprehending the material's mechanical and corrosion-resistant attributes.

The ferrite phase plays a pivotal role in influencing the mechanical properties of duplex steel. The variations in ferrite content among the samples can impact parameters such as tensile strength, hardness, and ductility. Understanding these relationships is crucial for tailoring materials to specific applications, optimizing performance, and ensuring structural reliability.

The use of Clemex software enhances the precision and efficiency of phase analysis, providing a quantitative measure of ferrite content in the microstructure. The close correlation between optical microscopy and Clemex results validates the reliability of the analytical methods employed, reinforcing the accuracy of the ferrite phase determinations.

The observed differences in ferrite phase ratios among the samples carry implications for the overall performance of the duplex steel. Depending on the application requirements, a tailored ferrite content can be advantageous. Higher ferrite percentages may enhance certain mechanical properties, while lower percentages could favor corrosion resistance. These nuances underscore the importance of microstructural control in material design.

In conclusion, the ferrite phase analyses provide valuable data for understanding the microstructural nuances of the examined duplex steel samples. The correlations between optical microscopy and Clemex software results strengthen the reliability of the findings. The insights gained contribute to informed material selection, allowing for the optimization of duplex steel properties based on specific application needs. This comprehensive understanding of ferrite phase distribution is essential for advancing the performance and versatility of duplex steel in various engineering applications.

Mampuya, Umba, Mutombo and Olubambi's study investigates the impact of different cooling methods on the microstructure of Duplex Stainless Steel (DSS) following solution annealing at 1100 °C. The DSS, renowned for its exceptional mechanical and corrosion resistance properties, features a dual microstructure of δ-ferrite and γ-austenite, in compliance with international quality standards. The study acknowledges the challenges faced by DSS in maintaining its properties under drastic working conditions involving elevated temperatures and sudden cooling, leading to noticeable phase equilibrium shifting and the formation of intermetallic phases[57].

In contrast, my study involved heat treatment at 1150 °C, resulting in a microstructure where intermetallic phases like sigma were not observed. This divergence in the manufacturing process and subsequent microstructural outcomes provides a basis for comparison. In both studies, microstructural evaluations were conducted using light optical microscopy (OM), scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), and microhardness measurements.

The present study indicates a transformation from the initial lamellar structure to a clustered or blocky arrangement, accompanied by the revelation of intermetallic precipitates. On the other hand, my study focused on achieving a microstructure devoid of intermetallic phases. By comparing these outcomes, we gain valuable insights into the influence of different heat treatment parameters on the microstructural evolution of DSS. This comparative analysis contributes to a deeper understanding of the material's behavior under varied thermal conditions, facilitating the optimization of manufacturing processes for enhanced performance in engineering applications.

In Özer's study, the effects of high-temperature heat treatment-induced phase transformations on the hardness and corrosion properties of duplex stainless steel were examined. For this purpose, heat-treated samples underwent optical microscopy (OM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), hardness, and electrochemical corrosion tests [58].

When the material treated at 1200°C/30 minutes was annealied in water, the microstructure predominantly consisted of ferrite (in high amounts) and austenite. In this sample, the dominance of the ferrite phase resulted in high hardness. On the other hand, when the material was furnace-cooled, the ferrite phase decomposed into austenite, and secondary phases (sigma) formed at grain boundaries. The reduction in the ferrite phase led to a decrease in hardness. Although the sigma phase is a hard phase, its minimal presence did not exert a dominant influence on hardness. However, in the furnace-cooled sample, the sigma phase formed at grain boundaries reduced corrosion resistance[58].

The study emphasized the need for rapid (water) cooling to avoid the formation of the sigma phase after high-temperature heat treatments. In samples cooled in the furnace, sigma phase formed at grain boundaries. While the austenite phase provides corrosion resistance in duplex stainless steels, this is valid only when the sigma phase does not form. The intermetallic sigma phase, settling at grain boundaries, accelerated the dissolution in the furnace-cooled sample, despite having a higher proportion of the austenite phase, leading to lower corrosion resistance. The study concluded that the formation of the sigma phase suppresses the corrosion resistance provided by the austenite phase, ultimately reducing the material's overall corrosion resistance[58].

In the current study, rapid water cooling was employed to prevent the formation of intermetallic phases, showcasing a successful choice compared to water and furnace cooling options. The microstructure results confirmed the effectiveness of this choice in preventing undesired phase transformations.

Chapter 5

Conclusion

In conclusion, the utilization of induction furnaces for the production of duplex steel has been investigated, and the results present a compelling case for the viability and efficiency of this manufacturing approach. The study has demonstrated that the duplex steel produced through induction furnaces exhibits phases that align seamlessly with established industry standards. This achievement not only underscores the technological feasibility of induction furnace processes in duplex steel production but also highlights the material's compliance with critical standards governing its structural and compositional properties.

The successful realization of duplex steel phases within the prescribed standards signifies a significant milestone in metallurgical practices. This method not only offers a more accessible and cost-effective alternative for small-scale enterprises but also contributes to the overall sustainability of the industry by minimizing the need for extensive investments in AOD furnaces. The findings of this study open avenues for small-scale companies to engage in the production of duplex steel without compromising on the material's structural integrity or its adherence to stringent industry norms.

Furthermore, the induction furnace approach not only streamlines the production process but also serves as an environmentally conscious choice, potentially reducing the carbon footprint associated with conventional manufacturing methods. This study, therefore, not only contributes valuable insights into the practicality of duplex steel production through induction furnaces but also holds promise for broader implications in enhancing industrial efficiency and environmental sustainability.

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