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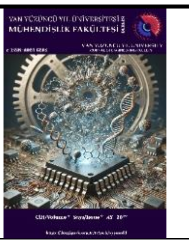

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Investigation of Manufacturing Duplex Steels by Using Induction Furnace

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ABSTRACT

Duplex steels, 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 petro-chemistry. The current production method of duplex steels, which are in demand with a wide usage area, is generally argon oxygen decarburization furnaces (AOD). 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 reduce production cost, minimize carbon emission and provide new markets. After the duplex steels were produced in the induction furnace, heat treatment was applied to the produced parts. The obtained parts were structurally and morphologically analyzed. As a result of the analysis, it was determined that the materials contained 50% ferrite and 50% austenite phases. Additionally, the mechanical properties of duplex steels produced in the induction furnace were evaluated.

Keywords: *Duplex steel, Induction furnaces, Heat treatment, Ferrite, Austenite.*

İndüksiyon Fırını Kullanılarak Dubleks Çeliklerin Üretiminin Araştırılması

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ÖZET

Yapısında ferrit ve ostenit fazları bulunan malzemelerden olan dubleks çelikler, yüksek korozyon direncine sahip olup, aynı zamanda iyileştirilmiş mekanik değerler göstermektedir. Yapıdaki ostenit genel korozyon direnci ve sünekliği sağlarken, ferrit ise gerilim korozyon çatlamasına direnç ve mekanik mukavemet sağlamaktadır. Dubleks çelikler özellikle denizcilik ve petro-kimyada sektörlerinde yaygın olarak kullanılmaktadır. Geniş kullanım alanına sahip olması sebebiyle yüksek talep gören dubleks çeliklerin günümüzdeki üretim yöntemi genellikle argon oksijen dekarbürizasyon fırınlarıdır (AOD). Yapısındaki ferrit ve ostenit fazlarının %50 değerlerinde olması beklenir, böylece korozyon direnci ve süneklik sağlanırken istenilen mekanik mukavemet elde edilebilir. Bu çalışmada, günümüzdeki üretim yöntemi argon oksijen dekarbürizasyon fırınları olan dubleks çeliklerin üretimi indüksiyon fırınları kullanılarak gerçekleştirilmiştir. Buna göre üretim maliyetinin düşürülmesi, karbon emisyonunun en aza indirilmesi ve yeni pazarlar sağlanması hedeflenmiştir. Dubleks çelikler indüksiyon fırınında üretildikten sonra üretilen parçalara ısıl işlem uygulanmıştır. Elde edilen parçalar yapısal ve morfolojik olarak incelenmiş ve yapıda %50 oranında

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ferrit ve ostenit fazları tespit edilmiştir. Ayrıca indüksiyon fırınında üretilen dubleks çeliklerin mekanik özellikleri değerlendirilmiştir.

Anahtar Kelimeler: *Dubleks çelik, İndüksiyon fırınları, Isıl işlem, Ferrit, Ostenit.*

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1. Introduction

Stainless steels are iron-based alloys that contain a minimum of 12% chromium (Cr). To achieve and support certain characteristic properties in stainless steels, elements like nickel, molybdenum, copper, manganese, titanium, aluminum, niobium, and silicon are added [1,2]. They exhibit high corrosion resistance based on the amount of chromium present in them. The chromium oxide layer formed on the surface of those steels provides high resistance to corrosion. The utilization of the stainless steels in the global industry has been steadily increasing leading to a growing variety of stainless steel types in recent years. They are primarily produced in the form of flat products, bars, pipes, and castings [1-3]. 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].

However, the mechanical properties of standard stainless steels, such as tensile strength, yield strength, and toughness, often fall short compared to other high-performance alloys. This shortcoming is primarily due to the microstructure and phase composition of conventional stainless steels. Austenitic stainless steels, which are known for their excellent corrosion resistance, generally have lower strength compared to ferritic or martensitic stainless steels. The presence of a single-phase austenitic structure limits the dislocation movement, resulting in lower yield and tensile strength [5,6]. One of the mechanisms contributing to this limitation is the lack of phase transformation hardening in austenitic stainless steels. Austenitic grades do not undergo significant phase changes that could enhance their mechanical properties during thermal or mechanical treatments. Additionally, the face-centered cubic (FCC) structure of austenitic stainless steels, while beneficial for corrosion resistance and ductility, does not provide the same level of barrier to dislocation motion as the body-centered cubic (BCC) structure found in ferritic steels [7].

These limitations in the mechanical properties of stainless steels have been overcome with the development of duplex stainless steels. These steels, which contain both ferrite and austenite phases, possess both corrosion resistance and high mechanical properties. They have extensive applications in areas such as defense, shipbuilding, and offshore operations [5,6]. Their multiphase structure makes these steels materials with both high strength and good toughness. This allows them to be used in areas difficult to apply in industry. For example, a study by Smith et al. [8] showed that austenitic stainless steels exhibit significantly lower yield strength under high-stress conditions than duplex stainless steels. Similarly, Johnson and Lee [9] demonstrated that the toughness and fatigue resistance of austenitic stainless steels are lower than those of duplex grades.

Currently, the production of 2205 duplex stainless steels is predominantly carried out using Argon Oxygen Decarburization (AOD) furnaces. This method is widely employed in the industry due to its effectiveness in controlling the chemical composition and achieving low carbon levels, which are critical for the desired properties of duplex stainless steels. The AOD process involves blowing argon and oxygen into the molten steel, which helps to decarburize and refine the alloy by reducing the carbon content and removing impurities such as sulfur and nitrogen. This process ensures a high degree of control over the final composition of the steel, leading to superior mechanical and corrosion-resistant properties [10,11].

Despite its advantages, the AOD process comes with several significant challenges and disadvantages. One major drawback is the high initial investment required for AOD furnaces, which includes not only the cost of the equipment itself but also the need for substantial infrastructure modifications. Small-scale companies, in particular, may find it difficult to justify the expense of installing AOD furnaces due to the high capital expenditure and the need for specialized personnel to operate and maintain the equipment. Additionally, AOD furnaces require considerable space and energy resources, which can be a limiting factor for companies with restricted facilities. The operational complexity and maintenance costs associated with AOD technology further add to the financial burden on these companies. Besides argon gas used in AOD requires additional costs. On the other hand, AOD is effective in reducing the carbon content in steel. However, it is not effective in achieving extremely low carbon levels. It does not provide good protection for alloying elements due to the lack of a vacuum environment that minimizes oxidation risks [10,11].

In light of these challenges, this study aims to facilitate the production of 2205 duplex steels using induction furnaces, as opposed to the current production method involving AOD 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 study is to create new markets using the existing system for firms producing with induction furnaces. In addition to this, the study aims to increase capacity, reduce current costs, and lower carbon emissions with the existing system.

On the other hand, studies indicate that the melting process within foundries is responsible for a major portion of the energy consumption, waste generation, and pollution release [11,12]. The primary goal of this study 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. Industrial-scale production of the process implemented in this study would prevent all these costs, energy consumption, and other negative aspects. Another significant objective of this study is to identify new market opportunities for companies that use induction furnaces for their production processes. Furthermore, the study seeks to enhance production capacity, reduce existing costs, and minimize carbon emissions within the current operational framework [12,13].

In this context, the first target was to produce duplex steel products in the induction furnace. Then, heat treatment was applied to the produced parts. The obtained parts were examined structurally and morphologically. Finally, the mechanical properties of these duplex steels produced in the induction furnace were evaluated.

2. Material and Method

1.4462 Duplex stainless steel (SAF 2205- Sandvik Austenite Ferrite) was purchased in steel bar from Pınar Döküm to manufacture automotive fittings. The material produced from the electric arc furnace and shaped to make steel bars by hot rolling was made ready for plastic shaping as a result of these processes. The chemical composition of the untreated 2205 duplex steel according to ASTM A276-98b standard is shown in Table 1.

Table 1. The chemical composition of the untreated 2205 Duplex steel

Grade	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Mo**	**Ni**
Duplex 2205	0.03	2.0	0.035	0.015	1.0	21.0-23.0	2.5-3.5	4.5-6.5

Duplex steel was manufacture by sand casting method. This method is a traditional casting method where the primary modeling material used to prepare the mold is sand. The basic flow of the traditional sand casting process consists of the following steps: Sand preparation, mold making, sand molding, pouring, sand removal etc. The study first started with placing the metal mold in the sand (Figure 1). It includes a stressed chrome model and thermal sand molding processes during the molding process. Thermal sand is a recycled form of silica sand. The mold fit was achieved by filling the sand used to create the internal shape of the casting around the desired model. The sand was placed in the entire cavity, the upper and lower sand were assembled. After the sand mold was obtained, the metal model was removed. The mold was painted with zirconium paint and sealed to complete the molding process.

Figure 1. Placing the model in the sand

An induction furnace with a capacity of 350 kg was used to melt the alloy material and create a qualified liquid metal (Figure 2). It was noted that the part and temperature of the molten metal were compatible. For this reason, care was taken to keep the distance between the molten metal and the mold very short during the pouring process. The molten metal was poured into the mold using a ladle. The pouring speed is also critical to ensure that the molten iron fills the entire cavity. 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. Finally, the sand was broken and the cast material was removed.

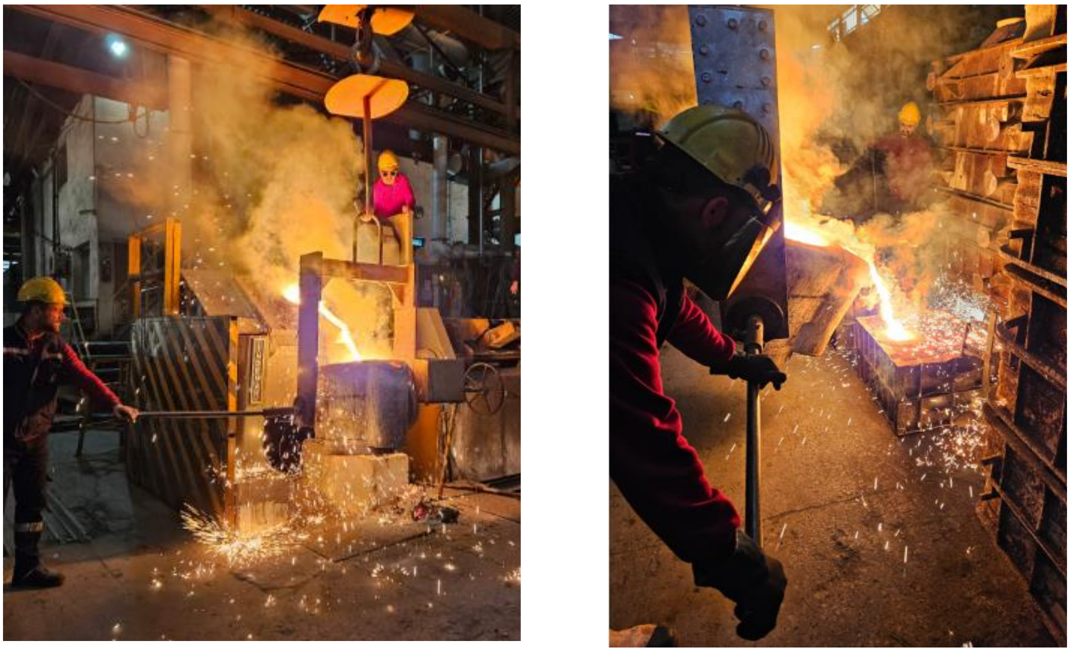
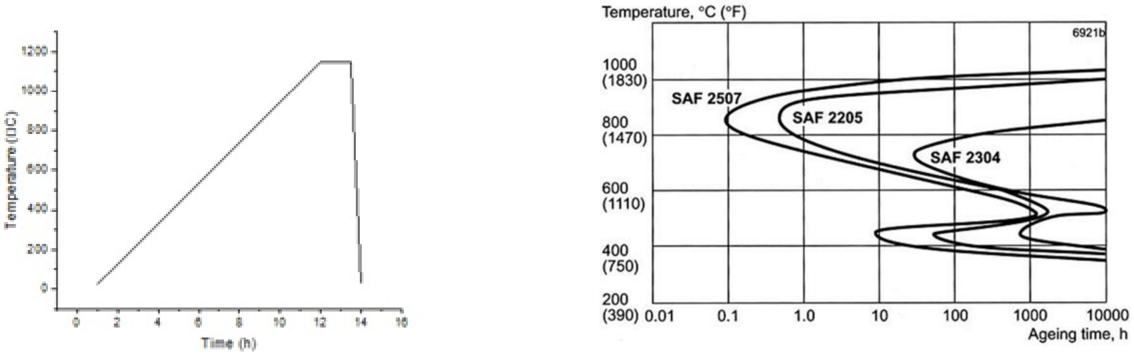


Figure 2. 350 kg Induction Furnace and casting process

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-a). TTT diagram of SAF 2205 duplex steels is shown in Figure 3-b. This controlled heating program was chosen to reduce the risk of thermal shock in the samples. Once the target temperature was reached, the samples were held at 1150°C for 2 hours and then removed from the furnace and rapidly cooled in air. This method was used to ensure homogeneity of the phases during solution annealing and to prevent the formation of the undesirable sigma phase through subsequent rapid cooling.



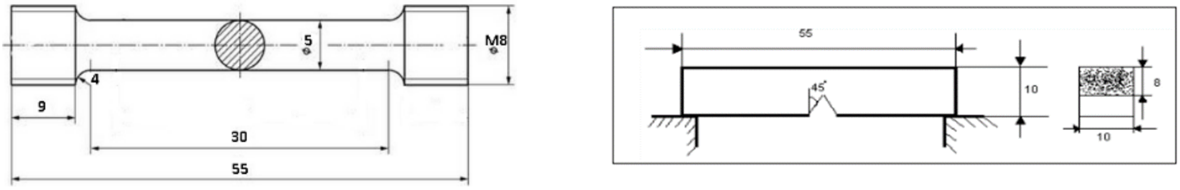
a) b)

Figure 3. a) Graph of heat treatment, b) TTT diagram of SAF 2205 dublex steel

Samples were prepared according to standard metallographic procedures prior to analysis. After grinding and polishing, etching was performed with a suitable abrasive to distinguish phases. ASTM E562 was used as the basis for determining phase volume fractions.

Then, mechanical tests were applied to the produced samples. According to the TS EN 6892 standard [13], the tensile samples were prepared according to the dimensions indicated in the standard (Figure 4.a). According to the TS EN ISO 148-1 standard [14], the notch-impact samples were prepared according to the dimensions of the technical drawing given in Figure 4.b.

The notch impact test was applied at two different temperatures: room temperature and -70 degrees. 3 samples charpy test performed room temperature, 3 samples charpy test performed -70 ℃. For -70 ℃, charpy test samples was freezed in box using nitrogen. The set up for preparing the samples is shown in Figure 5. The sample size for mechanical tests (n=3) was used as the lower limit. It would be more appropriate to develop validation plans with larger groups in future studies.



a) b)

Figure 4. Test specimen a) Tensile test and b) Charpy test

Figure 5. Preparation of the Charpy test samples in -70 °C

3. Results and Discussion

According to TS EN 10213-2010 (values taken from Key to Metals) [15] charpy test was performed with an impact value higher (or equal) to 30 j for 2205 duplex steels. The test results and the samples after the test are depicted in Figure 6 and Table 2. The results indicate a robust performance of the duplex steel samples. The energy absorption values, with an average of 186 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 [15,16].

Figure 6. The samples after Charpy test at room temperature

Table 2. Charpy test results at room temperature

Samples Number	**Test Temperature**	**Test Results**	**Average**	**Standard Deviation**	**Requested Values**
1	RT	182 J	186 J	4.0	Min 30 J
2	RT	185 J			Min 30 J
3	RT	190 J			Min 30 J

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. Those 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 [16]. 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 [16]. 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 [15,16]. 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, the impact test was performed at -70 degrees Celsius aiming to meet the specific standards requirement of a minimum 27 J. The samples after Charpy test at -70 degrees Celsius demonstrated in Figure 7. The obtained values were 31 J, 34 J, and 32 J for the respective test samples (Table 3). These results signify that the duplex steel samples not only meet but exceed the minimum threshold specified by the existing this specific demand, emphasizing the capability of small-scale firms to promptly address and fulfill pending standards requests [15,16].

Figure 7. The samples after Charpy test at -70 degrees Celsius

Table 3. Charpy test results at -70 degrees Celsius

Samples Number	**Test Temperature**	**Test Results**	**Avr.**	***Standard Deviation***	**Requested Values**
4	-70 ℃	31 J	32 J	1.5	Min 27 J
5	-70 ℃	34 J			Min 27 J
6	-70 ℃	32 J			Min 27 J

This outcome holds significant implications for smaller enterprises, highlighting their capacity to cater to existing demands effectively. The achieved impact toughness values at -70 degrees Celsius showcase the adaptability and responsiveness of small-scale firms to meet stringent specifications. This not only strengthens the current business relationships but also positions these firms as reliable partners capable of addressing a diverse range of 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. 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 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 expectations. According to TS EN 10213+A1:2016 standards [15] are depicted in Table 4, and the test results are demonstrated in Table 5. Results showed that experimental results compared to the standard values, this results was successful in tensile test. Following the tensile testing conducted at room temperature, the ultimate tensile strength (UTS) values for the three test specimens were recorded in sequence as 715 MPa, 712 MPa, and 670 MPa. The corresponding yield strength values were 559 MPa, 572 MPa and 526 MPa, while the elongation values stood at 35 %, 35%, and 36%, respectively. The samples after tensile test are shown in Figure 8.

Table 4. Tensile test standards

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

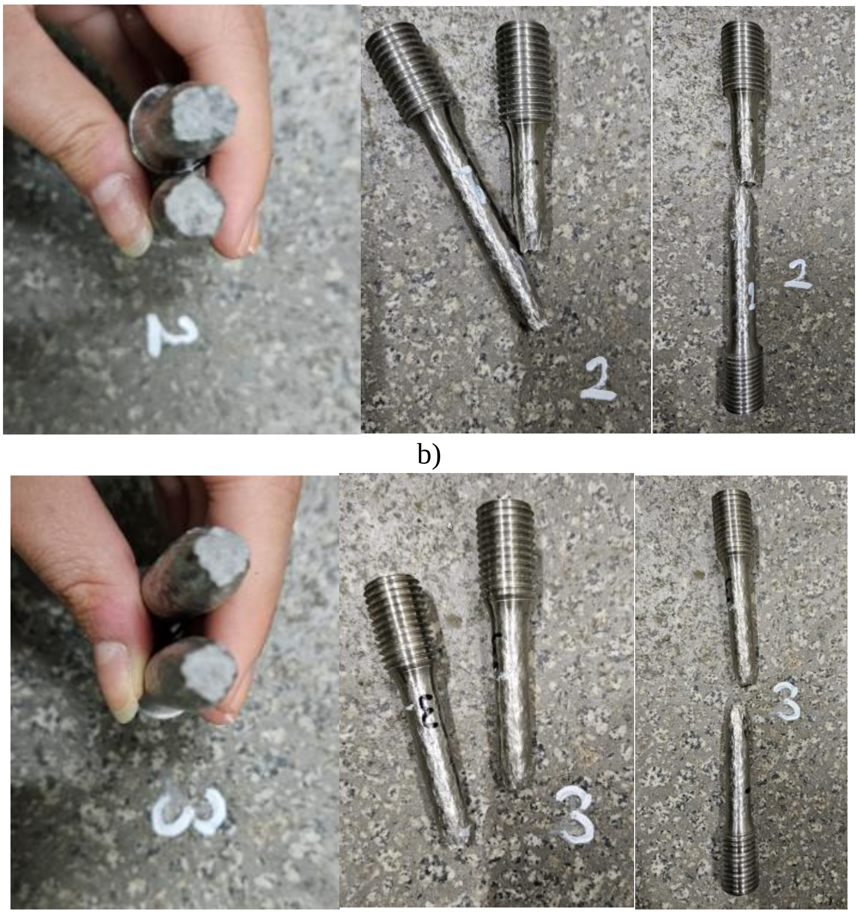
Table 5. Tensile test results

Samples Number	**Ultimate Tensile-Rm (MPa)**	**Yield Strength Rp02 (Mpa)**	**Elongation (%)**
1	715	559	35
2	712	572	35
3	670	526	36
Avr	699	552	35
Standard Deviation	*2.,9*	*23.7*	*0.4*

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.

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.

a)


b)

c)

Figure 8. Test samples after tensile test; a) Sample 1, b) Sample 2 and c) Sample 3.

Microstructure samples were prepared to examine the fracture surfaces of tensile tested samples. Different phases were calculated from the results of these analyses. The determined ferrite phase ratios reveal variations in the microstructure of the examined samples. As mentioned before, the aim in duplex steel is to have both austenite and ferrite phases in the system approximately half and half. 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 most suitable method to provide a quantitative measurement of the ferrite content in the microstructure, increasing the sensitivity and efficiency of phase analysis, is the Clemex Vision software. This is a fully integrated system that can achieve traceable, repeatable and accurate results. It automatically combines multiple fields to create a seamless composite image of the entire sample, which can then be analyzed and saved. The image analysis software is flexible and allows any number of different routines to be run on the same system. These routines are packaged as a library of existing applications or can be developed by our application experts. The close correlation between optical microscopy and Clemex results confirms the reliability of the analytical methods used and strengthens the accuracy of 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. 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.

In the study, the phases in the microstructure were determined as percentages with the Clemex Vision PE software. Images were captured with an optical microscope at 100× magnification. Automatic thresholding was performed using the gray-level histogram, followed by manual fine-tuning to ensure clear separation of phase boundaries. Brightness and contrast values were kept constant during imaging, and the same imaging protocol was followed for each sample, ensuring comparability between measurements. 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 Figure 9. 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. 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.

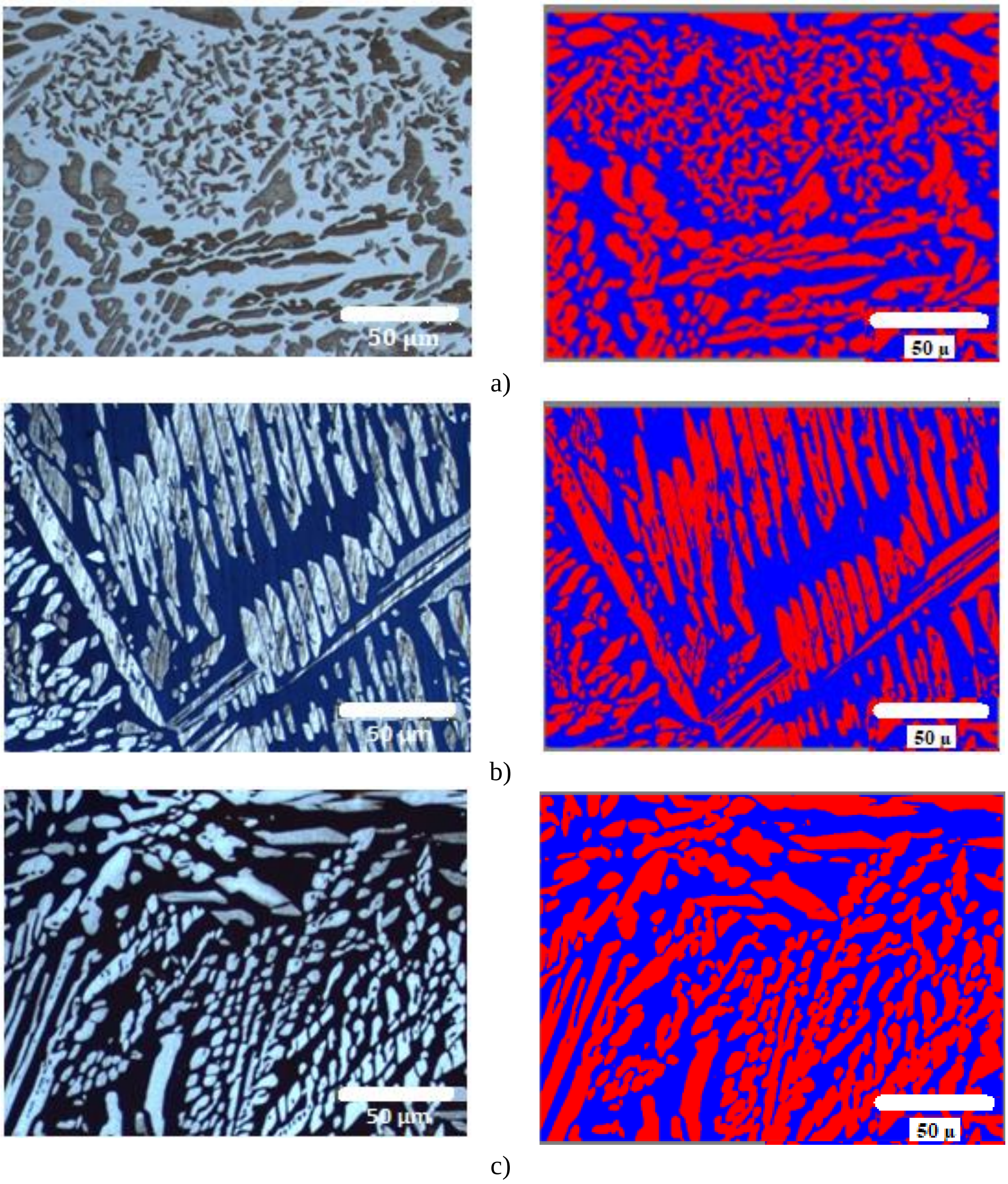


Figure 9. Samples 100X Clemex Results; a) Sample 1, b) Sample 2 and c) Sample 3.

Mampuya et al. [17] investigated 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.

In contrast, our 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 [18].

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, the 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 [18].

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 [19]. 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 [19].

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 [19].

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 [19]. 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.

4. Conclusions

In this study, 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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