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Integrity assessments of steel slabs for using as a base material for manufacturing of API X70 pipes

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ABSTRACT

The integrity of steel pipes is crucial for their application in petrochemical industries and refineries. Given the corrosive nature of the working environment containing sour gasses, the pipes must possess the ability to withstand pressure and temperature, resist corrosion, endure fatigue and comply to safety and environmental regulations. A significant challenge in steelmaking of distinctive steel products, especially high-strength low-alloy steels, is the segregation of carbon, sulfur, manganese, and other elements within the slab's core. Additionally, the solidification process in the slab could leads to the concentration and buildup of shrinkage cavities in the middle thickness of the slab. The Baumann test is a crucial examination in steelmaking process for manufacturing of the pipes and pressure vessels since it verifies the quality of the products. Mannesmann pipes are categorized differently according to this test. In the current research, the microstructure, location and type of defects, has been investigated and the degree of segregation and the shrinkage holes in the slab's cross-section have been studied. The results obtained revealed that the aggregation of alumina and manganese sulfide inclusions were the primary factors contributing to the rejection of Baumann test. The investigations have been revealed that by simultaneously controlling the alumina impurity and using the best practice of secondary cooling, and employing the soft reduction technology, the problem mentioned above could be entirely resolved.

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1. Introduction

Pipes utilized in petrochemicals and refineries are essential to the infrastructure of the oil and gas industry. They have a crucial function in transporting raw materials and petroleum products from their source to their intended location. These pipes, typically constructed from steel, convey crude oil, natural gas, gasoline, diesel, and other petroleum products. Pipes possess a notable attribute of being highly resistant to both pressure and temperature. These pipes must endure elevated pressures and varying temperatures during their operational lifetime. Furthermore, corrosion resistance is a crucial characteristic in oil pipelines due to the potential breakdown of metallic substances, which can result in leaks and pose significant hazards to both the environment and human beings. Furthermore, oil pipelines must adhere to safety and environmental regulations to mitigate the risk of incidents such as spills and explosions. Nevertheless, certain flaws can result in significant issues when steel pipes are utilized. One of the flaws that can occur is corrosion and oxidation, which can be triggered by exposure to chemicals in oil or specific environments like seawater. The process of corrosion can result in issues such as the development of leaks and the weakening of pipe structures. Furthermore, oil pipes might sustain damage due to elevated pressures or seismic activity, resulting in their rupture and subsequent leakage. Furthermore, the obstruction of pipelines is a prevalent issue that might diminish the oil flow and consequently

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impair the efficiency of the transmission system [1–3].

Figure 1-A depicts the schematic diagram of a steel slab casting process. When solidification in continuous casting, steel can occasionally create centerline segregation (CLS), different forms of internal cracks (ICC), and shrinkage cavities. These issues are directly related to the steel casting process, as shown in Figure 1-B. Various internal defects can occur during casting slabs, including CLS, transverse and longitudinal internal cracks, star cracks, and black spots. Two methods are employed to categorize the internal flaws of the slabs. One of these approaches involves performing macro-etching of the slab cross section and then comparing the defects with predefined images. The second technique employed is Sulfur printing technology, wherein defects are imprinted onto sulfur paper. The document is printed and then compared once more with reference photos. (Figure 1-C) Typically, CLS is formed in the middle and is visible as a dashed straight line (Figure 1-b). If the sulfur concentration is low, it is possible to utilize etch printing or macro-etching techniques. Stirring the melt inside the mold, reducing thermal gradients inside the mold and creating a larger equiaxed structure is less prone to segregation [4,5].

In the current research, the Baumann test for revealing the segregation of HSLA steel (APIX70) in the continuous casting of steel slabs has been done and the presence of the defects and their reasons have been investigated.

2. Materials and Methods

This study has been done on specimens from two cast slabs of HSLA steel of API X70 grade, which adheres to the stipulated specifications for usage in the petroleum industry. The final stage includes a spark emission spectroscopy analysis, according to the ASTME415 standard. The results of this analysis are presented in Table 1. Rectangular samples measuring 20 * 30 mm were obtained by employing the wire-cut method to conduct the required experiments (Figure 2). The samples' surfaces were polished using silicon carbide sandpaper ranging from 80 to 2400 grit, then polished with 0.25-micron diamond paste to get a fully polished surface. In order to eliminate any potential contamination from the surface of the samples, an ultrasonic washing process was conducted for 15 minutes using distilled water and ethanol. Subsequently, the samples were dried using cold air. To assess the current structure, the etching procedure was conducted by immersing it in a 10% Nital solution for 2-3 seconds. Figure 3 illustrates the casting direction and cutting location of the samples.

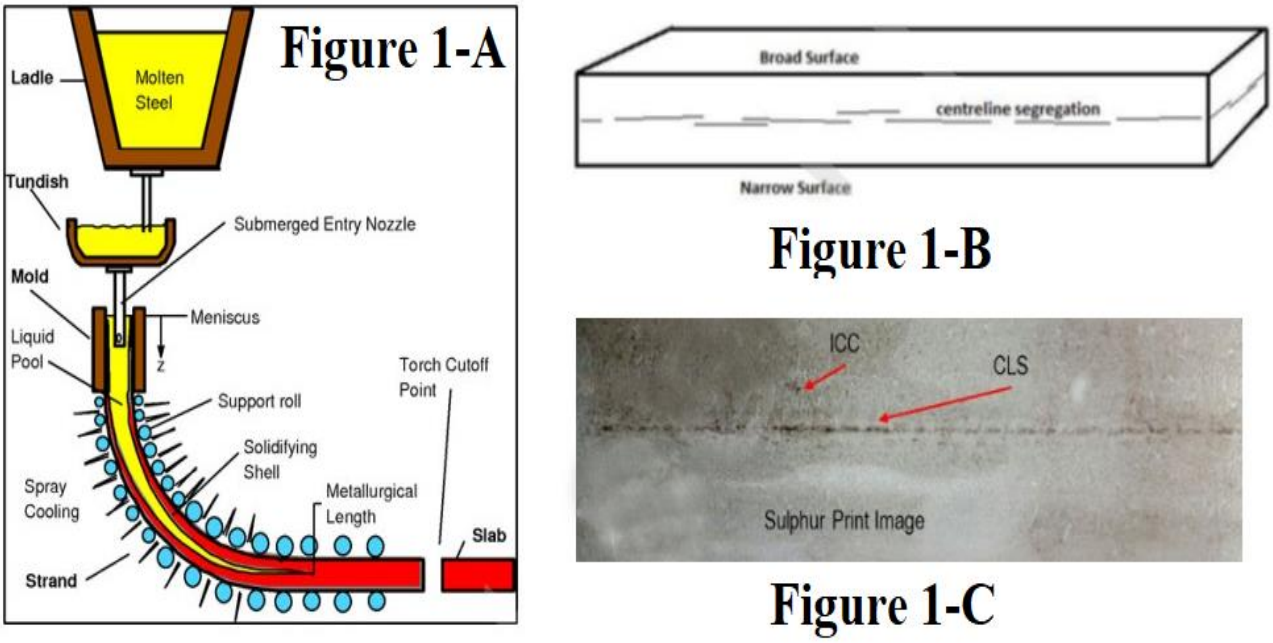


Figure 1. (a) Schematic of a slab casting, (b) slab and (c) sulfur printing of defects [1].

Table 1. Chemical composition of the investigated slabs.

Element (wt%)	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al	Ti	Nb
Slab 01	0.090	0.177	1.417	0.014	0.004	0.015	0.092	0.121	0.026	0.008	0.042	0.019	0.043
Slab 02	0.068	0.267	1.460	0.012	0.003	0.010	0.096	0.121	0.033	0.009	0.038	0.017	0.044

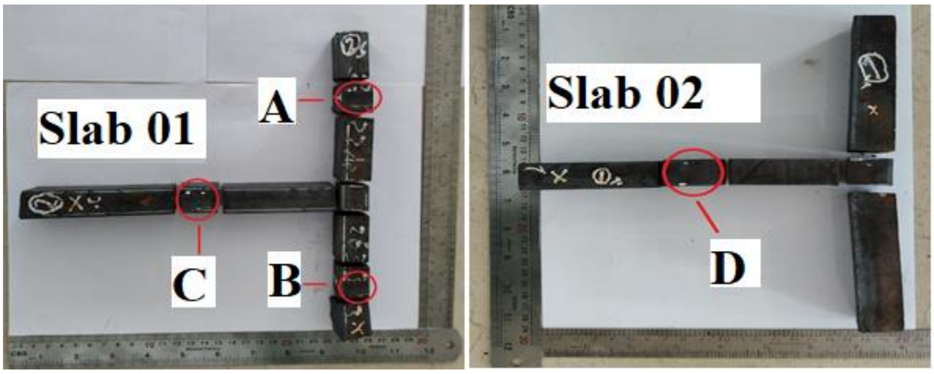


Figure 2. The image of the slabs and the place of cutting different samples by wirecut.

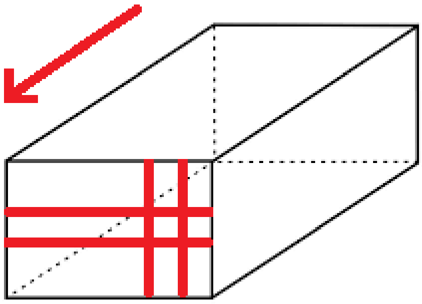


Figure 3. Schematic of the direction of casting and the place of cutting the samples.

The samples undergo the BAUMANN test to assess the slabs, which involves analyzing the sample's microstructure using optical microscope and electron microscope. Base on ISO 4968:2022, the Baumann test, formally known as the Baumann method for macrographic examination, is a qualitative technique used to evaluate the quality of steel by detecting the distribution of sulfur and identifying physical irregularities such as cracks and porosity. This method is particularly useful for assessing non-alloy and alloy steels, as well as cast irons with sulfur content below 0.40%.

3. Results and Discussion

To assess the presence of cracks, porosity, and contaminants, macrographic images of the slabs were acquired using sulfur printing, a testing technique known as the BAUMANN test. The results of the BAUMANN test on the slabs are depicted in Figures 4 and 5. The test result reveals the presence of shrinkage holes on the slabs, as evidenced by the straight-line pattern of dotted lines on their surface.

Casting steels can exhibit a range of defects, including segregation, porosity, inclusions, and cracking. To comprehensively investigate these surface defects, a prepared sample was examined using an Optical microscopy at three different magnifications, both on the surface and on the cross-section of the samples.

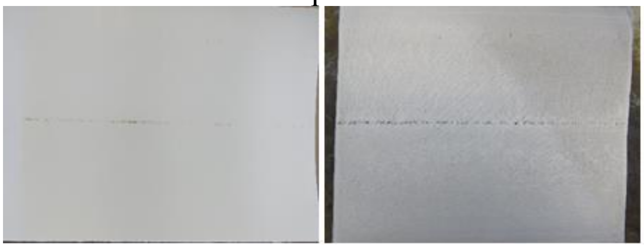


Figure 4. Images of BAUMANN test Slab 01.

Figure 5. Images of BAUMANN test Slab 02.

Slab 01 was used to investigate samples A, B, and C, while slab 02 was used to analyze the surface of sample D and the cross-section of samples C and D. The Optical microscopy was used at three magnifications of 50, 100, and 200. The surface scans revealed the presence of features such as a central impurities and porosities in the samples. The images depicting the cross-sectional view of samples C and D indicate the presence of segregation occurring at the center of the samples (Figure 6-11).

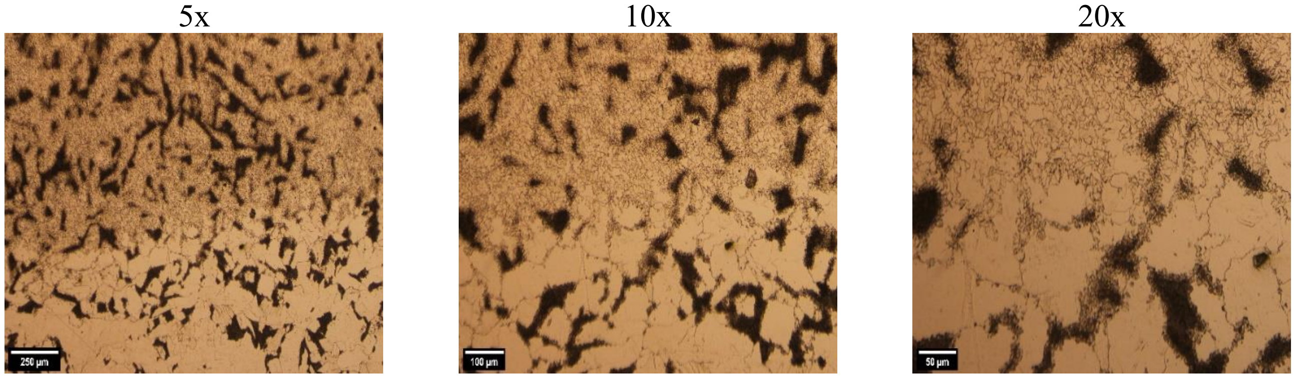


Figure 6. Optical microscopy images of the surface of sample A.

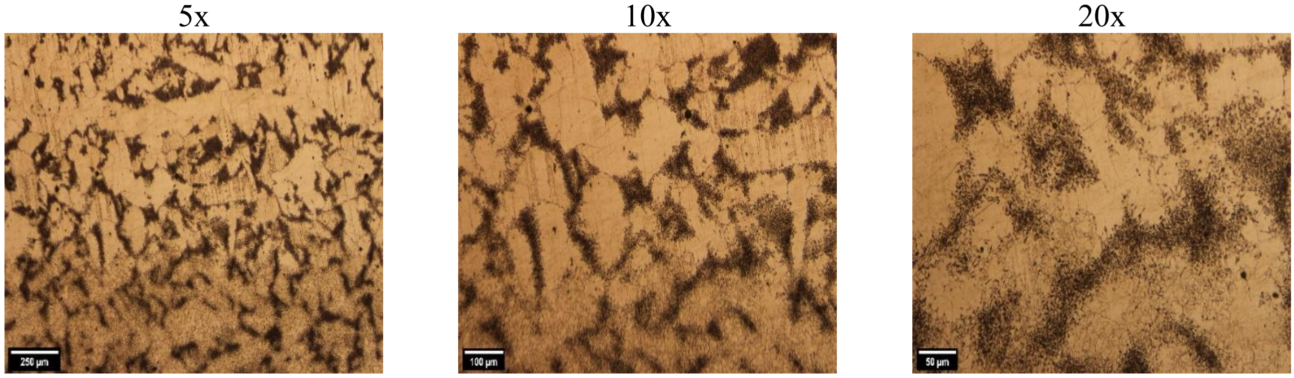


Figure 7. Optical microscopy images of the surface of sample B.

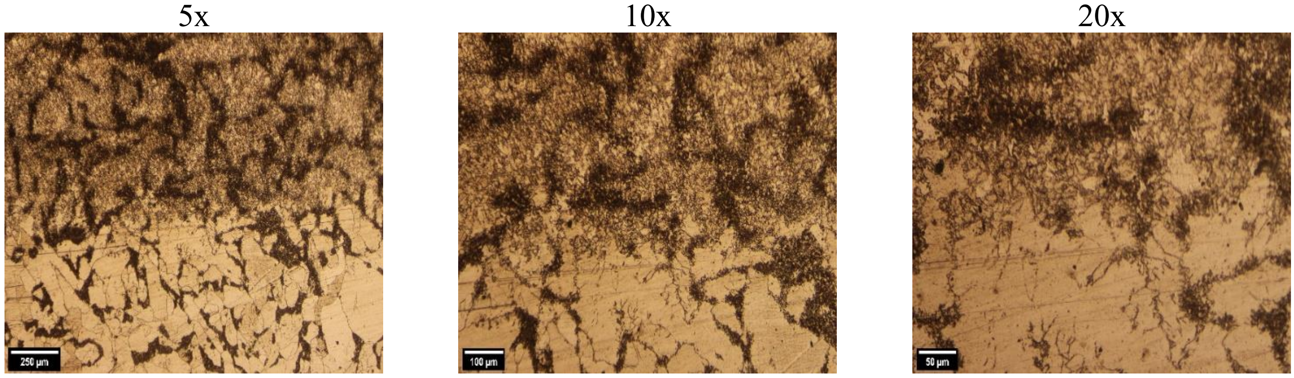


Figure 8. Optical microscopy images of the surface of sample C.

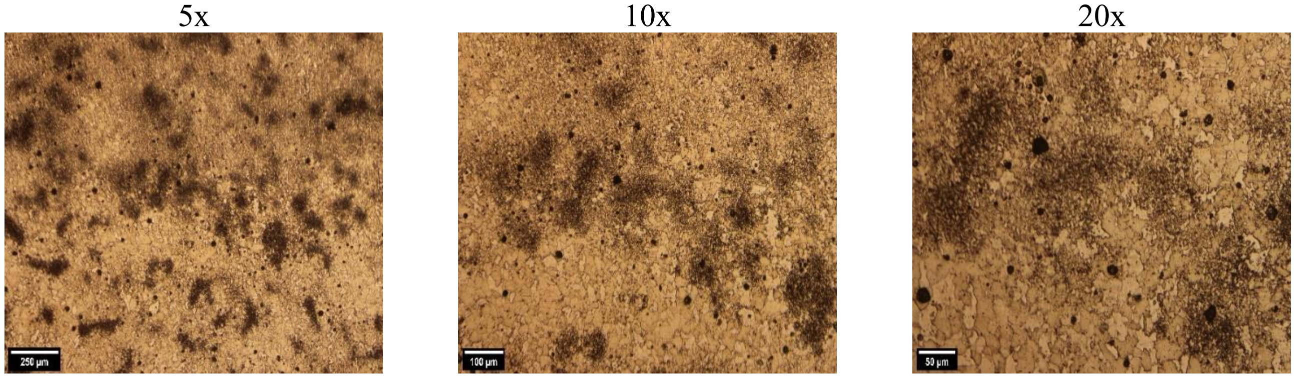


Figure 9. Optical microscopy images of the surface of sample D.

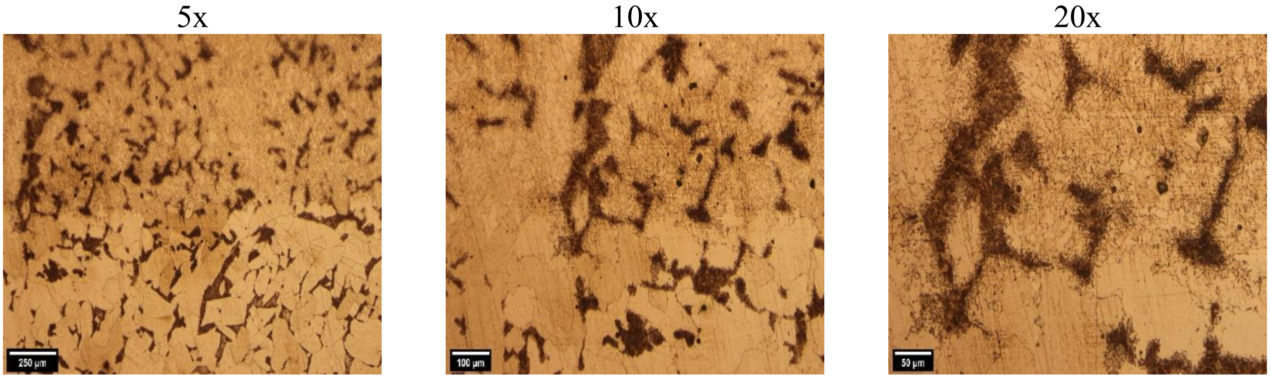


Figure 10. Optical microscopy images of the cross-section of sample C.

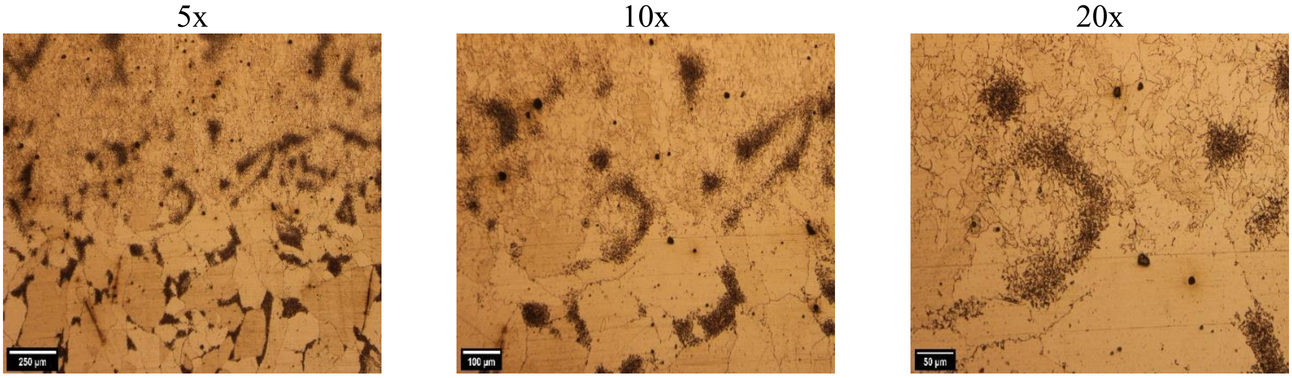


Figure 11. Optical microscopy images of the cross-section of sample D.

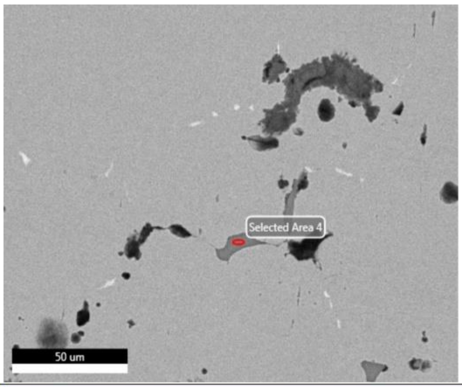
The electron microscope, a potent instrument for surface investigation, was utilized to evaluate the segregation and inclusions. Elaborate images of the imperfections were generated, accompanied by elemental analysis. The latest technology was used to inspect the surface of sample C thoroughly. The sample's surface in Figures 12 and 13 exhibits impurities and holes, which have been identified as oxides and sulfides using elemental analysis.

Additionally, the electron microscope was utilized to analyze the surface of sample D obtained from slab 02. Figures 14 and 15 depict the sample's surface, exhibiting impurities and shrinkage holes. Based on the elemental analysis of the impurities, which reveals the presence of sulfur, aluminum, oxygen, and manganese, it can be inferred that the impurities consist of both sulfide and alumina compounds.

Segregation is an intrinsic feature of the solidification process of steel. Typically, elements that are dissolved in a liquid have a more extraordinary ability to dissolve compared to when they are in a solid state. As a result, these elements tend to separate from the liquid and form a solid before the solidification process occurs. The presence of several elements in this substance might cause it to become stuck between the branches of growing dendrites, resulting in their segregation. The segregation of the material leads to a decrease in its strength and hardness, hence increasing the likelihood of the formation of bainite or martensite regions.

Understanding the factors influencing segregation in steel is crucial for our work. The chemical composition, high melting point, casting speed, secondary cooling, and various techniques to minimize segregation all play a significant role.

These techniques encompass the utilization of an electromagnetic stirrer, soft reduction (either mechanical or thermal), an optimal casting process (including casting speed), and the presence of high heat and cooling zones. Segregation diminishes with a rapid decrease in temperature. The solidification range and soft reduction automatically vary in response to changes in casting speed. Soft reduction technology is a technique used in the continuous casting of metals, particularly steel, to improve the quality of cast products by mitigating defects such as shrinkage holes and center segregation.



Element	*Weight %*	*Atomic %*
S K	*26.86*	*38.62*
MnK	*73.14*	*61.38*

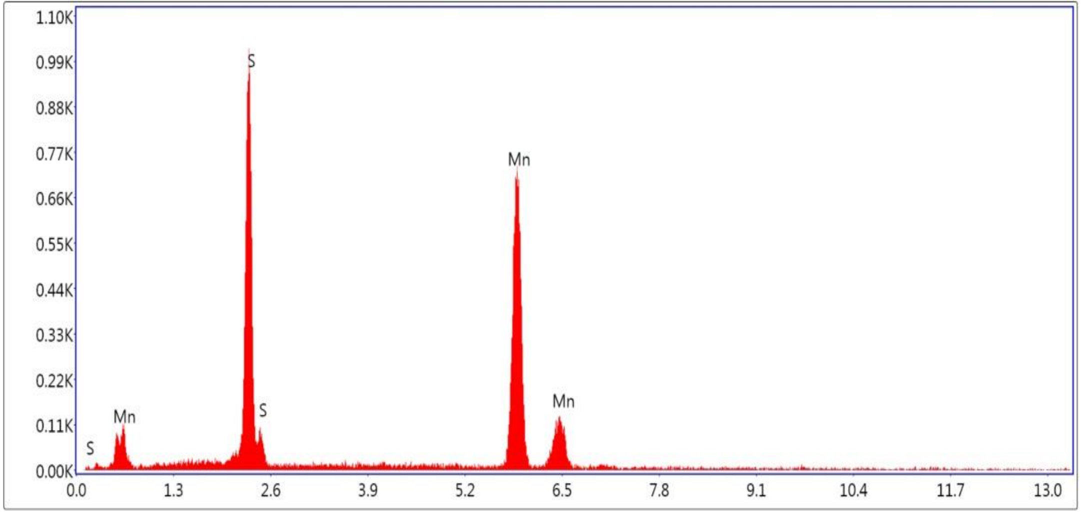
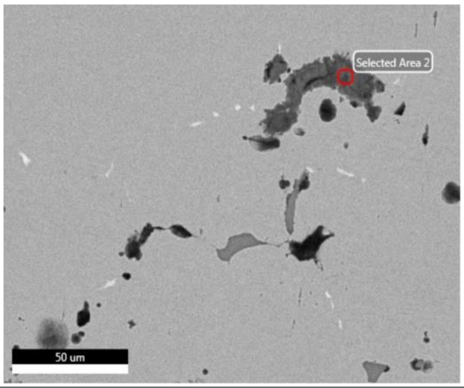


Figure 12. Electron microscope image and elemental analysis of impurity on the surface of sample C.



Element	*Weight %*	*Atomic %*
O K	*15.30*	*37.59*
AlK	*2.81*	*4.10*
CaK	*2.30*	*2.26*
MnK	*1.74*	*1.25*
FeK	*77.85*	*54.80*

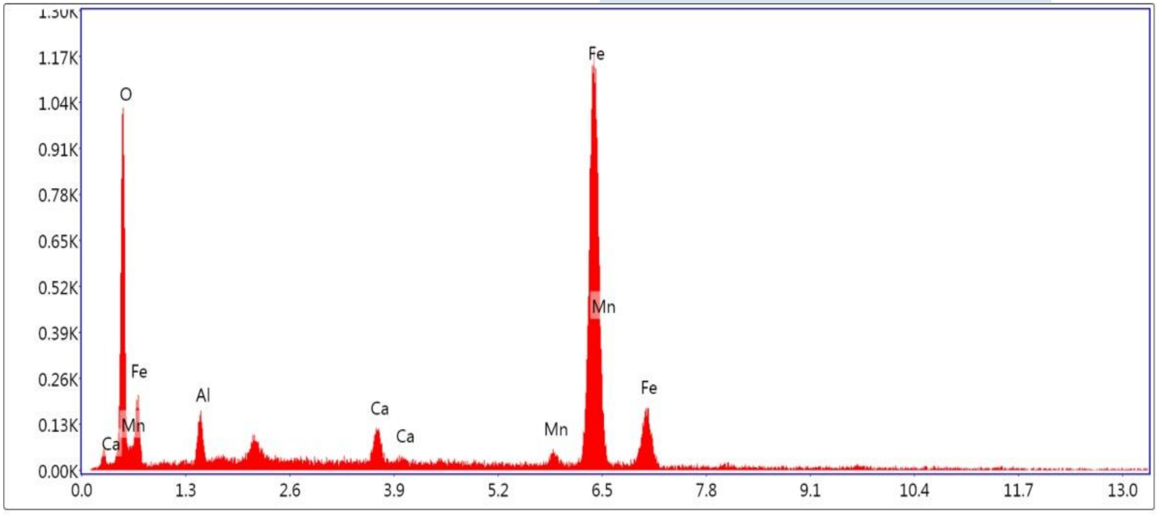
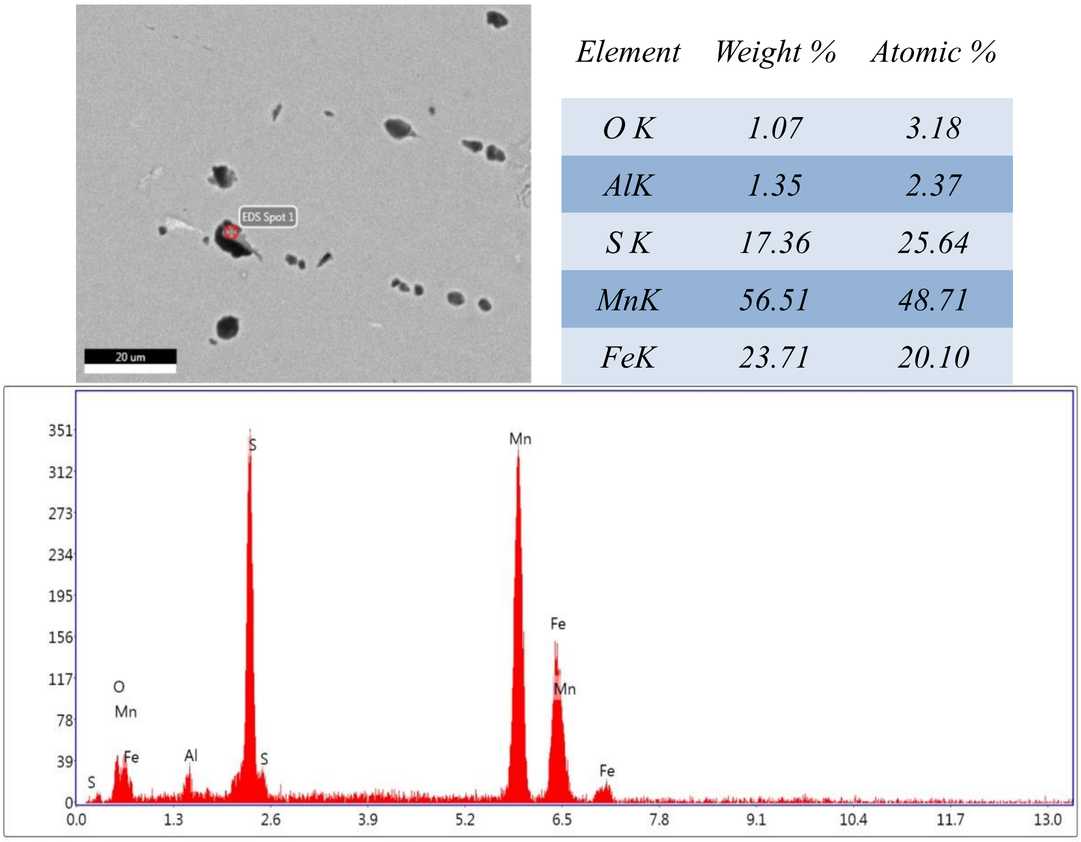
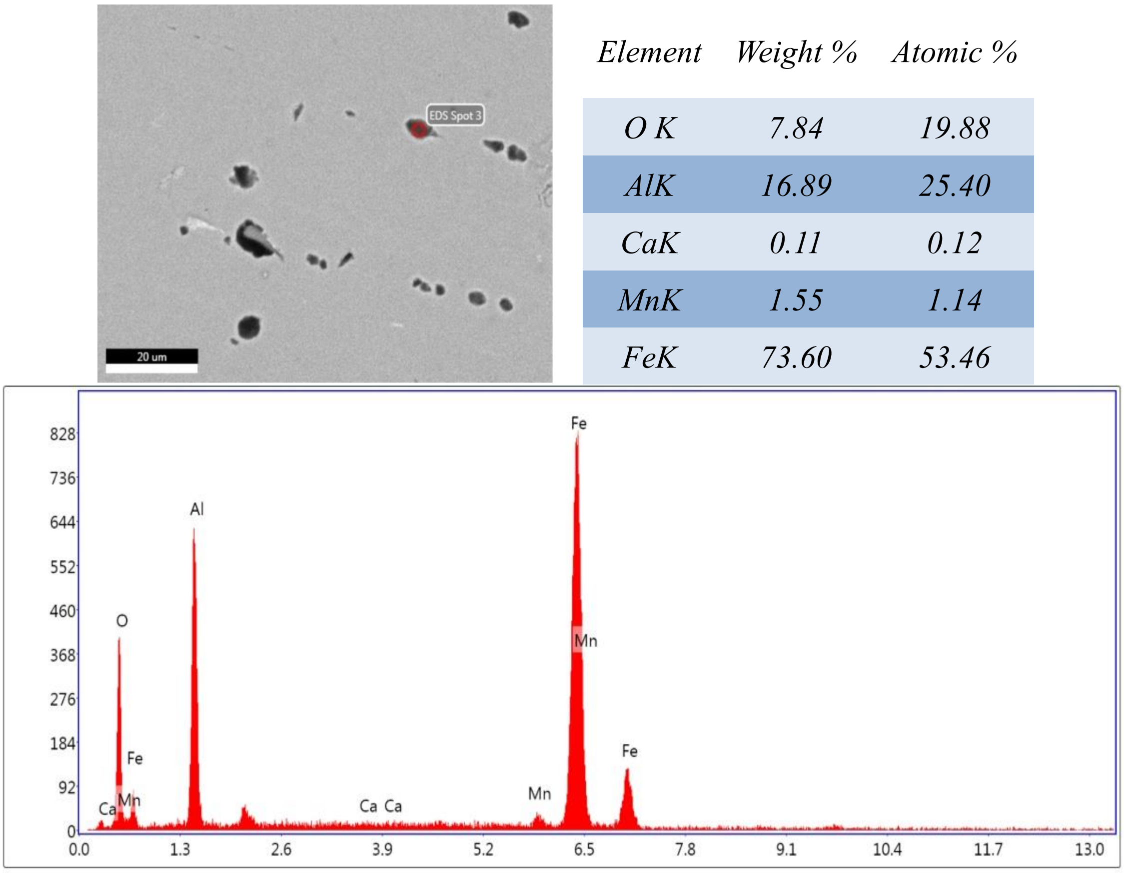


Figure 13. Electron microscopy image and elemental analysis of impurity in the sample C.



Element	Weight %	Atomic %
O K	1.07	3.18
AlK	1.35	2.37
S K	17.36	25.64
MnK	56.51	48.71
FeK	23.71	20.10

Figure 14. Electron microscopy image and elemental analysis of surface impurity of sample D.



Element	Weight %	Atomic %
O K	7.84	19.88
AlK	16.89	25.40
CaK	0.11	0.12
MnK	1.55	1.14
FeK	73.60	53.46

Figure 15. Electron microscopy image and elemental analysis of sample D.

This method involves applying controlled mechanical pressure to the partially solidified metal as it exits the mold, which helps to compact the material and reduce voids. Key parameters of soft reduction technology: timing of application, reduction amount, casting speed, thermal properties of the material, solid fraction, equipment control [5].

Shrinkage holes, a critical casting defect, have been the subject of considerable research. Understanding the causes of these voids is of utmost importance in our field. Most metals experience a reduction in volume during the solidification process, necessitating a way to offset this decrease. Shrinkage defects typically occur when there is insufficient molten material to compensate for the shrinkage that occurs during the liquid phase and solidification interval. The need for an appropriate and adequate feeding mechanism often causes this. The defects can be classified into two categories: feeding holes (also known as focused shrinkage) and shrinkage cracks (also known as diffuse shrinkage) [6,7]. This defect arises due to various variables, including the casting speed's fluctuation or instability, the cast steel's chemical composition, the product's shape and dimensions, the casting conditions, excessive heat of the melt, and excessive water content in the cold state. A secondary reason for failure is the inability to remove oxygen due to excessive gas content, the high viscosity of steel during solidification, the removal of molten metal from the mold during casting, or the completion of the casting process.

Shrinkage holes typically form in the thermal center of a part when the surface comes into contact with the mold wall or solidification media, disrupting the interaction between the internal melt and the surrounding air. In this scenario, a small amount of force is exerted within the liquid, forming a crust. One of the surface defects is the deformation of the top solid due to air pressure. Surface flaws typically occur in high-temperature discharge flow [5].

4. Conclusions

The findings of the inquiry into the origins of flaws in HSLA steel slabs, which are used to manufacture API X70 pipes, indicate:

1. The abundant presence of alumina in the sulfur print area, located in the center of the slab's thickness, in small sizes indicates the re-oxidation of the melt. This phenomenon significantly contributes to the production of the defect area.
2. The sulfide impurity indicates inadequate sulfide impurity shape and concentration regulation in the slab's central region during the later solidification phases.
3. The existence of shrinkage holes in the defect region suggests the necessity to enhance the Soft Reduction system.
4. This issue can be effectively managed by regulating the secondary cooling process, optimizing the intervals between the rollers in continuous casting, and maintaining complete control over the metallurgical length.
5. Controlling alumina impurities and optimizing the secondary cooling process are crucial steps to resolving segregation issues in High-Strength Low-Alloy (HSLA) steel slabs. Segregation can lead to non-uniform mechanical properties and defects, so it is important to address these issues effectively.

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