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Effect of Solution Treatment and Shot Peening Processes on the Mechanical Strength and Microstructure of Austenitic Manganese Steel for Rail Frognose Components

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Abstract

Wessel is a part of the railway track which functions as track switching. One of the components of Wessel, which is made through the casting process is called frognose. Frognose is the most critical component in the Wessel crossing, as it must withstand the impact load caused by the movement of train wheels. The production of frognose follows the EN 15689 standard and the Minister of Transportation Regulation of the Republic of Indonesia No. 60 of 2012. Austenitic manganese steel ASTM A 128 Grade C is chosen as the main material. This austenitic manganese steel has high-strain hardening properties when subjected to static, dynamic, and impact loads on its surface. In this study, a heat treatment process is used to improve the mechanical properties and carbide solubility of the casting results. Cooling the object from the casting process causes carbide growth which is caused by the cooling rate. Therefore, solution treatment is necessary to dissolve the carbides. The solution treatment process is carried out at various temperatures 1075ºC, 1150ºC, and 1225ºC. Subsequently, the optimized material from the solution treatment is subjected to shot peening deformation. Based on the research results, the solution treatment process at 1150ºC temperature shows the best toughness, thus it will be continued with the shot peening deformation process. The deformation caused by the shot peening process is able to change the crystal orientation by forming twinning, thereby increasing the material hardness value. The best mechanical properties are obtained in sample ST2 followed by the SP12 process with a combination of hardness value of 35 HRC at a depth of 0.05mm; impact energy of 82,92 joule/cm2 and mostly carbide-free microstructure.

Keywords: austenitic manganese steel, solution treatment, austenite, twin deformation

1. Introduction

The Frognose is one of the components switch rail that supports the movement of train wheels to switch tracks, typically made from casting materials. In its application, the Frognose must be able to withstand dynamic loads, compressive loads, and impact loads generated by the train wheels [1]. Therefore, a material with characteristics such as impact resistance, wear resistance, strength, and good toughness is needed for metal-to-metal contact applications.

The manufacturing process of the Frognose mostly uses austenitic manganese steel, where the running surface's strength is enhanced through explosive hardening. Explosive hardening is a strain hardening mechanism used to increase the hardness of austenitic manganese steel. This technique is commonly employed due to its ease of operation, high efficiency, and effective strengthening effect on austenitic manganese steel materials. However, it requires a very difficult permit, taking into account safety, location, and chemical used. The hardening mechanism of austenitic manganese steel through explosive hardening involves twin and dislocation formation [1] [2]. The workability of austenitic manganese steel is achieved by solution treatment. Solution treatment is used to dissolve carbides and create a homogenous austenitic structure by heating the material above 1000°C, followed by rapid cooling using water quenching. The presence of austenitic microstructure in manganese steel improves toughness, but even after solution treatment, there remains a small number of carbides at grain boundaries and within grains. Carbide solubility is influenced by factors such as austenitization temperature, heating rate, and cooling rate [3] [4].

According to the EN 15689 standard, the hardness requirement for Frognose should not be less than 34 HRC. However, achieving this hardness value solely through solution treatment can be difficult. In this research, the austenitic microstructure with minor carbide presence resulted in a maximum hardness value of 23.16 HRC at a temperature of 1075°C. The austenitic phase in austenitic manganese steel can be stable at room temperature, while the austenite-to-martensite transformation occurs when the temperature drops below the Ms line, which is below -195°C. The austenite-martensite phase transformation in austenitic manganese steel can be induced by applying deformation, which increases the driving force energy for transformation above the Martensite start temperature [5] [6].

Shot peening is carried out by applying impact loads using steel shots under pressure, with the goal of achieving optimal hardness without explosive processes. The impact loads from shot peening can transform the stable austenitic condition into a metastable due to deformation. Mechanical twinning and the austenite-martensite transformation are types of deformation that can occur in austenitic manganese steel [5]. Analysis of process parameters such as solution treatment and mechanical treatment like shot peening is used to determine its effect on mechanical properties and microstructure.

2. Methods

i. The manufacturing process of manganese steel was carried out at PT. PINDAD consists of molding and melting process. Furane as molding and Induction Furnace Medium Frequency 2000 Kg of capacity as a furnace for melting manganese steel. Design drawing and mold pattern are the first steps in specimen fabrication. The mold pattern is then progressed to the molding process through a furan binder-based process. After the mold is ready, the melting process is carried out where steel and its alloys are melted in a 2000 Kg capacity induction furnace, and temperature holding is performed within the temperature range of 1500 - 1550°. Subsequently, the liquid metal undergoes inspection using an OES machine, referring to the specifications of ASTM A 128 Grade C and the technical data of the specimen that govern both process and product requirements. If the material composition meets the requirements, the tapping process is carried out by transferring the liquid metal from the furnace into the ladle within the temperature range of 1480 - 1500ºC. Subsequently, the pouring continues into the mold within the temperature range of 1420 - 1470°C. The processing temperature of the austenitic manganese steel material must not be excessively high due to its impact on cracking and the size of austenite grains during cooling inside the mold. Furthermore, sand from the cast objects using a shakeout machine, and the process continues to the shot blasting process to clean cast objects from adhered silica sand. Finally, the finishing process is carried out to separate the cast object from the gating system.

ii. A solution treatment process is carried out at an austenitizing temperature, with a holding time of 1-2 hours per 25.4 mm thickness. Specimens in as-cast condition undergo solution treatment with varied temperatures, and then they are immersed in agitated water as shown in the graph depicted in Figure 1. In this study, variations in heat treatment are carried out to determine the most optimal solution treatment temperature, which is related to carbide solubility, toughness, and hardness. However, good toughness will lead to a decrease in hardness value. Therefore, work hardening is conducted in this research to optimally increase the hardness value. Plastic deformation in the form of shot peening is applied to the surface of specimens resulting from solution treatment with time variations of 4, 8, and 12 seconds.

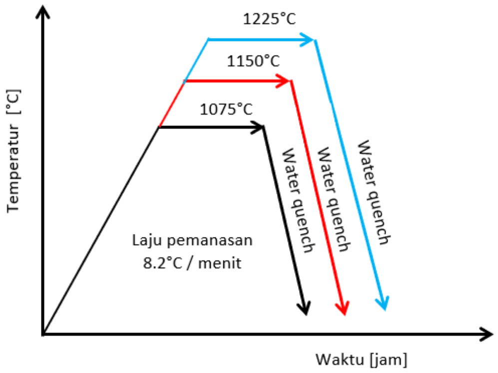

Figure 1: Solution Treatment Temperature

iii. Chemical composition testing is performed using the Optical Emission Spectrometry machine - Bruker Q4 Tasman. OES is an instrument that can measure the percentage of elements by applying electrical sparks to the metal surface, causing optical radiation with a very specific frequency, thereby generating data in the form of the percentage composition of its elements.

iv. Hardness testing is carried out using two methods: surface hardness testing for specimens resulting from solution treatment, and microhardness testing for specimens after the shot peening process. Surface hardness testing employs the Hardness Rockwell C (HRC) method using the Rockwell Hardness Testing Machine - Zwick Roell ZHR, following the ASTM E18 testing standard. Surface hardness testing is performed using a 120° diamond spheroconical indentation with a load of 150 kgf and an indentation time of 10 - 15 seconds. On the other hand, the microhardness testing machine uses the Micro Vickers Hardness Testing Machine - Zwick Roell, following the ASTM E92 testing standard. The microhardness testing employs a pyramid diamond indenter and a load of 0.5 gf. The tested surface is a result of EDM cutting. Micro hardness testing is conducted using the Digital Microhardness Vickers - Zwick Roell, referring to the ASTM E92 testing standard. The measurement process uses an indentation load of 200 grams for 10 - 15 seconds. Micro hardness testing is performed on specimens subjected to shot peening treatment, initially spaced at 0.05 mm and subsequently spaced at 0.1 mm for subsequent testing.

v. Impact testing is conducted using an Impact Testing Machine (Charpy) - Shimadzu. The testing procedure and the dimensions of the test specimens adhere to the ASTM E23 standard. The test specimens used have dimensions of 55 mm x 10 mm x 10 mm and feature a V-notch radius of 0.25 mm with a depth of 2 mm.

vi. Metallographic testing on austenitic manganese steel specimens is performed using a Light Optical Microscope - Nikon MA100N. Metallographic testing is used to observe phase changes before and after solution treatment, as well as phase changes on the surface after undergoing the shot peening process. These phase changes are closely related to alterations in the mechanical properties of the material. Sample preparation involves cutting the specimen, mounting it with resin, followed by grinding using sandpaper (grits 60, 180, 320, 600, 800, and 1500), polishing with alumina, and finally etching using aqua regia (HNO3, HCl, and water in a ratio of 3:1:2).

vii. The specimen consists of four codes, namely:
ST1: Solution treatment at temperature 1075°C.
ST2: Solution treatment at temperature 1150°C.
ST3: Solution treatment at temperature 1225°C.
SP4: Solution treatment – shot peening in 4 seconds.

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SP8: Solution treatment – shot peening in 8 seconds.
SP12: Solution treatment – shot peening in 12 seconds.

3. Result and discussion

3.1 Chemical composition

The following is the data obtained from the testing and analysis of the chemical composition of austenitic manganese steel using Optical Emission Spectroscopy (OES), along with its comparison to the standard composition of ASTM A 128 Grade C.

Table 1: The standard composition of ASTM A 128 Grade C material with chemical composition examination using OES.

Element	**OES Inspection (%)**	
	Specimen	**ASTM A 128 *Grade* C**
C	1.05	1.05 – 1.35
Mn	11.81	11.5 – 14.00
Cr	2.01	1.50 – 2.50
Si	0.47	1.00 max
S	-	-
P	0.09	0.07 max
Ni	0.08	-
Mo	0.03	-
V	0.01	-
Cu	0.05	-
Sn	-	-
Al	0.08	-
Fe	84.30	Bal

Based on Table I, the data from the chemical composition testing of the austenitic manganese steel specimen reveals that elements C, Mn, Cr, and Si are within the composition range of ASTM A 128 Grade C. However, the element Phosphorus exceeds the standard range of ASTM A 128 Grade C. The manufacturing process of ASTM A 128 Grade C involves steel ingots, automotive steel scrap, and other additive materials. Therefore, the presence of phosphorus exceeding the standard composition range originates from processes involving materials and their alloys.

3.2 Hardness Testing

Hardness testing was performed on specimens before solution treatment, after solution treatment, and after shot peening. According to Figure 2, the hardness of austenitic manganese steel in as-cast condition is the highest value, which is 41.63 HRC. This high hardness value resulted from slow cooling processes within the mold, causing carbides at grain boundaries and within the austenitic matrix. Additionally, the elements C, Mn, and Cr also contribute to carbide formation in austenitic manganese steel. Carbides in austenitic manganese steel form when the carbon composition exceeds 1.0% [7] Subsequently, the as-cast test samples were subjected to solution treatment at temperatures ST1, ST2, and ST3. All specimens that underwent solution treatment with varying temperatures exhibited decreased hardness values accompanied by austenite grain growth. Higher solution treatment temperatures reduced hardness values [8][9]. The most significant reduction in hardness occurred in the ST3 specimen, experiencing a decrease of up to 251% compared to the as-cast condition. A hardness decreases of 5.85% was observed from the ST1 to ST2 specimens, while the hardness of the ST2 to ST3 specimens decreased about 84.48%.

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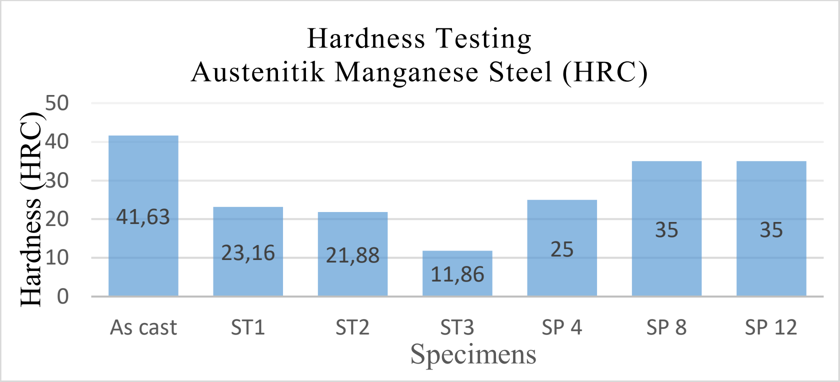


Figure 2: Hardness values of austenitic manganese steel before and after solution treatment with varying temperatures

Specimens with codes SP4, SP8, and SP12 are austenitic manganese steel specimens that underwent solution treatment at a temperature of 1150°C, followed by surface shot peening with varying durations of 4, 8, and 12 seconds. According to Figure 2, the shot peening test specimens increased in hardness compared to the solution treatment condition. A hardness increases of 14.25% from the ST2 condition occurred in the specimen treated with shot peening for 4 seconds. Meanwhile, the SP8 and SP12 conditions showed a hardness increase of 59.96% from the ST2 condition.

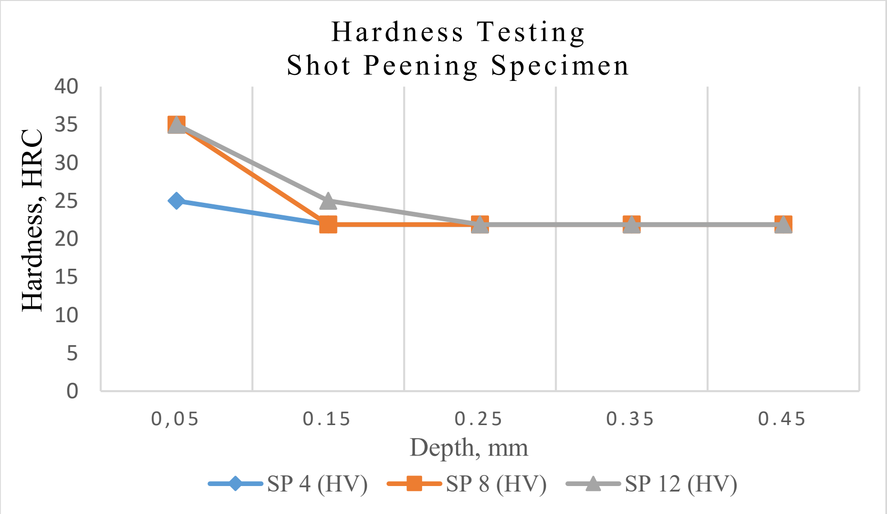


Figure 3: Effect of shot peening time on the depth of hardness.

Based on Figures 2 and 3, the shot peening method is capable of increasing not only hardness but also the depth of hardening, where a longer shot peening duration leads to higher hardness values and greater hardening depths [10]. The maximum surface hardness value obtained from the shot peening method is 35 HRC at a depth of 0.05 mm with shot peening durations of 8 and 12 seconds. Meanwhile, the optimal hardness and hardening depth values are achieved by the shot peening specimen with a duration of 12 seconds. In this case, the optimal surface hardness is 35 HRC, with a hardening depth of 0.05 mm, and it decreases by 40% at 0.15 mm. The significant increase in hardness observed in specimens treated with shot peening is attributed to the formation of twins, leading to strain hardening [8]. The twin phenomenon is a result of repeated force from steel shots, causing dislocation multiplication that refines the grain structure at the surface, thereby enhancing surface hardness [10].

3.1. Impact Testing

Toughness is the ability of a material to absorb energy without fracturing or breaking [10]. Impact testing was conducted on austenitic manganese steel test samples before and after solution treatment with variations in austenitization temperatures. According to Figure 4, the solution treatment process enhances the toughness value. A significant increase in impact value of 130.2 joules/cm2 occurred when the as-cast specimen underwent solution treatment at temperature ST1. This significant increase is attributed to the dissolution of carbides into the austenitic matrix. The highest impact value of 136.75 joules/cm2 was obtained at the ST2, representing a 2.1% increase from ST1. However, the impact value would decrease by 186% if the solution treatment condition was increased from ST2 to ST3. The decrease in impact value is due to the increased growth of austenite grains and the thinning of grain boundaries, resulting in a smaller work-hardening exponent [11].

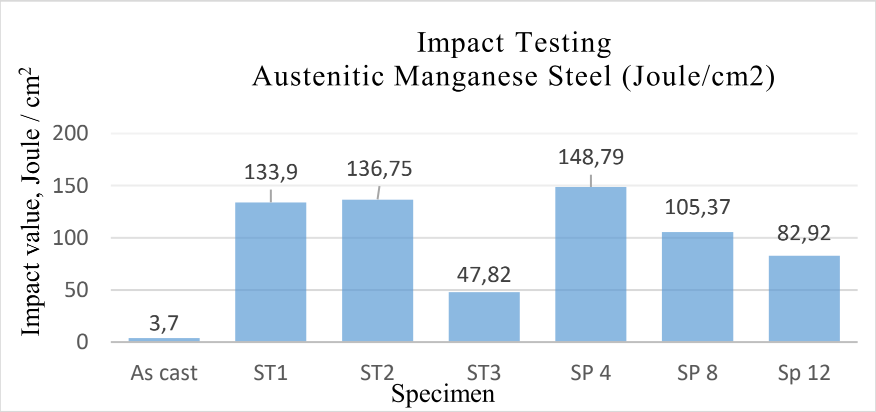


Figure 4: Impact value of austenitic manganese steel

The average impact values of the test specimens after shot peening indicate that the SP4 test specimen exhibits the highest toughness value at 148.79 joules/cm2. Subsequently, the toughness decreases by about 41% in the SP8 specimen and further decreases by 27% in the SP12 specimen. The reduction in impact values in the specimens after shot peening corresponds to increasing shot peening duration. Additionally, hardness values play a crucial role, as an increase in hardness values leads to a decrease in toughness, as shown in Figure 4.

3.2 Metallography Testing

Metallographic testing was conducted to observe the microstructure of austenitic manganese steel using an optical microscope. Figure 5 shows the microstructure before and after the solution treatment. The microstructure consists of an austenitic matrix and carbides $(Fe\ Mn)_3C$ dispersed at grain boundaries or within the matrix. In the as-cast sample, as shown in Figure 5a, carbides are formed almost throughout the observed area and extend continuously along the grain boundaries. These carbides are complex carbides that precipitate at the grain boundaries.

Figure 5 presents qualitative observations on samples subjected to various temperature solution treatments, labeled as ST1, ST2, and ST3. It can be seen as a fully austenitic microstructure with minor carbides within both the matrix and grain boundaries. The solubility of carbides in the austenitic matrix indicates that solution treatment processes above 1000°C are capable of dissolving carbides. Additionally, the temperature of the solution treatment also affects the size of the austenitic grains. Higher solution treatment temperatures lead to larger austenitic grains, and as the grain size of austenite increases, the grain boundaries become thinner.

There are two types of carbides formed through the solution treatment process in austenitic manganese steel: $(Fe, Mn)_3C$ and $(Fe, Mn, Cr)_3C$. The formation of $(Fe, Mn)_3C$ carbides is due to austenite's inability to retain carbon within the γ solid solution, whereas $(Fe, Mn, Cr)_3C$ carbides form due to the addition of chromium, which substitutes for iron and manganese. The addition of chromium above 1.05% increases the amount of $(Fe, Mn, Cr)_3C$ carbides in specimens treated solution treatment. Therefore, the chromium content of 2.01%, as indicated in Table 1, causes dispersed carbides within the austenitic matrix and at grain boundaries.

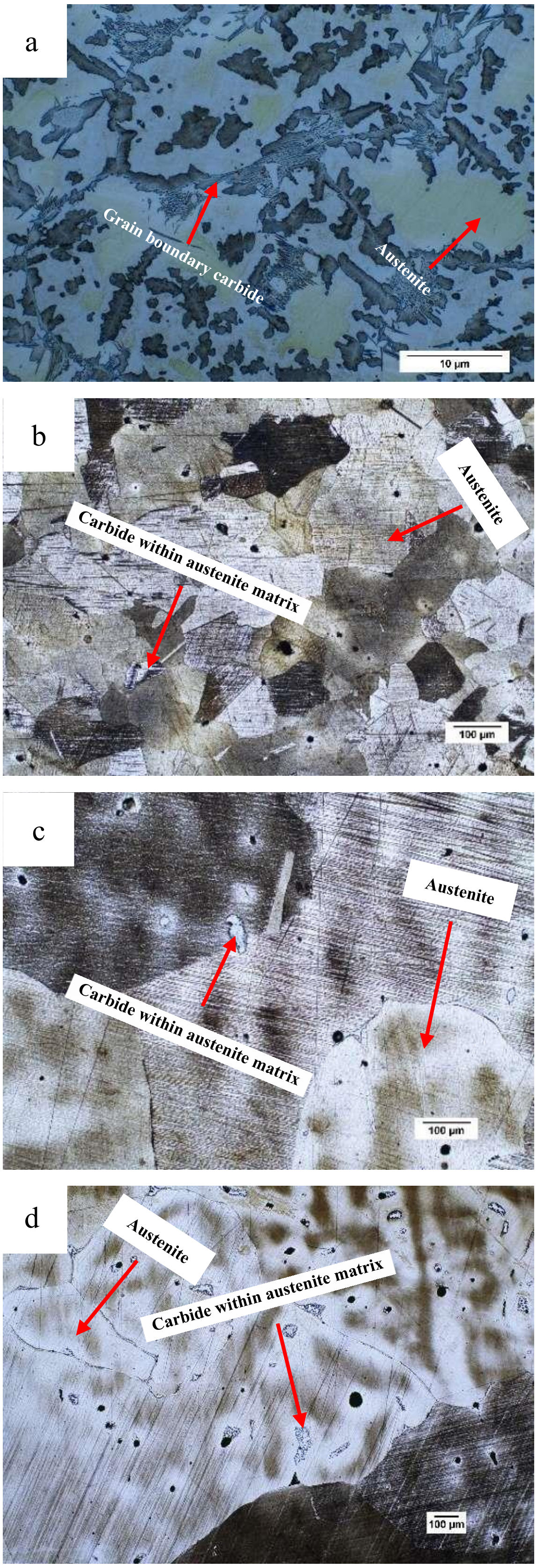


Figure 5: Optical microstructure: (a) as cast; (b) ST1; (c) ST2; (d) ST

Figure IV.5 shows the microstructure of shot peening SP4, SP8, and SP12, which have lines with specific inclinations and parallel to each other with different orientations. These lines are located within or intersect grain boundaries of austenite with varying densities. The parallel lines represent a twinning phenomenon caused by the shear mechanism within crystal planes due to plastic deformation during the shot peening process. This loading results in dislocation multiplication, leading to grain refinement, thus acting as a barrier dislocation movement and enhancing the strain hardening rate. As the strain rate increases, the surface hardness value will also increase [12].

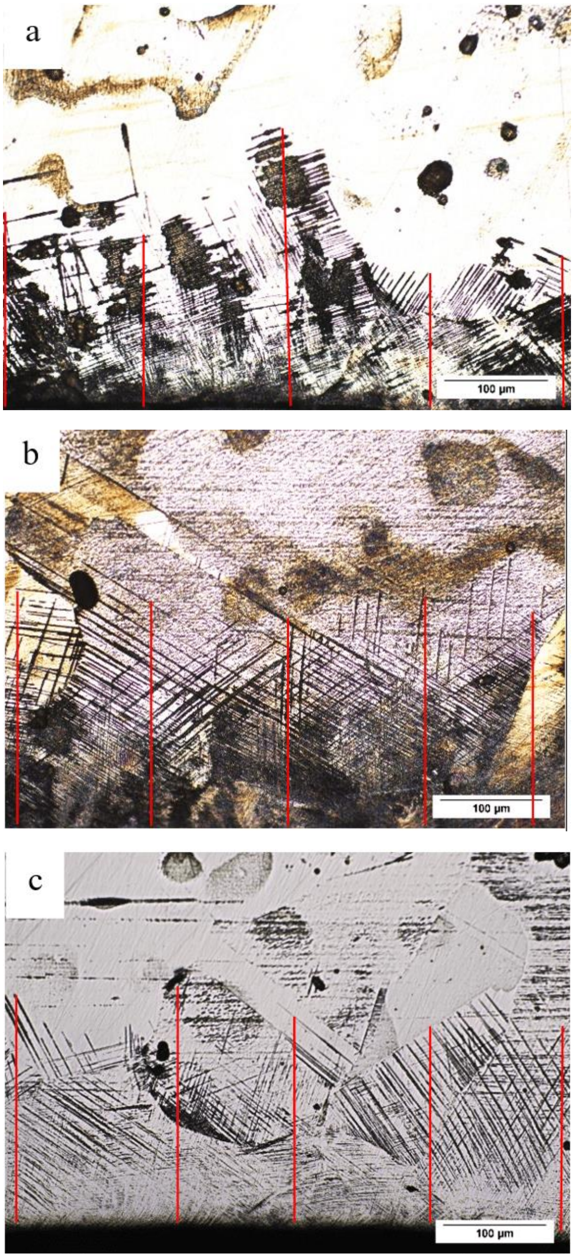


Figure 6: Optical microstructure: (a) SP4; (b) SP8; (c) SP12

Table 2: Table of shot peening specimen hardening depths (mm).

Shot peening hardening depth (mm)						
Specimens	Number of tests					Average
	1	2	3	4	5	
SP4	0.183	0.168	0.272	0.126	0.148	0.179
SP8	0.237	0.227	0.218	0.227	0.215	0.225
SP12	0.219	0.247	0.216	0.236	0.223	0.228

Figure 6a shows the microstructure resulting from 4 seconds of shot peening, it can be seen twinning deformation lines within and across grain boundaries. Based on Table 2, empirical calculations were performed by comparing the depth of hardening to the scale used. Specimens labeled as SP4, as shown in Figure 6a, have an average hardening depth of 0.179 mm. Specimens labeled as SP8, as shown in Figure 6b, have an average hardening depth of 0.225 mm, and specimens labeled as SP12, as shown in Figure 6c, have an average hardening depth of 0.228 mm.

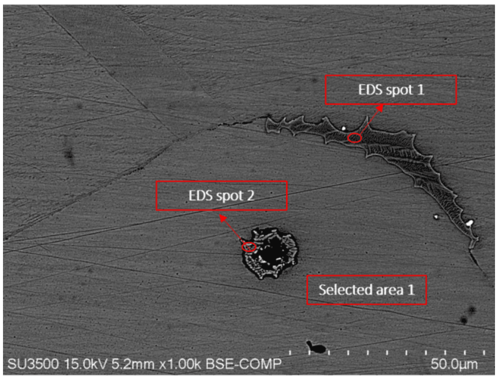
3.3 SEM EDS Testing

SEM-EDS testing of the microstructure and chemical composition of the material using the spot analysis method. SEM-EDS testing allows for the prediction of the presence of carbides in the ST2 specimen. Figure 7 displays the microstructure and the spectrum of the test results at the grain boundaries and austenitic matrix, while Table 3 presents the chemical composition analysis corresponding to the EDS spot areas.

EDS spot 1 was taken at the lamellar-shaped grain boundary. This area is dominated by elements C, Cr, Mn, and P. EDS spot 2 was taken within the round-shaped austenitic matrix, and this area is dominated by elements C, Cr, Mn, and P. The presence of phosphorus in both EDS spot 1 and EDS spot 2 comes from steel scrap. Based on the composition, it is predicted that both EDS spot 1 and EDS spot 2 are (Fe, Mn, Cr)$_3$C carbide type. The ((Fe, Mn, Cr)$_3$C) carbide is a type of carbide formed due to the addition of chromium, thus initiating the formation of alloyed cementite within the austenitic matrix. These carbides within the austenitic matrix are harder compared to the matrix itself [3].

The selected area is taken within the austenitic matrix, and this area is dominated by elements C, Mn, and Cr. In selected area 1, there is no presence of carbides. However, the presence of chromium in selected area 1 indicates that chromium is soluble within the austenitic matrix. The dominant presence of the austenitic matrix is closely related to the manganese content, that stable with a manganese content up to 20% after the quenching process [13].

Characterization SEM-EDS using the Backscattered Electrons (BSE) method with a voltage of 15 kV, allowing electrons to penetrate into the sample up to millimeter orders. Hence, certain impurity elements like F, P, and O can be detected even though their presence is outside the designated spot area.



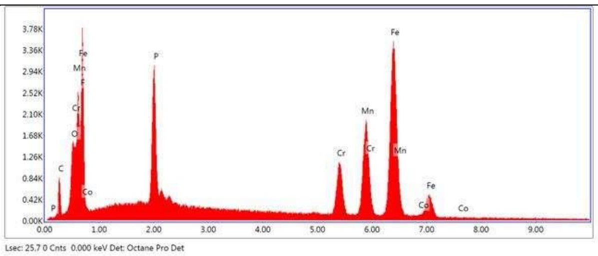
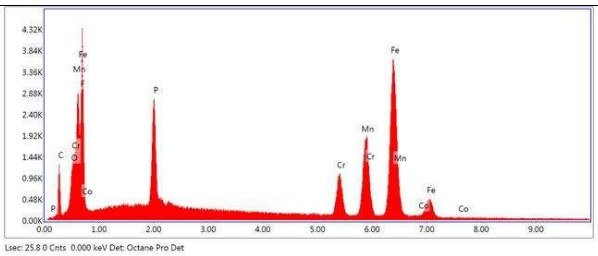
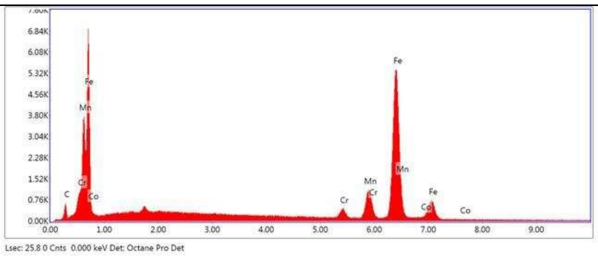
EDS Spot 1	
EDS Spot 2	
Selected area 1	

Figure 7: SEM EDS testing of specimen ST1

Table 3: Chemical composition analysis of the EDS test results

Elements	**EDS Spot 1**		**EDS Spot 2**		**Selected Area 1**	
	Weight %	**Atom %**	**Weight %**	**Atom %**	**Weight %**	**Atom %**
C	6.40	21.24	8.55	27.19	4.82	19.01
O	2.22	5.53	1.79	4.29	-	-
F	2.69	5.65	2.75	5.54	-	-
P	6.30	8.11	5.50	6.78	-	-
Cr	8.25	6.33	7.00	5.14	2.17	1.98
Mn	20.59	14.95	20.27	14.09	11.17	9.64
Fe	52.14	37.24	52.49	35.91	79.00	67.08
Co	1.42	0.96	1.64	1.06	2.85	2.29
Total	100	100	100	100	100	100

Conclusion

Based on the collected data and analysis conducted, the following conclusions are drawn:

1. The solution treatment process applied to the as-cast material at temperatures ST1, ST2, and ST3 effectively dissolved the lamellar carbides within the austenitic matrix. Optimum hardness was achieved through the ST1 process, resulting in a value of 23.16 HRC. On the other hand, the best toughness was obtained from the ST2 specimen with a value of 136.75 joules/cm².
2. The shot peening mechanism can enhance the optimal hardness on the surface of the SP2 specimen subjected to shot peening deformation for 12 seconds (SP12), reaching a value of 35 HRC down to a depth of 0.05 mm from the surface. The SP12 specimen exhibits an impact value of 82.92 joules/cm², decreasing by 64.91% from the ST2 condition. The increase in hardness value is influenced by the twinning mechanism, whereas the high hardness value leads to a reduction in impact value.
3. In this study, the microstructure, surface hardness, and chemical composition meet the requirements of the EN 15689 standard. However, the subsurface hardness at a depth of 5 mm has not been met.

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