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Effect of Filler Metal Selection on Microstructure and Hardness of MIL-DTL 46100E Armor Steel Welded by Gas Metal Arc Welding (GMAW)

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ABSTRACT

Welding is one of the manufacturing processes widely used in engineering fields such as vehicles, bridges, and others, including in the construction of combat vehicles (military) that have special materials with high hardness (Armor Steel). This study examines the effect of filler type on the welding process on the microstructure and hardness of MIL-DTL 46100E Armor Steel using the Gas Metal Arc Welding (GMAW) method. The fillers used were ER-110, ER-307, and ER-70S. The tests were carried out using metallographic analysis to study microstructural changes in the Weld Metal (WM) and HAZ areas and Vickers hardness testing. Macro testing results showed that the ER-307 filler produced a wider weld zone, while ER-70S produced a narrower weld zone. Microstructure testing revealed that ER-307 produced a finer and more stable structure, with a predominance of pearlite and ferrite phases in the Weld Metal and martensite in the HAZ. Hardness test results show that ER-307 has the highest hardness in the WM area at 411.9 HV and in the HAZ (501.6 HV), followed by the lowest hardness produced by the ER-70S filler at 297.5 HV and an HAZ value of 500 HV. Overall, ER-307 demonstrated the best performance for welding MIL-DTL 46100E steel, with stable hardness and optimal microstructure throughout the weld zone. This study provides guidance in selecting filler for welding armor steel, which can be applied to the development of combat vehicle technology.

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1. INTRODUCTION

Advances in defense technology require materials with superior mechanical properties, especially in the manufacture of combat vehicles such as tanks (Norrrahim et al., 2021; Sadhukhan et al., 2023; Shubham & Ray, 2024). MIL-DTL 46100E armor steel, with its high hardness, is widely used to protect combat vehicles from the impact of gunfire (Göde et al., 2023; Souza et al., 2021). Welding is one of the main techniques in the fabrication of combat vehicle components, with Gas Metal Arc Welding (GMAW) often chosen for its speed, clean welds, and ability to weld hard materials such as armor steel (Hawkes, 2021; Magudeeswaran et al., 2018; Son et al., 2023).

GMAW involves a wire electrode that melts and mixes with the base metal, with a shielding gas that prevents atmospheric contamination. The main advantage of GMAW is its ability to produce strong and clean joints in a short time (Hariprasath et al., 2022). However, the effect of filler selection on weld joint quality, particularly in high-hardness steels such as MIL-DTL 46100E, has not been widely discussed in the literature (Pacek et al., 2020; Su et al., 2021).

Most existing studies have focused more on the welding process on ordinary carbon steel or lower hardness steel, while applications on armor steel with MIL-DTL 46100E specifications are still limited (Nagentrau et al., 2019; Odebiyi et al., 2019).

Research related to filler selection in armor steel welding has focused more on other welding parameters, such as current or welding speed, while the effect of various fillers on the microstructure and hardness of welded joints in armor steel has not received sufficient attention (Fei et al., 2019; Morsy et al., 2022). Welding fillers such as ER-110, ER-307, and ER-70S are often used in the defense industry, but a comprehensive comparison of their effects on the microstructure and hardness of armor steel has not been widely studied (Cheng et al., 2022; Günen et al., 2020; Souza et al., 2021).

This study aims to explore the effect of welding filler selection (ER-110, ER-307, and ER-70S) on the microstructure and hardness of MIL-DTL 46100E steel welded using GMAW. The main focus of this study is to identify the effect of filler type on the microstructure and hardness in the weld, HAZ, and base material. This research will make a significant contribution and enrich the understanding of the influence of filler composition on weld joint quality, especially in high-strength steel, thereby providing recommendations for more efficient welding of armor steel.

2. RESEARCH METHOD

This study uses a quantitative approach with an experimental design involving statistical analysis to test the effect of filler on MIL-DTL 46100E steel welding using the Gas Metal Arc Welding (GMAW) method (Hawkes, 2021; Souza et al., 2021). The independent variables in this study were the types of welding filler wire (ER-110, ER-307, and ER-70S), while the dependent variables were the quality of the welded joints, which were analyzed through microstructure and hardness. The control variables applied were the steel material used, the type of welding, the welding speed, and the heat input.

The welding process was carried out using a controlled GMAW welding machine to produce consistent welding parameters, such as welding current, voltage, and wire speed. The electric current used was 236 amperes with an electric voltage of 26.2 volts. The filler types used were ER-110, ER-307, and ER-70S. The shielding gas in the welding process uses a mixture of argon and carbon dioxide (CO2) with a ratio adjusted for each filler to optimize the welding results and minimize oxidation (Farnsworth, 2021).

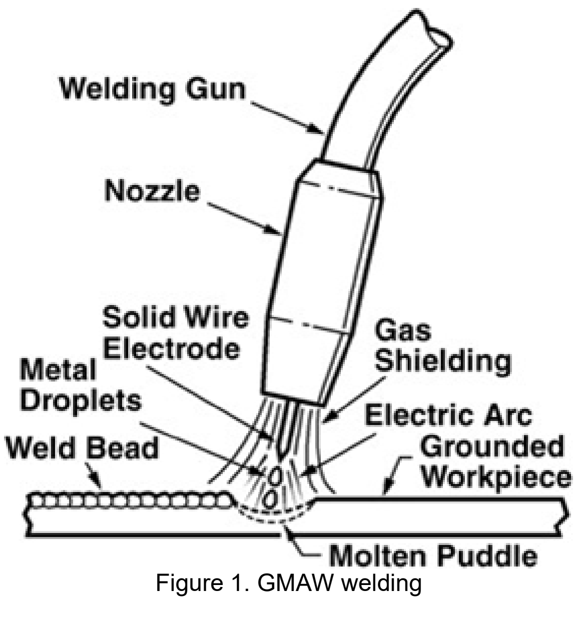

Figure 1. GMAW welding

Welding tests conducted include Metallographic Testing, namely macro and micro observations conducted to observe the phase structure formed in the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) areas. Hardness testing was conducted using a Vickers Hardness Tester applied to several points in the base material, HAZ, and weld metal areas. The test results will obtain average values in the three test areas to assess the effect of filler type on hardness in each zone.

Table 1. Chemical Composition MIL-DTL-46100

C	Mn	P	S	Si	Ni	Cr	Mo
0,32	1	0,02	0,005	0,6	0,6	0,7	0,3

Table 2. Mechanical Properties MIL-DTL-46100

σu	σy	ε	BHN
240 KSI	190 KSI	10%	477-534

Table 3. Chemical Composition ER110

C	Mn	Si	Ni	Cr	Mo
0,089	1,54	0,53	1,23	0,26	0,24

Source: (ESAB, 2014)

Table 4. Chemical Composition ER307

C	Mn	Si	Ni	Cr	Mo	Cu
0,08	7	0,9	8,1	18,7	0,2	0,1

Source: (ESAB, 2014)

Table 5. Chemical Composition ER70S

C	Mn	Si	Ni	Cr	Mo
0,089	1,54	0,53	1,23	0,26	0,24

Source: (ESAB, 2014)

3. RESULTS AND DISCUSSIONS

Macroscopic testing/observation showed differences in the width of the weld zone/area between the three types of filler used. The ER-307 filler had the largest weld cross-section compared to the ER-110 and ER-70S fillers. This difference reflects the magnitude of heat influence during the welding process..

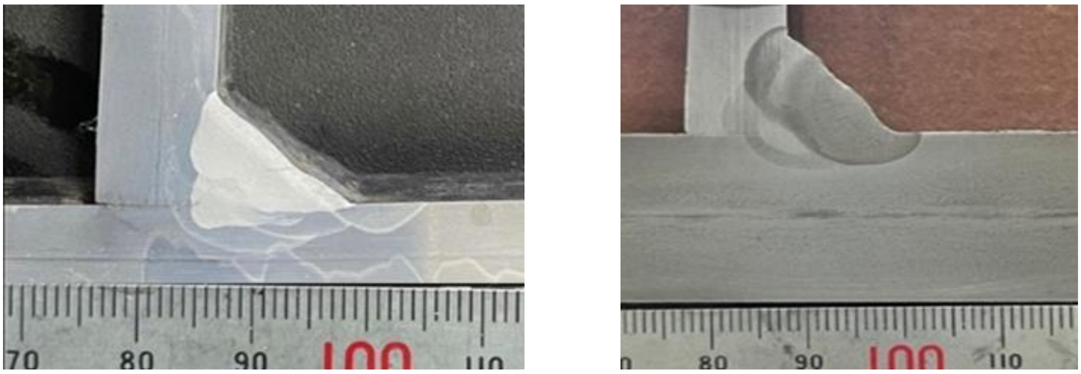

Figure 2. GMAW welding using a T-Join

Micro test results show significant differences in the phase structure formed in each filler. In the ER-110 filler, the microstructure in the Base Metal (BM) is dominated by the ferrite phase, while in the Weld Metal (WM) a ferrite and bainite structure is formed, known as dual phase steel. In the Heat Affected Zone (HAZ), martensite phase dominates due to high heating during welding..

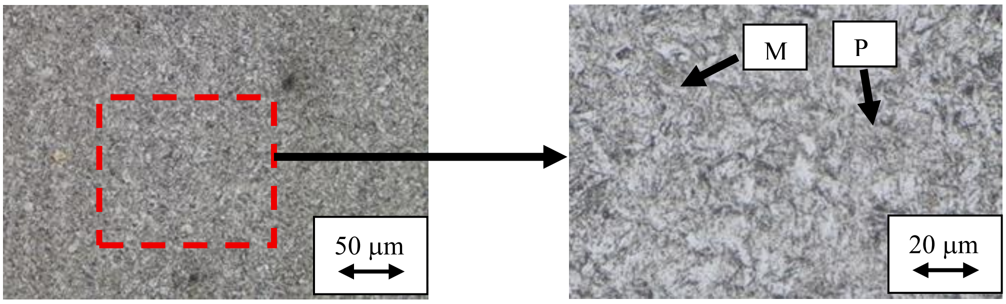

Figure 3. Microstructure of MIL-DTL-46100 Base Material

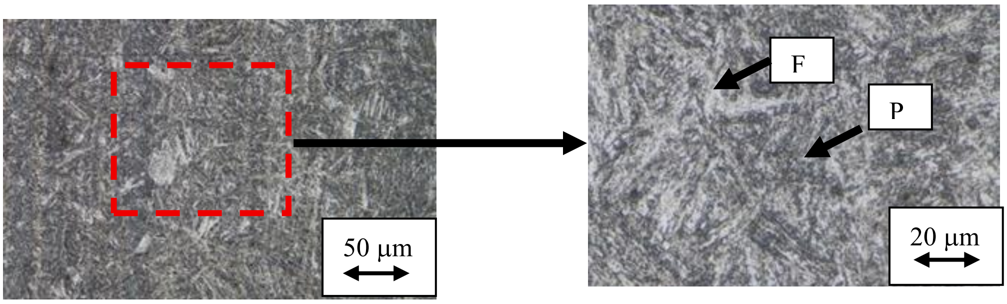

Figure 4. Microstructure of ER110 Filler HAZ

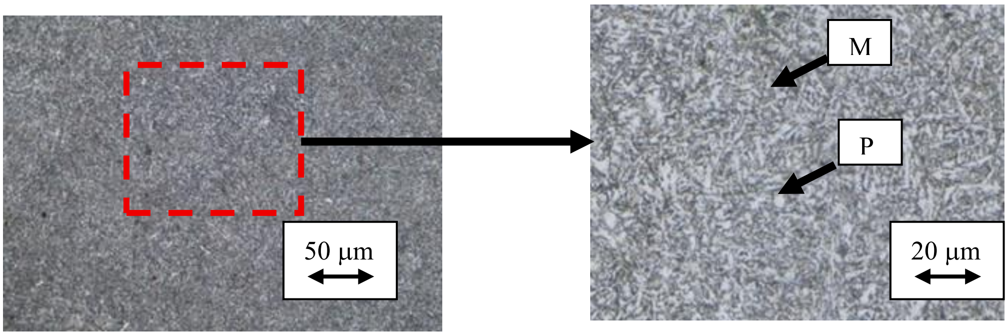

Figure 5. Microstructure of ER110 Filler Metal

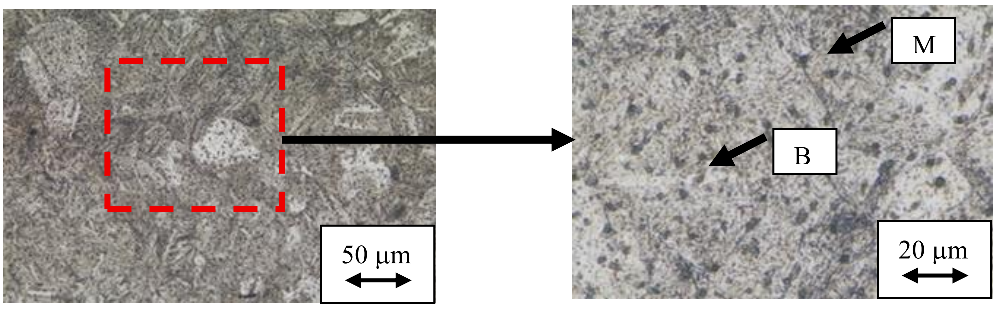

Figure 6. Microstructure of ER307 Filler HAZ

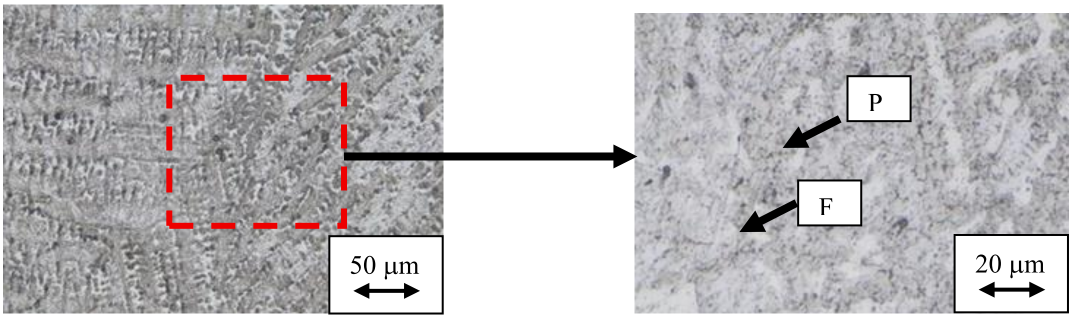

Figure 7. Microstructure of ER307 filler metal weld

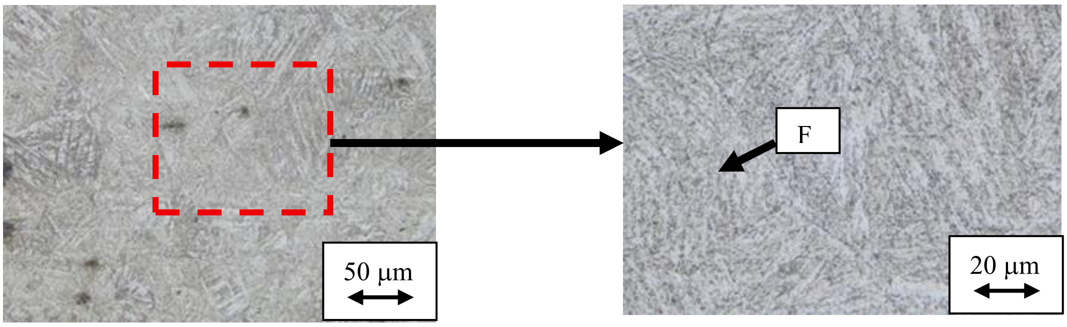

Figure 8. Structure of Micro HAZ Filler ER70S

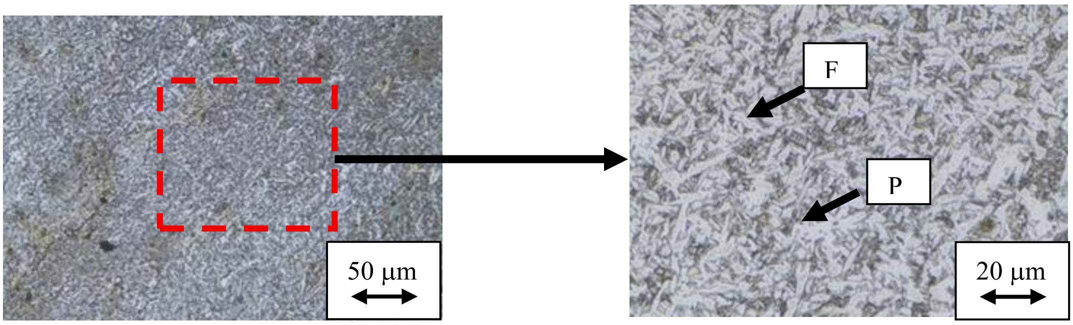

Figure 9. Structure of Micro Metal Welding Filler ER70S

Description: M = Martensite, P = Pearlite, F = Ferrite, B = Bainite

On the other hand, in Weld Metal (WM), the phase structure consists of ferrite and martensite with clearly divided area fractions. In ER-307 filler, the microstructure shows more pearlite and ferrite phases, with smoother results on the Fusion Line compared to ER-110. The martensite phase is also detected in the HAZ. Meanwhile, ER-70S produces a coarser microstructure with a larger and more distinct ferrite and pearlite phase ratio in the Weld Metal, while the HAZ shows a lamellar structure between ferrite and austenite. This indicates that ER-70S tends to produce welded joints with lower toughness compared to the other two fillers.

The microstructure test results in Figures 6 and 7 show that ER-307 is the most stable and relatively consistent filler across all zones (BM, HAZ, and WM) for welding MIL-DTL 46100E steel. The microstructure formed shows the influence of chemical composition and the filler's ability to modify the phase structure to produce optimal hardness. Overall, the selection of the right filler greatly affects the quality of welded joints in armor steel. The ER-307 filler provides the best results in terms of hardness and microstructure stability, making it a better choice for welding applications on MIL-DTL 46100E steel. This research makes an important contribution to optimizing the welding process of armor steel for defense applications by offering guidance on the selection of fillers that are more effective in producing high-quality welds.

Meanwhile, Figures 2 and 3 illustrate the microstructure of the Base Metal (BM), Heat Affected Zone (HAZ), and Weld Metal (WM) of ER 110 wire. The ER 110 weld metal shows a ferrite and bainite structure. These are two types of microstructures commonly found in steel. The combination of ferrite and bainite is known as dual phase steel, which occurs due to the rapid melting and solidification of molten metal during welding. The Heat Affected Zone (HAZ) shows a martensite phase structure resulting from the heat influence of the welding process. The Weld Metal (WM) has a ferrite-martensite phase area fraction where the dark area represents martensite, while the light area represents the ferrite phase.

Figures 4 and 5 illustrate the microstructure of ER 307 wire, showing ferrite and pearlite grains that have recrystallized into fine, round grains. This can occur due to changes in steel composition, particularly increased carbon content during heating at high temperatures. The Heat Affected Zone (HAZ) in ER 307 wire shows a pearlite phase structure.

Figures 8 and 9 illustrate the microstructure of ER 70S wire, showing ferrite and pearlite phases. In the weld metal, there is a phase transition from ferrite to pearlite. In the Heat Affected Zone (HAZ), there is a dark lamellar ferrite phase, while the light-colored area represents the austenite phase. The dark and light lamellar structures are formed as a result of heat treatment processes such as austenitization and subsequent cooling, which produce phase transformations. The Weld Metal (WM) consists of ferrite (light) and pearlite (dark) phases. Ferrite has a finer and lighter structure than pearlite. This is because the pearlite phase is formed at a higher temperature, resulting in a coarser microstructure.

Hardness test results show that ER-307 filler produces the highest hardness in the weld area compared to other fillers. In the HAZ zone, the highest hardness of 501.6 HV provides the welded joint with the highest hardness, especially in the HAZ zone, which reaches 501.6 HV. This shows that the ER-307 filler produces a more stable and consistent welded joint in terms of hardness compared to ER-110 and ER-70S. The ER-70S filler shows the lowest hardness value in the WM, reaching 296.8 HV, indicating that the hardness of the weld joint in this filler is lower, possibly due to its chemical composition which is unable to produce a sufficiently hard martensitic phase. ER-110 showed higher hardness values in the HAZ (505 HV), but decreased significantly in the WM (393.4 HV).

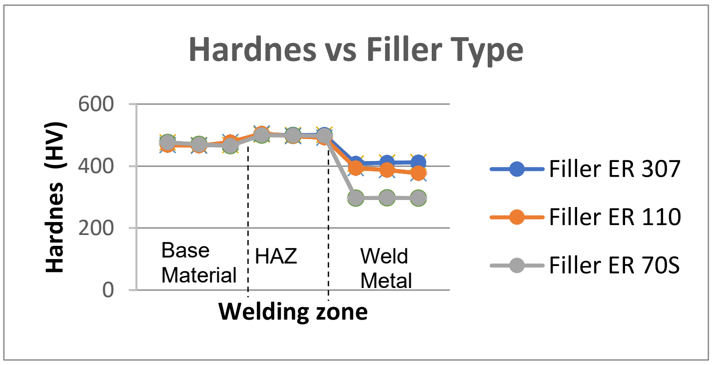

Figure 10. Graph showing the relationship between hardness and filler type

Based on the data in Figure 10, it is explained that the hardness distribution of each specimen in the Base Metal (BM), Heat Affected Zone (HAZ), and Weld Metal (WM) areas produces different hardnesses. The results of the hardness testing of carbon steel welding specimens show that the highest weld hardness is located in the HAZ due to the intense heat during the welding process. The lowest weld hardness is located in the Weld Metal, which is influenced by a chemical composition that is very different from the base material. ER 307 wire produced welds with the highest hardness and resulted in welds with hardness consistent with the base metal, and stability from the base metal (BM), Heat Affected Zone (HAZ), and weld metal (WM) areas, thereby maintaining consistent mechanical properties. The highest hardness value is obtained in the weld metal (WM) of ER 110 wire, which has the second highest hardness level after ER 307 wire. The heat affected zone (HAZ) of this wire has the highest hardness among the other two wires. ER 70S wire has the lowest hardness level of weld joints compared to the other two wires. The low hardness value indicates that ER 70S wire has low toughness.

4. CONCLUSION

Based on the results of the study, it can be concluded that the selection of welding filler has a significant effect on the microstructure and hardness of MIL-DTL 46100E steel welded using the Gas Metal Arc Welding (GMAW) method. The use of ER-307 filler produces a more stable microstructure with a predominance of pearlite and ferrite phases in the Fusion Line and martensite in the HAZ, which contributes to a consistent increase in weld joint hardness. Conversely, ER-70S filler produces a coarser microstructure, with larger ferrite and pearlite phases and lower hardness in the Weld Metal (WM). In terms of hardness distribution, ER-307 showed the best performance with the highest hardness in the HAZ (501.6 HV) and good stability throughout the welding zone. Meanwhile, ER-110 provided higher hardness in the HAZ (505 HV), but the hardness value in the WM tended to be lower. ER-70S has the lowest hardness in WM (296.8 HV), indicating a lower level of weld joint toughness. Thus, ER-307 can be recommended as the most effective filler for welding MIL-DTL 46100E steel because it provides stable and consistent hardness and an optimal microstructure for armor steel applications. As an alternative, ER-110 can be selected for applications requiring high hardness in the HAZ, although hardness in the WM needs to be considered, while ER-70S should be avoided as it produces welds with mechanical properties that are less suitable for high-hardness armor steel.

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