

Article

Impact of Welding Parameters in the Porosity of a Dissimilar Welded Lap Joint of CP800-XPF1000 Steel Weldment by GMAW-P

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Abstract: The use of the orthogonal array L_4 allows a determination of the effect between the welding parameters peak current (I_p), background current (I_b) and frequency (f) on the porosities in a dissimilar welded lap joint of CP800 and XPF1000 steel weldment by the gas metal arc welding process with the transfer pulsed mode. According to the results, modifications in the welding parameters affect the heat input during welding. A heat input higher than 0.30 KJ/mm generates up to 0.32% porosity in the weld metal, while a heat input lower than 0.25 KJ/mm generates up to 28% porosity in the weld metal. The variation in heat input generated by the process allowed the observation of the final microstructure of the welded joints and the effect of mechanical properties such as hardness because the results show values of hardness from 300 Hv to 400 Hv in the heat affected zone (HAZ).

Keywords: AHSS; zinc coating; porosities



Citation: Garcia-Guerrero, J.C.; Curiel-López, F.F.; López-Morelos, V.H.; Taha-Tijerina, J.J.; Sánchez-Cruz, T.J.; Ramirez-Lopez, M.d.C.; Cortes-Carillo, E.; Quinones-Salinas, M.A. Impact of Welding Parameters in the Porosity of a Dissimilar Welded Lap Joint of CP800-XPF1000 Steel Weldment by GMAW-P. *Metals* **2024**, *14*, 309. <https://doi.org/10.3390/met14030309>

Academic Editor: Masahiro Fukumoto

Received: 29 January 2024

Revised: 28 February 2024

Accepted: 1 March 2024

Published: 6 March 2024



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1. Introduction

With the development of new vehicles and the use of new steels for their manufacture, advanced high strength steel (AHSS) has been widely used, offering greater ductility with high strength [1–3]. AHSS steels are normally used in the manufacture of stirrups, stiffeners, or impact points in the frames of vehicles. The complex phase steel (CP) has a matrix of ferrite and bainite with a small volume fraction of perlite and retained austenite [4]. On the other hand, extra processing formability steels (XPF) are micro alloyed galvanized materials used for the manufacture of frames components in the automotive industry. The XPF1000 steel presents high mechanical strength and high elongation [5,6]. One of the main problems when joining such materials is the presence of cracks after the welding process once the component has been subjected to cyclic loading. This problem tends to reduce the lifetime of the components leading to premature failure during service. Nowadays, investigations related to the welding pool of AHSS are focused on overcoming the formation of porosities due to the evaporation of the zinc coating during the welding process. When this kind of steel is welded, the manifestation of bubbles of zinc oxide (ZnO) as a consequence of the high temperature generated during the welding process leads to the presence of discontinuities [7], where the vaporization temperature is around 906 °C, while in the weld pool it can reach a temperature in excess of ~1536 °C. As a result, the zinc vapor enters the melting pool, taking the form of a bubble, becoming trapped and generating porosity [5].

Recent research has focused on reducing this problem, e.g., Yu et al. [8] studied the effect of welding parameters such as current and torch aiming position on the porosity volume in a joint of hot-dip galvanized steel in the lap-joint configuration through the CMT welding process. According to the results, the welding current is the most important factor for minimizing the weld porosity because this parameter directly affects the arc force, heat input and the amount of zinc evaporated. Izutani et al. [9] determined the relationship between the frequency and the porosity in welded joints of galvanized steel; frequencies of 10 Hz and 20 Hz promote the release of the zinc gas. It was concluded that the waveform reduces the porosity more than the convectional process. Ahsan et al. [10] studied porosity formation in welded joints of galvanized steel using the CMT-GMAW process. According to the results, with a high heat input, the presence of porosities is higher, and these were found near to the surface of the weld pool. According to the results, a heat input greater than 350 J/mm causes high temperatures, and thus the weld pool becomes less viscous. Due to this low viscosity and the high vapor pressure, the bubbles of zinc vapor can expand in size and ascend more rapidly. As can be seen, several factors can affect the number of porosities in this kind of steel when welded with an advanced GMAW process. An effective and efficient tool used to reduce this effect is the design of experiments (DOE), specifically the Taguchi methodology, which helps in the optimization based on the principal parameters that affect the weld quality. This research focuses on the decrease in porosities in a dissimilar welded joint of CP 800 and XPF1000 steel in a lap joint configuration by means of the GMAW process with pulsed mode transfer.

2. Materials and Methods

2.1. Base Materials

Plates of commercially available 2.2 mm thickness XPF 1000 steel and 2.7 mm CP 800 steel-coated sheets were used in this study. The chemical composition of the different base materials determined by spark optical emission spectroscopy (SOES) is shown in Table 1. In the case of the filler material, an ER80S-D2 electrode of 1.2 mm in diameter with a chemical composition according to the AWS 5.28 standard was used [11]. The surface coating of the base materials was analyzed by SOES and the chemical composition in the case of XPF 1000 steel is shown in Table 2.

Table 1. Chemical compositions of the CP800 and XPF1000 steel and the filler material.

Material	C	Mn	Si	Cr	Nb	Ti	N	Al	Mo	Ni	Cu	V	Fe
CP800	0.08	1.43	0.49	0.34	0.005	0.09	0.002	0.03	0.004	0.19	0.002	0.01	91.6
XP1000	0.11	0.889	0.196	-	0.044	0.1	-	0.005	0.261	0.003	0.009	0.238	92.15
ER80S-D2	0.085	1.85	0.65	-	-	-	-	-	0.50	0.15	0.50	-	-

Table 2. Chemical composition of the zinc coating in the XPF100 steel.

Zn	Al	Mg	Pb	Sn	Cu	Fe
99.37	0.047	0.057	0.010	0.040	0.025	0.1

2.2. DOE and Orthogonal Array Experiments

The experimental design of this research uses the Taguchi methodology L_4 orthogonal array [12] for performing the weldments between the CP800 and XPF1000 steels with three main factors: peak current (I_p), background current (I_b) and frequency pulse (F_p) as is shown in Table 3. The combination of the different levels according to the DOE for the welding experiments is shown in Table 4.

Table 3. Welding conditions for the different levels.

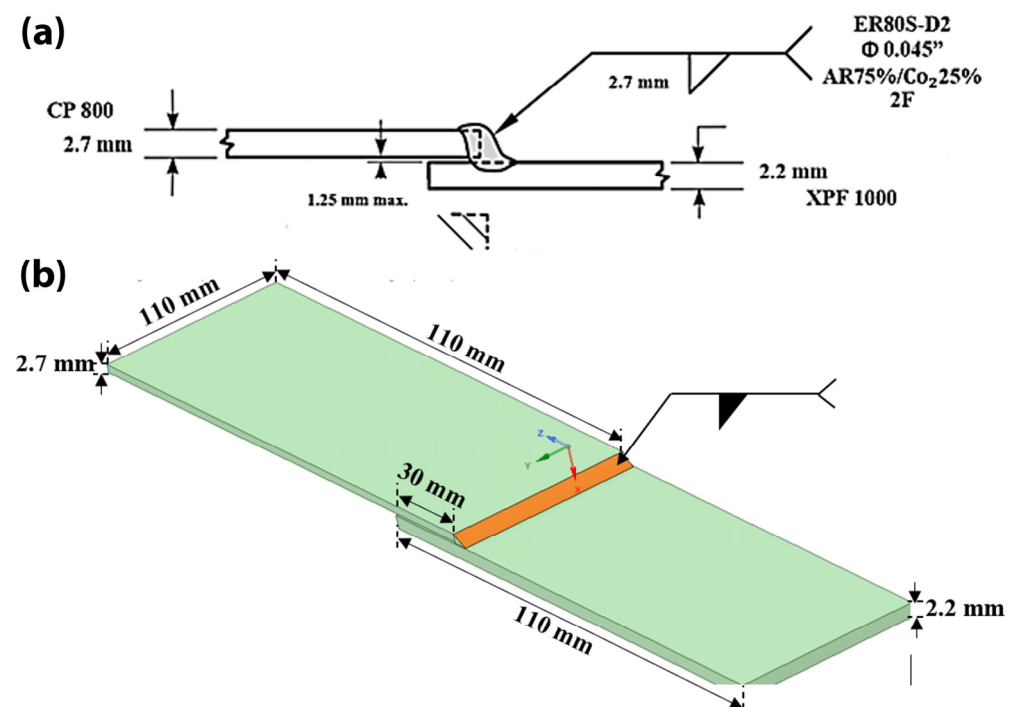
Welding Parameters	Symbol	Level 1	Level 2
Frequency pulse	F_p (Hz)	8	5
Peak current	I_p (A)	98	94
Background current	I_b (A)	87	83

Table 4. Experimental data using the Taguchi L_4 orthogonal array.

Trial	Welding Parameters		
	Frequency Pulse	Peak Current	Background Current
	F_p (Hz)	I_p (A)	I_b (A)
1	8	98	87
2	5	98	83
3	5	94	87
4	8	94	83

2.3. Welding Procedure

XPF 1000 and CP 800 steels were welded using a welding power source OTC Daihen model WelBee DP-400 (OTC Daigen, Osaka, Japan) to perform the GMAW-P with 23.1 V, stick-out of 12.7 mm, travel speed of 6.674 mm/s and a gas flow rate of 25 L/min using a mix of Ar 75% and CO₂ 25%. Figure 1a shows the welding symbol and the electrode and gas configuration and the dimensions used in the joints. Prior to welding, the sheets were degreased with acetone and dried. Subsequently, the sheets were placed at an angle of 45° with respect to the welding torch for better control of the deposit of the filler material as shown in Figure 1b.

**Figure 1.** Schematic of the overlap-welded joint. (a) Welding symbol and (b) lap joint.

2.4. Microstructural Characterization

For microstructural characterization, the samples were grounded with SiC emery paper of different grits and polished to a mirror-like finish with diamond paste. The

samples were etched with nital solution (5% HNO_3) to reveal the microstructure of the different base metals and the welded joints. To reveal the thickness of the zinc coating, Palmerton's reagent (20 mL H_2O , 0.3 g Na_2SO_4 and 4 g Cr_2O_3) was used by immersing the samples for 180 s with agitation. Then, the samples were characterized and analyzed by optical microscopy (OM) in an Axio Vert-A1 Inverted Microscope (Carl Zeiss, Germany) and scanning electron microscopy (SEM) JEOL-JSM7600f (Jeol, Japan) operating at 15 KeV in secondary electrons mode.

2.5. Weld Quality Assessment

The surface and volumetric quality of the weldments were evaluated by a visual inspection, liquid penetrant test according to the ASTM E165 standard [13] and industrial radiography test (General Electric, New York, NY, USA) according to the ASTM E1955 standard [14] using Iridium 192 as the radiation source with a sensitivity of level 3, with 0.005" to 0.010" lead screens at a distance from the film source of 10" and a focal point of 0.123" on 70 mm film.

2.6. Microhardness Profile Measurements

Microhardness profiles were performed in the cross section of the weldments according to the ASTM-E384-17 standard [15] with a Mitutoyo HM 210 hardness tester (Mitutoyo, Mapplewood, NJ, USA) using a load of 100 g for 15 s. The samples were previously prepared by a conventional metallographic procedure grinded and polished to a mirror-like finish. The distance between each indentation was 300 μm in the BM zone; the indentations distance in HAZ was 150 μm and in the WM, it was 100 μm . The data were plotted as a function of the distance in order to compare the differences in microhardness.

2.7. Root Test

With the purpose of evaluating the strength of the root in the welded joints, chisel tests according to the AWS D8.7 standard [16] were carried out. The test consisted of forcing a tapered chisel into the lap joint on the side of the CP800 and the side of the XPF1000 until the separation of the interface weld as shown in Figure 2. Care was taken not to touch the section to be analyzed with the tip of the chisel. After chisel test, the fractures surface was cut and observed and analyzed by SEM.



Figure 2. Chisel test performed in the lap joints.

3. Results

3.1. Base Materials

Figure 3 shows the micrographs obtained by SEM for each base material. Figure 3a shows the microstructure of CP800 steel characterized mainly by a ferrite matrix (F), and martensite island (M) [17]. This kind of steel presents as a principal element, Mn, which inhibits the precipitation of Fe_3S . In the case of XPF1000 steel, the microstructure is characterized by a ferrite matrix (F) with perlite (P) [18], as can be observed in Figure 3b.

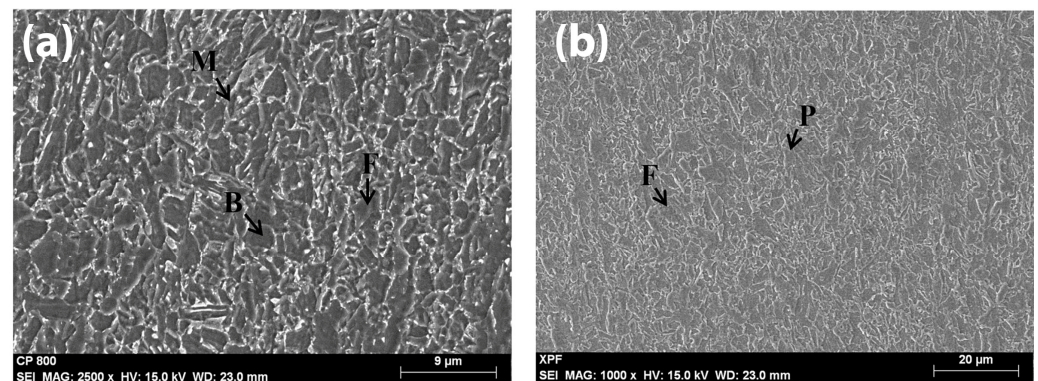


Figure 3. Base material (a) CP800 and (b) XPF1000.

Figure 4 shows the zinc coating characterized by SEM. The XPF100 steel presents a thickness of $\sim 17 \mu\text{m}$. In the zinc coating, irregularities are observed on the surface, presenting defects such as cavities, open cracks and a lack of fusion with the substrate, as can be seen in Figure 4a. Through line scan EDS in the coating (Figure 4b), the presence of the intermetallic ETA (η) can be seen in the upper section with a thickness of $\sim 0.57 \mu\text{m}$. Other intermetallics were found as ZETA (ζ) and DELTA (δ) with a thickness of ~ 14.61 and $1 \mu\text{m}$, respectively. Finally, the intermetallic GAMMA (Γ) is found at the substrate-coating interface with a thickness of $\sim 0.73 \mu\text{m}$.

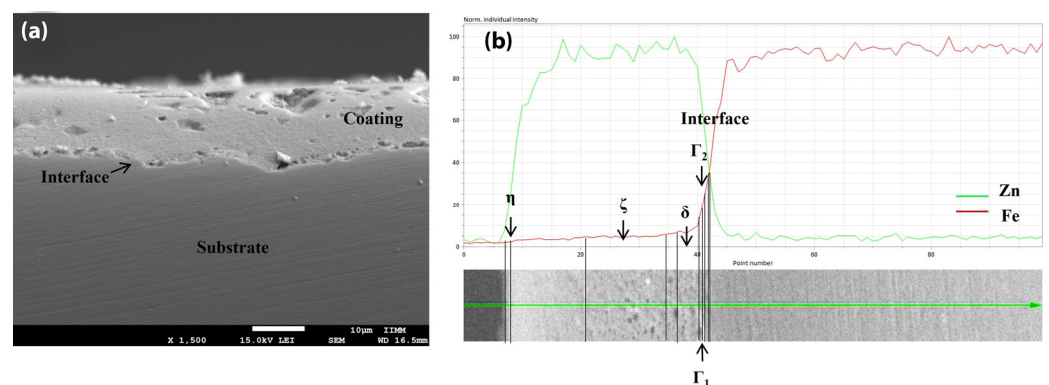


Figure 4. Characteristics of zinc coating analyzed by SEM. (a) XPF1000 base material and (b) line scan substrate.

3.2. Weld Quality Assessment

Macrostructural characteristics can be observed in Figure 5. Differences using different welding parameters can be distinguished. Figure 5a exhibits complete fusion between both plates with a heat input of 250 J/mm . In the case of Figure 5b, the lack of fusion is evident with a heat input of 245 J/mm . In the case of the weld shown in Figure 5c, there are no defects, no lack of fusion and the heat input provided was 238 J/mm . The weld with major defects can be observed in Figure 5d with the presence of pores and cracks that spread to the surface. The heat input for this condition was 236 J/mm . High heat input supplied in CP steels tends to generate softness, which decreases the fatigue life of the components [18,19]. The classification of CMT-GMAW is as follows: classify the range of heat input between 160 and 250 J/mm as low; with heat input higher than 500 J/mm , the percentage of porosities in the weld area decreases up to 1% . Ahsan et al. supplied a heat input of 350 J/mm to achieve a decrease in porosity of 2% in the weld area [10].

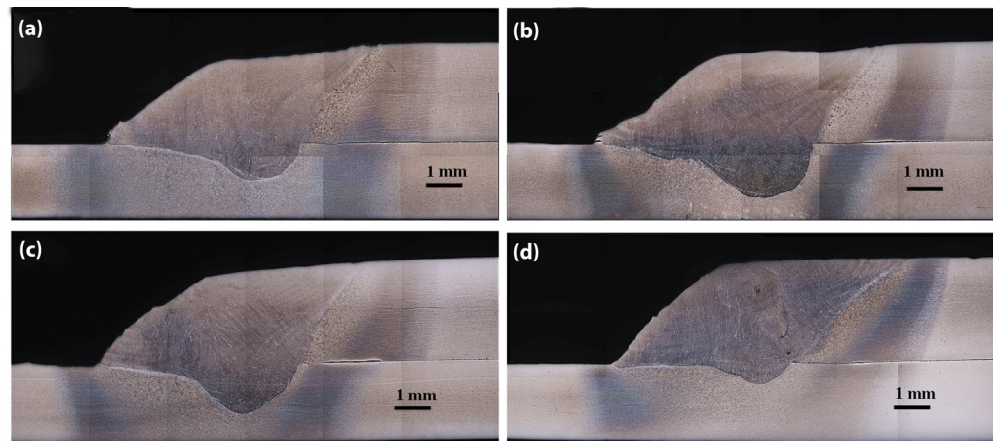


Figure 5. Macrophotography of the different welded joints from orthogonal array: (a) 250 J/mm, (b) 245 J/mm, (c) 238 J/mm and (d) 236 J/mm.

A more detailed evaluation allowed an observation of the effect of the use of orthogonal arrangements on welding quality through a penetrant liquids test and radiography test, as shown in Figure 6. In trial 1, no surface defects open to the surface are observed that indicate the presence of porosities (Figure 6a). In trial 2 (Figure 6c), a crater can be observed, resulting from the shrinkage of the filler material during solidification.

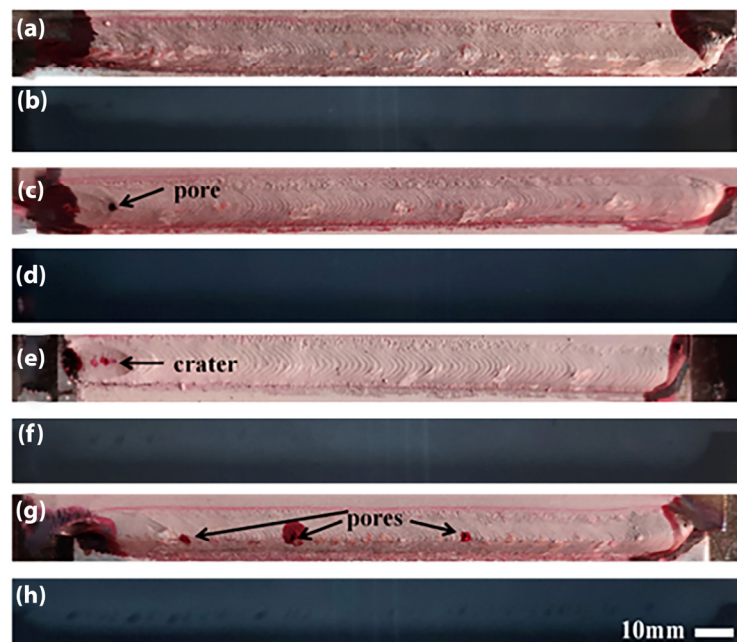


Figure 6. Liquid penetrant evaluation and radiography results by Taguchi orthogonal array: (a) 250 J/mm, (b) radiography 1, (c) 245 J/mm, (d) radiography 2, (e) 238 J/mm, (f) radiography 3, (g) 236 J/mm and (h) radiography 4.

Trials 3 and 4 (Figure 6e,g) show excessive exudation in the weld face, which indicates that the porosities can reach the root. In the case of the result of radiography, the radiographic film of trial 1 (Figure 6b) shows a round indication open to the surface at the end of the weld of 1 mm in diameter and two indications at the volumetric level of 0.26 mm, which means that only 0.32% of the weld shows porosity, which is below the 1% reported by Ahsan [10]. On the other hand, trial 2 (Figure 6d) shows a 1 mm round indication at the end of the weld open to the surface, which is less than 1.15 mm, and eight indications of 0.52 mm, smaller than 0.575 mm in diameter at the volumetric level, evenly distributed and generating 0.83% of porous area complying with the AWS D 9.1 standard.

Trial 3 shows (Figure 6f) one round indication open to the surface of 1.3 mm diameter, four round indications at a volumetric level of 1 mm and fifteen round indications of 0.4 mm diameter, giving a weld area with a porosity of 2%. Trial 4 (Figure 6h) shows linear porosity grouped with 28% of the weld area with pores.

3.3. Microstructural Analysis

According to the results in Figure 7, the heat input and, with it, the cooling rate led to changes in the solidification mode, which is influenced by the extent of solute partitioning and the phase formation [20]. Specifically, the use of the GMAW-P plays an important role, generating an undercooling that promotes the rapid formation of grains, which tends to be fragmented by the high convection generated in the melt pool due to the high droplet/s transfers, promoting the formation of ferrite (F) and dispersed acicular ferrite (AF) in the weld, as can be observed in all samples [21,22].

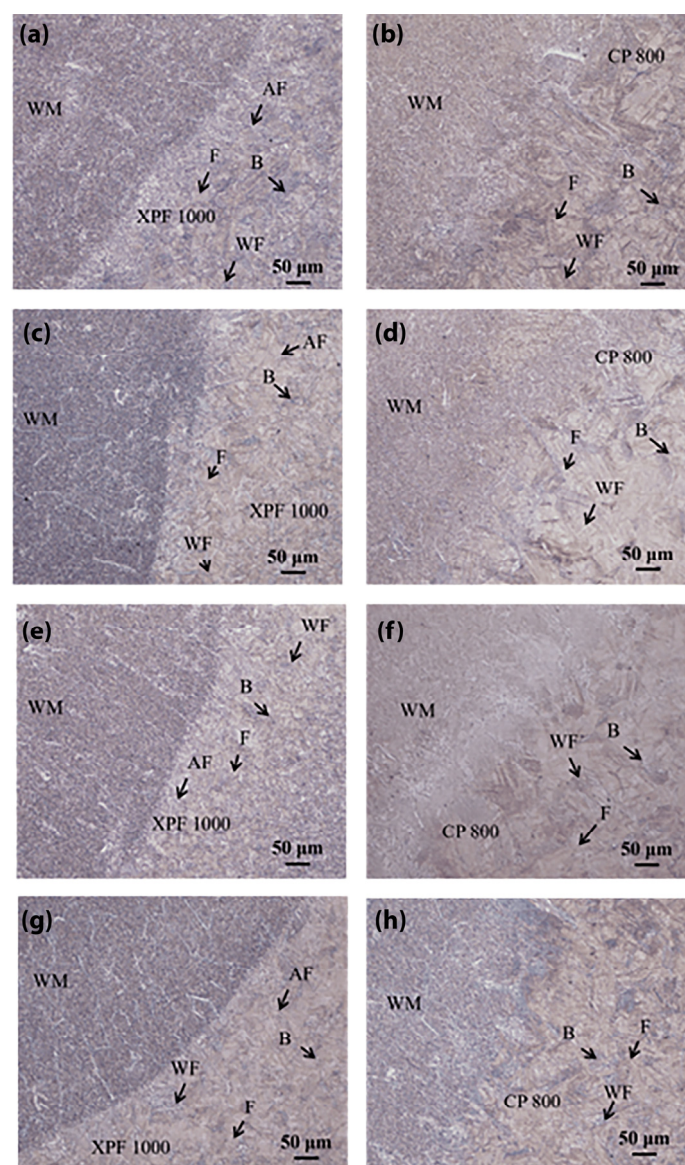


Figure 7. Microstructure of the Taguchi orthogonal array in the different interfaces of the WM-CP800 and WM-XPF1000 steel of trial 1 (250 J/mm). Interface welding metal (WM)-XPF1000 steel (a,c,e,g); interface CP800 steel-WM (b,d,f,h).

Trial 1 corresponds to Figure 7a,b, demonstrating the interface with XPF 1000 and CP800, respectively, and shows epitaxial growth from ferritic grains. At the interface with CP800, the columnar grains have a concentration of acicular ferrite grains. Other characteristics can be observed as the presence of different microstructures, e.g., in all samples of the interface welding metal (WM)-XPF1000 steel (Figure 7a,c,e,g) the presence of allotriomorphic ferrite (AL) and Widmanstätten ferrite (WF) is observed. The difference between these is the growth mechanism; in the case of AL, its formation involves diffusion at elevated temperatures, while in WF it does not include diffusion and takes place at low temperatures [23]. Therefore, the presence of these phases promotes an increase in hardness in this region, resulting in a loss of ductility in the welded joint.

In the case of the interface CP800 steel-WM (Figure 7b,d,f,h), the emergence of WF is also evident, a high amount of this morphology decreases the toughness impact [24,25]. Mechanical properties such as hardness, yield strength and other properties can be influenced by the heat affected zone (HAZ) structure, such as the volume fraction of ferrite or bainite, grain size, package size of the WF, distributions of precipitates, the thickness of the ferrite border, and the distance between the side plates in the WF [25,26]. Figure 8a–d show a higher magnification where the different microstructure can be appreciated because of the different heat input supplied.

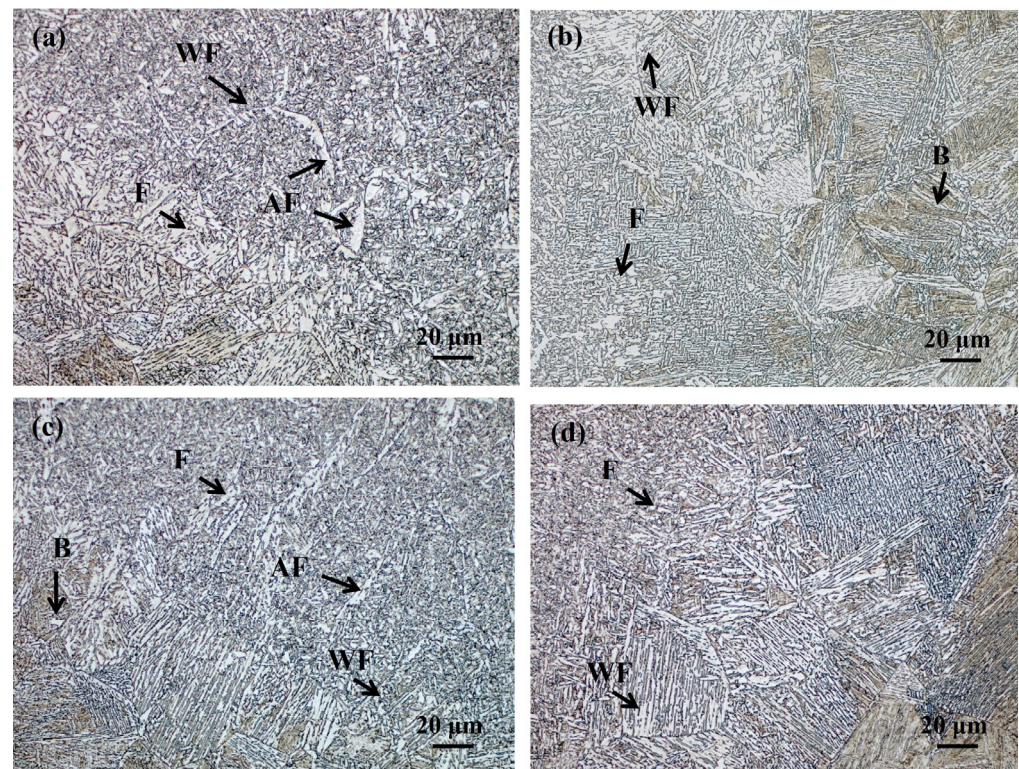


Figure 8. Microstructure difference in the interfaces of MW-XPF100 and CP-800-WM, from orthogonal array: (a,b) 250 J/mm and (c,d) 236 J/mm.

The results of the chisel test show the fractographies by SEM in Figure 9, where the cracks propagated through the porosities and the root for each welded joint; these porosities are formed when the zinc coating is vaporized during the arc welding [27]. Figure 8a, which corresponds to trial 1, shows a pore that, via EDS analysis exhibits a zinc content of 0.31%, while trials 2, 3 and 4 (Figure 9b–d) presented zinc contents of 0.85%, 1.45% and 2.23%, respectively, confirming the presence of zinc in the porosities. According to previous results, the size of the porosities is influenced by the zinc content, which in turn depends on the heat input and the cooling rate. The morphology of the pores indicates that they nucleate in the root, crossing the weld throat, and displacing to the weld face.

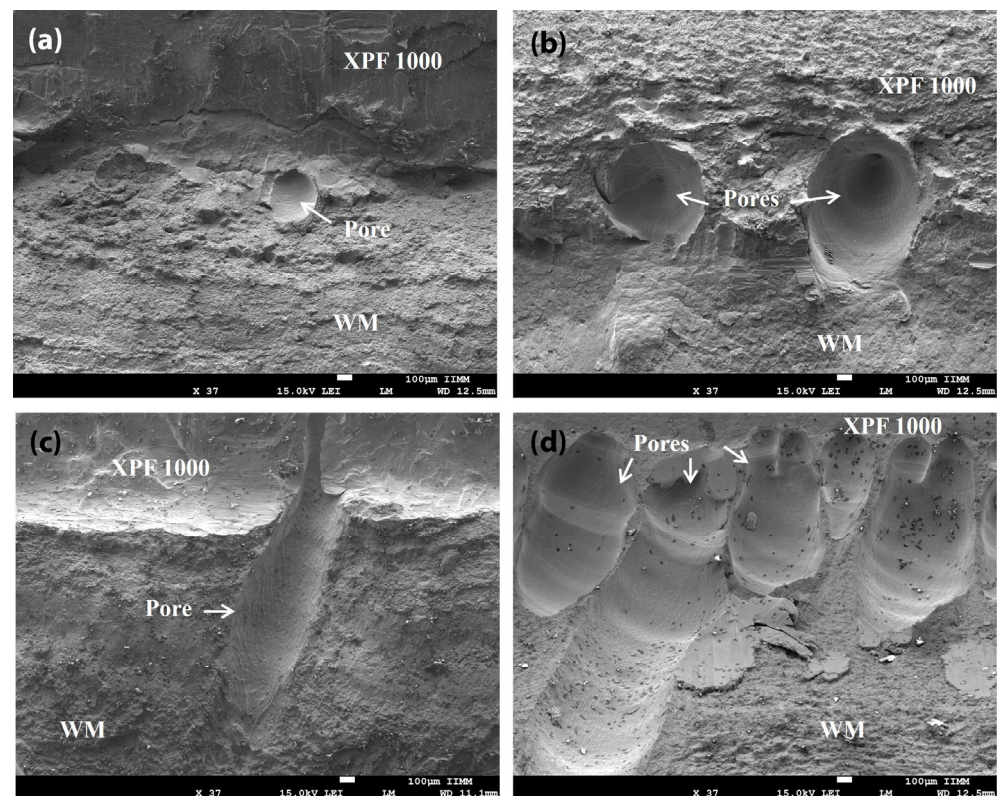


Figure 9. Fractographies by the Taguchi orthogonal array in the WM-XPF1000 side: (a) 250 J/mm, (b) 245 J/mm, (c) 238 J/mm and (d) 236 J/mm.

Based on the results, it can be observed that the use of a suitable experimental arrangement allows better conditions to be obtained, such as the decrease in porosities as well as their diameter, e.g., in the case of trial 1. The heat input of 250 J/mm favors the rapid evaporation of zinc towards the surface of the weld bead. On the contrary, a heat input of 236 J/mm is not enough for the zinc gases to leave the welding pool, remaining trapped in the cross section of the joint. Although there are other strategies for the reduction of this type of defect, such as a 0.5 mm separation in the overlapping of the joining method, currently, one of the best options to reduce porosity in the weld area is the GMAW-Pulsed welding process because it allows a better control of the parameters [28].

3.4. Microhardness Profiles Measurement

The hardness profiles for different conditions are shown in Figure 10. In the case of the side of CP800 steel, the hardness value is related to the different morphologies found at the interface, for example, allotriomorphic ferrite and Widmanstätten ferrite, which grow from bainitic grains. The WM region shows a hardness in the range of 240 and 340 HV₁₀₀ which is attributed to the presence of Widmanstätten and idiomorphic ferrite. In the case of the interface WM-XP1000, the hardness is 238–270 HV₁₀₀ and can be associated with the high concentration of Widmanstätten ferrite, which grows from ferritic grains with the precipitation of lamellar cementite. The microhardness is influenced by the microstructure and is dependent on welding parameters such as current and voltage, which play an important role in the heat input supplied [29,30].

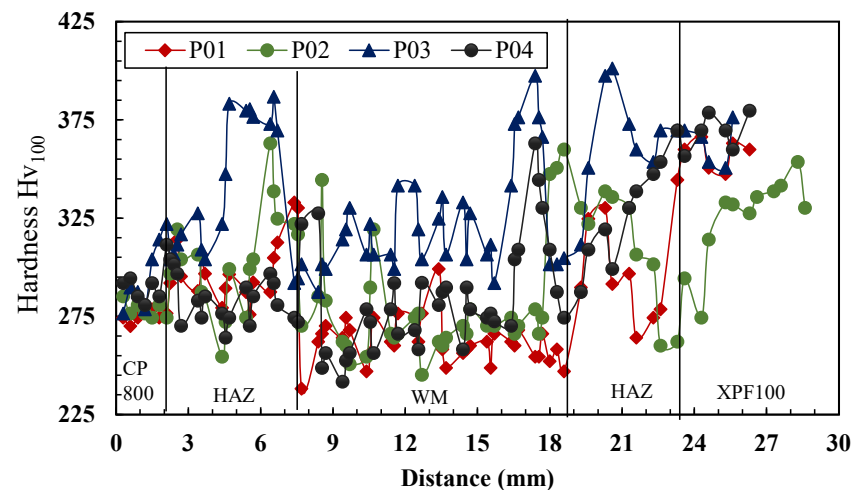


Figure 10. Hardness profile on welded joints: P01-250 J/mm, P02-245 J/mm, P03-238 J/mm and P04-236 J/mm.

4. Conclusions

According to the results of the different conditions from the orthogonal array L4, the minimum heat input to avoid porosities during the welding process was 250 J/mm. A heat input higher than 300 J/mm generates up to 0.32% porosity in the weld area. A heat input of less than 250 J/mm generates up to 28% porosity in the weld area. The microhardness values found in the HAZ in trial 1 show average values below 300 HV, while in the weld with very fast cooling, the values increase up to 400 HV. The mechanism suggests that a heat input between 250 and 300 J/mm allows the escape of zinc vapors towards the surface of the welding pool, reducing the presence of porosities.

Author Contributions: Conceptualization, F.F.C.-L. and J.J.T.-T.; Methodology, J.C.G.-G.; Validation, V.H.L.-M., M.d.C.R.-L. and E.C.-C.; Formal Analysis, T.J.S.-C. and M.d.C.R.-L.; Investigation, J.C.G.-G., M.A.Q.-S. and E.C.-C.; Resources, F.F.C.-L., V.H.L.-M., M.A.Q.-S. and E.C.-C.; Writing—Original Draft Preparation, J.C.G.-G., F.F.C.-L. and T.J.S.-C.; Writing—Review & Editing, V.H.L.-M., M.d.C.R.-L., M.A.Q.-S., J.J.T.-T. and E.C.-C.; Supervision, F.F.C.-L.; Project Administration, V.H.L.-M. and F.F.C.-L.; Funding Acquisition, F.F.C.-L. and J.J.T.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank Metalsa, for providing materials, the support by Universidad de Monterrey and Coordinación de la Investigación Científica (CIC) of the Universidad Michoacana de San Nicolas de Hidalgo, CONAHCYT for providing a scholarship to J.C.G.-G. during his master's degree studies and the aid from Antonio Rodriguez and Giovanni Candelario Justo with the SEM operation and welding facilities, respectively.

Conflicts of Interest: The authors declare no conflicts of interest.

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