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An Overview of Welding Processes Influence on P91 Steel's Mechanical Properties

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Abstract

Most power plants have employed P91 steel to construct boiler steam pipes because of its excellent mechanical qualities at elevated temperatures for more than 20 years. Nonetheless, following welding procedures, it is essential to evaluate the mechanical characteristics of P91 steel elements. P91 steel is frequently welded using a variety of techniques, such as metal inert gas welding, submerged arc welding, along with tungsten inert gas welding. The mechanical characteristics of P91 steel after welding are greatly influenced by the welding feed conditions. The influence of parameters related to welding upon the mechanical properties of P91 steel is highlighted in this paper. It also emphasizes the adjustments made to various welding processes in order to improve P91 steel's toughness, hardness, along with tensile strength. This review also identifies research gaps and potential research opportunities by performing an in-depth literature review, which might be helpful for researchers working in this area.

Keywords: P91 steel; Hardness; Toughness; Tensile strength; Welding

Abbreviations

ANOVA: Analysis of Variance; ASTM: American Society for Testing Materials; EBW: Electron Beam Welding; FBTIG: Flux-Bounded TIG; FCAW: Flux Core Arc Welding; GTAW: Gas Tungsten arc Welding; HAZ: Heat-Affected Zone; MMA: Manual Metal arc Welding; PWDT: Post-Weld Direct Tempering; PWHT:Post-Weld Heat Treatment; SAW: Submerged Arc Welding; SMAW: Shielded Metal Arc Welding; TIG: Tungsten Inert Gas Welding

Introduction

In 1960's, P91 was advanced technologically by Oak Ridge National Laboratory at Tennessee in united states. P91 comprises of mainly 9% Cr and 1% Mo. It was mostly utilized in breeder reactors and conduits for thermal/nuclear power plants, as well as petrochemical factories [1,2]. The mechanical characteristics of P91 weldment are enhanced by a variety of heat-treating techniques, including post-weld heat treatment (PWHT) along with normalizing and tempering (N&T). P91 steel has entirely a martensitic microstructure. P91 displayed precipitates whereas tempered martensite in discreet. Various microstructure types were seen in P91 weldment regions [3,4]. Steel grade P91, also known as modified 9Cr-1Mo-V, is denoted ASTM A335 for plates, T91 for tubes, and P91 for pipes. Seamless pipe is designated SA 335 P91, while seamless tube is designated SA 213 T91. P91 steel is more in demand due to nuclear and thermal power plants' increased efficiency, which reduces CO_2 emissions for the same amount of energy produced by operating at high temperatures and pressures. The improved composition of P91 steel allows for sustained operation at high temperatures (up to 600°C) without experiencing creep, regardless of extreme stress conditions.

P91 steel operates best at temperatures between 550°C - 650°C and pressures between 250 bar - 300 bar. Excellent temperature conductivity, substantial creep rupture resilience, high temperature rebellion, low thermal expansion value, excellent welding ability, good resilience, proper resistance to cracking throughout service, and exceptional corrosion resistance are all features of P91 steel. Regarding the next generation of nuclear, chemical, along with supercritical thermal power plant sections, P91 and its variations are widely employed [5]. Submerged arc welding, electron gas welding, activated TIG welding, and other arc welding methods are developed with high deposition rates, superior mechanical properties, high current densities, and high penetration depths. Submerged arc welding can be used at very deep penetrations. Thick plates may be easily welded using these welding procedures, increasing the fabrication industries' production and efficiency. By lowering CO_2 emissions, pollution to the environment can be decreased through the use of modern materials

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Table 1: Mechanical properties of P91 steel welds.

References	Voltage	Current	Speed(mm/s	Electrode	Ultimate TensileStrength (MPa)	Hardness	Toughness	Welding
	(V)	(Amp)						
[4]	110	12	-	-	1354	247±4 HV	-	TIG
[7]	240- 260	1250	-	-	547	-	-	SAW
[18]	28-32	350-450	0.66- 3.33	3	866	36.6 Rc	-	SAW
[20]	103	8-15	35	2.4	722	-	775°C, 30 min	GTAW
	143	21-28	50	4.2	-	-	138 MJ/m^3	SMAW
[21]	400	30	19.166	-	-	97.8 HRB		SAW
[24]	150	26	-	1.73-2.23	-	-	175	SMAW
	500	31	-	6.67	-	-	200	SAW
	230	11	-	1.33	-	-	240	TIG
[27]	35	635	0.0766	3.15	860	255 to 324 HV.	75	SAW
[28]	34	625	0.0075	3.15	790	400	20	SAW
[29]	35	-	-	-	1240 (P9 Filler)145 1 (P91 Filler)	430 VHN (P91 Filler)	100J (Incone l Filler)	Metal Arc Welding
[30]	-	-	-	2.4	-	-II -	20J, A- TIG&132J, GTA	TIG
[31]	-	-	-	4	1156 (Case-III)	470VHN	16	Shielded Metal Arc
[32]	200	13-14	1.66	2.9	-	423–431 (Vicker)	23.33	A-TIG
	80-95	12-12.5	1	2.9	52	438-446 (Vicker)	24	C-TIG
[33]	220	14-155	-	1.33	1309 ± 18	415 (As Welded) 266 (PWDT) 205 (PWNT)	-	TIG
[34]	20	110-125	2.11	1.6	-	247 ± 2HV,1150/800°C Norm/Tempering	200 ± 4 JV-groove & 202 ± 3	TIG
[35]	-	150-250	2.5-4.166	2.4	-	TIG (403VHN), FBTIG (390VHN)	-	FBTIG
[36]	95	14	0.7	2.4	696 ± 15, 20°C, 405 ± 9,600°C	356±16	-	GTAW
[39]	-	-	-	-	-	P91 weld with 91A filler as welded,1203	(J,narro8w5J)PWHT 760C/6h	Shielded Metal Arc
[40]	25	150	-	-	536	244 ± 9	-	TIG

such as P91 and P92 steel. The unstable structure formation caused by inconsistent cooling and heating throughout the welding thermal cycle remains the cause of the issues encountered when joining P91 steel in interchangeable combinations by various processes. This reduced the mechanical as well creep strength attributes of the weld metal in comparison to the P91 base metal as acquired [6,7]. P91 steel welding is currently a major problem in many industrial applications. For researchers, maintaining the mechanical attributes of P91 after welding presents a significant difficulty. P91 steels can be joined using a variety of welding techniques [8,9]. Any of the atomic bonding combining techniques, such as flux core arc welding (FCAW), submerged arc welding (SAW), gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), manual metal arc welding (MMA), along with electron beam welding (EBW), are used to join P91 steel. Figure 1 shows the optical micrograph plus secondary electron micrograph of the base P91 steel microstructure. In the weld fusion zone, the lath martensitic production resulted from the welding procedure. It has an impact on the microstructure of the weld fusion zone including the small region right next to the weld fusion boundary [10,11].

Welding Processes

A consumable electrode coated in flux is used in SMAW, for coating the weld. SMAW welding is applicable to several types of metal. The majority of heavy-duty work requiring industrialized steel and iron is done with SMAW welding. When electrode coatings are used properly, they can improve the mechanical properties of the weldment. Studies have also shown that employing an electrode created in a lab increased impact strength by 19% [10].

As seen in Figure 2, the TIG welding process entails creating an arc among the workpiece as well as a non-consumable tungsten electrode. In comparison with the majority of other fusion processes, this type of welding is renowned for producing welds of excellent quality. However, it has several disadvantages as well, such as inadequate penetration in one welding pass, uncontrollable penetration of the weld due to minute differences in the alloying materials, and the need for repeated passes when processing thick gauge portions. Additionally, TIG welding takes longer than other welding methods because of its slower velocity. It's frequently necessary to make many passes for heavier materials. TIG welding has limited penetration, can only be used to weld materials that are up to 3 mm thick, and has a low efficiency. Nevertheless, penetration along with overall weld quality can be improved by carefully choosing input parameters and using a variety of approaches. Many industries, including shipbuilding, energy generation, aviation, nuclear, steam power plants, as well as others, use tungsten inert gas welding [12-14].

These days, scholars are quite interested in thick steel plate welding. In the industrial setting, SAW is an ideal and efficient method for joining thick sections when compared to other arc welding methods. This is due to a number of benefits, including superior weld qualities, increased deposition rates, improved efficiency, automation, and reduced operator skill [15]. The efficiency of SAWs can be increased by adding metal powder during the welding process, using hot wire welding, multiplex electrode welding, cold wire welding, along with multiple wire welding. SAW is extensively utilized in the construction of offshore constructions, pressure vessels, marine vessels, as well as pipe lines due to its exceptional invisible arc, surface Gestalt, minimal welder skill demand, and significant deposition rate [16].

Welding of P91 Steel

The influence of SAW input process parameters was investigated in order to determine the mechanical characteristics of the welded Cr-Mo-V steel. Weld penetration, weld bead depth, weld the hardness of weld tensile strength, along with weld fortification are among the parameters that were evaluated. Research using the Taguchi technique found that submerged arc welding could produce welds with an optimal tensile strength of 940.9 MPa [17,18].

In a different study, the weld properties of normal TIG welding along with single-pass A-TIG welding using P91 steel were compared with those of MoO_3 and CeO_2-based activated flux. The findings showed that MoO_3 base flux A-TIG weldments were harder and had greater tensile strength that CeO2 base flux weldments [19].

Investigators also looked at the mechanical characteristics, fracture conduct, including microstructures of T91 steel that was arc-welded after being PWHT. The investigation found that the characteristics of T91 welds were considerably impacted by PWHT temperatures of about 775°C for thirty minutes [20].

The mechanical strength of SAW welds was the subject of an optimization analysis utilizing artificial neural network simulation, which found that current affected hardness more than voltage, feed rate, or voltage [21].

An additional study looked into how welding parameters affected the mechanical characteristics of SAW welds. The findings demonstrated that impact along with tensile strength declined as voltage increased, while hardness raised when welding current or arc voltage rose. Additionally, because delta ferrite did not fully transition into austenite, additional weld passes resulted in enhanced tensile strength as well as hardness [22].

Lastly, a study used factorial design analysis to examine the effects of four welding process variables: arc voltage, welding current, flux basicity, as well as travel speed. Higher welding present circumstances are associated with a higher percentage of pearlitic structures, a smaller percentage of bainitic structures, plus the existence of the ferrite phase, according to an investigation conducted using an Analysis of Variance (ANOVA). A key factor in determining the characteristics and microstructure for a weld is the flux's composition. The degree of hardness of the Heat-Affected Zone (HAZ) is directly impacted by the existence of bainite and martensite [23]. It was looked into how oxide particles affected the amended steel welds' toughness. SAW and SMAW welds had poor strength when in the as-welded state and had numerous MnSiO3 oxide particles visible upon the fracture surfaces.

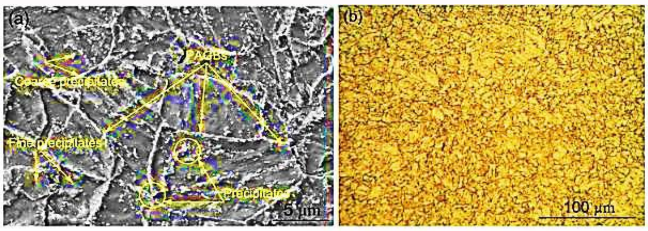

Figure 1: a) Typical secondary electron micrograph of P91 steel b) Optical micrograph of P91 steel [11].

On the other hand, none oxide particles were visible in the metal GTAW, which also demonstrated greater strength. Following PWHT, the strength of SAW and SMAW weld materials increased, which reduced the volume of oxide particles within the cracked surfaces [24].

Researchers looked at how the input SAW welding procedure variables affected the weld's structure along with characteristics. The SAW weld's mechanical characteristics were found to be mostly determined by its microstructure. Hardness rose with increasing welding current or arc voltage, while impact and tensile strength declined. As voltage rose, the weld breadth grew. To improve certain weld qualities, alloying materials such as silicon, sulfur, manganese, etc., have been included [25].

We looked at two different kinds of heat treatments: post-weld direct tempering (PWDT) and PWNT. PWNT increased the microstructure's uniformity. Furthermore, it was discovered that the impact resilience (1496 J) and the change in hardness throughout the welded joint (transverse direction) were better than the base metal's resilience [26]. An improvement in the degree of hardness associated with the weld became apparent with the inclusion of titanium dioxide, according to an investigation into the impact of TiO_2 on the mechanical characteristics and microstructure of P91 steel welded employing SAW [27].

Subsequent research concentrated on the effects of B_2O_3 in the flux on the microstructure as well as the mechanical properties of modified P91 steel during SAW. With 12.5% of B_2O_3, the highest hardness of 342 HV was attained. With the exception of the 12.5% B2O3 structure, the inclusion of boron helped to improve the tensile strength (790 MPa) of the joints that were welded. Boron enhancements, however, had no appreciable effect on toughness. Addition of boron trioxide enhanced the hardness in the weld, and boosting the amount of boron in the mixture elevated the tensile strength [28].

When P91 steel was modified and welded using three distinct filler materials, Inconel 182 weld metal was found to have a toughness of 100 J in its as-welded state. The impact of heat treatment parameters and diffusible hydrogen contents on the mechanical characteristics and microstructure of P91 steel following multi-pass SMAW was also examined in this work. According to the findings, P91 steel joints (butt) that had little diffusible hydrogen had greater toughness; nevertheless, toughness decreased as diffusive hydrogen content rose. For an electrode cooked for two hours at 300°C, the optimum toughness value recorded was 16 J. When compared to PWHT,

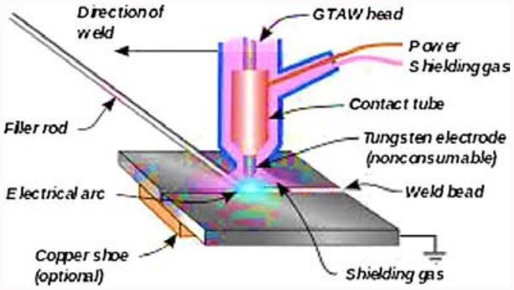

Figure 2: Gas tungsten arc welding process [17].

normalizing and tempering (N&T) treatment was more successful in producing a homogenized microstructure [29].

In an investigation to ascertain the consequences of flux on GTA and A-TIG welding procedures, the impact toughness, hardness, and microstructure of P steel welds have been studied. Because A-TIG had more carbon than GTA, the results indicated that A-TIG welds were harder than GTA welds. Following a post-weld heat treatment at 760°C–2h, the GTA welds showed a toughness of 132 J, that was superior than the A-TIG welds' toughness about 20 J. This is explained by the multi-pass accumulation in the GTA welds, which increases the tempering effects. The A-TIG welds demonstrated an impact energy of 61 J following post-weld heat treatment at 760°C for three hours, above the minimal energy needed of 47 J [30].

The impact of alumina flux on penetration of the weld in flux-bounded TIG (FBTIG) welding was the subject of another investigation. In comparison to TIG welding, it was discovered that the use of ceramic flux during FBTIG welding increased weld penetration thrice. But as in comparison with TIG welds in identical areas, the hardness of the FBTIG welds was poorer in the weld zone as well as heat-affected zone [31].

The effects of nitrogen plus tempering on the microstructure of P91 pipe weldments produced by GTAW were also investigated by researchers. According to their research, hardness rose as tempering temperatures rose. At 800°C and 760°C for tempering, the weldments actually showed greater toughness than the base metal [31].

Furthermore, when comparing A-TIG welding to traditional TIG welding, researchers found that the use of MnO2 flux increased the depth of penetration by 231%. They did discover, nonetheless, that activating flux TIG welding produced a lower tensile strength than normal multipass TIG welding. Furthermore, compared to multipass TIG welded joints, A-TIG welded joints showed greater toughness [32].

Additionally, a study examined how the microstructure of P91 weldments was affected by PWHT plus normalizing and tempering (N&T) treatments. The results showed that N&T therapy had a greater effect on the microstructure than PWHT afterward [33].

Mechanical Properties of Grade 91 Steel

Hardness: MoO_3 base flux weldments (A-TIG) had greater hardness and tensile strength over CeO_2 weldments [19]. Hardness is more influenced by welding current than by voltage, feed rate, or speed [21]. Arc voltage rises cause SAW hardness to rise [22]. PWNT was proposed in a different study on the welding of P91 steels to eliminate heterogeneity and guarantee consistent hardness across the weld joint [26]. According to the results of another investigation on SAW, the weld with 12.5% B_2O_3 had the highest hardness, measuring 342 HV, whereas the weld without boron had the lowest hardness, measuring 240.8 HV. Boron oxide addition typically results in a weld that is harder [28].

Pre-welding heat treatment of the weld contributed to reduce the micro-hardness levels in the weld fusion zone along with coarse-grained heat affected zone by 50%, according to a study based on the TIG welding of P91 steel [31]. After triggered TIG (A-TIG) welding, researchers looked at the impact of flux stimulation on the micro hardness of P91 steel. They found that A-TIG welds had smaller harness ratings than multi-pass welds prior to post-weld heat treatment [32]. Additionally, studies have shown that whereas a spike in tempering temperature causes the hardness of the weldment to deteriorate, an increase in normalization temperature leads to elevate the hardness of gas tungsten arc welded joints (P91 steel weldment) [33].

A study was done by researchers to see how heat treatment affected the mechanical properties of a material called P91. The base region of P91 has a normative hardness value of 247 HV, according to the data. By contrast to that, the initial state in the weld fusion zone was composed of untampered martensite lath thus had a higher hardness value (472 HV) that the base metal. The hardness variations seen in the various zones of the P91 weldment both before and after PWHT are shown in Figure 2. A second study on groove designs verified revealed in the coarse-grained heat-affected zone (CGHAZ) regions of P91 weld joints, narrow and V-shaped groove designs produced comparable hardness levels [34].

Although TIG normally produces high-quality welding connections, one of its drawbacks is low weld penetration. Using pulsed current and flux in TIG can help to increase weld penetration [35]. The effects of heat treatment cycles on P91 steel TIG welded joints were studied [36], with current and voltage fixed at 95 A and 14 V, accordingly. The heat-affected zones of base metals 1 and 2 were found to have hardness values of 195 and 191 HV, accordingly, based on the results. Pre-welding heat treatment is typically chosen to lessen the weldment's hardness.

Toughness: Investigators have looked at how heat treatment affects the welded P91 pipe microstructure along with hot durability in various zones. It is not advised to use P91 steel above 760°C, according to their opinion [4]. The impact energy estimates for P91 base metal at different operation temperatures are shown in Figure 3. According to a different study, high O_2 concentration SAW and SMAW welds showed poor durability when in the as-welded state, while fracture surfaces had a lot of $MnSiO_3$ oxide particles. On the other hand, GTAW metal had less oxide particles hence were more durable. Following post-weld heat treatment, the toughness of SAW with SMAW metals increased, which reduced the density of oxide particles on cracked surfaces [24]. Lower diffusible hydrogen content in P91 steel joints (butt) were associated with higher toughness, whereas high diffusive hydrogen values were associated with lower toughness. An electrode that was roasted for two hours at 300°C showed the highest toughness value of 16 J. When contrasted with post-weld heat treatment, normalizing and tempering (N&T) processing was more successful in producing a homogenized microstructure [26].

Researchers looked into how modified P91 steel in SAW's microstructure along with mechanical characteristics were affected by flux with B_2O_3. Their results showed that the weld zone's toughness

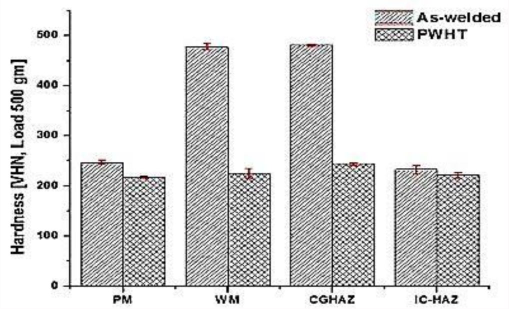

Figure 3: Variation in hardness values for various zones of P91 steel weldments in as welded and PWHT conditions [4].

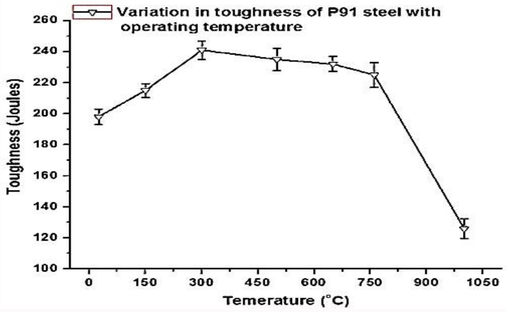

Figure 4: Effect of operating temperature on impact toughness value of P91 steel [4].

declined with the addition of boron [28]. When utilizing manually metal arc welding, Inconel 182 filler metal demonstrated a high level of toughness in the as-welded state, measuring about 100 J [29]. Furthermore, the effects of normalizing along with tempering (N&T) on the microstructure of different zones in GTAW P91 pipe welding were investigated by researchers. The study came to the conclusion that toughness rose as tempering temperature rose. Additionally, at tempering degrees of 760°C and 800°C, it was found that the hardness value was higher than that of the base metal [31].

Tensile strength: The most important factor in producing high tensile strength in P91 steel welding is welding current, according to research on submerged arc welding employing the Taguchi technique, which produced an ultimate weld tensile strength of 866 MPa [18]. It was discovered that the tensile strength of A-TIG weldments using MoO_3-based activating flux exceeded that of the base metal [20]. The joints having a minimal diffusible hydrogen content showed greater tensile strength, according to another study using P91 steel [26]. The tensile strength of P91 steel was enhanced by the inclusion of boron and TiO_2 [27]. When utilizing a 91A filler electrode, welding P91 steel sheets with various electrode formulations and post-weld tempering at 730°C and 760°C for 6 hours as well as 2 hours, accordingly, produced a P91 weld with a tensile strength of 1203 MPa [29]. As the normalizing temperature rose, so did the P91 weldments' eventual tensile strength plus yield strength [31].

When compared to comparable regions in traditional TIG welds, FBTIG demonstrated reduced hardness in the heat-affected zone along with weld zone [35]. In comparison to those created with CeO_2-based flux, the weldments made with MoO_3-based flux demonstrated higher eventual tensile strength and increased hardness [37]. Furthermore, compared to A-TIG welding, multi-pass TIG welding showed greater tensile strength in P91 steel [38].

Increased maximal tensile strength was achieved in P91 welds by using 91A filler material [39,40]. The mechanical characteristics (tensile strength, toughness, and hardness) of different P91 welds are shown in Table 1 together with the matching source welding parameters (arc voltage, welding current, temperature, electrode diameter, welding speed, flux, preheat temperature, etc.) (Figure 4).

Conclusions

A thorough analysis of the body of research on the mechanical characteristics of TIG and SMAW welds on P91 steel indicates that weldments with MoO_3 base flux (A-TIG) have greater hardness and tensile strength than weldments with CeO_2 base flux. Furthermore, the mechanical characteristics of P91 steel have been effectively improved by using the technique of Post Weld Heat Treatment (PWHT). According to the literature, submerged arc welding (SAW) produces welded P91 steel with a lower hardness, whereas TIG welding can reach greater tensile strengths for the same material. TIG welding has shown benefits in producing P91 steel welds with higher toughness. The literature that is currently accessible highlights how important welding input variables are for maximizing the mechanical properties of P91 welds. These parameters include welding speed, welding current, flux, and pre-heat treatments. Nevertheless, little research has been done on the subject of welding parameter optimization with a focus on P91 steel. Additionally, it is proposed that the use of statistical tools along with finite element methods for predicting and modelling the mechanical properties of P91 steel welds may help reduce input resources like materials, cost, along with time.

Author Contributions

K. C. Sunhare: Data curation; formal analysis; investigation; methodology; resources; writing – original draft. **S.** D. Patle: Conceptualization; data curation; project administration; supervision; writing – review and editing**.** H**.** K. Narang: Data curation; visualization; writing – review and editing.

Data Availability Statement

The data that support the findings of this study are available within the article.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI in Scientific Writing

The authors declare that they have No generative AI tool is used for writing, editing this manuscript.

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