



Coercivity Measurement as a Tool for Assessing the Quality of Post Weld Heat Treatment of T91 Boiler Tubes

Avijit Mondal*, Anil Kumar Das, Satish Chand, Sandeep Kumar,
Chandra Bhushan Kesari

NDE, Imaging and Life Management Lab, NTPC Energy Technology Research
Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.

*Corresponding author E-mail: avijitmondal@ntpc.co.in

Abstract. Modified 9Cr-1Mo steel (T91) is widely used in power generation due to its superior high-temperature strength, extended creep rupture life, excellent oxidation and corrosion resistance, and good weldability. However, weld joints in T91 components are often the most failure-prone regions, making it essential to assess their behaviour for long-term reliability. Post-weld heat treatment (PWHT) plays a critical role by relieving residual stresses and tempering the martensitic structure in the fusion zone, thereby minimizing strength gradients across the weld. In field applications, verifying the effectiveness of PWHT requires dependable non-destructive evaluation (NDE) methods. While portable hardness testing is commonly employed, it often yields inconsistent results and may not reliably reflect the overall condition of the material.

An alternative approach involves measuring Magnetic Coercive Force (MCF), which correlates with magnetic hardness in ferromagnetic materials. This study aimed to investigate the influence of different PWHT conditions on the MCF of T91 welds. The experiments examined how MCF varied under a range of PWHT cycles, with soaking temperatures up to 790°C and durations up to 120 minutes. Results indicated that higher soaking temperatures and longer durations led to a decrease in MCF values within the weld metal. This reduction aligned with lower hardness levels and increased carbide precipitation in the microstructure. Based on these results, a threshold for acceptable MCF values has been established. Exceeding this threshold can signal the need for corrective actions, enabling proactive maintenance and reducing the risk of premature failures or unexpected shutdowns in thermal power plants.

Keywords: Coercivity; Post Weld Heat Treatment; T91 Steels; Microstructures; Hardness.

1. Introduction

Modified 9Cr-1Mo (T91) steel belongs to a class of ferritic steel known for their exceptional creep resistance, making them well-suited for high-temperature environments. These steels are widely used in critical components such as main steam piping, superheaters, reheaters, and headers in fossil fuel-fired power plants, as well as in nuclear steam generators for fast breeder reactors. Their

expanding range of applications underscores their significance in contemporary power plant operations [1]. Growing interest is being directed toward investigating the welding characteristics of T91 steel due to its critical role in high-temperature applications. Studies have shown that a significant proportion of failures in steam generator components occur specifically at the weld joints [2]. The fusion zone of as-welded T91 steel contains newly formed martensite, a hard and brittle phase that heightens the risk of premature failure. Variations in strength across the weld axis arise due to differences in phase composition and grain size across the fusion zone, heat-affected zone (HAZ), and base metal. These issues are further intensified by residual stress generated during welding. To address these challenges, PWHT is employed to relieve residual stress and temper the martensitic phase, thereby minimizing strength gradients [3]. According to the ASME Boiler and Pressure Vessel Code - Section VIII, Division 1 [4], PWHT for T91 steel should involve soaking at temperatures between 730°C and 775°C. Without adequate PWHT, the martensitic phase remains un-tempered, resulting in elevated hardness levels that can compromise performance and increase the likelihood of failures. Multiple case studies [5-7] have documented failures in T91 steel components due to insufficient heat treatment, highlighting the critical importance of proper PWHT. To ensure the quality of PWHT, NDE methods are crucial, particularly in on-site conditions. Among these, portable hardness testing is the most employed technique to assess the effectiveness of PWHT. According to J. Parker [8], a maximum hardness value of 280 HB-measured using a portable hardness tester is the acceptance criterion for PWHT quality in modified T91 welds performed in the field. Despite its widespread use, this method has certain limitations. Numerous variables, such as the type of equipment and testing procedures, can significantly influence the results of field hardness tests. Achieving accurate hardness reading typically depends on meticulous surface preparation, including grinding and polishing, as well as the careful and consistent application of testing techniques by the operator [8].

Ferromagnetic steels like modified T91 exhibit magnetic properties that are highly responsive to variations in microstructure, stress levels, and corrosion. The coercive force /MCF, also known as coercivity; quantifies a material's resistance to demagnetization when subjected to an external magnetic field. Microstructural factors, including grain coarsening, precipitation, and defects like voids, dislocations, and inclusions, significantly influence MCF [1, 9-13]. These factors impede the movement of magnetic domain walls, resulting in an increased MCF. Variations in MCF can offer valuable insights into the microstructural condition of the material.

A review of multiple studies [1, 9-13] indicates that the magnitude of the MCF in ferromagnetic materials reflects their magnetic hardness. The ferromagnetic nature of modified T91 steel allows the use of micro-magnetic techniques-such as magnetic coercivity measurements-which are highly sensitive to microstructural and stress variations, to assess the effects of heat treatment on weld joints. Recent research has investigated how welding and PWHT influence

the MCF of both modified T91 and T22 steels [1, 9-13]. In particular, Sudharshanam et al. [1] and Mondal et al. [9-10] evaluated the quality of PWHT in modified T91 steel welds through MCF measurement. Similarly, Sambamurthy et al. [12] studied the PWHT behaviour of modified 9Cr-1Mo weldments using Magnetic Barkhausen Emission techniques. More recently, Roy et al. [13] examined the behaviour of post-weld heat-treated T22 steel joints using electromagnetic NDE parameters. The present study builds upon the findings of Sudharshanam et al. [1] and Mondal et al. [9-10]. However, a review of the literature reveals a notable gap: limited research specifically addresses the impact of welding and PWHT on the MCF of T91 boiler tubes. Of particular interest, Das et al. [14] recently demonstrated a novel application of MCF measurement for the in-situ detection and quantification of oxide scale exfoliation in stainless steel boiler tubes.

This study focused on examining the effects of various PWHT conditions on the MCF as well as on the hardness of T91 welds. The experiments tested soaking temperatures of up to 790°C and durations extending to 120 minutes. The primary objective is to establish MCF measurement as a dependable evaluation criterion, replacing hardness testing, to assess the quality of PWHT in T91 steel weldments.

2. Method of Investigation

T91 boiler tubes of thermal power plant, featuring an outer diameter of 44.5 mm and a wall thickness of 6 mm, were joined using the TIG welding technique. This process employed AWS E 9015 B9 low hydrogen electrodes with a diameter of 2.4 mm, in accordance with the Welding Procedure Specification (WPS) for T91 tubes. Throughout the welding process, a consistent root gap of 3 mm and an included groove angle of 60° were maintained. The preheating temperature was set at 220°C, and the inter-pass temperature was controlled and limited to 350°C. The various phases of the welding process for the modified T91 tubes are depicted in Figure 1. Following the welding procedure, the components were cooled to 90°C at a controlled rate of 150°C/h before commencing the PWHT cycle. Soaking temperatures were tested at five different levels: 700°C, 730°C, 750°C, 770°C, and 790°C. For each temperature, three soaking durations were applied: 30 minutes, 60 minutes, and 120 minutes, culminating in a total of fifteen PWHT cycles. The purpose of this experimental setup was to examine the relationship between the weld's hardness and its MCF values under different soaking temperatures and time durations. The minimum soaking temperature of 700°C was selected to simulate potential suboptimal PWHT conditions that might arise in field applications, while the maximum was capped at 790°C to prevent both the weld and base metal from surpassing the AC1 temperature of 830°C. Throughout all fifteen PWHT cycles, heating and cooling rates were consistently maintained at 150°C/h. To validate any potential relationship between hardness and MCF in as-welded conditions, two samples of welded tubes without PWHT were preserved. Metallographic specimens were prepared using standard grinding and polishing methods. For etching, Villela's reagent; consisting of 95 ml of

ethanol, 5 ml of hydrochloric acid (HCl), and 1 gm of picric acid-was applied to reveal the microstructure.

The hardness (Vickers hardness with a load of 5 kg) of the transverse cross-section samples taken from the weld tubes (Figure 4) was measured within the weld zone for all seventeen specimens. The hardness profiles for the base metal, heat-affected zone (HAZ), and weld zone across all seventeen samples are illustrated in Figure 5, with each sample undergoing a total of 22 measurements. Hardness measurements were conducted at a depth of 1 mm with a spacing of 1 mm between consecutive measurement points. The ten highest hardness values from the weld zone (Figure 4) were selected for analysis for each sample.

The MCF value for each PWHT sample was measured alongside that of the as-welded condition for comparison. Measurements were taken using a “Magnetic Structurescope,” an instrument equipped with magnetizing pole tips and a digital display, as illustrated in Figure 2. This device functions based on the principle of magnetic hysteresis. It applies current pulses to magnetize the material beneath the pole tips, followed by rapid demagnetization through current reversal. The reverse magnetizing force adjusts the magnetic retentivity, allowing the instrument’s internal circuitry to accurately compute the MCF. The measurement range of the device spans from 0.4 to 40 A cm⁻¹. The test setup used for evaluating MCF in welds is also depicted in Figure 2.



Fig 1. Photographs showing different stages of Welding of T91 Boiler Tubes. **(a)** Cut to Length, **(b)** Face or Bevel, **(c)** Cleaning, **(d)** Alignment, **(e)** Root Pass, **(f)** Hot Pass, **(g)** Heating Cycle in PWHT, **(h)** Soaking and Cooling Cycle and **(i)** Final Welded Tube

Table 1: Chemical Composition (wt %) of T91 As-received Tube

C	Si	Mn	P	S	Cr	Mo	Ni	Nb	V	Fe
0.135	0.275	0.46	0.012	0.004	8.4	0.90	0.13	0.09	0.2	rest



Fig 2. Photograph of MCF Measurement Test Setup Utilizing a Magnetic Structurescope.

3. Results and Discussion

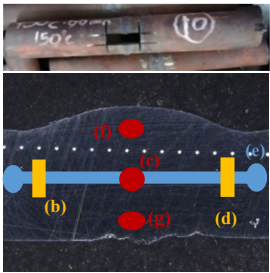
3.1 Material Composition

The composition of the as – received tube is shown in Table 1. The tube conforms to SA 213 – T91 grade of material.

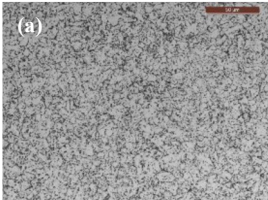
3.2 Micro Structural Analysis of As - received as well As-welded Structures of T91 Tubes

The ideal microstructure for Grade 91 components consists of tempered martensite, distinguished by a well-developed network of $M_{23}C_6$ carbides and MX-type carbo-nitrides. These precipitates generally form along lath boundaries and at defect sites within the substructure [11, 15]. Photomicrographs of properly heat-treated T91 steel typically reveal this characteristic tempered martensitic structure. However, the critical precipitate network responsible for the material's creep strength cannot be fully evaluated through optical microscopy alone. To achieve a detailed and accurate microstructural analysis, advanced characterization methods such as transmission electron microscopy (TEM) are required. Earlier studies [10-11] have shown that TEM analyses of as-received P91 pipes reveal a tempered martensitic matrix characterized by a high dislocation density and the presence of various precipitate types. Excessive tempering can adversely affect the martensitic structure, potentially leading to its complete degradation. While the cooling rate ultimately determines the final microstructure, factors such as the peak temperature and hold time during normalizing treatments significantly influence the size of the austenite grains. This grain size can be controlled by either adjusting the temperature or modifying the hold duration during the normalizing process. Pre-conditioning treatments, including normalizing and tempering, yield a tempered martensitic microstructure

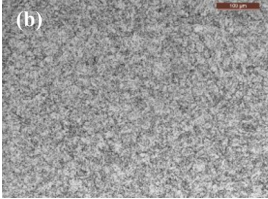
featuring acicular prior austenite grains in the base metal. Studies have demonstrated that a large number of precipitates-predominantly $M_{23}C_6$ carbides, where the metallic element M can include Cr, Fe, Mo, Mn, or their combinations-are commonly found along lath boundaries and prior austenite grain boundaries. When subjected to post-weld heat treatment (PWHT) at 770°C, the microstructures within both the heat-affected zone (HAZ) and the weld zone undergo significant transformations, as illustrated in Figure 3. Analysis of the weld zone at various depths indicates substantial reductions in the volume fraction of precipitates following annealing at this temperature. In the fusion zone, prior austenite grains transform into newly formed martensite, while tempered martensite coarsens as heat treatment temperatures rise. Studies have documented precipitation behavior in weld microstructures subjected to PWHT at 700°C for 60 minutes. At this soaking temperature, precipitates in the base metal zone align along lath boundaries. Increasing the soaking temperature to 770°C for the same duration leads to a significant increase in alloy carbide precipitation within the weld microstructure. Further elevation to 790°C results in additional coarsening of the tempered martensite, as noted in previous research [10].



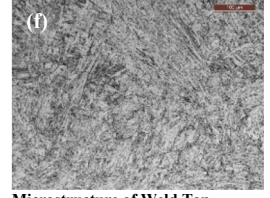
Schematic Illustration of the Sampling Locations Selected for Microstructural Analysis



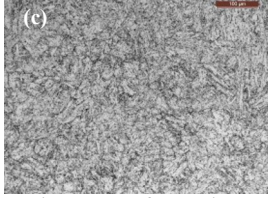
Microstructure of Base Metal (Left)



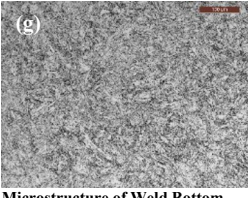
Microstructure of HAZ (Left)



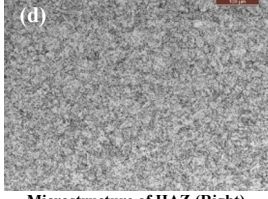
Microstructure of Weld Top



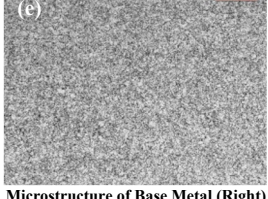
Microstructure of Weld Middle



Microstructure of Weld Bottom



Microstructure of HAZ (Right)



Microstructure of Base Metal (Right)

Fig 3. Microstructure of (a, e) Parent, (b, d) HAZ and (c, f, g) Weld Region after PWHT at 770°C, & 60 min of T-91 Weld Tubes.

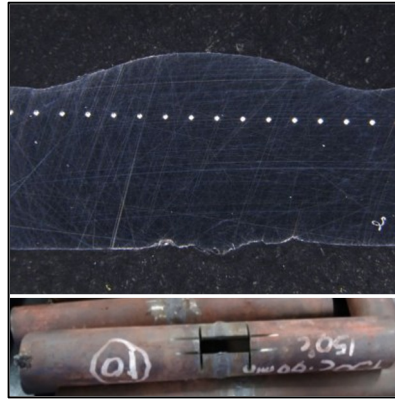


Fig 4. Photograph of Welded Tubes and Hardness Measurement Location

3.3 Hardness and Microstructural Influence of As welded and Post Weld Heat Treated Samples

Hardness measurements were performed along the transverse cross-section of the weld joints, with the results plotted as a function of distance from the weld centre (refer to Figure 5). These hardness values are closely linked to the underlying microstructure of the material. In the as-welded condition, the fusion zone exhibits a hardness of approximately 410 HV5, primarily due to the formation of fresh martensite. After PWHT, this hardness gradually declines as the martensitic structure undergoes tempering. The reduction in hardness within the fusion zone is further influenced by the coarsening of lath martensite and the transformation of retained austenite into softer alpha ferrite at elevated PWHT temperatures. In the as-welded state, the highest hardness-around 430 HV5 -is recorded in the coarse-grain heat-affected zone (CGHAZ), followed by a sharp decrease to about 330 HV5 in the inter-critical heat-affected zone (ICHAZ). This downward trend continues after PWHT, reflecting the thermal gradients experienced during the welding process. In the CGHAZ, temperatures can reach up to 1500°C, leading to carbide dissolution and an increase in hardness due to solid solution strengthening. In contrast, the ICHAZ-located further from the fusion line-experiences lower peak temperatures that are insufficient to dissolve carbides, resulting in reduced hardness in that region [16, 17]. Moving from the ICHAZ toward the base metal, a slight rise in hardness is observed for both as welded and PWHT samples. This increase is attributed to the limited impact of the welding thermal cycle on the base metal and the presence of a finer grain structure compared to the CGHAZ. Figure 6 illustrates a consistent decline in the hardness of the welds following PWHT cycles 1 to 15. This decrease in hardness is primarily due to the gradual reduction in dislocation density within the weld during these cycles. As the weld experiences progressive tempering throughout PWHT cycles 1 to 15, a steady decline in hardness is observed.

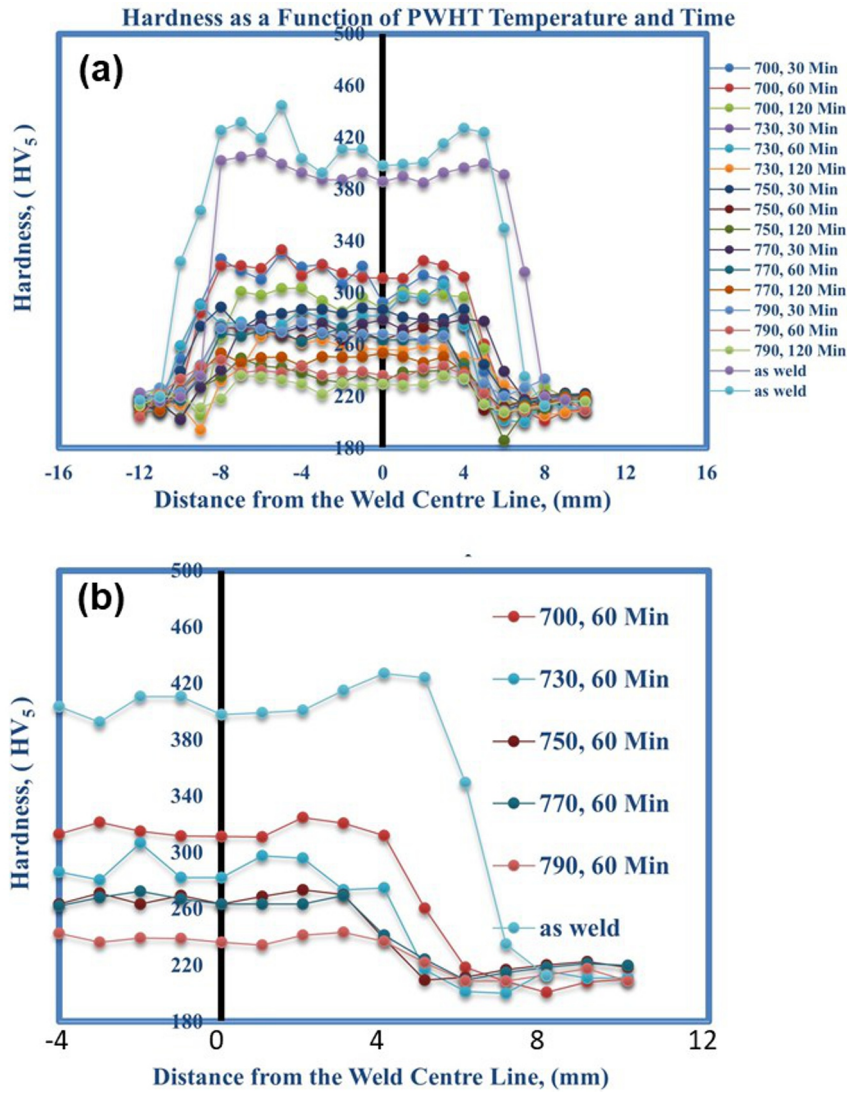


Fig 5. Hardness Variation with Distance from Weld Center for (a) All Samples and (b) Samples Soaked for 60 Minutes, Including the As - welded Sample.

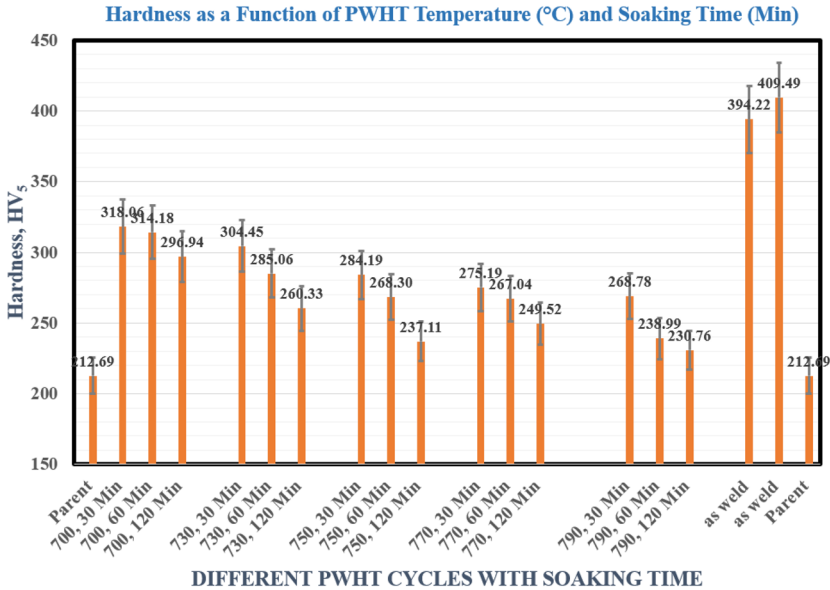


Fig 6. Hardness Variation Based on PWHT Temperature and Soaking Duration

3.4 Coercive Force in As welded and PWHT Samples

The MCF of the weld in its as-welded state ranges from 19.65 to 20.47 A cm⁻¹, exhibiting a gradual decrease as both soaking temperature and time increase during PWHT, as depicted in Figure 7. In the as-welded condition, the weld metal of T91 steel predominantly consists of martensite laths [17-20]. The elevated MCF observed in this state is primarily due to the presence of fine, newly formed martensite, which demonstrates greater magnetic hardness, along with residual stresses generated during the welding process. Martensite laths create a pinning effect that hinders dislocation movement, thereby increasing resistance to magnetic domain wall motion during magnetization. This restricted domain wall mobility explains the elevated coercivity observed in the as-welded condition. Following PWHT, the martensite laths in the weld metal begin to decompose, resulting in a lower dislocation density and a subsequent decrease in resistance to domain wall motion compared to the as-welded state. With fewer obstacles present, magnetization becomes easier, resulting in a consistent decline in coercivity throughout PWHT cycles 1 to 15, as illustrated in Figure 7. Recent studies [11] have shown that the filler material used in welding possesses lower coercivity than the base metal, making it magnetically softer. This disparity in magnetic coercivity is influenced by phase transformations that occur under varying PWHT conditions, as reflected in Figure 7. As PWHT temperatures increase, the number of pinning sites-such as dislocations, carbides, and grain boundaries-decreases, which facilitates easier movement of domain walls and contributes to lower MCF values. Figure 7 further illustrates that at a soaking

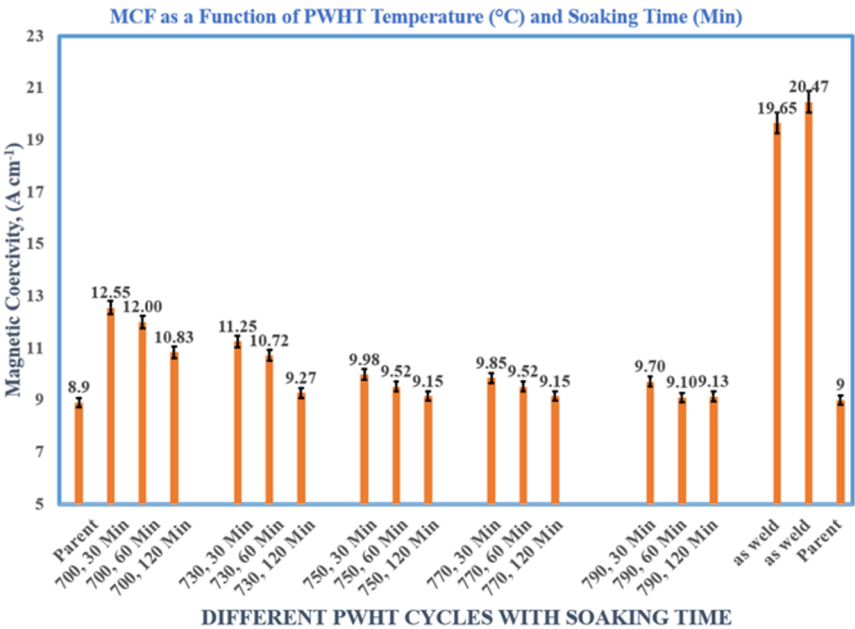


Fig 7. Coercive Force as a Function of PWHT Temperature and Holding Time

temperature of 700°C, increasing the soaking duration from 30 to 120 minutes leads to a more pronounced reduction in MCF. A similar trend is observed at soaking temperatures of 730°C, 750°C, 770°C, and 790°C. The most substantial reduction in MCF (55.39%) occurs at the highest soaking temperature (790°C) with the longest soaking time (120 minutes) among all fifteen PWHT cycles. This trend can be attributed to the increased activation energies available at elevated temperatures, which promote dislocation movement and lead to a notable reduction in dislocation density. The gradual decrease in MCF observed after PWHT cycles 1 through 15 can be attributed to the increased mobility of magnetic domain walls. This behavior in the base metal regions is consistent with findings reported in earlier studies [1, 9-11].

4. Establishment of a Criterion for Assessing the Quality of PWHT in T91 Welds.

Coercivity of the weld clearly reflects the extent of tempering achieved through PWHT, as discussed previously. Therefore, coercivity can serve as a qualitative measure for assessing the quality of PWHT in T91 welds. Additionally, Figure 8 illustrates that the percentage reduction in coercive force resulting from PWHT cycles 1 to 15 is directly proportional to the percentage reduction in weld hardness. To quantify this relationship, a regression equation was developed to mathematically represent the correlation between the percentage reduction in

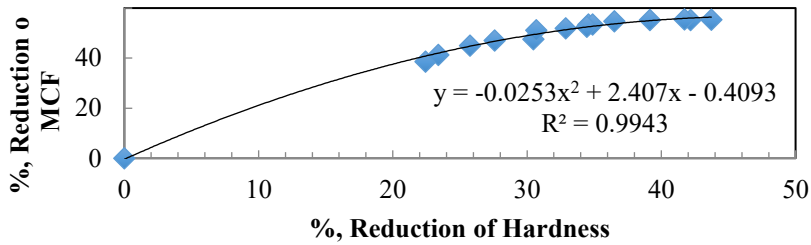


Fig 8. Correlation between %, Reduction in MCF and Hardness of T91 Weld Metal Following PWHT Cycles 1-15.

MCF and the percentage reduction in weld hardness, as shown below:

$$y = -0.0253x^2 + 2.407x - 0.4093, R^2 = 0.99433 \dots (1)$$

In this equation, ‘y’ denotes the %, reduction in MCF, while ‘x’ represents the %, reduction in hardness. The coefficient of correlation (R^2) for this equation is calculated to be 0.99433 (close to unity), indicating a very high degree of correlation. Additionally, according to EPRI document [8], the maximum permissible hardness for T91 steel welds that have undergone satisfactory PWHT should not exceed 280 HB, which is roughly equivalent to 294 HV.

Using this criterion, the equivalent condition for the coercive force of weld is established. In this study, the average hardness of the weld in its as-welded state is measured at 410 HV5 (Figure 5). With a target post-PWHT hardness set at 294 HV5, the necessary average reduction in hardness for acceptable PWHT quality is calculated to be 28.29%. According to Equation (1), this corresponds to an average reduction in MCF of 47.48%. Given an as-welded MCF value of 20.47 A cm⁻¹, it follows that a minimum reduction of 47.48% in MCF (equivalent to a 28.29% reduction in hardness) is required for the PWHT to be deemed acceptable. This results in a maximum allowable MCF value of 10.75 A cm⁻¹ for the weld following PWHT. The MCF values for the weld after PWHT cycles 1-4 exceed this acceptable limit of 10.75 A cm⁻¹. Furthermore, the lowest hardness recorded after these cycles is 296 HV5, which remains above the acceptable threshold of 294 HV5. Consequently, the quality of PWHT for welds from cycles 1-4 is considered unacceptable, as both MCF and hardness surpass the established limits. In contrast, PWHT cycles 5-15 yield weld hardness and MCF values fall below the specified limits, indicating acceptable PWHT quality. Thus, a criterion for acceptable PWHT quality in T91 welds has been established: “The MCF of the weld must not exceed 10.75 A cm⁻¹ after PWHT.” This finding offers a new and transferable framework for identifying T91 welds that have undergone inadequate PWHT. By employing this method, substandard welds can be readily identified, allowing for timely corrective actions to prevent premature service failures and unexpected plant outages.



Fig 9. In-Situ Evaluation of PWHT Effectiveness for T91 Boiler Tubes Through MCF Measurement.

5. Field Implementation: Evaluation of the Effectiveness of PWHT on T91 Tubes Through In-Situ Coercive Force Measurement

Following successful laboratory demonstrations, an MCF-based assessment of PWHT was carried out at a 660 MW NTPC plant as shown in Figure 9. This assessment involved measurements on 694 T91 tube welds, which included samples from the superheater header, outlet header, HRH, and superheater hanger tubes, as well as 156 T91 reheater inlet and outlet header tubes. A similar measurement technique had previously been utilized by the original equipment manufacturer (OEM) for T22 water wall tube welds at another NTPC facility. The field measurements revealed several advantages of using MCF-based assessments, including:

- a) High efficiency and speed of the process.
- b) Minimal surface preparation requirements compared to traditional hardness testing.
- c) Consistent and reliable results.

This measurement technique offers a rapid and dependable method for evaluating the effectiveness of PWHT on T91 welds, facilitating the quick identification of welds that require proper heat treatment or rewelding.

6. Conclusion

The research examined the MCF, microstructure, and hardness of T91 tube welds subjected to different PWHT conditions, which included control adjustments in soaking temperature and duration. The main findings are summarized as follows:

- i. **Base Metal Microstructure:** The base metal exhibited tempered martensite and acicular prior austenite grains, with numerous precipitates located along the boundaries of lath martensite and prior austenite. In contrast, the fusion zone displayed columnar grain structures lacking secondary particles.
- ii. **Hardness Distribution:** In the as-welded condition, the hardness increased from 410 HV5 in the fusion zone to 430 HV5 in the coarse-grained heat-affected zone (CGHAZ) due to the presence of dissolved and undissolved carbides. A sharp decrease to 330 HV5 was noted in the inter-critical heat-affected zone (ICHAZ).
- iii. **Effect of PWHT on MCF:** MCF values showed a consistent decline with increasing PWHT soaking temperatures, reaching up to 790°C, and longer soaking durations of up to 120 minutes.
- iv. **MCF as a Heat Treatment Indicator:** MCF measurements were effective in assessing the quality of PWHT in T91 welds.
- v. **Correlation Between MCF and Hardness:** A strong correlation was observed between the reduction in MCF and the decrease in weld hardness following PWHT.
- vi. **Quality Criterion:** A benchmark was established, suggesting that the MCF of the weld should not exceed $10.75 \text{ A}\cdot\text{cm}^{-1}$ after PWHT to ensure the weld's acceptable quality.

These findings provide valuable insights for evaluating the effectiveness of PWHT in T91 welds, particularly under practical field conditions.

Acknowledgments

The authors wish to extend their heartfelt gratitude to ED (NETRA) for his invaluable advice, suggestions, support, guidance, and encouragement in implementing these techniques at NTPC stations. They also thank the management of NTPC Talcher Kaniha and the coordinating departments for their cooperation and support during the welding experiments. Special thanks are due to Dr. V. Sudharsanam from WRI, BHEL, Trichy, for his significant assistance and contributions during the initial phases of the project. Additionally, appreciation is expressed to the NETRA Metallurgy Lab for their support in hardness measurement and microstructural characterization.

References

- [1] V. Sudharsanam, V. Senthilkumar, N. Raju, R. Vetrivelan, "Evaluation of Post Weld Heat Treatment Quality of Modified 9Cr-1Mo (P91) Steel Weld by Magnetic Coercive Force Measurements," *Archives of Civil and Mechanical Engineering* 15 (2015), 847-853.
- [2] I. A. Shibli, "Engineering Issues in Turbine Machinery, Power Plant and Renewables," In: *Proc. 6th Int. Charles Parsons Turbine Conf. on Dublin*: Maney Publishers; 2003, 261-79.
- [3] P. D. Smet, H. V. Wortel, "Controlling Heat Treatment of Welded P91 Hardness Testing Proves to be a Powerful Tool for Checking the Condition of P91," *Welding* 2006, 42-4.
- [4] American Society of Mechanical Engineers (ASME), *ASME Boiler and Pressure Vessel Code – VIII, Rules for Construction of Pressure Vessels, Division 1*, 2013 ed., The American Society of Mechanical Engineers, New York, 2013.
- [5] M.Z. Hamzah, M.L. Ibrahim, Q.H. Chye, B. Ahmad, J.I.I. Hussain, J. Purbolaksono, "Evaluation on the Hardness and Microstructures of T91 Reheater Tubes after Post-Weld Heat Treatment," *Engineering Failure Analysis* 26 (2012), 349–354.
- [6] D. Buzza, "P91 Piping Fabrication Guidelines, in: *American Electric Power Combined Cycle User's Conference, USA, 2013*, Available from: http://ccusers.org/wpcontent/uploads/2012/04/111031_CCUG_P91_Fabrication_Guidelines_Dave_Buzza-1.pdf (accessed: 05 May).
- [7] R.L. Klueh, J.P. Shingledecker, *Investigation of a Modified 9Cr– 1Mo (P91) Pipe Failure*, ORNL/TM-2006/1, Oak Ridge National Laboratory, Tennessee, 2006.
- [8] J. Parker, "The Use of Portable Hardness Testing in Field Applications for Grade 91 Steel," *The Electric Power Research Institute (EPRI) Report No: 1024695*, June 2012.
- [9] A. Mondal, A.K. Das, S. Chand, "Application of Advanced NDE Tools for Health and Life Assessment of Critical Power Plant Components During the Flexible Operation Regime," In: Ghose, B., Manoharan, V., Mulaveesala, R. (eds) (2024). *Advances in Non-Destructive Evaluation (NDE). NDE 2021. Lecture Notes in Mechanical Engineering*. Springer, Singapore. https://doi.org/10.1007/978-981-97-1036-2_17
- [10] A. Mondal, A.K. Das, "Internal AUSC Project Titled "Non-destructive Evaluation of Post Weld Heat Treatment Quality of Ferromagnetic Steel (P91) Weld by Magnetic Coercive Force (MCF) Measurement", Project No: AUSC-N-NTR-NDEL-006, Report Submission (July 2019).
- [11] R. K. Roy, A. K. Das, A. K. Metya, A. Mondal, A. K. Panda, M. Ghosh, S. Chand, S. P. Sagar, S. K. Das, A. Chhabra, S. Jaganathan, A. Mitra, "Microstructure Atlas of P91 Steel", Springer Singapore, Published: 27 April 2023, <https://link.springer.com/book/10.1007/978-981-19-9562-0>
- [12] E. Sambamurthy, S. Dutta, A. K. Panda, A. Mitra, R. K. Roy, "Evaluation of Post-Weld Heat Treatment Behavior in Modified 9Cr-1Mo Steel Weldment by Magnetic Barkhausen Emission," *International Journal of Pressure Vessels and Piping* 123-124 (2014) 86-91.
- [13] R. K. Roy, P. Murugaiyan and A. K. Panda, "Evaluation of Post-Weld Heat-Treated 2.25Cr-1Mo Steel Joint Behaviors by Electromagnetic NDE Parameters," *Journal of Superconductivity and Novel Magnetism, Research*, Volume 3, (July 2024), Pages 1677–1687.
- [14] A.K Das, A. Mondal, S. Chand, A. Chhabra "In-situ Detection and Quantification of Oxide Scale Exfoliation in Stainless Steel Boiler Tubes by Magnetic Coercive Force (MCF) Measurement., In: Mandayam S, Sagar SP (eds) *Advances in non-destructive*

evaluation. lecture notes in mechanical engineering. Springer, Singapore. https://doi.org/10.1007/978-981-16-9093-8_14.

[15] J. Shingledecker, "Evaluation of Grade 91 Microstructure and Creep Rupture Strength as a Result of Heat Treatment Around the Intercritical Zone," The Electric Power Research Institute (EPRI) Report No: 1015818, March 2009

[16] J. Siefert, "Creep Strength-Enhanced Ferritic (CSEF) Steel Welding Guide," The Electric Power Research Institute (EPRI) Report No: 1026584, August 2013

[17] M. Sireesha, S.K. Albert, S. Sundaresan, "Microstructure and Mechanical Properties Of Weld Fusion Zones in Modified 9Cr– 1Mo Steel," Journal of Materials Engineering and Performance 10 (3) (2001) 320–329.

[18] G. Guntz, M. Julien, G. Kottmann, F. Pellicani, A. Pouilly, J. C. Vaillant, The T91 Book: Ferritic Steel Tube and Pipe for High Temperature Use in Boilers. France: Vallourec Industries; 1990.

[19] J. Parker, "The Effect of Variables on the Results of Field Hardness Testing of Grade 91 Steel," The Electric Power Research Institute (EPRI) Report No:1024694, November 2011

[20] L. Cipolla, P. Folgarait, J. Parker "Advanced Metallurgical Characterization of Grade 91 Steel Samples," The Electric Power Research Institute (EPRI) Report No: 1024721, January 2012

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this chapter or parts of it.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

