# Welding technology of martensitic steel P91 and austenitic steel 304H – State of the art

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***Abstract:*** *Many industries nowadays with the development of technology require joints between different types of steel due to its various benefits such as production of lightweight machine parts, production of less expensive components with acceptable properties, high strength, acceptable corrosion resistance. One of the dissimilar welding challenges is the joint between martensitic steel P91 and austenitic steel 304H due to the dissimilarities in their chemical, physical and metallurgical properties. In this paper is going to be analysed the best way of joining the two different types of steel, the proper welding technique, the choice of filler material which according to carbon content can match only to one of the steels. At the end is discussed if the welding performance can meet the requirements of high-quality weld.*
***Keywords****: P91, 304H, DISSIMILAR METAL WELD, WELDING TECHNOLOGY*

## 1. Introduction

The coal-fired power plant systems today are striving to work in supercritical steam parameters and assure higher efficiency. The need for higher efficiency is met with higher steam parameters, increase of steam pressure and steam temperature. Another parameter that coal-fired power plants need to incorporate is the method for clean energy, the use of coal needs to satisfy the environmental requirements and take care about the air pollutants [1]. When it is discussed about higher efficiency in power plants and satisfying the environmental requirements for clean energy in coal-fired power plants it means a saving in fuel and less emission of carbon dioxide which reduces the rate at which damage is done to the global environment.

The need for higher efficiency in power plants today relates to the development of new materials with great properties on high temperatures. The possibility for higher steam parameters and working of the plant on super-critical temperatures is met with the development of new enhanced materials.

The new materials resistant to high operating temperatures, also called heat resistant steels, are used for manufacture of ultra-super critical parts of boiler plants such as steam lines, tubes for super heaters, collectors. Regarding construction of power units based on steam with ultra-supercritical parameters the operation of pressure elements in the high range of thermal and mechanical loads require the use of creep resisting construction materials with increased creep strength and advanced welding technologies for joining these materials. All the demands for high efficiency in power plants lead to development of enhanced materials like martensite steels, austenitic steels, Ni-alloys, alloys that work in high temperature applications.

## 2. Heat resistant steels in power industry

Steels which are used at temperatures up to the recrystallisation temperature are called heat resistant steels. They are characterized with good creep strength at high temperature. The materials that meet the above criteria are the ferritic (martensitic, bainitic) steels and austenitic steels. In table 1 is given the classification of creep resistant steels. The ferritic and martensitic steels have body-centered cubic crystal structure and in the iron is added chromium as one of the methods for improvement in high-temperature creep resistance and creep strength of steels used in power industry. Also adding alloy elements such as molybdenum, vanadium, niobium and nitrogen to improve their heat resistance [2].

Martensitic steels with chromium addition up to 12% are used for elements in construction that can withstand higher pressure and higher service temperature for application up to 650°C. Over 650°C are used austenitic steels that have nickel added to the iron-chromium composition and the alloy changes his body-centered cubic crystal structure to face-centered cubic crystal structure. In comparison, austenitic steels have highly strength and ductility, greater creep-rupture strength than martensitic steels. However, the austenitic steels are much expensive than martensitic steels for their high contents of alloy element additions.

Chromium is added for oxidation resistance, high temperature strength and carburization resistance. Nickel is added to increase ductility, high temperature strength and resistance to carburization and nitriding. With adding element nickel the atomic structure becomes austenitic.

***Table 1****: Classification of creep resistant steels*

| ***Heat-resistant steels and special materials*** | | | | |
|---|---|---|---|---|
| Bcc structure (body-centered cubic) | | | | Fcc structure (face-centered cubic) |
| Up to 400°C | Up to 500°C | 500 to 600°C | 600 to 650°C | Above 700°C |
| Unalloyed | Alloyed | | High-alloyed | |
| Ferritic-pearlitic steels, fine-grain structural steels | Mo- alloy steels | Bainitic (martensitic) ferritic steels | Martensitic 9 to 12% chromium steels | Austenitic steels, Ni and Co-materials |
| P235GH | 16Mo3 | 13CrMo4-5 | X10CrMoVNb9-1 | X8CrNiNb16-13 |
| P355NH | 18MnMo4-5 | 10CrMo9-10 | X22CrMoV12-1 | X8NiCr32-20 |
| No extra proven methods; higher purity; fine grain | Tr-increase through molybdenum alloying | Carbide/nitride formation + tempering | Precipitation hardening + spec. heat treatment | Fcc structure with high crystal recovery temperature |

In this paper the emphasis is on martensitic steel type P91 and austenitic steel type 304H. For example, for boiler components materials, the austenitic steel 304H is used for boiler super heater tubes, elements that are experiencing 630°C and for steam headers and piping is used martensitic steel P91. The heater tubes need to be welded with the steam headers, that is why the need for dissimilar welds become necessary.

A dissimilar metal weld (DMW) is when grades with different chemical compositions are welded together. In fossil-fired power plants dissimilar metal welds are very common in the present. Austenitic stainless steel attachments welded onto ferritic steel tubes and pipes, stainless steel thermowells or steam sampling lines in ferritic steel pipes. On figure 1 is shown the possible combination of materials used and the fabrication techniques and welding processes involved in the fabrication of a steam boiler component [3].


***Fig. 1**: Combination of materials, fabrication techniques and welding processes in fabrication of steam boiler [3]*

## *3. Welding of heat resistant steels*

Heat resistant steels with its strength at high temperatures needs to have sufficient resistance to creep processes. Creep usually occurs at high temperatures, where plastic deformation of materials takes place well below its yield strength under prolong stresses.

The dissimilar welded joints, used in piping systems, always represent a critical place in the system, in terms of possible occurrences of defects. The creep takes significant role in failure of these weld joints since it is the main cause of failure at elevated temperatures [4]. The dissimilar welded joints between martensitic and austenitic steel are often used in energy and process industry for new and refurbishment of existing plants. For creation of this type of joints and creation of weld with acceptable structural characteristics all recommendations and parameters of the welding process and heat treatment needs to be followed.

Matching filler metals for the new heat resistant steels and their great properties at elevated temperatures have been developed and qualified for all commonly used welding processes.

According to the different chemical composition of the materials for creation of dissimilar joint, one of the materials will encounter the carbon diffusion due to the difference in Cr content. Carbon moves from the material with low Cr content to material with high Cr content. The decarburization zone can be avoided with the use of nickel-base filler metal (fig.2), since carbon does not diffuse into the nickel-base material, using welding parameters such as preheating, and post weld heat treatment (PWHT) suitable to P91 [2].

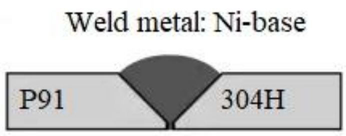


***Fig. 2*** *Dissimilar weld between martensitic and austenitic steels*

After 1970s, in research carried out by Electric Power Research Institute (EPRI) and other organizations, an increasing number of dissimilar metal welds in superheater and reheater tubes were fabricated as fusion welds using nickel-based filler metals, such as INCO 82, INCO 182 etc. The technical purpose for the switch to the nickel-based filler metals was the improved compatibility in thermal-physical properties with the lower alloyed materials [5].

Heat-resistant steels can be welded with use of various arc welding processes. In most cases, manual metal arc welding and tungsten inert gas welding are used. With tungsten inert gas welding of chromium-alloyed materials special attention must be dedicated to shielding the weld root, for this argon is suitable as a shielding gas.

To maintain and assure quality welds special attention should be dedicated to temperature time cycle of steel P91 as shown in figure 3 [6]. All heat treatment operations are a key factor when welding P91 steel for obtaining the required toughness and creep resistance. An extremely well controlled preheat, interpass temperature and PWHT are mandatory to ensure that the required creep rupture properties and toughness are obtained in the weldment.

The time at temperature for PWHT depends on the thickness of the part. The PWHT temperature should also be controlled so that the formation of austenite, which would result in the formation of untempered martensite, is avoided.

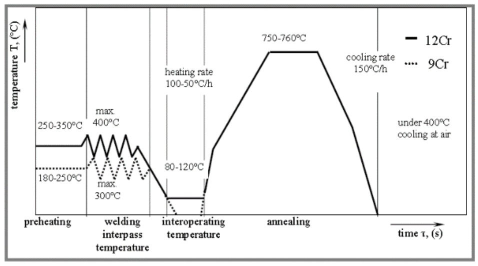


***Fig 3:** Temperature time cycle during welding of martensitic 9 or 12% chromium steels [6]*

On fig. 4 [7] is shown a reduction in dimensions of structural components used in power plant for work at elevated temperatures. The use of P91 results in lower costs by reducing the mass of the structure and the labor. The design parameters are: design pressure 280 bar and design temperature 550°C.

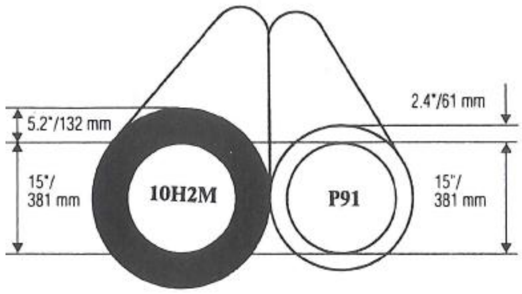


***Fig.4**: Wall-thickness of pipes used for same design parameters [7]*

When it comes about welding P91 certain welding procedures and specification needs to be managed. Creep strength martensitic steels are highly hardenable, and upon cooling after welding, they undergo phase transformation that results in a fully martensitic structure. To obtain the desired properties the welds must undergo PWHT and an interpass temperature must be maintained. All the welding procedures and recommendation needs to be fulfilled to obtain quality welds and avoiding failures in the fossil fired power plants [8].

P91 is used for heavy sections such as pipes and headers in the advanced fossil fired power plants and austenitic stainless steel 304H is candidate steel for superheaters and reheater pendants, where the temperature is high. The best way of joining and producing quality welds is TIG process [9]. Current dissimilar metal welds involve buttering one end of the base metal with a suitable filler metal, PWHT and joining to the other base metal. The buttering is used to deposit surfacing metal on the base metal surface to provide compatible weld metal for the subsequent completion of the weld (fig. 5) [10].

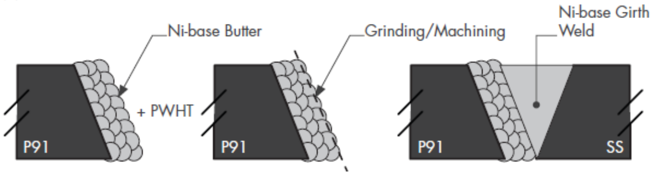


***Fig. 5**: Buttering of P91 steel [10]*

In the EPRI publication (11) several weld metal composition and choice of welding process is considered. The composition ranges differ for several elements but significant are nickel and manganese which influence on critical temperatures such as Ac1, Ms and Mf. The base metal specification allows maximum of 1% (Ni + Mn) whereas it is possible to have much higher levels in filler metal. When Ni+Mn reaches 1.4% the Ac1 decreases to 780°C, The Ms decreases below 350°C and Ms decreases below the required preheat temperature of 200°C. Cooling the weldment to room temperature prior to the PWHT is one way to avoid the formation of fresh martensite after PWHT. For good toughness in the weld seam, it is desirable to aim towards high nickel contents.

The filler material is mainly nickel based alloys which provide transition in coefficients of thermal expansion as well as proven to be beneficial for stopping the carbon diffusion from ferritic to austenitic side compared with conventional austenitic base filler [12].

## 4. Defects in Dissimilar Metal Welds

The dissimilar welded joints between martensitic and austenitic stainless steel always represent a critical place in the system, in terms of possible occurrences of defects. The chemical composition gradients (tab. 2) present unique issues relative to their design, behavior and life management especially operating at elevated temperatures.

***Tab.2:*** *Chemical composition of base metals and filler material (in wt.%)*

| | BM P91 | BM 304H | FM Thermanit Nicro 82 |
|---|---|---|---|
| C | 0,08 ÷ 0.12 | 0,04 ÷ 0.08 | 0.02 |
| Mn | 0.30 ÷ 0.60 | max. 2.00 | 3.0 |
| Si | 0.20 ÷ 0.50 | max. 1.00 | 0.1 |
| P | max. 0.015 | max. 0.035 | |
| S | max. 0.010 | max. 0.015 | |
| Cr | 8.00 ÷ 9.50 | 17.00 ÷ 19.00 | 20.0 |
| Ni | max. 0.40 | 8.00 ÷ 11.00 | >67.0 |
| Mo | 0.85 ÷ 1.05 | | |
| V | 0.18 ÷ 0.25 | | |
| Al | Max. 0.04 | | |
| Nb | 0.06 ÷ 0.10 | | 2.5 |
| N | 0.03 ÷ 0.07 | max. 0.11 | |
| Fe | Bal. | Bal. | <2 |

Failure mechanisms were noticed in thicker section between dissimilar weld with austenitic steel. For joining these two different materials, nickel base alloy filler material is used applying all the recommended welding parameters, preheat, interpass and PWHT for P91 steel. In EPRI report [13] where documented service experience of thick section of grade 91 in dissimilar welds. The most common failure has been cracking along the weld fusion line between grade 91 and the nickel base weld metal presented on fig. 6 [13].

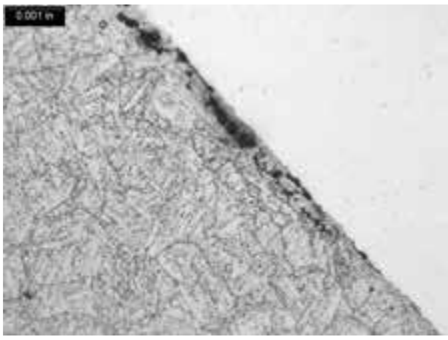

***Fig. 6****: Failure in grade 91 in DMW with nickel base weld metal [13]*

The premature failures are creep related, occurring in short service life duration of the weld and typically along the grade 91 to nickel-base weld metal fusion line. There is a need for research work between dissimilar welds of P91 steel and 304H stainless steel because of increased demand for this type of joints in ultra-super critical power plants because of their better performance [14]. For accurate prediction of weld joints, its accuracy in service life is essential. Therefore, special attention needs to be paid to creep phenomenon which occurs at elevated temperatures, applying PWHT in acceptable range of annealing temperature which contribute to accelerate damage during service and results in type IV cracking. The degraded microstructure of the dissimilar welded joints is seen occurring within HAZ on the P91 steel side [15].

## 5. Conclusion

When joining metals with different chemical compositions and metallurgical properties of importance is the welding technology with particular attention paid to filler metal chemistry and PWHT. Tungsten inert gas (TIG) welding is the most preferred method for joining these two metals, it gives a strong weld with the required parameters.

As coal fired power plants will remain major source of energy it is necessary to research in improvement in plant efficiency and reduction of carbon footprint. New materials with better high temperature creep properties are developed and special attention should be paid on the selection of a suitable welding process and the performance of a suitable welding technology. Because of the good great properties at elevated temperatures and their applications in ultra-super critical power plants needs to predict creep failure controlling mechanism for better performance of the power plant fulfilling the requirement for higher efficiency and clean energy.

## 6. References

1. Viswanathan, R., Henry, J.F., Tanzosh, J. et al., U.S. program on materials technology for ultra-supercritical coal power plants. J. of Materi Eng and Perform 14, 281–292 (2005)
2. Tasak E., Ziewiec A.: Weldability of construction materials. Volume 1. Weldability of steels, Wydawnictwo JAK – Krakow 2009.
3. R. Viswanathan, R. Purgert, S. Goldstine, J. Tanzosh, G. Stanko, J. Shingledecker and B. Vitalis: Proc. 5th Int. Conf. on ‘Advances in materials technology for fossil power plants’, Marco Island, FL, USA, October 2007, 1–15
4. S. Chaudhuri, NML Jamshedpur 831007, India, 2008, pp. 85-114
5. EPRI report 2008, Report 1015699
6. J. Pecha, D. Stano, O. Peleš, Welding of 9% Cr creep resisting steels for power Engineering equipment, Zavarivanje i zavarene konstrukcije (4/2004), str. 159-168
7. The success of a new material P91/T91 steel enhances power station efficiency, Mannesmann Rohrwerke report, S28/29
8. W. F. Newell, Jr.: ‘Welding and post weld heat treatment of P91 steel’, Weld. J., 2010, 33–36.
9. Echezona, Nnamdi & Akinlabi, Stephen & Jen, Tien-Chien & Fatoba, Olawale & Hassan, Sunir & Akinlabi, E.. (2021). Tig Welding of Dissimilar Steel: A Review. 10.1007/978-981-16-3641-7_1.
10. T. Totemeier, Dissimilar Metal Welds in Grade 91 Steel, Structural integrity 2018, volume 44, pg15-18
11. Coleman K, Gandy D. Guideline for welding P(T) 91, document 1006590, EPRI, 1300 W.T. Harris Blvd., Charlotte, NC 28262, USA; 2002
12. J.M. Rase, Carbon Diffusion Across Dissimilar Steel Welds 1992
13. EPRI report 2014, Report 3002006759
14. Krstevska, Aleksandra & Poser, Maja & Zdraveski, Filip. (2022). WELDABILITY BETWEEN STEEL TYPE 304H AND STEEL TYPE P91 FOR HIGH TEMPERATURE APPLICATIONS.
15. A Zielinski, G Golanski, P Urbanczyk, J Slania, J Jasak, Microstructure and properties of dissimilar welded joint between p91 and tp347hfg steels after 105 000 h service, Prace IMZ 1 2015