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# A statistical approach to demonstrate the variation in hardness of Heat affected zones and weld pool formed during TIG welding between P91-P22 grade steels

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*Abstract* -**The research outlined in this paper is an investigation of the microstructure and hardness of weldments of 2.25Cr-1Mo steel (P22) with 9Cr-1Mo (P91) before the application of preheat and/or post weld heat treatment. The dissimilar GTAW weld joints between P22 steel and P91 steel is commonly used in power plants. After welding, high hardness values of the Heat Affected Zone (HAZ) of those dissimilar weld joints were possibly obtained. In such weldments, carbon diffusion occurs during the welding due to the difference in chromium content of the materials. Carbon migrates from the lower chromium material to the higher chromium one. This high hardness HAZ also comes from the austenite transformation to martensite due to the high cooling rate. Weld pool and HAZ in P22 and P91 were mechanically tested and metallurgically examined after Tungsten Inert gas (TIG) welding. The present work highlights the uncovering impact of TIG welding on weld pool formed and HAZ of P91 and P22 steels with 95% confidence level. A statistical technique like one way ANOVA is used to expose the behavior of parent materials after TIG welding. Metallurgical images of the weld pool and HAZ are also demonstrated to support the findings.**

Keywords: Dissimilar weld joints, GTAW weld joints, Heat Affected Zone, Weld pool, Hardness, one way ANOVA

## 1. INTRODUCTION

The selection of modified 9Cr–1Mo steel for all the components, i.e., tubes, shell and thick section tube plates of steam generators of sodium cooled fast reactors (SFRs) is based on the low thermal expansion coefficient and high resistance to stress corrosion cracking in water–steam systems [Lundin CD, 1991 and SL Mannan, Chetal SC, B.Raj , SB Bhoje et.al 2003 ]. The steel also offers a good combination of high creep strength and ductility over long exposures at high temperatures [B.Raj and B.K. Choudhary, 2010]. The good weldability and micro structural stability over long exposures at elevated temperatures are other attractive features for the steel. Furthermore, the fabrication of steam generator in monometallic material enhances the reliability of the components including critical tube to tube plate welds [SL Mannan, Chetal SC, B.Raj , SB Bhoje et.al 2003]. P91 pipes have become a standard material for the design of new and refurbishment of existing Power Plants [Nattaphon Tammasophon, Weerasak Homhrajai and Gobboon Lothongkum et.al 2011]. In steam power plants of the Electricity Generating Authority of Thailand (EGAT), the dissimilar TIG weld joints between P22 (2.25Cr) steel and P91 (9Cr) steel using Inconel 625 as filler metal were used [Electricity Generation Authority of Thailand,2008]. The ASME Boiler & Pressure Vessel Code to the structural assessment and design optimization of dissimilar welded joints subjected to transitory thermo-mechanical loads. A large number of dissimilar P22/P91 steel welded joints of a power generation plant were taken into consideration. The joints vary in geometrical and operational conditions [L. Collini, M. Giglio and R. Garziera et.al 2012]. Several major failures have been encountered after fabrication of these new Creep Strength Enhanced (CSE) steels and are mainly attributable to improper practices Plants [Nattaphon Tammasophon, Weerasak Homhrajai and Gobboon Lothongkum et.al 2011].The lifetime assessment factors of welded components, implemented in the Design Codes, must be urgently updated for the modern materials and the advanced steam parameters used in the piping construction. The observed carbide depletion in the P22 weld metal adjacent to the fusion line of P91-P22 dissimilar welds and its effect on the weld strength reduction have to be taken into account [P.Seliger and A. Thomas ,2006]. It was found that, in both the as-welded and post-weld heat treated condition, the highest tensile stresses resided near the outer boundary of the heat-affected zone (HAZ), and towards the weld root region. The highest tensile residual stresses were found at boundary between HAZ and adjacent parent materials, hydrostatic residual stresses were generated in vicinity of HAZ and compressive residual stress [S. Paddea, J.A. Francis, A.M. Paradowska, P.J. Bouchard and I.A. Shibli et.al 2012]. Moreover, the highest tensile residual stresses (and significant hydrostatic stresses) coincided with the HAZ boundary and the parent material that leads to cracking

in these welds, in as-welded conditions [S. Paddea, J.A. Francis, A.M. Paradowska, P.J. Bouchard, I.A. Shibli(2012, B.K. Choudhary. Christopher, D.P. Rao Palaparti, E. Isaac Samuel and M.D. Mathew et.al 2013].
From Literature survey it was found that creep and fatigue failures are points of interest for the researchers in past decade. Moreover, creep and fatigue failures occur after prolonged time. Most of the literature includes similar metal welding and their joint strength but dissimilar metal joints were not the part of study of researchers. Only few practitioners showed their interest in failures occurred due to strength and hardness of the joint formed between dissimilar metals. In the present work a statistical approach is used to find the variation in harnesses of the different zones formed during welding of P91 and P22 grade steel.
This paper is organised as follows. Section 1 provides review of literature on P91 and P22 steel welding. Section 2 presents the details of adopted methodology. Section 3 gives the descriptions of results and discussions and conclusions from present work are drawn in section 4.

## 2. ADOPTED METHODOLOGY

Two seamless pipes (P91 & P22 grade steel) of diameter 36 mm, 6 mm thickness and 300 mm long were purchased from Industrial area phase- I Chandigarh and resized by power hacksaw in the size (50 mm each) as per TIG welding requirement. Their edges were being prepared at $45^0$ so that the single V butt joints were being prepared between them. Then these dissimilar grade steel pipes were welded (Figure 1) under skilled welding techniques which include preheating while maintaining inter pass temperature and post heat temperature according to AWS standards listed in table 1.

**Table 1: Process parameters used in TIG welding**

| | |
|---|---|
| Current | 11-13A |
| Voltage | 130-160 |
| Pre heat Temperature | 250 $^0$C |
| Inter pass Temperature | 300 $^0$C |
| Post heat Temperature | 350$^0$C |
| Travel Speed | 3-5 cm/min |
| Welding Pass | 3 |
| Pipe Dimension | 1.5” dia,6mm thickness, Seamless |

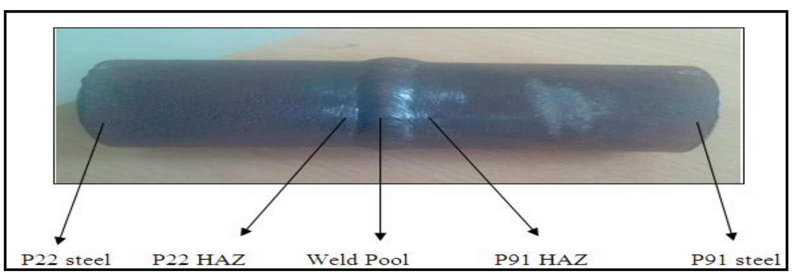


**Figure 1: Dissimilar welding Joint**

After welding Samples were again prepared (Figure 2) by using pipe cutter machine and investigated for micro hardness at 10 Kgf by using Vickers hardness tester at CITCO Chandigarh at different 5 zones viz. P91 base metal, P91HAZ, Weld pool, P22 HAZ and P22 base metal. For each zone set of 4 readings were being taken.

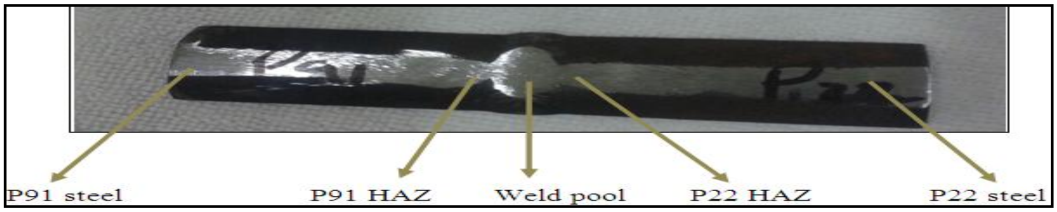


**Figure 2: Prepared Sample for Hardness test**

Microstructures of different regions were studied by using Optical microscope at 200X. Abrasive papers ranging from P80 down to P4000, with approximate particle diameters of 180 to 3µm respectively were used with a constant flow of water. Before observations samples surfaces were being etched by Villella's Agent and properly polished. Scanning Electron micrograph (SEM) of one sample was carried out at 3000 magnification on 15kev, which has Weld diameter of 15mm. Energy dispersive x-ray spectrometry (EDS) analysis was also carried out to investigate the peaks of chromium in HAZ and weld pool.

## 3. RESULTS

### 3.1Optical Micrography

Figure 3 illustrate the effect of TIG welding on the microstructures obtained for the different regions formed between P91 and P22 steel. The microstructure of P91 consists of Tempered Martensite while P22 consists of polygonal ferrite embedded in bainitic ferrite matrix. Since in the Heat affected zones, initial microstructure of P91 and P22 were dissimilar, and have been affected differently by the heat produced in the weld zone. HAZ of P91 consists of martensite and retained austenite while HAZ of P22 consists of ferritic bainitic microstructure with finer grains as compared to base metal.

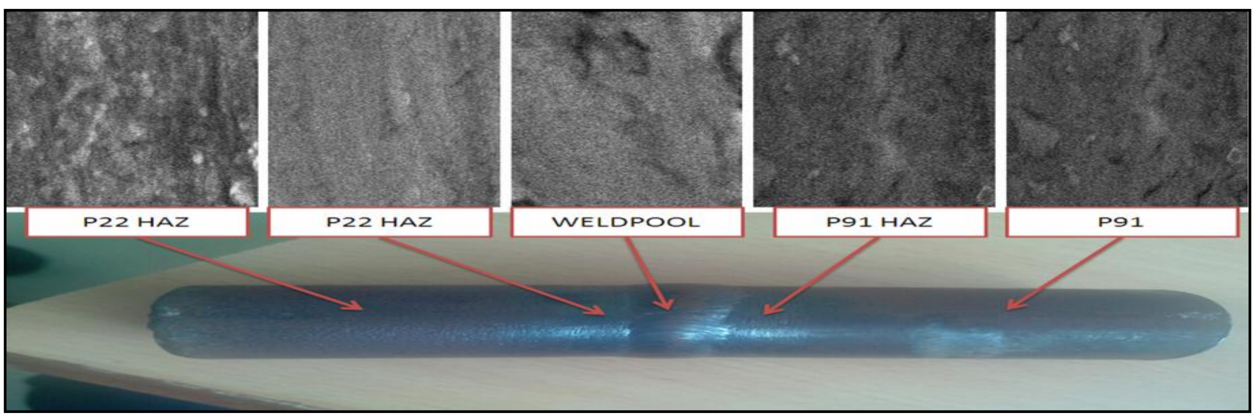


**Figure 3: Optical micrographs of different regions**

Weld pool consists of bigger grain size structure of martensite and retained austenite phases due to higher temperature conductivity of filler material. Some Carbide precipitation also occurred when the chrome and carbon in the austenitic steel is drawn out of the material and reacts to the atmosphere which make this zone much harder than the other zones.

### 3.2 SEM/EDS analysis

SEM of P91 HAZ (Figure 4) at 3000 magnification on 15kv shows coarse prior austenite grains with fine prior delta ferrite grains which occurred due to phase transformation from martensite to austenite at higher temperature near weld zone. Where as P22 HAZ (Figure 4) consists of ferritic bainitic microstructure with finer grains.

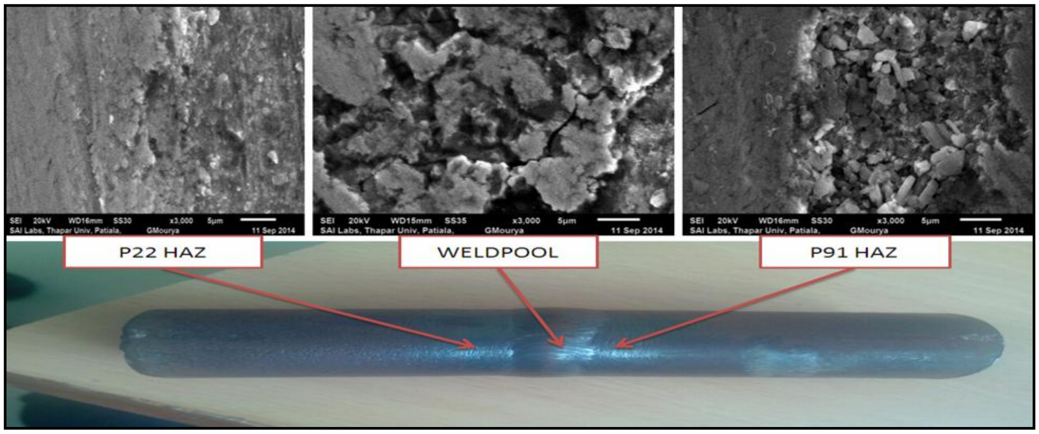


**Figure 4: SEM of P22 HAZ, Weld pool, P91 HAZ**

Compared to HAZ of parent materials SEM of weld pool (Figure 4) showed ($C_{23}C_6$) carbides at grain and sub grain boundaries and fine MX precipitate within sub grains. Both these phases were stable in temperature range from 525 to 625°C and cause high creep strength of steel.

Figure 5 Showed EDS analysis of P91 HAZ, Weld pool and P22 HAZ. The peaks in graphs showed the major elements present in steels i.e. iron, chromium and carbon.

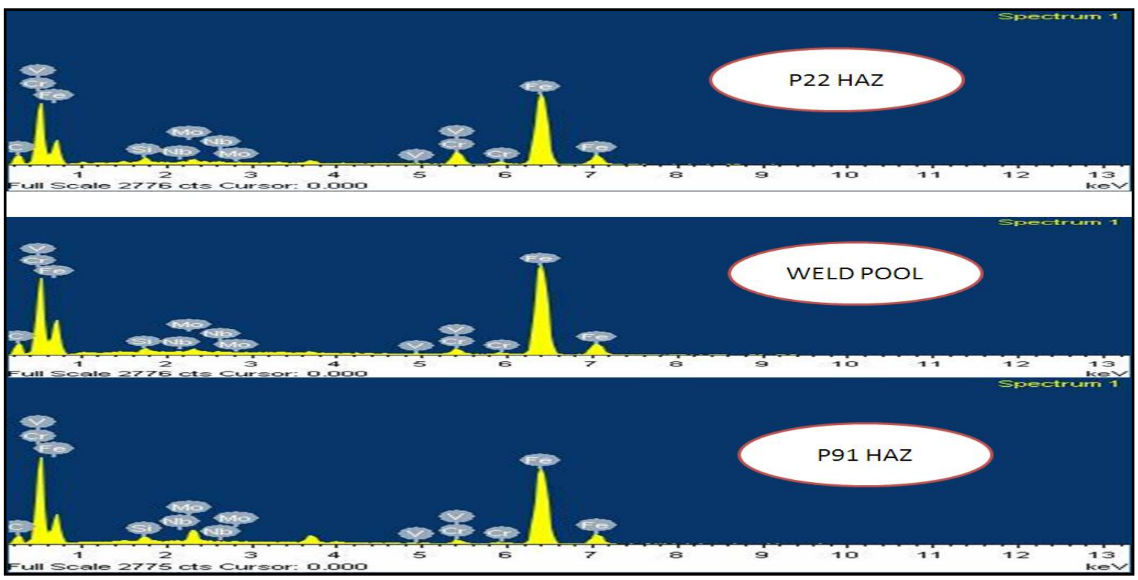


**Figure 5: EDS analysis of P22 HAZ, Weld pool, P91 HAZ**

From this analysis it can be conclude that the percentage of carbon was more in P91 HAZ where as hardly any carbon on P22 HAZ lead to decarburized zone. EDS analysis of weld pool showed the percentage of carbon and chromium increase in this zone and presence of molybdenum indicate the formation of ($C_{23}C_6$) with MX. Hence better hardness was obtained for this zone as compare to other zones.

**Hardness determination of welded samples**

Table 2 shows the harnesses of all the zones for different samples on a Vickers's Hardness Testing machine at 10kgf load.

**Table 1: Micro Hardness of different zones**

| P22 Base Metal | P22 HAZ | Weld Pool | P91 HAZ | P91 Base Metal |
|---|---|---|---|---|
| 202 | 289 | 312 | 290 | 231 |
| 201 | 296 | 298 | 292 | 233 |
| 204 | 282 | 319 | 273 | 236 |
| 200 | 338 | 350 | 333 | 234 |
| 200 | 276 | 288 | 272 | 235 |
| 202 | 325 | 342 | 330 | 232 |
| 203 | 336 | 342 | 334 | 231 |
| 205 | 328 | 342 | 331 | 231 |
| 201 | 325 | 336 | 320 | 232 |
| 203 | 290 | 313 | 290 | 231 |
| 203 | 296 | 301 | 290 | 232 |
| 203 | 280 | 319 | 272 | 233 |
| 203 | 339 | 352 | 334 | 234 |
| 201 | 278 | 284 | 271 | 236 |
| 202 | 325 | 344 | 330 | 233 |
| 200 | 336 | 341 | 333 | 231 |
| 204 | 329 | 342 | 331 | 232 |
| 204 | 326 | 334 | 322 | 230 |
| 201 | 289 | 314 | 291 | 230 |
| 204 | 295 | 304 | 292 | 232 |
| 201 | 280 | 321 | 273 | 230 |
| 204 | 339 | 350 | 333 | 234 |
| 201 | 278 | 286 | 272 | 235 |
| 200 | 328 | 347 | 331 | 235 |
| 203 | 337 | 341 | 334 | 231 |
| 204 | 328 | 345 | 331 | 231 |
| 200 | 325 | 338 | 320 | 230 |
| 202 | 289 | 312 | 290 | 231 |
| 204 | 296 | 304 | 292 | 233 |
| 202 | 284 | 320 | 272 | 232 |
| 200 | 340 | 351 | 332 | 233 |
| 203 | 276 | 284 | 272 | 235 |
| 204 | 327 | 345 | 332 | 234 |
| 205 | 337 | 343 | 333 | 230 |
| 204 | 329 | 343 | 332 | 232 |
| 204 | 325 | 335 | 320 | 232 |

According to [Singh and Khanduja et.al ,2012], the consistency of result from only thirty six readings was quite hard to access. So to predict with 95% confidence, a hypothetical test known as 'One wat anova' had been performed on the achieved results (refer figure 6). It was further helpful to draw more rational inferences by using capabilities of associated statistics. Test was executed by using Minitab-16 software and its output was quoted as below. Necessary hypothification had been formulated by assuming Null Hypothesis as 'no affect of TIG welding on the harnesses of different zones' whereas Alternate Hypothesis as 'significant affect of TIG welding'.

**One-way ANOVA: P22, P22 HAZ, Weld Pool, P91 HAZ, P91**

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Method

Null hypothesis          All means are equal
Alternative hypothesis   At least one mean is different
Significance level          α = 0.05

Equal variances were assumed for the analysis.
Factor Information

Factor  Levels  Values
Factor       5  P22, P22 HAZ, Weld Pool, P91 HAZ, P91

Analysis of Variance
Source   DF  Adj SS  Adj MS  F-Value  P-Value
Factor    4  544499  136125   439.38    0.000
Error   175   54217     310
Total   179  598717

Model Summary
      S    R-sq  R-sq(adj)  R-sq(pred)
17.6015  90.94%     90.74%      90.42%

Means
Factor      N     Mean  StDev          95% CI
P22        36  202.417  1.592  (196.627, 208.206)
P22 HAZ    36   310.42  24.60  ( 304.63,  316.21)
Weld Pool  36   337.14  16.34  ( 331.35,  342.93)
P91 HAZ    36   331.92  25.90  ( 326.13,  337.71)
P91        36  232.444  1.827  (226.655, 238.234)

Pooled StDev = 17.6015
```

Since p value (0.000) obtained was less than 0.05 hence it could be predicted with 95% confidence level that TIG welding had a serious effect on the harnesses of different zones formed. The affect of TIG welding could not be ignored as far as harnesses of different zones are concerned. Moreover, the standard deviation pinpointed the degree of variability in hardness during formation of different zones while TIG welding.

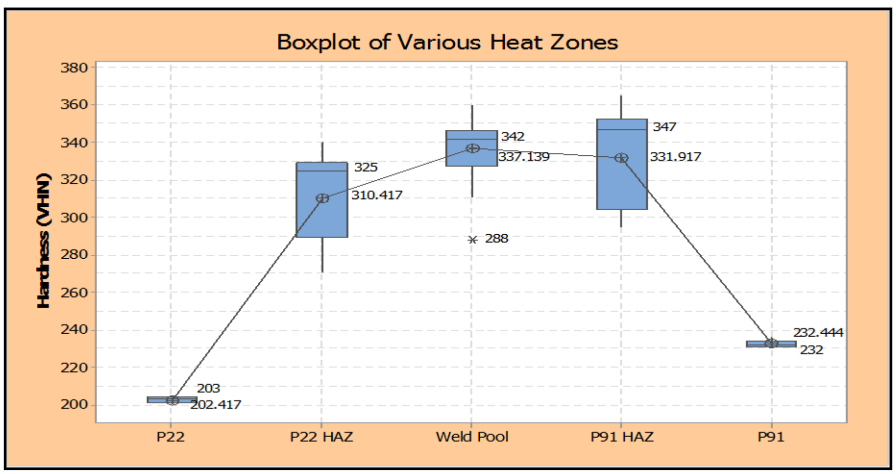


**Figure 7: Box plot of various heat zone**

High deviation in P22 HAZ, weld pool and P91 HAZ reflected more unpredictability of hardness after TIG welding. The box plot and individual value plot (refer figure 7 and 8) also indicated a substantial difference harnesses. That's why the line joining means of five groups was not straight or parallel to x-axis. The gap between median line and the corresponding mean point highlighted the large standard deviation while calculating hardness. Moreover, Individual value plot (figure 8) represents distribution of harnesses (table 2) for different zones with their mean values.

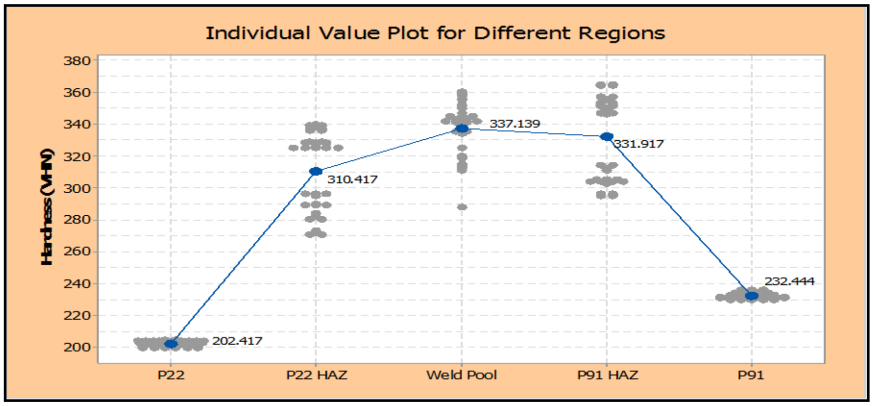


**Figure 8: Individual value plot for the harnesses of different zones**

For P22 base metal the average hardness found is 202.417 VHN Where as in HAZ of P22 average hardness is 310.417 VHN due to carbon rich zone as compared to the base metal. The mean hardness of Weld pool is maximum amongst all with indicating value 337.139 VHN on graph, which is due to the formation of carbides at high cooling rates. HAZ of P91 is also found much harder as compared to their base metal. The average hardness of P91 HAZ is 331.917 VHN, where as for base metal it is 232.444 VHN.

## 4. Conclusions

In this study, single V butt joints were prepared between P91 and P22 grade steels by using simple economical TIG welding. After welding samples were examined for optical micrography. The obtained micrographs showed that HAZ of P91 consists of martensite and retained austenite while HAZ of P22 consists of ferritic bainitic structure. Weld pool consists of bigger grain size structure of martensite and retained austenite phases due to higher temperature conductivity of filler material. Some Carbide precipitation also occurred when the chrome and carbon in the austenitic steel is drawn out of the material and reacts to the atmosphere which make this zone much harder than the other zones. One way Anova results showed that the affect of TIG welding could not be ignored as far as harnesses of different zones are concerned. The obtained p value (0.000) was less than 0.05 hence it could be predicted with 95% confidence level that TIG welding had a serious effect on the harnesses of different zones formed.

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