Testing and Characterization of Service Exposed P22 Welded Steel

S. E. Eren[1,a], A. Tonti[2,b], B. Petrovski[1], V. Ventzke[1] and M. Koçak[3,c]

[1] GKSS Research Centre, Max-Planck.Str. 1, 21502 Geesthacht, Germany

[2] Istituto Superiore per la Prevenzione e la Sicurezza del Lavolo – ISPESL, Via Urbana 167, 00184 Rome, Italy

[3] Gedik Welding Inc., Ankara Cad., 34913 Şeyhli, Pendik, İstanbul, Turkey

[a] elvin.eren@gkss.de, [b] andrea.tonti@ispesl.it, [c] mkocak@gedik.com.tr

Abstract

The quality of a fitness-for-service (FFS) analysis is strongly dependent on the quality of material property data used in the analysis. However, current codes for design and assessment of welded components operating at elevated temperatures [1]-[7] are relatively simplistic since they do not take full advantage of the recent developments in understanding the mechanism of deformation [8]. Additionally, the degradation of material properties, which may occur if the components are operating at high temperatures during their service life, are not taken into account in these procedures or in other words these codes were not sufficiently validated for the service exposed components.

In this study, service exposed P22 steel base and weld materials were fully characterized using mechanical testing and metallurgical examination to provide input data for the assessment of welded components of P22 in high temperature service. These investigations were conducted to determine the effect of service exposure (aging) on the tensile and fracture toughness properties. The results of the systematic examination of service exposed (110.000 hrs at 540°C under 200 bar) P22 steel were compared with the available virgin material properties to demonstrate the effect of aging on the microstructure and mechanical properties of the welded joints.

Detailed testing and analysis of the service exposed P22 steel weld joints (pipe to pipe as butt joint and pipe to pipe as nozzle weld joint) have been conducted both at room and higher (540°C) temperatures. Additionally, microstructural examination was carried out to identify microstructural features (grain boundary characteristics) of the base and weld materials. This paper reports only the results of these investigations.

Keywords: *P22 Steel, Joining, Aging, Plant Integrity, Fracture, Creep*

1. Introduction

Headers and pipes of coal fired boiler/steam turbine power plants have traditionally been manufactured from low alloy steels such as P22, which are usually subjected to the 540°C main steam temperature during operation. Although several new generation ferritic steels have emerged succeeding P22, e.g. the modified 9Cr alloy P91, which is quite popular in Europe, there are still a great number of power plants operating with tubes and pipes made of P22 steel [9]. P22, P91 and many other commercial steels like HT9, HT91, HCM12M etc. suitable for high temperature service are well-established steels with extensive mechanical properties database of both virgin base material and some types of conventional welds, see e.g. [10]-[17].

Recently, studies covering dissimilar joints of high temperature components [18]-[20] and the role of residual stresses in the creep behaviour of components containing similar and dissimilar joints have also been conducted in the frame of European Union funded projects and within the collaborative research activities supported by industry [21]-[22].

However, the degradation of materials in components of plants in high temperature services which are reaching or even already running beyond their designed service lives necessitate procedures and data for assessing their service performance for safe operation and avoiding costly operations.

Therefore, full characterization of materials of service exposed components is imminent. Due to long service exposure above 100 000 hours, study of damage and crack initiation are of utmost importance. Along with creep damage, creep crack initiation, which is measured using continuum mechanics approach to determine creep (crack initiation) toughness, on which the British Energy (BE) – time dependent failure assessment diagram (TDFAD) concept is based, has not been verified using service exposed materials such as P22 of industrial time scale.

Within the experimental program discussed in this paper, ASTM A335 Grade P22 (2.25Cr1Mo) low alloy ferritic bainitic steel, (see Table 1 for chemical composition), for high temperature tubing and pipework in power generation and petrochemical plants was investigated. The service exposed material after 110.000 hours of service at 540°C and 200 bar was supplied by ENEL.

The as-received materials, outlet header designed as SH2, was sectioned for the characterization of both butt joint and the nozzle fillet weld with connection pipe to same purpose header. 700 mm long SH2 outlet header (Figure 1) possessing a diameter of 665 mm was further cut into four pieces for the manufacturing of specimens (Figure 2). Additionally, in Figures 3-5 one can see the exact locations of the specimens.

Table 1. – Chemical composition of P22 steel

	Cr	Mn	P	S	Si	Cr	Mo
Min	0,05	0,30				1,90	0,87
Max	0,15	0,60	0,025	0,025	0,50	2,60	1,13

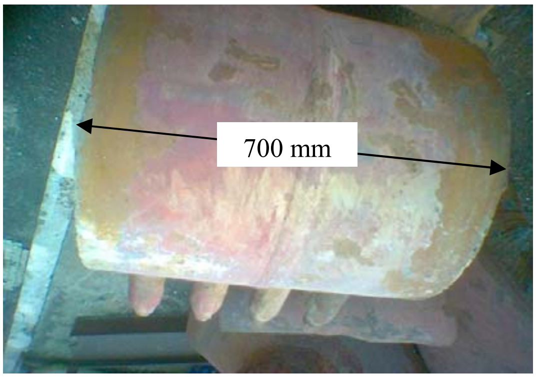


Figure 1 a) 700 mm long 110.000 hrs at 540°C service exposed header with butt joint.

Figure 1b. As-received outlet header used for the characterization of service exposed 145 mm thick base material with butt joint.

In the following Sections 2, 3 and 4, the results of tensile, CTOD fracture toughness and Charpy-V tests are reported.

Section 2 reports tensile properties at RT and at 540° C, while Section 3 presents the results of the CTOD fracture toughness tests in accordance with the British Standard BS 7448 [23]-[25] using C(T)40 or C(T)50 specimens at RT and at 540° C, and finally the Charpy-V impact test results at RT were introduced.

Additionally, metallurgical examinations for the clarification of degradation was also conducted, the results of which are discussed in Section 5.

Figure 2. As-received nozzle sections (100 mm thickness welded to 150 mm thick material) after cutted into two pieces and etched for identification of weld area.

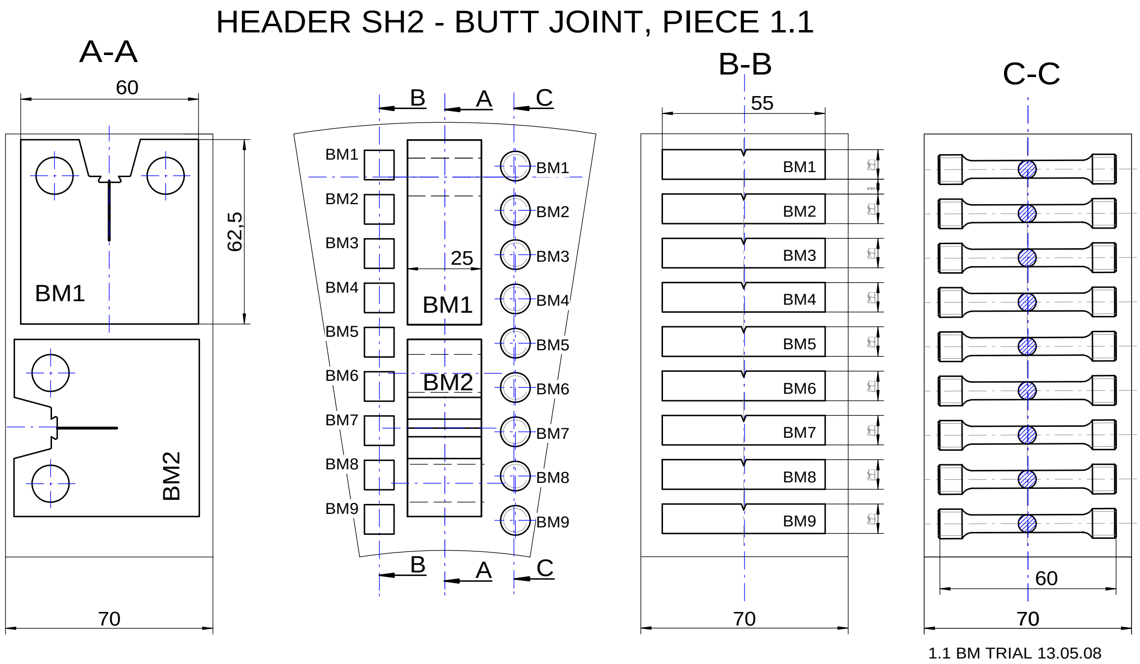


Figure 3. Partial cutting plan of Base Material

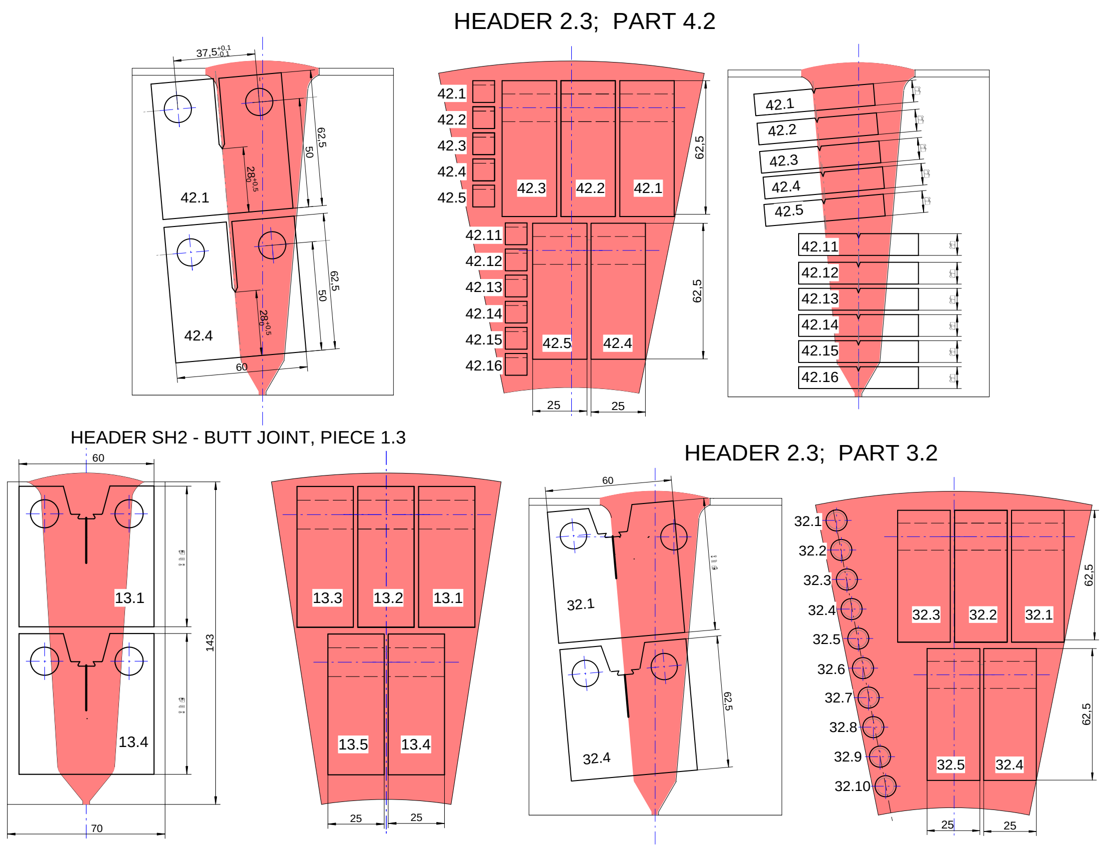


Figure 4. Partial cutting plan of Butt Joint

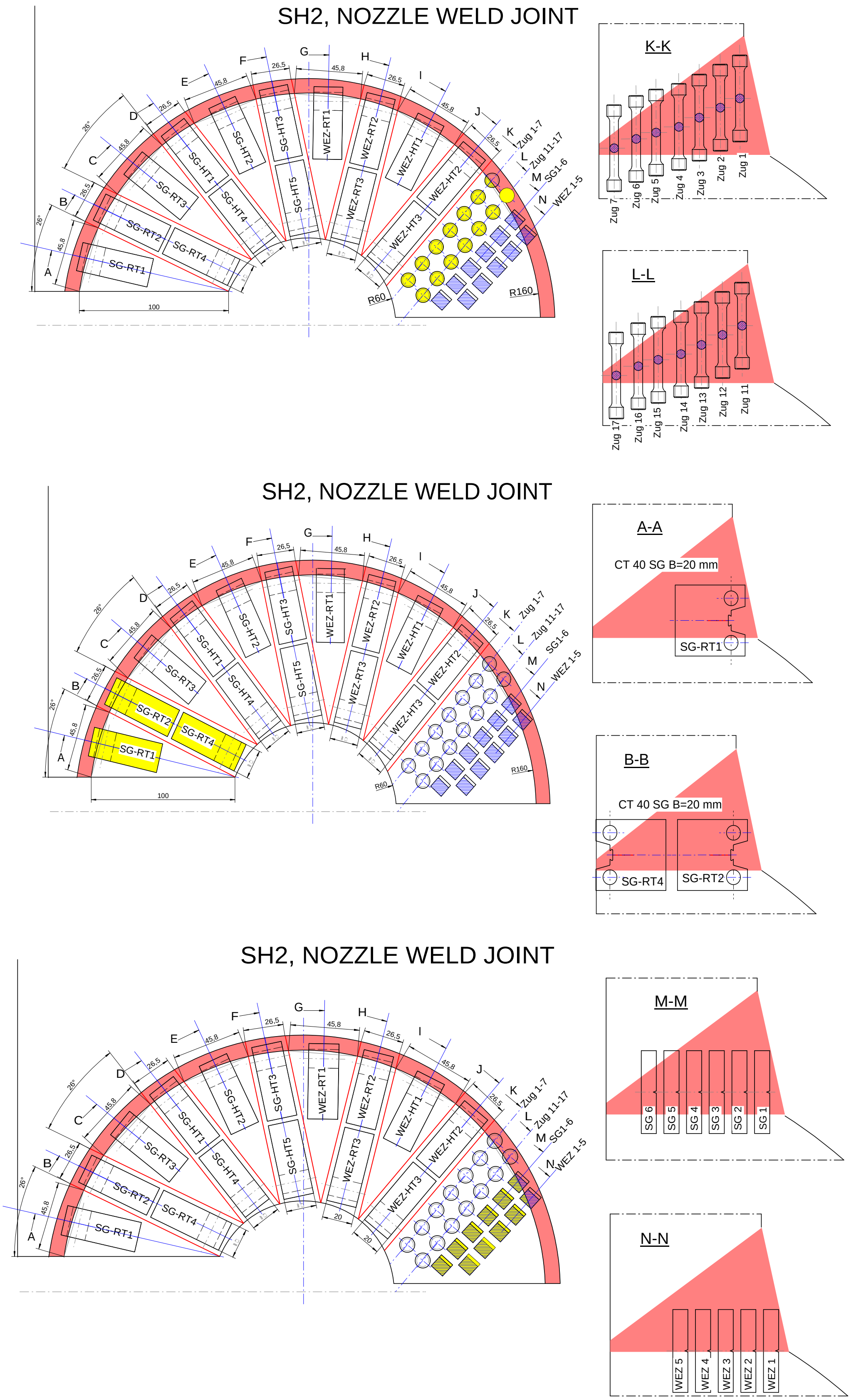


Figure 5. Partial cutting plan of Fillet Weld of Nozzle

2. Characterization of P22 Base Material

The plate thickness of butt joint was 145 mm, while nozzle materials were 100 mm and 155 mm thick. Tensile properties of the P22 base material were obtained from testing of round all-weld metal tensile specimens, with a gauge length of 25 mm. The average yield strengths of the BM extracted from two different bulk material locations were found to be 300 and 362 MPa respectively. The average tensile strengths of the same pieces were obtained as 490 MPa and 521 MPa for both material pieces with elongation values of 31% and 28%. In Figure 6, a typical stress-strain curve of P22 steel exhibiting continuous yielding behaviour can also be seen.

When the same type of specimens was tested at 540°C, the yield strength of the BM was found to be 243 MPa while exhibiting a tensile strength of 266 MPa, as given in Table 3. The elongation was obtained from only one specimen which was 40%.

Compared to RT results of the same material, tensile strength has shown reduction from 521 MPa to 266 MPa when temperature goes up from RT to 540°C.

CTOD fracture toughness obtained from C(T)50 specimens in accordance with the British Standard BS 7448 were found to be ranging from 0.714 mm to 1.031 mm at RT and from 0.240 mm to 0.394 mm at 540°C . During Room Temperature tests, some specimens have shown ductile fracture type of failure, as Load vs. CMOD diagrams of the BM and WM shown in Figure 7. Therefore, CTOD values of the maximum load attained were calculated for such specimens. Where unstable fracture occurred such as in BM specimen obtained from outlet Header SH2 the CTOD value of failure point was taken.

Charpy-V impact properties of the P22 material were obtained from testing of minimum of 5 specimens. The Charpy-V specimen results have shown some variation for the Base Material, 42 J being the minimum value and 99 J being the maximum value.

3. Characterization of Butt joint

Figure 8 shows the middle of the weld joint which was originally 145 mm thick. The hardness measurements has already indicated slightly undermatching (lower yield strength level in the weld metal compared to the base metal) behaviour, average of measurements being 160 HV in the Base Material and 150 HV in the Weld Material.

Tensile properties of the weld material were also obtained from testing of round tensile specimens. The average value of the yield strength and the ultimate tensile strength after testing 10 specimens was found to be 344 MPa and 483 MPa respectively at RT. The elongation was obtained as 31% which is comparable to the base metal.

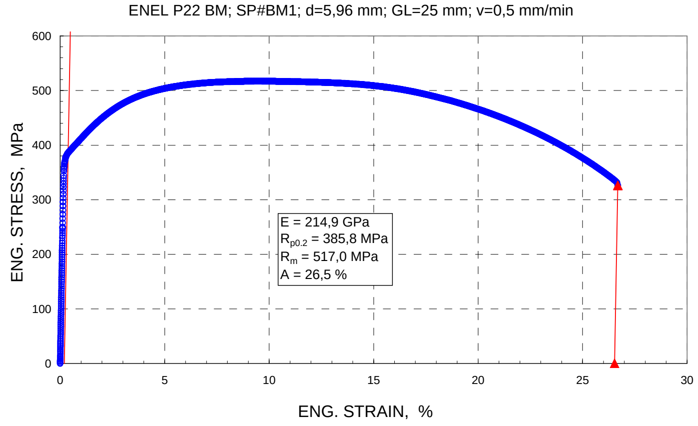


Figure 6. Typical stress-strain curve of the service exposed (110.000 hrs/540°C) P22 steel

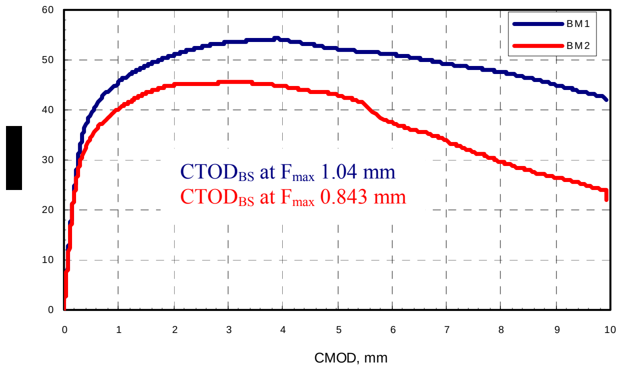


Figure 7. Load vs. CMOD diagrams of the two CTOD fracture toughness C(T) 50 specimens of the base material tested at Room Temperature

Figure 8. Macrograph of service exposed P22 butt joint – middle

Yield and tensile strength of the P22 weld material at 540°C obtained from testing of two round tensile specimens were found to be 211 MPa and 243 MPa respectively. Approximately 50% reduction of tensile strength was observed for the weld material compared to

RT values.

The fracture toughness results given in Figures 9 and 10 are showing clearly that weld metal and partly HAZ are having lowest fracture toughness values compared to the base material. Similar results were obtained from Charpy-V tests. The Charpy-V specimen results have shown some variation for the Weld Material (20.3 J being the minimum value and 87.1 J being the maximum value) and for Heat-Affected Zone (22 J being the minimum value and 95.6 J being the maximum value) too. Fracture mechanics specimens are also showing the same trends.

Apparently, the weld material has gone most degradation process during service exposure and exhibits very low RT fracture toughness properties. When the tests conducted using standard C(T)50 specimens at 540°C, both values of BM compared to RT have shown lower values, whereas WM specimens exhibit higher values than the RT values.

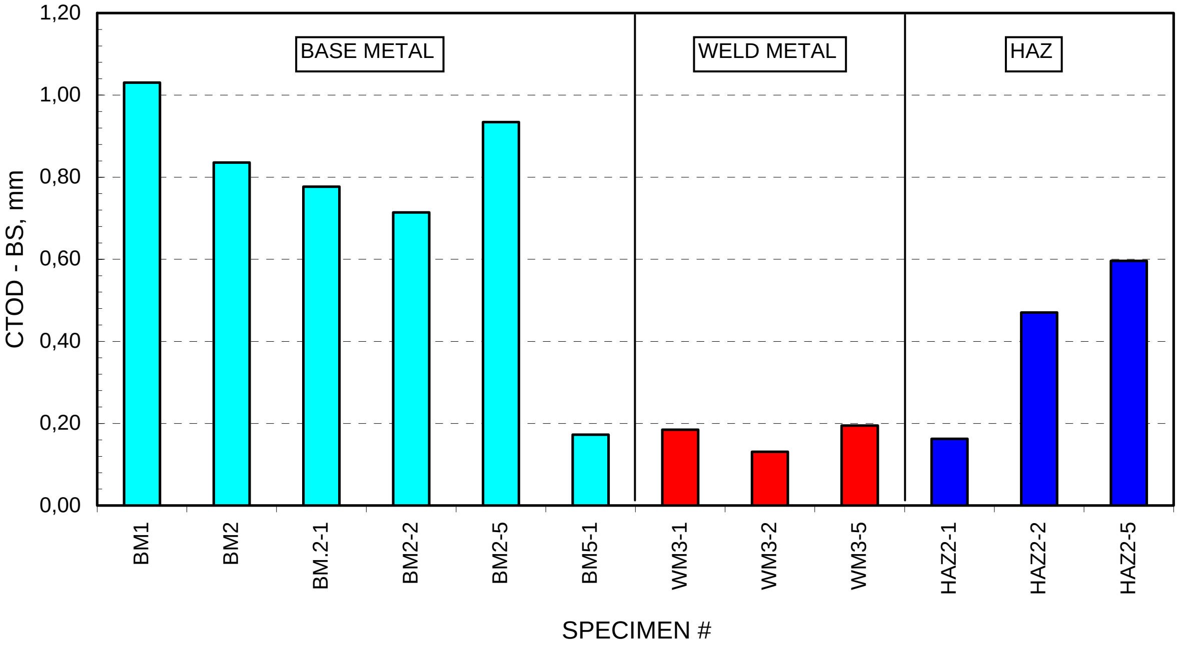


Figure 9. Fracture toughness of P22 Base Material, Weld Material and Heat-Affected-Zone at RT

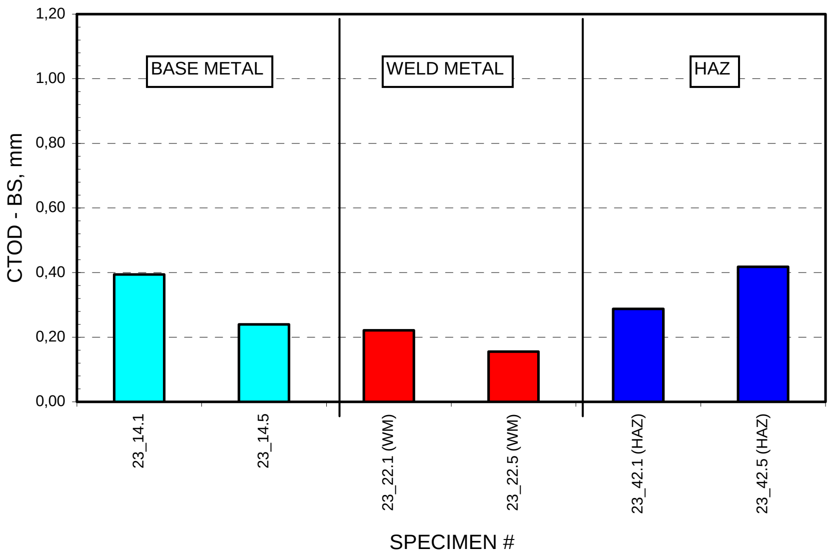


Figure 10. Fracture toughness of P22 Base Material, Weld Material and Heat-Affected-Zone at 540°C

4. Characterization of Fillet Weld

The other component examined was the nozzle, principal drawing of which is below and the thickness of this weld was approximately 100 mm. A micrograph taken from the middle of the weld can be seen in Figure 12. Hardness measurements on the sectioned specimen showed an average value of 162 HV. However, fillet weld exhibited a clear overmatching characteristic with an average value of 183 HV.

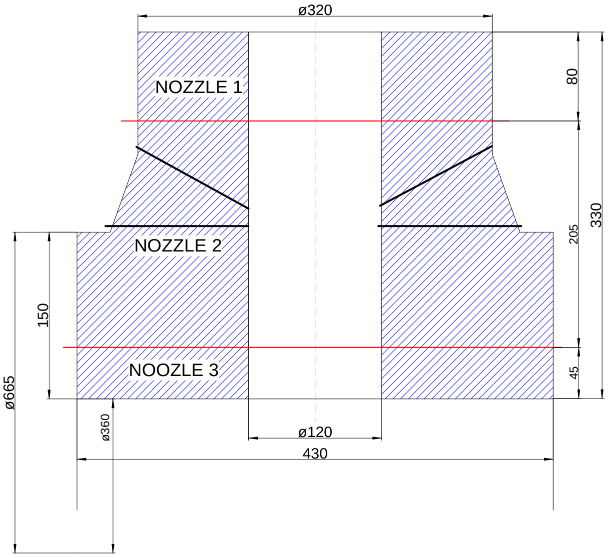


Figure 11. Principal drawing of nozzle, "Nozzle 2" section was used for characterization

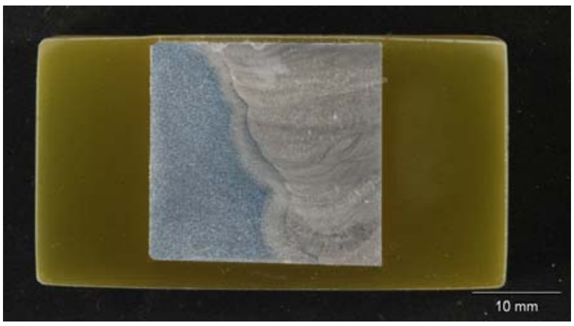


Figure 12. Micrograph of service exposed P22 fillet weld – middle section

Tensile properties of the weld material were obtained from testing of round tensile specimens both at RT and 540°C (see Figure 5 for the description and location of the specimens tested).

Although the average yield strength of the joint at RT is calculated as 325 MPa and the ultimate tensile strength as 461 MPa, these values should be used with precaution. Since as can be seen Figure 5, the specimens include different portions of weld material (see Zug 1 – Zug 7 in Figure 5). While only specimens designated as "Zug 1" and "Zug 2" are all weld metal specimens, the other specimens include decreasing percentage of weld material and that enables testing of the joint itself including base material, weld material and also heat affected zone (HAZ). However, the average values obtained from these two specimens were found to be 292 MPa and 443 MPa for yield strength and the tensile strength of the weld material.

At 540°C, from "Zug 11" and "Zug 12" all weld metal specimens, yield strength value was obtained as 220 MPa and the tensile strength as 230 MPa, lower than the room temperature values, as expected.

CTOD fracture toughness properties of the weld material and the HAZ at RT and 540°C were obtained using C(T)40 specimens which were fatigue pre-cracked with an R-ratio of 0.1.

During RT tests some specimens have shown ductile fracture type of failure. The results ranging between 0.295 mm and 0.383 mm are showing clearly that HAZ exhibits a more stable trend while the weld material is showing large scatter ranging from 0,173 mm to 0,615 mm.

Similar trends were observed from Charpy-V tests (29 J being the minimum of WM and 71 J of HAZ), fracture mechanics specimens are also showing the same trends. The weld material of the nozzle has also gone severe degradation during service exposure and exhibits very low RT fracture toughness properties as was the case for the butt joint.

The 540°C CTOD fracture toughness of HAZ was found to be higher when compared with the RT values of the same region. However, reaching a conclusion for the WM examining the WM results was not possible due to scatter in the data.

5. Metallurgical Examinations

Aims of the metallurgical examination were to investigate the morphology of the microstructures in the base material, HAZ and the weld material using Scanning Electron Microscopy (SEM) and to obtain the local chemical composition in the weld joint employing EDX technique.

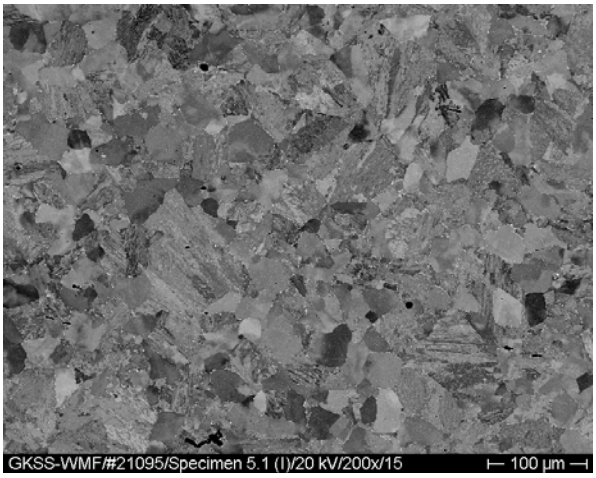
The examination has revealed that the service exposed P22 steel is composed of ferritic matrix with embedded carbide, in which molybdenum carbide dominates. The carbides are to be found not only in the grains but also in the grain boundaries too. Based on the chemical composition, P22 is a CrMo steel and was delivered in tempered condition.

Annealed martensite is the characteristic of the weld region and it is considerably finer grained than the base material and appears to be carbides homogeneously distributed. The chemical composition of the weld zone is marginally different from the composition of the base material's.

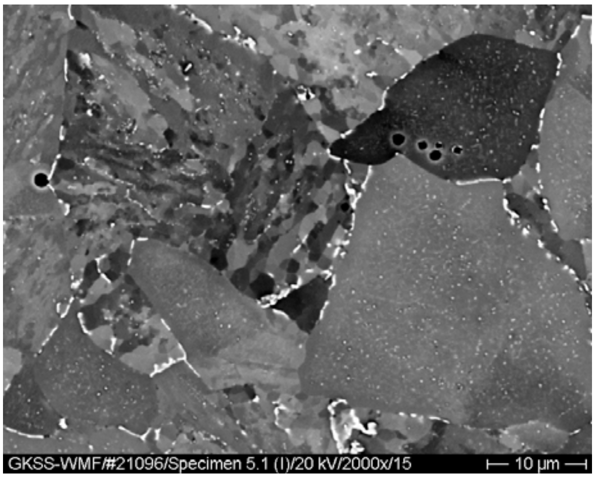
The microstructure of the weld region contains annealed martensite and other types of martensite like blockky martensite or lath martensite were not apparent in the weld zone. The microstructure of HAZ was difficult to discriminate from the base material. Transition microstructure of bainitic nature was also not observed.

After this short summary of the microstructural findings, the detailed description of the microstructural analysis can be found below beginning with the base material and followed by weld region.

When the SEM images are magnified, it is evident that there exist segregations in the grain boundaries. The segregations at different locations were analysed with respect to chemical composition, see Figure 13. Additional analyses points were chosen in the matrix too, see Table 2.



a)



b)

Figure 13. a) Microstructure of the base material (200x SEM) and b) segregations in the grain boundaries of the base material (2000x SEM)

Table 2. EDX analysis results of target point analyses in the Base Material (Pos. 1-5: Matrix; Pos. 6-10: Segregations)

Pos.	Si	Cr	Mn	Fe	Mo
1	0,25	1,62	0,42	97,50	0,21
2	0,14	1,65	0,42	97,79	0,00
3	0,24	2,03	0,44	96,25	1,04
4	0,14	2,11	0,35	96,41	0,99
5	0,28	2,23	0,55	96,43	0,52
6	1,82	4,42	0,70	76,11	16,96
7	1,98	3,52	0,95	78,52	15,03
8	1,86	2,48	0,53	81,39	13,74
9	0,24	2,01	0,73	96,41	0,61
10	0,23	1,89	0,62	96,37	0,89

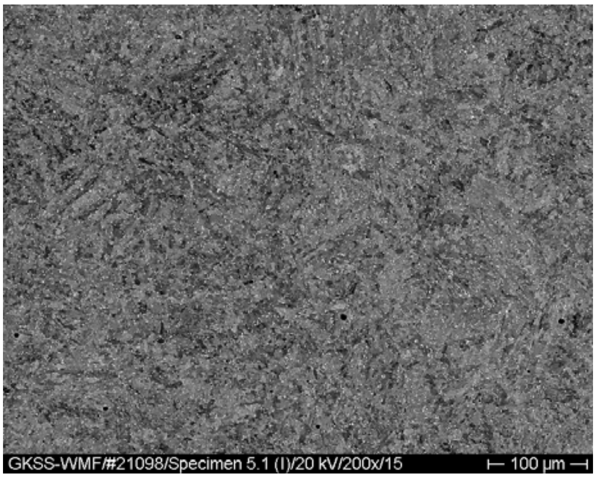
Identical to the examination of the base material, two quantitative EDX-Analysis were carried out in the region seen in Figure 12. Si was in the range of 0.10 – 0.15 %, Cr in the range of 2.29 – 2.31 %, Mn in the range of 1.64 – 1.67 % and Mo in the range of 0.80 – 0.99 % mass percentage. The chemical composition of the weld zone is in accordance with the chemical composition of the base material. However, Si concentration is slightly lower whereas Mn and Cr concentrations are slightly higher.

The target point analysis results in Table 3 show that Mo-concentration is higher at locations designated as 6, 7, 9 and 10. Figure 14 is also showing that the carbides have deposited at the grain boundaries which is an indication for the property degradation under service conditions.

Additional to the detailed EDX analysis described above, the base material and weld materials of SH2 outlet header's butt joint and fillet weld were subjected to the emission spectroscopy. Since the constituents of the materials, the weight concentrations of whose are below 0.1 % cannot be detected by EDX, the emission spectroscopy measurements were conducted for a more detailed analysis, see Table 4-Table 6.

Table 3. EDX analysis results of target point analyses in the weld zone (Pos. 1-5: Matrix; Pos. 6-10: Segregations)

Pos.	Si	Cr	Mn	Fe	Mo
1	0,09	2,09	1,48	96,13	0,22
2	0,00	2,27	1,34	96,39	0,00
3	0,11	2,10	1,35	96,25	0,19
4	0,00	2,04	1,48	96,27	0,21
5	0,09	2,12	1,32	96,21	0,25
6	1,22	2,44	1,57	82,74	12,03
7	0,48	2,50	1,62	89,96	5,43
8	0,21	2,12	1,43	95,82	0,43
9	0,09	2,08	1,44	95,22	1,17
10	0,32	2,46	1,32	91,71	4,19



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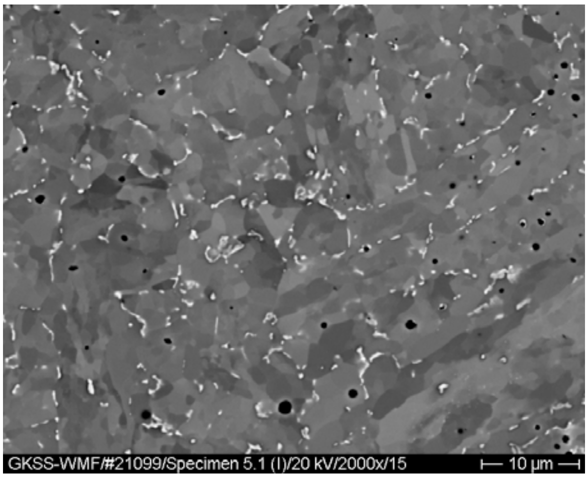

b)

Figure 14. a) Microstructure of the weld zone (200x SEM) and b) the segregations in the weld zone (2000x SEM)

Table 4. Emission spectroscopy measurement results of Service Exposed P22 Base Material [%]

C	**Si**	**Mn**	**P**	**S**	**Cr**
0.0743	0.317	0.47	0.034	0.034	2.1
Mo	**Ni**	**Al**	**Co**	**Cu**	**Nb**
1.04	0.12	0.005	0.01	0.133	0.005
Ti	**V**	**W**	**Pb**	**Sn**	**Fe**
0.005	0.008	0.010	0.002	0.0175	95.62

Table 5. Emission spectroscopy measurement results of Service Exposed P22 Butt Joint – Fusion Zone

C	**Si**	**Mn**	**P**	**S**	**Cr**
0.0221	0.182	1.55	0.052	0.034	2.24
Mo	**Ni**	**Al**	**Co**	**Cu**	**Nb**
1.09	0.17	0.01	0.01	0.271	0.005
Ti	**V**	**W**	**Pb**	**Sn**	**Fe**
0.005	0.012	0.01	0.002	0.0179	94.32

Table 6. Emission spectroscopy measurement results of Service Exposed P22 Fillet Weld – Fusion Zone

C	**Si**	**Mn**	**P**	**S**	**Cr**
0.0267	0.302	0.68	0.059	0.033	2.46
Mo	**Ni**	**Al**	**Co**	**Cu**	**Nb**
1.19	0.05	0.005	0.010	0.029	0.005
Ti	**V**	**W**	**Pb**	**Sn**	**Fe**
0.014	0.012	0.010	0.002	0.0114	95.10

6. Conclusions

Detailed mechanical testing and microstructural analysis of the service exposed P22 steel weld joints have been conducted both at room and higher (540 °C) temperatures. Additionally, microstructural examination was carried out to identify microstructural and grain boundary characteristics of the base and weld materials.

The locations and orientations of the specimens together with the cutting plans and extracted round tensile, Charpy-V and CTOD specimens are important to describe the material properties. Therefore, detailed description and schematic drawings of the specimen locations and orientations are also given.

The purpose of these investigations is to determine the effect of service exposure (aging) on the tensile and fracture toughness properties. Therefore, the results shown in this work were compared with virgin material properties, provided by ENEL S.p.A., to demonstrate the effect of aging on the microstructure and properties of the welded joints.

According to the database of ENEL, it is expected that P22 base material exhibits a yield strength of 205 MPa, ultimate tensile strength of 415 MPa, 22% elongation in longitudinal direction and 14% elongation in transversal direction at ambiente temperatures. At higher temperatures, P22 is expected to exhibit a lower yield strength, appoximately 181 MPa. After 100000 hours of service period, the rupture strength can even fall to 148 MPa. Ultimate tensile strength of the service exposed material was found to be 266 MPa, well below 415 MPa.

For the comparison of RT tensile properties of P22 Base Material, values from three different virgin steel charges were provided. The average values of yield and tensile strength were approximately 455 MPa and 605 MPa respectively, which are both higher than the yield and the tensile strengths of the service exposed Base Material.

However, it was not possible to compare the properties of HAZ and weld zone of the service exposed material with the virgin weldments due to lack of data.

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