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Microstructural and Mechanical Characterization of High Temperature and Creep Resistant Steel Weldments

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Abstract

Demand for the new fossil power plants, wind and solar energy systems as well as nuclear energy is rapidly increasing. In order to fulfill this increasing energy requirements with power plants while assuring safety and efficiency, new high heat and creep resistant steels and consumables, are needed. The Cr-Mo steel weldments are used in steam plants, aircraft parts, oil refineries, fusion reactors, pressure vessels, boilers and other high temperature applications.

High temperature strength values and creep properties of the steels used in new power plants are progressively increasing. High creep strength steels make possible to operate with higher pressure resulting an increase in plant efficiency. Therefore, nowadays P91 and P92 grade higher creep strength steels are preferred instead of conventional grades such as P22 and P23 although P22 is cheaper. Besides, P92 grade steels and their weldings are anticipated to use in Sinop, Mersin and Denizli nuclear station projects of Turkey.

In this study, with currently available and newly developed welding electrodes and wires (solid or characterization work) that are not being produced in Turkey at the present time will be experienced. Intended target and innovation needed for production such welding electrodes and wires, can be reached in a short time with the industry-university cooperation based on the Gedik's knowledge and experience.

With this research complex chemical composition of low carbon (<0.1%) and Cr, Mo, W, Nb, N and Si containing welding electrode and wire developments, projected values of weld zone conformation by metallurgical inspection and subsequent corrosion and high temperature mechanical tests (Charpy- V, Tensile etc.) are planned. Newly developed technology, knowledge and emergent product will be protected with a patent.

Keywords: *High chrome-molybdenum weld, welding for nuclear stations, high heat resisting steel alloys, high creep resisting steel alloys, welding metallurgy, mechanical properties, microstructure*

1. Introduction

Cr-Mo steels are also called creep resistant steels which means that they do not sag even at high temperatures. Cr-Mo steels should be welded with similar consumables and a very precise method should be followed. Preheat and post weld heat treatment are almost always involved. The most common consumables according to AWS have a suffix of B2, B3 such as E8018-B2 and are only designed for welding CrMo steels. They are highly crack sensitive [1].

Creep strength-enhanced ferritic steel (CSEF) and advanced chromium-molybdenum steels are used worldwide. The higher efficiency needs gave rise to a search for advanced materials with superior material properties at higher temperatures. Advanced chromium-molybdenum pipe and tubing such as 9 CrMoV [P(T)91], tungsten, and/or boron-enhanced materials (i.e., Grades 92, 122, E911, 23, 24, etc.) are now being specified [1,2].

Emphasis placed on the importance of maintaining preheat, interpass temperature, and dangers inherent in interrupted heating cycles or improper postweld heat treatment. In addition, detailed attention to filler metal procurement to avoid metallurgical complications is equally true for the other advanced chromium-molybdenum alloys [2].

While power plants built in the 1970s used 21/4Cr-1Mo steel (P22), today they increasingly use a modified 9Cr-1Mo-V (P91). The family of 2.25% Cr started a long time ago with T/P22(10CrMo9-10), a steel with 2.25% Cr and addition of around 1% Mo. The development of the new T/P23 and T/P24 grades was made on the same basis as grade 22 but alloyed with the specific addition of new elements. This has led to a strong increase of the creep properties. Initially developed for water wall panels in supercritical and USCB plants, these grades also found application in reheaters, superheaters in conventional boilers, and HSRG. The development in pipes leads in application for headers and steam piping [2,3].

On the same basis, but for more severe applications, the development of grades 92 and 911 increased the creep behaviour by 10–20% compared with T/P91. Consequently, it is possible to decrease the wall thickness of the component and to obtain economical advantages on the cost of tubes and pipes. Moreover, the technical advantages reduce the thermal fatigue susceptibility. This advanced material is becoming a good choice for USCB, where high pressure means heavy-wall products. Table 1 shows the current status of standardisation for these steels. They are standardised in ASTM and ASME for USA. T/P91 and T/P22 are included in the European Standard EN10216-2, when the process to integrate grades T/P23, 24, 911 and 92 in EN has been started [3].

Table 1. Evolution of Coal-Fired Power Generation Boiler Temperature and Materials [1,3]

Live Steam		Application Date	Alloy	Equivalent Material
Pressure psi	Temperature °F			
<2.90	<968	Since the early 1960s	X20	CrMoV111
<3.62	<1.004	Since the early 1980s	P22	2 1/4 Cr Mo
<4.35	<1.040	Since the late 1980s	P91	9Cr - 1Mo
<4.78	<1.148	Since 2004	P92	X10CrWMoVNb 9-1, STBA29-STPA29,
<5.07	<1.292	Expected in 2010	Super Alloys	CCA 617 -IN 740 Haynes 230-Save 12

Development of Grade 91 began in 1978 by Oak Ridge National Labs for the breeder reactor and further developed by other researchers since then. Other grades such as grade 92, 23, 24, 911 and others are also under development. After the development of the well-known T/P91 grade in the early 1980s and the long industrial experiences since the early 1990s, it has been necessary to develop new steels to answer the demand of the powergen industry. New (ultra) super critical boilers require materials with advanced creep properties to reach severe steam parameters [3,4].

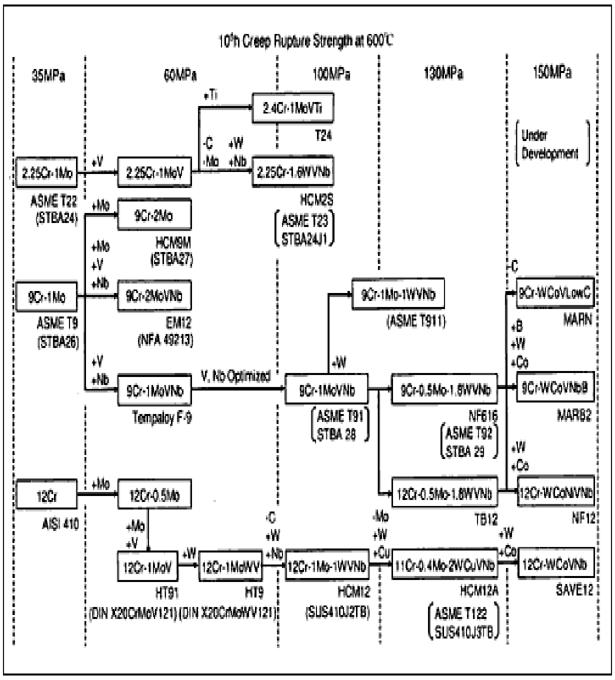

Figure 1. Chart of the progressive development of Cr-Mo steels [5]

2. Comparison of Properties

These CSEF alloys have similar compositions within a given alloy family. Specific properties, particularly strength or enhanced corrosion resistance at elevated temperatures, are achieved by controlled alloy additions such as tungsten, vanadium, or boron. Compositions for candidate advanced chromium-molybdenum steels for high temperature service are shown in Tables 2. Base material development and code acceptance have preceded effort and research in the areas of weld properties and welding consumables for the advanced chromium alloys. Like P(T)91, dealing with the HAZ in other CSEF alloys may in fact offer the most challenges [4,5].

The improvement of thermal efficiency by increasing the operating temperature and pressure of boilers has recently led to the development of new families of creep-resistant steels. For 9–12% Cr steels, grade T/P91 (X10CrMoVNb9-1 according to EN 10216-2), developed at the end of the 1970s in the USA, marked the starting point for these developments. With its excellent mechanical characteristics at elevated temperatures and good workability, it was rapidly adopted worldwide for applications in the field of new power stations. The tube design temperature is limited to around 610 °C inside the combustion chamber. This limit depends on such factors as heat flow and corrosion [5,6].

More recent developments to produce new grades such as T/P911 (European E911;X11CrMoWVNb9-1-1) and T/P92 have improved mechanical properties at high temperatures, in particular an increase in creep strength of 10–20% in 100,000 h at 600 °C. This makes it possible to reduce the wall thickness of the pipes and consequently improve their behaviour to thermal fatigue. The new grades T/P23 and T/P24 (7CrMoVTiB10-10) are well suited for boiler components working at lower temperatures. While these grades were initially developed for manufacturing water wall panels for ultra super critical boilers (USCB), they are also used for the superheaters and reheaters of conventional boilers and heat recovery steam generators (HRSG). In addition to their excellent workability, they have the advantage of being used without post-weld heat treatment (PWHT) in case of welding thin-walled tubes. Furthermore, owing to the good creep properties, they can be used to replace P22 and for some applications even P91, with the advantage of lower costs [6].

2.1. Chemistry

In comparison with grade T/P22, the chemical composition of T/P23 and T/P24 shows the following:

- Low C content, which provides a good workability (welding for example). It allows one to avoid PWHT for thin products (tubes for water wall panels or superheaters).
- Additions of V, Nb (or V, Ti for grade 24) which, combined with C and/or N, form carbides, nitrides and/or carbonitrides of MX type and cause a fine precipitation in the matrix, increasing the strength of the materials.
- In grade 23, tungsten is added (at reduced Mo content) to further improve the creep resistance. In comparison with T/P91, the creep resistance of steel grades T/P911 and T/P92 is improved by the addition of W, which acts by strengthening the material mainly through Laves phase precipitation. An addition of up to 0.006% B also improves creep resistance. All elements are described in Table 2 [5,6].

2.2. Mechanical properties

All grades given in the previous table are commercialised in normalised–tempered condition. For T/P23 and T/P24, it may be necessary to accelerate the cooling rate by water quenching in order to obtain the required structure and mechanical characteristics. This depends on wall thickness. For grades T/P23 and T/P24, the microstructure is composed of tempered bainite and martensite. For grades T/P91, T/P911 and T/P92, the structure is purely tempered martensite. The requirements for the mechanical properties are described in Table 2. In ASTM, maximum hardness is required, while in EN there is a requirement on a maximum value for the tensile. Linked with the pressure equipment directive (PED) there are requirements on the toughness in the EN Standard [7].

Table 2. Typical Weld Metal Deposit Compositions and Mechanical Properties [1, 7]

Element Wt (%)	Steel Types			
	P22	**T23**	**P911**	**P92**
C	0.1	0.04-0.10	0.08-0.13	0.08-0.13
Mn	0.69	0.10-1.00	0.50-1.20	0.40-1.00
P, max	-	0.020	0.02	0.020
S, max	-	0.015	0.01	0.015
Si, max	0.36	0.50	0.15-0.50	0.40
Cr	2.20	1.9-2.6	9.0-10.0	8.0-9.5
Mo	1.02	0.05-0.30	0.9-1.1	0.30-0.60
W	-	1.45-1.75	0.9-1.1	1.5-2.0
Ni, max	-	0.80	0.40-0.80	0.80 (0.6)
V	-	0.20-0.30	0.18-0.25	0.15-0.25
Nb	-	0.02-0.08	0.04-0.07	0.04-0.07
N, max	-	0.03	0.04-0.07	0.03-0.07
Al, max	-	0.03	0.02	0.02
B	-	0.0005-0.006	0.005	0.001-0.005
Ti	-	-	-	-
Cu, max	-	0.15	-	0.15
UT, MPa	473	510	621	621
YS, MPa	276	400	441	441
ε %	20	20	20	20

3. Heating Operations

Proper application of heating operations is critical to success. Application and rigorous control of preheat, interpass and postweld heat treatment (PWHT) are mandatory and critical to the service life of the alloy and to ensure that desired toughness and creep resistance. Induction heating is a growing method for preheating and PWHT [7].

Control of preheat and interpass temperatures and even postbaking operations are necessary to avoid hydrogen retention/cracking problems in this extremely hardenable alloy family. Flame, furnace heating, electrical resistance, and electrical induction heating have been used successfully. Temperature monitoring and control of thermal gradients is extremely important. For these reasons, local flame heating is not recommended and should not be permitted. Changes in section thickness, chimney, and position effects must also be considered. If unknown, mock-ups should be used to establish heated band, soak times, and actual thermal gradients [2,7].

3.1. Preheat

The literature suggests that 200°C (~400°F) is adequate for preheating P91 and P92 weldments. Fabricators typically aim for 200°C to 250°C (~400°F to 500°F), but will go as low as 121°C (~2500 °F) for root and hot pass layers, thin walled components or where GTAW is utilized. Preheat temperature should be considered an interpass minimum, since cooling to room temperature before the completion of the weld, without proper precautions, is not advisable when using flux bearing processes. Evaluation data indicates that no elevated preheat is required for T23 or T24 weldments however some code bodies including ASME require preheat or PWHT for these alloys. Recommended preheat temperatures are listed in Table 3 [7,8].

3.2. Interpass

A typical interpass maximum is 300°C (~600°F), slightly less is acceptable but no more than 370°C (700°F). The interpass maximum helps to prevent the possibility of hot cracking due to the silicon and niobium content of the weld metal. Also, allowing the weldment to cool to below the martensitic start temperature (Ms; typically less than 200°C (400°F), and in some cases ~100°C (~200°F)) allows some of the martensitic microstructure to be tempered by subsequent beads. Field operations rarely have problems with interpass temperature limitations on heavy sections. Shop operations using SAW may exceed interpass temperatures and require cooling between passes. 350°C (700°F) appears to the upper practical interpass temperature because of bead shape control limitations [8].

3.3. Postweld Heat Treatment

Application of PWHT is absolutely necessary with Grade 91, 911, 92, and 122 weldments, regardless of diameter or thickness. PWHT is one of the most important factors in producing satisfactory weldments. The PWHT methodology and implementation must be verified to ensure that the weldments are actually receiving PWHT at the proper temperature. Additional thermocouples or qualification testing may be required. Proper tempering of the martensitic microstructure is essential for obtaining reasonable levels of toughness. In practice, this involves selecting both an appropriate temperature and time in accordance with governing code requirements [6,7,8].

Figure 2. Welding a Cr-Mo steam pipe in a power station [4,9]

The photo in Figure 2 shows a power station steam pipe. Insulation covers heating coils were used to preheat the pipe to 250°C followed by PWHT of around 700-730°C. The welding consumables were TIG for the root deposit (AWS ER90S-B3, 2.4mm wire), then MMA 3.2 and 4.00mm electrodes for the fill and cap (AWS E9018-B3). Often FCAW is used for filling and capping these large bore pipes (AWS E91T1-B3) [9,10].

Table 3. Overview Of Typical Guidelines For Preheat & Interpass Temperatures and PWHT as SR and STC Guidelines For Cr-Mo Steels [1,2,11]

CrMo Type	Standard	Preheat & Interpass Temperature, PWHT as SR and STC* Guidelines For CrMo Steels			
	ASTM & ASME	T_p [°C]	T_i [°C]	SR** [h] @ [°C]	PWHT/STC [h], [°C]
0.5Mo	T/P 1	RT	RT	2-4 @ 580-630	
1.25Cr-0.5Mo	T/P 11	200-250	>200	2-4 @ 660-700	STC***
1Cr-0.5Mo	T/P 12	200-250	>200	2-4 @ 660-700	
2.25Cr-1Mo	T/P 22	200-300	200-300	2-4 @ 670-720	
2.25Cr-1MoVW	T/P 23	200-300	200-300		0.5-4h @ 740°C****
5Cr-0.5Mo	T/P 502	225-300	>225	2-4 @ 730-760	
9Cr-1Mo	T/P 9	200-300	200-300	slow cool after welding	xh @ 750°C
9Cr-1Mo mod.	T/P 91	200-300	200-300	slow cool after welding	
9Cr-0.5MoWV	T/P 911	200-300	200-300	slow cool after welding	xh @ 730-780°C
9Cr-0.5MoWV	T/P 92	200-300	200-300	slow cool after welding	xh @ 730-780°C
12Cr-1MoNiV		200-280	200-280	slow cool after welding	xh @ 760°C

* STC: Step Cooling
** SR: Stress Relieving
***depends on application
x depends on thickness
****no PWHT required for GTAW up to wall thickness of 10mm

4. Experimental Work

As a start point for Cr-Mo weldments, the metallurgical differences between the welds made with O electrode alloyed from the coating and its equivalent E electrode alloyed from the core are being investigated. Therefore, single pass, double pass and five passes weldments were made to both St52 and X70 steel base metals with both O and the other electrode E separately and their chemical analyses, micro & macro photos, HV hardness measurements, Charpy-V Notch and bending tests results were taken. Single pass welding by O is called O1, single pass welding by the other electrode is called E1 and double passes are called O2 and E2. And five passes weldings are called O5 and E5. The research is continueing.

4.1. Welding Parameters

The welding parameters for five passes weldments are; The Root gap: 2,5 mm, Root diversity: 2 mm, Interpass temperature: 150°C, Root pass: 130-140 Amper, Other passes: 160-170 Amper with (+)DC current. The first and second passes are welded with 3.2 mm diametered electrodes and the other passes are welded with 4 mm diametered electrodes.

Table 4. Chemical compositions of our weldments with O and its equivalent (E) electrodes

Welding Electrode	Chemical Composition (wt%)						
	Si	Mn	Cr	Mo	Ni	Cu	C
O	0.23	0.64	2.15	1.08	0.006	0.025	0.071
E	0.56	0.69	1.91	0.68	0.030	0.091	0.033

The difference of the chemical compositions of the two different weld metals by O and E electrodes can be observed from the Table 4 above. According to this chemical analysis, the Cr and Mo contents of the weld seam by O electrode are a bit higher than the weld seam by E electrode.

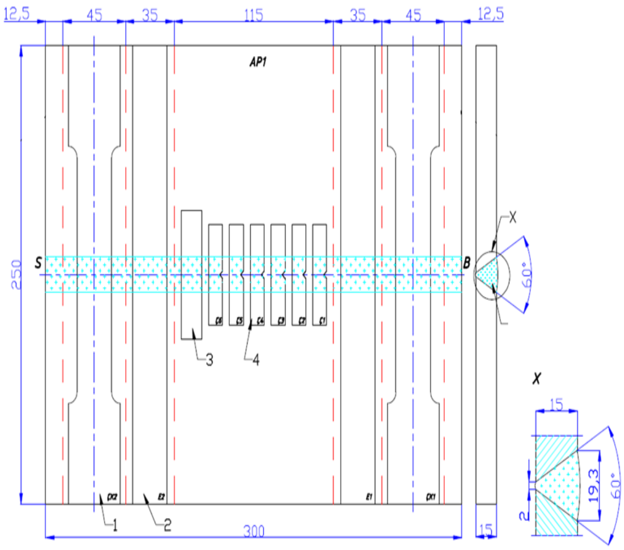

Figure 3. Cutting plan for mechanical tests: tensile (1), bending (2), macrography and micrography (3), charpy V-Notch (4)

4.2. Results of The Analyses

The samples were cut according to the cutting plan seen in Figure 3 above. And then, the related tests were conducted with these samples. The results are as following:

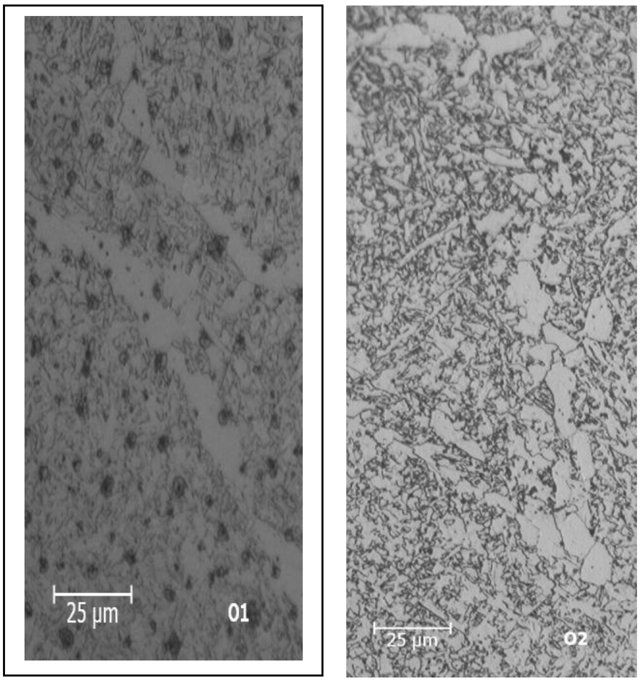

Figure 4. Weld metal microstructures of O1 (single pass weldment to St52 base metal with O electrode) and O2 (double passes weldment to St52 base metal with O electrode) respectively

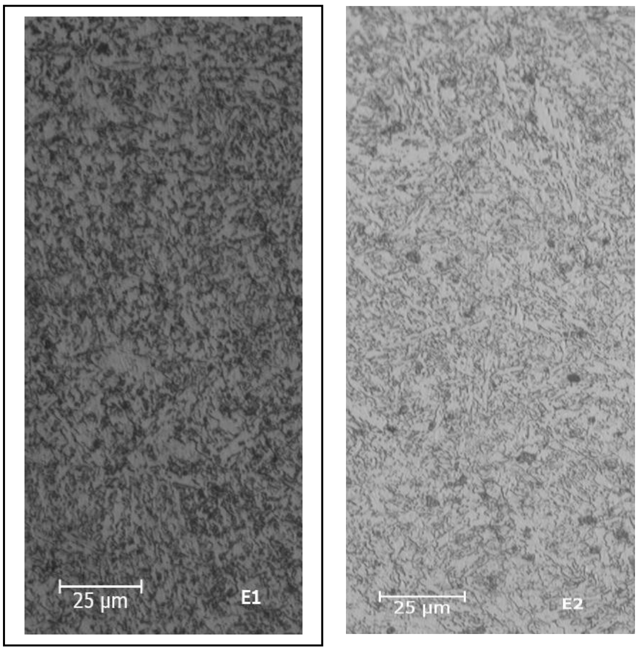

Figure 5. Weld metal microstructures of E1 (single pass weldment to St52 base metal with E electrode) and E2 (double passes weldment to St52 base metal with E electrode) respectively

Similar ferritic-perlitic microstructures and carbid formations can be observed from the microstructure pictures in Figure 4 and Figure 5 above. In order to take these microstructure photos; the samples were sandpapered with 120, 240, 500, 600 and 1000 numbered SiC emeries respectively on the rotating disc. The polishments were carried out with 6μ,3μ,1μ and 0,04μ diamond solutions. And then, the micro and macro photos were taken after etching with 3% nital solution.

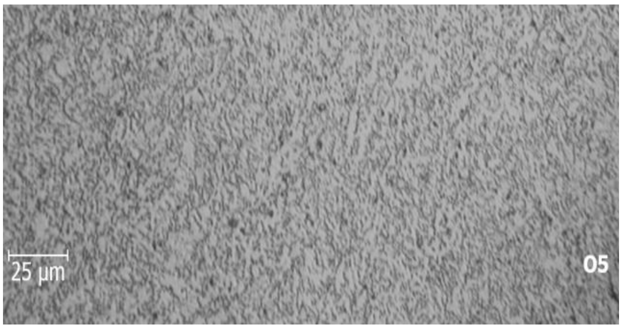

Figure 6. Weld metal microstructure of O5 (five passes weldment to St52 base metal with O electrode)

Figure 7. Weld metal microstructure of E5 (five passes weldment to St52 base metal with E electrode)

When the microstructures for multipass weldments in Figures 6&7 and single pass weldments in Figures 4&5 are compared, more fine grained ferritic-perlitic micro structure was observed for multipass weldments. The grains are smaller with carbid formations for multipass weldments in Figures 6&7.

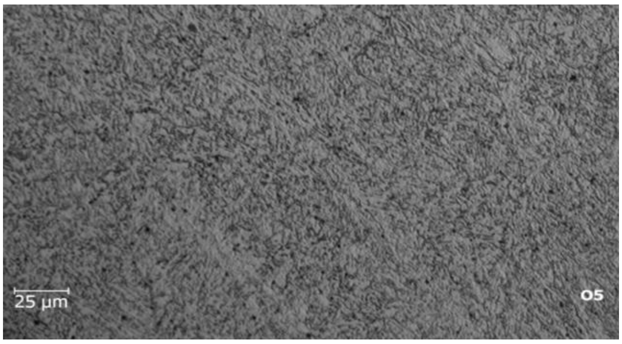

Figure 8. Weld metal microstructure of O5 (five passes weldment to X70 base metal with O electrode)

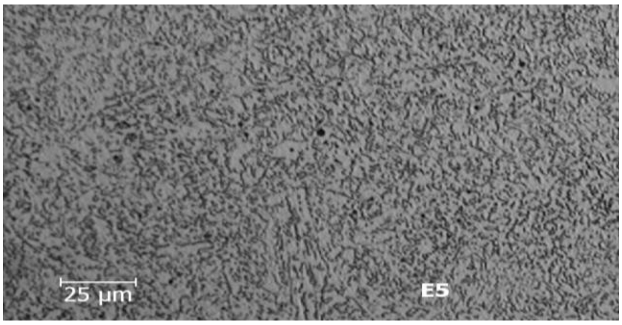

Figure 9. Weld metal microstructures of E5 (five passes weldment to X70 base metal with E electrode)

Weld metal microstructures to X70 base metal in Figures 8&9 are more fine grained and without Widmanstatten structures compared to the other microstructures.

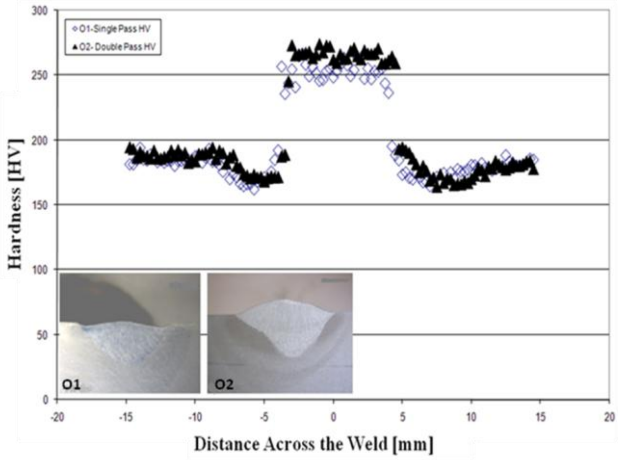

Figure 10. Comparison of hardnesses of O1 and O2 weldings and their macro pictures respectively.

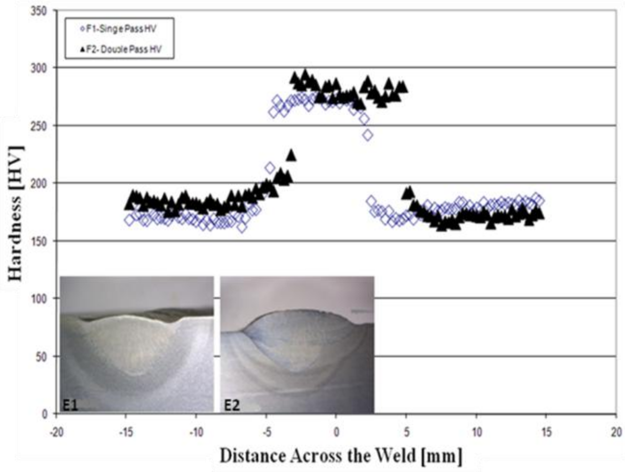

Figure 11. Comparison of hardnesses of E1 and E2 weldings and their macro pictures respectively.

According to these values of hardness results, the hardnesses of the weld metal is higher than 250 HV which shows their high strength. Besides, for the five passes weldments, higher than 250 HV values of hardnesses were investigated as seen from the Table 5 below.

Table 5. Results of the HV hardness values of five passes weldments to St 52 base metal with O5 and E5 electrodes

Specimen	Hardness (HV)
O	304, 309, 314, 314, 318 Av.: 312
E	303, 318, 323, 332, 342 Av.: 324

However, comparing the hardness values for five passes weldments and single&double passes weldments from the Table 5, Figure 10 and Figure 11; it is observed that the values are getting a bit higher for multipass weldments.

Table 6. Results of the Charpy V-Notch tests of five passes weldments

Specimen	Energy (J @ RT) (St52)	Energy (J @ RT) (X70)	Energy (J @ RT after heat treatment: 720°C/1h/300°C air) (X70)
O	55, 30, 36, 42, 38, 53 Av.: 42	48, 52, 43 Av.: 48	98/104/152 Av.: 118
E	51, 49, 50, 52, 39, 52 Av.: 49	37, 52, 43 Av.:44	82, 82, 94 Av.: 86

According to these results of Charpy V-Notch tests seen from the Table 6 above, the minimum Charpy-V energy of O welding is 30 Joule and the minimum Charpy-V energy of the other E welding is 39 Joule for St52 weldments. The Charpy-V energies are rather higher after heat treatment.

Table 7. Results of the tensile test of five passed X70 weldments

Specimen	Tensile Strength (N/mm^2 @ RT)	Fracture Location
O	630, 619 Av.: 625	Base Metal
E	625, 614 Av.: 620	Base Metal

Since the hardness of the weld metal is higher, the specimens were fractured from the base metal. Additionally, the hardness values of O and E weldments are close however the tensile strength of O weldment is a bit higher as seen from the Table 7.

a- E5 Specimen b- O5 Specimen

Figure 12. The shapes of the samples after bending tests

The specimen in Figure 12-a is multipass welded St52 with E electrode and the other specimen in Figure 12-b is welded St52 with O electrode. O weldment was bended more which shows its better ductility. However, X70 bendings was OK.

5. Conclusion and Outlook

Cr-Mo steels can be welded by: SAW, GTAW, GMAW, FCAW, and SMAW. The welds have a tensile strength of 413 MPa to 651 MPa as welded. This type of material lends itself to joints in thin sections. Preheat and PWHT are mandatory and critical to the service life of the alloy. Induction heating is a growing method for preheating and PWHT. Therefore, high Cr-Mo welding is very useful for high temperature, high creep and high pressure applications.

This study revealed the fine grained microstructures and high strength of Cr-Mo weldments besides the researches are still continueing.

At Gedik, there is a technological capability to produce Cr-Mo based products to answer the demands of Turkey's nuclear power plants. This will enhance Gedik's position as the leading welding company in Turkey and a global player in its segment.

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