Effects of HFRW Variables on Weldded Joint Quality of the Ferritic Stainless Steel to Cr-Mo Low Alloy Steel in Heat Recovery Steam Generator

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Abstract

Heat recovery steam generator (HRSG) is obviously a very desirable and environmental friendly energy source, increasing thermal efficiency while reducing energy costs is possible through the use of industrial boilers. In this study, the effect of high frequency resistance welding (HFRW) variable factors on joints between AISI 409 stainless steel finned to 2 ¼ Cr-1Mo alloy steel tube as helical finned tube was investigated. So HFRW was implemented on actual samples by changing multiple factors including travel speed, electric potential, current of welding and fin pitch. Meanwhile metallography of weld joint, tensile strength and hardness tests were carried out several sections of the samples according to international standard fin tube. The diffusion zone indicating metallurgical joining more than 90% was measured at the weld interface, with applying optimum welding parameters, fin-tip and tube-tip position and hydraulic pressure jack setting on squeeze rollers. Furthermore as the lower pitch and fin thickness are selected, the higher quality of fin tube welding joint is achieved. On the other hand as the pitch and fin thickness are reduced, the output transfer surface treatment in final process diminished. However, this paper presents emphasis on finned tube manufacturing processes and the best weld parameters conditions have been reached a sound joint.

Keywords: Heat Recovery Steam Generator, Resistance Welding, AISI 409, Finned Tube, 2 ¼ Cr-1Mo.

1. Introduction

Boiler and HRSG designs are being continuously improved to meet the challenges of higher efficiency and lower emissions and to handle special requirements if any. Today's plants must also meet strict environmental regulations relating to emissions of NOx, SOx, CO, and CO2 which adds to the complexity of their designs [1].
A combined cycle power plant (CCPP) recycles the hot exhaust gas from the gas turbine into HRSG to use it as the heat source to generate high temperature and high pressure steam to operate a steam turbine and generator to produce secondary electricity [2]. Aerial view of CCPP is demonstrated in (Fig. 1).
Finned tubes used a HRSG is the core facility of a combined cycle thermal power plant. In the fin tube welding process rolled steel strip is continuously welded in spiral form on the outside diameter of a tube. This type of weld is comprised of a fusion between two portions of parent metal without the introduction of a filler material [3].
The weld is simply produced by heating the interfaces to be joined to a semisolid state and applying pressure. An electrical current with frequency range of 400 KHz is normally used for high-frequency welding. [4].

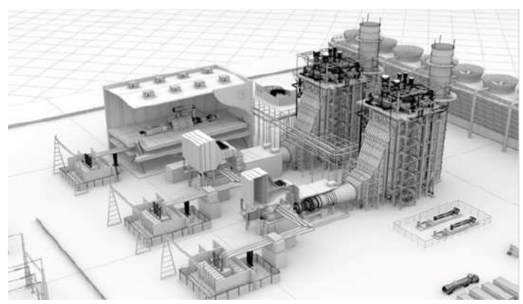

Fig. 1. Aerial view of combined cycle power plant (CCPP) [2].

Increase the rate of heat exchange in the HRSG tubes, the surface area on the outside of the tubes is extended by finning [5]. Finned tubes position of harp modules in HRSG is demonstrated in (Fig. 2). R. Kocurek and J. Adamiec [6].

Fig. 2. Finned tubes position of harp modules in HRSG [5].

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Table. 1. Chemical composition (%wt.) of the studied AISI 409 St-St fined and ASTM A240TP409L. [17]

Steel Finned	C	Mn	P	S	Si	Cr	Ni	Ti
AISI 409 St-St	0.060	0.290	0.020	0.015	0.570	11.140	0.140	0.190
ASTM A240-TP409L	0.080	1.000	0.045	0.045	1.000	10.500-11.750	0.500	$0.500_{(max)}$

Table. 2. Chemical composition (%wt.) of the studied 2 ¼ Cr-1Mo alloy steel tube and ASTM A213T22 .[18]

Steel Tube	C	Mn	P	S	Si	Cr	Mo
2 ¼ Cr-1Mo	0.120	0.400	0.013	0.003	0.230	2.150	0.930
ASTM A213-T22	0.050-0.150	0.300-0.600	$0.025_{(max)}$	$0.025_{(max)}$	0.500-1.000	1.900-2.600	0.870-1.130

studied that there are several technologies of making finned tubes As a result, they are a suitable candidate for using and so that one of the most efficient welding processes of dissimilar metals and alloys is laser welding technology [6].
J. Adamiec and M. Więcek [7] mentioned that laser welded joints of fin tubes made of alloy Inconel 625 are resistant electrochemical and pitting corrosion in the base material.
N. Erling [8] reported that high-frequency welding is a solid resistance heat energy.
By the use of high-frequency current resistance welding, heat generated within the work piece so that the work piece surface is heated up to melt the weld zone or close to a plastic state, then applied (or not applied) upsetting force to achieve binding metal. S. R. Mcilwain [9] explained that it is a solid-phase resistance welding methods, with this technique, the fin is wound on edge around the tube spirally and a continuous weld is obtained.
The high frequency resistance welding process produces a strong metallurgical joining between the fin and the tube while minimizing the heat affected zone (HAZ) in the tube as stated by Noordermeer J.and Eng P. [10].
R. Huseman [11] investigated that the fins greatly enhance the heat transfer surfaces, allowing the full optimization of heating surfaces of the boiler, which is achieved by reducing the dimensions of the boiler, and thus reducing its weight. As shown by H. Kushima et al [12]. , for 2 ¼ Cr-1Mo steels, degradation occurs due to long-term service at elevated temperatures.
B. King [13]. revealed that welding 2 ¼ Cr-1Mo steel is to use preheat and post welding heat treatment (PWHT) to improve weldability. L. Wagner Ferreira et al [14]. investigated on the microstructural evolutions and creep properties of 2 ¼ Cr-1Mo ferrite-pearlite and ferrite-bainitic steels after exposure to elevated temperatures. The observations of the ferrite-bainite steel show a more stable behaviour at the aging temperature and time considered. However, creep tests revealed that the ferrite-pearlite microstructure possesses a better rupture time performance.
S. Zuback et al. [15] demonstrated that dissimilar joints between 2 ¼ Cr-1Mo steel to austenitic alloy (800H) and show that eliminates abrupt changes in mechanical properties, microstructure, and composition with reduces carbon potential gradient.
C. Ornek [16] observed the position of AISI 409 St-St finned the lowest chromium content of all stainless steels in Schaeffler diagram.
HFRW are currently the most widely used one spiral finned tubes, is now widely used in heat recovery steam generator and this paper presents emphasis on finned tube manufacturing processes and the best weld parameters conditions have been reached a sound joint.

2. Materials and Methods

Chemical composition AISI 409 (UNS S40900 or EN 1.4512) is titanium stabilized ferritic St-St (FSS) cold rolled of coil strips containing about 11% chromium shown in Table. 1. (according to ASTM A240).
The presence of Cr leads to the formation of a passive surface film which provides corrosion resistance.
The addition of Ti prevents formation of harmful Cr carbides which can lead to inter granular corrosion in service. Type 409L are very similar to carbon steel but 409L offers improved corrosion resistance in comparison to carbon steel.
2 ¼ Cr-1Mo steels exist in the form of seamless steel for boiler, super heater, and heat exchanger tubes. The standard actually covers 14 different grades of ferritic steels and 14 different grades of austenitic steels. A typical analysis of ferrite-pearlite steel is given in Table. 2., along with the ASTM A213-T22 compositional tolerances.
The addition of Cr to this alloy provides oxidation resistance and microstructural stability. Cr forms carbides within the grains that anchor the structure at high temperatures.
Cr additions also significantly increase the hardenability of the alloy, thus increasing as-welded strength. The purpose of Mo in the alloy is to increase creep strength. HFRW process shown is

demonstrated in (Fig. 3.a). Serrated finned tubes and solid finned tubes are two types of spiral wrapped finned tubes used HF as illustrated in (Fig. 3.b).

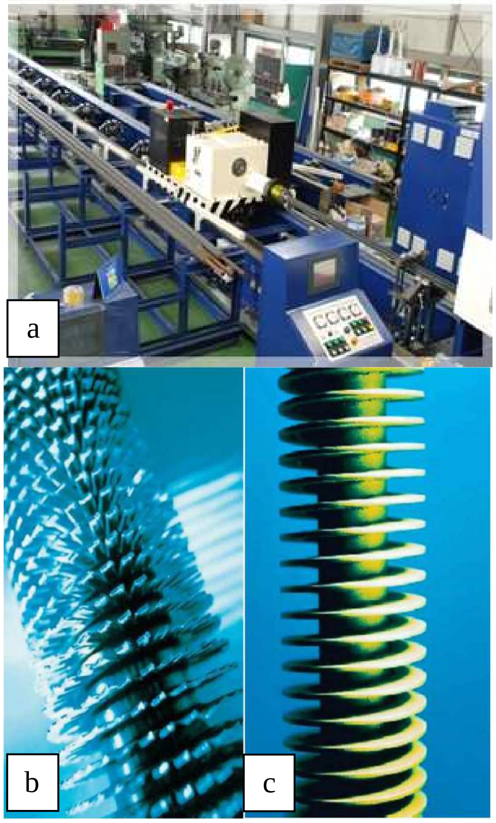

Fig. 3. (a) Automated line for welding process currents of high frequency (b) Tube with serrated fins (c) Tube with solid fins .

Solid and serrated fins are widely used solutions for improving heat transfer in fired heaters. The important fact that designers often overlook while selecting the fins is that serrated fins can provide larger surface area and significantly higher fin efficiency compared with solid fins.

Sample preparation of finned tubes welding metallography include sample of weld joint tests, tensile strength and hardness tests were prepared as illustrated in (Fig. 4.).

In this research 4 essential welding parameters including current, electric potential, welding speed (rotation speed) and pitch were assumed as variables and 10 simples were selected by Taguchi method and welding process was performed according to the conditions mentioned in Table. 3. by "HANSUNG HFS-9488pu" HFRW machine.

After welding process, the samples were performed according to ASTM E3 and ASTM E340. Metallography for joints was done by Olympus DMI3000M optic microscope which was equipped with Image Analyzer.

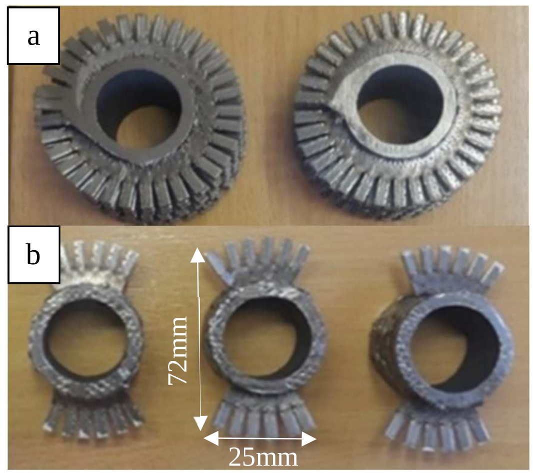

Fig. 4. Sample tests preparation of AISI 409 stainless steel finned to 2 ¼ Cr-1Mo alloy steel tube, (a) metallography and hardness, (b) tensile strength.

The dimension of 2 ¼ Cr-1Mo steel tube for welding experiments 38.1×2.9mm were selected. According to ASTM E340-19, at least 8 samples were prepared for metallography Examination.

Table. 3. HFRW Welding parameters of test samples.

Sample No.	2 ¼ Cr-1Mo Tube O.D × Thickness	AISI 409 Finned Width×Thickness	Travel Speed (RPM)	Potential, Welding (V)	Current, Electric (A)	Pitch (Fins/Meter)
1	38.1×2.9	17×1.2	560	10.8	12.9	126
2	38.1×2.9	17×1.0	540	10.5	12.3	126
3	38.1×2.9	17×1.2	520	11.2	13.4	180
4	38.1×2.9	17×1.0	520	11.0	13.1	180
5	38.1×2.9	17×1.2	500	11.5	13.9	240
6	38.1×2.9	17×1.0	500	11.4	13.8	240
7	38.1×2.9	17×1.0	480	11.7	14.0	276
8	38.1×2.9	17×1.2	480	11.8	14.2	276
9	38.1×2.9	17×1.0	430	12.1	14.5	305
10	38.1×2.9	17×1.0	460	12.3	15.1	305

Microstructure should be analyzed weld joint and acceptance criteria was according to standards specifications of welding machine manufacture in order to obtain a minimum of 90 % joining. Tensile test (1 mm/min) was done by SANTAM-STM-600. Mechanical properties such as tensile tests and hardness shall be performed on finned samples. A section of one wrap of fin with a maximum width of 50% of bare tube diameter was placed in a tensile testing machine with suitable grips. The finned tube was cut including more than 4 fins and the tube was cut to be 19~25mm of fin length. The fins except 1 fin shall be removed to tube surface. Tensile test was carried out using tensile test machine which is calibrated. (The quantity of test piece is 6 per 1 tube). The minimum value of tensile strength is 275 MPa for weld applied according to ASTM A370-19. Hardness test was done by DRMC-250.The applied force was 500 gram-force and the dwell time was 15s in 4 connecting positions. Alloy steel and stainless steel samples require Micro hardness HV1 (Vickers diamond 136° indenter) according to ASTM E384-19. The hardness test was carried out at 3 points (Fin, HAZ, and Tube) per each sample. Hardness shall not be over max. 400Hv, hardness at heat affected zone (HAZ) shall be under 150Hv for fin tube.

3. Results and Discussion

The microstructure of AISI 409 stainless steel finned is illustrated that (Fig. 5a). The chromium content is usually above 11 weight-percent with low carbon, these alloys are classified as ferritic.

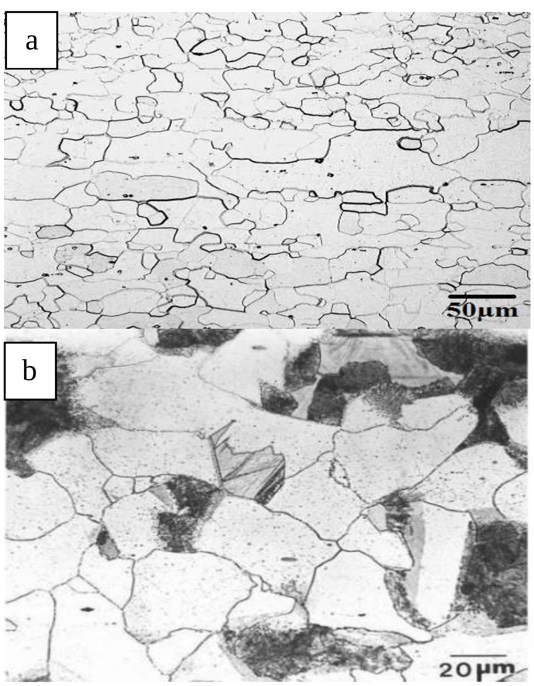

Fig. 5. The microstructure of (a) AISI 409 stainless steel finned, (b) 2 ¼ Cr-1Mo alloy steel tube.

It is shown the ferritic structure with smaller grain size for the stainless steel 409.

As well as the microstructure of typical 2 ¼ Cr-1Mo alloy steel tube (ASME SA213 type T22) is shown on (Fig. 5b).

The microstructure consists of ferrite (light etching constituent) and a small amount of pearlite (dark etching constituent).

Even for tubes (ASTM A213), it can be furnished in the full-annealed, isothermal annealed, or normalized and tempered condition.

Each condition would have a different microstructure.

Martensitic phase in this steel is affected by the production method, according to continuous cooling transformation (CCT) diagram for 2 ¼ Cr-1Mo steel is shown in (Fig. 6).

According to Schaeffler diagram, in this case, the amount of chromium and nickel equivalent is display in (Fig. 7). The examined sample steel had ferrite type.

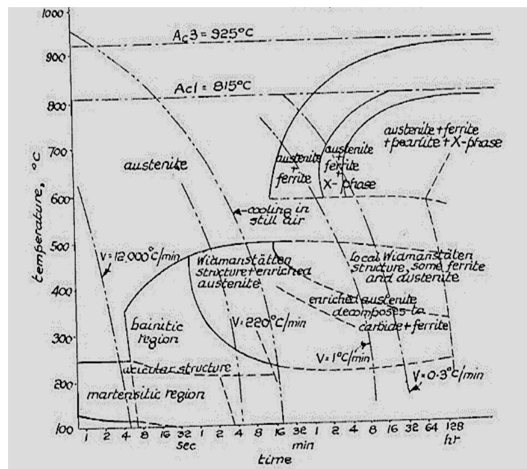

Fig. 6. CCT diagram of 2 ¼ Cr-1Mo steel.[13]

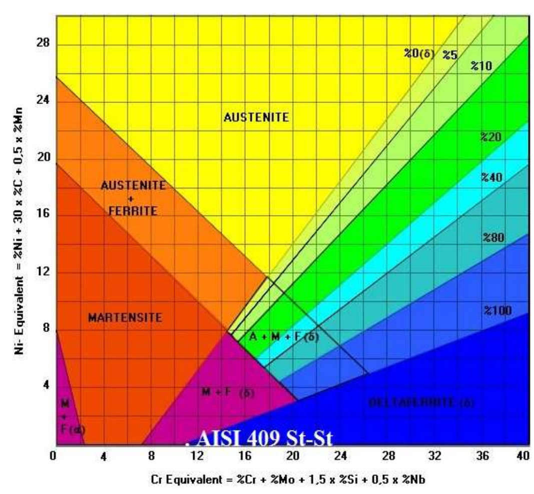

Fig. 7. The position of AISI 409 stainless steel in Schaeffler diagram .[16]

Fin to tube penetration of the welded joint is illustrated in (Fig. 8.).
T=Nominal fin thickness
S= Weld width
D=Weld depth (weld penetration)

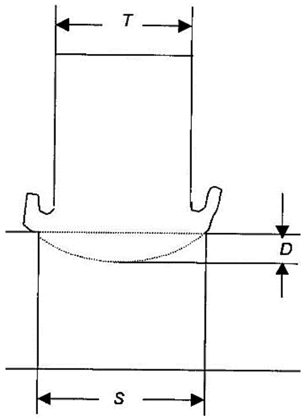

Fig. 8. Fin to tube penetration (weld width and weld depth).

Light optical microscopy image (relevant to sample 7) is shown that (Fig.9a) the full penetration finned to tube joints was 100% weld joint and simultaneously 3 morphologies of heat affected zone (HAZ) are display.

The average width of the weld joint between finned and tube should be a minimum of 90 percent, according to standard specification for high frequency electric resistance welded finned tubes. The microstructure of lack of penetration (LOP) finned to tube joints is marked by the red circle in (Fig. 9.b). It has insufficient quality welding and rejected because there are no optimum welding parameters apply because that the weld joint is 78%.

Table. 4. Average of welding joint sample.

No.	Fin to tube weld joint	Result
1	100 %	Accept
2	100 %	Accept
3	96 %	Accept
4	100 %	Accept
5	97 %	Accept
6	98 %	Accept
7	100 %	Accept
8	100 %	Accept
9	100 %	Accept
10	100 %	Accept

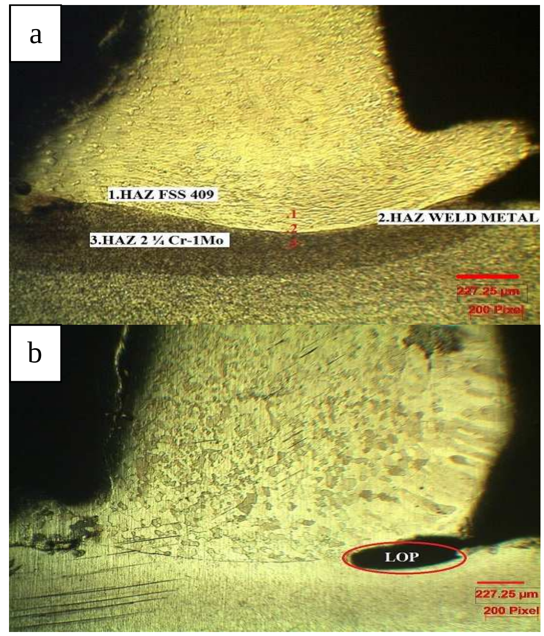

Fig. 9. Light optical microscopy image of AISI 409 St-finned to 2 ¼ Cr-1Mo alloy steels tube, (a) Accepted sample: 100% weld joint and the sub-zones of the heat affected zone (HAZ), (b) Rejected sample: 78% weld joint.

Tensile strength curves of 6 fin joints to tube illustrated that (Fig. 10.a) rejected sample and (Fig. 10.b) accepted sample No.7. As well as the result of tensile strength are given in Table. 5.a rejected sample and Table. 5.b accepted sample No.7.

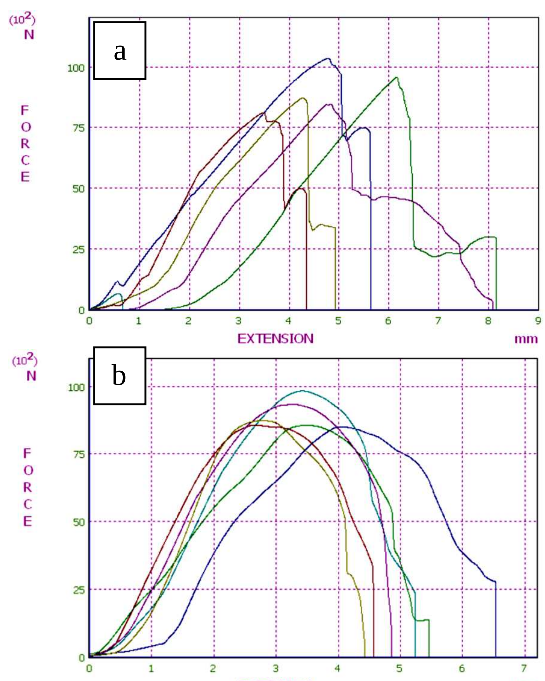

Fig. 10. Tensile strength tests of tube to fins according to ASTM A370-19, (a) rejected sample, (b) accepted sample No.7.

Table. 5. Result of tensile test (6 fin joint to tube), (a) rejected sample, (b) accepted sample No.7. (a)

Specimen	Thickness(mm)	Sec. Area (mm^2)	Total Load (N)	UTS (MPa)	Location of Failure
T1	1.2	32.812	10354.5	315.57	Weld
T2	1.2	28.756	9572.1	332.87	Weld
T3	1.2	30.056	674.4	22.43	Weld
T4	1.2	29.316	8100.6	276.34	Weld
T5	1.2	28.575	8458.7	296.01	Weld
T6	1.2	30.251	8729.7	288.57	Weld
Result	**REJECT**				

(b)

Specimen	Thickness(mm)	Sec. Area (mm^2)	Total Load (N)	UTS (MPa)	Location of Failure
T1	1.2	26.76	10192.6	380.88	Fin
T2	1.2	26.36	10133.7	384.37	Fin
T3	1.2	26.24	10051.6	383	Fin
T4	1.2	26.91	10376.5	375.51	Fin
T5	1.2	27.61	10366.7	375.44	Fin
T6	1.2	27.61	10052.8	368.23	Fin
Result	**ACCEPT**				

The result of tensile strength in Table. 5. indicate that the lowest ultimate tensile strength (UTS) was 368.23 MPa and the average of UTS in theses case was 379.57. Table. 6. is given that result of tensile strength (6 fin joints to tube) in 10 average welding samples. Furthermore, all of the sample tests were accepted because the average of tensile strengths were more than 275MPa.

Table. 6. Average tensile strength of welding sample.

No.	Tensile strength (MPa)	Result
1	380.31	Accept
2	378.39	Accept
3	375.34	Accept
4	377.85	Accept
5	376.24	Accept
6	381.15	Accept
7	380.17	Accept
8	379.57	Accept
9	375.61	Accept
10	379.73	Accept

The results of hardness test in Table 7 is shown the hardness of the samples according to the conditions indicated in Table. 3. at various zones. The result of hardness test in Table 7 show that the highest hardness in HAZ alloy steel tube 272 HV was related to sample No.7 and the lowest hardness in alloy steel tube 250 HV was related to sample No.4. As well as the highest hardness in HAZ St-St finned 173 HV was related to sample No. 1 and the lowest hardness in HAZ St-St finned 161 HV related to sample No.7. The most hardness variation between HAZ fin to fin 165 HV related to sample No. 2 and the most hardness variation between HAZ tube to tube 169 HV related to sample No. 1.

The result of hardness test that according to ASTM E384-019 standard all of the hardness samples were in acceptance criteria, as well as in Table. 8., one rejected sample was provided just to be compared with accepted samples.

Table. 7. Hardness results of various sample (HV).

No.	Fin HAZ	Hardness Variation of fin to fin HAZ	Tube HAZ	Hardness Variation of tube to tube HAZ
1	173	151	252	169
2	162	165	270	166
3	165	156	263	163
4	170	149	250	167
5	166	160	264	165
6	171	150	267	168
7	169	148	265	164
8	161	162	272	165
9	172	159	262	162
10	164	161	258	164

Table. 8. Hardness result of rejected sample.

No.	Hardness			
	Fin HAZ (HV)	Hardness Variation of fin to fin HAZ(HV)	Tube HAZ (HV)	Hardness Variation of tube to tube HAZ(HV)
1	195	187	275	175

We have different conditions on serrated fin tube and solid fin tube types. Solid and serrated types of fin tube produced by HFRW depend on fin height, fin thickness and tube O.D. The result of analyzes show that as the lower pitch and fin thickness, the higher quality of fin tube welding joint is achieved.

On the other hand as the pitch and fin thickness is reduced, the output transfer surface treatment in final process decreases. So for increasing performance in the aspect of process design and welding engineering, the current welding set on optimum electric potential and it is depend on travel speed of welding. As well as selecting suitable finned obtained by over 15mm fin width(coil strip before welding), 1mm fin thickness and 276 per meter of fin pitch and the higher quality of finned tube welding joint is achieved.

4. Conclusions

In this research, the effects of HFRW variable factors on joints between AISI 409 St- St finned to 2 ¼ Cr-1Mo alloy steel tube as helical finned tube used in industrial boilers were investigated and the summary of the results are mentioned below.

1. In the base metal, the microstructure of 2 ¼ Cr-1Mo steels tube consists of ferrite and a small amount of pearlite on CCT diagram and AISI 409 in Schaeffler diagram showed that this steel finned had ferrite type microstructure.
2. The penetration zone indicating metallurgical joint more than 90% was measured at the weld interface, by applying optimum welding parameters, fin-tip and tube-tip position and hydraulic pressure jack setting on squeeze rollers.
3. Cyclic heat due to high cooling rate accompanied by water spray lead to the grain size microscopic structure and HAZ limited in section welding so that the average of tensile strength more than 275 MPa and all of the hardness samples were in acceptance criteria.
4. Solid and serrated types of helical finned tube produced HFRW depend on fin high, fin thickness and tube O.D.
5. Selecting suitable finned obtained by over 15mm fin width , 1mm fin thickness and 276 per meter of fin pitch and the higher quality of finned tube welding joint is achieved.

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