

Advanced Manufacturing and Eco-friendly Welding Between AISI 409 Finned to High Pressure T22 Boiler Tube by HFRW Clean Energy

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Abstract

In this paper, advanced manufacturing and eco-friendly welding between AISI 409 finned to high pressure T22 boiler tube produced by "High-frequency resistance welding (HFRW)" process has been studied. The current development in the power generation industry is HFRW clean energy contributes to the resolution of the greenhouse effect. HFRW technology was implemented on actual samples by changing multiple parameters. Meanwhile metallography of weld bond, tensile strength and hardness tests were performed on several sections of the samples according to international standard finned tube. The diffusion zone indicating the schematic of weld width and weld depth of finned tube observed under the scanning electron microscopy (SEM) which is used for analyses width are that the weld width must be $\geq 90\%$ of fin thickness which can be calculated at the weld interface, with applying optimum welding parameters. Moreover, as the pitch and fin thickness are reduced, the output transfer surface treatment in final process diminished. Hence, the parametric optimization HFRW and the higher quality of finned tube welding bond is revealed by the best conditions of fin pitch.

Keywords: Advanced Manufacturing, High-Frequency, Resistance Welding, AISI 409, T22 Tube.

1. Introduction

Finned tube of headers are routinely used in high temperature applications in which heat recovery steam generators (HRSGs) are an integral part of any modern combined cycle power plant (CCPP). These heat exchangers are designed to recover the heat from a gas turbine exhaust and convert this to steam, which drives a turbine and ultimately a second generator. Because the gas turbine operates efficiently at high temperatures and heat is removed down to nearly ambient temperature, increasing flexibility and response to load dispatch. HRSG can be complex to analyse and also difficult to effectively test and prove their performance. [1] The current development in the power generation industry is of increasing demand for combined cycles with improved efficiency and reduced delivery time. Improved efficiency reduces the fuel related cost and, at the same time, contributes to the resolution of the greenhouse effect. Finned tubes position of harp modules in HRSG are key components in the combined cycle. [2] A block of combined cycle power plant (CCPP) is demonstrated in (Fig. 1). The surface area on the outside of the tubes is extended by finning in order to increase the rate of heat exchange

in the heat recovery steam generator (HRSG) tubes. [3].



Fig. 1. A block of combined cycle power plant (CCPP).

In the finned 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. The weld is simply produced by heating the interfaces to be joined to a plastic state and applying pressure. The current frequency range used for high-frequency welding 400 KHz. [4]. Spiral finned tubes, is now widely used in electricity, metallurgy, cement industry, waste heat recovery, and petrochemical industries. Finned tubes, is to improve the efficiency of heat transfer, usually in the surface of the heat

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transfer tubes by adding fins, increasing heat transfer tube outer surface area (or internal surface area), so as to improve heat transfer efficiency purposes, such a change heat pipe. Finned tubes with continuous rib or serrated, depending on the operating parameters of the working medium and the flue gas can be used as: heaters, economizers or super heaters. [5] HFRW technologies of making finned tubes is demonstrated in (Fig. 2.a). Automated line for welding process currents of high frequency is illustrated in (Fig. 2.b).

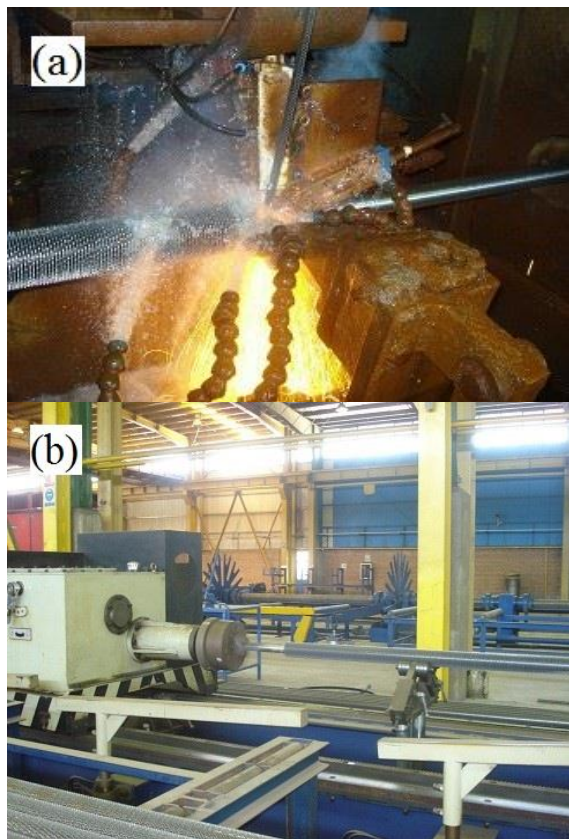


Fig. 2. (a) HFRW technologies of making finned tubes (b) Automated line for welding process currents of high frequency.

Kocurek and Adamiec. 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]. Adamiec and Więcek. mentioned that laser welded joints of fin tubes made of alloy Inconel 625 are resistant electrochemical and pitting corrosion in the base material [7]. Erling. reported that high-frequency welding is a solid resistance heat energy. The use of high-frequency current welding resistance heat generated within the work piece so that the work piece surface is heated to melt the weld zone or close to a plastic state, then applied (or not applied)

upsetting force to achieve binding metal [8]. Mcilwain. 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 [9]. The high frequency resistance welding process produces a strong metallurgical bond between the fin and the tube while minimizing the heat affected zone (HAZ) in the tube as stated by Noordermeer and Eng. [10]. Huseman. 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 [11]. As shown in Kushima et al., metallographic atlas for 2.25 Cr-1Mo steels and degradation due to long-term service at elevated temperatures [12]. King. performed that welding 2.25 Cr-1Mo steel is to use preheat and post welding heat treatment (PWHT) to improve weldability [13]. Wagner Ferreira et al. indicated that microstructure evolution and creep properties of 2.25 Cr-1Mo ferrite-pearlite and ferrite-bainite steels after exposure to elevated temperatures. The observations of the ferrite-bainite steel show a more stable behaviour at the ageing temperatures and time considered. However, creep tests revealed that the ferrite-pearlite microstructure possesses a better rupture time performance [14]. Zuback et al. demonstrated that dissimilar joints between 2.25 Cr-1Mo steel to austenitic alloy (800H) and show that eliminates abrupt changes in mechanical properties, microstructure, and composition with reduces carbon potential gradient [15]. Ornek. observed the position of AISI 409 finned the lowest chromium content of all stainless steels in Schaeffler diagram [16]

2. Materials and Methods

Chemical composition AISI 409 is titanium stabilized ferritic stainless steel (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 409 are very similar to carbon steel but 409 offers improved corrosion resistance in comparison to carbon steel. Ferritic stainless steels suffer embrittlement on welding due to grain growth and grain boundary, martensite formation in the heat affected zone that is heated above 1100°C. Preheat to 200°C and post-heat treatment at 750–850°C are recommended.

Table 1. Chemical composition (wt.%) of the studied FSS fined and ASTM A240TP409 specification.

Steel Fined	C	Mn	P	S	Si	Cr	Ni	Ti
AISI 409 FSS	0.060	0.290	0.020	0.015	0.570	11.140	0.140	0.190
ASTM A240TP409	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 T22 (2.25 Cr-1Mo) tube and ASTM A213T22 specification.

Steel Tube	C	Mn	P	S	Si	Cr	Mo
T22 (2.25 Cr-1Mo)	0.120	0.400	0.013	0.003	0.230	2.150	0.930
ASTM A213T22	0.050-0.150	0.300-0.600	0.025 _(max)	0.0250 _(max)	0.500-1.000	1.900-2.600	0.870-1.130

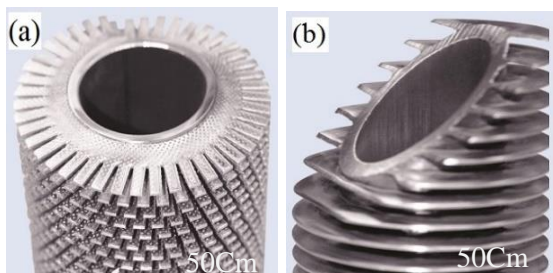
Table 3. HFRW Welding parameters of sample test.

Sample No.	A213T22 Tube Outside Diameter × Thickness	AISI 409 Fined Width × Thickness	Travel Speed (RPM)	Potential, Welding (V)	Current, Electric (A)	Pitch (Fins/Meter)
1	38.1×4.4	17×1.2	580	10.9	12.8	126
2	38.1×4.4	17×1.0	550	10.7	12.4	126
3	38.1×4.4	17×1.2	530	11.3	13.5	180
4	38.1×4.4	17×1.0	530	11.1	13.1	180
5	38.1×4.4	17×1.2	510	11.6	14.0	240
6	38.1×4.4	17×1.0	510	11.5	14.2	240
7	38.1×4.4	17×1.2	475	11.7	14.3	276
8	38.1×4.4	17×1.0	475	11.8	14.4	276
9	38.1×4.4	17×1.2	430	12.1	14.5	305
10	38.1×4.4	17×1.0	460	12.3	15.1	305

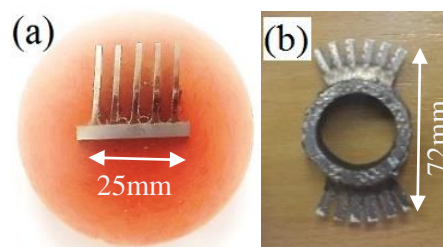
Table 2. presents the chemical composition of the SA213-T22 (2.25 Cr-1Mo) material used in this study by an optical emission spectrometer, along with the ASTM A213-T22 compositional tolerances.

High pressure T22 has the 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. 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. Serrated finned tubes and solid finned tubes are two types of spiral wrapped finned tubes used HF as illustrated in (Fig. 3).

**Fig. 3. Type of finned tubes HFRW process. (a) Serrated finned tubes, (b) Solid finned tubes**

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 bond tests, tensile strength and hardness tests were prepared as illustrated in (Fig. 4).

**Fig. 4. Sample tests preparation of AISI 409 st-st to T22 boiler tube (a) metallography and hardness (b) tensile strength.**

In this research 4 essential welding parameters including current, electric potential, welding speed (rotation speed) and pitch were assumed as variables and 10 samples 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, sampling was performed according to international standard for tests of high

frequency resistance welded fins based on ASTM E3 and ASTM E340. Metallography for welding bond was done by Olympus DMI3000M optic microscope which was equipped with Image Analyzer. The dimension of 2.25Cr-1Mo steel tube for welding experiments 38.1×4.4mm were selected. According to ASTM E340-22, at least 8 section were prepared, for welding bond of metallography test. The microstructure of the joints are analyzed with respect to their welding bond value. A minimum of 90 % welding bond should be obtained for acceptance according to standards specifications of welding machine manufacturer. Fin to tube penetration of the welding bond illustrated in Fig. 5. The 90 % welding bond minimum criterion is for each tube-fin joint.

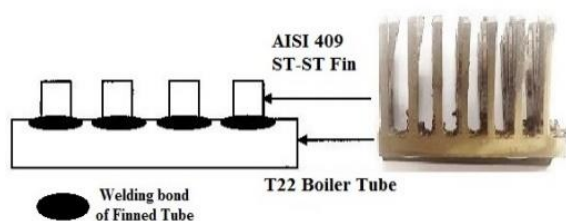


Fig. 5. Fin to tube penetration of the welding bond.

Tensile strength (1 mm/min) was done by SANTAM-STM-60. 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 A370-22. Hardness test was done by DRMC-250. The weight was 500 gram-force and the time was 15s in 4 connecting positions. Alloy steel and stainless steel samples require Micro hardness HV1 (Vickers diamond 136° indenter) according to ASTM E384-22. 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 ferritic grade of type 409 stainless steel finned is illustrated in Fig. 6.a Recrystallized microstructure with an abundance of titanium carbides and carbonitrides. (Etch: 25 ml HNO₃, 25 ml acetic, 5 ml Hel, 50 ml glycerol) A straight chromium steel in which the carbon is

deliberately kept as low as to have a negligible hardening effect is classified as ferritic.

The chromium content is usually above 11 weight-percent with low carbon and no nickel, these alloys are permanently ferritic. It is shown the ferritic structure with small grain size for the stainless steel 409. As well as the microstructure high pressure T22 boiler tube is shown in Fig. 6.b.

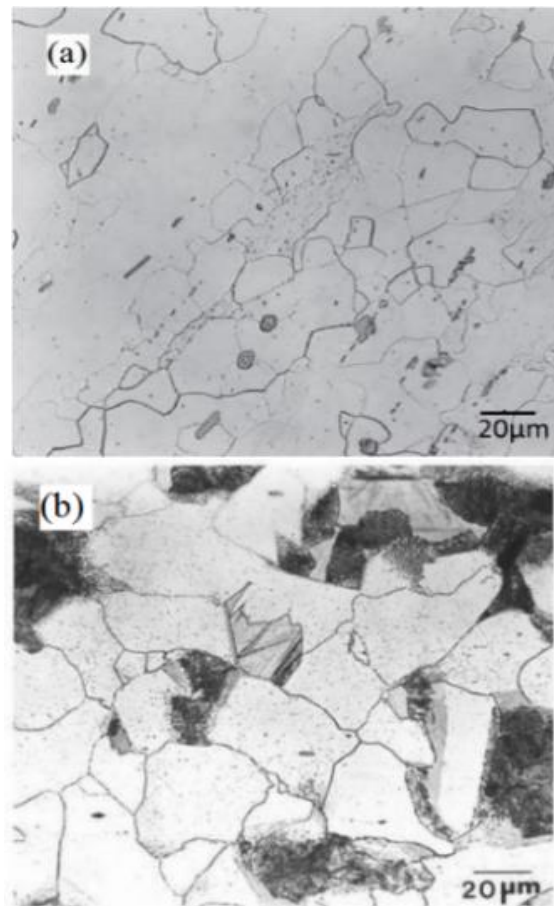


Fig. 6. The microstructure of (a) AISI 409 stainless steel (b) High pressure T22 boiler tube.

The microstructure of typical 2.25 Cr-1Mo alloy steel tube consists of ferrite (light etching constituent) and a small amount of pearlite (dark etching constituent). Light tan areas are martensitic. It is interesting to note that if the same steel was used for a forging or plate, it may have a different microstructure because of the different specified heat treatment. ASTM A213 tubes, 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 due to production method, according to continuous cooling transformation (CCT) diagram for 2.25Cr-1Mo steel and Schaeffler diagram, in this case, the amount of chromium and nickel equivalent is display in the examined sample steel had ferrite type. [17]

A fin to tube joint showing a 100% welding bond is shown in Fig. 7.a. By contrast, a joint showing an incomplete 84% welding bond is shown in Fig. 7.b. The welding bond should be at least 90 percent according to standard specification for high frequency electric resistance welded finned tubes.

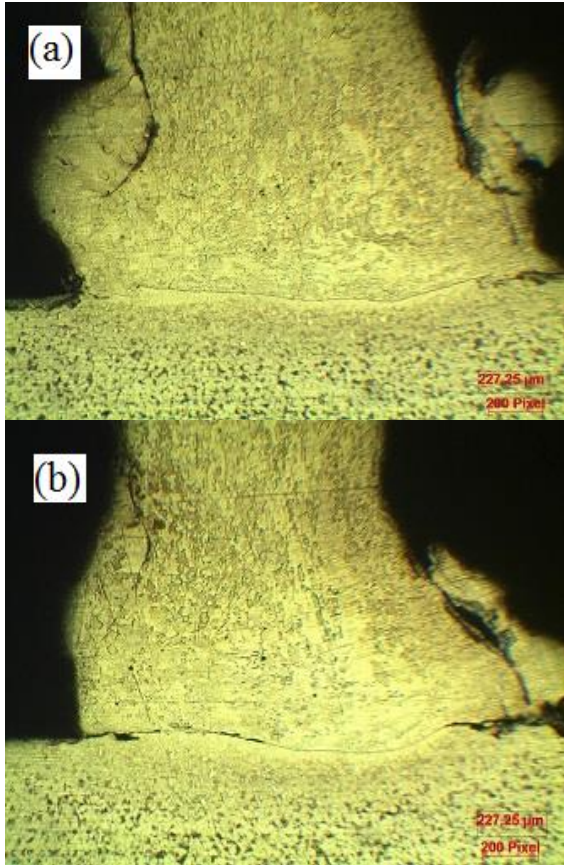


Fig. 7. The microstructure of AISI 409 FSS to T22 boiler tube (a) Accepted sample: 100% weld bond (b) Rejected sample: 84% weld bond.

Butt weld joint is quantitatively considers the specimen using the acceptance criteria (Q) by measuring S (weld width (mm)) and D (weld depth (mm)) values from the microstructure micrograph, Fig. 8. Shows the schematic of weld width and weld depth of finned tube observed under the scanning electron microscopy (SEM) which is used for analyses melting and weld depth determination. There requirements or the acceptance criteria of weld width are that the weld width must be $\geq 90\%$ of fin thickness which can be calculated using equation (1) and the weld depth must be in the range of 0.05 - 0.30 mm.

a) Weld width: $Q = (S/T) \times 100$ (1)
When T = Nominal thickness of fin (mm)
S = Weld Width (mm)

Acceptance Criteria: $Q \geq \text{Average } 90\%$ of nominal fin thickness

b) Weld Depth

Acceptance Criteria: $0.05 < D < 0.30$ mm

At least 8 samples finned to tube were prepared, for welding bond test. As shown in Table. 4., we obtained clearly more than 90% welding bond average quality for ten samples by applying optimum welding parameters, fin-tip and tube-tip position and setting on squeeze rollers with hydraulic pressure jack: a) Air pressure of fin tip holder is 0~4 kg/cm², b) Air pressure of tube tip holder 0~5 kg/cm², pitch or fin per meter (FPM).

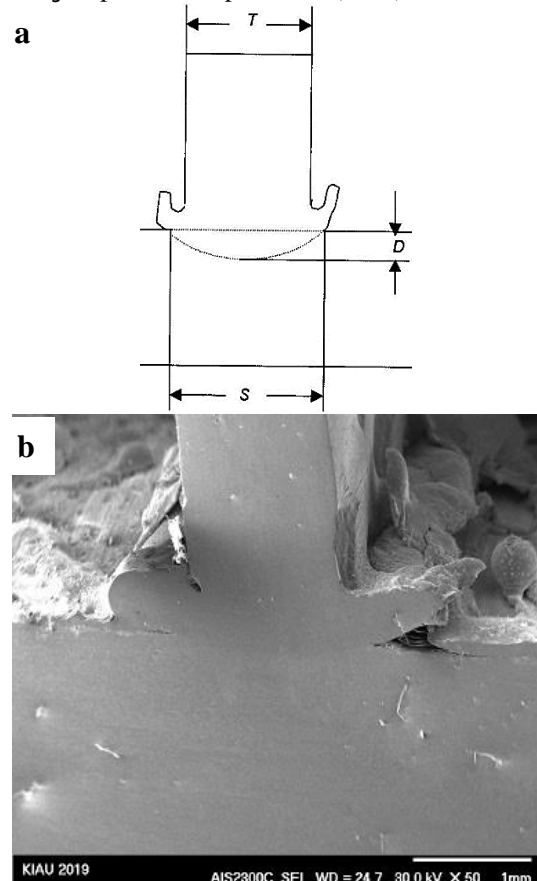


Fig. 8. (a)Schematic of weld width and weld depth of finned tube (b) the scanning electron microscopy (SEM).

Table. 4. Average of welding bond sample.

No.	Fin to Tube Weld Bond	Result
1	100 %	Accept
2	100 %	Accept
3	95 %	Accept
4	100 %	Accept
5	97 %	Accept
6	99 %	Accept
7	100 %	Accept
8	100 %	Accept
9	100 %	Accept
10	100 %	Accept

Tensile strength curves of 6 fin joints to tube illustrated that Fig. 9.a rejected sample and Fig. 9.b accepted sample No.8. As well as the result of tensile strength is displayed in Table. 5.a rejected sample and Table. 5.b accepted sample No.8

Table. 5. Result of tensile strength (6 fin joint to tube) (a) rejected sample (b) accepted sample No.8.

a					
Specimen	Thickness(mm)	Sec. Area (mm ²)	Total load (N)	UTS (MPa)	Location of Failure
T1	1.2	29.244	7141.88	244.27	Weld
T2	1.2	25.428	9863.14	387.88	Weld
T3	1.2	27.756	5817.53	209.56	Weld
T4	1.2	26.364	9188.7	348..53	Weld
T5	1.2	26.592	7176.63	269.88	Weld
T6	1.2	27.492	726.55	26.43	Weld
Result	REJECT				
b					
Specimen	Thickness(mm)	Sec. Area (mm ²)	Total load (N)	UTS (MPa)	Location of Failure
T1	1.0	27.564	10847.2	393.53	Fin
T2	1.0	30.072	9841.68	327.270	Fin
T3	1.0	30.132	10347.51	343.40	Fin
T4	1.0	30.468	10262.69	336.83	Fin
T5	1.0	30.06	9747.67	324.92	Fin
T6	1.0	28.152	9137.61	324.58	Fin
Result	ACCEPT				

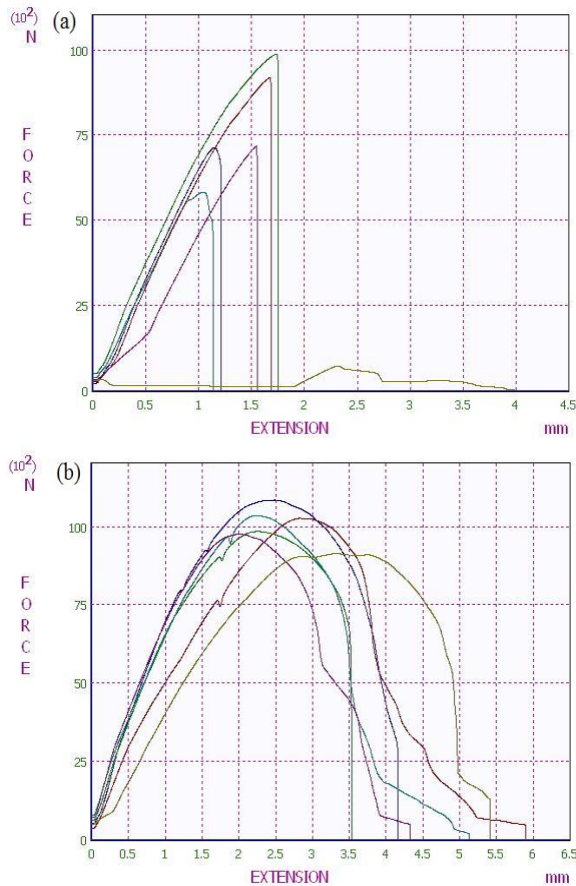


Fig. 9. Tensile strength of tube to fins according to ASTM A370-22 (a) rejected sample (b) accepted sample No.8.

The result of tensile strength in Table. 5. indicate that the lowest ultimate tensile strength (UTS) was 324.58 MPa and the average of UTS in these case was 341.76. Table. 6. shows results of average tensile strength for the 10 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 tests at four different places in the samples are given in Table. 7., as well as the hardness variations. The position of hardness test (fin, tube and HAZ) is exhibited in Fig. 10.

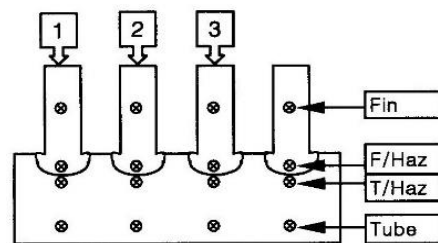


Fig. 10. Position of hardness test (fin, tube and HAZ).

The highest hardness in HAZ alloy steel tube 273 HV was related to sample No.8 and the lowest hardness in alloy steel tube 249 HV was related to sample No.4. As well as the highest hardness in HAZ St-St finned 174 HV was related to sample

No. 1 and the lowest hardness in HAZ St-St finned 160 HV related to sample No.8. 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 168 HV related to sample No. 1. Cycle 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 that according to ASTM E384-022 standard, 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	174	151	252	168
2	162	165	270	166
3	165	156	263	163
4	170	149	249	166
5	166	160	264	164
6	171	150	267	167
7	169	148	265	163
8	160	162	273	164
9	172	159	262	161
10	164	161	258	162

Table. 8. Hardness result of rejected sample.

No.	Hardness (HV)			
	Fin HAZ	Hardness variation of fin to fin HAZ	Tube HAZ	Hardness variation of tube to tube HAZ
1	198	189	277	178

We have different conditions on solid fin tube types and serrated fin tube. Serrated and solid 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 are selected, the higher quality of fin tube welding bond 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 high, 1mm fin thickness and 276 per meter of fin pitch and the higher

quality of finned tube welding bond is achieved.

4. Conclusions

In this research, advanced manufacturing and eco-friendly welding between AISI 409 finned to high pressure T22 boiler tube produced by HFRW clean energy process were investigated and the summary of the results are mentioned below.

1. In advanced manufacturing and eco-friendly welding parameters and setting on squeeze rollers show that the higher quality of metallurgical bonding finned tube is revealed by the best conditions of fin pitch.

2. The current development in the power generation industry is HFRW clean energy process of increasing demand for combined cycles with improved efficiency which reduces the fuel related cost and, at the same time, contributes to the resolution of the greenhouse effect.

3. The diffusion zone indicating the schematic of weld width and weld depth of finned tube observed under SEM which is used for the weld width must be $\geq 90\%$ of fin thickness which can be calculated at the weld interface.

4. 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.

5. The parametric optimization HFRW of finned tube welding bond is achieved and the best conditions of fin pitch obtained by 276 per meter of fin pitch, over 15mm fin high and 1mm fin thickness.

6. The key factor produced HFRW depend on fin high, fin thickness and tube O.D in solid and serrated types of spiral finned tube.

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