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Effect of HF Welding Process Parameters and Post Heat Treatment in the Development of Micro Alloyed HSLA Steel Tubes for Torsional Applications

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Abstract

The aim of the present study is to investigate the effect of High frequency (HF) Electric resistance welding process parameters and post heat treatment on the torsional fatigue life of micro alloyed HSLA steel tubes. Micro alloyed grades exhibit higher strength and formability owing to the presence of fine recrystallized ferritic grains due to thermo mechanical treatment and presence of alloying elements like Vanadium, Niobium and Titanium. Welded tubular components made of micro alloyed HSLA steel grades are highly emerging and manufacturing them remains quite challenging. Weld bond width, HAZ width and bond angle are the significant factors that directly influences the Weld quality and strength. The effect of key welding parameters like Heat input, welding temperature, squeeze roll pressure, Vee-angle, Vee-length and Impeder diameter on the above mentioned significant factors was analysed. Narrow bond, Minimum HAZ width with pronounced Hour glass pattern and optimum bond angle resulted in superior bond strength and formability of HSLA tubes. Microstructural characterization of the samples was carried out using Light optical microscopy and Scanning electron microscopy. Residual stress was determined using X-ray diffract meter and tube slitting method. Higher tensile residual stress of magnitude 200 MPa was observed in the weld region. Since such high magnitude of tensile residual stress is detrimental to torsional fatigue life, stress relieving of the tubes was carried out at different subcritical temperatures 650°C and 700°C with soaking time of 45 minutes. Without significant drop in the tensile properties, compressive residual stress of magnitude 129 MPa was observed at a particular stress relieving cycle. As an effect of stress relieving heat treatment below Ac1 temperature, there is a significant improvement in the Torsional fatigue life of the HSLA steel. Thus, High Frequency welded micro alloyed HSLA steel tubes with enhanced torsional fatigue performance were successfully developed.

Keywords: HSLA steel; High frequency (HF) electric resistance welding; Stress relieving; Residual stress; Fatigue test

Introduction

In automobile industry, High strength low alloy steels were primarily developed to replace the conventional carbon steels in order to improve the strength to weight ratio without affecting its performance and efficiency. HSLA steels have unique properties, such as high strength, formability, excellent ductility, good weld ability and good low temperature impact toughness. It has fine ferritic microstructure with small amount of pearlite less than 10% volume fraction [1]. Among the different categories of HSLA steel, micro alloyed ferrite-pearlitic steel has small amount of alloying elements like Vanadium, Niobium and Titanium and it forms strong carbides and carbo nitrides for the precipitation strengthening, grain refinement and transformation temperature control [2]. Generally welding of HSLA steel tube is very difficult and it requires rigid forming stands, accurate forming rolls and efficient welding parameters. High Frequency tube welding is one of the most forgiving industrial processes and it is possible to produce high bond strength welded tubes for many applications. High frequency welding is electric resistance welding which works on the electromagnetic induction principle mainly and it is associated with proximity effect and skin effect. Because of skin effect and proximity effect, increasing the frequency helps to concentrate intense current closer to the strip edges. This combined effect results in less metal being heated, using less current, which translates into higher efficiency. In general, frequencies used for tube welding range from 100 kHz to 800 kHz for the ferrous material. Apart from Frequency, Induction current coil, impeder design plays a big role in increasing the weld efficiency. Vee length, Vee angle and impeder design and position helps to heat the strip corners first and it leads to the Hour glass shape in the Heat affected zone [3,4]. In HF induction welding of HSLA steel, the better weldment can be obtained by applying sufficient cold forming, controlling the strip width, strips edge quality, applying sufficient and uniform squeeze out pressure, optimizing and monitoring the effective weld parameters/heat input, avoiding negative inside bead and optimizing post heat treatments [5]. Weldment microstructure of the HSLA steel depends on the cooling rate, heat input and the material cleanliness. As a consequence of lower heat input and faster cooling rate, finer grain microstructure consisting of acicular ferrite, upper bainite and small clusters of low carbon marten site formed in the weldment and it possess high weld strength and ductility [6,7].

Heat affected zone width and the hardness transverse along the weldment depends on the heat input and the cooling rate in the welding process [8]. Low temperature impact toughness was found high in the HAZ region of the lower heat input weldment, in the Niobium added HSLA steel. Lower heat input reduces the prior austenite grain coarsening by controlling Ac3 temperature, which resulted in very high toughness [9-11]. Also, by the effect of alloying elements, recrystallization temperature got increased in the HSLA steel [12]. Reheating the heat treated HSLA steels in the intercritical temperatures

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with high cooling rates results in the microstructure of marten site with retained austenite on grain boundaries, leads to poor impact toughness. Lowering the rate of cooling leads to high impact toughness because of its upper bainite and pearlitic microstructure [13].

In HSLA steel, various research works have been done to improve the weldment characteristics, low temperature impact toughness and increasing the strength level etc. and it becomes new and challenging to study the torsional fatigue characteristics of HSLA steels in automobile application. The present investigation in this material is to study the effect of high frequency electric resistance welding parameters and the post heat treatment influence on the torsional applications.

Experimental and Simulation Methods

Material

Hot rolled high strength low alloy steel with the strength level of 800 MPa and the chemical composition of which is listed in Table 1 was used for the study. Micro alloying of the steel with addition of Niobium and Titanium and thermo mechanical treatment by the steel supplier has resulted in precipitation strengthening and grain refinement in the raw material. Microstructure of the micro alloyed HSLA steel (Figure 1) shows very fine ferrite grains of size less than 10 μm.

Energy Dispersive spectroscopic analysis was done in the raw material, at the precipitates in the grain boundary (Figure 2). Analysis confirms the presence of Ti and Nb precipitates in the HSLA steel.

High frequency welding of tubes

HF welded steel tube is normally made from rolled steel coils. Rolled steel coils were slit into different widths according to tube dimensions. At the first stage, the strip is gradually cold formed into a circular tube shape through series of rolls. Subsequently the edges of the strip are then heated to a welding temperature by the high frequency induction coil. The heated edges are then squeezed and pressure is applied to form a forged weld (Figure 3).

Weld bond width, HAZ width and bond angle are the significant factors that directly influences the Weld quality and strength. The effect of key welding parameters like Heat input, welding temperature, squeeze roll pressure, Vee-angle, Vee-length and Impeder diameter on the above mentioned significant factors was analysed and parameter optimization was carried out.

Stress relieving heat treatment

Stress relieving annealing at different temperatures like 650°C and 700°C in the sub critical range below Ac1 temperature, to study the effect of post heat treatment on the fatigue life of the component. Stress relieving Heat treatment was carried out in electric heating muffle furnace without controlled atmosphere. The primary objective of stress relief annealing is to reduce the residual stress produced due to welding and forming.

Residual stress measurement

HF Electric resistance welding of the HSLA strips is intended to induce residual stresses in the final tube. The residual stress plays a significant role in the torsional fatigue life of a component. Two methods were used to experimentally determine the circumferential (hoop) residual stresses in the tubes:

Slitting method for tubes

X-ray Diffract meter

Slitting Method is one of the destructive techniques that rely on the introduction of an increasing cut to a part containing residual stresses. In slitting method, a narrow cut of progressive depth is introduced into a part containing residual stresses and the relieved strain is measured in terms of tube dimension. In this technique, the cutting may alter the original residual stresses through temperature rise and plastic deformation near the cut. Hence EDM cutting is preferred for slitting the tube

Residual stress is calculated using the formula:

$$S = \left(\frac{Et}{1-\mu^2}\right) * \left(\frac{Df - Do}{Df * Do}\right)$$

Element	Wt.%
Carbon	0.074
Silicon	0.231
Manganese	1.62
Phosphorus	0.015
Sulphur	0.0025
Chromium	0.017
Aluminium	0.051
Titanium	0.127
Niobium	0.059
Molybdenum	0.103
Nickel	0.006

Table 1: Chemical composition of the steel.

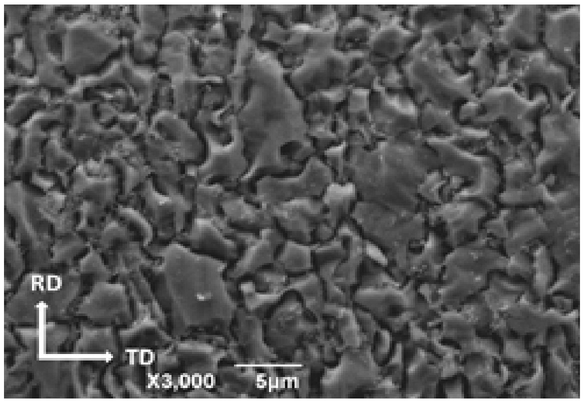

Figure 1: SEM micrograph of the raw material.

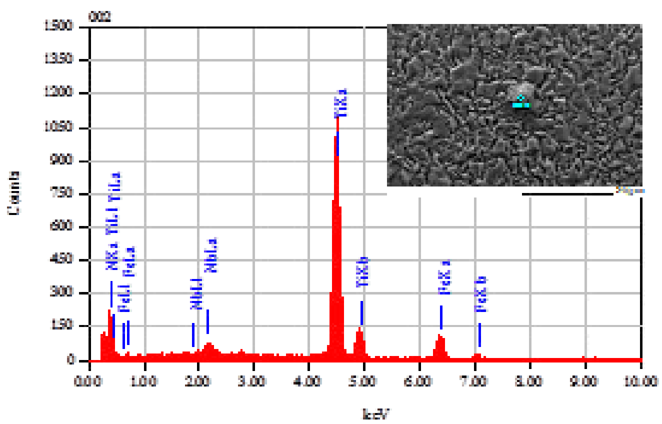

Figure 2: EDS spectrum taken at the precipitate.

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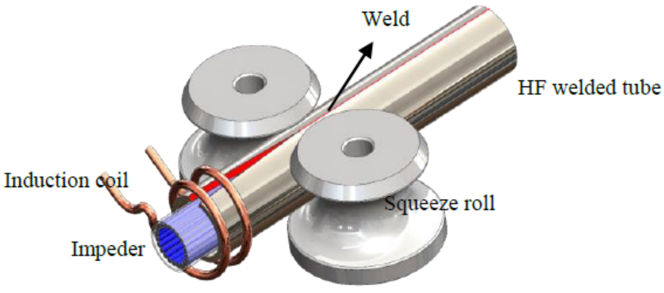

Figure 3: Schematic diagram explaining the components of HF welding.

S: Residual stress in the circumferential direction, MPa

E: Modulus of Elasticity, MPa

μ: Poisson's ratio

T: Thickness of the tube, mm

Do: Mean Outer diameter of tube before slitting, mm

Df: Mean Outer diameter of tube after slitting, mm

XRD is a quantitative and precise technique used for residual stress measurement. Portable residual stress analyser iXRD Proto was used to determine the circumferential residual stress at the surface of tube. In x-ray diffraction residual stress measurement, the strain in the crystal lattice is measured, and the residual stress producing the strain is calculated, assuming a linear elastic distortion of the crystal lattice. Testing was done based on SAE HS 784.

Torsional fatigue testing

Instron Servo hydraulic rotary actuator (Figure 4) was used to carry out fatigue testing of the HSLA tubes in the non-heat treated and post heat treated condition. Prior to torsional fatigue testing, welded tubes were formed into a particular profile as per design requirement and the ends of the tube were welded with suitable fixtures for actuator. Actuator head is connected with one end of the component and the other end remains fixed. Testing was done based on the design specification, which states maximum stress condition as half the yield strength of the tube.

Simulation using ANSYS: Simulation was done at different Torsional moments 300 Nm, 400 Nm and 500 Nm and the maximum stress resulted are shown in Figures 5-7. The result shows that 400 Nm torsional moment develops maximum stress of value 358 MPa, which is roughly half of yield strength of this tube. Hence 400 Nm was selected as the input torsional moment for the experimentation of fatigue testing.

The aim of the study is to investigate the effect of HF welding process parameters and post heat treatment on the torsional fatigue life of micro alloyed HSLA steel tubes.

Results and Discussion

HF welding parameter optimization

Micro alloyed HSLA steel tubes were manufactured by the conventional HF welding route. To obtain very high weld bond strength and weld quality, several iterations were carried out. Major parameters like Strip width, power, speed, Vee-length and Impeder diameter were considered. Vee-angle maintained was 2 degrees.

Table 2 explains the different trials conducted by varying the key parameters to produce HF welded HSLA steel tube of outer diameter of 88.9 mm and thickness of 2.9 mm, with very high weld bond strength.

Critical V forming test was developed to assess the weld quality. For this test, specific tool was manufactured with respect to the tube dimension (Figure 8). The tube was formed to the profile shown in Figure 9 such that the weld region falls in maximum strain region. Maximum strained region was initially identified through simulation using Finite element analysis (LS Dyna software). Simulation of the forming proves that maximum strain falls in the corners of the V profile (Figure 9). Tube samples of 100 mm length were taken and formed with the weld in the maximum strain position.

Samples from each trial were subjected to V-forming as a qualifying test and results are monitored. Trial H samples results in line with our expectation and it shows the weld bond strength and formability. Trial H samples withstood maximum load of 156 kN during max strain condition. Initially trial resulted in very wide HAZ width (Figure 10), but increasing the impeder diameter from 45 mm to 60 mm improves the concentration of current in strip edges and avoids heat loss. Optimised Vee-length and the increased mill speed resulted in the pronounced hour glass pattern; narrow bead width and required bond angle of 60-65 deg. Bead width of the resultant tubes measured around 994 μm.

Material characterization

Following optimisation, welded HSLA steel tube with high bond strength was identified and taken for micro structural characterisation and mechanical properties assessment. Zeiss Optical microscope and JEOL Scanning electron microscope were used for characterization. Picral and 2% Nital reagents etchants were used to view the weld flow and microstructure respectively. Base region has very fine ferrite grains lesser than 10 μm (Figure 11a). Weld region has the mix of microstructure – Low carbon martensite, bainitic ferrite and polygonal ferrite (Figure 11b). Presence of Bainitic ferrite improves the toughness of weld region. Polygonal ferrite and bainitic ferrite was observed in HAZ region (Figure 11c)

Stress relieving of the HF welded tube samples was done below the A_1 critical temperature at 650°C, and 700°C with the soaking time of 45 min. The very high recrystallization temperature of the material rules out possibility of grain coarsening during SRA Microstructural analysis of the stress relived samples also confirms the same.

Mechanical properties of the HSLA steel tube in the HF welded condition and after stress relieving heat treatment was evaluated as per the ASTM E8 and the results are shown in Table 3

Figure 4: Image of torsional fatigue test rig.

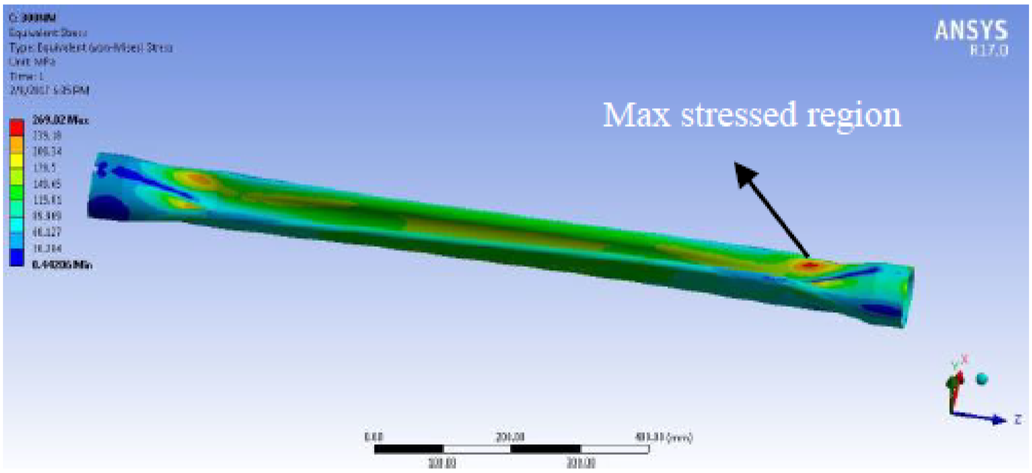

Figure 5: Stress analysis of the twisted model – 300 Nm.

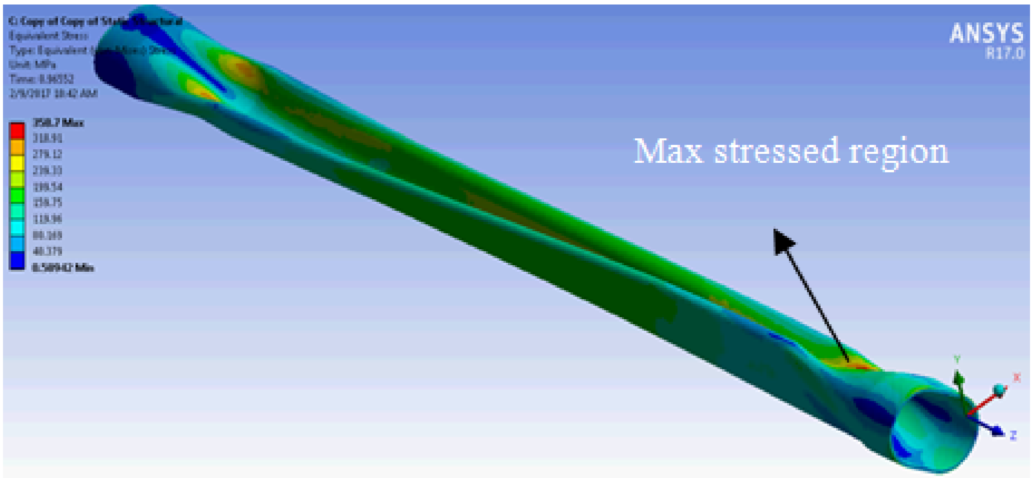

Figure 6: Stress analysis of the twisted model – 400 Nm.

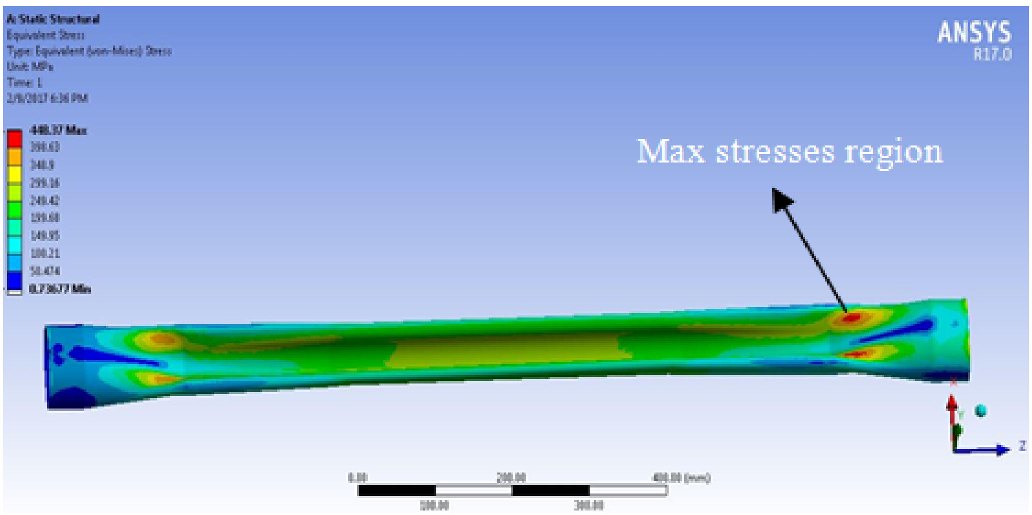

Figure 7: Stress analysis of the twisted model – 500 Nm.

Trial	Strip width (mm)	Power (kW)	Speed (mpm)	Vee length* (mm)	Impeder diameter (mm)	V forming test result	Remarks
A	276.5	102-104	10.2	175	45	Weld failure	Insufficient material flow
B	278	110	11	175	45	Weld failure	Insufficient material flow
C	279	110	11	175	45	Weld failure	Sufficient material flow
							Wider weld bead
							Poor hour glass pattern
							tube failed in V-forming operation
D	279	110	11	175	60	Weld failure	Sufficient material flow
							Narrow weld bead
							Poor hour glass pattern
							Tube Failed in V-forming operation
E	279	118	11	175	60	Stitch mark	Stitch mark defect after V-forming
F	279	102	11	175	60	Weld failure	Paste weld
G	279	110	11	145	45	Weld failure	Material flow is sufficient
							Narrow weld bead
							Poor hour glass pattern
							Tube failed in critical V-forming
H	279	110	11	145	60	OK	Material flow is sufficient
							Narrow weld bead
							Pronounced hour glass pattern
							Tubes passed in critical V-forming

*Vee length is the distance between centre of coil and apex.

Table 2: HF welding process parameter optimization.

Figure 8: Image of the forming tool.

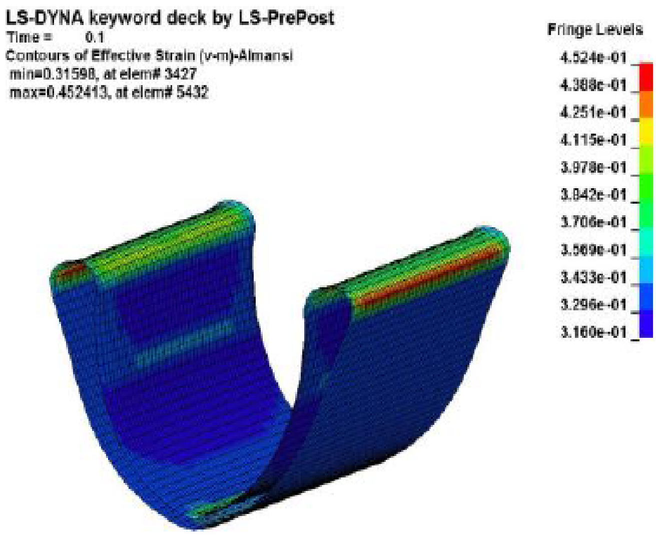

Figure 9: Strain plot of V-formed tube.

As a consequence of stress relieving heat treatment, there is a slight drop in the mechanical properties of the tube. Uniform elongation increases to 10% from 5.5%, because of the grains recovery during stress relieving. This is evident from the stress strain graph shown in Figure 12. Weld ductility also improves on stress relieving.

Residual stress measurement

The results of residual stress analysis are given in Table 4. Measurements were carried out at the base and weld region in the circumferential (hoop) direction using XRD and slitting method.

Higher magnitude of tensile residual stress was observed in the base material of the micro alloyed HSLA tube. This might be attributed to the forming of the strips to tubular form. Stress relaxation occurs on stress relieving and the results convey that the magnitude of residual stress has decreased to greater extent in the post heat treated tubes.

Torsional fatigue testing

As a design requirement, HF welded tubes were mechanically formed to a particular profile before the torsional fatigue testing. Torsional fatigue testing was done at the maximum stress level of half the yield strength as the design criteria. Maximum stress of 358.7 MPa was developed in the tubes for the torsional moment of 400 Nm was determined through ANSYS simulation. Testing was carried out in the formed condition i.e. component form.

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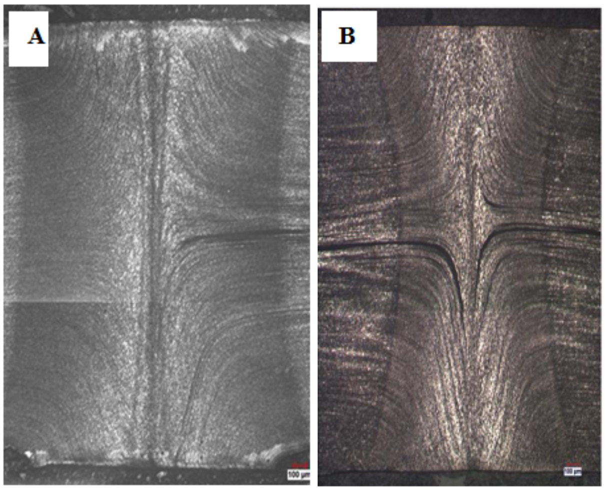

Figure 10: Optical micrographs showing the weld region: (A) Trial C sample; (B) Trial H sample.

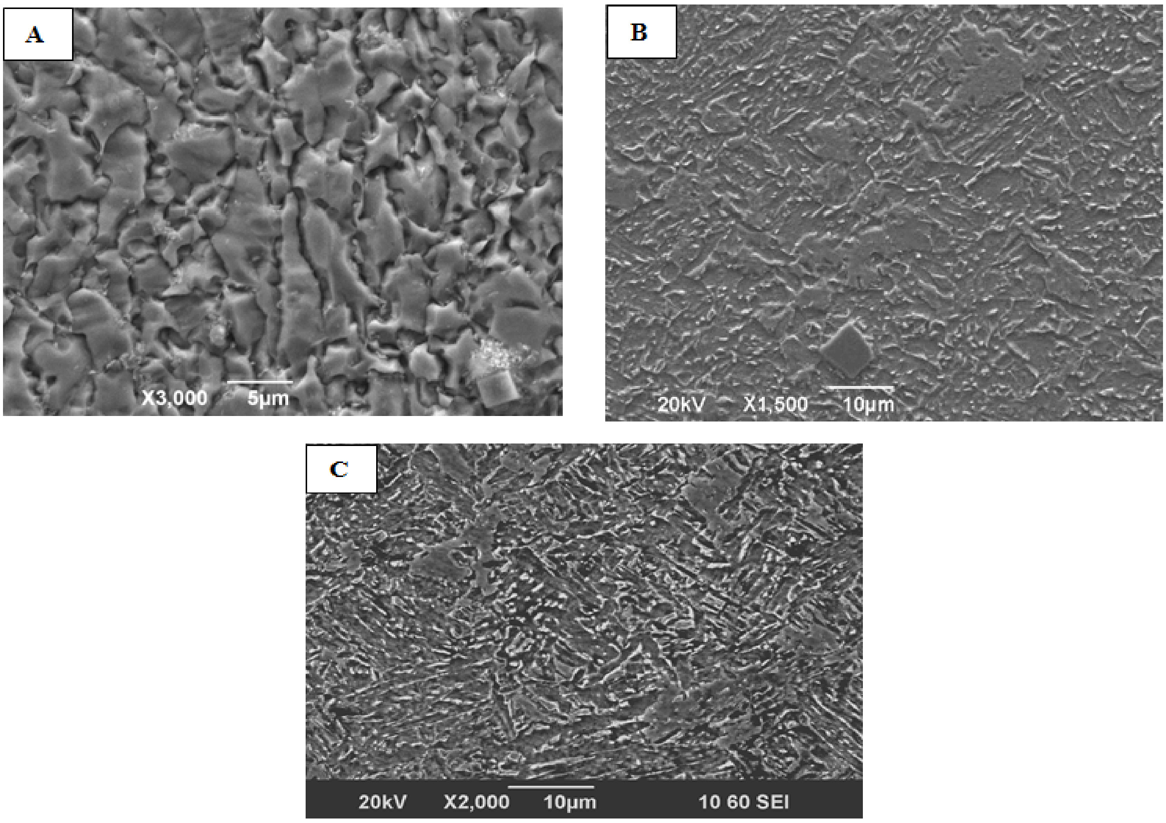

Figure 11: SEM micrographs showing the microstructure of different regions in the HF welded micro alloyed HSLA tube: (A) Base; (B) HAZ; (C) Weld.

Sample condition	Stress relieving temperature[a]	YS[b] (MPa)	UTS[b](MPa)	% of Uniform elongation[b]	% of elongation[b]
As HF welded	-	790	845	5.5	6
As Stress relieved	650°C	775	815	9.5	11
	700°C	750	790	10	17

[a]Stress relieving was performed for soaking time 45 minutes followed by air cooling.

[b]The reported values are average of three tensile samples (ASTM E8).

Table 3: Mechanical properties of the micro alloyed HSLA tubes.

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Test Parameters: Torsional Moment-400 Nm; Frequency-2 Hz

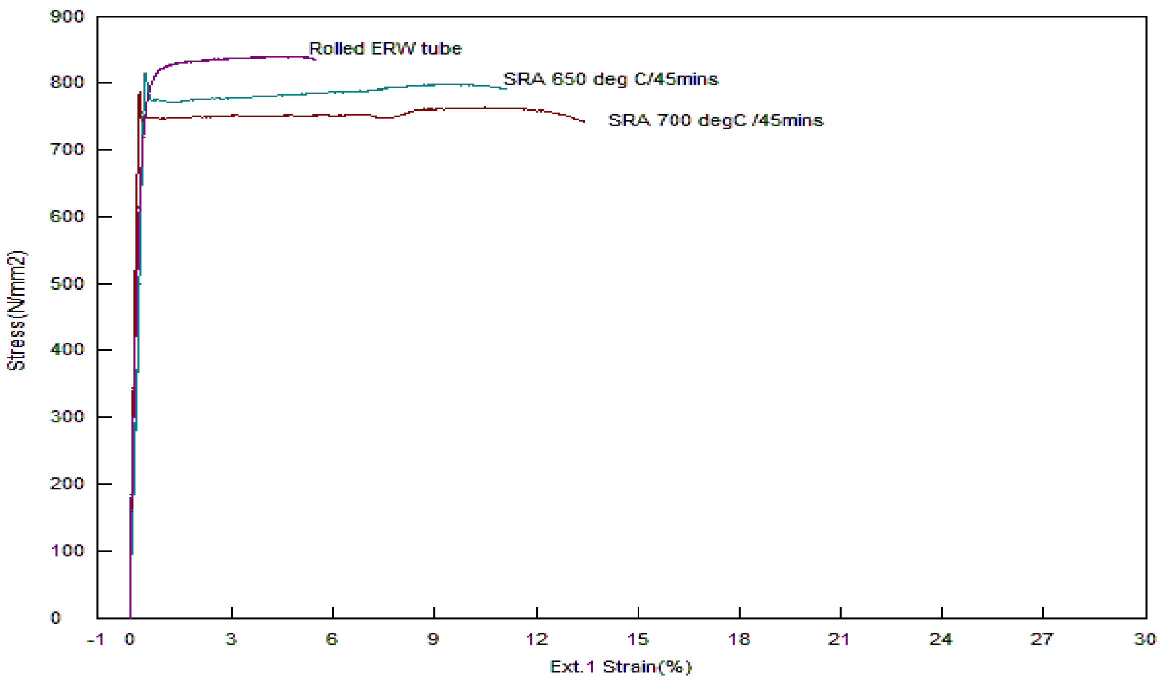
Failure occurred in the base material region of the HF welded HSLA steel tube component and the crack has initiated in the maximum stressed region, as indicated in the simulation results (Figure 6). Table 5 explains the fatigue life of the HF welded tubes.

Stress relieved samples were tested in the same test condition and the samples crossed 1000000 cycles without failure. This explains the effect of stress relieving heat treatment of the HSLA steel in improving the torsional fatigue life.

Conclusions

The objective of the study is to investigate the effect of HF welding process parameters and post heat treatment on the torsional fatigue life of micro alloyed HSLA steel tubes. The following conclusions can be made from the study:

1. The role of HF welding parameters on the weld quality of micro alloyed HSLA tubes is clearly evident from the work. Optimum combination of factors like Strip width, Vee-length, Impeder diameter, Heat input and Vee-angle leads to superior weld characteristics
   - Pronounced Hour Glass pattern
   - Narrow Weld Bead width
   - Optimum Weld Bond angle
   - High Bond Strength
2. Critical V forming test proves to be a best qualitative test to assess the weld quality of tubes. It reveals the importance of development of application related testing methods in manufacturing industries.
3. Mechanical properties like YS, UTS did not vary significantly



*SRA: Stress Relieving Annealing.

Figure 12: Stress-strain graphs of As HF welded and SRA* samples.

Sample condition	Circumferential residual stress(MPa)		Nature of stress
	XRD	Slitting method	
As HF welded	195 ± 04*	195	Tensile
650°C SRA[1]	-70 ± 5*	-2	Compressive
700°C SRA[1]	-129 ± 7*	-5	Compressive

*Residual stress measurement was carried out in the base material region.

[1]SRA stands for Stress relieving annealing.

Table 4: Residual stress values – XRD and Slitting method.

Sample condition	Number of samples tested	Number of cycles to failure
HF welded	3	398791
		238808
		219882

Table 5: Results of torsional fatigue test.

between HF welded and post heat treated tubes. Improvement in Uniform elongation is observed in the post heat treated tubes. Hence stress relieving heat treatment enhances the formability of the HSLA tubes. It is advantageous, because yield strength of the material directly influences the fatigue life.

4. Magnitude of tensile residual stress at the base region of HF welded tubes is 195 MPa whereas the magnitude of residual stress drops to 129 MPa in 700°C stress relieved sample and it is compressive in nature. Thus stress relieving of HSLA tubes aids in elimination of residual stress.

5. The Significant improvement in fatigue life of HSLA steel tubes heat treated sub critically (below A1) is mainly attributed to the absence of tensile residual stresses, which was developed in the HF welded tube due to forming and welding operation. Thus, residual stress plays an important role in the torsional endurance life of micro alloyed HSLA steel tubes and stress relieving heat treatment of the micro alloyed HSLA tubes enhances its fatigue life.

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References

1. Lee CH, Bhadeshia HKDH, Lee HC (2003) Effect of plastic deformation on the formation of accicular ferrite. Material Science Engineering A 360: 249-57.
2. ASM International, Materials selection, Alloying-understanding the basics #06117G, ISBN: 978-0-87170-744-4.
3. Wright J, Equipment EH (1999) Optimizing Efficiency in HF Tube Welding Processes. Electronic Heating Equipment, Inc. Bonney Lake. USA. s/f.
4. Haga H, Aoki K, Sato T (1980) Welding phenomena and welding mechanisms in highfrequency electric resistance welding-1st report. Welding Journal 59: 208s-212s.
5. Babakri KA (2010) Improvements in flattening test performance in high frequency induction welded steel pipe mill. Journal of Materials Processing Technology 210: 2171-2177.
6. Nathan SR, Balasubramanian V, Malarvizhi S, Rao AG (2015) Effect of welding processes on mechanical and microstructural characteristics of high strength low alloy naval grade steel joints. Defence Technology 11: 308-317.
7. Kang J, Wang C, Wang GD (2012) Microstructural characteristics and impact fracture behaviour of a high-strength low-alloy steel treated by intercritical heat treatment. Materials Science and Engineering: A 553: 96-104.
8. Reddy GM, Mohandas T, Papukutty KK (1998) Effect of welding process on the ballistic performance of high-strength low-alloy steel weldments. Journal of materials processing technology 74: 27-35.
9. Shi Y, Han Z (2008) Effect of weld thermal cycle on microstructure and fracture toughness of simulated heat-affected zone for a 800MPa grade high strength low alloy steel. Journal of materials processing technology 207: 30-39.
10. Quesnel DJ, Meshii M, Cohen JB (1978) Residual stresses in high strength low alloy steel during low cycle fatigue. Materials Science and Engineering 36: 207-215.
11. Show BK, Veerababu R, Balamuralikrishnan R, Malakondaiah G (2010) Effect of vanadium and titanium modification on the microstructure and mechanical properties of a micro alloyed HSLA steel. Materials Science and Engineering: A 527: 1595-1604.
12. Zhang YQ, Zhang HQ, Li JF, Liu WM (2009) Effect of heat input on microstructure and toughness of coarse grain heat affected zone in Nb micro alloyed HSLA steels. Journal of Iron and Steel Research, International 16: 73-80.
13. Davis CL, King JE (1993) Effect of cooling rate on intercritically reheated microstructure and toughness in high strength low alloy steel. Materials Science and technology 9: 8-15.