Durability improvements of Exhaust pipe joints during operating Condition

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Abstract- Medium and Heavy Commercial Tipper vehicles in India are mainly used for off-road and mining applications where the vehicles are subjected to severe and irregular road load patterns. In such cases it is imperative that quality of weld joints in Exhaust pipes should be capable of withstanding off road duty cycle. The negative impact of any kind of defect will be magnified due to presence of such harsh road & environment conditions. The current paper focus discussion on the various failures and defects found in weld joints of exhaust pipes. Various methodology has been introduced to detect the modes of Weld failure. After detailed study and analysis, a set of recommendations are proposed for welding of Exhaust pipe flange joints to ensure high durability life of weld joints.

Keywords: Weld Fatigue analysis, Flange joint, Exhaust Pipe

Introduction

The main objective of the exhaust system is to offer a leakage proof, noise proof, safe route for exhaust gases from engine to tailpipe, where they are released into the environment, while also processing them to meet the emission norms. New stringent emission norms demand 'near-zero' leakage exhaust systems, throughout vehicle life bringing the joints into focus as they are highly susceptible to leakage [3]. Needless to say, this necessitates them to endure not only structural but also the environmental loads, throughout their life. Thus, the fatigue life or durability tests become the most critical part of the exhaust system development.

One of the significant changes in exhaust pipe for BSVI vehicle in comparison to BSIV vehicles has been change of material from Mild steel to Stainless steel. With this change, came certain unforeseen leakage issues especially due to failure of welded joints of exhaust pipe [4].

To resolve problem of weld failure between Exhaust pipe and flange joint, Weld Fatigue Analysis of exhaust system is done based on duty cycle operated by customer.

Problem Definition

During vehicle operation in off-road, recurring appearance of cracks reported at welding joint of exhaust pipe with flange.
Cracks appear periodically over the same area at overlap joining of exhaust pipe and flange with fillet weld.

This problem was resolved with an Engineering process of Weld Fatigue Analysis to meet the durability target of the vehicle.

General Recommendations for Commercial Vehicle Exhaust Flange & Tube Welding

This document prescribes the general recommendations, precautions and methods, which need to be adopted while welding solid exhaust flange to Tube. The applicability of this document is limited to the Exhaust assembly with details given in below table.

Tube material	SS441- 1.6mm
Flange material	SS304- 10mm
Electrode material	ER430LNb (AWS A5.9)
Electrode Diameter	0.8 mm

Identified challenge is the welding of Thick Flange to Thin Tube. The problem arises due to the high thickness combinations ratio (10:1.6 mm). The welding parameters and torch angle, if not set correctly, can cause heavy weld penetration (70-100%) in tube at multiple locations, circumferentially. It will cause local material in-homogeneity along the circumference. It can lead to crack & fracture failure due to vibration and stresses in the vicinity of weld.

Fig.1 100% Weld Penetration

Circled areas in Fig.1 showing through weld penetration (100%), these areas form local inhomogeneous material regions with different properties, circumferentially.

Failure Mode Observations of Exhaust Pipe Assembly

Crack observed immediately after weld bead towards exhaust pipe body parallel to weld. Crack was occurring at both square and triangular flange. It was also observed on inner side of pipe body. These are forming and propagating only on pipe (FSS 441)-A case of transition joint failure in dissimilar welds.

Fig. 2 Directional Scratch in Exhaust Pipe Joint

Directional scratch/notch marks was observed inside the pipe along both longitudinal and transverse direction which can be observed in Fig.2

Fig.3 Gas cavity inside weld bead

Welding defect Blow hole was observed on weld near flange end as shown in Fig. 3

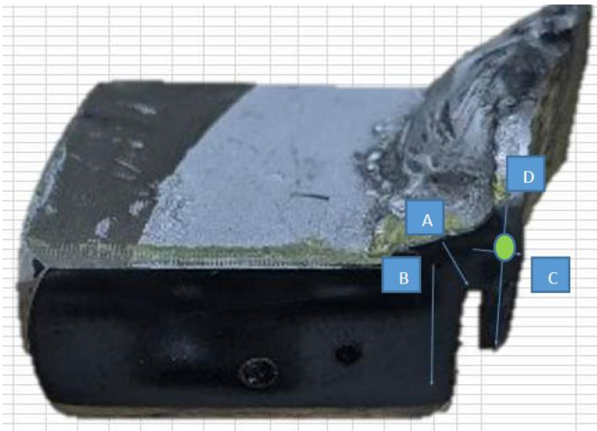
Metallurgy Observations

Hardness drop observations:

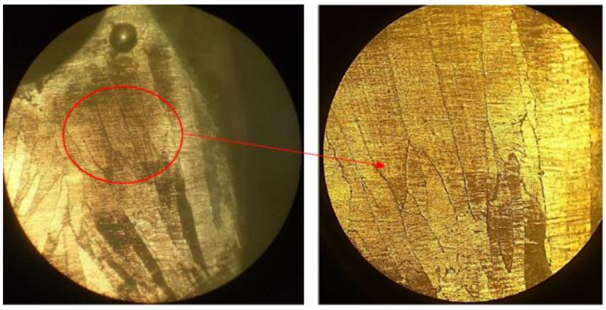
For Analysis of welding joint failure between exhaust pipe and flange a sample is prepared for the section of the welding area which will consist of the following parameters

a) Weld fusion area
b) Weld to Flange area
c) Weld to pipe area
d) Fracture area-weld pipe

The hardness values are then measured at several distances from a starting point along the lines A, B, C & D shown in Fig. 4.



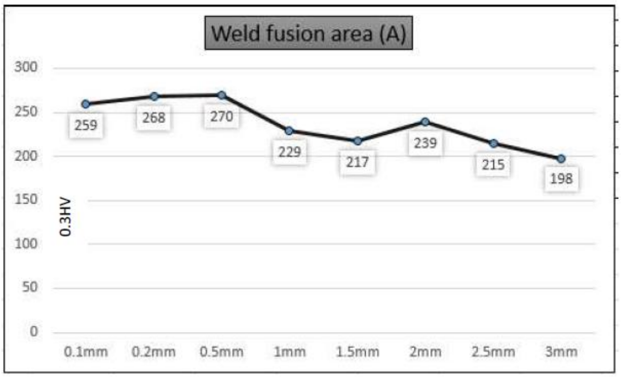
(a)



(b)

Fig.4 a) Cross-section of weld zone b) Microscopic image of weld zone

Above details of microstructural images in Fig.4 helped to identify the points where spikes can be seen. For example in Fig.4 , sudden spikes in hardness can be observed in graph C and D at the intersection point of two lines (highlighted in green). Crack also observed in the same area parallel to weld zone (Fig.4-a, b)



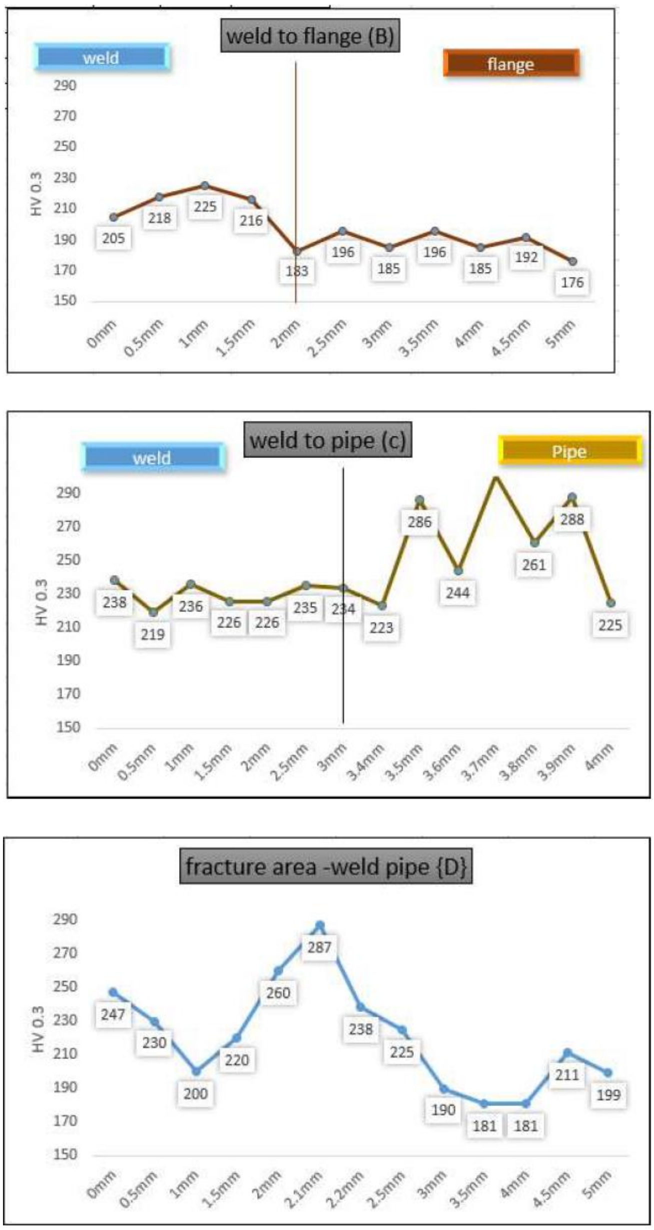


Fig.5 Hardness Value at different identified locations

Fig.5 gives Hardness values at different distances along the directions A, B, C & D

Welding penetration:

Arc welding penetration was observed as per specification, leg length and weld throat thickness mentioned as per Standard. A weld joint cross section sample was prepared and observed under microscope and weld penetration was measured with the inbuilt software of microscope as shown in Fig.6. The weld penetration in flange in some samples were found less than that specified in standard.

CO2 welding charecteristics		%penetration	Remarks
weld penetration into triangular flange	0.249mm	15.5625	Insufficient penetration observed on flange side
Weld penetration into Pipe	0.618mm	38.625	
length of thinner member=pipe	1.6mm		

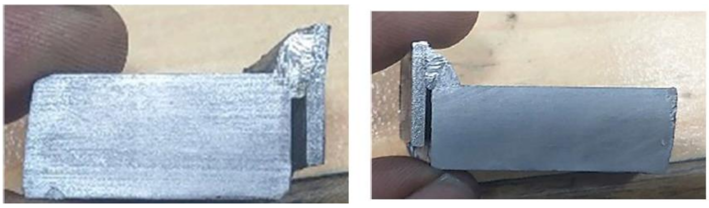


Fig.6 Images of weld penetration

Scanning Electron Microscopy- Energy Dispersive Spectroscopy (SEM-EDS) Analysis:

A sample having a fillet weld joint between SS304 flange and SS441 pipe was used for analysis. The cross section of joint and inner surface of the SS tube at the joint were prepared metallo-graphically and etched with Glyceragia. The SEM- EDS investigation of weld sample was carried out in a FEI-Nova Nano scanning electron microscope.

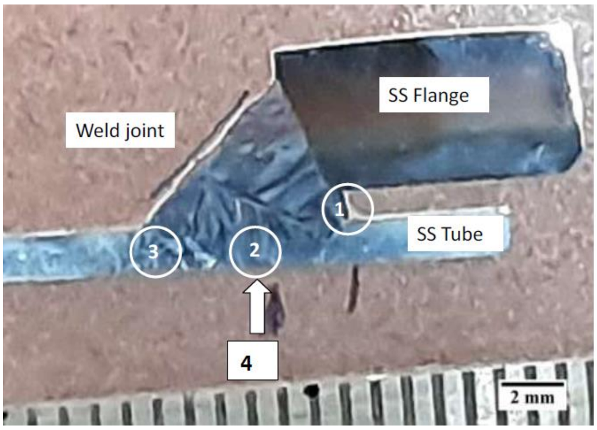


Fig.7 SS Weld joint - SEM imaging locations are encircled and numbered

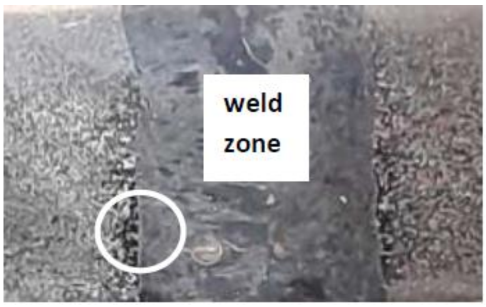


Fig.8 Inner diameter surface of SS Tube at location 4 of Fig.7

SEM Location-1:

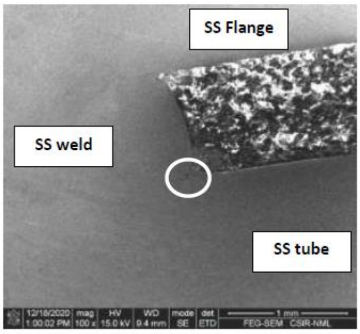


Fig.9 Low Magnification image of location 1 in Fig.7

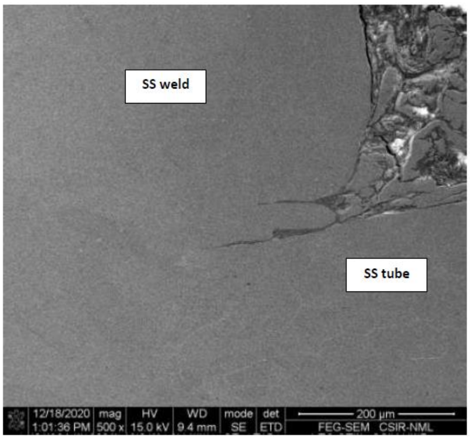


Fig.10 High Magnification image of circled region in Fig 8

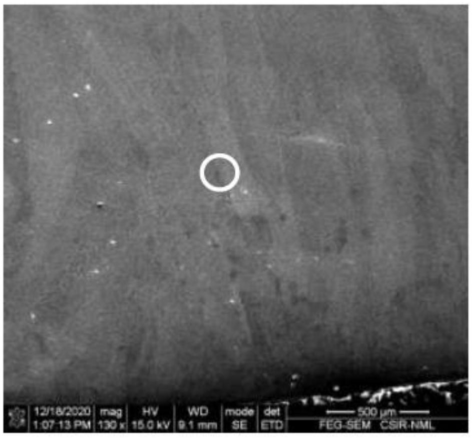
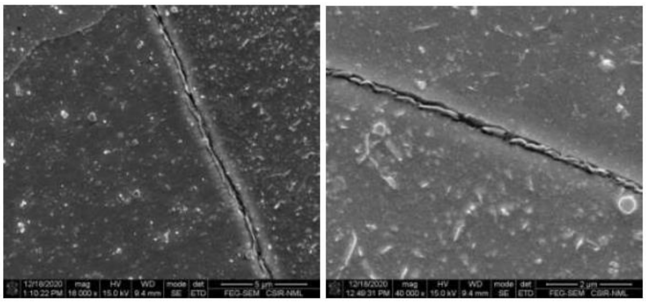


Fig.11 Low Magnification image of location 2 in Fig.7 (columnar grain)

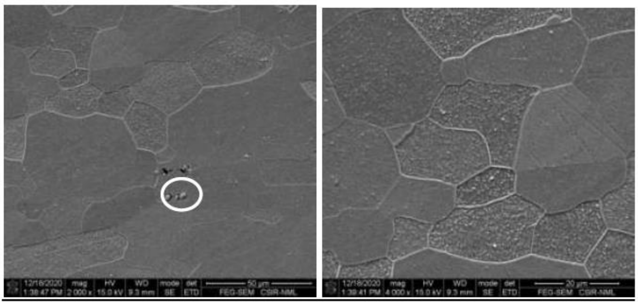


(a) (b)

Fig.12 High Magnification image of circled region in Fig.12

Carbide precipitation at grain boundaries of columnar grain can be observed from Fig.12

SEM Location-3:



(a) (b)

Fig.13 SEM images on location 3, show equiaxed grain.

SEM Location-4:

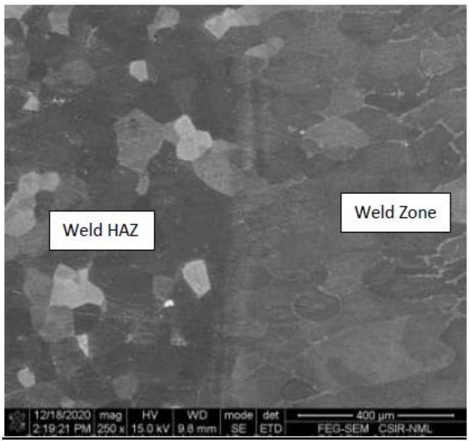


Fig.14 SEM image of marked location in Fig.8

SEM Observations:

1) There is a gap of ~1mm between SS flange and SS tube in the lap part of the weld joint (as shown in Fig.7).

2) There is small crack / undercut on the both sides of weld pool between SS flange and SS tube towards the SS flange side of the weld joint (as shown in Fig. 11 and Fig. 12).

3) The weld fusion affected zone up to inner diameter surface of SS tube showed columnar grains with heavy carbides precipitated at grain boundaries (as shown in Fig. 13 and Fig. 14.

4) Figs.12, 13 and 14 shows the polygonal equi-axed grains on the SS tube HAZ side with expected precipitates of rich in Nb and Ti. No abnormal carbide precipitation at GB was observed as in the case of columnar grain boundaries.

5) The EDS microanalysis showed SS 304 composition on flange side and SS 441 composition on tube side with Nb and Ti in the form of precipitates. The Cr and Mn content in weld pool is lower due to heavy carbide precipitation (refer Fig.7 and 13).

Stereomicroscopy and Optical Microscopy:

A failed weld joint between SS304 flange and SS441 exhaust pipe as shown in Fig.17 was used for analysis. The cross-section of the failed joint was prepared metallo-graphically and etched with Glyceragia for microstructure study. The SEM fractography of the failed weld sample was carried out in a FEI-Nova Nano scanning electron microscope.

Fig.17 Stereomicroscopy of failed weld joint of exhaust pipe showing the fracture surface location on the SS tube

Microstructure study was done at three different zones of the weld joint.

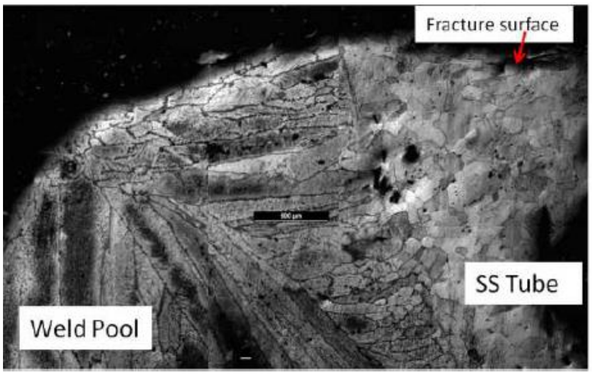


Fig.18 Cross-section montage microstructure at the fracture location

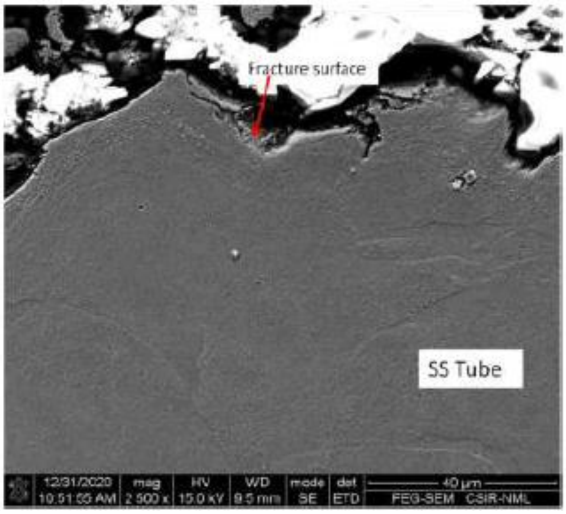


Fig.19 Cross-section microstructure at the fracture location (SEM)

SEM Fractography:

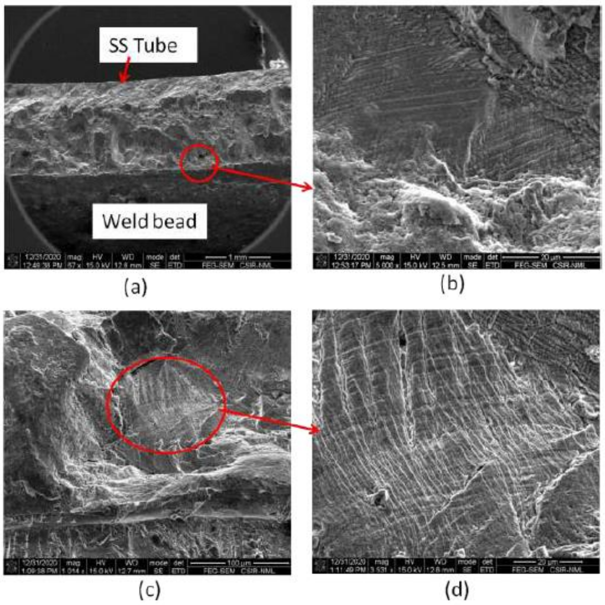
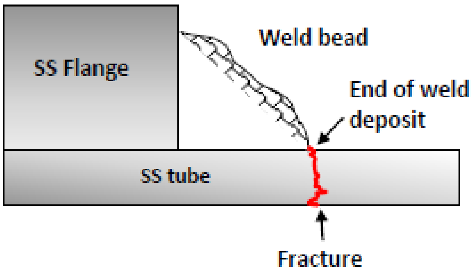


Fig.20 SEM Fractographs (a) Low magnification (b) High magnification region of (a) showing fatigue beach marks/striations (c) High magnification at another location (d) Fatigue Striations at high mag. taken from encircled region of fig.(c)

Observations from fractography and microstructure:

1) The cross-section microstructural examination at the failure location clearly revealed that the fracture has occurred at the SS tube with the polygonal grain microstructure. No abnormalities like cracks from the weld zone or inter-granular cracking connected to the fracture surface were observed (Fig.19 and Fig.20).
2) The fracto-graphy studies clearly showed the striation features/marks. Presence of striation marks on the fracture surface indicates failure due to fatigue loading. Further, the fracture has initiated from multiple sites on the circumference of the pipe at the location where the weld deposit ends and it propagated towards the inner surface of the tube leading to a failure (Fig.20).
3) The studies clearly indicated that the fracture of the exhaust gas pipe has occurred due to Fatigue / cyclic type of loading at the place where the weld deposit ends.



Digital Verification

RLDA based pipe joint Fatigue Analysis:

In order to simulate fatigue behavior of weld joints in actual loading conditions, Road Load data was captured using accelerometers. The PSD profile (Fig. 22) thus captured used in fatigue analysis of the weld joints. The acceptance criteria of the design was set at D<1 (D- Cumulative damage Factor).Refer Fig 22

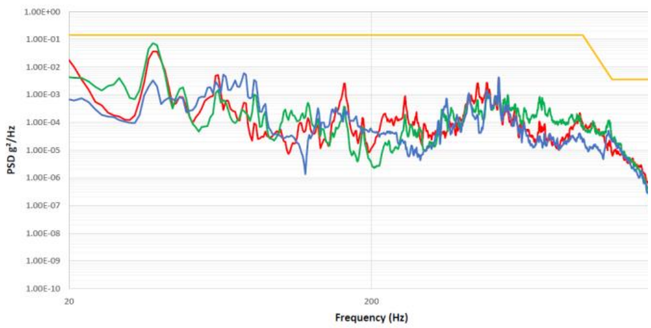


Fig. 21 Example of a PSD profile

Structural Durability Modal Analysis:

In case RLDA data are not available, Modal analysis can be done where we find out the different mode shapes of the pipe layout and find the frequency at which maximum displacements are present at our area of interest. After this, resonance vibration analysis is carried out at the selected resonance frequency to check whether the stresses at the weld joints are within the endurance limit of the class of weld.

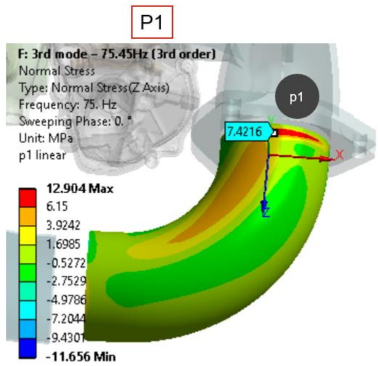


Fig. 22 Resonance vibration analysis of weld joint

Recommendation

The general recommendations are given below, which are to be used as references to improve weld quality:

1. Weld penetration on tube wall should be limited to 20-50%.
2. Weld parameters should be selected to ensure enough weld penetration on flange (>20%).
3. Weld heat should be focused on Flange. A guiding ratio of 70% (flange) and 30% (tube) for weld heat distribution should be applied. The concentrated heat on flange should be sufficient to generate enough wetting/puddle on tube to produce 20-50% weld penetration on tubes. A good number of cut samples should be analyzed to confirm the penetration as recommended in earlier points
4. Optimum torch angle which can produce results described in above points should be recorded in Welding Procedure Specification (WPS).
5. Micro hardness should be measured and difference in Parent metal and HAZ hardness should not be more than 15% of base metal.
6. Welding process should ensure that there should not be grain sensitization and excessive grain growth in HAZ. Grain size of HAZ should be ASTM number 5 and finer.
7. In the case of welding on outer diameter (OD), tack welds preferably to be made inside and arc heat should be concentrated on flange. The number of tack welds

should be as low as possible while avoiding any mismatch in fit up and warpage.
8. Weld start and stop should not overlap the weld seam of tubes.
9. Weld spatters should be avoided; post weld grinding should be limited.
11. Robotic welding should be preferred for critical welds.
12. Annular clearance between tube and flange should be uniform to avoid any pre stress and ovality. The clearance should be selected by exhaust system suppliers based on the electrode diameter.

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