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Durable Stainless Steel Tubes for Exhaust System

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***Abstract*— The demanding high mileage warranty requirements mandate stainless steel tubes to be mechanically and thermally durable. This paper deals with the requirements of the coated and uncoated stainless steel tubes for the sustainability in the exhaust system. Manufacturing process, sheet metal dimensions, high frequency welding parameters, roller and cutting tools play vital role in the effective utilization of stainless steel tubes. Mechanical, chemical and microscopic analysis had been performed to prove the durability of the stainless steel tubes. Tube flaring test performed up to 50% expansion showed no damage across the seam of the tube proving the survivability and stability for any operations such as forming, stamping etc. Flatness test performed showed no defects on the tubes both on the base material and across the seam. Yield strength measurement with varying thickness and diameter of different materials had been compared.**

***Keywords*—Chemical, High frequency, Mechanical, Microscopic analysis, Roller, Stainless steel, Flattening, Flaring.**

I. Introduction

The use of stainless steel in automotive exhaust system has been growing rapidly for the past decades, especially in very high temperature conditions. In every aspects of an engine, there exits some unwanted air pollutant, pressure flow and heat. The full exhaust system from the engine head face to tail pipe has two major functions, hot end to comply with emission requirement and the cold end to meet the NVH target. As temperature soar from 550˚C to 900˚C, there is a need for careful and efficient material selection and manufacturing process. Field failure analysis and benchmarking are required to choose the right pipe for the right application. Exhaust system experiences thermal load, engine load and road load along with corrosion and erosion. The exhaust pipes are required to survive with the heat and the vibrations occurred due to these exerting load. The exhaust system pipes should possess high corrosion resistance both inside and outside the pipe. The pipe should also be salt corrosion resistant from outside in environment and chemical corrosion resistant from inside out. The pipes should be oxidation resistant throughout the temperature region.

II. Tube Manufacturing Process

Tube manufacturing starts in the steel mill where either slabs or billets are cast. Production of seamless tubes starts from billets. Large diameter and heavy-walled pipes are made from hot-rolled plate, while strip welded tubes are mainly produced from cold-rolled or hot-rolled slit pre-material. Commonly high frequency welding, electro fusion welding and induction welding process are used in tube manufacturing.

A. Seamless tubes

The seamless tube is formed by drawing a solid billet over a piercing rod to create the hollow shell. The seamless tube manufacturing process does not have any welding process and it is manufactured using die method and hydro forming method. Seamless tubes are perceived to be stronger and reliable. When compared to the other tubes seamless tube has higher pressure withstanding capability. The seamless tubes are easily available than seam tubes. Normally this type of tubes has greater thickness as well as greater diameter. The hydro formed pipe has different shapes and diameter. Tube hydro forming has many advantages such as part consolidation, weight reduction, improved part strength and highly accurate dimensions and low spring back, lower tooling cost and fewer integrated processes which all promote rapid spreading of this technology in the automotive, household and aerospace industries. A pulsating hydro forming process of tubes has been developed for the forming of hollow products with a complex shape. Hydro forming technology is being developed to achieve reduced number of manufacturing steps and part consolidation. One of the beneficial factor is it doesn't require welding. It leads to minimize the bond line defects and having better corrosion resistance, more homogeneous grain structure.

B. Tubes with Seam

The seam tubes are manufactured by converting the metal sheet into tube shapes by forming and both ends are properly welded together. Normally, hot rolled or cold rolled metal sheets are used. Based on the material properties of the metal sheet, suitable welding process is selected. The following figures 1, 2, 3 and 4 illustrate the steps involved in seam tube manufacturing.

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Figure 1 Edge remover

Figure 2 Edge finisher

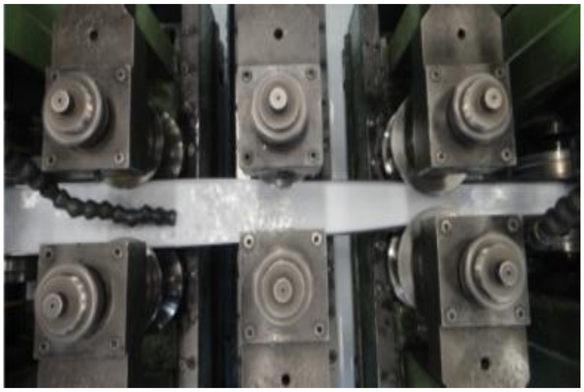

Figure 3 Roller

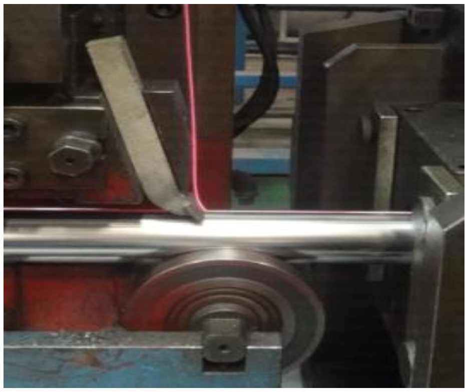

Figure 4 Weld bead remover

By comparing the stiffness of seam tube and seamless tubes, the seam tubes has higher stiffer than that of seamless tubes. On stiffness basis the seam tubes are selected for exhaust system applications. The tubes have narrower tolerances, nominal wall thickness, better concentricity, higher internal surface quality.

C. Defects in the seam tube making process

1. Sheet metal misalignment during welding.
2. Roller miss-feed, improper sizing and surface finish.
3. Improper welding parameters like frequency range flow of current and voltage.
4. Poor weld and bead removing.
5. Material properties.

The welding defects are depicted in the following figures,

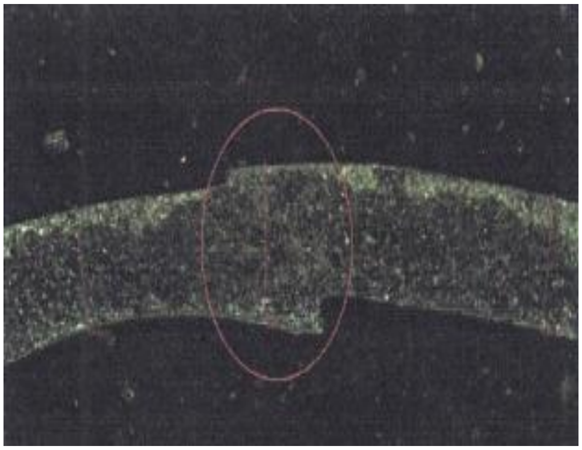

Figure 5 Sheet metal misalignment

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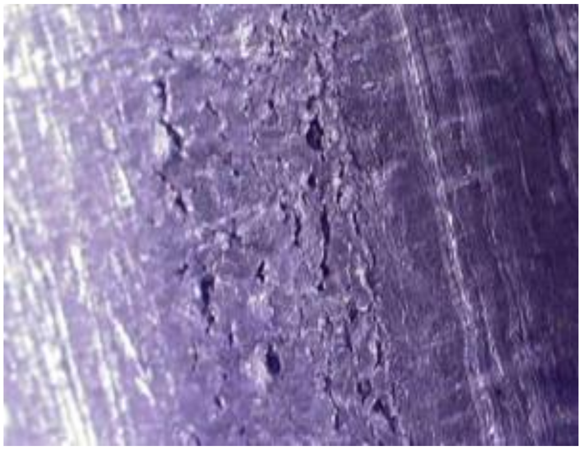

Figure 6 Improper welding parameters

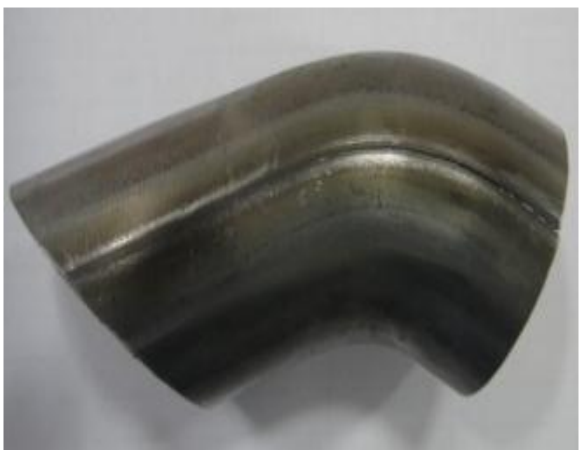

Figure 7 Improper welded bend pipe

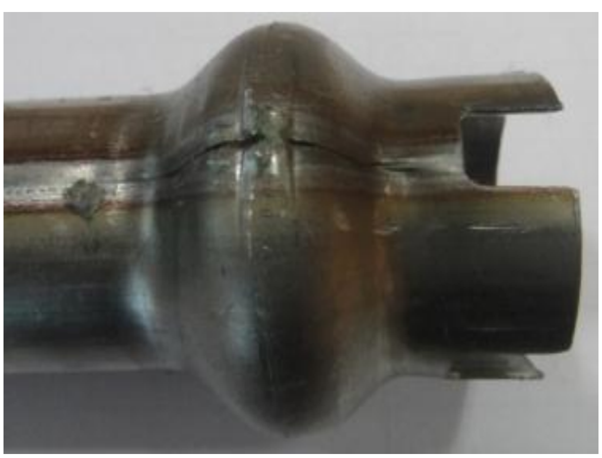

Figure 8 Improper welded CVS clamp joint

Figure 9 Pipe weld defect

TABLE I
DESIRABLE PROPERTIES OF STAINLESS STEEL TUBES

Properties and Chemical Composition of SUS 409L & STAC Material				
			SUS 409 L	STAC
Mechanical properties	Tensile test	Y.P (N/mm^2)	Min 175	-
		T.S (N/mm^2)	360	Min 30
		EL (%)	25	33
	Hardness test	Base (Hv)	Max 200	-
		Welded Area(Hv)	Max 250	-
	Bending test	Angle (degrees)	90	90
		Radius (mm)	2D	2D
	Flattening test	Max Height (mm)	1/2D	1/3D
	Flaring test	Min Dia (mm)	1.20t	4.25D
Chemical composition	C	Max %	0.03	0.12
	Si	Max %	1	0.35
	Mn	Max %	1	0.6
	P	Max %	0.04	0.04
	S	Max %	0.03	0.04
	Ni	Max %	-	-
	Cr	Max %	10.50 - 11.75	-
	Others	Ti 6XC %	0.75	-

III. Testing Methods

Tubes can be tested using various methods namely destructive, non destructive. Destructive comprises the following methods

- Dye penetrates test.
- Magnetic particle test.
- Radiographic test.
- Ultra sonic test.
- Eddy current test.
- Thermal infrared test.
- Acoustic emission test.

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Destructive tests comprise the following methods

- Flaring test.
- Flattening test.
- Expansion test.
- Microscopic analysis.
- Hardness test.
- Durability test.

A. Non destructive test

A general definition of nondestructive testing (NDT) is an examination or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or discontinuities that may have an effect on the usefulness or serviceability of that object. Nondestructive tests may also be conducted to measure other test object characteristics such as; size, dimension, configuration or structure and including alloy content, hardness, grain size, etc. It plays a significant role in minimizing the possibilities of failure.

a. Dye penetration test:

Penetration testing (PT) is one of the most widely used non-destructive testing methods for the detection of surface discontinuities in nonporous solid materials. It is almost certainly the most commonly used surface NDT method today because it can be applied to virtually any magnetic or non-magnetic material.

Figure 10 Cleaner, Penetrant, Developer

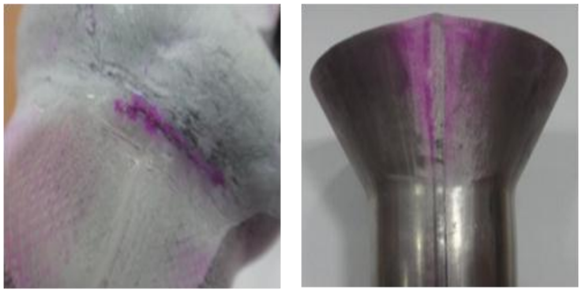

Figure 11 Penetrate Tested Sample

- The part would be cleaned with a cleaner solvent and left to dry.
- Then spray the penetrant on the cleaned surface and wait for 10 minutes for penetration.
- After penetration or dwell time the penetrant should be removed using a strong solvent.
- The part must be wiped until dry and clean.
- Then apply the developer.
- Using ultra violet rays surface cracks are visually checked. It is indicated the figure 11 shown above.

b. Eddy current test:

Eddy current testing (ET) is the most dominating NDT method for testing strip welded tubes produced inline from coil. It is a fast, efficient and accepted method of testing in EN 10217-7, ASTM A 312, A 790, etc. ET is the base for welding factor 1.0 in Europe and a substitute for hydrostatic testing (HT). It is, however, normally limited to tubes with wall thickness of less than 6 mm.

Figure 12 Eddy current testing

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Figure 13 Eddy current Plot

B. Destructive testing

The design of weld test procedures is extremely important, since a poorly designed test can lead to either rejection of material which is actually within product specifications or to approval of rejectable material. Flaring test and flattening test is the most common test that should be conducted on the welded wall stainless steel tubes.

a. Tube flaring test:

Tests were conducted on standard 150mm length stainless steel tube sample according to the JIS specification with various diameter and thickness made by high frequency welding process. The selected test sample must be free from weld beads, rust and burr of both internal and external surfaces. Thus, if the weld beads were not removed, small grooves must be cut in the flare mandrel to provide clearance for the beads. Otherwise, the bead will be forced into the I.D. of the tube causing stress risers which can cause premature failure. The flaring test was conducted by using fully computerized servo hydraulic landmark machine having 100KN force capacity and ±125mm axial displacement. This machine is very helpful to yield accurate outputs such as force, displacement and stress-strain curves. In this test, flare tool or insertion tool design play a vital role. The tool having 60^{o} cone angle and 150mm vertical height with good surface finish (followed by JIS standards)

Figure 14 Test specimen loaded in the testing machine

TABLE II
TEST OBSERVATION TABLE

Pipe Material: SS409L Specification : Ø50.8mm X 1.5mm Tk X L 163.49mm					
S.No	Disp (mm)	Pipe Wall Thickness (mm)	Pipe Dia (mm)	Force Applied (KN)	Result
1	0	1.5	50.8	0	No Damage
2	5	1.44	55.77	15.395	No Damage
3	10	1.4147	60.58	24.668	No Damage
4	15	1.379	64.32	36.932	No Damage
5	20	1.33	68.214	45.668	No Damage
6	25	1.294	71.742	62.264	No Damage
7	30	1.294	75.297	65.882	No Damage
8	35	1.279	78.287	79.413	No Damage
9	40	1.215	81.32	83.516	Crack initiated
10	45	1.163	84.25	95.357	Cracked

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The test was conducted under STP condition and the readings are observed for every 5 mm insertion height.

Figure 15 Crack initiated in base material

Figure 16 Crack initiated in the weld region

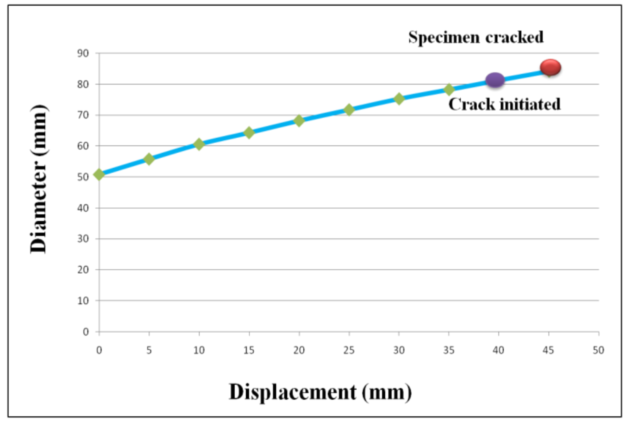

Figure 17 Displacement Vs Diameter plot for SUS 409 material

TABLE III
COMPARISON TEBLE

	STAC60/60 Ø50.8X1.6 X 150mm		SS409L Ø50.8X1.6 X 150mm	
S.No	**Displacement (mm)**	**Diameter (mm)**	**Displacement (mm)**	**Diameter (mm)**
1	0	50.8	0	50.8
2	5	57.77	5	54.985
3	10	62.58	10	59.926
4	15	65.32	15	63.507
5	20	68.214	20	66.405
6	25	73.742	25	70.052
7	30	77.297	30	73.915
8	35	80.287	35	77.19
9	40	83.32	40	80.402
10	45	85.92	45	83.028
11	50	87.61	50	85.38

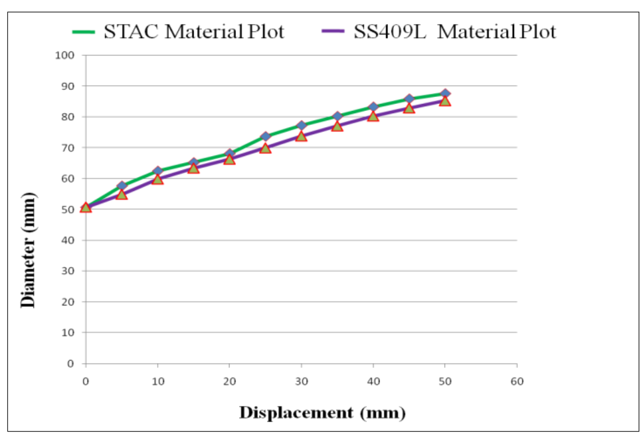

Figure 18 Displacement Vs Diameter comparison Plot

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b. Tube flattening test:

Tests were conducted to predict the bond line defects in the tubes. The test may be conducted with two orientations. First, the seam of the tube lie 90^{o} to the spindle axis (Figure19 A) and the second condition is to keep the seam in the vertical direction shown below (Figure B).

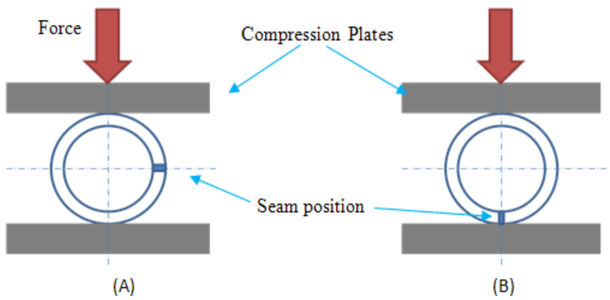

Figure 19 Testing orientations

The flattening tests was conducted on the standard 50 mm (minimum) length stainless steel tube and possess various diameter and thickness made by high frequency welding process.

Typically, when specified by JIS, the pipe sample must be crushed to a specified height (1/2D, 1/3D, 2t) without fracture in the weld. Crushing the sample in the position A puts the ID in compression and the OD in tension and the second position puts the ID in tension and the OD in compression. Welds due to improper normalizing or welding will usually fail before the minimum height is reached. The presence of bond line defects will also cause premature failure.

Figure 20 Flattening test Setup

Figure 21 Tested sample (STAC 60/60)

Figure 22 Tested sample (SUS 409L)

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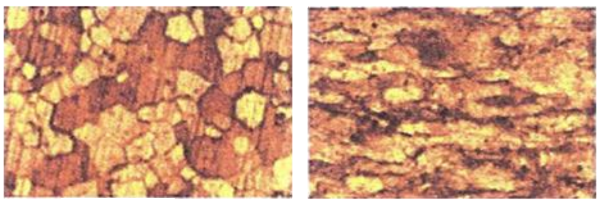
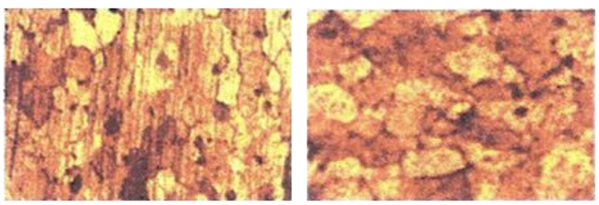
c. Microscopic analysis on tested Specimens:

The grain size analysis has been done under 100X magnification from metallurgical microscope. The grain size analysis has been done in accordance with the JIS specifications. The acceptable grain size number limit for stainless steel material is from 5 -10.



GS - 8 **GS - 6.5**

Figure 23 Base material grain size before & after test



GS - 7.5 **GS - 7.5**

Figure 24 Weld region grain size before & after test

IV. Conclusions

The coated and uncoated stainless steel tubes showed no damage across the seam up to 50% expansion proving the survivability and stability for any type of operation using the tube. The samples are weakened nearer the weld regions because of the stress and strain generated due to rigid body motion. Flatness test performed showed no defects on the tubes both on the base material and seam. Yield strength measurement with varying thickness and diameter of coated and uncoated materials has been compared. Coated material showed higher elongation and less durability than that of the similar thickness uncoated material.

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Abbreviations

ET : Eddy current testing
PT : Dye penetrate test
NDT : Non destructive testing
HT : Hydrostatic testing
STP : Standard Temperature Pressure
O.D : Outer Diameter
I.D : Inner Diameter
GS : Grain Size Number
JIS : Japanese Industrial Standards