On the Use of Laser Beam Welding for Austenitic Stainless Steel Type 316L and Stainless Steel Type 304 for Aerospace Applications.

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Abstract*: Currently wide range of aircraft parts have been welded by using laser beam welding. In this paper we have analyzed the strength of laser beam welded joint of stainless steel materials 316 L and 304. The Micro and Macro welding techniques are used for dissimilar stainless steel materials. The metal sheets are welded with a laser power of 1000 w with a bead width of 0.5 mm on both sides of the sheet by using micro laser beam welding and the macro laser beam welding is used to weld the metal sheets with 1800 w laser power along with a bead width of 3mm on one side of the sheet. The strength and mechanical properties of laser beam welded samples are found out by subjecting it to various tests such as Tension test, Bend test and Hardness test. Since stainless steel used in the aircraft parts are subjected to high temperature in the engine exhaust part, these samples are heated to temperature of 1040ºC. Aircraft icing occurs on parts of aircraft, where temperature falls below 0ºC, hence laser beam welded samples are cooled to a temperature of -30ºC. The behavior of laser beam weld portions under these conditions are studied. The Microstructure of the welded sample is obtained from the Scanning electron microscope is also discussed. The results obtained from the tensile test are compared with the structural analysis done using Finite Element Analysis. From the results we found that, macro welded sample is having good tensile strength of 582.753 MPa and no cracks were occurred during the bending test.

Keywords*: Laser beam welding, Dissimilar materials, Microstructure, Hardness, Tensile Strength, SEM, Finite Element Analysis.

I. INTRODUCTION

Many aircraft industries are now using laser beam welding instead of riveting because of its disadvantages such as: riveted assembly has more weight, holes cause stress concentration, high cost, time consuming, projection causes adverse effect etc. Among all class of stainless steel group Austenitic stainless steel accounts for about 70 %, each with individual characteristics such as weld ability, corrosion resistance, toughness, hardness and ductility.

Stainless steel finds its application in Aeronautical and Aerospace industries used in external tanks of space shuttles, fasteners, gas turbine engine internal parts, nozzle parts, turbine blades, upper surface blowing flaps etc. [1,2]. Stainless steel 304 and stainless steel 316L being two major metals used in that region of Aircrafts and Space crafts that are subjected to high temperature, because of the properties they exhibit such as good corrosion resistance, thermal resistance, weld ability, work under hot and cold treatment, machinability and good strength. [3].

Stainless steel 304 used in general purpose applications has a composition as shown in the table I. Chromium and nickel are the major constituents. Chromium present in the metal gives the property of corrosion resistance. Stainless steel 316L has a composition s shown in the below table II. These are called as Mo alloys which gives the metal an additional corrosion resistance property and resistance to stress corrosion cracking property.

Table- I: Stainless steel 304 Composition

Element	C	Mn	P	S	Si	Cr	Ni	Fe	N
SS304%	0.08	2	0.045	0.03	0.75	20	10.5	66.5	0.10

Table-II: Stainless steel 316L Composition

Element	C	Mn	P	S	Si	Cr	Ni	Mo	N	Fe
SS316L %	0.03	2	.045	.03	.75	16-18	10-14	2-3	0.10	60-70

Welding is the permanent process of joining two materials. There are several welding process such as arc welding, gas welding, solid state welding, resistance welding, thermo chemical welding and radiant energy welding. Laser beam welding and Friction stir welding are the two main joining methods used in Aeronautical and Aerospace industries. The major advantage of using these methods are they can be used for welding dissimilar metals, complicated parts can be joined, consumes less time, faster welding rate, low thermal distortions etc. Laser beam welding is a joining methodology used to obtain welds with great depth-width proportions, high superiority, high accuracy and minimum distortion.

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Laser Beam Welding (LBW) utilizes the radiant energy with beam cross-section of predominantly very high power density, to focus on the boundary surfaces of the two portions to be joined or welded together. These provide good strength to the welded metals.

Parts of aircraft such as engine nozzles, turbine blades etc. are subjected to very high temperature. The aircraft parts are subjected to high temperature of about 1400ºC in the engine exhaust part where high temperature exhaust gas is ejected out of the nozzle. This makes it necessary to find out the strength and mechanical properties of the welded joints under high thermal conditions. The laser beam welded samples are heated to a temperature of 1040ºC and is suddenly dipped in a solution. This technique is called as solution zed quenching. This technique is used to remove the carbon precipitation. These samples are tested for tensile and bend loads. Hardness being another property of the material which determine the strength of the material.

Aircraft when in operation at higher altitude leads to ice formation on the leading edge of the wing and tail surfaces, cockpit, engine inlets, nose fuselage etc. The icing occurs on the part of aircraft, where the temperature falls below 0ºC up to -20ºC. The behavior of laser beam weld portions under these conditions are studied. This changes the properties of the materials as well as strength. This makes sense to determine the strength and mechanical properties under these conditions, so as to make the material to be used in the region withstanding these conditions, without much change in the strength. The laser beam welded samples are cooled to a temperature of -30ºC and the materials are tested for tensile, bend loads and to check the hardness of the laser beam welded samples.

Scanning Electron Microscope (SEM) is the instrument used to find out the microstructure of the metals under study, using concentrated beams of electrons to produce high resolution, three dimensional images. These images deliver the data on topography, morphology and composition. Electrons are produced by electron source, and are accelerated down the column that is under vacuum. Vacuum helps to prevent any atoms and molecules present in the column from interacting with the electron beam and confirms good images. The SEM micrographs are obtained and are studied [4].

Finite element analysis (FEA) is a numerical method for solving problems of engineering and mathematical physics. The FEA is a computing method which is used to get estimated results of boundary value problems. It utilizes Finite Element Method (FEM), it comprises a computer model of a design that is loaded and investigated for explicit results. This method was initially developed to be used in the field of aerospace and nuclear engineering. The dissimilar materials welding analysis results so obtained by using FEM are compared with the experimental values [5].

II. MATERIALS AND METHODS

The material selected for our study is stainless steel 316L and stainless steel 304, as shown in Figure 1, because of its properties as discussed earlier. Material of dimensions 100*100*3mm are cut and are polished to remove the grease and dirt. The laser beam welding is done using 4kW Nd: YAG laser [6].

Stainless steel 304

Stainless steel 316L

Fig. 1. Stainless steel 304 and Stainless steel 316L

Two kinds of laser beam welding are done.

1. Micro laser beam welding: The metal sheets are welded with a laser power of 1000 W, with a bead width of 0.5 mm on both sides of the sheet.
2. Macro laser beam welding: The metal sheets are welded with a laser power of 1800 W, with a bead width of 3 mm on one side of the sheet.

Laser power is proportional to the weld bead. The laser beam welding set up is shown in Figure 2.

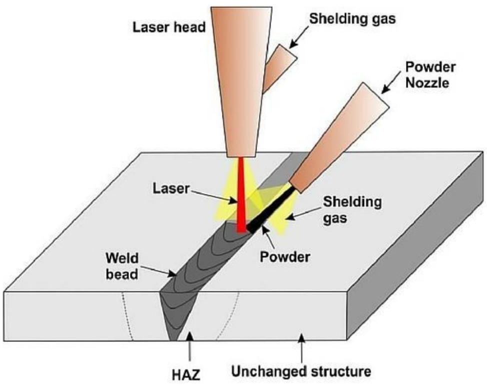


Fig. 2. Laser beam welding set-up

The laser beam welded sample is shown in the Figure 3. Argon (Ar) was used as a shielding gas with a constant flow rate of 1.5 lpm. Argon gas avoid the fusion zone contamination by making the gas remain neutral and there by not involving in chemical reaction. The sheet is then cut into small pieces of dimensions 200*20*3 mm using hydraulic cutting machine for tensile test, hardness test and bend tests.

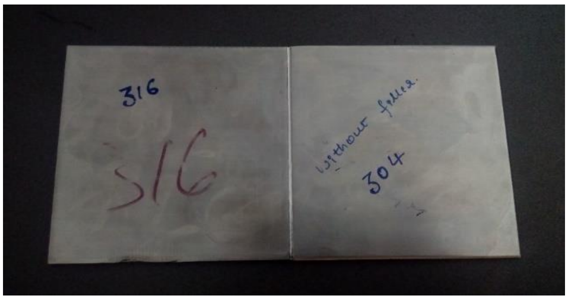


Fig. 3. Laser beam welded sample

Table- III: Laser beam welding parameters

Micro welding		Macro welding	
Laser power	1000 Watt	Laser power	1800 Watt
Pulse width	7.5 ms	Pulse width	10 ms
Bead diameter	1.1 mm	Bead diameter	3 mm
Frequency	8.0 Hz	Frequency	20,000 Hz
Speed	2 m/min	Speed	2 m/min
Gas flow	1.5 LPM	Gas flow	4 LPM

The laser beam welding is done as per the parameters given table III [7,8,9]. The weld bead is then removed for the smooth finish of the surface. The tensile specimen is done according to the ASTM E8/ E8M standard with a gauge length of 50 mm by means of lathe machine and the tensile test is carried out by Universal Testing Machine (UTM). The Ultimate tensile strength (UTS) was determined for both micro and macro welded samples. Micro hardness values of Weld zone (WZ), Heat affected zone (HAZ) and Base metals (BM) are found based on ASTM E384 standards using Rockwell hardness tests (HRB and HRC). Bend test is also conducted in Universal testing machine (UTM) and the load at peak are tabulated and strength of laser beam weld is checked out. Once all the tests are done, another set of samples are heat treated and are subjected to hardness, tensile and bend tests the results are then tabulated. The Samples were cold treated, the samples were subjected to various tests and the strength was determined. But it was found that the cold treated samples turned out to give poor results, hence these samples were ruled out and only heat treated samples were considered to be compared for strength with the normal welded samples [10].

III. RESULTS AND DISCUSSION

A. Tensile Strength:

Normal Micro/Macro Welded Samples and Heat Treated Micro/Macro Welded Samples:

The micro and macro welded samples were tested for maximum tensile strength under tensile load of 20 KN in Universal testing machine (UTM). The maximum tensile strength of the micro welded sample was found to be 212.42 MPa and that of the macro welded samples were found to give a maximum tensile strength of 582.753 MPa. The other parameters recorded during the test is given in the table IV.

The micro welded sample welded with a power of 1100 Watt broke exactly at the weld portion at a load of 7.62 KN with an elongation of 2.2 mm. The micro welded sample is shown in the Figure 4. The maximum of 7.62 KN is taken by the specimen for the cross head travel of 2.2 mm, giving out a maximum tensile strength of 212.42 MPa. The specimen broke exactly at the weld portion. It is clearly evident that the weld joint shows the perfect break at the weld zone giving rise to its tensile strength. When the cross head is moved to 1mm the load applied was found to be 1.6 KN, for a cross head travel of 2mm, load of 6.4 KN is applied and for a cross head travel of 2.2mm, a maximum of 7.8 KN is applied, travel of crosshead above this load leads to breakage of sample exactly at the weld zone. The maximum tensile strength noted being 212.42 MPa. The macro welded sample gave a maximum tensile strength of 582.753 MPa at a load of 20.922 KN, welded with a power of 1800 Watt. The macro welded sample is shown in Figure 5 [11,12]. When the laser beam welded samples were heated the grain structure changed within the weld zone. The fusion zone had a larger sized grain which were spherical as evident from the microstructure, the penetration of crack was faster in case of large sized grain, making the samples exhibit low tensile strength. Heat treated micro welded sample is shown in Figure 6. The above graph depicts the graph for micro welded sample, where the load of 4.92 KN is where the material breaks with elongation of 1.3 mm. The sample exactly broke in the weld region. The maximum tensile strength being 138.12 MPa. The macro welded sample which was heat treated gave out a maximum tensile strength of 507.166 MPa.

Heat treated macro welded sample is shown in the Figure 7. Surface plot of peak load (kN), Surface plot of Elongation at peak and Surface plot of Tensile Strength Vs Laser power and Weld trial are given in Figures 8, 9 and 10.

Fig. 4. Micro laser beam welded sample (Trail-1)

Fig. 5. Macro laser beam welded sample (Trail-2)

Fig. 6. Heat treated micro welded samples (Trail-3)

Fig. 7. Heat treated macro welded samples (Trail-4)

Table- IV: Tensile test of the Normal/Heat treated micro and macro welded samples

Weld trial	Laser power (W)	Peak load (KN)	Elongation at peak (mm)	Tensile strength (N/mm^2)
1	1100	7.62	2.2	212.42
2	1800	20.922	21.450	582.753
3	1100	4.98	1.3	138.12
4	1800	23.61	24.38	507.166

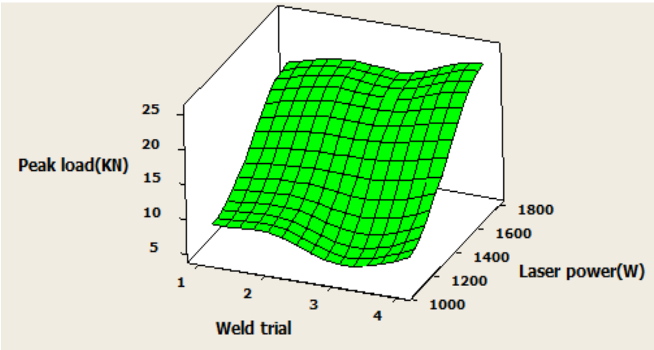


Fig. 8. Surface plot of peak load (kN) Vs Laser power and Weld trial

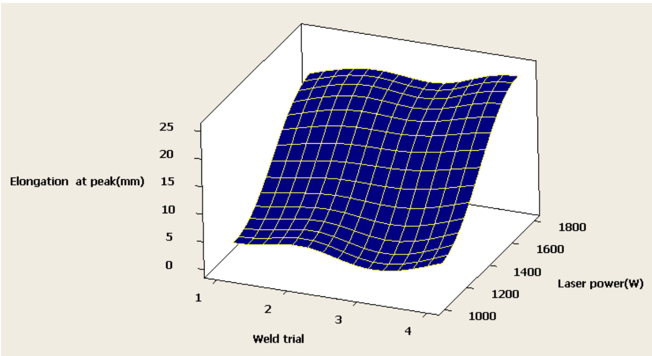


Fig. 9. Surface plot of Elongation at peak (mm) (kN) Vs Laser power and Weld trial

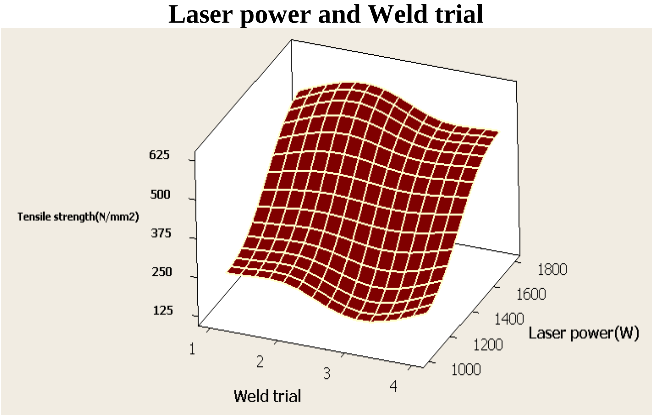


Fig. 10. Surface plot of Tensile strength (N/mm^2) Vs Laser power and Weld trial

B. Cold Treated Samples

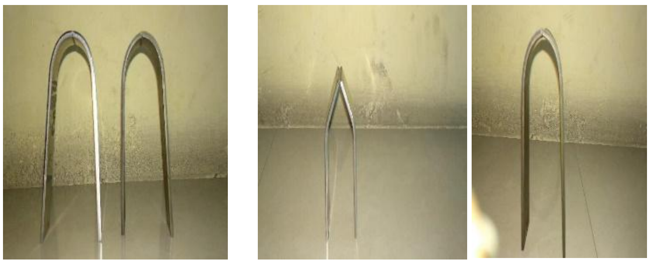
The micro welded samples were cooled to a temperature of -30ºC and were tested for tensile load. It was found that the micro welded samples gave the least tensile strength of all. Hence the macro welded samples for cold treated conditions were not considered. This was done in the view of reducing cost and time. The cold treated micro welded sample is given in the Figure 11.

Fig. 11. Cold treated micro welded sample

The cold treated micro welded sample gave a tensile strength of 147.29 MPa, with a maximum elongation of 8 mm, for a load of 5.34 KN. Since the cold treated samples were considered to give average results, the tension test for macro welded samples were not done. The cold treated samples turned out to give poor results, for the tests being conducted, because of the poor strength of the weld joint after cooling. This shows that the laser beam welding cannot be used in the regions which are subjected to icing conditions. From the above tests it is clear that the normal samples turned out to be the best and the heat treated samples being the worst. Further tests were carried out considering only the normal and heat treated micro and macro welded samples.

C. Bend Test:

The laser beam welded samples are tested for the bending tests evaluation of weld joint performance. The macro and micro welded samples were subjected to a maximum bend load of 100 KN, the macro welded samples bent to 180º forming a "U" shaped samples for a load of 9 KN, without any noticeable break in the welded portion. This indicates the good quality of laser weld process without any breaking on the weld joint surface in case of macro laser beam welded samples, indicating that the joint is free from any major imperfections and apparent visible defects, which reveals good quality of laser weld samples with full penetration. The test samples are shown in Figure 12 [13,14].



Macro welded samples **Micro welded samples**

Fig. 12. Bended macro and micro welded samples

Micro welded samples did not turn out to give good results, because they lack full penetration of the material. These instead turned out to form "V" shape with complete breakage of the weld portion on application of load.

But the heat treated micro welded samples turned out to bend to 180º, without any crack in the weld portion. This represented a good bend strength of the heated micro welded samples. Micro laser beam welded parts used in the region subjected to bend load and high temperature shows good bend strength.

D. Rockwell Hardness Test:

Hardness test is done to determine hardness property which is the resistance exhibited by the material for surface penetration and abrasion. The diamond indenter is used to form indentation on the weld zone of the laser beam welded samples. The indentation is directly read on the B and C scale as a Rockwell hardness number. The micro welded samples are checked for the hardness in the Weld zone (WZ), Heat affected zone (HAZ) and the Base metals (BM). The hardness values are tabulated in table V. The hardness test samples are shown in Figure 13.

Fig. 13. Hardness test sample

Table-V: Hardness number for micro welded samples

Weld trial	Scale	Weld Portion	Heat affected zone	Base metal 304	Base metal 316L
Normal	B	72	69	62	84
	C	42	39	32	54
Heat treated	B	95	84	95	75
	C	65	54	65	45

The micro welded samples showed good hardness number in the region of weld zone. The heat treated micro welded samples gave the highest hardness number of all. The various harness numbers in the region of weld zone are plotted in the bar graph as shown Figure 14.

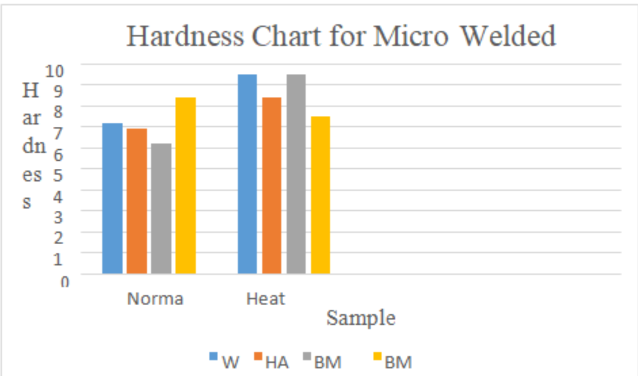


Fig. 14. Hardness Chart for Micro Welded Samples

From the above graph it is evident that the weld zone of the heat treated micro sample exhibited higher hardness value, when compared to other samples. The WZ of the normal welded samples showed a hardness value of 72. The BM 316L showed a highest hardness value of 84. The WZ and BM 304 exhibited the hardness value of 95, which is the highest among all. This shows that the weld zone has good strength. The hardness values for macro welded samples are tabulated as shown in the table VI and the hardness values are plotted in the bar graph as shown Figure 15.

Table-VI: Hardness number for macro welded samples

Material	Scale	Weld portion	Heat affected zone	Base metal 304	Base metal 316L
Normal	B	73	78	81	98
	C	43	48	51	68
Heat treated	B	73	81	73	76
	C	43	51	43	46

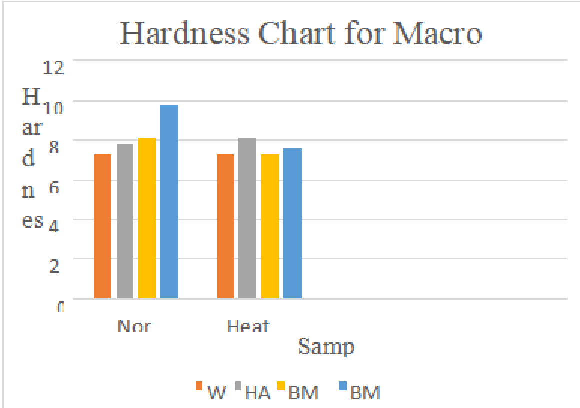


Fig. 15. Hardness Chart for Macro Welded Samples

The WZ of the normal macro welded sample turned out to have least hardness value of 73. The BM 316L showing a maximum hardness value of 98 among all.

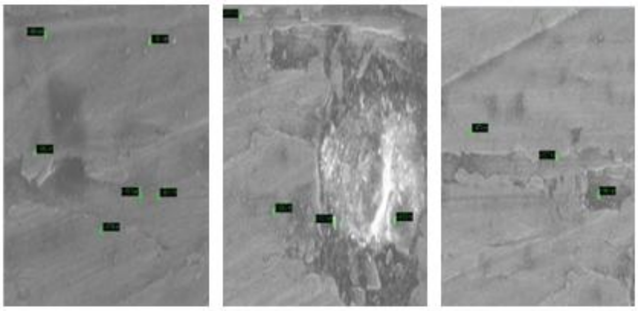
The HAZ of macro welded samples gave good hardness value of 81, which is being the maximum value compared to WZ and BM regions. Comparing the harness values of WZ of both normal and heat treated samples, there was no change in the hardness value. Both the samples exhibiting the same hardness value of 73. The above graph explains the maximum hardness value exhibited by the macro welded samples. Irrespective of the fact that the samples differ in their microstructure due to the heat treatment, they had the same hardness property.

E. Scanning Electron Microscope

The samples of dimensions 200*20*3 mm were cut into a specimen of dimensions 80*20*3 mm, for the specimen to be easily placed on the test bed. The SEM micrographs were obtained by zooming into the different sections of the weld zone for the visible magnifications. The SEM micrographs are shown in Figure 16. Only the macro welded samples were considered, because they turned out to be the best samples, giving high tensile strength when compared to micro welded samples and the microstructure of theses samples were obtained [15,16,17].

Fig. 16. SEM specimens

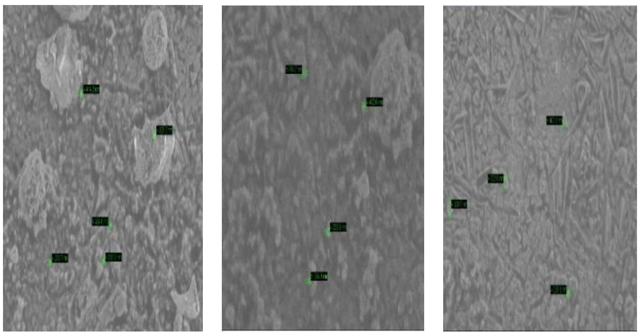
The microstructure of the macro welded samples contained grains which were small and spherical in size. Various region of the weld zone had grains which varied in size. These are represented by the black labeling on the micrographs. Figure 17 (b) represents the defect in the weld zone. This defect was due to improper laser power or improper supply of the shielding gas leading to the blast in the weld region. However, the strength of the weld portion did not decrease due to the defect. The defect did not affect the strength of the weld in any way. Figure 17 (c) showed the grain structure, with varying size in different regions.



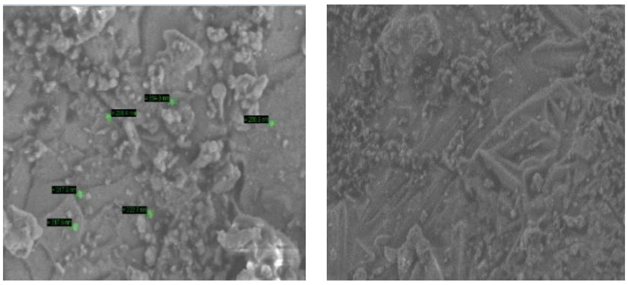
a) *(b)* *(c)*

Fig. 17 SEM micrographs of macro welded samples

The heat treated samples micrographs are shown in the Figure 18. The heat treatment changed the grain shape of the weld zone. Figure 18 (a) shows that the grain has increased in size, which were spherical in shape. The grains were distributed over a region, reducing the strength, as a result of weak bond between the grains. Grain boundaries were not able to differentiate. Figure 18 (c) represented rod shaped larger grains. Grains with varied grain size at various regions were represented by the black marking in the micrographs. Figure 18 (d) and (e) represents the grain structure in various regions of weld zone.



(a) **(b)** **(c)**



(d) **(e)**

Fig. 18. SEM micrographs of heat treated macro welded sample

Because of the heat treatment, the grains increase in size. Heat treatment helps in removing the carbide precipitation and help to increase the corrosion resistance property of the weld joint.

F. Finite Element Analysis

It was evident from the tensile test, bend test, hardness test and the SEM micrographs that the macro welded samples turned out to have good strength at the weld region. In order to check for the exactness of the ultimate tensile strength of the welded samples, model of the sample was prepared in the Ansys workbench as per the dimension given below and the model is shown in Figure 19. The mechanical properties of the material were specified [18].

Table-VII: Dimensions and mechanical properties of laser beam welded samples

Length	200 mm
Breadth	20 mm
Thickness	3 mm
Material	SS 304 and SS 316L
Density	7.85e-006 kg/mm3
Yield strength	250 MPa
Tangent modulus	1450 MPa
Young's modulus	0.2e-005 MPa
Poisons ratio	0.3

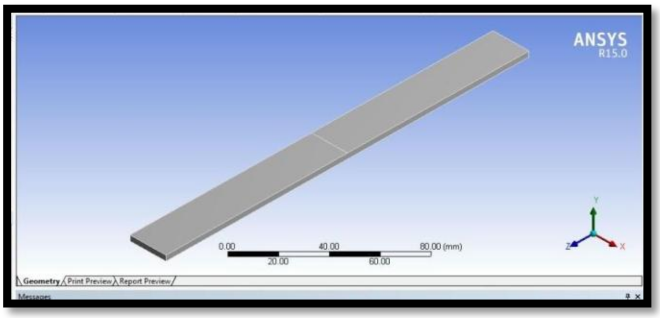


Fig. 19. The model of the sample done in the Ansys workbench

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The model is then meshed according the parameters given below and the model is given in the Figure 19.

Table-VIII: Parameters for meshing.

Object Name	Mesh
State	Solved
Physical Preference	Mechanical
Relevance	0
Sizing	
Use advanced Size Function	On : Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Growth Rate	Default (1.20)
Minimum Edge Length	3.0 mm
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layer	5
Growth Rate	1.2
Nodes	3710
Elements	476
Mesh Metric	None

The model of welded sample of stainless steel 304 and stainless steel 316L is meshed as per the mesh parameters given in the table VIII. The model is meshed with number of nodes being 3710, elements being 476. Transient analysis is done with a minimum edge length of 3mm. A maximum of 5 layers is being applied. Growth rate being 1.2.

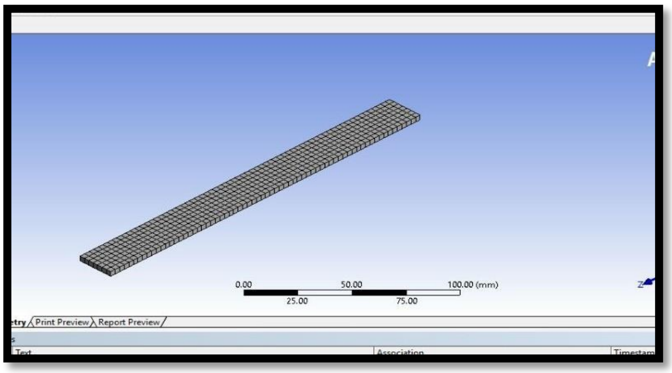

Fig. 20. The meshed model

A maximum load of 600 KN is applied to the free end of the model, in steps of 1 KN and the model breaks taking a load of 20 KN, with a maximum deformation of 0.27 mm, as shown in Figure 21.

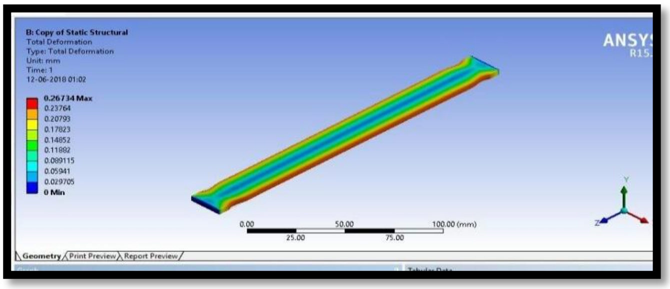

Fig. 21. The deformed body

Transient analysis of the model is done. The model was subjected to a tensile load of 20KN. The body deformed as shown in Figure 21 and the maximum deformation was observed in the outer edge of the sample.

Table-IX: The minimum and maximum deformations with respect to time.

Time [s]	Minimum [mm]	Maximum [mm]
9.00E-02		1.95E-02
0.1305		3.83E-02
0.171		5.01E-02
0.2115		6.08E-02
0.27225		7.66E-02
0.36338		0.10063
0.50006		0.13686
0.70509		0.19066
1	0	0.26734

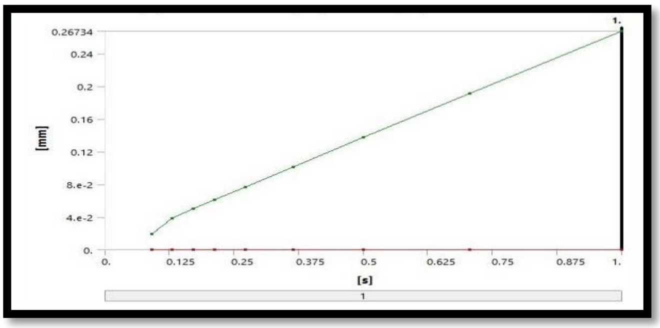

Fig. 22. The graph of deformation (mm) vs time (s)

The above graph shows the deformation of the samples as and when the load is applied in terms of time. The minimum deformation of the body was recorded, which was found to be zero. The maximum deformation of the body was found to be 0.26734 mm.

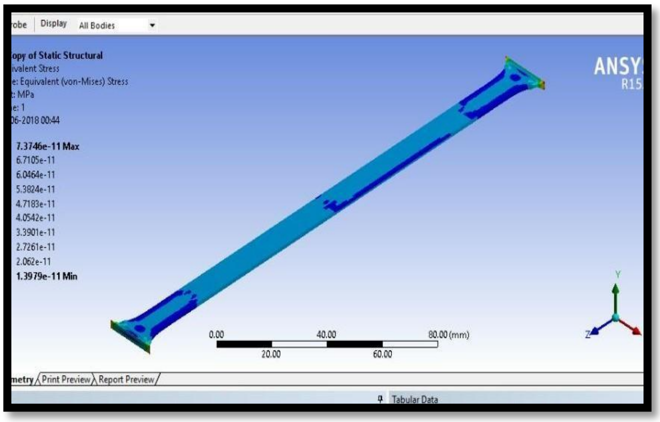

Fig. 23. Stress value obtained from FEA

The stress value varied from a minimum of 186.61 MPa to a maximum value of 535.79 MPa. All the tensile stress values along with the time is plotted in the graph and are given in the table X.

Table-X: Minimum and Maximum Tensile Stresses with varied time

Time [s]	Minimum [MPa]	Maximum [MPa]
9.00E-02	186.61	535.79
0.1305	235.3	366.91
0.171	235.79	369.02
0.2115	236.27	371.05
0.27225	237.04	373.99
0.36338	238.18	378.26
0.50006	239.86	384.47
0.70509	242.16	393.49
1	245.3	406.07

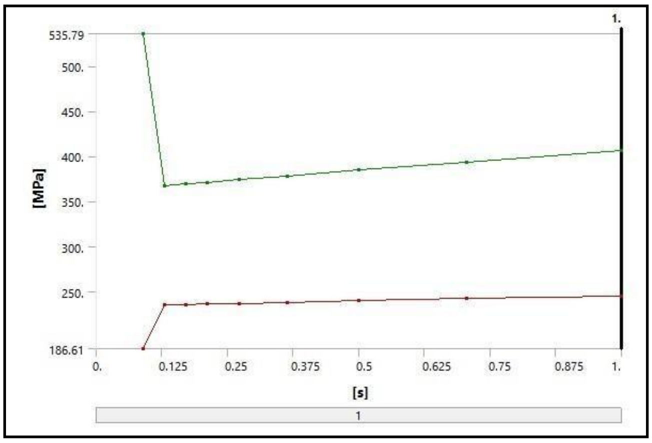

Fig. 24. Graph of Tensile stress (MPa) vs time (s)

The above graph shows the minimum and maximum stress values with respect to time. It was found that the minimum stress value of 186.61MPa was obtained and the maximum tensile strength being 535.79MPa. The results so obtained were compared with the experimental values.

IV. CONCLUSION

In this paper we have analyzed the strength of laser beam welded joint of stainless steel materials 316 L and 304 by keeping the speed of the weld constant and by varying the laser powers. The dissimilar stainless steel materials are welded by using the Micro and Macro welding techniques. The metal sheets are welded with a laser power of 1000 w with a bead width of 0.5 mm on both sides of the sheet by using micro laser beam welding and the macro laser beam welding is used to weld the metal sheets with 1800 w laser power along with a bead width of 3mm on one side of the sheet. From the analysis we have found that macro welded samples gave best results in all aspects when compared to micro welded samples. Tests were done in three phases, one is experimental analysis of strength of the weld by subjecting it to various loads and checking for its strength. Second the microstructure was obtained from SEM, explaining the strength of the weld by looking into the grain patterns. Finally, third approach involved obtaining the theoretical results, using FEA method and to compare these results with that of the experimental values. Thus making our result acceptable. From the discussion made in the result section, it is clear that the macro welded samples turned out to be the best samples with good tensile strength of 582.753 MPa, bend strength without any crack in the weld portion etc. The micro welded samples which were heat treated turned out to be the second best samples, as they exhibited good bend strength compared to the macro welded samples with no cracks in the weld zone. Also hardness values of heat treated samples were the maximum of all the other samples, hardness value being 95. The cold treated samples were taken out as they exhibited properties lying between normal and heat treated samples.

However, the normal samples being the best and cold treated samples being the least. It was evident from the FEA results that the maximum tensile stress represented was 535.79 MPa, which was almost near to the theoretical tensile strength 582.753 MPa. This proved that the tensile strength found out experimentally was correct and was the best value.

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