Mechanical Engineering Research; Vol. 3, No. 1; 2013
ISSN 1927-0607 E-ISSN 1927-0615
Published by Canadian Center of Science and Education

Thermo-Mechanical Characterization of Laser Weld 316L(N) Stainless Steel

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Received: December 20, 2012 Accepted: January 8, 2013 Online Published: January 23, 2013

doi:10.5539/mer.v3n1p77 URL: http://dx.doi.org/10.5539/mer.v3n1p77

Abstract

316L(N) stainless steel is an austenitic stainless steel variety strengthened by nitrogen through solid solution hardening. The effects of nitrogen on the mechanical properties of 316L(N) SS have not been studied extensively in the past and is the study of current research. The nitrogen content when added to 316L stainless steel in the range 0.07 wt% - 0.21 wt% improves room temperature and high temperature mechanical properties. The loss in strength due to reduced carbon content in 316L(N) SS can be more or less compensated by the addition of nitrogen. Laser welded joints have been fabricated on 316(L)N SS using CO_2 laser protecting the environment by employing nitrogen shielding and tested the welded joints under tension at room temperature and at 650 ˚C (923 K). In the as - welded condition Transmission Electron Microscope (TEM) revealed the presence of the deformation bands, high density of dislocations and carbides or carbo -nitrides on dislocations near the grain boundary regions which may be in the Heat-Affected Zone(HAZ). At both the test temperatures failure occurred in the base metal by transgranuler mode with the nucleation of cavities. In the present work, laser welding process has proved to be effective in producing satisfactory welded joints.

Keywords: laser welding, 316L(N) stainless steel, deformation bands, transgranular fracture, tension test

1. Introduction

The 316L(N) Stainless Steel (SS) is used as a structural material in the construction of Fast Breeder Reactor (FBR) components due to its compatibility with liquid sodium coolant, excellent high temperature mechanical properties, good weldability, freedom from sensitization during welding and the associated stress corrosion cracking that may occur during storage of these components in chloride environments in coastal construction site prior to installation and commissioning of the nuclear plants, availability of design data, indigenous availability, good service life under FBR operating conditions, vast experience and enhanced pitting resistance in the presence of molybdenum (Narayana, 2010; Baldev et al., 2010; Srinivas et al., 2011; Harish-Kumar et al., 2012; Girish-Shastry et al., 2004).

The weldability aspects of 316L(N)SS has been documented in the recent literature (Mathew et al., 2010, 2012; .Saktivel et al., 2012; Ganesan et al., 2008, 2010) with the intention that the service life of FBR can be extended from the present 40 years service life to 60 years service life. The comparative work (Tjong et al., 1995) on CO_2 laser welded and electron beam welded 316L SS had shown that the high temperature properties of both these processes were lower compared to the base metal. The properties were reduced by a factor of two compared to the base metal. Also, it was noted that the mechanical properties were same in the case of both the welding processes. Both these welding processes deposited negligible amount of delta-ferrite in the fusion zone during welding. These studies were based on the employment of helium for protecting the environment during laser welding. The studies on argon shielding during welding of 316L(N) are incomplete. It may be understood that argon has better advantages than helium. Argon is cheap, requires less volume for adequate shielding and it has lower ionization potential compared to helium. Investigations (Ramazan-Yimaz et al., 2002) on the mechanical properties of 304L and 316L stainless steel welded by Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) had shown that the mechanical properties such as yield strength, tensile strength, impact strength and micro-hardness values of GTAW were higher as compared to those of GMAW. Studies (Kim et al., 2007) on the mechanical properties of Submerged Arc Welded (SAW) 316L(N) SS revealed that the ultimate tensile strength values for the base and weld metal were almost similar at all the stress temperatures tested in the range 25-700 MPa. However, in the case of yield stress values the weld metal values were increased above about 50 MPa at all temperatures to the base one. Especially, the elongation value of the weld metal was decreased by about 50% to that of the base one. Investigations have also been carried out on the tensile properties of A-TIG welded and Multi-pass TIG welded 304LN SS and 316L(N) SS (Vasudevan, 2007; Vasudevan et al., 2008). It has been noted that transverse strength properties of the 316 and 316L(N) SS welds produced by A-TIG welding exceeded the minimum strength values of the base metal. Improvement in toughness values were observed in the 316L (N) SS produced by A-TIG welding (Vasudevan, 2007; Vasudevan et al., 2008).

The effects of cold deformation on nitrogen content (0.03-0.18 %) on the mechanical properties of austenitic stainless steels of AISI 316L type were also reported (Ehrnsten, 2005). It was noted that nitrogen alloying increases the strength properties of AISI 316L stainless steel in the temperature range of 200-400 ˚C. Elongation to fracture decreases with increasing nitrogen content except for the commercial AISI 316NG stainless steel which demonstrates the highest elongation of the fracture in the whole temperature range of testing. Also, the elongation to fracture varies only slightly as a function of temperature. The strain hardening coefficient (n) increases with increasing test temperature and decreasing the nitrogen content. Yield strength decreases with testing temperature, while tensile strength is almost constant in the study of the temperature range.

2. Experimental Details

316L(N) SS plates of 300 mm x 125 mm x 5.5 mm thick were flat machined in the thickness direction and ensured zero gap between the plates when the two plates were fitted together and clamped prior to laser welding. Two weldments have been fabricated using CO_2 laser welding employing nitrogen shielding environmentally protecting the fusion zone during laser welding. These weldments were radiographed and ensured prepared joints were radiographically sound. Two different laser powers were used in the preparation of these weldments. One weldment was CO_2 welded with 3KW laser power and other one was fabricated using 3.5 KW.

Table 1. Chemical composition (wt%) of the 316L(N) base metal and the weld deposits

Material	C	Cr	Ni	Mo	Mn	Si	N	S	P	Fe
316L(N)SS Base plate	0.028	17.5	12.2	2.3	1.65	0.44	0.085	0.01	0.024	Balance
316L(N)SS Weld Metal	0.025	17.6	12.2	2.41	1.7	0.36	0.082	0.006	0.021	Balance

Table1 gives the chemical composition (wt%) of type 316L(N) SS base metal and deposited weld metals. Transverse tensile samples were machined from the two weldments for carrying out the room temperature and high temperature tension tests. High temperature tension tests were carried out at 650 ˚C (923 K). The equipment used for tensile test manufactured by Hung Ta Model HT 2402 Universal Testing Machine with the capacity of 100 KN (10 Tonne) supplied by Blue star India and E 8/E 8M-09: Standard Test Methods used for Tension Testing of Metallic Materials.

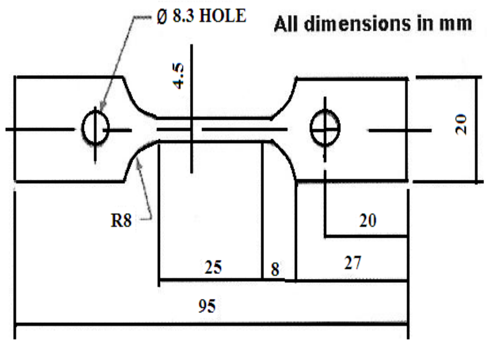
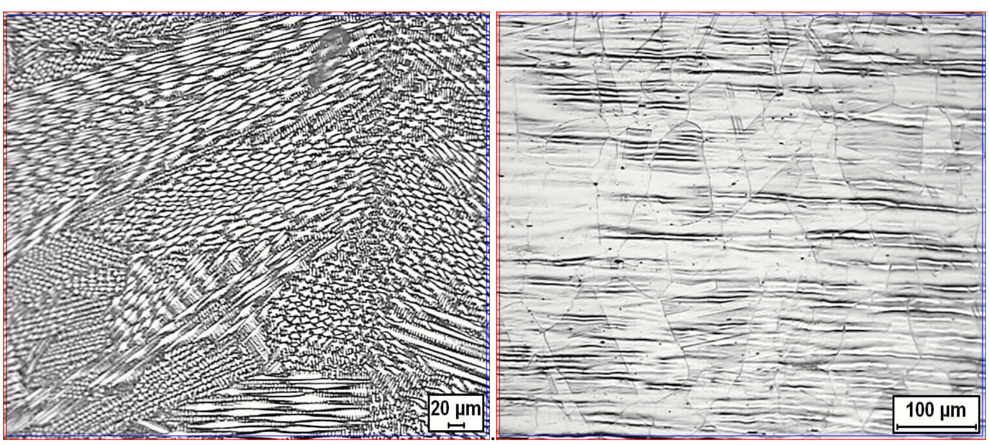


Figure 1. Tension test sample design

Figure 1 shows the sample design of the tension tests. Tensile testing was performed in accordance with ASTM E 8. For high temperature tension test, the test temperature was controlled within ± 2 K. Ferrite scope was used to measure the ferrite content of the weldmetal in the as-welded condition. Optical, Scanning Electron Microscopy [SEM], and Transmission Electron Microscopy [TEM] studies were also carried out on the welded joints. SEM was used to know the type of fracture of the room temperature tension tested and high temperature tension tested samples. For the observation of the micro structures using TEM in the as welded condition transverse sections of about 1mm thickness were cut from the weldments. These were mechanically polished to a thickness of about 0.1mm and were then electro-polished using the jet polishing technique. Electrolyte used for this technique consists of 80 % methanol and 20 % perchloric acid. The electrolyte bath was maintained at 238 K and a polishing voltage of about 20 volts was employed. The thin foils were observed in a Philips EM 400 TEM. Optical microscope was used to know the microstructures of the base metal, fusion zone and heat affected zone. Grain size measurements were also carried out on the base metal after electrolytic etching in an electrolytic bath of 60 % HNO_3, and 40 % water.

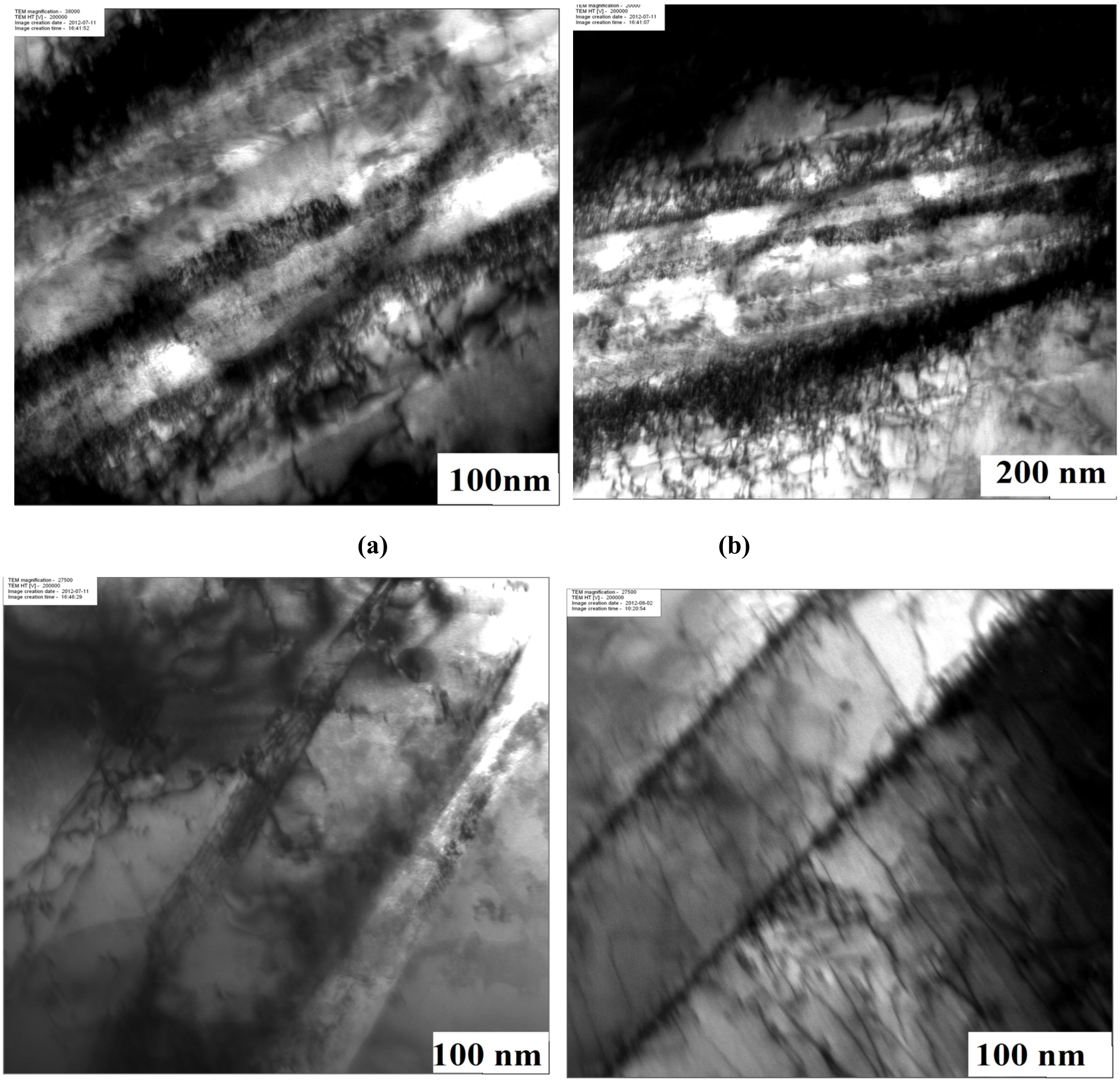
3. Results and Discussions

The as welded microstructure of the laser welded 316L(N)SS using 3.5 KW laser power is shown in Figure 2(a). It shows columnar dendritic and equiaxed dendritic microstructures. The microstructure shown in Figure 2(b) is the base metal microstructure of 316L(N)SS. It shows equiaxed grain structure. The average grain size of the base metal when measured using linear intercept method was found to be around 75 µm. The melted base metal insitu solidified due to the conduction of heat through the base metal perpendicular to the welding direction. As a result, the base metal acted as a nucleation site causing the dendritic grains to grow towards the centre of the fusion zone. On other hand the equiaxed grains might have developed by homogenous nucleation. The growing dendrites might have broken and there by acted as nucleation site.



(a) **(b)**

Figure 2. (a) Optical microstructure of the 3.5KW laser welded fusion zone; (b) Optical microstructure of the 316L(N) basemetal



(c) (d)

Figure 3. (a) Bright field TEM microstructure showing high density of dislocation and deformation bands; (b) Bright field TEM microstructure showing deformation bands and dislocations; (c) Bright field TEM microstructure showing deformation bands and Dislocations; (d) Bright field TEM microstructure showing high density of dislocation

When observed the weld deposits under TEM, dislocations and deformation bands were observed. (Figures 3a-3d). The appearance of these microstructural features may be due to the result of solidification process which may introduce strain due to shrinkage stresses. Carbides were also observed near the grain boundary region.

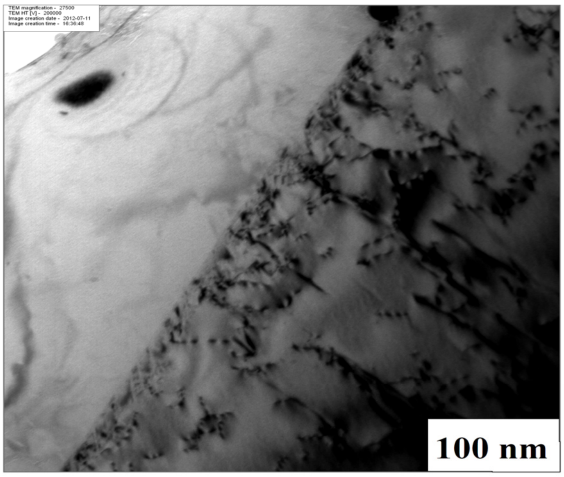


Figure 4. Bright field TEM microstructure of the grain boundary region showing carbonitrides on dislocations

Figure 4 shows the grain boundary region where fine precipitation of carbo-nitrides on the dislocations were apparent which may be in the heat affected zone. No delta-ferrite was observed under optical microscope when both the weld deposits were metallographically polished and immersion etched in boiling murakkami's reagent. TEM observations of 316L(N) SS weld deposits in the as received condition has not shown the presence of delta-ferrite. However the ferrite scope did reveal the delta- ferrite as 0.09 ferrite number which considered to be insignificant. Formulae were also available for estimating the delta-ferrite using Schaeffler diagram and Delongs diagram. In the present investigation no such diagrams were also used by calculating the chromium equivalents and nickel equivalents and estimating the volume fraction of the ferrite in the weld deposits. Both the diagrams revealed the presence of 0 % delta ferrite in the fusion 30 mm.

The room temperature tension tested sample when observed under SEM showed ductile transgranular fracture with familiar dimples on the fracture surface (Figures 5a and 5b).

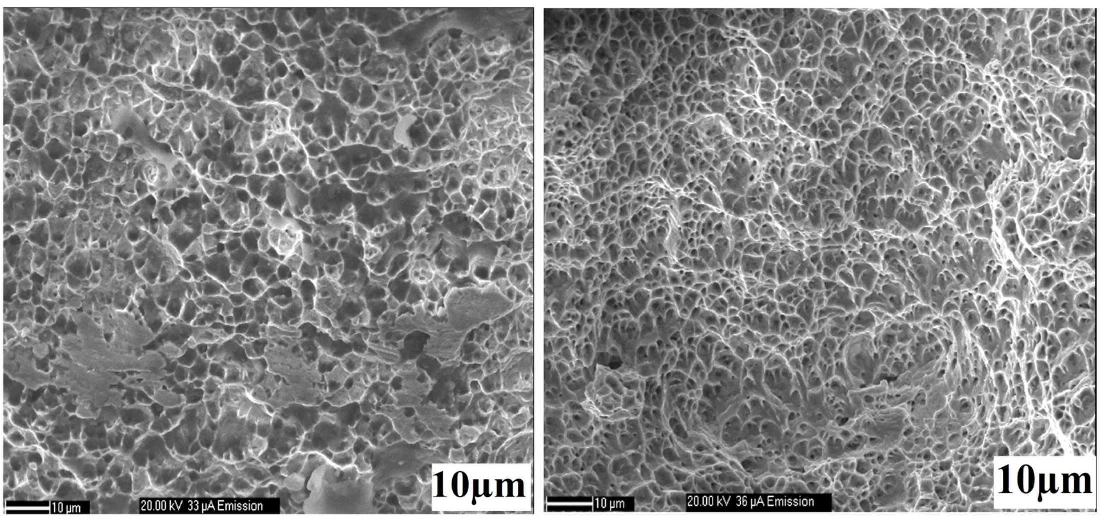
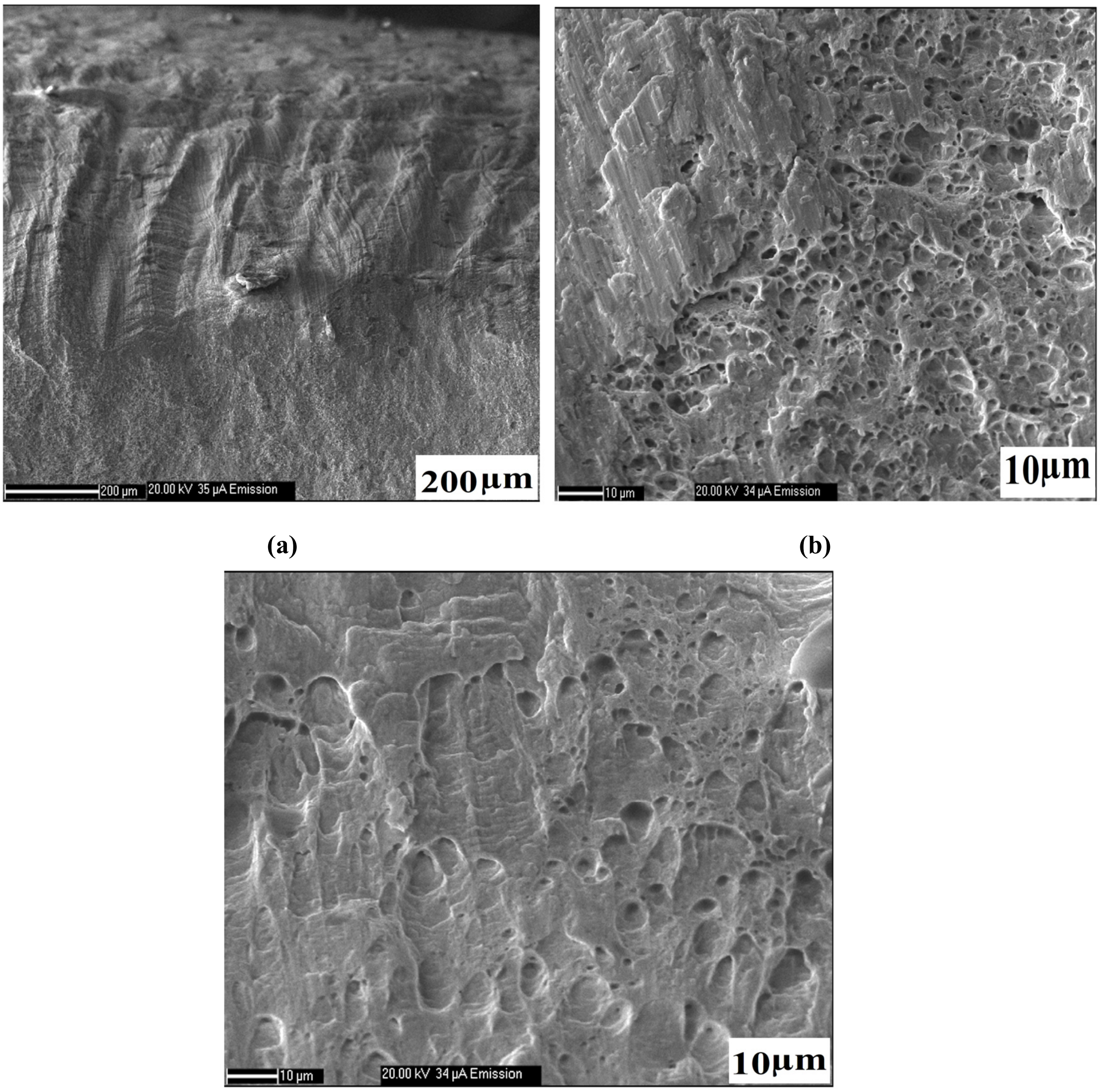


Figure 5. (a) SEM microstructure of the room temperature tension tested 3.0 KW laser welded 316L(N)SS; (b) SEM microstructure of the room temperature tension tested 3.5KW laser welded 316L(N)SS

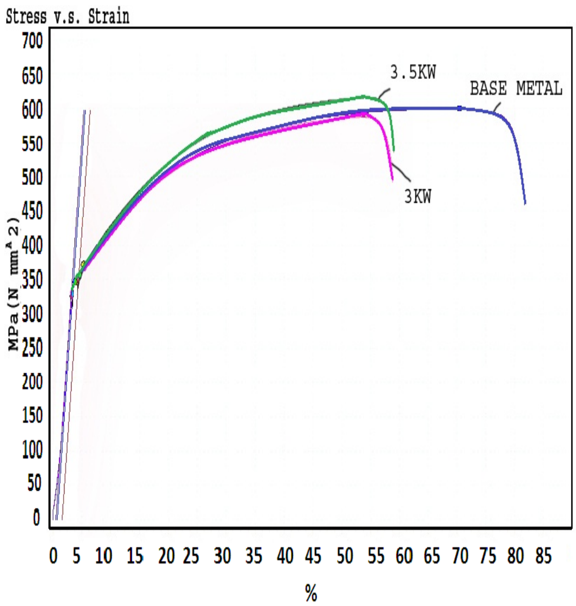
Both the weld deposits failed in the base metal. High temperature tension tested welded samples of 316L(N) SS showed mixed mode of fracture in the case of 3 KW laser power (Figures 6a and 6b) and inter granular fracture in the weld deposits of 3.5 KW laser power (Figure 6c). Microstructure clearly shows the columnar grain boundaries and cavities on the facets signifying that there was a cavitation prior to the fracture.



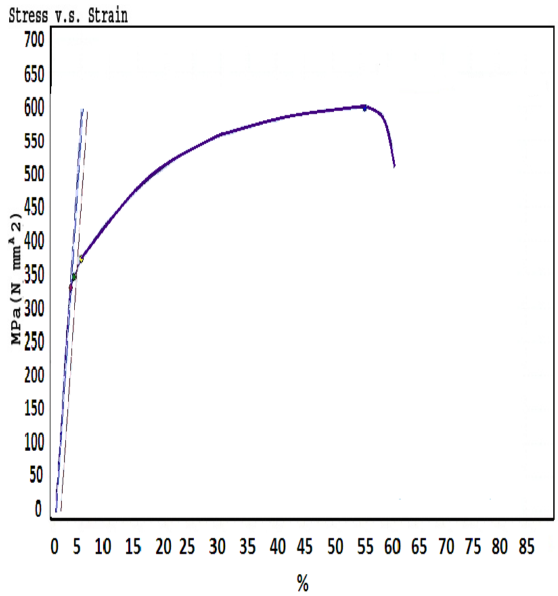
(a) **(b)**

(c)

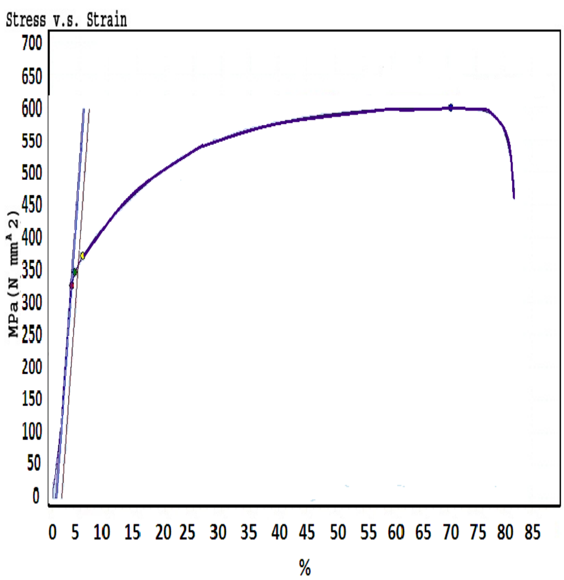
Figure 6. (a) SEM microstructure of the high temperature tension tested 3.0 KW laser welded 316L(N)SS; SEM microstructure of the high temperature tension tested 3.0 KW laser welded 316L(N)SS; (c) SEM microstructure of the high temperature tension tested 3.5 KW laser welded 316L(N)SS



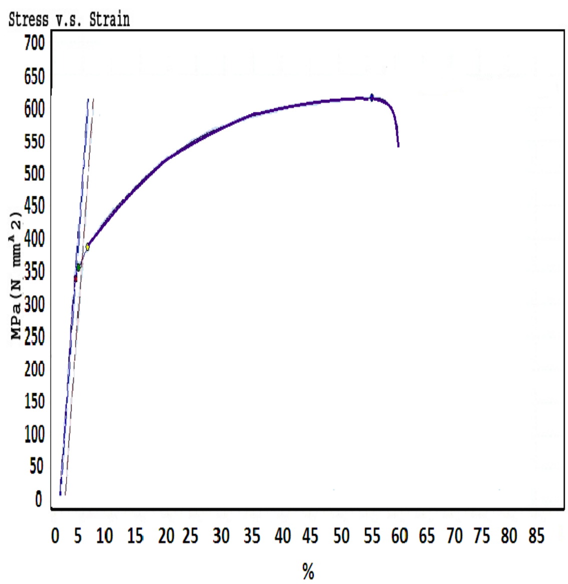
7(a)



3Kw

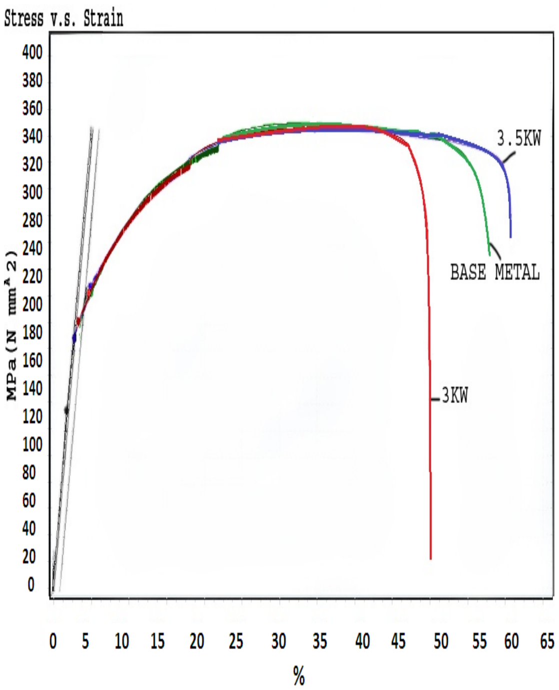


BASE METAL

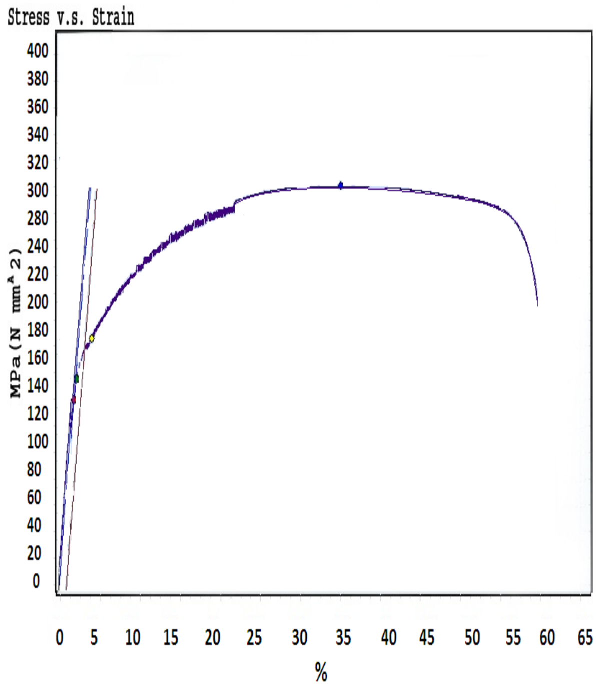


3.5 Kw

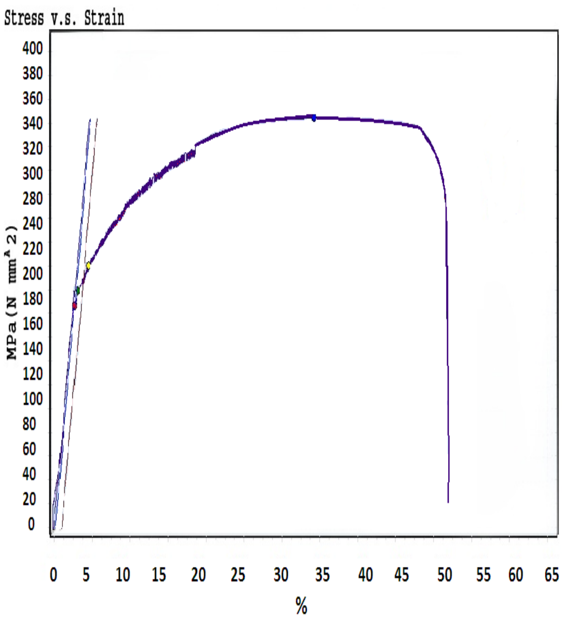
Figure 7(a). Comparison of the stress-strain curves of room temperature tension tested 316L(N) base metal, 3.0 KW laser welded and 3.5 Kw laser 316L(N) weldments



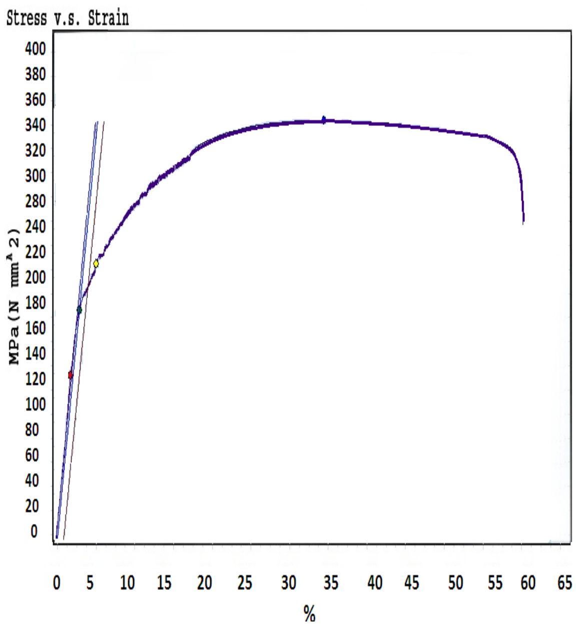
7(b)



BASE METAL



3 Kw



3.5

Figure 7(b). Comparison of the stress-strain curves of high temperature tension tested 316L(N) base metal, 3.0KW laser welded and 3.5Kw laser 316L(N) weldments showing serrated yielding

Table 2. Room temperature and high temperature mechanical properties of 316L(N)SS base metal and the weld deposits

Sl No.	Power, KW	Tensile Properties										Impact Properties
		Room Temperature					6500C					Room Temperature
		0.2% Proof Tress MPa	Y.S., MPa	U.T.S MPa	%E	%R.A.	0.2% Proof Tress MPa	Y.S.	U.T.S	%E	%R.A.	J/ mm2
1	3	329.3	344.41	593.3	57.04	16.01	187.5	200..1	345.4	39.52	15.11	0.70
2	3.5	326.7	344.3	602.7	38.24	14.47	135.9	189.4	347.2	43.28	14.73	0.68
3	Base Metal	325.0	345.4	598.6	46.55	20.6	179.7	190.3	348.25	36.6	22.13	0.79

Table 2 gives the room temperature and high temperature mechanical properties of the both the weld deposits along with the base metal. It could be seen that the room temperature and high temperature yield strength and ultimate tensile strength values of both the weld deposits are more or less similar to those of the base metal.

The high temperature deformation of the 316L(N) SS is seen in the form of serrated yielding (Figures 7a and 7b). This may be due to the fact that the interstitial elements carbon and nitrogen diffuse and pin the dislocation structure. The serrated yielding is variously known as dynamic strain ageing, negative strain rate sensitivity and changes in the internal friction behavior (Ehrnsten, 2005).

4. Conclusions

1) The welded microstructure of the laser welded 316L(N)SS shows columnar dendritic and equiaxed dendritic microstructures. The base metal microstructure of 316L(N)SS shows equiaxed grain structure.

2) The room temperature tension tested sample when observed under SEM showed ductile transgranular fracture with familiar dimples on the fracture surface.

3) The room temperature and high temperature yield strength and ultimate tensile strength values of both the weld deposits are more or less similar to those of the base metal.

4) When observed the weld deposits under TEM, dislocations and deformation bands were observed.

5) Both the weld deposits failed in the base metal.

6) High temperature tension tested welded samples of 316L(N) SS showed mixed mode of fracture in the case of 3KW laser power and inter granular fracture in the weld deposits of 3.5 KW laser power.

7) The laser deposited weldments were considerably stronger, ductile and the mechanical property values were equivalent to those of the base metal.

8) Laser welding can be used with confidence for the joining of the 316L(N) SS.

9) Laser welded joints more or less satisfied the ASME Boiler and pressure vessel code based on the ductility criteria. However weld deposits stronger than the base metal have to be achieved.

Acknowledgements

The Authors wish to acknowledge the help of G. R. Padmanabhan and Shanmugarajan, International Advanced Research Centre for Power Metallurgy and New Materials (ARCI), Balapur, Hyderabad in carrying out the laser welding of 316(L)N SS material at their premises. The authors are also grateful for the director of IGCAR Kalpakkam for testing the 316L(N) material in carrying out the research work. Dr. A. Somi Reddy is greateful for the management of VITS group of Institutions, Bommakal, Karimnagar for their encouragement on the research work. D. Harish Kumar is also greatful for the Mechanical Engineering Department of KITS, Warangal for their constant encouragement on his research work.The authors wish to acknowledge permission of Dr. Vijayalakshmi, Head of Physical Metallurgy Division, IGCAR, Kalpakkam for doing the TEM work.

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