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Investigation of Microstructure and Mechanical Properties of Super Alloy C-276 by Continuous Nd: YAG laser Welding

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Abstract

The present work investigates the microstructure and mechanical properties of the alloy C-276 by using continuous neodymium: yttrium aluminum garnet (Nd: YAG) laser welding process. Weldingtrials were carried out by varying the scan speed of the laser beam from 550 mm/min to 1200 mm/min. The scan speed of 550 mm/min was found to give good weld quality with no lack of penetration, and was adopted for the work reported here.The laser power was kept constant at 2 KW.Optical microscope and Scanning Electron Microscope (SEM) were used to study the microstructural features of the weld joint. Energy Dispersive X-ray Spectrometry (EDS) analysis was carried out to study the extent of segregation in the weld joint. Tensile tests were carried out to determine the strength and ductility of weldment. The microstructure in the fusion zone is predominated by fine cellular structure. The higher hardness in the weld zone is believed to be resulting from the fine dendritic structure compared to the relatively coarse grain structure of base metal. Microsegregation in fusion zone was found to be within acceptable limits, but there was evidence for macrosegregation.The weld joints exhibited tensile strength matching well with that of base metal (760 MPa) with good ductility (40 %).

Keywords: continuous Nd :YAG laser welding; micro-segregation; microstructure; mechanical properties

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Nomenclature

EDS	Energy Dispersive X-ray Spectrometry
GTA	Gas Tungsten Arc
GMA	Gas Metal Arc
k	Distribution coefficient
Nd:YAG	neodymium: yttrium aluminum garnet
SEM	Scanning Electron Microscope

1. Introduction

Alloy C-276 is a solid solution strengthened Ni based alloy. The major alloying elements are Cr, Mo and W. These alloying elements are very effective solid-solution strengtheners (ASM Handbook Volume 13b). Alloy C-276 is widely used in many industrial applications such as marine, chemical and nuclear industries due to its excellent resistance to corrosion to a variety of chemical environments. The welding of alloy C-276 is possible by well known commercial welding processes such as Gas Tungsten Arc (GTA) and Gas Metal Arc (GMA) welding. However the elemental segregation, hot cracking and non equilibrium solidification during these processes deteriorate the metallurgical and mechanical properties. Cieslak et al. (1986) reported the formation of various inter-metallic phases such as P, μ and carbide phases while welding of alloy C-276. According to these, the P phase usually precipitates within few minutes of heat treatment at 875^0C, whereas the μ phase precipitates at a much higher temperature. Ahmad et al. (2005) studied the microstructure and hardness of joints produced by electron beam welding of C-276 and concluded that the μ phase forms at a temperature of 950^0C. Guangyi et al. (2011) reported that micro-segregation of C-276 is relatively less in pulsed laser beam welding when compared with other welding processes. Hashim et al. (2013) concluded that the cooling rate during welding is more influential in determining the micro-structural features and elemental segregation. Laser welding process has more advantages than the conventional welding processes as this involves no use of filler wire, low heat input, high energy density, narrow HAZ and high welding speed. Further, Nd: YAG laser welding has higher energy absorption rate due to low reflectivity, higher welding speed and low residual stress compared to the CO_2 laser [Sun and Ion (1995), Sun and Kuo (1999), Wang et al. (2000), Sanderson et al. (2000), Mai and Spowage (2004)]. It is felt that there is very limited literature available on the weldability of alloy C-276 by using advanced welding processes. There is no report available for example on the weldability of alloy C-276 by non pulsing laser welding technique. The aim of this present work is to optimize the parameters for Nd :YAG laser welding of alloy C-276 and investigate the mechanical and metallurgical properties of weld joints of alloy C-276 produced using the optimized parameters.

2. Experimental Procedure

In this study, a continuous Nd: YAG laser welding [JK 2003SM (Make: United Kingdom with ABB Robo assist (China)] was employed as shown in Fig.1. The welding was carried out in an argon(80%) + CO_2(20%) gas atmosphere with a flow rate of 30 L/min. Alloy C-276 was procured in the form of 4 mm hot rolled plate and the chemical composition is shown in Table 1.

Table 1. Chemical composition of as received base alloy C-276.

Base Metal	Chemical Composition (% Wt.)							
	Ni	Mo	Cr	W	Co	Mn	Fe	Others
Alloy C-276	Bal	16.36	15.83	3.45	0.05	0.41	6.06	0.17 (V), 0.005(P), 0.002 (S), 0.02 (Si), 0.005(C)

Fig. 1. Experimental Setup

The process parameters were chosen based on the bead-on-weld trials performed on the plate. The welding parameters used in the present study are given in the Table 2.

Table 2. Welding Parameters

Parameters	Value
Laser Power (KW)	2
Welding Speed (mm/min)	550,600,650,700,900,1200
Focal Length (mm)	200
Laser Spot diameter (mm)	0.6
Shielding gas	80% Ar + 20% CO_2
Flow Rate (l/min)	30

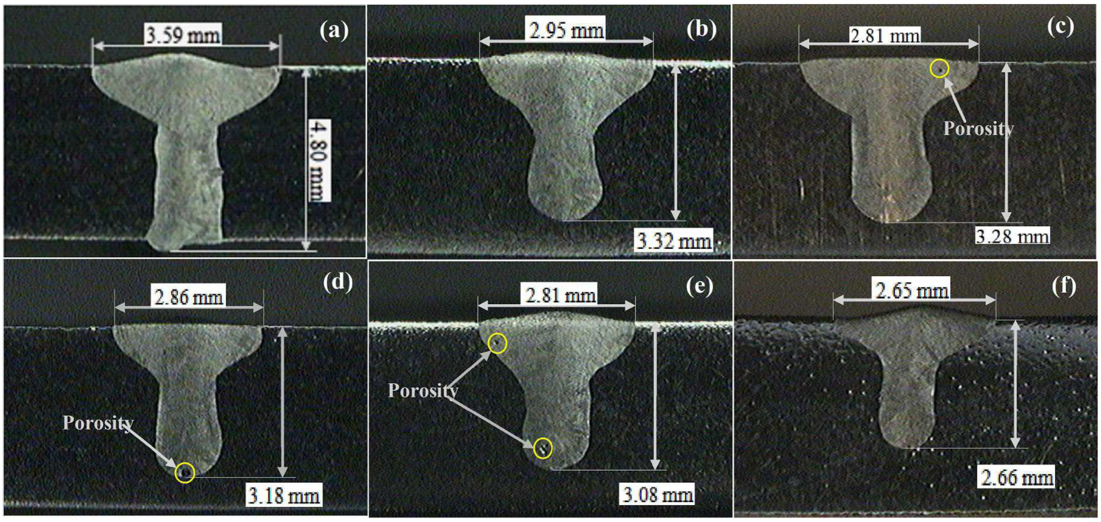

Fig.2. Macrograph of Bead on plate produced by Nd: YAG continuous Laser welding with 2 KW power. (a) 550 mm/min; (b) 600 mm/min; (c) 650 mm/min; (d) 700 mm/min; (e) 900 mm/min and (f) 1200 mm/min.

The laser power was kept at 2 KW and the scan speed of the laser beam was varied between 550 to 1200 mm/min. A macrostructural analysis was carried out to determine the depth of penetration; bead width and penetration values obtained for various scan speeds are shown in Fig. 2.It can be seen from the figure 2 that weld joint with full penetration was obtained at the scan speed of 550 mm/min at 2 KW power. Before starting the welding process, the surface of the base metal was cleaned properly and the plate was fixed firmly with the aid of jigs. The square butt welding was carried out by continuous Nd: YAG laser and the welded sample is shown in Fig. 3(a).

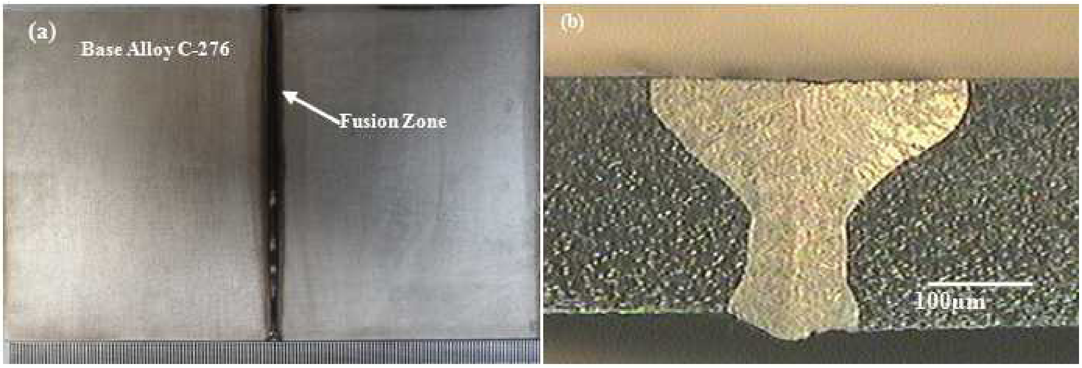

Fig. 3. (a)Photograph of weld joint; (b) Macrostructure of 550mm/min with 2 KW laser Welded alloy C-276

The macrograph of square butt weld joint is shown in Fig. 3(b).Metallurgical characterization was performed with the use of optical microscope and scanning electron microscope on the weldment, comprising of base metal and fusion zone. Standard metallographic procedure was adopted to prepare the samples for examination. The microstructure was revealed using an etchant containing 80 ml HCl, 4ml HNO_3, 1gm $CuCl_2$, and 20ml glycerol. The EDS analyses were carried out to evaluate the extent of segregation in the weld fusion zone. Hardness measurement was carried out on the composite region of the weldment using Vicker's Micro-hardness tester with a load of 500 gf for a dwell time of 10 s at regular intervals of 0.25 mm. Tensile test coupons were prepared by wire cut EDM process as per ASTM E8/8M standard. Two tests were carried out at a strain rate of 2 mm/min to check the reproducibility of the results.

3. Results and Discussion

3.1. Macrostructure examination.

Figures2(a-f) show the macrographs of bead on weld plates. Welding was carried out by employing six different sequences, i.e., by keeping constant laser power and varying the scanning speed from 550 to 1200 mm/min. The effect of varying the scanning speed on weld bead geometry and penetration has been evaluated and the results presented in the Fig. 2. The Figs. 2(a-f) shows that with increase in scan speed from 550 mm/min to 1200 mm/min the depth of penetration decreases. From the results of bead-on-weld, it is thus clear that complete weld penetration occurswhen scanning speed of 550 mm/min is adopted(Fig. 2(a)).With this scanning speed and other parameters as given in Table 2. Welding was carried out on alloy C-276 plate of size 100 x 50 x 4 mm; Fig. 3(a) gives the photograph of the weld joint produced and Fig. 3(b) is the macrograph of the cross section of the weld joint. No defect were noticed in the weld joint and penetration was complete.

3.2. Microstructure analysis

Figure 4(a) Shows the as received alloy C-276 microstructure and Fig. 4(b) shows the micrograph of the fusion zone. Microstructure of fusion zone (Fig. 4(b))is predominantly fine cellular.

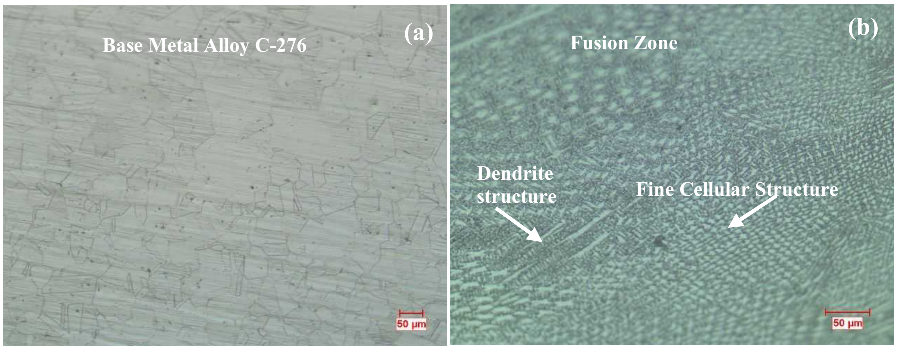

Fig. 4. Micrograph of weld joint produced by Nd: YAG continuous Laser welding.
(a) Base Metal; (b) Weld Centre

SEM micro-graphs of weld interface and fusion zone of alloy C-276 are represented in Fig. 5(i) and Fig. 5(ii) respectively. The fusion zone consists of fine parallel columnar dendritic structure. The columnarity is not there in the dendritic structure seen in the interface region. Extremely high cooling rate obtained in the laser welding (~10^{40}C/s) is believed to be responsible for the very fine dendritic structure formation in the fusion zone as also emphasized by Janaki Ram et al. (2005).No HAZ was observed near the fusion boundary; this is due to the extremely localized heat input employed during laser welding process.

3.3. EDS analysis.

The micro-segregation plays a very important role in controlling the mechanical and metallurgical properties of the alloy C-276 weldment. The purpose of carrying out the EDS analysis is to find out the extent of microsegregation across the dendritic and inter-dendritic substructure. Earlier studies of alloy C-276 [Cieslak et al. (1986), Raghavan et al. (1982), Akhter et al. (2001), and Tawancy (1981)] reported the formation of the P and µ phases at the terminal stage of the solidification. These phases are generally brittle in nature. The major constituents of these phases are Ni, Cr, Mo and W. Hence these alloying elements were selected in the present study for the EDS analysis to evaluate the micro-segregation in the weldment. The results of EDS analysis of sub-grain boundary and sub-grain body in the weld interface and weld centre are shown in Fig. 5(a-d) and summarized in Table 3.Table 4 shows the composition of (i) base metal used in the present work, (ii) base metal used in earlier study reported by Guangyi et al (2011), (iii) subgrain boundary in fusion zone after pulsed laser welding as reported by Guangyi et al (2011) and (iv) subgrain boundary in fusion zone after continuous Nd:YAG laser welding based on the present research.

Table 3.EDS element Composition of Laser welded alloy C-276.

Zone	Ni	Cr	Mo	W
Weld subgrain boundary	58.51	15.25	17.06	3.02
Weld subgrain body	58.85	16.17	16.32	2.73
Weld interface-subgrain boundary	52.68	15.35	18.18	3.59
Weld interface-subgrain body	54.24	16.13	19.29	4.24

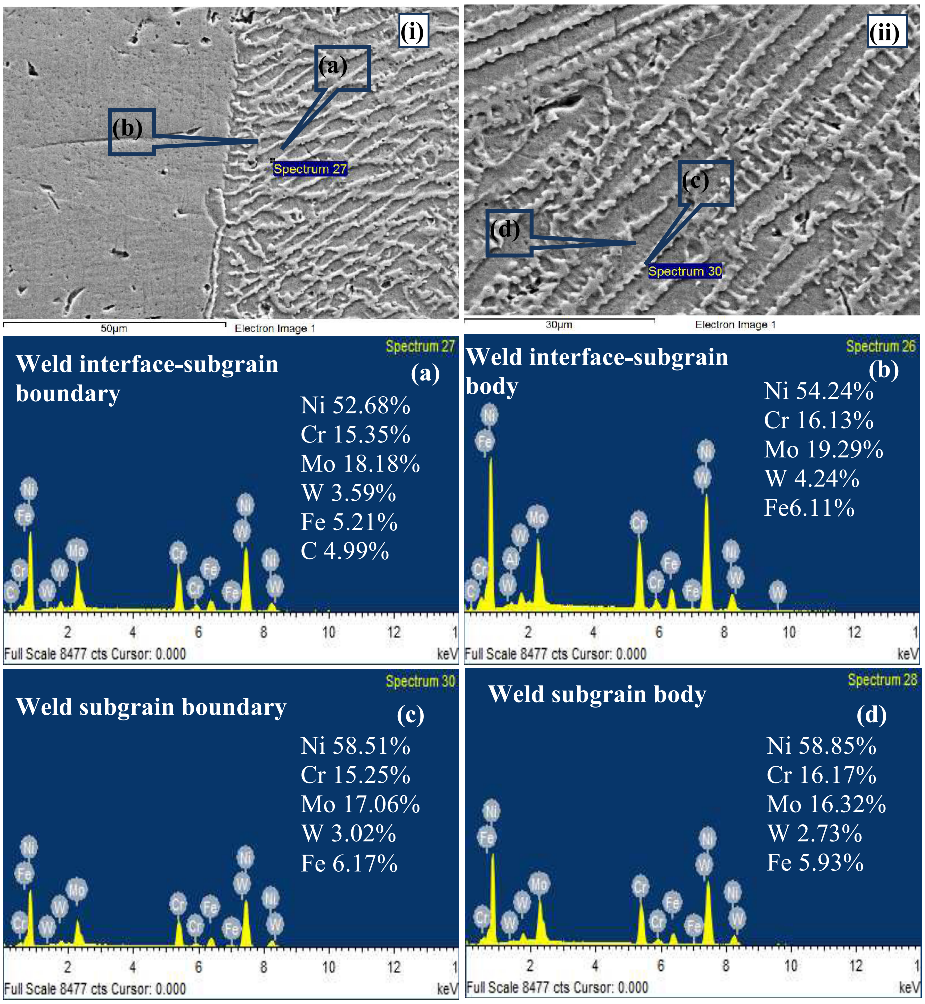

Fig. 5.SEM/EDAX analysis of continuous Nd :YAG Laser welded alloy C-276 for different region of the weldment.(i)SEM- Weld Interface; (ii) SEM- Weld Centre; (a) Weld interface-subgrain boundary; (b) Weld interface-subgrain body; (c) Weld subgrain boundary; (d) Weld subgrain body.

Table 4.Chemical composition of base metal and grain boundary regions in weld fusion zone.

	Composition (wt %)				
	Ni	Cr	Mo	W	Fe
Base metal composition[this research]	57.63	15.83	16.36	3.35	6.06
Base metal composition[Guangyi et al (2011)]	58.75	16.0	15.7	3.3	5.6
subgrain boundary in pulsed laser Welding as fraction of base metal composition[Guangyi et al (2011)]	0.91	1.00	1.14	1.62	0.98
subgrain boundary in fusion zoneas fraction of base metal compositon in continuous Nd:YAG laser [this research]	1.01	0.96	1.04	0.88	1.01

It emerges that the extent of segregation witnessed in the grain boundary regions in the present study is less severe than that reported byGuangyi et al (2011). Table 5 shows the distribution coefficient (k, where k = C_{body}/ C_o; C_o= elemental level as per nominal alloy composition and$C_{body}$is the elemental level in the body of subgrains in fusion zone) values of arc welding, pulsed laser welding and continuous Nd: YAG laser welding. It is again seen that the extent of segregation seen in present study is less severe than that reported by Guangyi et al (2011). It is thus interesting to note that laser welding even without pulsing can lead to weld joints with microsegregation occurring well within acceptable limits. The macrosegregation during welding also an important issue as bought out byKou (2002). The EDS analysis shown in Table 3 suggest that macrosegregation of Mo and W is occurring in the weld fusion zone, area near the interface containing higher level of these elements compare to area away from the interface. This aspect needs to be investigated further.

Table 5.k Values of Different alloying elements in Hastelloy C-276

Elements	Cr	Mo	W	Fe
In arc welding DuPont et al (2009)	0.95	0.82	1.01	1.01
In pulser laser welding Guangyi et al (2011)	0.92	0.90	1.39	1.04
In continuous Nd : YAG laser welding	1.02	1.00	0.80	1.00

3.4. Micro hardness test.

The average hardness values of as-received alloy C-276 is 212 HV. Hardness measurement has also been carried out acrossthe entire width of the weldments and the results are shown in Fig. 6. It is observed that the average hardness at the weld zone is 261HV; peak hardness value in the weld zone was as high as 270 HV. The hardness at the weld interface was 234 HV.A hardness minimum (196 HV) was observed next to the weld interface in the direction of base metal.

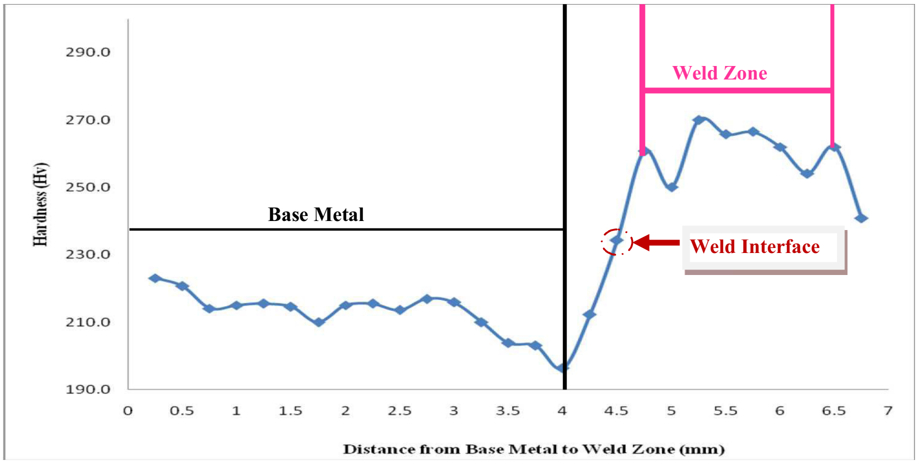

Fig. 6.Hardness Profile of alloy C-276.

The average micro-hardness value at the weld zone works out to be 33% greater than that of the base metal. The higher hardness values at the weld zone believed to be mainly due to the refined microstructure in the weldment. As can be seen in Fig. 4(b) microstructure in the weld zone is predominantly fine cellular. The origin for the hardness minimum observed next to weld interface is not known. That was to grain coarsening in this region and in fact no HAZ could be delineated next to weld interface.

3.5. Tensile studies.

Tensile properties of base metal and weld joints fabricated by continuous Nd: YAG laser weld are given in Table 6. Fracture always occurred in the fusion zone (Fig. 7). The average tensile strength was 761MPa with 40% average elongation. The obtained results indicate a small increase in the ultimate tensile strength of the weld joint as compared with that of base metal. That the failure occurred in the weld zone is to be explained based on the elemental segregation in the fusion zone as brought out by the EDS results (Fig. 5) and Table 3.

Table 6. Tensile properties of weld joints produced in Alloy C-276 using continuous Nd : YAG laser

Trial No	Tensile Properties			
	UTS (MPa)	Average UTS (MPa)	% Elongation	Average % Elongation
Base Metal	750		75	
1	764	761	40	40
2	758		40	

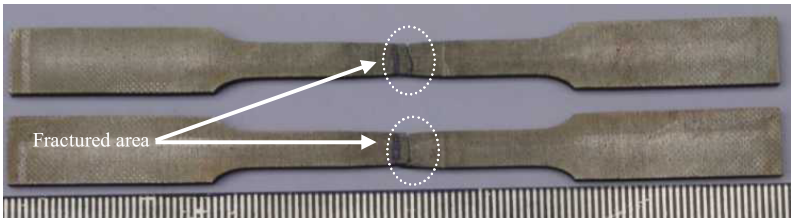

Fig. 7. Photograph of tensile failure specimen.

4. Conclusion

- Defect free weld jointswith good penetration were obtained at 2 KW laser power with 550 mm/min welding speed.
- There isno significant heat affected zone due to narrow heat input in the laser welding process used.
- Microsegregationin the weldment was within acceptable limits; this is believed to be due to rapid solidification associated with laser welding technique.
- Hardness is higher in the weld zone compared to the base metal region due to the refined grain structure in the former. The refined microstructure is also responsible for the high tensile strength with good ductility obtained on the weld joint.
- There is evidence for macrosegregation occurring during welding; this aspect has to be investigated further.

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