Influence of laser power and welding speed on dendrite structure growth of low power pulsed laser welded super alloy

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Abstract. The influence of different welding parameters like welding speed and laser power on microstructure and the mechanical properties of low power pulsed Nd: Yag laser welded Nickel based super alloy inconel 617 sheets of thickness 1.5 mm has been investigated. In the present study, the welding of the specimens was done in a single pass aimed to full depth penetration. The microstructure of the various samples at fusion zone and at heat affected zone was characterized by field effect scanning electron microscope (FESEM) while the weld size of the welded metal at different parameters were measured using optical microscope (OM). The microhardness in the various zones for the welded sample has also been investigated. The microhardness of the welded samples was compared with base metal after experimental observations. The XRD technique was used to analyze the crystallography of the material at (2θ degree). The material has been used for the present study because of its exceptional properties of heat resistant and corrosion resistant. The Nd: YAG pulsed laser has been used because of its overlapping factor during welding that reduces porosity in the weld zone.

Keywords: Nd: YAG laser welding, Inconel 617, microstructure, FESEM, Optical microscope, microhardness, XRD.

1. Introduction

The material used for this experimental study is a Nickel based super alloy termed as Inconel 617 having the composition of group VIII elements in the periodic table i.e. Nickel (Ni), Cobalt (Co), Iron (Fe) with Nickel having maximum share of percentage to which other alloying elements are added(Ahmed et al., 2015). It is one of the best materials which has excellent strength, stability, creep-rupture strength and oxidation resistance at very high temperatures above 750°C that makes it the most appropriate next generation material for high temperature power plants (Park et al., 2011) and (Viswanathan et al., 2013). Hot corrosion behaviour of Inconel 617 superalloy at temperature 700°C, 800°C and 900°C for different exposure times to up to 100 hr has been studied (El-Awadi et al., 2016). Due to high oxidation resistance and corrosion resistance properties Inconel 617 has very wide range of applications in electric-resistance heater, gas turbines, petrochemical industries, aerospace industries and also as pressurized water reactors (PWR) in nuclear reactors (Yeh et al., 2014) and (Tung and Stubbins, 2012). The chemical composition of Inconel 617 is presented in table 1

| Elements | Ni  | Cr  | Mo  | Fe  | Co  | Ti  | Si  | Al  | C   | O   | Cl  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Weight%  | 50.79| 21.13| 9.76| 1.07| 10.97| 0.45| 0.27| 1.05| 3.04| 1.06| 0.42|

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The laser welding technology is one of the most important metals joining techniques because of its high peak power, precise welds with high aspect ratio, least thermal distortion, high welding velocity, design flexibility, low heat input and very high energy efficient process (Zhou and Tsai, 2008) and (Kazemi and Goldak, 2009). This technique is widely used in automotive, electric and electronics industries (Tzeng, 2000). The key feature of the laser welding technique is the ability to weld any material without using filler materials (Pang et al., 2008). The Nd: YAG pulsed laser welding has been chosen for the present work. This method allows more precise heat control as compared to other joining process. Nd: YAG laser welding of the material also reduces the region of heat affected zone (HAZ), residual stresses and discontinuities because of its overlapping factor(X.-L. Gao et al., 2014). Nd: YAG pulsed laser welding is featured by its periodic heating of the weld pool and its overlapping factor. Because of its high peak power density melting and solidification in the weld pool occur consecutively but solidification time is shorter as compared to other laser and conventional welding processes(Ventrella et al., 2011). There are a very few research works available on Inconel 617 material and especially with Nd: YAG laser welding process. The research work on Nd: YAG laser of other materials are available but very few research works are available for Inconel 617 material. The effect of overlapping factor on porosity, microstructure and mechanical properties of pulsed Nd: YAG laser welded Ti₆Al₄V sheet has been investigated(X. L. Gao et al., 2014). The fatigue damage evolution on pulsed Nd: YAG laser welded Ti₆Al₄V sheet has been analyzed(Liu et al., 2014). In the present study, a nickel based superalloy Inconel 617 has been welded using pulsed Nd: YAG laser system. The microstructure, microhardness and the other mechanical properties like tensile strength has been investigated experimentally for the single pass full depth penetration welding. The microstructure has been analyzed using field effect scanning electron microscope (FESEM) and optical microscope. The microhardness value has been taken using Vickers microhardness tester. Each and every observation has been analyzed in the weld zone and compared these values with the values obtained in the heat affected zone (HAZ) and base metal zone.

2. Experimental setup and procedure

A pulsed wave Nd: Yag laser welding was used to weld the Nickel based super alloy Inconel 617 sheets as specified in Table 2. The shielding gas used during the welding process was nitrogen gas. The schematic representation of Nd:Yag laser welding setup was presented in Fig.1.

Table 2 Nd:Yag setup specifications

| Laser setup | Wavelength (in µm) | Max. Avg. Power (in Watt) | Max. Pulse energy (in Joule) | Pulse duration (in ms) | Max. Frequency (in Hz) | Focus Diameter (in mm) | Peak pulse Power (in KW) |
|-------------|--------------------|---------------------------|-----------------------------|------------------------|------------------------|------------------------|--------------------------|
| Nd: Yag laser | 1.06 | 600 | 100 | 0.5-20 | 1000 | 0.3-2.2 | 10 |

Fig.1 Setup of Nd: Yag laser welding
In the present study, a Nickel based super alloy Inconel 617 of thickness 1.5 mm thin sheet has been used as the work material. For better welding quality, two of the major welding parameter welding speed and laser were varied and rest of the parameters were kept constant.

**Table 3** Fixed parameters for present study

| Type of weld joint     | Butt joint |
|------------------------|------------|
| Laser beam dia. in mm  | 0.75       |
| Focal position in mm   | At the surface |
| Shielding gas pressure in litre/min. | 5 |
| Stand-off distance in mm | 160     |
| Pulse width in ms      | 2.1        |

Table 3 shows the parameters and their values remains fixed during the study while Table 4 shows the observed values recorded during the experiment for the combination weld parameters.

**Table 4** Combination weld parameters

| Sample | Power in watt | Speed in mm/s |
|--------|---------------|---------------|
| K1     | 320           | 2.5           |
| K2     | 340           | 2.5           |
| K3     | 380           | 2.5           |
| K4     | 380           | 3             |
| K5     | 400           | 3             |

**Table 5** parameters applied for preparing mould

| Parameters                  | Values       |
|-----------------------------|--------------|
| Temperature                 | 160 °C       |
| Pressure                    | 100 Kg/cm²   |
| Time of heating             | 6 min.       |
| Time of cooling             | 3 min.       |

**Fig.2** prepared mould specimen
The specimens were then prepared by grinding with different grits such as 400, 600, 800, 1000, 1200 and 1500 of SiC paper. Every sample were polished at 400, 600 and 800 grit sizes in the clockwise direction and for remaining grit size papers in the reverse direction. The grinding time for each sample for either rotating direction was 8 minutes. Etching was done for the polished surfaces for each sample at room temperature to see the images at various magnifications with the help of optical microscope and FESEM. The time of etching for each sample was 2 minutes for OM and 4 minutes for FESEM observations. The different reagents were used for getting images on OM and FESEM, glycergia reagent (a mixture of 10 ml glycerol, 10 ml hydrochloric acid and 5 ml nitric acid) was used for OM and a solution which was combination of hydrofluoric acid (HF), nitric acid (HNO₃) and distilled water was used for FESEM. Microhardness was measured at the interval of 200 µm distance which includes all the three zones in the sample i.e. base metal zone, HAZ and welding zone. The load applied on the sample was 0.1 Kgf and dwell time of 10s during the hardness testing.

3. Results and discussions

3.1. Microstructure and XRD analysis

The various region of a welded sample was shown in Fig.5 and the different regions i.e. base metal zone (BMZ), HAZ and FZ were indicated in the figure. The image shown was taken through optical microscope.

![Fig.5. Represents all three zones of welded sample](image)

The microstructure of the samples were analysed through FESEM as shown in Fig.6a, 6b and 6c that shows the microstructures of the specimens at various region i.e. base metal region, HAZ and FZ. The coarser grain size in the base metal region in which crystal orientation was not specified was observed while in the HAZ and FZ a fine equi-axed grain structure was observed due to fully dynamic recrystallization of material at elevated temperature. The change in microstructure was observed in the HAZ region due to recrystallization of the materials while it meets its austenitic temperature. The grain structure in the HAZ and FZ region of the samples were seems like branch of tree, known to be dendrite structure in terms of metallurgy(Kumar et al., 2017). These structures were growing significantly as molten metal freezes. The dendrite structure of the superalloy Inconel 617 was also
observed by some other researchers (Ren et al., 2015). The surface energy present in the liquid solid interface is the main reason for the growth direction. The dendrite growth at HAZ was observed due to re-solidification process of the crystals when molecules were start to contract and tries to minimise its area of surfaces having maximum surface energy. The size of the grain largely related to the nucleation and the crystals growth in case of equi-axed grain structure. The dendritic growth of the crystals was shown in fig at HAZ while a fully developed dendrite structure was observed at FZ. Fine M$_{23}$C$_6$ carbides, Ti(C, N) carbide and nitride also exist at FZ and crack at FZ was also observed in Fig.6d.

![Fig.6a Base metal](image1)

![Fig.6b HAZ region](image2)

![Fig. 6c FZ region](image3)

![Fig.6d shows M23C6, Ti(C, N) and crack at FZ](image4)

The chemical composition of the material at base metal region and FZ region was shown in Fig.4a and 4b. A very little change was observed in the composition of sample at welded region in comparison with base metal. The composition of the sample was observed through EDAX analysis. The presence of nitrogen was observed as nitrogen gas was used as shielding gas which is very stable at room temperature but become unstable at elevated temperature. The increase in percentage of carbon element in the welded region shows the tendency of formation of carbide at elevated temperature of this superalloy.
The XRD analysis was carried out to analyse the crystallographic structure of the samples at various positions (2θº) as shown in fig. The analysis was done using X’pert Highscore plus software. The compounds like carbides, oxides and nitrides formed by the major elements such as Ni, Cr, Co, Mo etc. of the alloy were identified at the peak positions.

For both the regions, the positions ranged from 20º to 80º and the compounds formed by the major elements were identified at the peaks as shown in Fig.5a and 5b. For the BM region, oxides of the major elements were identified as some oxygen was present in the base metal but nitrides and carbides compounds were negligible as the carbon element was stable at room temperature. For welded region, nitrides of the major elements were identified and also there was some carbide compounds formation took place. As the nitrogen gas was used as shielding gas, the nitrogen molecules become unstable at elevated temperature that cause the bond dissociation of the nitrogen molecules which lead to the formation of nitride compounds such as chromium nitride (CrN), Molybdenum nitride (MoN). The formation of carbide compounds like cobalt carbide (CoC) of
major elements was also observed in the weld zone. The domination of nitride and carbide compounds in the fusion zone shows anisotropic behaviour of the material in this zone as face centre cubic (fcc) structure of the crystals were observed along various directions.

3.2. Weld width

The images shown in fig. were taken through optical microscope and size of the weld width from bottom to top of the weldment was measured using software. The images shown of the welded samples clearly indicate the full depth penetration welding of the samples. The larger weld width on the top of the weldment as compare to bottom part of the weldment indicates the effect of heat input or laser power on the size of weld width.

The graph shown in fig.10 indicates the effect of laser power on the size of weld width which explains that the size of weld width increases as laser power increases. In case of welding, welding speed also plays a vital role, as the welding speed increases the size of weld width decreases therefore, various combination of power and speed was used and analyzed to get lower size of weld width and HAZ along with high quality of weldment. The value of the weld width for the 400W laser power was found to be highest in the top side of the weldment and lowest in the root side.
Fig. 10. Represents bar chart between laser power and weld width

3.3. Microhardness

The graph shown in Fig. 11a and 11b represent the microhardness distribution of two different samples welded at the same laser power but at different welding speed for various zones. In both the cases the maximum value of microhardness was observed in the FZ region while the least value was observed at BMZ region. The high value of microhardness in the weld zone was due to the presence of temperature gradient at FZ and HAZ which caused rapid cooling rate. At lower welding speed, due to preheating process of metal the temperature gradient was found to be low as compare to high welding speed. Therefore, high hardness value was observed in the FZ and HAZ region in case of high welding speed with same laser power. The high value of microhardness in the FZ region indicates increase in brittleness of the material when compare to original material. The rapid cooling rate during welding process was main cause of formation of hard and brittle structure at the weld zone which is also supported by the results of some other researchers (Casalino et al., 2015). At 380W laser power and 2.5mm/s welding speed the maximum value of microhardness at FZ was found to be 296.54HV while the maximum value for 324.26HV.

Fig. 11a Microhardness of sample K3
Fig. 11b Microhardness of sample K4

4. Conclusions

The present work was mainly focused on the study of influence of laser power and welding speed on the microstructure, weld width and mechanical properties such as tensile strength and microhardness of the low power Nd:Yag laser welded Inconel 617 thin sheet of thickness 1.5mm. From the above results, we conclude that the weld quality was very good as the tensile strength of the welded specimen were greater than 95% of the tensile specimen of base metal. To ensure even greater weld quality to get the tensile strength of welded specimen upto or greater than 100%, the inert gas (like
Argon, CO₂, etc. can be used as shielding gas for further research work so that the gas could not be entrapped within the specimen during welding and will not have any alter effect. The entrapped nitrogen was seen during EDAX analysis and also observed due to formation of nitride compound in the XRD analysis. The microstructure was identified as dendrite structure and the coarser grain structure of base metal and the fine grain structure in the weld zone of the sample was identified from the fractograph of the tensile specimen. The weld size was directly affected with heat input and the welding speed as the heat input increases the size of weld width also increases but low weld width was observed at high welding speed. The microhardness analysis confirmed the formation of hard and brittle fusion zone.

References
[1] Ahmed, G.M.S., Mohiuddin, M.V., Sultana, S., Dora, H.K., Singh, V.D., 2015. Microstructure Analysis and Evaluation of Mechanical Properties of Nickel Based Super Alloy CCA617. Mater. Today Proc. 2, 1260–1269.
[2] Casalino, G., Mortello, M., Campanelli, S.L., 2015. Ytterbium fiber laser welding of Ti6Al4V alloy. J. Manuf. Process. 20, 250–256.
[3] El-Awadi, G.A., Abdel-Samad, S., Elshazly, E.S., 2016. Hot corrosion behavior of Ni based Inconel 617 and Inconel 738 superalloys. Appl. Surf. Sci. 378, 224–230.
[4] Gao, X.-L., Liu, J., Zhang, L.-J., Zhang, J.-X., 2014. Effect of the overlapping factor on the microstructure and mechanical properties of pulsed Nd:YAG laser welded Ti6Al4V sheets. Mater. Charact. 93, 136–149.
[5] Gao, X.-L., Zhang, L.J., Liu, J., Zhang, J.X., 2014. Porosity and microstructure in pulsed Nd:YAG laser welded Ti6Al4V sheet. J. Mater. Process. Technol. 214, 1316–1325.
[6] Kazemi, K., Goldak, J.A., 2009. Numerical simulation of laser full penetration welding. Comput. Mater. Sci. 44, 841–849.
[7] Kumar, P., Saw, K., Kumar, U., Kumar, R., Chattopadhyaya, S., Hloch, S., 2017. Effect of laser power and welding speed on microstructure and mechanical properties of fibre laser-welded Inconel 617 thin sheet. J. Brazilian Soc. Mech. Sci. Eng. 17, 734-738
[8] Liu, J., Gao, X.-L., Zhang, L.-J., Zhang, J.-X., 2014. A study of fatigue damage evolution on pulsed Nd:YAG Ti6Al4V laser welded joints. Eng. Fract. Mech. 117, 84–93.
[9] Pang, M., Yu, G., Wang, H.H., Zheng, C.Y., 2008. Microstructure study of laser welding cast nickel-based superalloy K418. J. Mater. Process. Technol. 207, 271–275.
[10] Park, Y.S., Ham, H.S., Cho, S.M., Bae, D.H., 2011. An assessment of the mechanical characteristics and optimum welding condition of Ni-based super alloy. Procedia Eng. 10, 2645–2650.
[11] Ren, W., Lu, F., Yang, R., Liu, X., Li, Z., Elmi Hosseini, S.R., 2015. A comparative study on fiber laser and CO₂ laser welding of Inconel 617. Mater. Des. 76, 207–214.
[12] Tung, H.M., Stubbins, J.F., 2012. Incipient oxidation kinetics of alloy 617 and residual stress of the oxide scale formed in air at temperatures between 850 and 1000°C. J. Nucl. Mater. 424, 23–28.
[13] Tseng, Y.-F., 2000. Process Characterisation of Pulsed Nd:YAG Laser Seam Welding. Int. J. Adv. Manuf. Technol. 16, 10–18.
[14] Ventrella, V.A., Berretta, J.R., De Rossi, W., 2011. Micro welding of Ni-based alloy Monel 400 Thin foil by pulsed Nd:YAG laser. Phys. Procedia 12, 350–357.
[15] Viswanathan, R., Henry, J.F., Tanzosh, J., Stanko, G., Shingledecker, J., Vitalis, B., Purger, R., 2013. U.S. Program on materials technology for ultra-supercritical coal power plants. J. Mater. Eng. Perform. 22, 2904–2915.
[16] Yeh, T.K., Chang, H.P., Wang, M.Y., Yuan, T., Kai, J.J., 2014. Corrosion of Alloy 617 in high-temperature gas environments. Nucl. Eng. Des. 271, 257–261.
[17] Zhou, J., Tsai, H.L., 2008. Modeling of transport phenomena in hybrid laser-MIG keyhole welding. Int. J. Heat Mass Transf. 51, 4353–4366.