An investigation on laser induced downward expanded vapour region in laser weld butt joint of AISI 316L stainless steel

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Abstract. The physics of laser - AISI 316 stainless steel interactions discussed stage-by-stage including the formation of plasma plume around the keyhole during the laser welding. This work reveals that the pulsed laser heat input is a highly successful tool to join 2 mm thick 316L stainless steel welding by a single pass, that too autogenously! However, inadequacy in laser input power leads to the incomplete penetration at weld joint and poor bead formation and whereas excess heat input causes root concavity (loss of material) at the bottom. It has observed a vapour region near bottom of the keyhole while the joint fully penetrated and it slightly expanded due to excess heat input, known as downward expanded vapour region. Consequently, downward expanded vapour region results in excess melting; it leads to loss of material by spatter during welding that causes root concavity at the bottom, which will affect the joint integrity. Therefore, it is important to identify and control the expansion of vapour region by optimizing the input power of the laser. To ensure optimization of the operating parameters and the integrity of weld joints are qualified through Vickers micro hardness test and X-ray radiography test.

1. Introduction

Laser assisted material processing offers online monitoring and control of operating parameters is becoming a driver for the manufacturing industries development and sustainability [1]. Therefore, laser assisted welding became an important joining technique than the other welding techniques. Hence, laser welding will be right choice to join almost all kind of stainless steels that can promote their wide range of applications in many industries [2], because of, their excellent properties to high temperature resistance, or good corrosion resistance properties. AISI 316L stainless steels which is an extra-low carbon version of AISI 316 stainless steel, used extensively for welding where its immunity to carbide precipitation due to welding that assures optimum corrosion resistance [3]. Laser welding is an efficient process to join AISI 316L stainless steel that achieves deep penetration by forming keyhole that provides better joint strength with very small heat affected zones at rather high travel speeds. Hence, it is necessary to have a clear understanding of all the physical processes involved in keyhole welding to construct accurately placed, strong, and repeatable welds.
This article is to discuss about the formation of a keyhole in an autogenous butt joint of AISI stainless steel in the order of four states viz, solid, liquid, vapour, and plasma. The effect of increase in laser input power on AISI 316L stainless steel joints are experimented in order to optimize laser parameters for full penetration welding and discussed. The downward expanded vapour region identified on the bottom side of the welding joints and investigated.

2. Experimental Techniques

Sample materials considered is AISI 316L stainless steel plates having dimensions of 150 mm (length) x 50 mm (width) x 2 mm (thickness). A 500 Watts PC controlled Nd: YAG laser, wavelength of 1.064 μm, has delivered through 600-μm diameter silica core step index type optical fibre cable. The vertically focused beam on the surface operated with TEM$_{00}$ Gaussian distribution mode and the spot diameter is 451μm at the focal length 200 mm. Nd: YAG laser source attached with highly précised CNC workbench for accurate alignments. Welding velocity fixed as 3 mm/sec on CNC machine. High purity of Argon (Ar) used as shielding gas, supplied at the flow rate 20 l/min at the upper and lower faces of the plates at an angle 45º and the nozzle placed behind the laser beam at the ambient temperature 24ºC. The prepared weld sample and its operating parameters are given in figure 1 and table 1.

![Photographic view of AISI 316L stainless steel butt joint welding and bead profile](image)

Table 1: Operating parameters for pulsed laser welding

| Descriptions           | Values     |
|------------------------|------------|
| Average Peak Power     | 2050-2150 W|
| Spot Size              | 451 μm     |
| Pulse duration         | 12 mS      |
| Frequency              | 15 Hz      |
| Welding Velocity       | 3 mm/sec   |
| Interaction Time       | 48 mS      |
| Duty Cycle   | 18%       |
|--------------|-----------|
| Pulse shape  | Recatngular pulse |
| pulse energy | 25.8 J    |
| Pulse over lapping % | 58%         |

The weld joints sectioned by manual sawing are to fit in to size and shape of mounting tool. The presences of burs in the edges removed using a machine run-emery sheet. Mixture of methyl methacrylate and polyvinyl formaldehyde used as resin and hardener to mount the samples and allowed to cure up to 15-30 min. Prior to electro polishing, each specimen are grinded with 120, 240, 600 and 800 emery grits using polishing machine. 9-μm, 6-μm and 3-μm diamond slurry used to achieve fine polishing. Liquid state Mecaprex diamond compounds LD 33E for 9-μm and LDP for 6-μm are used for fine polishing respectively. Reflex 24270 used as coolant during using machine polishing. Electrolytic etching for AISI 316L Stainless Steel joints etched in a solution containing 20 ml hydrochloric acid, 1.0 g of sodium meta bisulphate and 100 ml distilled water.

Each sample are micro graphed at the range of magnification 100 μm to investigate the evolved weldpool and the keyhole regions at the cross sections of butt joint using analySIS software with PC controlled optical microscope.

3. Results and Discussions

3.1 Physics of laser–material interaction

In laser-material interactions, varieties of physical processes occur that are heating, melting and vaporization. According to plank’s theory of radiation, atoms in a solid are not static; they are continuously vibrating about their mean positions. Laser, as an electromagnetic radiation, has an electric and a magnetic vector fields oscillating with very high frequency. If the frequency of the laser radiation does not correspond to a natural resonance frequency of the particle, then fluorescence or absorption will not occur, but a forced vibration would be initiated at the surface of AISI 316L stainless steel. Hence, an average kinetic energy of these vibrations increases above the ambient temperatures roughly proportional to absolute temperature that results in increases in mean atomic distances, leading to thermal expansion against strength of the atomic bonds. However, these magnitudes of vibrations induced are very small and are incapable of vibrating an atomic nucleus. Therefore, laser irradiation assumed as photons that interacting with electrons that are either free or bound at surface. This processes of absorption photons by electrons and grow into an exited state known as “inverse bremsstrahlung effect” [5]. These excited electrons collide with lattice atoms and with other electrons and spontaneously emit its energy to all directions, since the mean free time of electrons in a conductor is 10^{-13}s. Hence, the energy transferred exited electrons to lattice atoms and transferred among the atoms via phonons that cause the lattices to vibrate beyond the activation energy (270 kJ/kg) of 316L stainless steel and small fraction atoms relocate themselves. Thus, atomic diffusion (heat flux) transmitted through space lattice as a normal diffusion-type process [6]. This cycle repeated according to the
pulse repetition rate (15 Hz) with very high amount of peak power density at 1.28~1.35 MW, then, the phonon vibration increases in space lattice and atomic diffusion increases above melting point (1703 K) of 316L stainless steel [7]. Therefore, the stretched molecular bonding linkages are no longer capable of exhibiting mechanical strength, melting occurs, forms weld pool. The temperature of the heat flux beyond the weld pool decreased below melting point that forms heat affected zone. However, the range of melting and subsequent diffusivity in radial distances are limited to very few millimetres in stainless steels since, they are exhibiting high resistance to heat [8]. At this stage, most of the beam energy transferred in the direction of irradiation rather than conducts radially [9].

3.2 The process of formation of keyhole

On further heating, the temperature of the weld pool increases, the large temperature difference along the free surface of the weld pool due to the TEM\(_{00}\) mode of Gaussian distribution of laser pulses. This laser-induced thermal gradient starts to push down the molten metal under the laser beam and accelerate from a static condition to the surface of the weld pool; leads to a high temperature-dependent melt flow known as Marangoni flow. In accordance with the welding velocity (3mm/sec) and direction, the temperature gradient is very high in front of the laser spot whereas Marangoni flow is positive along the weld pool surface, which drives the molten metal to flow outwards. However, behind the laser spot where temperature gradient is lesser, the Marangoni flow is negative along the weld pool that forces the liquid metal to flow inwards. Under the hydrodynamic force and the Marangoni flow, this squeezed molten metal flows upwards along the keyhole wall, which facilitates the formation of a crater and hence the penetration depth increases, thus, a keyhole formed in the weld pool [10] as shown in figure 2. This squeezed molten metal flows upwards along the weld pool are form a humps for each pulses behind the laser spot known as weld bead as shown in figure 6.

![Micrographs of keyhole on 316L stainless steel](image)

Fig. 2: Micrographs of cross sectional view of keyhole on 316L stainless steel at average peak power (a) 2050W, (b) 2100W and (c) 2150W.

3.3 The process of formation of plasma in keyhole

The keyhole behaves as an optical black body in the sense that radiation entering the hole is subject to multiple reflections before escaping, as a result, the absorptivity is close to 100% [11]. In such highest absorption, temperature increased above boiling point (3090 K) of 316L stainless steel and evaporation takes place by drastic increase in phonon vibration that leads to sudden increase in temperature beyond the vaporization point (5000°C) of 316L stainless steel that
beaks the metallic bonds of molten material. Hence, a significant part of the absorbed energy can be directly lost by evaporating molten material and after such intensity of evaporation, recoil pressure developed. The recoil pressure brings melting point of the material closer to the boiling point by Clapeyron – Clausius principle on latent heat, hence the wall thickness of the keyhole become more thinner, which is easier to stabilise the keyhole, helps to greater penetration depth.

That pushes down the liquid in the weld pool and acts as the main driving force for the keyhole formation and eventually keyhole depth increase takes which leads to even higher absorptivity due to multiple reflections. Hence, the structure of keyhole became a cavity [12], filled with mixture of vapour that surrounded by a molten region as the laser beam moves along the welding direction that forms deep penetration welds as shown in figure 3[13]. The vapour still capable of absorbing the radiation, leads to acquiring sufficient energy to induce ionization in vapour region [14]. In further irradiations, the set of the evaporated atoms with a mixture of ablated electrons and ions (electron-ion-atom) formed over the surface through the process of “inverse bremsstrahlung” phenomenon, called plasma [12] having maximum electron temperatures about 8467 K and 17,931 K[5]. Since the electron density of Argon (shielding gas) plasma is higher than the density of free electron in plasma, hence the recombination rate of electron-ion-atom lowered. So, the plasma state conserved well over the surface of the specimen for a while[15].

3.4 Study of laser induced downward expanded vapour region

Laser-induced plasma plays two-fold roles during keyhole formation that the “inverse bremsstrahlung” effect absorption increases the energy coupling leading to plasma re-radiation and the absorption of reflected laser pulses from inner surfaces, called Fresnel absorption that facilitates the keyhole formation at the initial stage. In plasma, density of free electron increases and hence the current induced magnetic force increases, hence, plasma cloud start to flow that formed a vortex at the upper part of keyhole [16] as shown in figure 5. This vortex exhibit drastic change in melting point by Kerr effect and Pockel’s effect; leads to a strong convectional movements in the melt pool, which has significant influence on heat transfer as discussed earlier about “Marangoni flow” [16, 17]. On further increase in laser power as 2150 W, the interaction of plasma and vapour plume of keyhole generates the side flows of the melt generated beneath the focal spot by the local ‘piston effect’ [18]. The tilting of the keyhole front wall and the corresponding dynamic pressure of the ejected vapour plume control the degree of coupling between the vapour plume and the melt pool [5]. When the downward-flowing vapor on the front
keyhole wall combined with the upward-flowing vapor, the flow field of the vapor became unstable and fluctuated rapidly. The ideal state of equilibrium of the keyhole wall was broken, and the initial wave generated on the rear keyhole wall due to the friction force between the vapour and melt flow and the fluctuating pressure of the vapor flow known as vapour-generated wave (VGW) as shown in Figure 5. From the ideal state of equilibrium, the keyhole wall appears oblique when the VGW occurred. The oblique keyhole wall indicates that the force balances are more complicated. The VGW generated in the middle of the keyhole wall moved to the bottom of the keyhole are observed as shown in micrographs (b) and (c) in figure 3. The VGW generated relative lower pressure existed at beneath of the keyhole where there is no direct laser irradiation, results in a downward-flowing vapour along the front keyhole wall. When the upward-flowing vapour of vortex met the downward-flowing vapour at the keyhole bottom generates a whirlpool and drove the suspended droplets to move in a random directions [19] as shown in the artistic image of real micrographs (b) and (c) in figure 3. Hence, the volume of the vapour region is swells known as laser induced downward expanded vapour region. It has verified with change in diameter of those keyholes obtained against the depth of the weld joints for three different laser powers as shown in table 2 and the results plotted for the comparison as shown in figure 4.

Fig. 4: Identification of downward expanded vapour of keyhole diameters in 316L stainless steel obtained for average peak power (a) 2050W, (b) 2100W and (c) 2150W.

Fig.5: Comparision of generation process of the laser induced vapour region inside the keyhole wall of cross section of 316L stainless steel joint [19]
Table 2: Diameter of different keyholes of 316 L stainless steel obtained for an average peak power such as (a) 2050W, (b) 2100W and (c) 2150W

| Depth of keyhole (mm) | Keyhole diameter From the top (mm) |
|----------------------|-----------------------------------|
|                      | Welding Trial I (2050W) | Welding Trial II (2100W) | Welding Trial III (2150W) |
| 0.00                 | 2.4730                 | 2.5516                 | 2.5665                 |
| 0.20                 | 2.1335                 | 2.3336                 | 2.2494                 |
| 0.40                 | 2.0321                 | 1.7981                 | 1.9913                 |
| 0.60                 | 1.9444                 | 1.4228                 | 1.6256                 |
| 0.80                 | 1.3841                 | 1.1978                 | 1.4062                 |
| 1.00                 | 1.0212                 | 1.1509                 | 1.2310                 |
| 1.20                 | 0.9784                 | 1.1551                 | 1.1344                 |
| 1.40                 | 0.7093                 | 1.1440                 | 1.0226                 |
| 1.60                 | 0.6324                 | 1.1551                 | 1.0516                 |
| 1.80                 | 0.5520                 | 1.1827                 | 1.1150                 |
| 2.00                 | 0.5244                 | 1.2213                 | 1.1606                 |

Figure 4 also reveals the melt pool-HAZ boundaries of 316 L stainless steel joints and hence the swallow structure of the keyhole i.e., wider top and narrower towards bottom. The downward expanded vapour region appeared during keyhole mode welding of 316L stainless steel joints and it keep expanding when the excess heat supplied than it actually required power to achieve full penetration. However, it is interesting to point out that no signs of either vapour region or downward expanding vapour region identified from micrographs of nearly full-penetrated 316L stainless steel joint obtained for 2050W as shown in figure 3(a).

Generally, shielding gases used to protect the beam transmission by minimizing beam expansion and scattering. In the present work, high purity Argon (Ar) used as shielding gas and gas flow rate maintained at 20 l/min that is well enough to grant a suitable cost effective welding environment for stainless steels [20]. Since, Ar is a dense shielding gas flowing at the rate of 20 l/min exerts considerable amount of mechanical pressure [20] mounted on plasma that enable deep penetration and it’s lesser absorption coefficient helps to protect plasma, gives best efficiency between the laser beam and specimen at the given laser power[22].

Figure 6 shows the bead morphology obtained from top and bottom of the weld joints for the different input power of the laser. Though it has reached full penetration for 2050 W, sound weld bead observed at the top and poor weld bead formed due to the insufficient melting at the bottom.
Table 1. Weld bead morphology of 316L stainless steel joints obtained from top and bottom for different average peak power (a) 2050W, (b) 2100W and (c) 2150W.

| Welding trials | Top bead | Bottom bead |
|----------------|----------|-------------|
| I (2050W)      | ![Top bead image] | ![Bottom bead image] |
| Comment Trial I: Sound weld bead found on top surface, but, incomplete penetration at the bottom |
| II (2100W)     | ![Top bead image] | ![Bottom bead image] |
| Comment Trial II: Sound weld bead found on top and bottom surface, full penetration achieved |
| III (2150W)    | ![Top bead image] | ![Bottom bead image] |
| Comment Trial III: Sound weld bead found on top surface, but, spatters found at the bottom bead |

Fig.6. Weld bead morphology of 316L stainless steel joints obtained from top and bottom for different average peak power (a) 2050W, (b) 2100W and (c) 2150W.

Whereas in 2100 W, acceptable weld bead has observed at both top and bottom. At the same time in 2150 W, acceptable weld bead has observed at both top and bottom but significant spatter has observed due to the downward expanded vapour region. This leads to loss of material by spatter during welding that causes a shallow groove that may occur in the root of a butt weld known as root concavity. Root concavity caused by shrinkage of the larger weld pool due to excess input power in the through-thickness direction of the weld. In effect, the standards require that the minimum design throat thickness of the finished weldment. Therefore, it is important to identify and control the formation of downward expanded vapour region by optimizing the operating parameters, mainly by input power and welding speed.
3.5 Qualification of weld joints

3.5.1 Vickers micro hardness test

Micro hardness measured using a Vickers micro hardness tester with diamond indenter across top surface of the welded 316L stainless steel joint shown in Fig.7. In the narrow fusion line, there is an increase in hardness compared to the HAZ due to its finer microstructure around the keyhole region. It has seen that the base metal hardness is lower compared to the hardness of both HAZ and fusion zone. The hardness value decreases towards HAZ and parent metal due to the decrease in cooling rate as a function of distance from the centreline weld. The distribution of micro hardness of 316L stainless steel joint reveals the integrity of weld by exchanging molten materials from both end of the parent materials by convective flow across the fusion zone. Thus, an efficient weld joints made with different combination of 316L stainless steel plates using pulsed Nd: YAG laser source.

![Micro hardness across 316L stainless steel joint welded at 2150 Watts](image)

Fig.7: Micro hardness across 316L stainless steel joint welded at 2150 Watts

3.5.2 X-Ray radiography test

YXLON 225 equipment having 0.8x 0.8 mm focal spot size operated at the power supply 100 kV and 10 mA that is adequate for X–ray to test steel and its alloys up to 1 inch. X-rays exposed for 2 min. at source to film distance (SFD) 800 mm. ASTM 5 hole type and ASTM 1A 06 wire type penetrometer used as image quality indicators (IQI). The test results permanently recorded in AGFA D4 type 380x100 mm size photographic films by single wall single image technique. Radiograph of 316L stainless steel weld made by pulsed Nd: YAG laser welding as shown in Fig.8.
Fig. 8: Radiograph of 316L stainless steel joint made by pulsed Nd: YAG laser welding at 2150 Watts

Figs. 8 shows the radiographic test results of 316L stainless steel (SMW01), possibility of 0.5 mm dia porosity reported for the entire segment of A-B and weld spatters observed on the top surface. The slight root concavity throughout the length of the segment A-B has reported for 316L stainless steel that can be eliminate by providing suitable shroud gas or backup material at the bottom of the weld joint. Otherwise, root concavity can be eliminating by optimizing/reducing input power of the laser pulse. There is no such problem arises in 316 stainless steel weld joint made with 2100 watts laser pulse as heat input power. However, no other defects reported from the joint, hence, this results categorized as No Significant Defect (NSD) welds. Similarly, no signs of thermal induced stress reported from both the weld joints (Report no: QAD/R258/RT058/13/246/14).

4. Conclusion

AISI 316L Stainless Steel plates are butt-weld autogenously using pulsed Nd: YAG laser and hence, the systematic of formation of melt, vapour and plasma plume in the keyhole during welding are discussed. Hence, the deductions made as follows,

1. Pulsed Nd: YAG laser is a highly successful tool to join 2 mm thick 316L stainless steel welding by a single pass that too in an autogenous way!
2. Inadequacy in laser input power leads to the incomplete penetration at weld joint or poor bead formation results at the bottom.
3. It has observed that the cone shaped vapour and melt regions near the bottom of the keyhole looking slightly expanded due to a downward expanding vapour region in the case of full penetration with excess power.
4. At the same time, downward expanded vapour region at the bottom leads to loss of material by spatter that causes the root concavity along weld joint. Therefore, it is important to identify and control the expansion of vapour region by optimizing the input power of the laser.
5. Vickers micro hardness test and X-ray radiography test were carryout in order to ensure optimization of welding parameters and hence, the integrity of weld joints qualified.

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