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Optimization of Operating Parameters for Autogenous Welding of AISI 316L Stainless Steel and Steel Using Pulsed Nd: YAG Laser

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Abstract: *An attempt made to optimize the operating parameters involved in an autogenous pulsed Nd: YAG laser welding process of similar and dissimilar combinations of butt joint of 2 mm thick 316 L stainless steel and mild steel. Influence of prominent laser welding parameters such as average peak power, defocus position, spot position, and shielding gas were investigated for welded joints considered. Thus, parameters are optimized for different combinations of welding joints such as similar 316L stainless steel, similar mild steel and dissimilar 316L stainless steel-mild steel made successfully.*

Keywords: *Pulsed laser, AISI 316 L stainless steel, mild steel, peak power, defocus position, spot position, and shielding gas.*

I. Introduction

Recently, the manufacturers prefer laser beam welding that offering many advantages than the conventional welding methods. One of the many features of laser welding is the capability to weld stainless steel without filler material (autogenous welding) with various joints types under normal or submerged circumstances (1). The components made in stainless steel alloys having thickness in the ranges from 2 to 10 mm (2) finds variety of applications where requiring corrosion resistance even at elevated temperature (3). Owing to its importance, we chose different combinations 2 mm thick AISI 316L stainless steel and steel plates to weld using pulsed Nd: YAG laser.

A pulsed Nd: YAG laser welding is a multi-input process hence there are more parameters to control to obtain a good welded joint. Operating parameters categorised as absolute factors and relative factors together influencing the laser welding as shown in figure 1. These parameters of laser welding process have been optimized through various techniques for different welding processes using statistical and numerical approaches (4). Those techniques help us to optimise the welding parameters and as well as to investigate the various behaviours of materials. For instance, the reduction of hot cracking of some "special" alloys such as Al-Mg-Si alloys using added material rate (5), changing the microstructure and mechanical property at the joint position of Ni Ti Alloys (6), increases the penetration depth, bead length and bead width of the welded steel (7), bead depth, stability, penetration depth and keyhole formation of AISI 304 stainless steel (8), penetration depth, weld zone width and heat affected zone width (weld bead geometry) of medium carbon steel (9), stabilization of the weld bead of ultra-fine grained steel (10), no formation of cracks, improved mechanical strength and the electrical conductivity of copper-stainless steel dissimilar connections (11), effects of shielding gas on AISI 904L stainless steel (12), AISI 409 stainless steels with rapid speed and relatively low thermal distortion (13), fabrication of the hydraulic valves of AISI 304L to AISI 12L13 stainless steels butt weld with control solidification cracking and micro fissuring (14), AISI 304 stainless steel and low carbon steel butt welded by wire feed for various distance between the joint gap to extend for many demanding industrial applications (15). As an outcome of this literature, it is logical that welding parameters are depends on material type and their thickness and also the welding method and type of welding joint for some extend. Hence, there are no standard or fixed parameters readily available for any combination of materials at any specified thickness to perform laser welding.

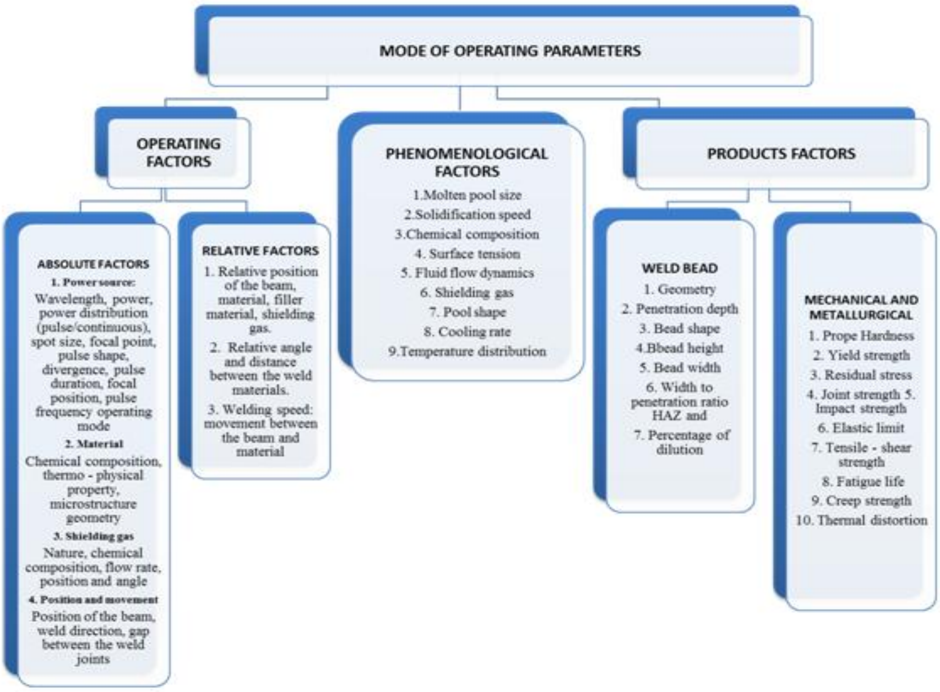

Fig. 1: The operating parameters that influencing any kind of laser welding processes

This paper is to discuss about the development and optimization of the prominent operating parameters to obtain the full penetration of 2 mm thick 316 L stainless steel and steel plates in different combination using pulsed Nd: YAG laser. The influence of parameters such as average peak power, defocus position, spot position, and shielding gas were investigated for weld joints considered.

II. Experimental Techniques

AISI 316L stainless steel and steel plates having dimensions of 150 mm (length) x 50 mm (width) x 2 mm (thickness) are considered for butt joint welding. A systematic Nd: YAG laser beam with wavelength of 1.064µm has delivered through 600µm diameter silica core step index type optical fiber cable. The vertical laser beam focused at the focal distance of 200 mm that having the waist diameter 451 µm and target on the surface. The laser pulses are assumes as Hermit–Gaussian pulse, a volumetric heat source that are spatially distributed in Transverse Electro Magnetic (TEM00) mode with pulse duration of 12 mS. The Nd: YAG laser beam source attached with highly précised CNC machine for accurate alignment at welding velocity fixed as 180 mm/sec. High purity of Argon (Ar) used as shielding gas, supplied at the flow rate 20 l/min at the upper face of the plate at an angle 45º and the nozzle placed behind the laser beam and the operating parameters are given in table 1. The polished samples subjected to electrolytic etching in 10% oxalic acid for stainless steel and Nital for steel to expose the features of the weld joint. The ambient temperature was 293K.

Table 1: Welding conditions for 316 L Stainless Steel and steel using a pulsed Nd: YAG laser

S.No	Description	Parameters	Units / Remarks
1.	Joint type	Butt joint welding	][
2.	Gap between the joint	Zero gap	mm
3.	Source	Pulsed Nd:YAG Laser	λ=1.064 µm
4.	Core Diameter	Step index fiber @ 600 dia	µm
5.	Beam quality	25	mmrad
6.	Beam nature	Pulsed	Volumetric source
7.	Transmission mode	TEM_{00}	Gaussian Distribution
8.	Pulse shape	Triangle	Δ
9.	Beam angle	90º	Degree
10.	Filler wire	No filler wire used	Autogenous
11.	Focal length (Lens)	200	mm
12.	Defocus position	On the surface (0)	mm
13.	Shroud Gas flow rate	Ar gas @ 20	l/min
14.	Shroud Gas position	Behind the beam	-
15.	Shroud Gas angle	45 degree	Degree
16.	Angle between the beam and	90 degree	Degree

	weld materials		
17.	Distance between the beam and weld materials	200	mm
18.	Ambient temperature	293	Kelvin

III. Result And Discussion

1.1 AISI 316L stainless steel welding by bead on plate method

The initial parameters presumed from the numerical[18], analytical modeling [19] considered for the present work and some parameters referred from the literatures are applied to join the 2 mm thick similar AISI 316L stainless steel plates by trial and error method until reaching full penetration. Fig. 2 shows the penetration depth of AISI 316L stainless steel plates by bead on plate welding method using a pulsed Nd: YAG laser source by varying some important parameters such as average peak power, pulse duration, frequency, welding speed, focused spot size and defocusing position (on the surface). The parameters used for this set of experiment were given in table 2. In pulsed laser welding, penetration depth is a function of input power and since the average peak power raised by pulse duration and pulse repetitive rate. In fact, speed is independent of power, but it was chosen with respect to adequate pulse overlapping percentage to achieve good quality of welding. Since, the weldpool obtained from trial VI appeared with concavity at the top and bottom bead, but the trial V gives acceptable volume of melt without any concavity at the top however, a slight concavity noticed at the bottom. Hence, from the parameters in trial V of table 2, the average peak power of laser lies among 2050-2150 Watts is most adequate along with the other parameters for 2 mm thick similar AISI 316L stainless steel plates using pulsed Nd: YAG laser by bead on plate welding method.

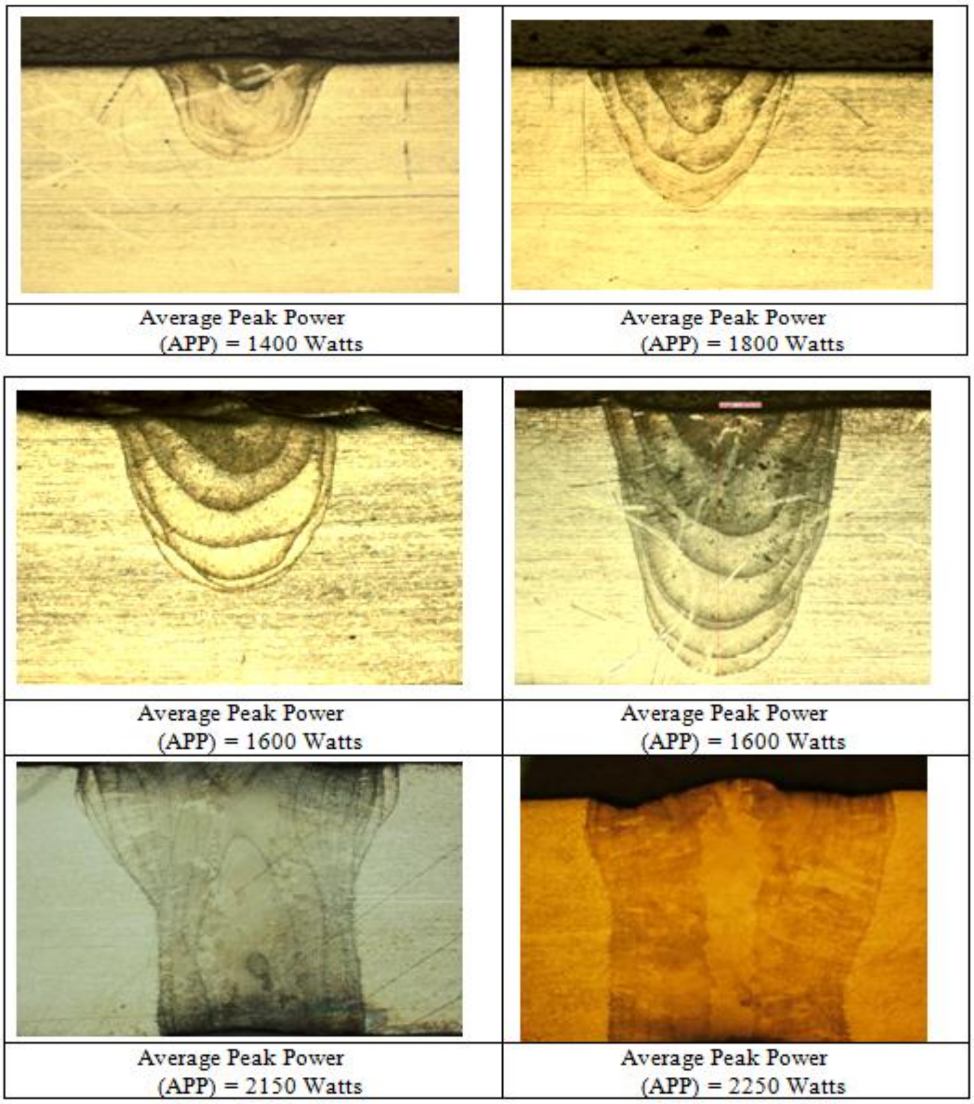

Fig. 2: The penetration depth for various input of similar 316 L stainless steel plates

Table 2: The penetration depth of similar 316 L stainless steel plates by bead on plate method

Trials	Average Peak Power (W)	Pulse duration (mS)	Beam dia (µm)	Frequency (Hz)	Speed (mm/min)
I	1400	8	0.451	15	180
II	1800	8	0.451	15	180
III	1600	10	0.451	15	180
IV	1600	12	0.451	15	180
V	2150	12	0.451	15	180
VI	2250	12	0.451	15	180

1.2 AISI 316L Stainless steel by butt joint welding method

From optimized parameters of AISI 316L stainless steel by bead on plate method, the suitable parameters applied to weld the 2 mm thick of AISI 316L stainless steel by butt joint welding method. The operating parameters used for the butt joint welding of 2 mm thick AISI 316L stainless steel were given in table 3. The weldpool and its constituents obtained for AISI 316L stainless steel are given as shown in fig. 3. The weldpool obtained from trial II appeared with considerable volume of melt that enables to achieve efficient joint and no concavity found in top and bottom bead. In trial I, a bit of incomplete penetration observed and in trial III, some excess melting cause's concavity at the top and bottom. Hence, from the parameters in Trial II of table 3, the average peak power of laser between 2100 Watts is most adequate along with the other parameters for 2 mm thick similar butt joint welding AISI 316L stainless steel plates using pulsed Nd: YAG laser by butt joint welding method.

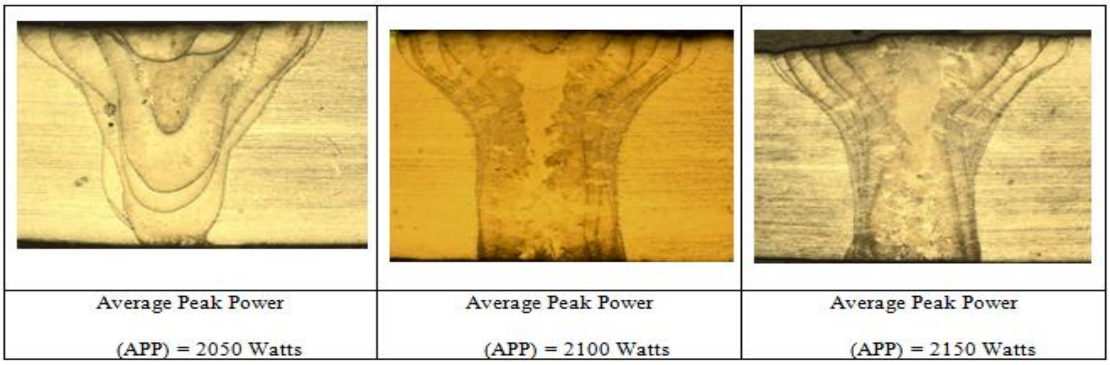

Fig.3. Full penetration welds achieved using optimized parameters for AISI 316L stainless steel joints

Table 3. Optimized parameters for similar 316 L stainless steel by butt joint method

Trials	Average Peak power (W)	Pulse duration (mS)	Beam dia (µm)	Frequency (Hz)	Speed m/min)
I	2050	12	0.451	15	180
II	2100	12	0.451	15	180
III	2150	12	0.451	15	180

1.3 Process of optimization of operating parameters for mild steel

Similarly, full penetration is successfully achieved in autogenous butt joint welding of 2mm thick similar mild steel plates using a pulsed Nd: YAG laser beam with the parameters at the average peak power (1950 - 2050 Watts), pulse duration (12 mS), frequency (15Hz) welding speed (3mm/S), spot size (0.451mm) and defocusing position (on the surface) without back forging. Again, Shielding gas (Ar) at the flow rate 20 l/min maintained to protect the welding joint free from corrosion and oxidation.

In similar butt joint welding, the beam spot located exactly on centreline weld and hence the heat distribution made equally on each side plates that provide acceptable weld joint and weld bead. The parameters used for this set of experiment were given in detail in table 4. The penetration depth of butt joint of mild steel plates achieved using laser as shown in figure 4. The weldpool obtained from trial I appeared with considerable volume of melt that enables to achieve efficient joint and a slight concavity noticed in top and bottom bead. In trial II & III, relatively larger concavity noticed in top and bottom bead. Hence, from the parameters in trial I of table 4, it is clear that the average peak power of laser lies between 1900-1950 Watts may adequate for 2 mm thick similar butt joint welding mild steel plates for pulsed Nd: YAG laser.

Table 4: Optimized parameters for similar steel by butt joint method

Trial	Average Peak power (W)	Pulse duration (mS)	Beam dia (µm)	Frequency (Hz)	Speed (mm/min)
I	1950	12	0.451	15	180
II	2000	12	0.451	15	180
III	2050	12	0.451	15	180

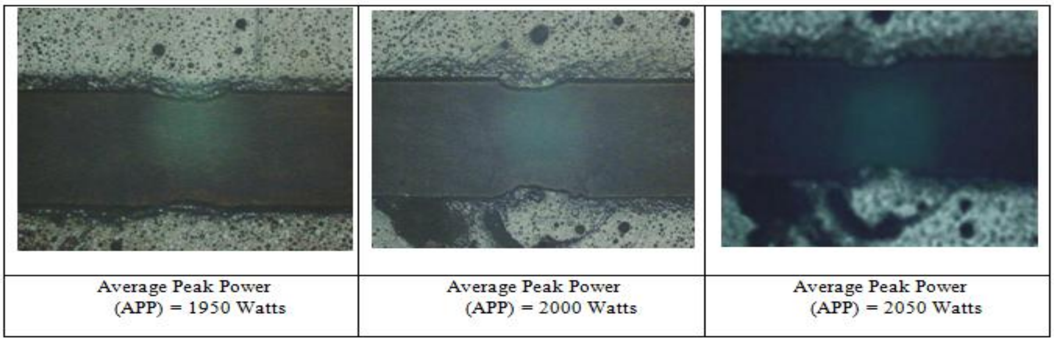

Fig. 4 The penetration depth of butt joint of mild steel plates

1.4 AISI 316L Stainless steel-mild steel without offset-ting the laser spot

Similar welding of AISI 316L stainless steel and mild steel joints shows equal distribution of temperature on both the sides since the laser spot symmetrically focused across butt joint. However, the laser spot located on centreline of dissimilar joint 316L stainless steel–mild steel do not give the equal heat distribution because of the different thermal conductivities. Therefore, the full penetration was not achieved and unable to provide acceptable weld joint and weld bead. The parameters used for this set of experiment were given in detail in table 5. The penetration depth of butt joint of AISI 316L stainless steel - mild steel plates without offset-ting the laser beam achieved are given as shown in fig.5. From the list of trials in table 5, fails to achieve full penetration while using the optimized parameters for AISI 316L stainless steel and mild steel in the range of average peak power of laser lies between 1950-2050 Watts during 2 mm thick dissimilar AISI 316L stainless steel-mild steel welding using pulsed Nd: YAG laser.

Table 5: Parameters for dissimilar 316L stainless steel-mild steel by butt joint method

Trial	Average Peak power (W)	Pulse duration (mS)	Beam dia (μm)	Frequency (Hz)	Speed (mm/min)
I	1950	12	0.451	15	180
II	2000	12	0.451	15	180
III	2030	12	0.451	15	180
IV	2050	12	0.451	15	180

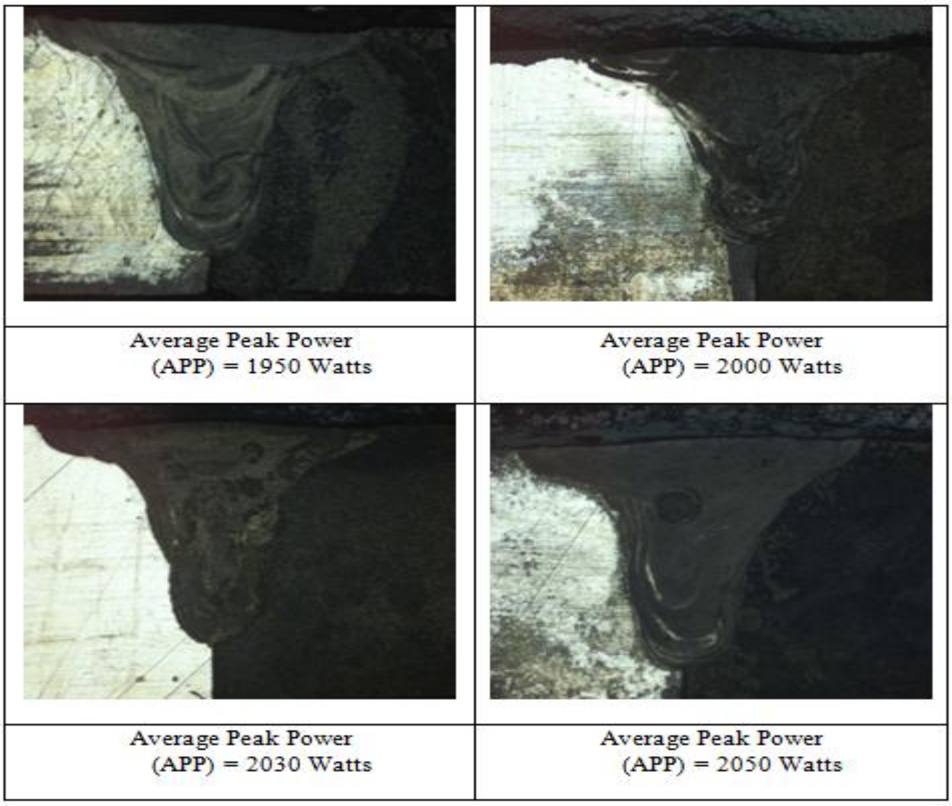

Fig. 5: The penetration depth of butt joint of 316L stainless steel- steel plates without offset-ting the laser beam

1.5 AISI 316L Stainless steel-mild steel welding by offset-ted laser beam position

Since, the 316L stainless steel-mild steel welding results in incomplete penetration, it was decided to move the laser spot towards the relatively low thermal conducting of AISI 316L stainless steel side by 2 µm. Hence, the maximum heat exerted on AISI 316L stainless steel side and melted whereas lesser heat input given to the mild steel side. The higher temperature molten AISI 316L stainless steel driven towards the lower melting point of mild steel side and melts occurred. Hence, the full penetration of thickness reaches quickly and provides the reasonable weldpool for efficient joint. The parameters used for this set of experiment were given in detail in table 6. The penetration depth of butt joint of AISI 316L stainless steel-Mild steel plate achieved by offset-ting the laser beam position were given as shown in fig. 6.

Table 6. Optimized parameters for 316L stainless steel-mild steel by butt joint method

Trial	Average Peak power (W)	Pulse duration (mS)	Beam dia (µm)	Frequency (Hz)	Speed (mm/min)
I	2100	12	0.451	15	180
II	2130	12	0.451	15	180
III	2150	12	0.451	15	180
IV	2180	12	0.451	15	180

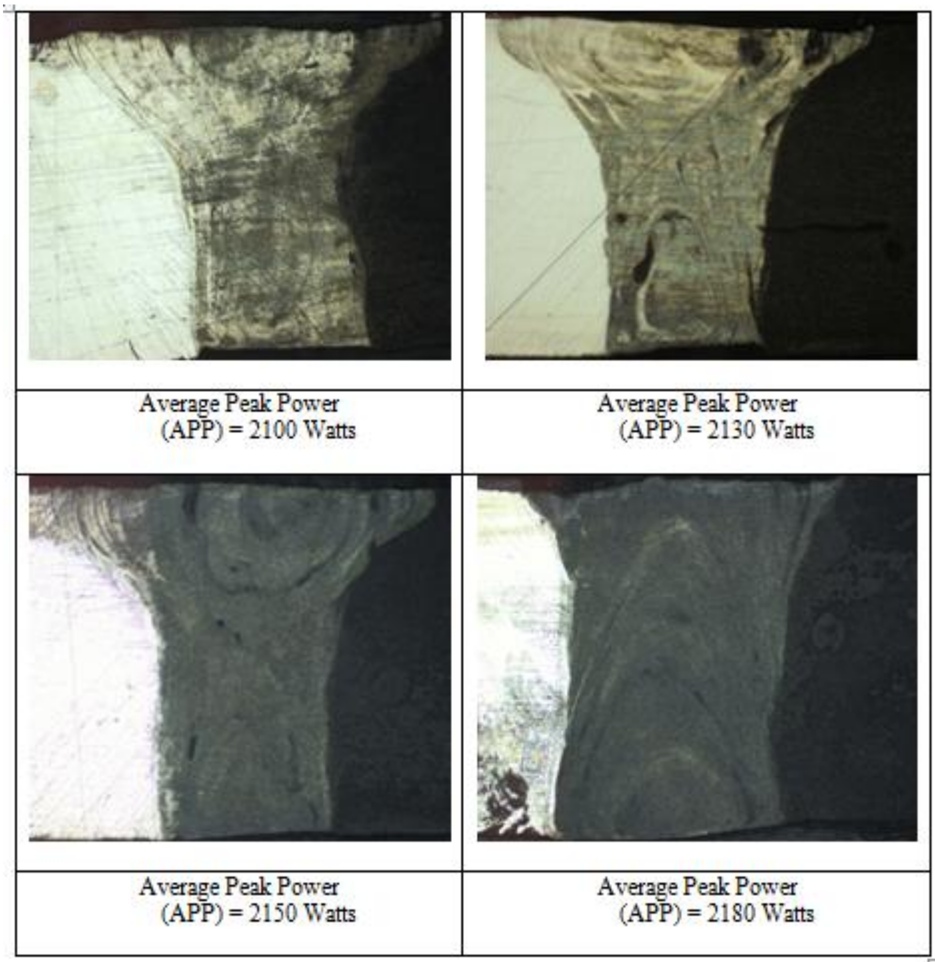

Fig. 6: The penetration depth of 316L stainless steel-mild steel by offset-ted the beam position

The weldpool obtained from trial III appeared with considerable volume of melt with full penetration that equally distributed weldpool on each side and no concavity noticed in top, and bottom bead was found. In trial I, II & IV, an uneven distribution of melt pool and concavity noticed in top and bottom bead. Hence, from the parameters in trial III of table 6, it is clear that the average peak power 2150 Watts may adequate for 2 mm thick similar butt joint welding mild steel plates for pulsed Nd: YAG laser with offset-ted beam position.

Therefore, decision to move the laser spot towards AISI 316L stainless steel was justified for dissimilar welding of 316L stainless steel–mild steel joint. This approach can be very useful to join many other possible dissimilar materials joints having different thermo physical properties using pulsed Nd: YAG laser.

IV. Effect of Prominent Operating Parameters

1.6 Mean power of laser beam on 316L stainless steel

Generally, the quality of a weld joints directly influenced by the welding input parameters during the welding process, therefore, welding considered as a multi input, multi output process. Power of laser beam is an important parameter to achieve the desired penetration depth. The penetration depth of the 2 mm thick AISI 316L stainless steel was predicted based on Metzbower equation (16). Fig.7 shows the influence of mean power of laser beam on variation in penetration depth of 316L stainless steel joint. The predicted penetration depth curve appeared linearly whereas experimental curve has vast deviations because penetration depth is not only the function of mean power but also other parameters such as pulse duration, frequency welding velocity and shroud gas. However, increase in mean power increases the penetration depth of 316L stainless steel.

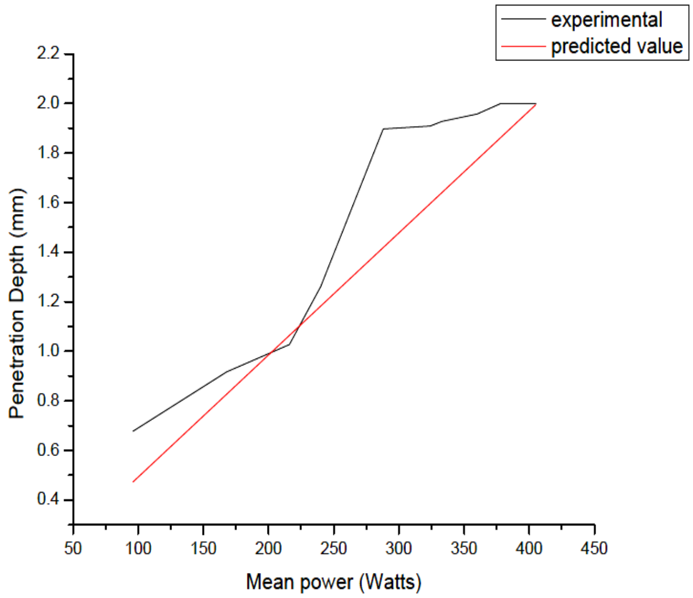

Fig. 7: Effect of input power of laser beam on penetration depth in 316L stainless steel

1.7 Defocus position of laser beam on 316L stainless steel

As a part of optimization of operating parameters, an experiment was carryout for different defocus position of laser beam on and above the surface of similar AISI 316L stainless steel plates. Fig. 8 and Fig. 9 show the greater influence of defocus position on the penetration depth during welding process. Even though laser power is maximum at the 1st and 2nd locations but it focused above 3 mm from the surface of AISI 316L stainless steel results in very poor penetration depth. Similarly, the locations 4th, 5th, 6th, and 7th shows incomplete penetration since it has focused above the surface at 1mm. On the other hand, when we focused laser beam on the 3rd location it was reaches to full penetration of AISI 316L stainless steel even the lesser power of 378 Watts than other locations. Thus, it was justified that the defocus point on the surface of the specimen results in maximum penetration depth during welding. Hence, the same defocus point has chosen and followed throughout the experiment.

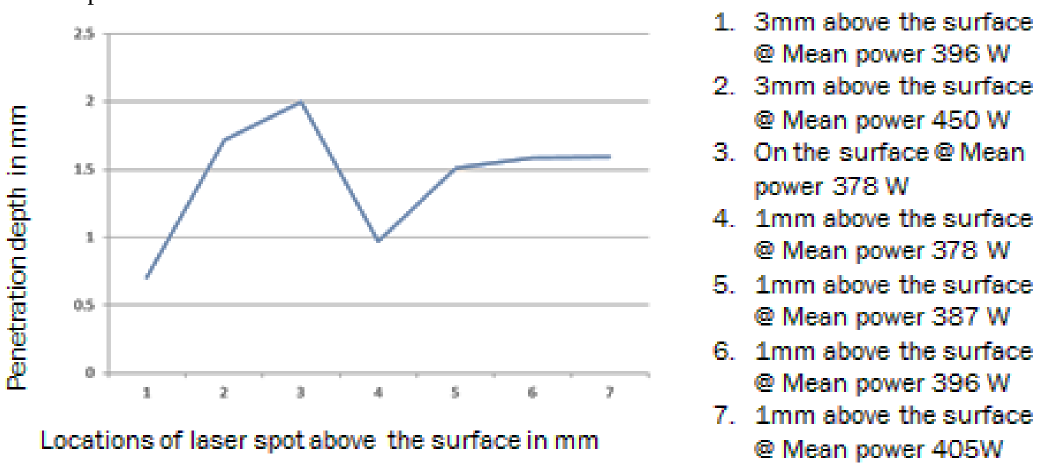

Fig. 8: Effect of defocus position on penetration depth in 316L stainless steel

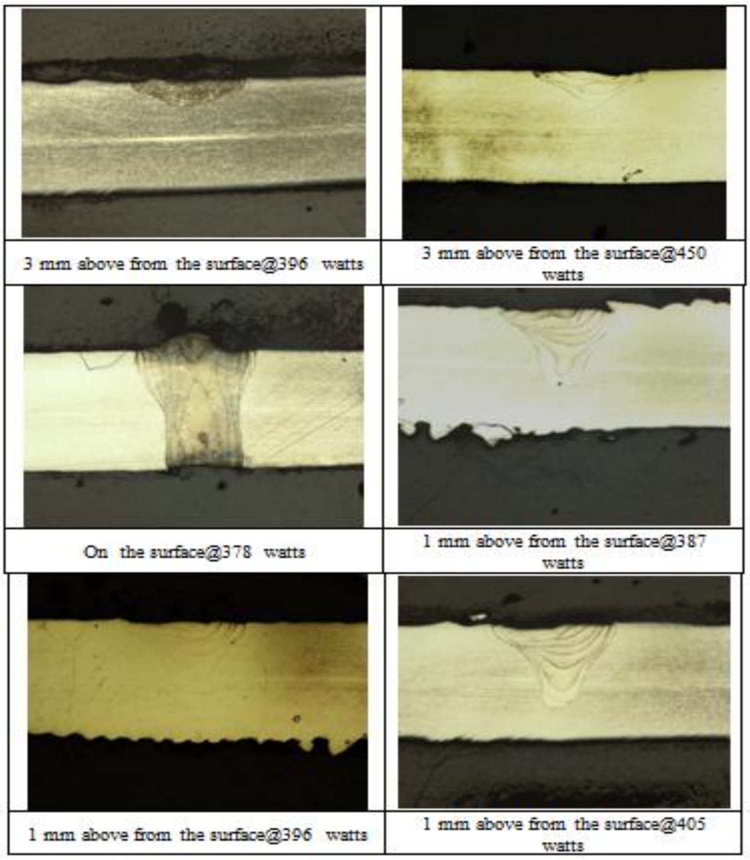

Fig. 9: The penetration depth for various defocus position on 316L stainless steel

1.8 Shielding gas

The selection of the shielding gas should take into account chemical and metallurgical process between the gases and molten pool. Generally, shielding gases used to protect the beam transmission by minimizing beam expansion and scattering. In the present work, 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 (17). Fig. 10 shows the oxidized bottom beads since there was no back forging done during welding.

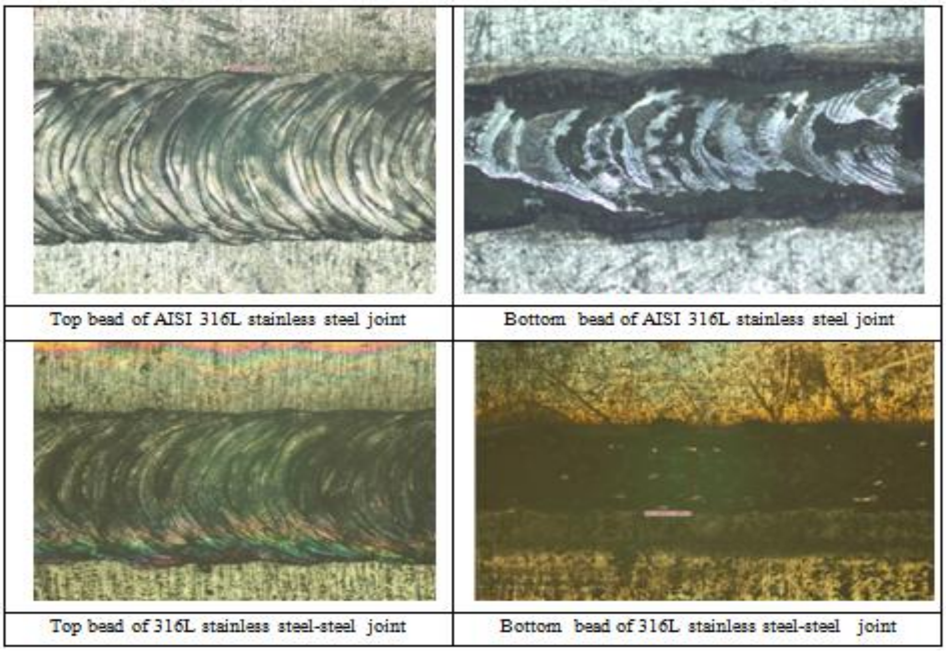

Fig.10: Influence of shielding gas on AISI 316L stainless steel and steel joints

V. Conclusions

1. Among many operating parameters in pulsed laser welding process, a set of parameters optimized for 2 mm thick AISI 316L stainless steel plate welding using pulsed Nd: YAG laser by bead on plate method. Hence, another set of parameters optimized for 2 mm thick similar AISI 316L stainless steel plates welding using pulsed Nd: YAG laser by butt joint method.
2. Similarly, a set of parameters optimized for 2 mm thick similar mild steel plates welding using pulsed Nd: YAG laser by butt joint method.
3. The laser spot position has shifted towards AISI 316L stainless steel side by 2 µm to achieve the full penetration welding of dissimilar 316L stainless steel-mild steel since, the symmetrically focused laser spot position across the weldline welding results in incomplete penetration. Thus, a set of parameters optimized for 2 mm thick dissimilar AISI 316L stainless steel-mild steel plates welding using pulsed Nd: YAG laser by butt joint method.
4. The effect of prominent operating parameters such as average peak power, defocus position, spot position, and shielding gas are investigated during pulsed Nd: YAG laser welding process.

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