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NUMERICAL APPROACH TO STEADY STATE TEMPERATURE DISTRIBUTION IN PULSED ND: YAG LASER WELDING OF HASTELLOY C-276

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ABSTRACT

The influence of heat source in Nd: YAG laser welding of Hastelloy C-276, subjected to varying welding speeds (350 mm/min-450 mm/min), is presented in this study. The temperature distribution across various regions viz., base alloy, heat affected zone (HAZ) and fusion zone are determined by SYSWELD 16 - a 3D finite element software package. Numerical simulation for the attempted welding speeds shows complete penetration, though the morphology of the weld differs. The maximum temperature was obtained in the fusion zone in the attempted welding speeds. The aspect ratio (depth/width) of the weld pool increases with welding speed.

Key words: *Pulsed laser welding; Hastelloy C-276; SYSWELD 16; aspect ratio; Temperature distribution.*

1. Introduction

Hastelloy C-276, a nickel-chromium-molybdenum alloy, is extensively used in chemical industries, aerospace and nuclear plants due to its higher corrosion resistance. Though welding of Hastelloy C-276 by conventional methods is possible, formation of undesirable intermetallic compounds suppresses the utilization [1]. Laser welding offers a reliable solution to weld Hastelloy C-276, with negligible inter-metallic compounds, owing to lower power usage, better weld bead geometry and minimum heat affected zone (HAZ) [2]. Modeling and simulation of pulsed laser welding is very effective in research, design and industrial application as it provides detailed information about the weld characteristics and the prevailing interrelationship between various process parameters viz., welding speed, laser power, pulse energy, focal position, pulse repetition rate and shielding gas. Numerical simulation of pulsed laser welding enables the estimation of weld pool geometry, transient temperature, stresses, residual stresses and distortion [3]. Understanding the interaction prevailing between thermal, mechanical and microstructural phenomenon dictates the nature of weld and consequently the weld quality. Numerical simulation of laser welding on different metals and alloys is reported by various researchers. Mazumder and Steen [4] developed the first numerical model of the continuous laser welding process which implements a finite difference technique for a Gaussian beam intensity distribution.Kazemi and Goldak [5] employed ANSYS software to determine the temperature and the nature of weld during laser welding. Balasubramanian et al. [6] performed simulation on AISI 304 in a laser beam welded butt joint configuration using SYSWELD and concluded that the welding speed decides the nature of the joint. In another study, Azizpour et al. [7] studied the relation between the laser welding speed and bead geometry of titanium sheets using SYSWELD. Shanmugam et al. [8] replicated a laser welded T-joint on AISI 304 where the beam angle was observed to be of major influence. Though, numerical simulation of laser welding of metals and alloys are reported by earlier researchers, studies on the effect of welding speed on Hastelloy C-276 using pulsed Nd: YAG laser welding is limited. Hence, in this study, numerical simulation using a steady state heat source is employed to determine the temperature, aspect ratio (depth/ width) of the weld using SYSWELD.

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Table 1.Chemical Composition of Hastelloy C-276

Material	Ni	Cr	Fe	C	Mn	Si	Mo
Wt (%)	Bal	15.5	5	0.02	1	0.08	16
Material	**W**	**Co**	**V**	**P**	**S**	**Cu**	
Wt (%)	3.75	2.5	0.35	0.03	0.03	0.013	

2. Theoretical description

The determination of temperature in fusion and heat affected zones of laser welding is complicated owing to highly collimated and concentrated energy emanating from the laser source. Hence, SYSWELD-a finite element package with few user subroutines is employed.

Table 2. Thermal Properties of Hastelloy C-276

Properties	Density (g/cm³)	Thermal conductivity (W/m°C)	Sp. Heat (J/kg° C)	Melting point (°C)
Value	8.89	10.5	427	1350

The heat transfer during the process is determined by applying heat conduction equation and assumed that the dimensional changes during welding are not significant and the mechanical work is negligible when compared to thermal changes. The heat source along the welding direction (y) and the direction of work piece thickness (z) with respect to origin is determined by [9]

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(q_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(q_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(q_z \frac{\partial T}{\partial z}\right) + q_v(x,y,z) \quad \ldots\ldots\ldots\ldots\ldots(1)$$

Where 'ρ' is the density, Cp is the specific heat, 'T' is temperature,'t' is the time, qv (x, y, z) is the volumetric heat input which varies with beam power. The heat transfer along the three axes is given by Fourier equation

$$q_x = -k_x \frac{\partial T}{\partial x} \quad \ldots\ldots\ldots\ldots(2)$$

$$q_y = -k_y \frac{\partial T}{\partial y} \quad \ldots\ldots\ldots\ldots(3)$$

$$q_z = -k_z \frac{\partial T}{\partial z} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

Where, k_x, k_y and k_z are the conductivity of material in X, Y and Z axes respectively.

Also, the initial condition to be considered as $T(x, y, z, 0) = T_0(x, y, z)$. T_0 is the ambient temperature.

In this study, the standard heat source model, Heat Source Fitting (HSF) available in SYSWELD is utilized for simulating the heat input. A steady state heat source assists in determining the temperature profile, weld width and aspect ratio (depth/width). A three dimensional Gaussian model mathematically defined below is utilized for determining the heat source [7].

$$Q = Q_0 \times \exp\left(\frac{-r^2}{-r_0^2}\right) \ldots\ldots\ldots \quad (5)$$

$$r^2 = (x^2 + y^2)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots,(6)$$

$$r_0(z) = r_e + \frac{r_i - r_e}{z_i - z_e}(z - z_e) \ldots\ .(7)$$

Where Q_0 - Heat flow density (W/m³), r_e, r_i– 3D Gaussian radii (m), z_e, z_i – determinate length of 3D Gaussian(m) and x, y, z – point coordinates.

3. Numerical simulation

Finite element model for the butt welding of Hastelloy C-276 (chemical composition given in Table 1) having dimensions 100 mm x 60 mm x 1 mm for different welding speed (350 mm/min-450 mm/min) at constant heat input (pulse energy 10 J for 7 ms) and pulse repetition rate of 20 Hz using SYSWELD was attempted. The thermal properties of the base alloy are given in Table 2. The ambient temperature and the constant flow of argon were assumed to be 27 ºC and 10 l/min respectively. The density and shape of the mesh plays a vital role in determining the nature and behavior of base alloy, especially in HAZ. Hence a dense mesh is designed at interface than as that in the peripheral of base alloy. The size of the cuboidal mesh at the interface is 0.2 × 0.2 × 0.25 mm³, while the size of the mesh at the periphery and the base alloy is chosen as 1 × 1 × 0.25 mm³ (Fig.1).

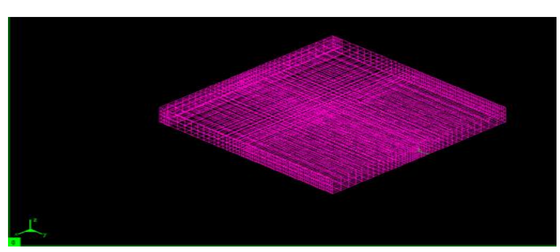


Fig. 1 Three dimensional mesh of the base alloy

4. Results and Discussion

The temperature developed in different regions of the weld viz., base alloy, fusion zone and heat affected zone (HAZ) at varied welding speeds are given in Fig.2 (a-c). For the weld conditions imposed in this study, the depth of penetration and bead profiles can be observed to vary widely. Sathya and Jaleel [10] reported that the focused laser beam is one of the power density sources and evaporates the participant materials to form a hole, which then transverse through the materials, with the molten welds closing behind to execute a 'keyhole' weld. The heat input into the system, as defined by heat input=average laser power/ welding speed, dictates the weld contours, with reference to weld depth and width [11].

The weld zone morphology in pulsed Nd: YAG laser welding is influenced by Effective Peak Power Density (EPPD), the actual energy supplied to the weld pool [12].

EPPD = Peak power × Overlapping index/Work piece spot area …………..(8)

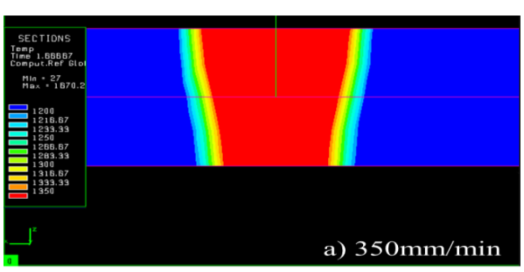
Where, the overlapping index (OI) is the cumulative factor of successive overlapping pulses determined by

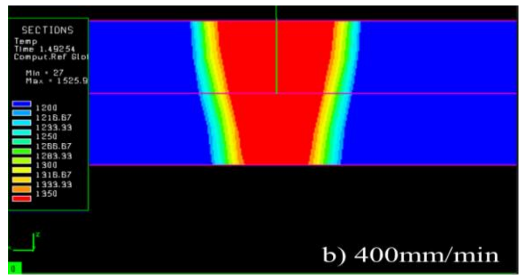
$OI=1+ n\{1-(n+1) S/(2fD)\}$ where $n=[D\times(f/S)]$ ……(9)

Where, 'S' is the welding speed (mm/min), 'f' is the laser frequency (Hz) and 'D' is the laser spot diameter (mm).

4.1 Temperature Distribution

Figure.2 (a-c). show the weld profile of 1 mm thick Hastelloy C-276 pulsed laser welds, for which a near perfect 'Barrel' structure is evident for higher heat input. As the heat input is reduced, the shape is mutated to a 'wine-glass'. The top view of the simulation is given in Fig. 3.





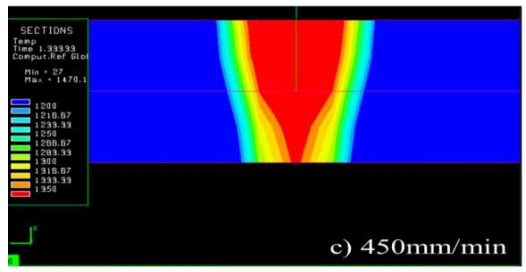


Fig. 2 (a-c) Temperature profile at various welding speeds

At 350 mm/min welding speed, an overlapping factor of 76.5% is attained following higher EPPD (3211.711 W/mm^2), while for a higher welding speed of 400 mm/min, the overlapping factor and EPPD reduces to 73.26% and 2922.81 W/mm^2, respectively. Further reduction in overlapping factor (70%) and EPPD result (2636.55W/mm^2), with the increase in welding speed (450 mm/min). Consequently, the weld zone morphology changes due to an unsteady fluid flow in weld pool resulting from electromagnetic and surface tension gradient forces.

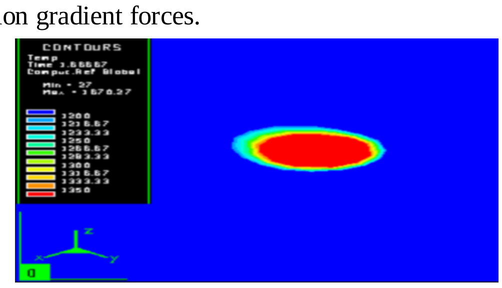


Fig.3 Top view of the weld bead

The significant variation in temperature at different regions viz., base alloy, HAZ and fusion zone are clearly visible. Further, it is observed that the maximumtemperature is found to be at the fusion zone for all welding speeds. At lower welding speed (350 mm/min), the temperature developed at the interface is higher (1870.27 °C) due to higher heat input. When the welding speed is increased to 400 mm/min, maximum temperature reduces to 1525.5 °C. Further increase in welding speed reduces the maximum temperature by 5%(1470^{o}C). The reduction in temperature with welding speed is consistent with the report of Balasubramanian et al [6].

In laser welding, the molten metal transfers heat from the top of weld pool towards lower depth of weld pool by conduction and convection. The peripheries of participant metals are directly heated involving adsorption of beam energy and subsequent transfer of energy into the surrounding environment by conduction during the welding of high thermal conductivity metals. In case of lower thermal conductivity metals, heat will permeate only by convection [13]

4.2 Aspect Ratio

The relationship between maximum temperature and weld dimensions at the top, middle and bottom section of weld is given in Table 3. A lower welding speed (350 mm/min) indicates higher heat input and effective peak power density (Eq.8)causing the interface to attract additional laser energy to produce a wider fusion zone and hence, a lower aspect ratio as reported by Saravanan et al [14]. Nevertheless, Torkamany et al. [13], who joined titanium and niobium, opined that fluid flow in weld pool is reduced in pulsed wave mode and consequently, the transmission of heat from the apex to the bottom of the weld is restricted toresult in an enlargement in weld head as observed in Fig. 4.

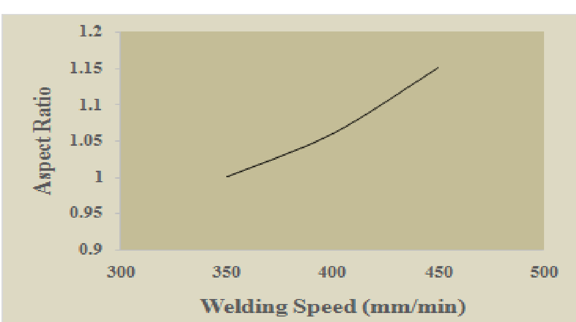


Fig. 4Welding speed vs. aspect ratio

Table 3. Results

S No.	Welding Speed (mm/min)	Heat Input (J/mm)	Max. Temp. (°C)	Weld dimensions (mm)		
				Top	Middle	Bottom
1	350	34.28	1670.2	1	0.92	0.82
2	400	30	1566.3	0.94	0.87	0.71
3	450	26.67	1470.1	0.87	0.74	0.56

5. Conclusion

Numerical simulation of laser welding Hastealloy C-276, leads to the following salient conclusions.

- The energy spent at the interface (EPPD) dictates the nature of laser welds.
- The maximum temperature of fusion zone exceeds the melting point of base alloy.
- Welding speed is inversely proportional to the maximum temperature developed in the fusion zone due to variation in heat input.
- The aspect ratio of the weld pool increases with increase in welding speed.

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