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EFFECT OF WELDING SPEED ON MICROSTRUCTURAL AND MECHANICAL PROPERTIES OF PULSED ND:YAG LASER WELDED DISSIMILAR METALS

***Shanthos kumar G[1], Sivagurumanikandan N[1], Saravanan S[2] and Raghukandan K[1]**

[1] Department of Manufacturing Engineering, Annamalai University, Annamalai nagar – 608002, Tamilnadu, India.
[2]Department of Mechanical Engineering, Annamalai University, Annamalai nagar – 608002, Tamilnadu, India.

ABSTRACT

This paper reports the effect of welding speed (350 mm/min-450 mm/min) on microstructural and mechanical characteristics of pulsed Nd:YAG laser welded Hastelloy C-276 and Monel 400 (0.5 mm thick) dissimilar sheets. The welding speed influences the heat input, overlapping factor and thereby, dictating the width, depth and nature of weld. While fine dendritic grains are seen at the weld zone, fine dendritic and columnar grains are observed at the weld interfaces. Maximum hardness and tensile strength are obtained at a welding speed of 400 mm/min owing to formation of finer grains as the tensile failure occurs in weaker parent metal (Monel 400). The average hardness, tensile strength and elongation of the dissimilar weld is 276 Hv, 664 MPa and 13.43 % respectively. Ductile fracture mode is observed in the Monel 400 laser welds.

Key words: *Pulsed Nd:YAG laser welding, dissimilar metals, microstructure, microhardness, tensile strength.*

1. Introduction

Hastelloy C-276, a nickel-chromium-molybdenum alloy, is mainly used in chemical, aerospace and nuclear industries due to its high corrosion resistance and high strength at elevated temperatures [1]. Monel 400, a solid solution alloy, is widely preferred in industrial applications because of its high strength and toughness over a wide temperature range and excellent resistance in corrosive environments. In addition, good ductility and easy to cold work make Monel 400 a very attractive for a wide variety of applications in atmospheric, salt water and various acid and alkaline media [2].

Hastelloy C-276 and Monel 400 weld is widely used in the chemical processing equipment viz., heat exchangers, reaction containers, and evaporators [3]. Some of the researchers studied the properties of similar and dissimilar combination of Hastelloy C-276 and Monel 400 using conventional welding processes. Ramkumar et al. [3] welded Monel 400 and Hastelloy C-276 by Pulsed Current Gas Tungsten Arc Welding and reported greater hardness and tensile strength at the weld zone due to grain refinement. Sadek et al. [4] and Ramkumar et al. [5], in two different publications attempted dissimilar joining of Continuous Current Gas. Tungsten Arc Welding of Monel 400 with different grades of steel and reported failure in weaker metal (Monel 400). Laser welding process is efficient than conventional fusion welding processes owing to high aspect ratio, narrow heat affected zone, minimum thermal distortion, ease of automation, high welding speed, greater design flexibility, clean, high energy density and low heat input [6]. The quality of dissimilar laser weld depends on various process parameters viz., peak power, pulse duration, frequency, focusing length and welding speed [7]. Though few researchers have attempted welding of Hastelloy C-276 – Monel 400, studies on pulsed laser welding at varied welding speed is limited and attempted herein.

2. Experimental work

Welding of Hastelloy C-276 and Monel 400 (chemical composition and mechanical properties are given in Table.1 and Table.2 respectively) using pulsed JK 600 Nd:YAG laser welding machine equipped with robot (JK 600 HPS) with a pulse energy 10 J, frequency 20 Hz, and pulse duration 6 ms is attempted. The base metals (150 mm × 60 mm × 0.5 mm) were prepared and cleaned using acetone in order to remove the contaminations on the surface. The dissimilar metals were butt welded at three different welding speeds (350 mm/min, 400 mm/min and 450 mm/min), utilizing

**Corresponding Author - *Email: shanthosg4@gmail.com*

Table 1.Chemical composition of base metals

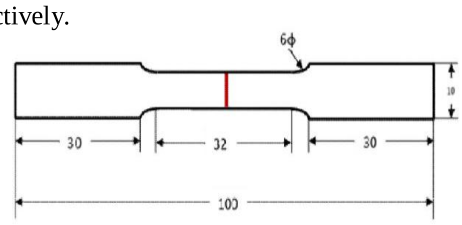
Materials (wt %)	C	Si	Mn	S	P	Cr	Fe	Mo
Hastelloy C-276	0.004	0.029	0.387	0.006	0.003	14.96	5.53	15.68
Monel 400	0.092	0.035	0.849	0.006	-	0.09	2.45	0.01
	Co	**Nb**	**Cu**	**V**	**Al**	**Ti**	**W**	**Ni**
	0.224	0.010	0.138	0.023	0.085	0.006	3.15	Bal.
	0.080	-	31.23	-	0.151	0.008	-	Bal.

Table 2. Mechanical properties of base metals

Properties	Hastelloy C-276	Monel 400
Hardness (Hv)	378	184
Ultimate tensile strength (MPa)	1290	570
Yield strength (MPa)	1186	465
Elongation (%)	16	23

argon (10 lit/min) as the shielding-gas, which prevents the welding zone and its front from strong oxidization.

After welding, the grinded samples were polished by using grit of various grade emery sheets (220-2500 SiC) and diamond paste for microstructural study. A solution containing 15 ml HCl, 10 ml HNO3 and 10 ml glacial acetic acid is applied on the cross section of Hastelloy C-276 and Marbles reagent (20 ml HCl, 20 ml H2O and 2 g CuSO4) is applied on the cross section of Monel 400 and weld zone. Microhardness measurements across the interface were determined by a Vicker's micro hardness tester (ZWICK-3212), the applied load and time period being 300 g and 10 s respectively.



All the dimensions are in mm

Fig. 1 ASTM E8 standard tensile test specimen

The tensile samples were prepared as per ASTM E8 standard [8] with sub size dimensions 100 mm × 10 mm × 0.5 mm (Fig.1), and the tensile test was performed in a universal testing machine (UNITEK-94100). The tensile fracture surface was analyzed by a JSM-6610LV Scanning Electron Microscope.

3. Result and Discussion

3.1 Macrostructure

The weld bead profile of dissimilar weld (Fig.2) show complete penetration, devoid of cracks and porosities irrespective of the welding speeds attempted. Neves et al. [9], while joining AISI 304 - Inconel 600 by pulsed laser welding, reported that homogenous penetration is obtained, as a significance of the high solidification and cooling speed, being generated by the high rate of heat removal from the welded joint. The heat input to the system, as defined as heat input = average power (KW)/welding speed (mm/min) dictates the weld width, depth and quality of weld. The welding speed characterizes the overlapping factor in pulsed laser welding as given by [10]

$$\text{Overlapping Factor } (O_f) = 1 \quad \frac{V/f}{D \ \ VT} \times 100\,\% \quad (1)$$

Where V, f, D and T are the welding speed (mm/min), pulse frequency (Hz), spot diameter on the work piece (mm) and pulse duration (ms) respectively. When the welding speed is minimum, the overlapping of successive pulses is higher due to higher heat input, leading to higher energy spent at the interface to produce a deeper weld as reported by Cao and Jahazi et al. [11]. At lower welding speed, wider weld width (1.148 mm) emerges following maximum heat input (34.28 J/mm). Conversely, when the welding speed increases, width of weld bead decreases as the overlapping factor and heat input reduces. The overlapping factor for the welding speed attempted in this study was determined as 74.33 % (350 mm/min), 70.8 % (400 mm/min) and 67.2 % (450 mm/min).

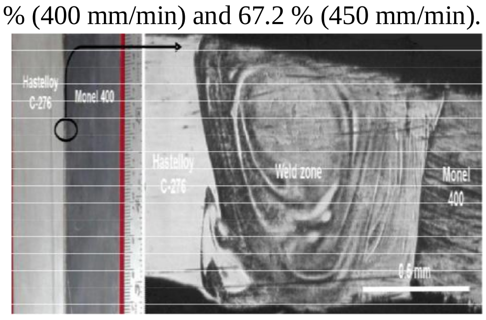


Fig. 2 Macrostructure of dissimilar Hastelloy C-276 and Monel 400 weld

3.2 Microstructure

The microstructure of base metal Hastelloy C-276 (Fig.3.a) exists with austenitic grains along with annealed twins which prevent the dislocation movement during the deformation and holds a positive effect on the strength of cubic materials [12]. On the other hand,

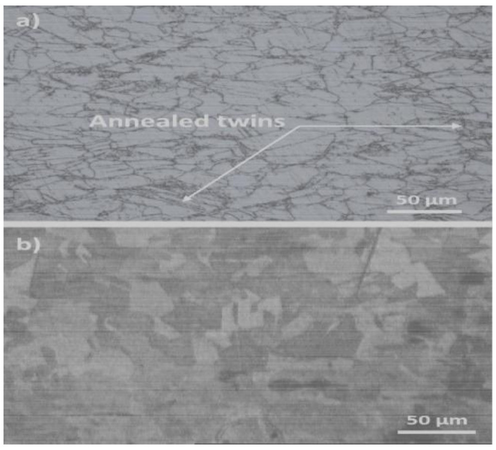


Fig. 3 Microstructure of the base metals a) Hastelloy C-276 b) Monel 400

Monel 400 (Fig.3.b) has a stable solid solution of Ni-Cu rich phases. The grain boundaries are easily distinguishable and the grains are evenly distributed throughout the structure on both alloys.

The interfacial microstructure of Hastelloy C-276-weld zone (Fig. 4.a) shows the growth of fine grains from base metal to weld zone and a narrow heat affected zone. Fine equiaxed grains are seen at the bottom side of weld zone, whereas columnar grains are observed at the weld zone top side. Furthermore, formation of fine dendritic and columnar grains is observed in the Monel 400 side (Fig. 4.b) due to the presence of Cu in Monel 400 and the back plate (Cu) used in the welding process which dissipates more heat. A heat affected zone (HAZ) is observed in the interface microstructure of both sides owing to lower heat input in pulsed laser welding. However, the size of HAZ (30 µm) at both the interfaces is lower than GTA welding attempted by Ramkumar et al. [3].

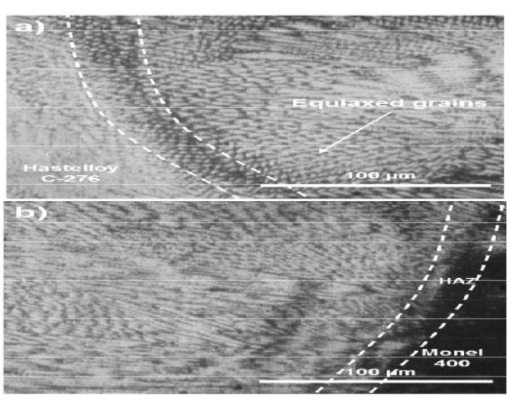


Fig. 4 Interface microstructure showing (a) Hastelloy C-276 side and (b) Monel 400 side

The rapid cooling in laser welding and the solidification of the sub grain boundary promotes formation of finer grains in the dissimilar laser weld zone (Figs.5.a & 5.b) at varied welding speeds attempted (350 mm/min and 400 mm/min). Kazzaz et al. [13] while joining magnesium alloy opined that the increase in heat input either by increasing laser power or by reducing welding speed leads to increase in average grain size. At lower welding speed (350 mm/min), the grains in weld zone are coarser (Fig.5.a), the formation of coarser grains at the weld zone could be attributed to the higher heat input developed during the lower welding speed. While increasing the welding speed the heat input in the welding process is decreased and the transformation of coarser grains to fine dendritic grains occurs as observed at the 350 mm/min welding speed (Fig.5.b).

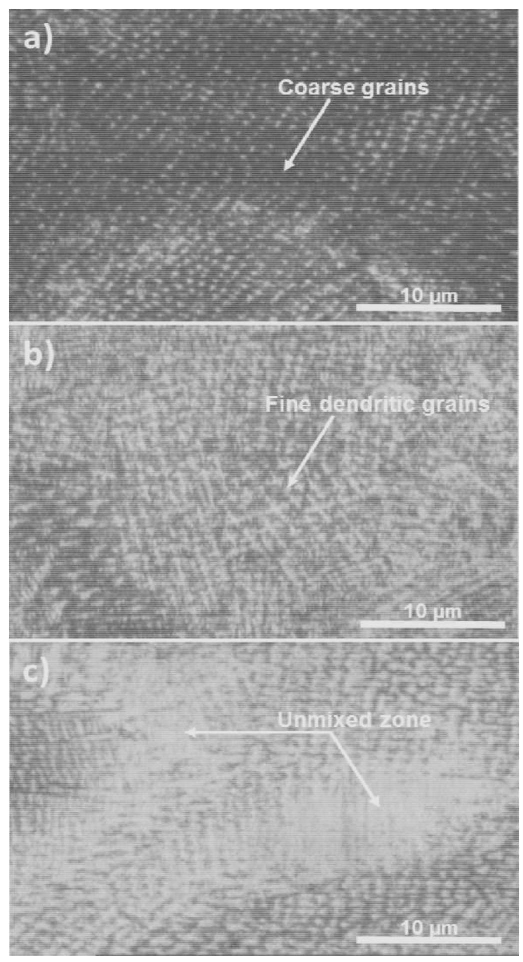


Fig. 5 Weld microstructure at different welding speeds a) 350 mm/min, b) 400 mm/min and c) 450 mm/min

The lower molybdenum segregation in the Hastelloy C-276 and Monel 400 weldments also leads to equally dispersed fine dendritic grains observed at a welding speed of 400 mm/min (Fig.5.b). Hossenini et al. [14] while welding inconel and stainless steel reported finer microstructure along with lower segregation ratio of molybdenum. Due to lower heat input in higher welding speeds (450 mm/min), small unmixed zone and higher size grains were observed in the weld zone microstructure (Fig. 5.c). The formation of finer grains enhances the mechanical strength of the weld and detailed in next section.

3.3 Microhardness

The hardness of weld zone varies from 245 Hv to 292 Hv for the welding speeds. The average hardness of weld zone (276 Hv) is higher than weaker parent metal Monel 400 (Fig.6), and is consistent with Ramkumar et al. [4], indicting stronger weld zone. However, the maximum hardness is lower than Hastelloy C-276 (Fig. 6). The maximum hardness is obtained in the welding speed 400 mm/min due to the presence of refined grains in the weld zone, devoid of defects as mentioned in the previous section. The hardness of weld zone decreases at higher welding speed (450 mm/min), as the overlapping factor (Eqn.1) and heat input reduces leading to formation of unmixed zone as observed in the microstructure (Fig.5.c).

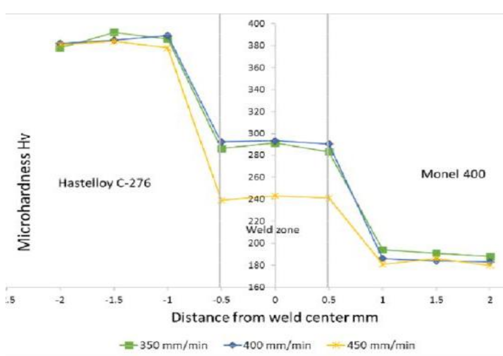


Fig. 6 Hardness profile of pulsed laser welding of Hastelloy C-276 and Monel 400

3.4 Tensile strength

The measured tensile strength, yield strength and elongation of dissimilar weld at varied welding speeds are given in Fig.7. The tensile strength of dissimilar laser weld is higher than weaker of the base metal (Ultimate tensile strength of Monel 400 – 570 MPa as testing samples were broken in the Monel side for attempted conditions indicating stronger weld zone (Fig.8). The average ultimate tensile strength, yield strength and elongation of the dissimilar weld zone was found to be 664 MPa, 548 MPa and 12.83 % respectively. Due to lower heat input and faster cooling rate in pulsed laser welding, the ultimate strength, yield strength and elongation initially increases with welding speed (350 mm/min and 400 mm/min) and tends to decrease at higher welding speed (450 mm/min).

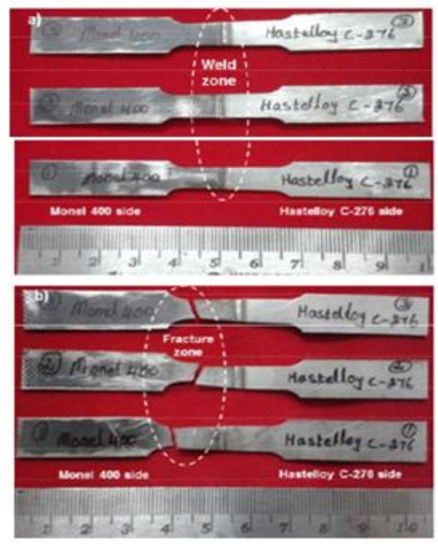


Fig. 7 Tensile test samples a) before fracture b) after fracture.

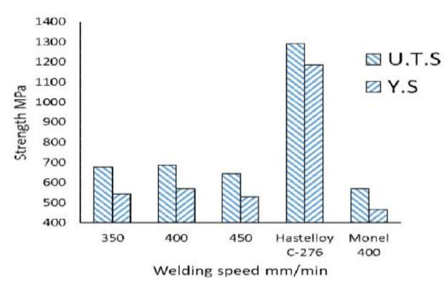


Fig.8 Effect of welding speed on tensile properties.

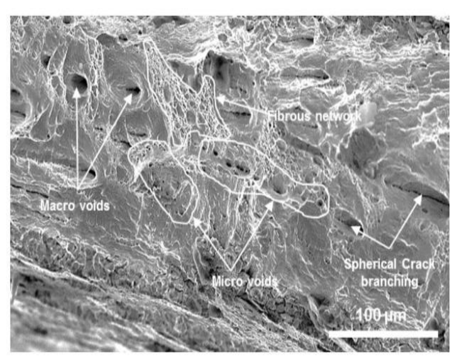


Fig. 9 SEM fractograph of tensile tested sample.

Speed of 400 mm/min results in maximum strength and is shown in Fig.8. The formation of unmixed zone and lower cooling rate at higher welding speed (450 mm/min), tensile strength reduces and is consistent with Aravind et al. [15]. The average tensile strength and microhardness value at the weld zone with different welding speeds is shown in Table 3. SEM fractograph (Fig. 9) reinforces that the tensile fractures are of ductile in nature owing to prominent quantity of micro/macro-voids with the ductile tearing ridges, spherical shape crack branching and micro-voids coalesced in a continuous fibrous network, thereby supporting higher mechanical strength.

Table 3. Average tensile strength and microhardness value at the weld zone with different welding speeds

Sl. No.	Welding speed (mm/min)	Ultimate tensile Strength (MPa)	Yield strength (MPa)	Micro hardness (Hv)
1	350	672	544	288
2	400	685	570	292
3	450	635	530	245
Avg.		664	548	276

4. Conclusion

The Nd:YAG laser welding of Hastelloy C-276-Monel 400 at varied welding speeds leads the following major conclusions.

- Defect free welding of Hastelloy C-276 -Monel 400 was achieved by pulsed Nd:YAG laser welding.
- Fine dendritic grains were observed in the weld zone at a welding speed of 400 mm/min.
- The average hardness of weld zone is lower than Hastelloy C-276, but higher than Monel 400 side. Maximum hardness value was obtained at the welding speed of 400 mm/min.
- Maximum strength and elongation was obtained at the welding speed of 400 mm/min owing to ductile fracture took place in Monel 400 for attempted conditions.

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