



## EFFECT OF ANNEALING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Nd: YAG LASER WELDED NICKEL BASED ALLOYS

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### ABSTRACT

This study reports the effect of post weld annealing on the microstructure and mechanical strength of pulsed Nd: YAG laser welded Hastelloy C-276-Monel 400 sheets. The as weld microstructure reveals the dendritic mode of grain solidification, whereas, post annealing reveals a finer and columnar micro dendritic structure. Vickers micro-hardness and tensile strength of the annealed weld joints, as per standard procedure, were determined and correlated with the as-welded one. The annealed samples show marginal reduction in mechanical strength than the as-weld condition.

*Key words: Pulsed Nd: YAG laser welding, dissimilar materials, annealing; micro-hardness, 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 temperature [1]. Similarly, 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]. Welding of Hastelloy C-276-Monel 400 is mandatory, as they are widely used in the chemical processing equipments viz., heat exchangers, reaction containers, and evaporators [3]. Few researchers have attempted welding of nickel based alloys viz., Hastelloy C-276 and Monel 400 plates with other metals by gas tungsten arc welding process. Ramkumar et al. [3] attempted Hastelloy - Monel welds and reported higher strength at the weld zone - following grain refinement at the interface.

Meanwhile, Sadek et al. [4] while attempting low carbon steel-Monel joints reported a wider heat affected zone (HAZ) and fracture in the weaker base alloy (Monel 400) during mechanical testing. In another study, Ramkumar et al. [5], while joining dissimilar grade Monel plates, reported a reduction in mechanical strength owing to the formation of a wider HAZ. In this context, laser welding offers a reliable alternative to weld nickel based alloys with minimum HAZ, because of lower heat input, concentrated energy delivery, high aspect ratio, narrow heat affected zone, minimum thermal distortion, ease of automation, high welding speed, greater design flexibility, clean and high energy density [6]. The quality of similar/dissimilar laser weld depends on the range of process parameters viz., peak power, pulse duration, frequency, focusing length and welding speed [7]. In this study, a novel approach of dissimilar laser welding of Hastelloy C-276 – Monel 400 sheets and subsequent annealing is attempted, and the variation in mechanical strength, due to annealing is reported.

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## 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 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 was attempted.

**Table 1: Chemical composition of participant alloys**

Elements Wt. (%)	C	Si	Mn	Cr	Fe	Mo	Co	Nb	Cu	Al	V	Ti	W	Ni
<b>Hastelloy C-276</b>	0.01	0.029	0.39	14.96	5.53	15.68	0.22	0.01	0.138	0.085	0.023	0.006	3.15	Bal.
<b>Monel 400</b>	0.09	0.035	0.85	0.09	2.45	0.013	0.08	-	31.23	0.151	-	0.008	-	Bal.

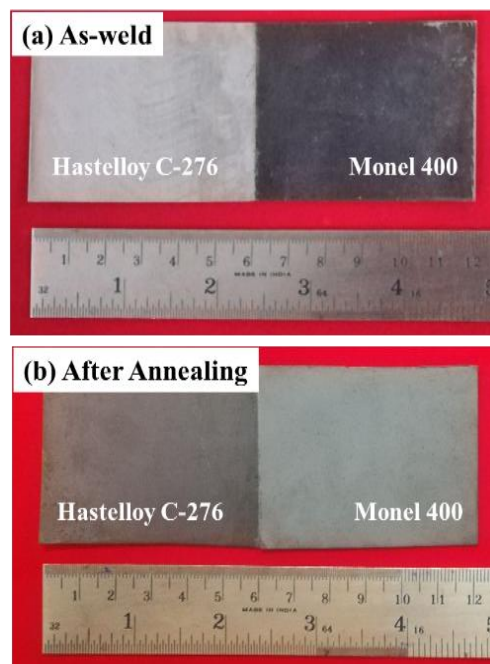
The base alloys (150 mm × 60 mm × 0.5 mm) were cleaned using acetone in order to remove the contaminations on the welding surface. The dissimilar metals were butt welded at a welding speed of 400 mm/min, laser power 200 W and focusing the laser beam on the surface, utilizing argon (10 lit/min) as the shielding-gas, which prevents the welding zone and its front from strong oxidization. After welding, the as-weld specimens were subjected to annealing at 960° in an INDFUR furnace for one hour and cooled in the furnace. The as-weld samples (Fig. 1. a) and annealed samples (Fig. 1. b) were polished by using grit of various grade emery sheets (220-2500 SiC) and diamond paste for the microstructure analysis. A solution containing 15 ml HCl, 10 ml HNO<sub>3</sub> and 10 ml glacial acetic acid is applied on the Hastelloy C-276 region, while Marbles reagent (20 ml HCl, 20 ml H<sub>2</sub>O and 2 g CuSO<sub>4</sub>) being applied on the Monel 400 region and weld zone.

testing was performed in a universal testing machine (UNITEK- 94100) at ambience.

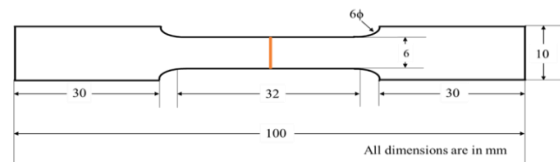
**Table 1: Mechanical properties of participant alloys**

Materials	Tensile strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (Hv)
<b>Hastelloy C-276</b>	1120	1036	11	386
<b>Monel 400</b>	525	392	18	195

Micro-hardness measurements of the as-weld and annealed samples across the interface were determined by a Vickers micro hardness tester (ZWICK-3212), the applied load and time period being 300 g and 10 s respectively. Similarly, tensile samples were prepared as per ASTM E8 standard with sub size dimensions 100 mm × 10 mm × 0.5 mm (Fig.2), and the



**Fig. 1 Nd: YAG laser welded joints (a) as-weld (b) annealed**



**Fig.2 ASTM E8 standard tensile test specimen**

### 3. Results and discussion

#### 3.1 Microstructure

The interface microstructure of laser welded Hastelloy - Monel sheets exhibit complete penetration of weld, free from defects and cracks, similar to the results of Neves et al [8].

The complete penetration is attributed by the faster solidification rate and cooling speed due to the higher heat removal rate. The nature of microstructure formation at the weld zone and HAZ are dictated by the heat input to the interface. The heat input depends on the process parameters viz., laser power and welding speed given by [9]

$$\text{Heat input} = \text{average power} / \text{welding speed} \quad (1)$$

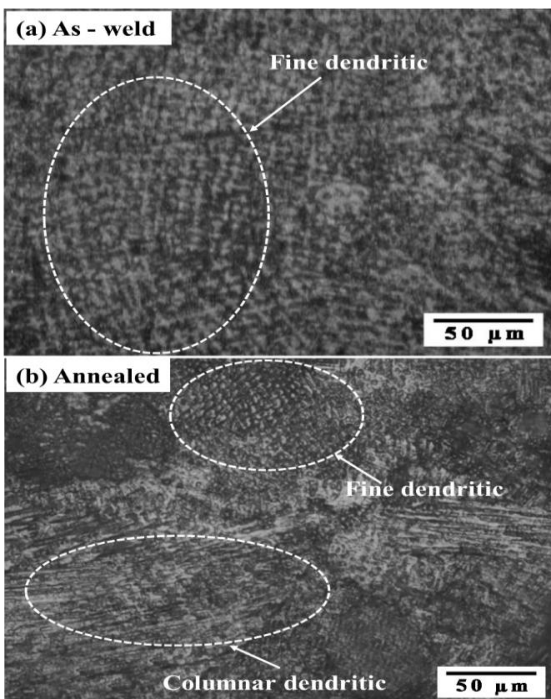


Fig.3 Microstructure of the dissimilar weld (a) as-weld (b) annealed

The microstructure of the dissimilar weld, in as-weld condition (Fig. 3 a), show the formation of fine dendritic grains at the bottom and columnar grains at the top. The variation in the solidification is attributed by the welding conditions and the selection of process parameters. Dendritic grains are formed due to the increase in growth velocity towards the center of the weld. Post annealing, the dendritic and columnar grains are still finer (Fig.3 b) in different regions of the weld

zone. The heat treatment provides energy for the generation of new smaller grains from the bigger grains nucleated in the as-weld condition. The increase in temperature is also attributed by the presence of copper in the participant metals. Kumar et al [9], while joining Hastelloy C-276 - Monel 400 at different welding speeds, opined that the minimum segregation of molybdenum from the weld zone leads to equally dispersed fine dendritic grains as observed in Fig. 3.b.

#### 3.2 Micro-hardness

The variation in hardness in the weld zone and heat affected zone of the as-weld and annealed dissimilar laser weld is shown in Fig.4. The hardness of as-weld weld zone varies from 288 Hv to 297 Hv for the attempted condition. The average hardness of the weld zone (292 Hv), in as-welded condition, is higher than the weaker parent metal (Monel 400) indicating stronger weld zone consistent with Bagchi et al [10]. However, subsequent to annealing, the hardness at various regions of the weld reduces by 10 % (Fig. 4). Saravanan et al. while attempting post weld heat treatment of SDSS alloy, opined that the softening of grains, due to annealing, decreases the hardness and is consistent with this study [11].

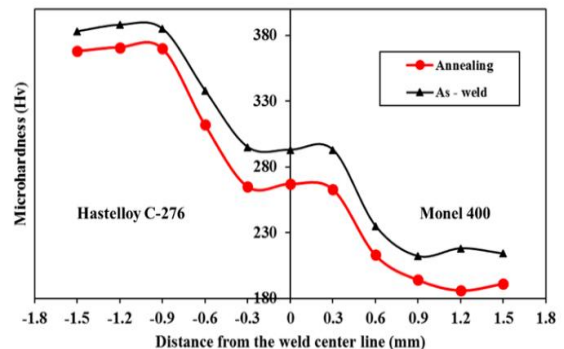


Fig.4 Microhardness profile of laser welded Hastelloy C-276 – Monel 400

#### 3.3 Tensile strength

The tensile specimens in as-weld and annealed conditions, prior and post testing are shown in Fig. 5.a and Fig. 5.b respectively. During the application of tensile load, fracture took place in the Monel 400 side, in both as-weld and annealed conditions, indicating stronger weld zone (Fig. 5.b). operate satisfactorily in an operating condition at elevated temperature.

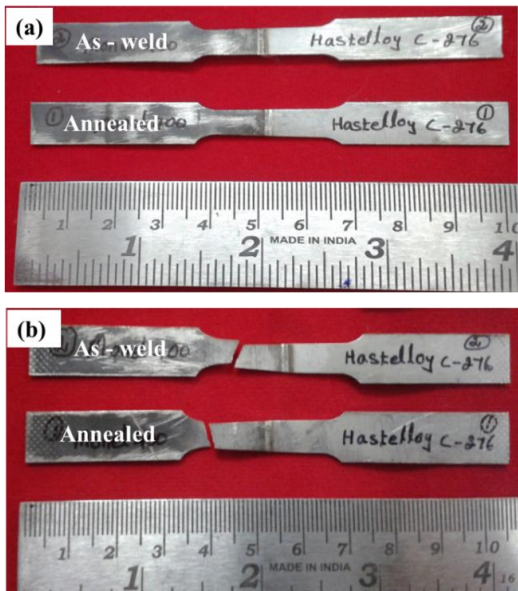


Fig. 5 (a) Tensile specimens (b) Fractured specimens

The tensile strength of the as-weld joints is higher than the annealed weld joints. The average tensile strength of as-weld dissimilar joints (685 MPa) is 4 % higher than the annealed joints (655 MPa). However, the higher tensile strength of the annealed joint is higher than the weaker base alloy, consistent with the reports of Saravanan et al [11]. Hence, it is inferred that, the weld joint can effectively

#### 4. Conclusions

The Nd: YAG laser welding of Hastelloy C-276-Monel 400 sheets and the same subjected to annealing leads the following major conclusions.

- The dissimilar weld can effectively employed at higher operating temperature.
- The nature of interface and the weld zone microstructure is attributed by the heat input.
- Annealing promotes the formation of finer grains at the weld zone.
- Micro-hardness and tensile strength of the dissimilar laser weld joints marginally reduces after annealing.
- Both as-weld and annealed tensile specimens failed in the weaker base alloy, indicating a stronger weld zone.

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