

Analysis of Hole Taper, Recast Layer and Heat Affected zone in pulsed O₂ and N₂ laser drilling of Difficult-to-cut alloy Nimonic C-263

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Abstract. The quality and performance of the drilled component is of prime importance in the development of aero-engine components and are directly related to the quality of HAZ, Recast Layer and Hole taper. In order to maintain and/or improve the reliability of aerospace components, it is first essential to be aware of the possible damages that can be imparted to a material when it is drilled. Therefore, an attempt has been taken to investigate the effect of laser drilling parameters such as Gas Type: O₂, N₂; Power: 3200Watts, 3900Watts and Pressure: 4 bars, 5 bars, while laser drilling the Nimonic C-263 super alloy. Laser drilling trails have been conducted with different combinations of drilling parameters. The quality of the drilled holes such as Hole Tapper, HAZ and Recast Layer were evaluated quantitatively and analyzed through scanning electron microscope (SEM).

Key Words: Laser Drilling, N₂ –Nitrogen, O₂- Oxygen, Nimonic C-263, Hole Taper, Recast Layer and Heat Affected Zone (HAZ).

1.Introduction

Nickel based super alloys are finding wider applications in the development of critical components for high-performance aircraft gas turbine engines due to their superior mechanical properties that are maintained to elevated temperatures and the reliability is also most important in the manufacture of aerospace components and therefore, aerospace manufacturers need to maintain high-quality on a consistent basis. [1]. The microstructure also affects the machinability of alloys in two ways: The presence of graphite or sulphide phases greatly improves machinability. Hard phases, such as carbides, nitrides, carbonitrides, oxides, silicates and possibly the γ' phase (Ni₃ (Al, Ti)), are abrasive causing rapid tool wear. The super alloy or high-performance alloy exhibits excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. Super alloys typically have a matrix with an austenitic face-centred cubic crystal structure. Their high temperature performance is distinguished in their tensile strength, hot hardness, creep resistance, and corrosion resistance at elevated temperatures are the important mechanical properties of interest [2].

Among the varieties of heat resistant materials, nickel based Nimonic C-263 super alloy finds wider use in the combustion portion of the gas turbine, heat exchangers, power generators and it is



becoming important in the manufacturing of components such as casings, rings, seals etc. and some components are shown in the Fig.1, in which the drilling operations are used to make holes.

Laser drilling technique is widely used in the aerospace industry for manufacturing effusion-cooling holes on aerospace components as this technique is able to drill super alloys at acute angles [3]. Sanasam Sunderlal Singh et al [4] stated that the Laser- Induced Micro machining (LIMM) produced better machining efficiency than other non-conventional machining processes in terms of the machining rate, metal removal, surface morphology and capability to machine wide range of materials irrespective of its hardness and electrical conductivity. The micro scale mechanical drilling is difficult in the parts made of difficult to cut materials and also number of researchers said that the chisel edge contributes to the total thrust force [5]. Ahn et al [6] investigated the effects of machining parameters on thermal characteristics, kerfwidth and the heat transfer phenomenon in laser cutting of Inconel 718 alloy sheet using a CW Nd: YAG laser and the temperature distribution in the vicinity of the cut section has also been quantitatively evaluated. Venkata Rao et al [7] reviewed the optimization aspects of various parameters of the modern machining processes such as laser beam machining, electric discharge machining, abrasive jet machining, ultrasonic machining, electrochemical machining, , micro-machining, nano-finishing and they also stated that these machining processes are useful to do precise machining operations.

R. Biswas et al [8] said that the taper formation and production of non-circular holes are the characteristics of the laser drilling and the laser machining depends on the interaction of a laser beam with inherent focusing characteristics and they further said that the modeling and optimization of the process parameters are needed to control the laser drilling characteristics. Habib Alavi et al [9] experimentally investigated ultrasonic vibrations-assisted continuous wave laser drilling of materials. They stated that the drilling rate and the quality of laser drilled holes depend on the material removal mechanism. Sanjay Kumar et al [10] observed that the laser trepan drilling (LTD) produces better quality holes compared to laser percussion drilling (LPD) and they optimized multiple quality characteristics using computer-aided genetic algorithm-based multi objective optimization (CGAMO). Tatjana V. Sibalija et al [11] presented a hybrid design such as Quality loss function Grey relational analysis and Neural network Genetic algorithm for the determination of the optimum laser drilling parameters which simultaneously meets the requirements of quality characteristics of the holes produced during pulsed Nd:YAG laser drilling of a thin sheet of nickel-based super alloy Nimonic 263.

Bandyopadhyay et al [12] conducted an experiment to study the effect of the process variables such as pulse energy, pulse repetition rate, pulse duration, focal position, nozzle standoff, type of gas and gas pressure on the quality of the hole based on the Taguchi design and these process variables were optimized and they reported that the low level of pulse duration and pulse energy are the ideal conditions to obtain minimum taper-drilled hole. Ghoreishi et al [13] investigated the interaction effect of laser peak power, laser pulse width, pulse frequency, number of pulses, assist gas pressure and focal plane position on the hole taper and circularity in laser percussion drilling on stainless steel and mild steel based on the central composite design (CCD). They reported that the pulse frequency has significant on the hole entrance diameter and hole circularity in drilling stainless steel.

Sanjay Mishra and Vinod Yadava [14] developed a prediction model for laser beam percussion drilling (LBPDP) using coupled methodology of FEM, ANN. They developed FEM based thermal models for LBPDP by considering the temperature-dependent properties, optical properties and phase change of aluminum and the results obtained through FEM is validated and compared with experimental results for hole taper. Further, they developed ANN model to predict the hole taper and material removal rates by considering the process variables such as pulse width, pulse frequency, in which they found out that pulse width affects significantly the responses where as the pulse frequency affects significantly the HAZ. Naifei Ren et al [15] investigated the influence of laser parameters such

as laser energy and pulse number on the quality of the drilled holes and they observed that the crater depth and the diameter are increased by increasing the number of laser pulses and laser energy.

Based on the literature, it was found there is no comprehensive study on the influence of laser drilling parameters in laser drilling of Nimonic C-263 alloy. In the present investigation, the laser drilling of Nimonic C-263 is performed by using O₂ and N₂ gases and the effects of process parameters such as power, pressure and type of gases on the responses such as Hole taper, Recast layer and Heat Affected Zone (HAZ) have been studied and analysed.

2. EXPERIMENTAL DETAILS AND PROCEDURE

Nimonic C-263 alloy of 75 mm diameter and 5mm thickness was used as work material for all the experiments. The chemical composition of the Nimonic C-263 alloy is such as: Ni52.49%, Si0.19%, Mn0.46%, Cr20%, Mo6.29%, Cu0.07%, Fe1.0%, Co16.7%, Ti1.94%, Al0.48%, W0.15%, Va0.02%, C0.02%, S0.001% and Tan 0.007%. The microstructure of Nimonic C-263 alloy is shown in figure.1. In addition, the Nimonic C-263 alloy was identified by the Electro Dispersive Spectroscopy (EDS) analysis to contain Ni (higher content), Cr, Co, Ti, Mo, Al and V elements as shown figure.2. From the microstructure of this alloy, significant amounts of MC type carbides (enriched with Ti) within the grains are seen (as black dots) in the solution treated specimen of the nimonic C-263 alloy. The mechanical properties of the Nimonic C-263 alloy are given in Table 1. The experimental study was carried out by using TRU Laser 3040 machine with the following specification: Laser capacity of 4000Watts, Main supply of 400V/50HZ, connected load of 88 KVA, Control voltage of 24V, Preliminary fuse of 3x/160A, Air connection of 7-10 bar, Nitrogen supply of 30 bar, Oxygen supply of 20 bar and Machine No AO24OAO536. The experimental set-up is shown in figure. 3.

Laser drilling tests were carried by varying the machining parameters such as: Power; 3200Watts, and 3900Watts; Pressure: 4 bars, 5 bars and Gas Type: N₂ and O₂. The laser drilling performance was evaluated by the following responses such as Hole Taper angle, Heat Affected Zone (HAZ) and Recast layer. The laser drilled work piece at different level machining parameters is shown in figure .4.

Table 1 Mechanical Properties of Nimonic C-263 alloy

S.No	Properties	Units	Values
1	Yield strength	MPa	689
2	0.2 % Proof Stress	MPa	692
3	Ultimate strength	MPa	1060
4	Elongation	%	35
5	Reduction in area	%	28
5	Hardness	HV	320

3. RESULTS AND DISCUSSION

3.1 Influence of the machining parameters on the Hole Taper, HAZ and Recast Cast Layer

The hole taper angle of a drilled hole is one of the main characteristics of its quality since it affects geometrical characteristics and ultimately, the reliability of the product. The hole taper angle can be calculated from the Eq. (1).

$$\text{Taper (deg)} = (d_{\max} - d_{\min}) / 2t \times 180 / \pi \quad \text{----- (1)}$$

Where, d_{\max} is the entrance diameter of the hole, d_{\min} is the exit diameter of the hole, t is the material thickness [13]. Hole Taper angles in laser drilling of Nimonic C-263 alloy at different level of power and pressure while O₂ and N₂ gases are illustrated in figure .5. (a-b). From the illustration it is observed, that, as the power is increased, the hole taper angle

reduced at higher pressure level of 5 bar while using O₂ gas, it is due to that, the effect of high pressure at hole exit diameter is higher than the hole entrance diameter and high power produces large entrance diameter. [3], however the Hole Taper angle is increased while drilling using N₂ gases.

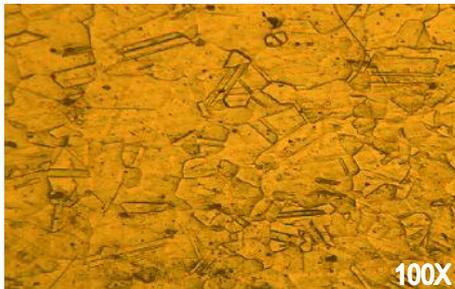


Figure .1.Microstructure of Nimonic C-263 Alloy

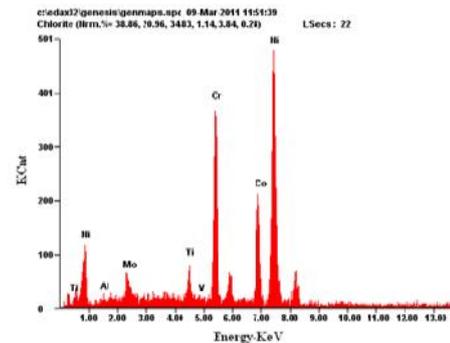


Figure.2.EDS Analysis of Nimonic C-263 Alloy

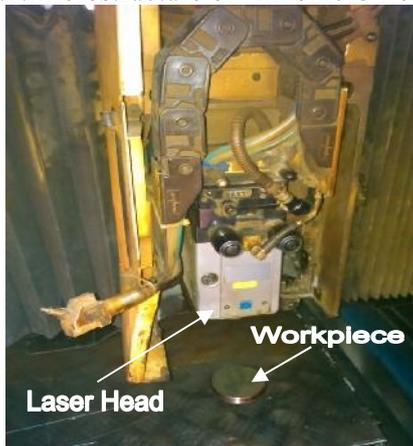


Figure. 3 .Experimental set up



Figure.4. Laser Drilled Work piece at different level of Machining Parameters

Hole taper angle is increased at high power and low pressure in laser drilling of Nimonic C-263 alloy while using O₂ and N₂ gases. Hole taper angle observed at 3900 watts, 4 bars during laser drilling while using O₂ gas is 1.57 times higher than the Hole Taper observed at 3200 watts, 4 bars by using N₂ gas, which is shown in figure.5.(b).The hole taper angle observed at 3900 watts, 5 bars in laser drilling of Nimonic C-263 alloy while using N₂ is 1.064 times higher than the hole taper angle observed at 3900 watts, 5 bars while using O₂ gas and the hole taper angle observed at 3200 watts, 5 bars while using O₂ gas is 1.14 times higher than the hole taper angle observed at 3200 watts, 5 bars while using N₂ gas, which is shown in figure.5. (a).From the Fig.6 (b), it is further observed that the hole taper angle at 3900 watts, 4 bars during laser drilling of Nimonic C-263 alloy while using O₂ is 1.50 times higher than the hole taper angle observed at 3900 watts, 4 bars while using N₂ gas and the hole taper angle observed at 3200 watts, 4 bars while using O₂ gas is 1.47 times higher than the hole taper angle observed at 3200 watts, 4 bars while using N₂ gas.

From figure.5. (a-b), it is revealed that the parameters such as power, pressure and gas type significantly affect the Hole Taper angle. The quality and the performance of a drilled component are also directly related to the quality of HAZ. The hole quality was examined by analyzing the SEM

image of the hole entrance and exit, after laser drilling at different levels of machining parameters and the affected zone were also measured quantitatively.

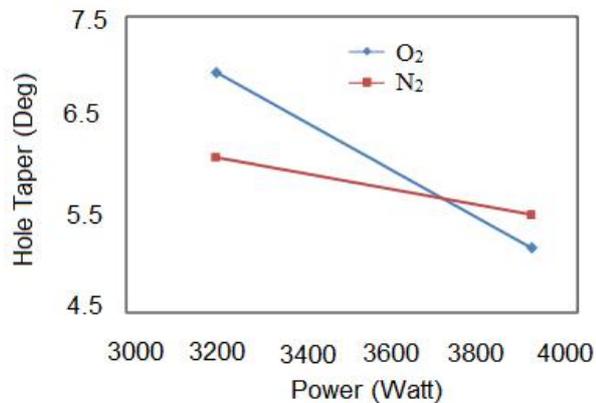


Figure.5. (a) Hole Taper for different level of Power at a Pressure of 5 bars.

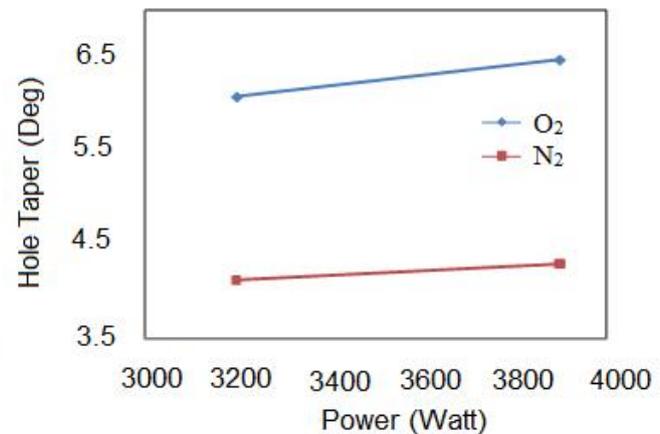


Figure.5. (b) Hole Taper for different level of Power at a Pressure of 4 bars.

Figure.5. (a-b) Hole Taper at different power and pressure While using O₂ and N₂ Gas

The Heat Affected Zone (HAZ) of laser assisted drilled hole is defined as a thin region on hole walls in which microstructure and properties are altered by laser drilling and HAZ determines the region with which the micro structure properties of the work piece is altered because of the thermal energy of the laser beam. [3]. The defects such as HAZ, Recast layer and spatter limit, the application of laser drilling and elimination of these defects are important to carry out precision drilling of variety of components. [16].HAZ in laser drilling of Nimonic C-263 alloy at different levels of power and pressure using O₂ and N₂ gases is illustrated in figure.6. (a-b).From the illustration it is observed that as the power is increased, the HAZ reduced at higher pressure level of 5 bars when O₂ gases is used, however the HAZ is increased while laser drilling by using N₂ gases. The HAZ is reduced when the power is increased from 3200 Watts to 3900 Watts, while drilling using O₂ gas at 4 bars, whereas the HAZ is increased when the power is increased from 3200 Watts to 3900 Watts, while laser drilling by using N₂ gas at 4 bars, which is 1.0923 times higher than the HAZ observed at 3900 watts, 4 bars while using O₂ gas, which is shown in figure.6. (b), it is due to hot molten metal flow [13], it is eventually shown in the Fig.9. (h), in which larger HAZ is observed in the drilled hole at exit. From figure.6. (a-b) revealed that the parameters such as power, pressure and gas type significantly affect the HAZ.

HAZ observed at 3900 watts, 5 bars while laser drilling of Nimonic C-263 alloy using N₂ is 1.20 times higher than HAZ observed at 3900 watts, 5 bars while using O₂ gas and the HAZ observed at 3200 watts, 5 bars while using N₂ gas is 1.071 times higher than the HAZ observed at 3200 watts, 5 bars while using O₂ gas, which is shown in figure.6. (a). From the figure.6 (b), It is observed that the HAZ at 3900 watts, 4 bars while laser drilling of Nimonic C-263 alloy using N₂ is 1.15 times higher than the HAZ observed at 3900 watts, 4 bars while using O₂ gas and the HAZ observed at 3200 watts, 4 bars while using O₂ gas is 1.06 times higher than the HAZ observed at 3200 watts, 4 bars while using N₂ gas. From figure.6. (a-b), it is revealed that the parameters such as power, pressure and gas type significantly affect the HAZ.

The hole quality is also related to the formation of Recast layer in the drilled hole and is examined by analyzing the SEM image of the hole entrance and exit after laser drilling at different levels of machining parameters and the Recast layer were also measured quantitatively. The Recast layer

in laser drilling of Nimonic C-263 alloy at different levels of power and pressure using O₂ and N₂ gases is illustrated in figure.7. (a-b). From the illustration it is observed, that as the power is increased, the Recast layer is increased at higher pressure level of 5 bars when N₂ and O₂ gases are used, however higher Recast layer is observed at 3900watts, 4 bars while drilling using N₂ gas which 1.68 times higher than the Recast Layer observed at 3200 watt, 4 bars using N₂ gas.

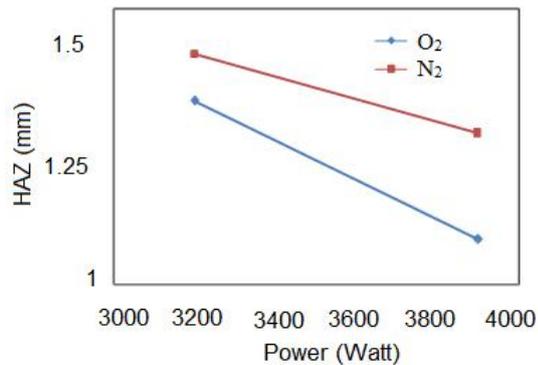


Figure.6. (a) HAZ for different level of Power at a Pressure of 5 bars.

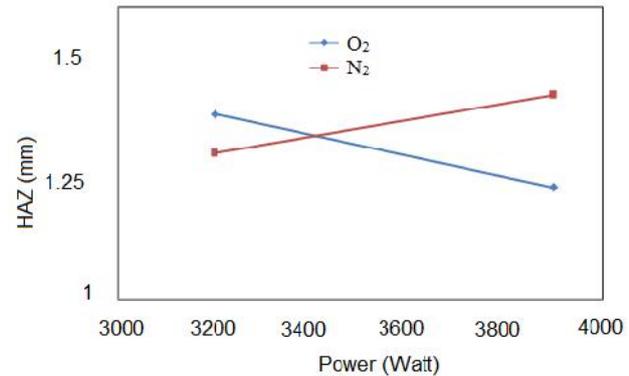


Figure.6. (b) HAZ for different level of Power at a Pressure of 4 bars.

Figure.6. (a-b) HAZ at different power and pressure While using O₂ and N₂ Gas

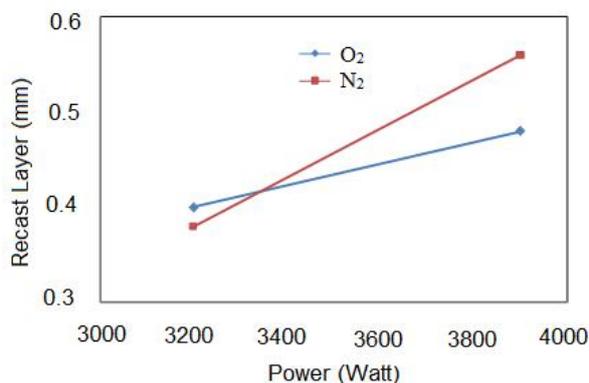


Figure.7. (a) Recast Layer for different level of Power at a Pressure of 5 bars.

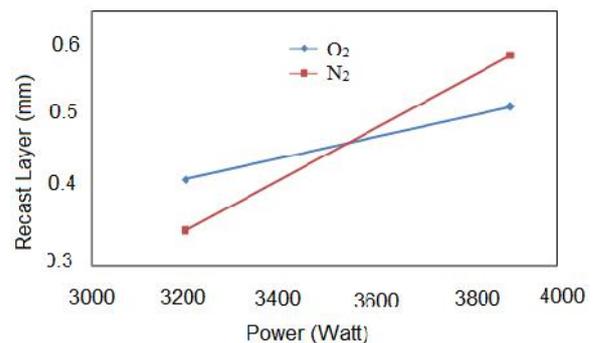


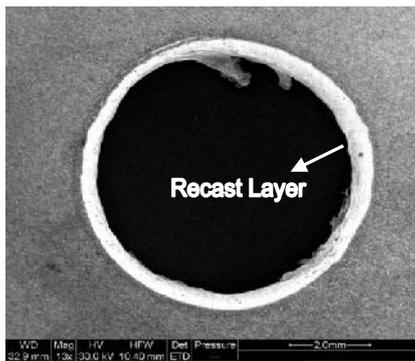
Figure.7. (b) Recast Layer for different level of Power at a Pressure of 4 bars.

Figure.7. (a-b) Recast Layer at different power and pressure While Using O₂ and N₂ Gas

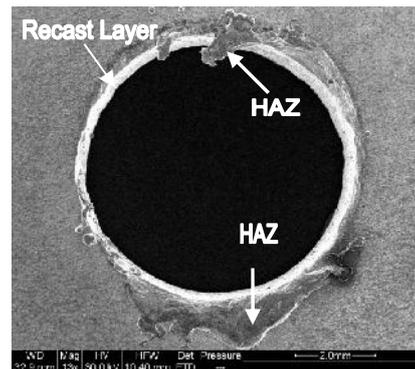
The Recast layer observed at 3900 watts, 5 bars while laser drilling of Nimonic C-263 alloy by using N₂ is 1.164 times higher than the Recast layer observed at 3900 watts, 5 bars while using O₂ gas and the Recast layer observed at 3200 watts, 5 bars while using O₂ gas is 1.05 times higher than the Recast layer observed at 3200 watts, 5 bars while using N₂ gas, which is shown in figure.7. (a). From the figure.7 (b), it is observed that the Recast layer at 3900 watts, 4 bars while laser drilling of Nimonic C-263 alloy by using N₂ is 1.134 times higher than the Recast layer observed at 3900 watts, 4 bars while using O₂ gas and the Recast layer observed at 3200 watts, 4 bars while using O₂ gas is 1.2 times higher than the Recast layer observed at 3200 watts, 4 bars while using N₂ gas. From figure.7. (a-b), it is revealed that the parameters such as power, pressure and gas type significantly affect the Recast layer.

Figure.8. (a-p) shows the SEM images of laser drilled holes while using O₂ and N₂ gases at different power and pressure. The damages such as recast layer, HAZ, oxide layer and spatter are all observed. Figure.8. (a-p) revealed that the HAZ is observed mostly at the drilled hole at exit, however the HAZ is also observed at the hole entry which is shown in Figure 3.1.4 (k,m,o) and these HAZ are

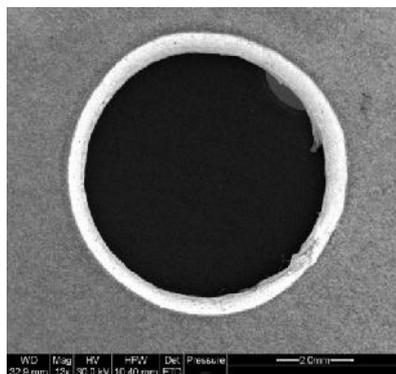
lower than the HAZ observed at exit drilled hole. The Recast layer is observed in the laser drilled hole at both entry and exit of the drilled hole for all cutting conditions, which is eventually shown in figure.8. (a-p), however the higher Recast layer is observed in figure.8. (a-h).The oxide layer is observed in the drilled hole at exit only while drilling this Nimonic C-263 alloy which is eventually shown in the figure.8 (f, j, l, n, p),however higher oxide layer is observed at 3200 watts while drilling at 4 and 5 bars with respect to O₂ and N₂ gases , which is eventually shown in figure.8. (J, l, n) and oxide layer is not observed at hole entry. The distinct oxide inclusions were also observed at 3200 watts, 5 bars while using O₂ gas which is shown in figure.8.(j). It can also be observed that the laser assisted drilling exhibit spatter is shown in figure.8.(f, g, n).



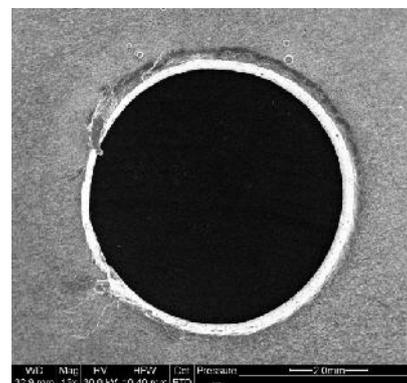
a. Laser drilled hole at entry at 3900 Watt,5 bars using O₂



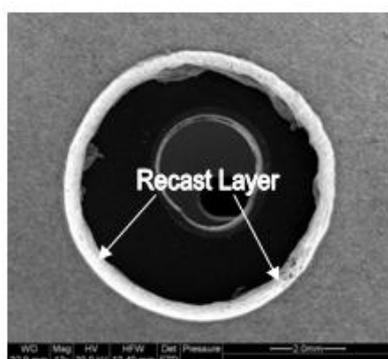
b. Laser drilled hole at exit at 3900 Watt. 5 bars using O₂



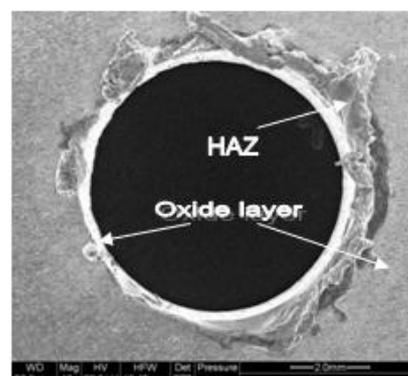
c. Laser drilled hole at entry at 3900 Watt, 4 bars using O₂ gas



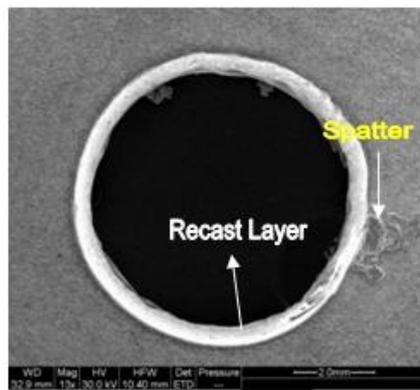
d. Laser drilled hole at exit at 3900 Watt, 4 bars using O₂ gas



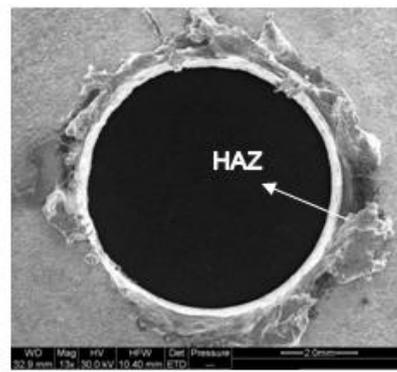
e. Laser drilled hole at entry at 3900 Watt, 5 bars using N₂



f. Laser drilled hole at exit at 3900 Watt, 5 bars using N₂



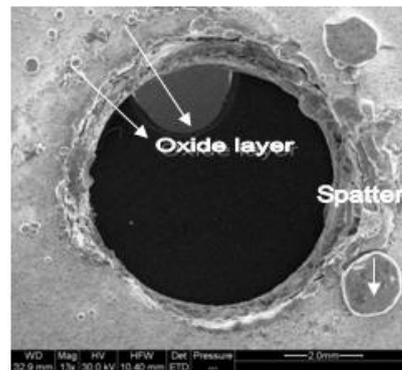
g. Laser drilled hole at entry at 3900 Watt, 4 bars using N2



h. Laser drilled hole at exit at 3900 Watt, 4 bars using N2



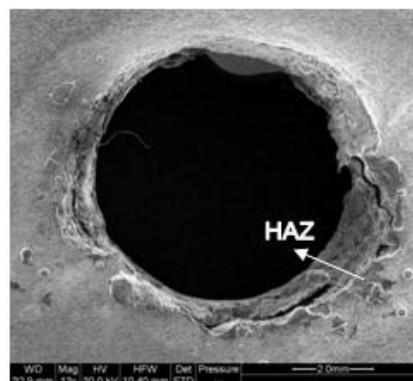
m. Laser drilled hole at entry at 3200 Watt, 5 bars using N2



n. Laser drilled hole at exit at 3200 Watt, 5 bars using N2



o. Laser drilled hole at entry at 3200 Watt, 4 bars using N2



p. Laser drilled hole at exit at 3200 Watt, 4 bars using N2

Figure.8. (a-p) Typical SEM Images of Laser drilled hole at different power and pressure using N₂ and O₂ gases

Figure.9. shows the experimental results of HAZ, Recast layer of the drilled hole at different cutting conditions with respect to N₂ and O₂ gases and the corresponding typical SEM images of the drilled holes are also shown. It is observed from these figure.9, that the thickness of the HAZ and Recast layer varied when cutting conditions varied. An increase in HAZ and Recast layer occurs while drilling Nimonic C-263 when the power is reduced from 3900watts to 3200 watts.

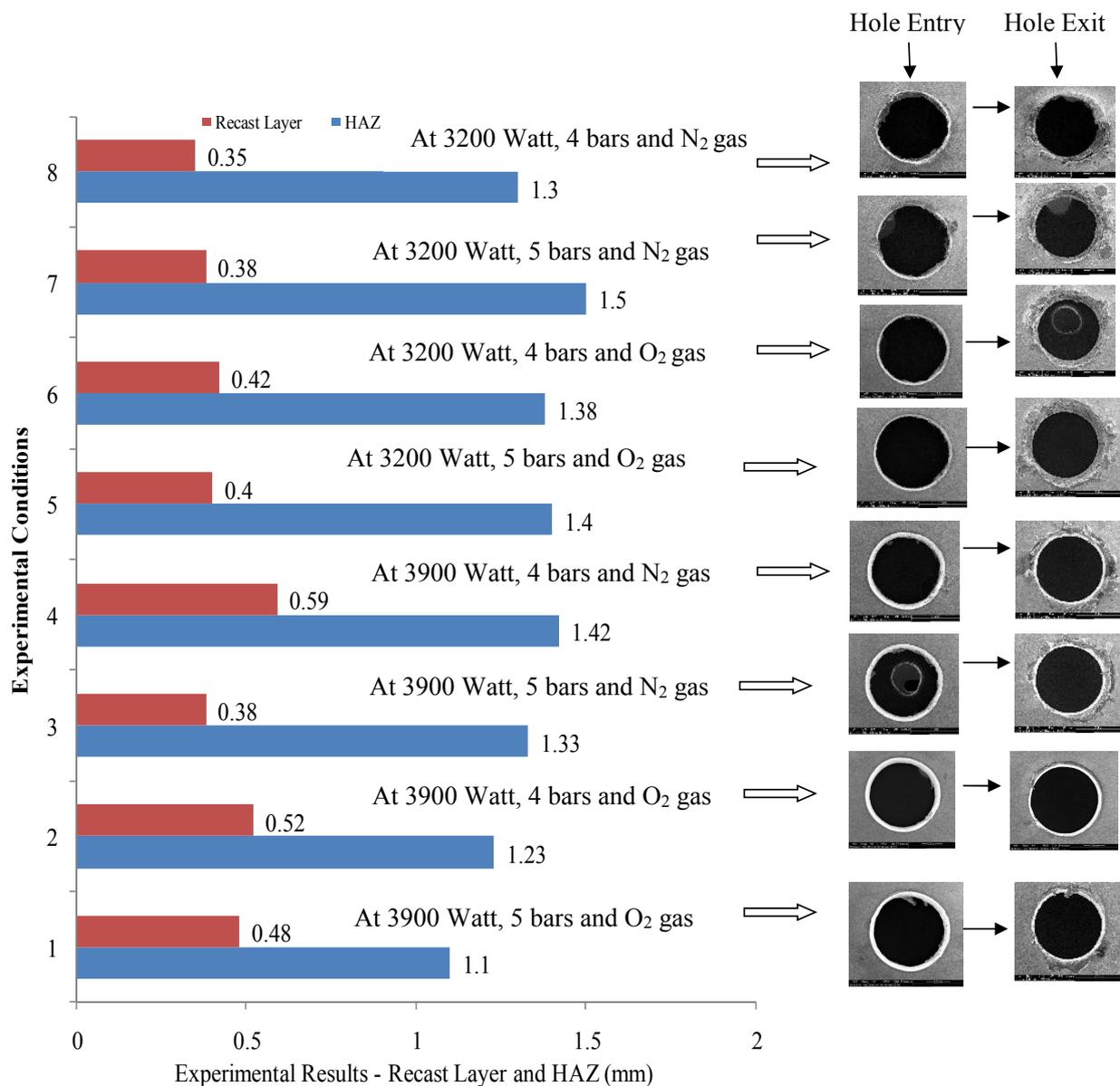


Figure.9. Experimental Results of HAZ, Recast Layer and Typical SEM Images of the drilled hole at different machining conditions.

4. Conclusion

The laser drilling of a difficult-to-cut alloy Nimonic C-263 using O₂ and N₂ gases has been performed and the effect of input parameters such as Pressure, power on Tapper angle, HAZ, and Recast layer were determined and the following conclusions were drawn.

- Higher Hole Tapper angle is observed at 3900 watt, 4 bars while drilling using O₂ gas, which is 1.57 times higher than the Hole Tapper angle observed at 3200 watt, 4 bars using N₂ gas.
- More cylindrical hole with less Hole Tapper angle of 4.12 is observed at 3200 Watt and 4 bars while drilling using N₂ gas.
- Higher HAZ is observed at 3900 Watt and 4 bars while drilling using N₂ gas, which is 1.0923 times higher than the HAZ observed at 3900 watt, 4 bars using O₂ gas.
- Higher Recast layer is observed at 3900 watt, 4 bars while drilling using N₂ gas which 1.68 times higher than the Recast Layer observed at 3200 watt, 4 bars using N₂ gas.
- The effect of laser parameters on the responses are observed as follows:

- When the power reduces from 3900 watts to 3200 watts at 5 bars and O₂:
Hole Tapper angle – Increases, HAZ-Increases, Recast Layer-Reduces
- When the power reduces from 3900 watts to 3200 watts at 5 bars and N₂:
Hole Tapper angle – Increases, HAZ-Increases, Recast Layer-Reduces.
- When the power reduces from 3900 watts to 3200 watts at 4 bars and O₂:
Hole Tapper angle – Reduces, HAZ-Increases, Recast Layer-Reduces.
- When the power reduces from 3900 watts to 3200 watts at 4 bars and N₂:
Hole Tapper angle – Reduces, HAZ- Reduces, Recast Layer-Reduces.
- When the power increases from 3200 watts to 3900 watts at 5 bars and O₂:
Hole Tapper angle – Reduces, HAZ-Increases, Recast Layer- Increases
- When the power increases from 3200 watts to 3900 watts at 5 bars and N₂:
Hole Tapper angle – Reduces, HAZ- Reduces, Recast Layer- Increases.
- When the power increases from 3200 watts to 3900 watts at 4 bars and O₂:
Hole Tapper angle – Increases, HAZ- Reduces, Recast Layer- Increases.
- When the power increases from 3200 watts to 3900 watts at 4 bars and N₂:
Hole Tapper angle – Increases, HAZ- Increases, Recast Layer- Increases.
- The oxide layer is observed in the drilled hole at exit only while drilling this Nimonic C-263 alloy.
- The damages such as Recast Layer, HAZ, Oxide Layer and Spatter were observed.

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