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Effect of Cutting Parameters on Drilled Hole Quality of Laser Machined AISI 304

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ABSTRACT

This study investigates the impact of material thickness on drilled hole quality during laser beam machining of AISI 304 stainless steel. Specifically, it explores the effects of cutting parameters, including material thickness, assist gas pressure, and nozzle size, on key performance indicators such as kerf width ratio (KWR) and heat-affected zone (HAZ). The results highlight the significant correlations between material thickness, cutting parameters, and hole quality, offering insights into optimizing laser machining for varying material thicknesses. This work contributes to the understanding of the intricate relationship between material properties and cutting parameters, providing valuable guidance for industries utilizing AISI 304 in precision manufacturing.

Keywords: Assisted Gas Pressure, Heat-Affected Zone (HAZ), Kerf Width Ratio (KWR), Laser Beam Machining (LBM).

1. INTRODUCTION

Laser Beam Machining (LBM) is a non-conventional processing technique that utilizes a focused laser beam to remove material through melting and vaporization, enabling high-precision machining of hard and brittle materials. This method is integral to industries such as aerospace, electronics, and manufacturing, where precision and material integrity are paramount. AISI 304 stainless steel, prominent for its exceptional corrosion resistance, formability, and mechanical strength, is widely used in LBM applications [2]. The process benefits from the use of assist gas pressure, which aids in the removal of molten material, prevents oxidation, and ensures clean cuts, thereby contributing to the overall quality of the machined features [3].

The optimization of cutting parameters, including material thickness, assist gas pressure, and nozzle size, plays a critical role in enhancing the performance of LBM. Thicker materials demand higher laser power and slower cutting speeds, which significantly influence kerf width and the heat-affected zone (HAZ). While assist gas pressure facilitates material removal and cooling, excessive pressure may lead to an enlarged kerf width, hence negatively impacting precision [4]. Nozzle size, which determines the focus and intensity of the laser beam, also influences cut quality. Optimizing these parameters is critical for achieving precise hole geometry, minimizing defects such as recast layers, and preserving the structural integrity of AISI 304 stainless steel [5].

This study provides a deeper understanding of the interactions between cutting parameters in laser hole drilling, such as laser power, pulse duration, and assist gas pressure, in a way to reduce HAZ, improve kerf quality, and mitigate thermal damage [7]. The insights derived from this

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research are expected to have significant implications for industries relying on AISI 304 stainless steel, promoting cost-effective, efficient, and high-precision manufacturing [8].

2. MATERIAL AND METHODS

This study investigates the cutting quality of AISI 304 stainless steel during laser hole drilling on AISI 304 stainless steel with thicknesses of 1.0 mm, 1.5 mm, and 2.0 mm. The mechanical and physical properties of AISI 304 stainless steel used are provided in Table 1. Testing samples were prepared by a laser hole drilling process using the Oree Laser OR-S1309 Fiber laser machine, as shown in Figure 1. Fixed machining parameters on the laser machining operational setup are shown in Table 2.

Table 1: Mechanical and physical properties of AISI 304.

Properties	AISI 304
Hardness (max)	215HBW
Tensile Strength (min)	500-700MPa
Yield Strength (min)	205-240MPa
Elongation after fracture (long. Min.)	45
Impact energy (min)	100J
Specific heat 0°C -100°C	500J/kg.K
Electrical resistivity	720 Ω.m

Table 2: Fixed parameters for laser beam machining operation.

Parameters	Unit/Description
Cutting speed	6000mm/min
Laser power	1000w – 3000w
Assisted gas type	Oxygen

Figure 1: Oree Laser OR-S1309 Fiber laser beam machine.

2.1 Taguchi Experimental Design Method

The experiment is designed using the Taguchi L9 orthogonal array. Table 3 shows machining variable parameters; material thickness, nozzle size, and assisted gas pressure were varied at three levels: Material thicknesses of 1 mm, 1.5 mm, and 2 mm, nozzle sizes of 1.0mm, 2.0mm, and 2.5mm, and assisted gas pressures of 4 bar, 5 bar, and 6 bar, respectively.

Table 3: Cutting parameters and levels for laser machining operation.

Cutting Parameters	Level		
	1	2	3
Material thickness [mm]	1.0	1.5	2.0
Nozzle size [mm]	1.0	2.0	2.5
Assist Gas Pressure [Bar]	4	5	6

2.2 Kerf Measurement

Kerf measurement specifies the width of the material that is removed during laser cutting from both the top (entry kerf) and bottom (exit kerf) surfaces of the sample, as shown in Figure 2. The kerf width on both top and bottom surfaces was measured using an optical microscope.

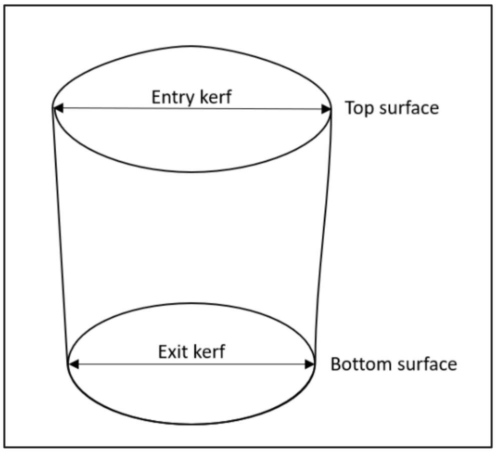


Figure 2: Entry kerf and exit kerf on a laser-drilled hole.

The kerf width ratio (KWR) in laser drilling is calculated from the differences of kerf measurement at the entry kerf and exit kerf using Equation (1).

$$Kerf\ Width\ Ratio = \frac{(X_1 - X_2)}{t} \quad (1)$$

Where X_1 is the kerf width at the top surface of the material in (mm), X_2 is the kerf width at the bottom surface of the material in (mm), and t is the material thickness in (mm).

2.3 Heat-Affected Zone (HAZ) Observation

Heat-Affected Zone (HAZ) is a material region that undergoes microstructural and mechanical changes due to the heat generated during laser cutting. The Heat-Affected Zone (HAZ) was observed using the IMT cam FHD optical microscope to evaluate the thermal effects on the material's surface at the entry and exit points on the laser-drilled hole. Macrostructural images were analyzed to assess the influence of cutting parameters on hole-edge quality.

3. RESULTS AND DISCUSSION

Results present the influence of material thicknesses (1.0 mm, 1.5 mm, 2.0 mm), assisted gas pressures (4 bar, 5 bar, 6 bar), and nozzle sizes (1.5 mm, 2.0 mm, 2.5 mm) on the precision and quality in laser hole drilling presented by the results of KWR measurement and thermal defect characterization from HAZ observation.

3.1 Effect of Material Thickness on Kerf Width Ratio (KWR)

Figure 3 shows the results of the kerf width ratio (KWR) for different material thicknesses (1.0 mm, 1.5 mm, and 2.0 mm) at various assisted gas pressures (4 Bar, 5 Bar, and 6 Bar). As material thickness increases, a decline in KWR is observed, which can be attributed to enhanced vertical heat concentration and reduced lateral heat dissipation in thicker materials. The lack of effective cooling results in a higher KWR because the laser energy is not entirely dissipated, leading to an expanded kerf width [9].

Assisted gas pressure shows its role in reducing the kerf width ratio as the pressure increases. At lower assisted gas pressures (4 Bar), the kerf width ratio is higher, particularly for the thinner materials, as the material is not efficiently cleared from the cutting zone. As the pressure increases to 5 Bar, a slight reduction in KWR is noted, indicating better material removal and cooling, leading to more controlled cutting and precision. At 6 Bar, the KWR decreases further, particularly for the 1.0 mm material, as the increased gas pressure helps to improve material removal and cooling. The increased assist gas pressure ensures that molten material is rapidly expelled from the cutting area, preventing the material from re-solidifying on the cut surface, thus decreasing the likelihood of recast layers and thermal damage.

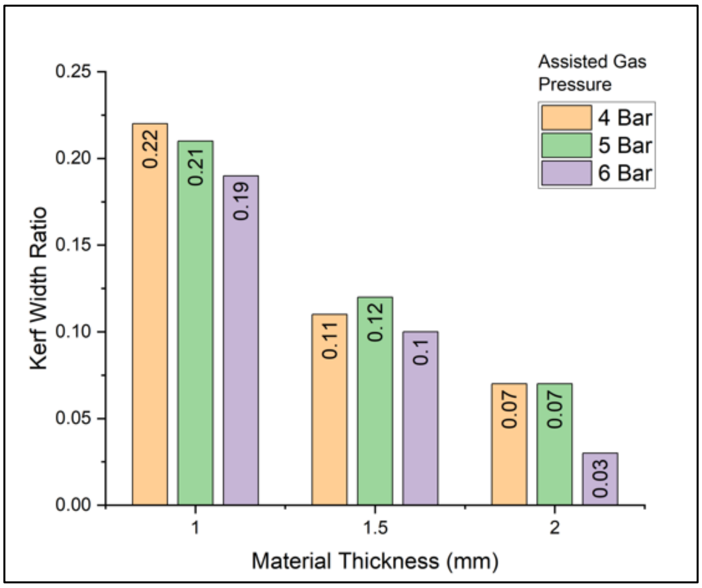


Figure 3: Effect of material thickness on Kerf Width Ratio.

3.2 Effect of Assisted Gas Pressure on Kerf Width Ratio (KWR)

Figure 4 below shows the kerf width ratio for different assist gas pressures across various material thicknesses. Increasing material thickness leads to a consistent decrease in KWR. This is attributed to the reduced lateral heat dissipation and enhanced vertical heat concentration in thicker materials, which causes the kerf width to increase, thereby lowering the precision of the cut. For 1.0 mm thick material, the KWR is significantly higher compared to the thicker materials (1.5 mm and 2.0 mm), indicating that the laser energy is more evenly distributed, resulting in better precision and a narrower kerf width.

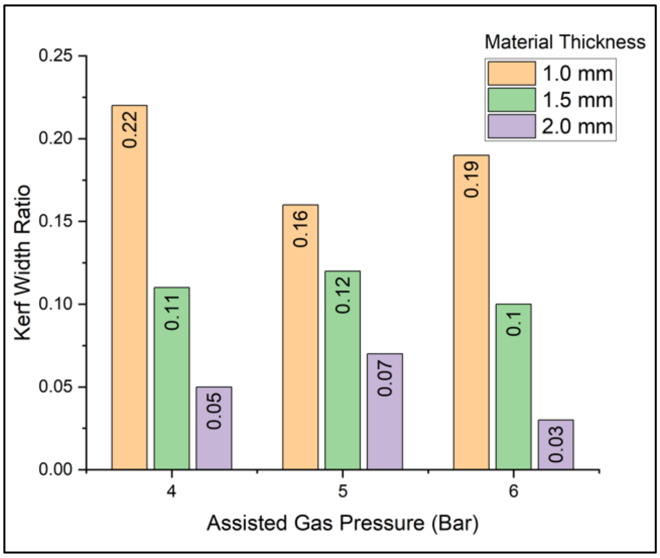


Figure 4: Effect of assisted gas pressure on Kerf Width Ratio.

3.3 Effect of Nozzle Size on Kerf Width Ratio (KWR)

Figure 5 shows the kerf width ratio for different nozzle sizes across material thicknesses. For 1.0 mm material, the KWR is notably higher at 1.5 mm nozzle size, indicating that the larger nozzle increases the laser beam's focus, causing a wider kerf due to the more concentrated energy. As the nozzle size increases to 2.0 mm and 2.5 mm, the KWR decreases significantly, showing that larger nozzle sizes promote better energy distribution, improving cutting precision and reducing the kerf width.

The kerf width ratio becomes more stable for thicker materials (1.5 mm and 2.0 mm) at higher nozzle sizes. This is attributed to the enhanced thermal dissipation and efficient material expulsion afforded by larger nozzles, hence maintaining cut quality [10].

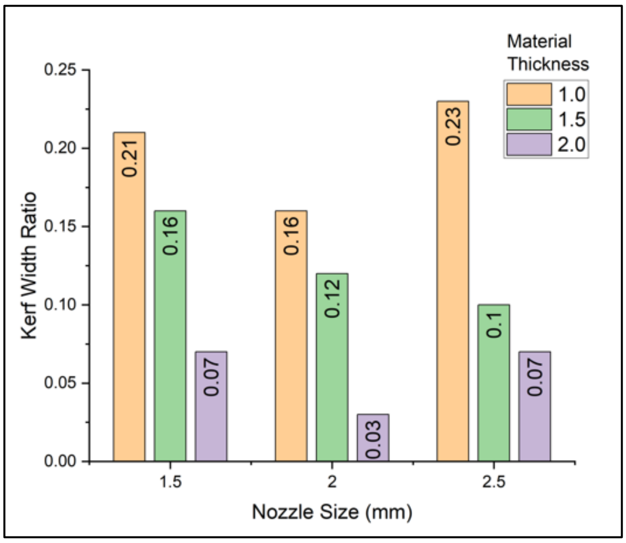


Figure 5: Effect of assisted gas pressure on Kerf Width Ratio.

3.4 Heat-Affected Zone (HAZ) Observation on Material Thicknesses

The Heat Affected Zone (HAZ), as observed in Figure 6, demonstrates the impact of material thickness on thermal damage on the top surface of laser-drilled holes for materials of 1.0 mm, 1.5 mm, and 2.0 mm thicknesses. The 1.0 mm material exhibits the least recast layer, whereas the 2.0 mm material shows a severe recast layer, indicating more significant thermal damage. Thicker materials absorb more laser energy, causing more heat to accumulate and hence expanding the heat-affected zone.

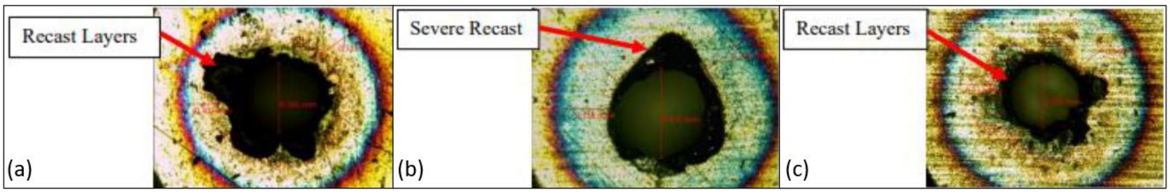


Figure 6: Heat Affected Zone (HAZ) observed from the top surface of laser-drilled holes, for (a) 1.0mm, (b) 1.5mm, and (c) 2.0mm material thicknesses.

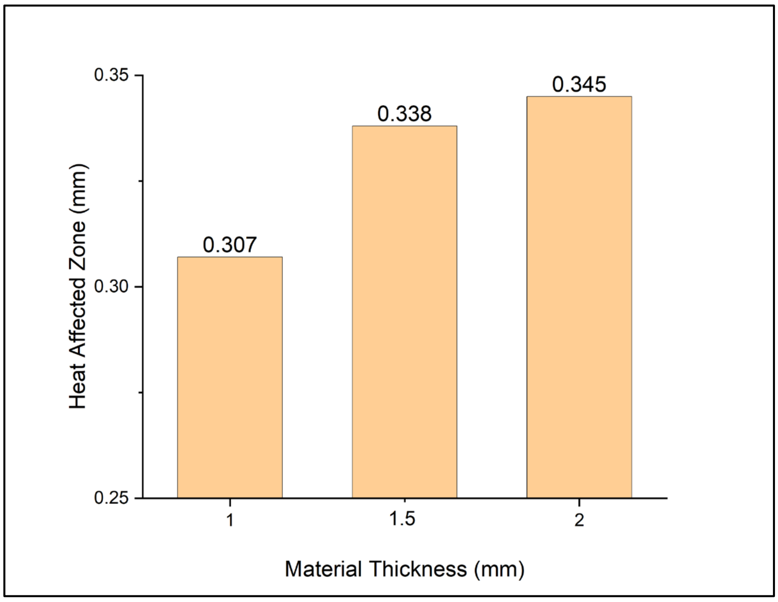


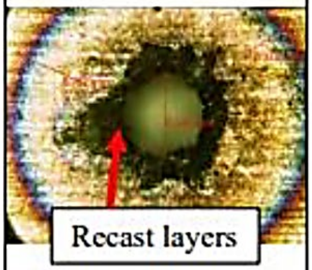
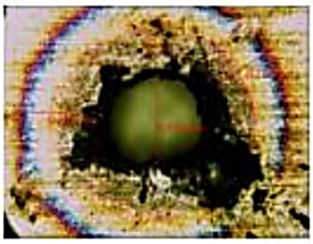
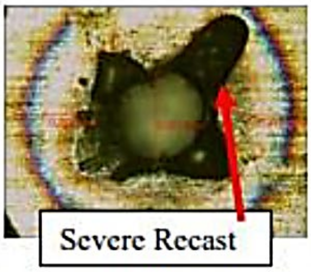
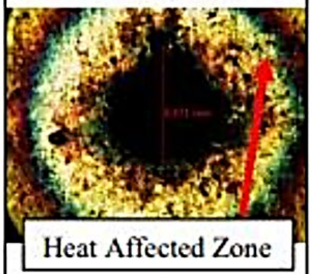
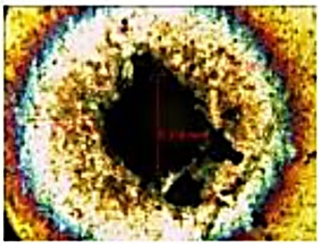
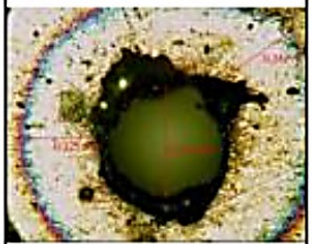
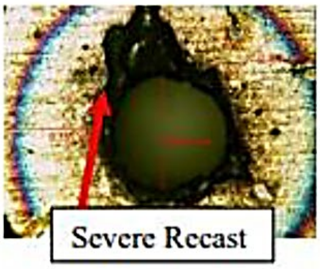
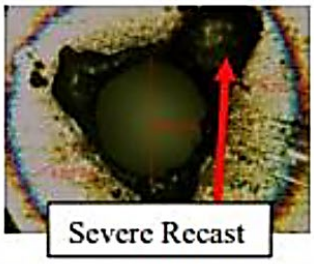
Figure 7: Heat Affected Zone (HAZ) on different material thicknesses.

Figure 7 quantitatively supports the macrography observations with the HAZ measurements for different material thicknesses. The HAZ increases with material thickness, with 1.0 mm showing a 0.307 mm heat-affected zone, 1.5 mm at 0.338 mm, and 2.0 mm at 0.345 mm. HAZ increases due to the greater energy absorption and reduced cooling efficiency in thicker materials, which results in a larger thermal footprint around the drilled hole [11].

3.5 Heat-Affected Zone (HAZ) Observation on Assisted Gas Pressures

Table 4 below shows the heat-affected zones for different assisted gas pressures and material thicknesses. The optical macrograph finds that increasing assisted gas pressure reduces heat buildup and minimizes HAZ in thicker materials. At 4 bars, there is uneven heat dispersion and recast layers build up, while at 6 bars, there is overcutting and material turbulence. The HAZ remains large across all gas pressures, particularly at 6 bar, and severe recast continues widening, caused by the fact that more laser energy is required, hence leading to higher thermal impacts on the material [11].

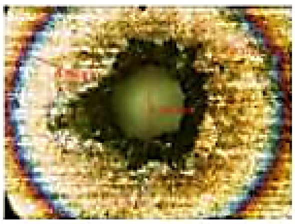
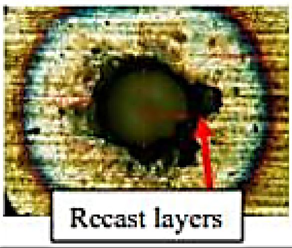
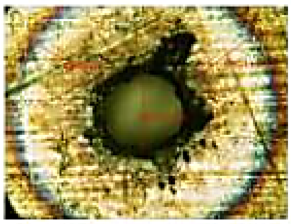
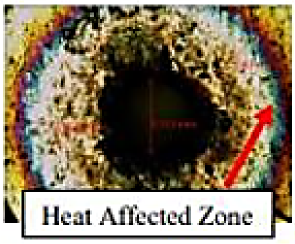
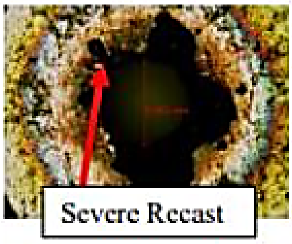
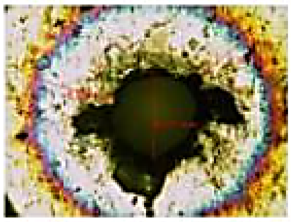
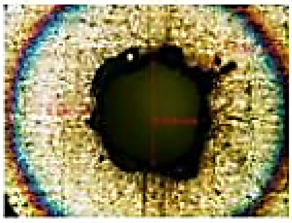
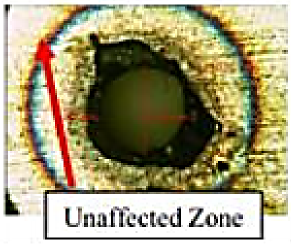
Table 4: Heat Affected Zone on different assisted gas pressures and material thicknesses.

Material Thickness	Assist Gas Pressure		
	4bar	5bar	6bar
1.0mm			
1.5mm			
2.0mm			

3.6 Heat-Affected Zone (HAZ) Observation on Nozzle Sizes

Table 5 below shows the heat-affected zones for different nozzle sizes and material thicknesses. Nozzle size strongly influenced HAZ formation. Smaller nozzles (1.5 mm) produced concentrated heat, minimizing HAZ for thin materials, while larger nozzles (2.5 mm) caused wider HAZ due to dispersed energy and slower cooling. At 1.0 mm material thickness, a 1.5 mm nozzle results in recast layers around the drilled hole, indicating a higher heat concentration. As the nozzle size increases to 2.0 mm and 2.5 mm, the HAZ becomes more pronounced, and the recast layer builds up more, indicating higher energy input and heat accumulation during the cutting process. These results suggest that larger nozzle sizes tend to increase the energy distribution over a wider area, leading to more thermal damage to the material, especially for thinner materials [12].

Table 5: Heat Affected Zone on different nozzle sizes and material thicknesses.

Material Thickness	Nozzle Size 1.5mm	Nozzle Size 2.0mm	Nozzle Size 2.5mm
1.0mm			
1.5mm			
2.0mm			

4. CONCLUSION

The investigation into laser machining parameters for AISI 304 has highlighted material thickness, assist gas pressure, and nozzle size as factors influencing drilled hole quality. In this study, it can be concluded from the results that a material thickness of 2.0 mm achieved the best kerf width ratio (KWR), efficiently absorbing energy for precise cutting. A gas pressure of 6 bar was found to enhance molten material removal, ensuring better hole accuracy and quality, while minimizing thermal damage. Additionally, a 2.0 mm nozzle size effectively balanced control and efficiency, optimizing the kerf width ratio and minimizing the Heat-Affected Zone (HAZ). These results highlight the importance of optimizing cutting parameters to achieve precise, high-quality cuts and minimize material and thermal defects, providing valuable insights for improving laser hole drilling processes across different materials.

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