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Effect of Cutting Parameters on Cutting-Edge Quality in Laser Machining of Various Metals

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ABSTRACT

This study investigates the effects of cutting speed and assisted gas pressure on the cutting-edge quality in laser machining of High-Speed Steel (HSS) and Mild Steel (MS) using oxygen as the assisting gas. The kerf width ratio (KWR) studied at the entry, middle, and exit points and the heat-affected zone (HAZ) was observed. Taguchi L9 orthogonal array was employed to optimize the experimental design, minimizing trials to achieve parameter impacts. Measurements of KWR and microscopic analysis of the HAZ were conducted to assess laser machined surface quality. Results reveal that cutting speed significantly affects KWR, with higher speeds producing narrower kerfs due to improved heat dissipation. HAZ analysis highlights distinct thermal effects, such as recast layers and gradients, with variations between HSS and MS attributed to differences in thermal conductivity and material properties. These findings provide valuable insights into optimizing laser machining parameters to enhance accuracy and efficiency, offering recommendations for various industrial applications.

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

1. INTRODUCTION

Laser Beam Machining (LBM) is a highly precise and versatile technology widely used in modern industries to cut, shape, and drill various materials with minimal thermal distortion. This non-contact process employs a concentrated laser beam combined with assisting gases like oxygen or nitrogen to achieve accurate and efficient material removal. Compared to conventional machining techniques, LBM offers significant advantages, including reduced tool wear, improved dimensional accuracy, and the ability to process a broad range of materials such as metals, ceramics, and composites. The adaptability of LBM has made it indispensable in sectors like aerospace, automotive, and electronics, where precision and quality are paramount. However, optimizing the cutting parameters, such as cutting speed and assisted gas pressure, remains critical to ensure consistent cutting-edge quality, minimize heat-affected zones (HAZ), and improve material utilization.

This study aims to investigate the influence of cutting speed and assisted gas pressure on the cutting-edge quality of High-Speed Steel (HSS) and Mild Steel (MS) during laser machining. The research employs the Taguchi L9 orthogonal array to systematically evaluate the kerf width ratio (KWR) across entry, middle, and exit points, as well as the impact on the HAZ. By exploring the thermal and mechanical interactions between the laser beam and materials, this study seeks to provide valuable insights into optimizing laser cutting operations for enhanced accuracy and efficiency in industrial applications.

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2. MATERIAL AND METHODS

This study focuses on laser beam machining of two materials: High-Speed Steel (HSS) and Mild Steel (MS), both with a thickness of 1.5 mm. These materials were chosen based on their widespread industrial applications with distinct thermal and mechanical properties. HSS is known for its superior hardness, thermal resistance, and wear properties, while MS is recognized for its ductility and ease of fabrication. Testing samples were prepared by laser cutting using the Oree Laser OR-S1309 Fiber laser beam machine, as shown in Figure 1. Fixed machining parameters such as nozzle size, laser power, and assisted gas type are shown in Table 1.

Figure 1: Oree Laser OR-S1309 Fiber Laser Beam Machine.

Table 1: Fixed Parameters for Laser Beam Machining Operation.

Parameters	Unit
Nozzle Size	2.0 mm
Laser power	1000 W – 3000 W
Assisted gas type	Oxygen

2.1 Taguchi Experimental Design Method

The experiment is designed using Taguchi L9 orthogonal array. There are 9 experimental trials for each material. Table 2 shows two machining parameters; cutting speed and assisted gas pressure were varied at three levels: 5 mm/min, 6 mm/min, and 7 mm/min, and 4 bar, 5 bar, and 6 bar, respectively. Table 3 and Table 4 show the variable parameters: cutting speed and assist gas pressure for High-Speed Steel (HSS), and Mild Steel (MS), respectively. Oxygen was used as the assisting gas in all trials.

Table 2: Cutting parameters.

Cutting Parameters	Level		
	1	2	3
Cutting Speed [mm/min]	5	6	7
Assist Gas Pressure [Bar]	4	5	6

Table 3: Experimental Trials based on L9 Taguchi Orthogonal Array Design for HSS.

High-Speed Steel (HSS)		
No. Experiment	**Cutting Speed**	**Assist Gas Pressure**
1	5	4
2	5	5
3	5	6
4	6	4
5	6	5
6	6	6
7	7	4
8	7	5
9	7	6

Table 4: Experimental Trials based on L9 Taguchi Orthogonal Array Design for MS.

Mild Steel		
No. Experiment	**Cutting Speed**	**Assist Gas Pressure**
1	5	4
2	5	5
3	5	6
4	6	4
5	6	5
6	6	6
7	7	4
8	7	5
9	7	6

2.2 Kerf Measurement

Kerf measurement specifies the width of the material that is removed during laser cutting from both the top and bottom surfaces of the sample. Using an optical microscope, the kerf width ratio (KWR) was measured at the entry, middle, and exit points along the cutting path (Figure 2).

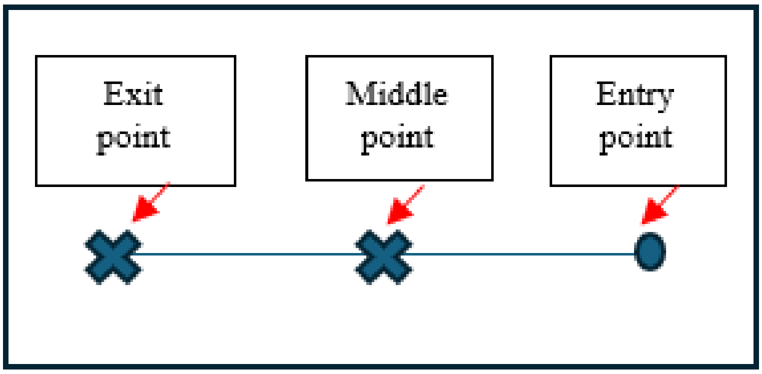

Figure 2: Entry point, middle point, and exit point of laser cutting path.

The kerf measurement focused on the upper and lower sides of the plates, and the results were calculated using Equation 1.

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

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

The Heat-Affected Zone (HAZ) was observed using the IMTcam FHD optical microscope to evaluate the thermal effects on the material's surface at the entry, middle, and exit points along the cutting path. Macrostructural images were analyzed to assess the influence of cutting parameters on cutting-edge quality.

3. RESULTS AND DISCUSSION

Results present the influence of cutting paths, entry, middle, and exit, on KWR and thermal defect characterization from HAZ observation for both materials.

3.1 Effect of Cutting Speed on Kerf Width Ratio (KWR) on Different Cutting Paths on High-Speed Steel (HSS)

The results show that Kerf width ratio (KWR) changes correspond to cutting speed and path points. Figure 3 shows the kerf width ratio across cutting speeds. The middle point consistently exhibited the lowest KWR across all cutting speeds due to stable heat distribution and uniform material removal. The exit point at a higher cutting speed (7 mm/min) demonstrated the highest KWR = 0.11 mm, attributed to heat accumulation and reduced material support. Increased cutting speed improves heat dissipation, reducing kerf width, whereas lower cutting speed allows heat accumulation [1]. In contrast, lower cutting speed (5 mm/min) resulted in broader kerfs at the entry point due to prolonged heat exposure.

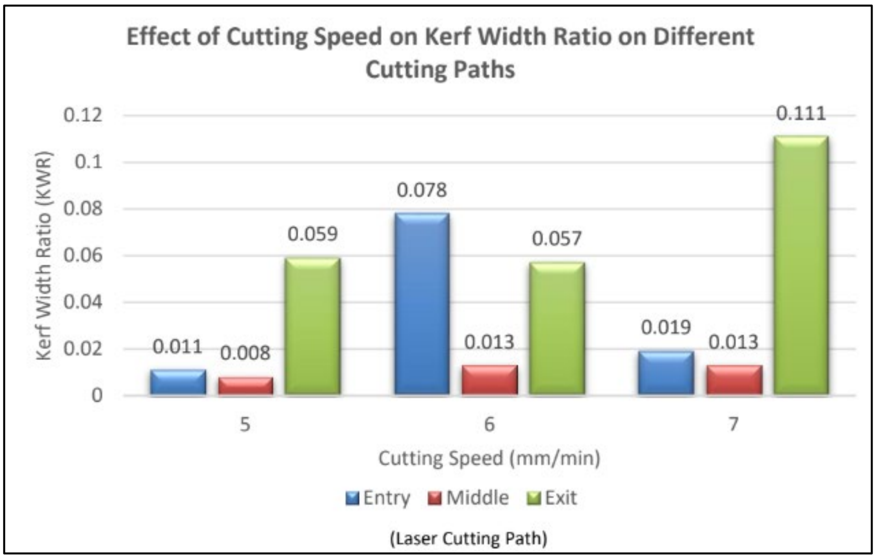

Figure 3: Effect of Cutting Speed on Kerf Width Ratio on Different Cutting Paths on HSS with Assisted Gas Pressure (5 Bar).

3.2 Effect of Cutting Speed on Kerf Width Ratio (KWR) on Different Cutting Paths on Mild Steel (MS)

Figure 4 illustrates the impact of cutting speed on KWR across the cutting paths. The results highlighted a consistent trend, with the middle point exhibiting the lowest KWR attributed to uniform heat distribution and stable material removal. At a lower cutting speed (5 mm/min), the entry point recorded high KWR = 0.065 mm due to prolonged heat exposure and increased material removal. Conversely, at higher cutting speed (6–7 mm/min), the exit point results from high KWR (0.054 mm) driven by thermal accumulation and minimized heat dissipation time, affecting kerf width consistency [2].

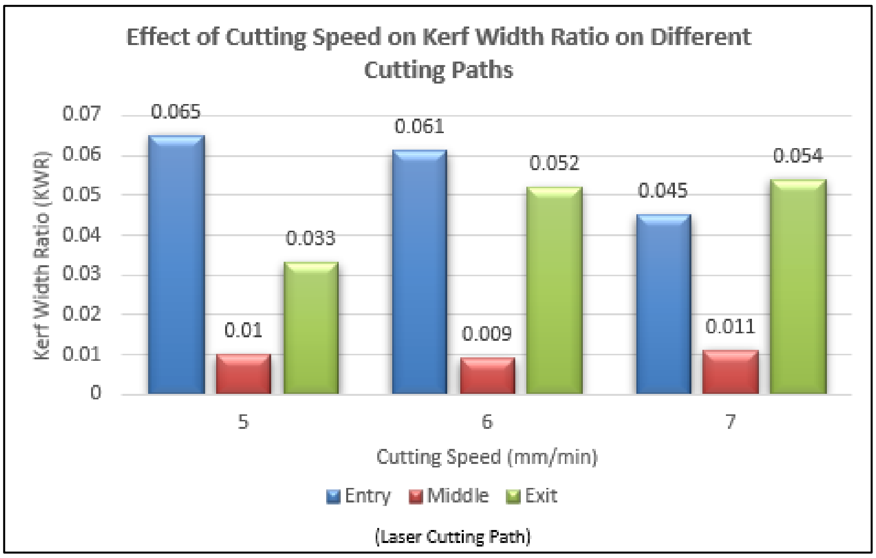

Figure 4: Effect of Cutting Speed on Kerf Width Ratio on Different Cutting Paths on MS with Assisted Gas Pressure (5 Bar).

3.3 Effect of Assisted Gas Pressure on Kerf Width Ratio (KWR) on Different Cutting Paths on High-Speed Steel (HSS)

Figure 5 shows the variations in KWR with changes in gas pressure. The results found a consistent pattern with the middle point exhibited the lowest KWR (0.013–0.014) across all gas pressures due to uniform energy distribution and minimal turbulence. At 5 bar of assisted gas pressure, the entry point has the highest KWR = 0.078 mm, attributed to excessive material removal caused by irregular gas flow and concentrated laser energy. Elevated gas pressures enhance material ejection but may increase turbulence, particularly at the edges, leading to higher kerf widths [3].

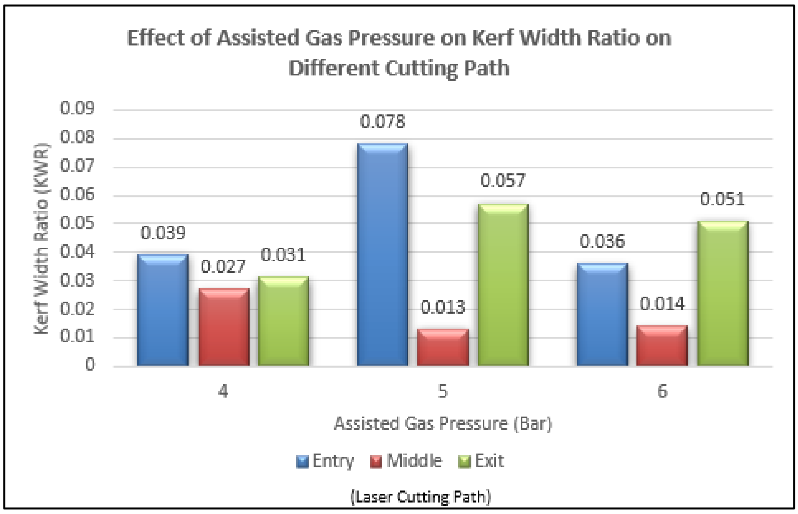

Figure 5: Effect of Assisted Gas Pressure on Kerf Width Ratio on Different Cutting Paths on HSS with Cutting Speed (6 mm/min).

3.4 Effect of Assisted Gas Pressure on Kerf Width Ratio on Different Cutting Paths on Mild Steel (MS)

Figure 6 illustrates the variations in kerf width ratio on different gas pressures and cutting paths. The result shows that, for all three cutting points, high gas pressure (6 bar) resulted in smaller kerf width ratios at the middle path, compared to 4 bar gas pressure. This is attributed to enhanced material ejection and stable heat dissipation [4]. However, excessive gas pressure at the entry and exit points led to turbulence, causing wider kerf widths, particularly at 5 bar for the entry point. Optimal gas pressure stabilises material removal and reduces kerf inconsistencies [5].

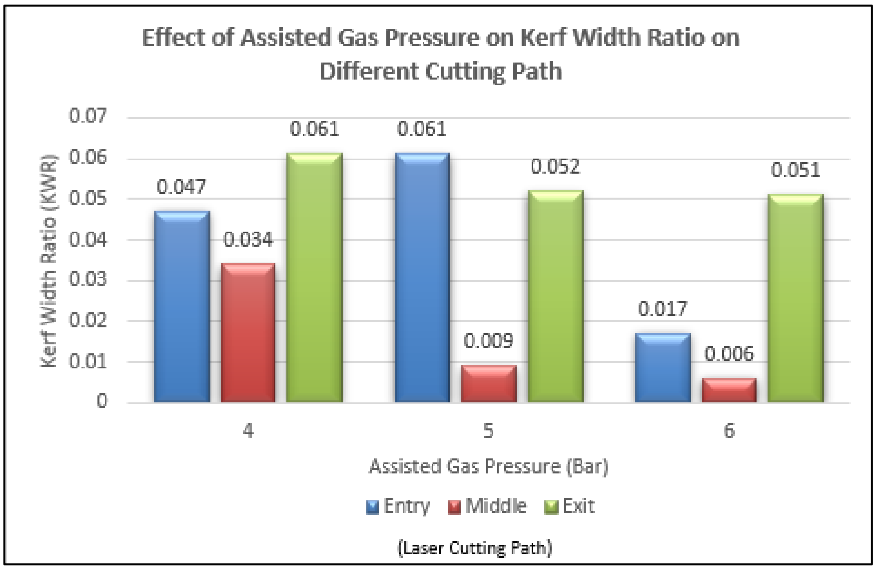

Figure 6: Effect of Assisted Gas Pressure on Kerf Width Ratio on Different Cutting Paths on MS with Cutting Speed (6 mm/min).

3.5 Kerf Width Ratio (KWR) Comparison for High-Speed Steel (HSS) and Mild Steel (MS) on Different Cutting Paths

Figure 7 shows the effects of cutting speed on KWR for both High-Speed Steel (HSS) and Mild Steel (MS). HSS consistently achieved narrower kerf widths on the middle point due to its superior heat resistance and stability. However, both entry and exit points exhibited wider kerfs, particularly at higher speeds and pressures, due to heat accumulation and material expansion [6][7]. Conversely, MS has a wider kerf at low cutting speed due to its material characteristics, which make it softer and more susceptible to heat distortion. These findings highlight the importance of optimizing cutting parameters to achieve precision and reduce inconsistencies for both materials.

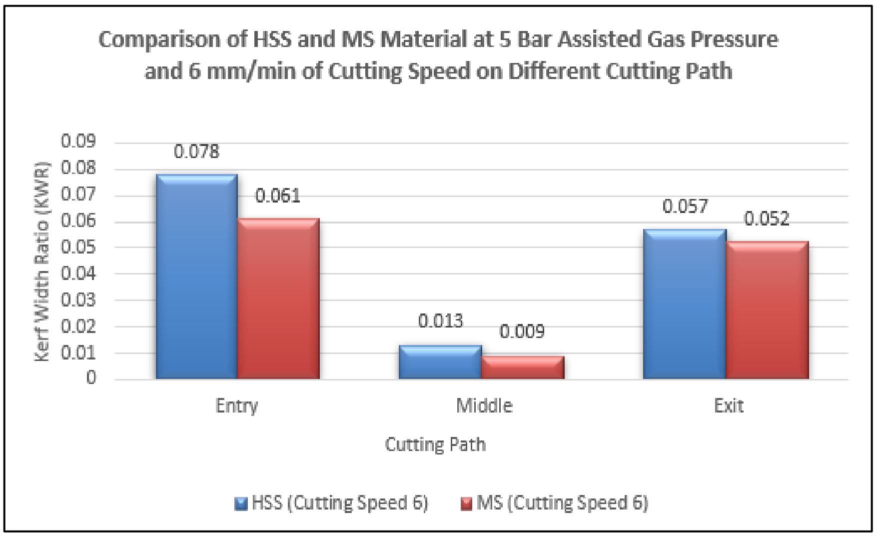

Figure 7: Comparison of HSS and MS Materials at 5 Bar of Assisted Gas Pressure and 6 mm/min of Cutting Speed on Different Cutting Paths.

3.6 Observation of Heat-Affected Zone (HAZ) on The Surface Quality of High-Speed Steel (HSS)

Microscope observations show that the HAZ's size and characteristics varied significantly depending on the cutting speed and assist gas pressure. At the entry point, high gas pressure causes HAZ and irregularities such as severe recast layers due to turbulence and uneven heat distribution (Figure 8). Uniform HAZ is observed at the middle point, which is attributed to stable heat dissipation and material support during laser cutting (Figure 9). Heat accumulation and reduced material support at the exit point led to an uneven HAZ area with a visible recast layer and thermal gradient (Figure 10). These findings highlight the significant effect of the control parameter on surface quality. Higher cutting speeds show HAZ size reduction from limited heat transfer [8][9].

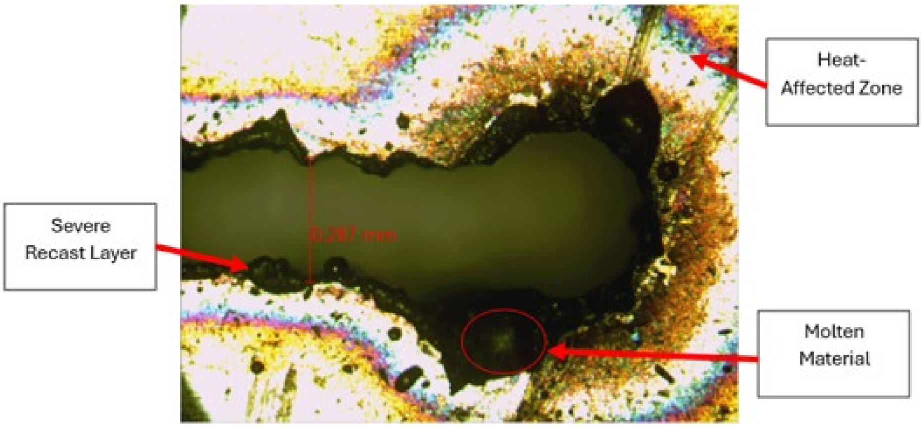

Figure 8: HAZ observation of HSS at the entry kerf, with cutting speed 5 mm/min and assisted gas pressure at 5 Bar under magnification of 10X.

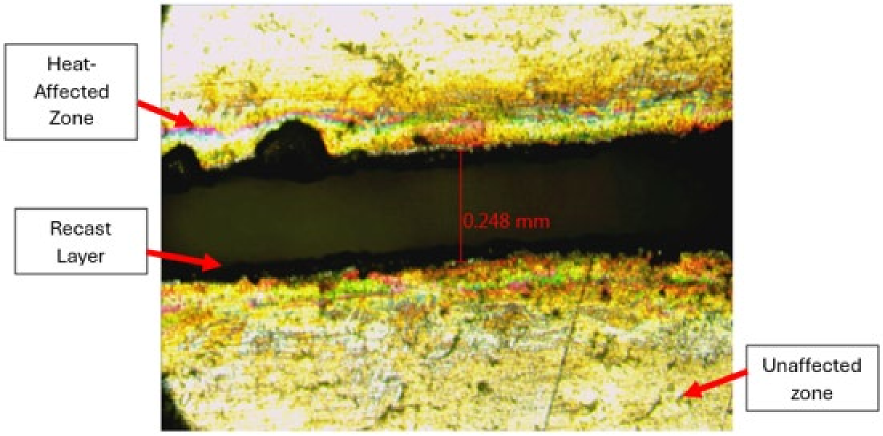

Figure 9: HAZ observations of HSS at the middle kerf, with cutting speed 6 mm/min and assisted gas pressure at 4 Bar under magnification of 10X.

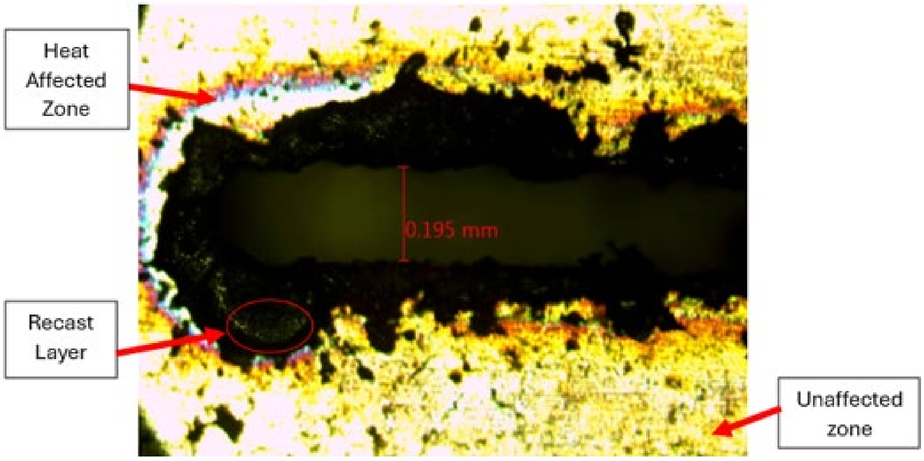

Figure 10: HAZ observation of HSS at exit kerf, with the cutting speed of 6 mm/min and assisted gas pressure at 6 bar under magnification of 10X.

3.7 Observation of Heat-Affected Zone (HAZ) on The Surface Quality of Mild Steel (MS)

Microscope observations highlighted significant effects in HAZ from varying cutting speed and assist gas pressure. Low cutting speed and high gas pressure at the entry point resulted in larger and uneven HAZ due to prolonged heat exposure and turbulence during material removal (Figure 11). The middle point consistently shows a uniform HAZ, benefiting from stable heat distribution and material support (Figure 12). At the exit point, there is burr formation from heat buildup. Reduced material support led to wider HAZ with irregular thermal gradients and surface roughness (Figure 13). Lower cutting speeds are observed to increase HAZ along cutting paths, while excessive gas pressure introduces thermal inconsistencies, particularly at the edges [10][11].

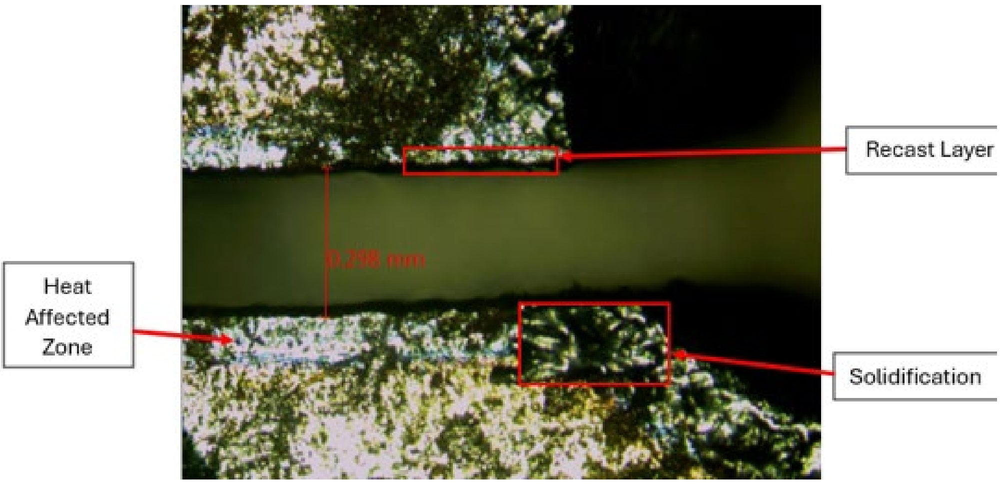

Figure 11: HAZ observation of MS at entry kerf, with the cutting speed of 6 mm/min and assisted gas pressure at 5 Bar under magnification of 10X.

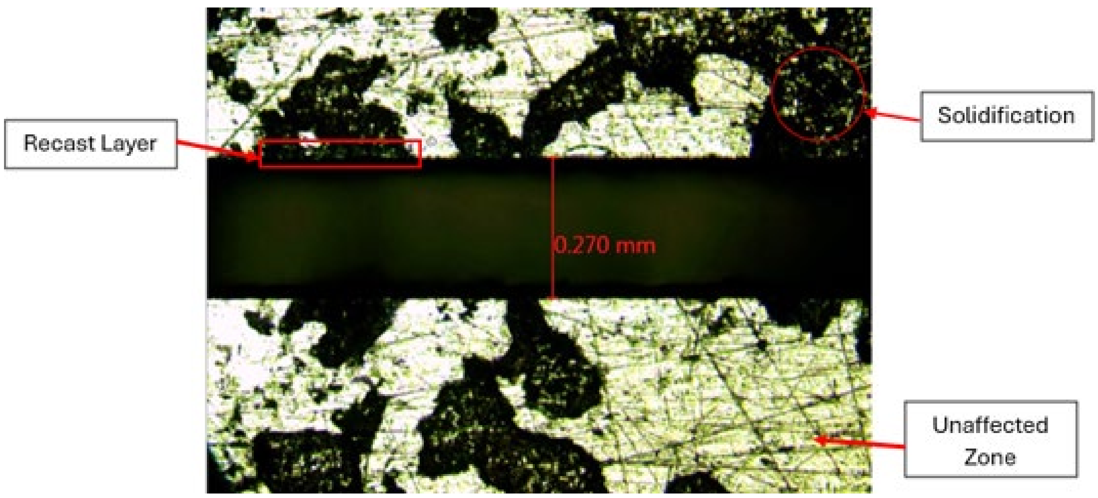

Figure 12: HAZ observation of MS at middle kerf, with the cutting speed of 7 mm/min and assisted gas pressure at 4 Bar under magnification of 10X.

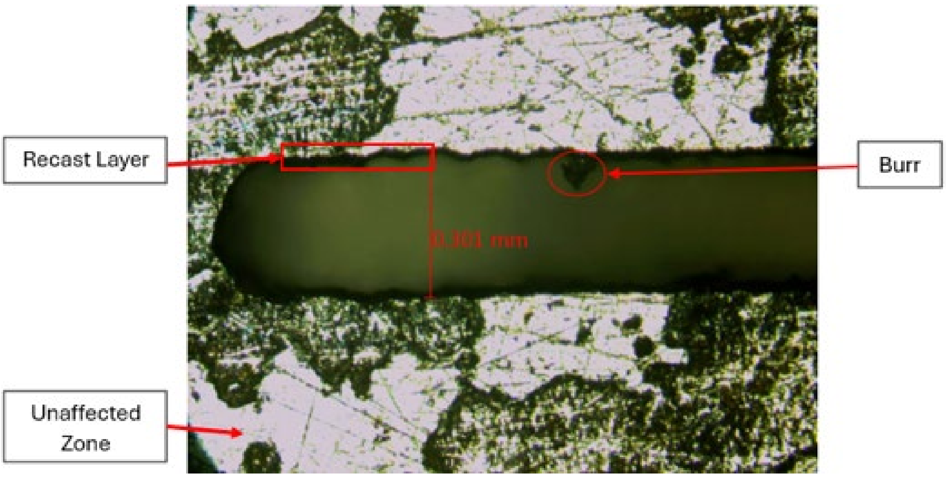

Figure 13: HAZ observation of MS at exit kerf, with the cutting speed of 5mm/min and assisted gas pressure at 6 Bar under magnification of 10X.

4. CONCLUSION

This study investigated the effects of cutting speed and assist gas pressure on the kerf width ratio (KWR) and Heat-Affected Zone (HAZ) for High-Speed Steel (HSS) and Mild Steel (MS) in laser machining. The findings revealed that higher cutting speeds consistently improved cutting precision by reducing KWR and minimizing HAZ, particularly along the middle cutting path. However, excessive gas pressure introduced inconsistencies at the entry and exit paths due to turbulence and uneven material ejection. HSS demonstrated greater stability and heat resistance, while MS was more prone to thermal distortion and irregularities under varying parameters. 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 machining processes across different materials.

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