Influence of CO_2 Laser Cutting Parameters on Machining Performance of Mild Steel and Stainless Steel Sheets

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Abstract

CO_2 laser cutting is a widely adopted non-conventional machining process for manufacturing sheet metal components because it offers high dimensional accuracy, process flexibility, and rapid production capability. The quality of laser-cut parts is primarily governed by machining variables including laser power, cutting speed, assist gas pressure, and workpiece thickness. These parameters directly influence important quality measures such as kerf width and the heat-affected zone (HAZ). In this study, an experimental investigation was carried out to examine the effect of selected CO_2 laser cutting parameters on the machining performance of Mild Steel (MS) and Stainless Steel (SS) sheets. Controlled machining trials were performed using a CNC CO_2 laser cutting system under different operating conditions. The measured responses were analysed to evaluate the relationship between process variables and cutting quality. A comparative assessment of both materials was also conducted to examine the influence of their thermal and physical characteristics on kerf formation and HAZ. Based on the experimental observations, suitable machining conditions were identified to improve dimensional accuracy, reduce thermal damage, and enhance overall cutting efficiency. The outcomes of this work provide useful guidance for optimizing CO_2 laser cutting operations in industrial sheet metal manufacturing.

Keywords: CO_2 laser cutting, process optimization, sheet metal machining, kerf width, heat-affected zone, Mild Steel, Stainless Steel.

1. Introduction

Laser machining has become an important manufacturing technology for producing accurate and complex profiles in metallic and non-metallic materials. Since the process is based on a non-contact thermal mechanism, it eliminates tool wear while maintaining high cutting speed and dimensional precision. Among the available laser systems, CO_2 laser technology continues to be extensively employed in industrial applications because of its stable beam characteristics, dependable operation, and suitability for processing a broad range of engineering materials.

Mild Steel (MS) and Stainless Steel (SS) are commonly used in automotive, aerospace, construction, and general fabrication industries owing to their favourable mechanical properties and ease of manufacturing. During laser cutting, the quality of the machined component is commonly assessed using parameters such as kerf width, edge quality, and the heat-affected zone (HAZ). These characteristics are significantly influenced by machining conditions including laser power, cutting speed, assist gas pressure, focal position, and material thickness. Consequently, careful selection of process parameters is essential to achieve accurate cuts with minimum thermal distortion.

Improper combinations of machining variables may result in excessive kerf width, dross formation, enlarged HAZ, poor surface finish, and dimensional inaccuracies, thereby increasing production cost and reducing component quality. Although numerous investigations have examined laser cutting of different engineering materials, comparatively fewer studies have presented a systematic comparison of CO_2 laser cutting behaviour for Mild Steel and Stainless Steel under identical machining conditions. The present work therefore investigates the influence of major process parameters on machining performance and identifies suitable operating conditions for improving cut quality and manufacturing efficiency.

2. Objectives of the Present Study

i. The present investigation is intended to examine the influence of major CO_2 laser cutting parameters on the machining quality of sheet metal components. The study focuses on understanding the relationship between machining variables and the quality characteristics of laser-cut Mild Steel (MS) and Stainless Steel (SS). The specific objectives are:

ii. To investigate the influence of CO_2 laser cutting parameters on important quality characteristics, particularly kerf width and the heat-affected zone (HAZ), during the machining of sheet metals.

iii. To analyse the effect of laser power and cutting speed on the cutting performance of Mild Steel (MS) and Stainless Steel (SS) sheets of different thicknesses.

iv. To evaluate the contribution of assist gas pressure in improving cut quality, enhancing molten material removal, and reducing thermal damage.

v. To compare the machining behaviour of Mild Steel and Stainless Steel under identical machining conditions and examine the influence of their thermal and physical properties on cutting performance.

vi. To identify an appropriate combination of machining parameters capable of minimizing kerf width and the heat-affected zone while maintaining satisfactory cutting quality and process efficiency.

3. Literature Review

The application of CO_2 laser cutting has attracted considerable research interest because of its ability to produce precise, high-speed, and flexible machining of engineering materials. The quality of laser-cut components is largely governed by process variables such as laser power, cutting speed, assist gas pressure, focal position, and material properties. Consequently, numerous experimental and analytical studies have been conducted to investigate the influence of these parameters on machining performance and to develop optimization strategies for improving cut quality.

Scintilla et al. performed a comparative investigation of CO_2 and disk laser cutting processes for steel sheets. Their study demonstrated that CO_2 laser systems are particularly effective for cutting medium and thick sections, primarily due to their superior thermal energy distribution and efficient removal of molten material. The researchers also emphasized that appropriate control of laser power and thermal input is essential for achieving improved edge quality and reduced kerf irregularities.

Riveiro et al. examined the laser machining behavior of carbon fiber reinforced polymer (CFRP) composites using a CO_2 laser. Their findings indicated that careful adjustment of machining parameters significantly reduced the heat-affected zone while maintaining acceptable cutting quality. The study highlighted the importance of parameter optimization, particularly when processing materials that are highly sensitive to thermal damage.

Syn et al. introduced a fuzzy logic-based predictive model for evaluating surface roughness and dross formation during CO_2 laser cutting. Their experimental results showed strong agreement between predicted and measured values, demonstrating that intelligent computational techniques can effectively assist in selecting suitable machining conditions and improving process reliability.

Li and Tsai applied Grey Relational Analysis (GRA) to optimize multiple quality characteristics in laser cutting operations. Their research confirmed that multi-objective optimization methods are capable of simultaneously minimizing surface roughness, kerf width, and the heat-affected zone. Likewise, **Çaydaş and Hasçalık** employed Taguchi methodology combined with Grey Relational Analysis to determine optimal laser cutting parameters for structural steel. Their work established that statistical optimization techniques provide an efficient approach for enhancing machining performance while reducing the number of experimental trials.

Stournaras et al. carried out an experimental study on CO_2 laser cutting of aluminum alloys to investigate the influence of laser power and cutting speed on kerf geometry and thermal damage. Their analysis revealed that laser power has a dominant effect on kerf width and heat-affected zone, whereas cutting speed primarily controls the duration of laser-material interaction and overall cutting efficiency.

Although substantial research has been conducted on laser cutting of different engineering materials, comparatively fewer studies have focused on the systematic optimization of CO_2 laser cutting parameters for **Mild Steel (MS)** and **Stainless Steel (SS)** under identical industrial operating conditions. The thermal conductivity, optical absorption characteristics, and oxidation behavior of these materials differ considerably, resulting in variations in machining performance and cut quality. Therefore, further experimental investigations are required to establish optimized parameter combinations that can consistently produce high-quality cuts for both materials.

The present study addresses this research gap by experimentally evaluating the influence of key CO_2 laser cutting parameters on kerf width and heat-affected zone in Mild Steel and Stainless Steel sheets. The investigation also aims to identify suitable operating conditions that improve dimensional accuracy, minimize thermal damage, and enhance the overall efficiency of industrial laser cutting processes.

4. Experimental Setup and Methodology

4.1 CO_2 Laser Cutting System

The experimental work was conducted using a CNC-controlled CO_2 laser cutting machine (**Trumpf Trumatic L2530**) available at an industrial laser processing facility. The machine is equipped with a high-power continuous-wave (CW) CO_2 laser source capable of producing a stable laser beam for precision sheet metal cutting. Its integrated CNC control system allows accurate adjustment of machining parameters and ensures consistent operating conditions throughout the experimental trials. The machine's high positioning accuracy and repeatability make it suitable for investigating the influence of laser cutting parameters on cut quality.

4.2 Selection of Workpiece Material

Two engineering materials widely employed in manufacturing industries, namely **Mild Steel (MS)** and **Stainless Steel (SS)**, were selected as workpiece materials for this investigation. These materials are extensively used in automotive, aerospace, structural, and fabrication applications because of their desirable mechanical properties and industrial significance.

Test specimens of different thicknesses were prepared according to standard machining practices. Before conducting the experiments, the workpieces were thoroughly cleaned to eliminate contaminants such as dust, grease, oil, and oxide layers, thereby ensuring uniform cutting conditions and improving the reliability of the experimental results.

4.3 Assist Gas and Optical Configuration

Assist gas plays an essential role in the laser cutting process by facilitating molten material removal, improving cut quality, and reducing thermal damage. In the present investigation, **oxygen** was employed as the assist gas during the cutting of Mild Steel to enhance the cutting process through oxidation, whereas **nitrogen** was used for Stainless Steel to minimize oxidation and obtain cleaner cut edges.

The assist gas pressure was varied within a predetermined range to evaluate its influence on kerf width and the heat-affected zone (HAZ). A suitable focusing lens was used to concentrate the laser beam, while the focal position was maintained close to the workpiece surface during all experimental runs to ensure consistent energy delivery.

4.4 Selection of Process Parameters

The machining parameters selected for the experimental study were determined based on preliminary investigations, machine capability, and commonly adopted industrial practices. The primary process variables considered in this research include:

- Laser power
- Cutting speed

- Assist gas pressure
- Material thickness

Each parameter was systematically varied while keeping the remaining parameters constant to evaluate its individual influence on the quality characteristics of laser-cut components. The selected parameter ranges were chosen to represent practical operating conditions commonly encountered in industrial sheet metal processing.

4.5 Experimental Procedure

A series of straight-line cutting experiments was carried out on Mild Steel and Stainless Steel specimens using different combinations of the selected process parameters. Each experimental trial was repeated under identical conditions to ensure repeatability and improve the accuracy of the collected data.

After completion of the cutting operation, the specimens were allowed to cool naturally under ambient conditions. The kerf width of each specimen was measured at several locations along the cutting path using an optical microscope, and the average value was considered for analysis. The heat-affected zone was assessed through visual observation and microscopic examination of the cut edges to evaluate the extent of thermal damage produced during the cutting process.

4.6 Evaluation of Cutting Performance

The quality of laser-cut specimens was primarily evaluated using **kerf width** and **heat-affected zone (HAZ)** as performance indicators. These quality characteristics are directly associated with dimensional accuracy, edge quality, and the structural integrity of laser-cut components.

The experimental measurements were analyzed to determine the relationship between the machining parameters and cutting performance. Based on the observed trends, suitable parameter combinations were identified for minimizing kerf width and reducing the heat-affected zone during the CO_2 laser cutting of Mild Steel and Stainless Steel sheets. The optimized conditions obtained from the study can serve as practical guidelines for improving productivity and cut quality in industrial sheet metal manufacturing.

5. Results and Discussion

The experimental data obtained from the CO_2 laser cutting of Mild Steel (MS) and Stainless Steel (SS) sheets were systematically analyzed to evaluate the influence of various process parameters on cutting quality. Particular emphasis was placed on two critical performance characteristics, namely kerf width and the heat-affected zone (HAZ), as these directly affect dimensional accuracy, edge quality, and the overall performance of laser-cut components. The discussion presented below explains the individual effects of the selected machining parameters and identifies the conditions that lead to improved cutting performance.

5.1 Influence of Laser Power

Laser power was identified as one of the most significant factors influencing both kerf width and the heat-affected zone. Increasing the laser power supplied more thermal energy to the workpiece, resulting in greater material melting and consequently a wider kerf. For both Mild Steel and Stainless Steel specimens, higher laser power produced larger kerf widths because of increased heat transfer to the surrounding material.

The extent of the heat-affected zone also increased with laser power, as additional thermal energy penetrated deeper into the workpiece. However, when laser power was set too low, insufficient energy was available to achieve complete material penetration, leading to poor cut quality and incomplete separation, particularly in thicker sheets. Therefore, selecting an appropriate laser power is essential for balancing cutting efficiency and dimensional accuracy while minimizing thermal damage.

5.2 Influence of Cutting Speed

Cutting speed exhibited a strong influence on the quality of laser-cut edges. At lower cutting speeds, the laser beam remained in contact with the material for a longer period, allowing excessive heat to accumulate around the cutting region. This prolonged exposure resulted in wider kerf widths and a larger heat-affected zone.

As the cutting speed increased, the interaction time between the laser beam and the workpiece decreased, reducing the amount of heat transferred into the material. Consequently, narrower kerf widths and smaller HAZ values were obtained, leading to improved cut quality. However, excessively high cutting speeds reduced the available energy required for complete material removal, causing unstable cutting conditions, incomplete penetration, and the formation of surface striations.

Furthermore, Stainless Steel required relatively lower cutting speeds than Mild Steel to achieve satisfactory cutting performance because of its lower thermal conductivity and higher laser reflectivity.

5.3 Effect of Assist Gas Pressure

Assist gas pressure played an important role in removing molten material from the cutting zone and maintaining the quality of the cut surface. The selection of an appropriate assist gas also influenced oxidation behavior and thermal characteristics during machining.

For Mild Steel, oxygen was used as the assist gas because it promotes an exothermic reaction that increases cutting efficiency. Although this reaction improved material removal, excessive oxygen pressure produced wider kerf widths and increased oxidation near the cut edges.

In contrast, nitrogen was employed during the cutting of Stainless Steel to suppress oxidation and produce cleaner cut surfaces. Increasing nitrogen pressure enhanced molten material removal and improved edge appearance. However, very high gas pressures slightly increased kerf width due to the mechanical action of the gas jet on the molten material.

The experimental observations indicate that optimum assist gas pressure is necessary to achieve efficient molten material ejection while maintaining minimum kerf width and controlled thermal damage.

5.4 Effect of Material Type and Thickness

The physical and thermal properties of the workpiece material had a significant influence on laser cutting performance. Under identical machining conditions, Mild Steel generally produced larger kerf widths because oxygen-assisted cutting generated additional heat through oxidation. Conversely, Stainless Steel exhibited comparatively narrower kerfs but a slightly larger heat-affected zone due to its relatively lower thermal conductivity.

Material thickness also affected the cutting process considerably. As sheet thickness increased, greater laser energy was required to ensure complete penetration. This requirement was achieved either by increasing laser power or by reducing cutting speed. Regardless of the material type, thicker sheets consistently exhibited increased kerf width and larger heat-affected zones, emphasizing the importance of selecting appropriate process parameters for different material thicknesses.

5.5 Optimization of Process Parameters

Based on the experimental analysis, suitable combinations of laser cutting parameters were identified to achieve superior cutting performance. The optimization strategy focused on selecting moderate laser power, relatively higher cutting speeds within stable operating limits, and appropriate assist gas pressures.

For Mild Steel, the combination of moderate laser power, oxygen assist gas, and comparatively higher cutting speed produced improved edge quality with reduced kerf width and acceptable thermal damage. In the case of Stainless Steel, optimum results were obtained using nitrogen as the assist gas together with controlled laser power and carefully selected cutting speeds, resulting in clean edges, reduced oxidation, and minimal heat-affected zones.

Overall, the investigation demonstrates that no single machining parameter can independently produce optimum cutting quality. Instead, the interaction among laser power, cutting speed, assist gas pressure, material properties, and sheet thickness collectively determines the final machining performance. Therefore, simultaneous optimization of these parameters is essential for achieving consistent, high-quality laser cutting in industrial sheet metal manufacturing.

6. Conclusions

Based on the experimental investigation and detailed analysis of the CO_2 laser cutting process for Mild Steel (MS) and Stainless Steel (SS) sheets, the following conclusions can be drawn:

The experimental results demonstrate that laser power and cutting speed are the most influential process parameters affecting the quality of CO_2 laser cutting. These parameters have a direct impact on kerf width, heat-affected zone (HAZ), and overall machining performance.

An increase in laser power enhances the thermal energy supplied to the workpiece, leading to improved material penetration. However, excessive laser power causes wider kerf formation and an enlarged heat-affected zone due to increased heat input. Conversely, insufficient laser power results in incomplete cutting and deteriorated edge quality.

Cutting speed significantly influences the interaction time between the laser beam and the material. Higher cutting speeds generally reduce kerf width and HAZ by limiting heat accumulation, whereas excessively high speeds may produce incomplete cuts, unstable machining conditions, and surface defects such as striations.

The choice of assist gas and its operating pressure plays a vital role in determining cutting efficiency and edge quality. Oxygen-assisted cutting improves the machining performance of Mild Steel through exothermic oxidation, while nitrogen-assisted cutting of Stainless Steel minimizes oxidation and produces cleaner cut surfaces.

Material properties, including thermal conductivity, reflectivity, and oxidation characteristics, considerably affect the laser cutting behavior of Mild Steel and Stainless Steel. As a result, identical machining parameters do not produce the same cutting performance for both materials.

The experimental investigation confirms that selecting an appropriate combination of moderate laser power, optimized cutting speed, and suitable assist gas pressure effectively minimizes kerf width and the heat-affected zone while maintaining excellent cut quality.

Overall, the study establishes that simultaneous optimization of multiple process parameters is essential for achieving accurate, efficient, and high-quality CO_2 laser cutting. The optimized machining conditions identified in this work can assist manufacturing industries in improving productivity, reducing thermal damage, and enhancing the dimensional accuracy of laser-cut sheet metal components.

7. Future Scope

Although the present investigation provides valuable insights into the optimization of CO_2 laser cutting parameters, several opportunities remain for extending this research to further improve machining performance and process understanding.

Future studies may employ advanced multi-objective optimization techniques, such as Taguchi–Grey Relational Analysis (GRA), Response Surface Methodology (RSM), or Genetic Algorithms (GA), to simultaneously optimize multiple quality characteristics including kerf width, surface roughness, dimensional accuracy, and the heat-affected zone.

The application of artificial intelligence and machine learning approaches, including Artificial Neural Networks (ANN), Support Vector Machines (SVM), and deep learning models, can be explored to develop predictive models for laser cutting performance and intelligent process optimization.

A comparative investigation between CO_2 laser systems and modern fiber laser technologies may be conducted to evaluate differences in cutting efficiency, energy consumption, processing speed, and cut quality for various engineering materials.

Additional process variables such as focal position, nozzle stand-off distance, nozzle diameter, beam mode, pulse characteristics, and laser wavelength can be incorporated into future experimental studies to obtain a more comprehensive understanding of their influence on cutting performance.

Detailed metallurgical and microstructural characterization of laser-cut edges using techniques such as optical microscopy, scanning electron microscopy (SEM), and microhardness testing may be carried out to investigate thermal effects on material properties and structural integrity.

Future research may also focus on cutting advanced engineering materials, including high-strength steels, titanium alloys, aluminum alloys, and composite materials, to establish optimized machining conditions for emerging industrial applications.

Finally, integrating real-time monitoring systems and Industry 4.0-based intelligent manufacturing technologies with laser cutting machines could facilitate adaptive process control, improve production efficiency, and ensure consistent cut quality in automated manufacturing environments.

References

1. L. D. Scintilla, L. Tricarico, A. Wetzig, and E. Beyer, "Investigation on disk and CO_2 laser beam fusion cutting differences based on power balance equation," International Journal of Machine Tools and Manufacture, vol. 69, pp. 30–37, 2013.
2. A. Riveiro, F. Quintero, F. Lusquiños, J. del Val, R. Comesaña, M. Boutinguiza, and J. Pou, "Experimental study on the CO_2 laser cutting of carbon fiber reinforced plastic composite," Composites Part A: Applied Science and Manufacturing, vol. 43, pp. 1400–1409, 2012.
3. C. Z. Syn, M. Mokhtar, C. J. Feng, and Y. H. P. Manurung, "Approach to prediction of laser cutting quality by employing fuzzy expert system," Expert Systems with Applications, vol. 38, pp. 7558–7568, 2011.
4. C.-H. Li and M.-J. Tsai, "Multi-objective optimization of laser cutting for flash memory modules with special shapes using grey relational analysis," Optics & Laser Technology, vol. 41, pp. 634–642, 2009.
5. A. Stournaras, P. Stavropoulos, K. Salonitis, and G. Chryssolouris, "An investigation of quality in CO_2 laser cutting of aluminum," CIRP Journal of Manufacturing Science and Technology, vol. 2, pp. 61–69, 2009.
6. M. Kurt, Y. Kaynak, E. Bagci, H. Demirer, and M. Kurt, "Dimensional analyses and surface quality of the laser cutting process for engineering plastics," International Journal of Advanced Manufacturing Technology, vol. 41, pp. 259–267, 2009.
7. M.-J. Tsai, C.-H. Li, and C.-C. Chen, "Optimal laser-cutting parameters for QFN packages by utilizing artificial neural networks and genetic algorithm," Journal of Materials Processing Technology, vol. 208, pp. 270–283, 2008.
8. U. Çaydaş and A. Hasçalık, "Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics," Optics & Laser Technology, vol. 40, pp. 987–994, 2008.
9. A. A. Cenna and P. Mathew, "Analysis and prediction of laser cutting parameters of fibre reinforced plastics (FRP) composite materials," International Journal of Machine Tools and Manufacture, vol. 42, pp. 105–113, 2002.
10. J. Wang, "An experimental analysis and optimization of CO_2 laser cutting process for metallic coated sheet steels," International Journal of Advanced Manufacturing Technology, vol. 16, pp. 334–340, 2000.