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A study on the laser cutting quality of ultra-high strength steel

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ABSTRACT

Ultra High Strength Steel (UHSS) has been used in a vehicle as it is able to improve the durability of the vehicle while reducing mass. Laser cutting process has been an alternative choice in trimming the UHSS boron steel to regain the final shape. This study was intended to investigate the effect of input parameters of carbon dioxide (CO_2) laser cutting on the 22MnB5 boron steel, focusing on the cutting quality and mechanical properties. CO_2 laser cutting machine was used to perform the experimental process with 1.7 mm thickness 22MnB5 boron steel as the working material. Kerf width, taper angle, and Heat Affected Zone (HAZ) formation were evaluated as the cutting quality with variations on the laser power, cutting speed and assisted gas pressure. The result shows that power intensity at focusing point reflected the outcome on the cutting quality. The smallest kerf width, taper ratio, and HAZ region were obtained with the value of 0.252mm, 0.03 degree, and 116µm respectively. The relationship between kerf and taper inversely interacted where the narrowest kerf formation and HAZ would produce the biggest taper angle. Apparently, gas pressure does not greatly influence in determining the cutting quality but significantly influencing the changes of material properties, especially the HAZ formation.

Keywords: boron steel; carbon dioxide laser; kerf width; heat affected zone

INTRODUCTION

The development of new material in the automotive sector has been evolving rapidly, especially on the weight reduction of a commercial vehicle. UHSS has been introduced to fulfil the requirements needed on the current vehicle as it offers better mechanical properties. Formed by the hot press forming, the mechanical properties of the material itself have increased but the common stamping process is unable to trim the side edge of the material. Laser cutting has been an alternative choice in trimming the parts into its final shape together with advanced processing technology with excellence quality offered by the laser beam machining. Laser cutting has been used in the metallic and non-metallic application [1-3]. Among all types of laser, Nd:YAG and CO_2 are most widely used in the laser beam machining application. CO_2 has a longer wavelength that is 10.6µm and produces better efficiency and good beam quality. It is suitable for the fine cutting of sheet metal at high speed [2]. The laser cutting process and cutting quality depends on the proper selection of the laser parameters and workpiece parameter [4-8]. Dubey and

Radanovic reported that the laser power and cutting speed were the critical parameters studied in the laser processing parameters [9, 10]. Lamikiz et al. [11] did a research on the Advanced High Strength Steel (AHSS) and concluded that the kerf width size resulted from the selection of laser power and cutting speed. Research on the ultra-high-strength steel is less favoured due to the invention of new material that undergoes the hot pressed forming and machine capabilities limitation. This gap creates niche and demand, especially the studies on the ultra-high strength material focusing on the boron steel 22MnB5.

Laser power is an essential parameter in the cutting process as it requires sufficient amount of power to heat up the materials before the penetrating and cutting process completed. Chen [12] reported while working on a 3mm thickness mild steel that the cutting quality and performance depend on the laser power. Eighty percent of researchers using laser power as the main input parameters showed the significant effects of laser power in determining the cutting quality [10]. Hascalik [13] concluded that laser power contributes about 26% of the kerf taper compared to cutting speed. The kerf formation also increased as bigger laser power was used and this affected the surface quality of the cutting materials [4, 14, 15]. The effects of laser power had been studied intensively by various authors and it was concluded that positive interaction occurred between the laser power, kerf width formation, and HAZ region [5, 14-17]. Cutting speed is considered as a main input parameter in the laser cutting process as it possesses the effects of power intensity on the laser beam. Radovanovic [10] reported that 86% of CO_2 laser cutting research included cutting speed as the main input parameters. The interaction between the cutting speed and material thickness can be seen where the decrement of cutting speed is needed as the thickness of material increases [18, 19]. This statement emphasises the effects of cutting speed in determining the power intensity thus resulting in the cutting quality. Besides that, the increment of cutting speed resulting in the decrement of kerf width, hardness, and HAZ region [4, 11, 13-15]. The relationship of cutting speed was also studied by Cekic et al. [5], Hascalik [13] and Yilbas [20] where all authors reported the increment of cutting speed reduced the formation of kerf width and HAZ region. Assisted gas is one of the variable parameters in laser processing, especially during the cutting process. The selection of proper gas is crucial in determining the cutting quality and reduction of isothermal reaction at the cutting region [21]. The effect and type of assisted gas are less investigated compared to other input parameters as this area is less concerned, especially by most researchers. Nitrogen gas is needed to expel the molten material without allowing it to drop on the underside to form dross adhesion. Chen [12] reported that nitrogen gas was able to improve the cutting quality compared to oxygen. Therefore, this project was conducted to evaluate the cutting performance of CO_2 laser with the aid of nitrogen gas. In this paper, a study on the cutting quality of 22MnB5 ultra high strength steel was done using the CO_2 laser cutting machine. The laser power, cutting speed and assisted gas pressure were varied to evaluate the effect of these input parameters on the kerf width formation, taper angle, and changes in material properties, especially at the cutting edges. The interaction using the graphical method was developed to identify the effect of each parameter reflecting the responses selected.

MATERIALS AND METHODS

This study was conducted to evaluate the laser cutting quality of 22MnB5 UHSS on two aspects namely dimensional accuracy and surface integrity. On the dimensional accuracy aspect, the top kerf, bottom kerf and taper angle were evaluated based on the parameter setting. Meanwhile, in terms of surface integrity, heat affected zone (HAZ) was evaluated. Laser processing was performed using Mitsubishi CO_2 laser cutting machine with the maximum power of 4kW and 190.5mm focal distance. The experimental process was conducted in a continuous wave mode with a variation of the laser power, cutting speed and assisted gas pressure. The calibration process was made in terms of the output power, processing mode and beam size and the calibration were made by the machine principles to ensure the accuracy of the result obtained. Table 1 shows the selected process parameters with three input parameters manipulated with three levels for each parameter. In this experiment, the nozzle gap and laser focus distance were kept constant at 1 mm from the top of the workpiece surface while the focus was kept on the top surface for the whole experiment. Details on the experimental operation are illustrated as in Figure 1 while Table 2 shows the mechanical properties of the 22MnB5 boron steel.

Table 1. Processing parameter on 22MnB5 boron steel.

Factors		Material thickness = 1.7mm Level		
Parameters	Units	1	2	3
Laser power, P_{avg}	W	750	1750	2750
Cutting Speed, V_c	mm/min	1500	2500	3500
Gas pressure	MPa	0.25	0.50	0.75

Table 2. Mechanical properties of 22MnB5 [22].

Martensite temperature (°C)	Yield stress (MPa)		Tensile strength (MPa)		Elongation A_{80}%	Hardness H_V
	Original	Hot Pressed	Original	Hot Pressed		
410	457	1010	608	1478	6	520

Figure 2 shows the experimental setup of the workpiece on the laser machine with the jigs calibrated to ensure the perpendicularity between the laser beam and working material. Working at 90 degrees is important to ensure that the laser beam is focusing at desired area thus resulting in accurate kerf formation. The K-type thermocouple wires were attached at each cutting path to record the material surface temperature during the cutting process. The thermocouples were connected to the data logger to record the temperature data. To ensure the formation of kerf width remained constant, the gap of 5 mm was set. The cutting process was conducted until it reached the cutting distance of 20 mm. MITUTOYO TM 505 optical microscope with an accuracy of 10µm was used to capture and measure the top and bottom kerf as well as the taper angle for the dimensional accuracy evaluation. The Kerf width was measured along the material thickness and an average of five measurements was made to ensure the consistency and accuracy of the result obtained. The detail of the measurement is illustrated in Figure 3. The evaluation on taper angle was made in two aspects where the actual taper was obtained from the metrological process using the MITUTOYO TM 505 optical microscope while the calculated taper angle was determined based on Eq. (1):

$$Calculated \cdot taper(\deg) = \frac{(W_t - W_b)180}{2\pi t} \tag{1}$$

where, W_t is the top kerf width; W_b is the bottom kerf width; t is the material thickness.

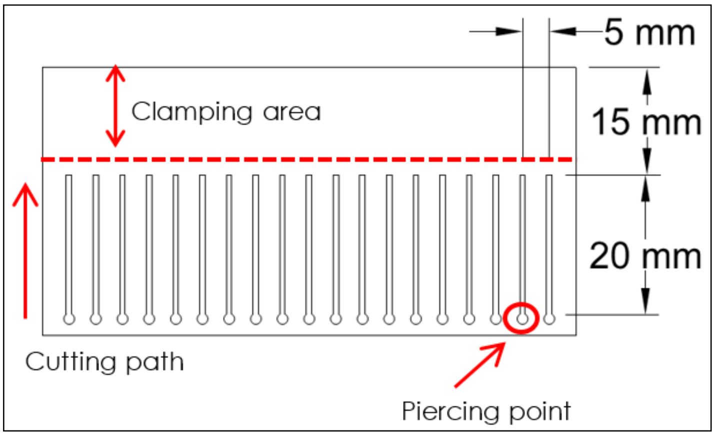


Figure 1. Experimental operation [23].

Furthermore, the region of HAZ was measured using the OLYMPUS STM6 microscope. The samples were prepared according to the ASTM E3-01 standard before etched using 2% Nital for 5 seconds. The HAZ region was determined by observing the white band along the material thickness. The white band is known as the transition region between the HAZ region and base material [24]. The similar averaging process was made in the HAZ region where five measurements were made along the HAZ region to identify the HAZ thickness.

RESULTS AND DISCUSSION

Kerf width

The top and bottom kerf were evaluated and the early conclusion was found that the assisted gas supply is crucial in determining the kerf width formation. It was found that the kerf was unable to form without assisted gas due to the lack of cutting catalyst. Chen [12] also concluded that suitable gas is needed to determine the cutting quality. Figure 4 shows the width of kerf formation with variation in gas pressure. The top and bottom kerf were evaluated side by side as in Figure 4 with three splines representing the cutting speed with different colours. The effect of variation in the laser power, cutting speed and assist gas pressure can be seen clearly as illustrated in Figure 4 where the kerf formation varies along the cutting path and material thickness. From the result obtained, the width of top and bottom kerf was between 0.25 and 0.43mm, 0.20, and 0.39mm respectively. The widest top and bottom kerf were recorded happen at sample 21 where 2750 Watt of the laser power with the cutting speed of 1500 mm/min together with 0.75MPa of assisted gas pressure was applied. This shows that the high laser power with slow cutting speed will produce the widest kerf and this was well agreed by various authors that came up with the same conclusion [24-26].

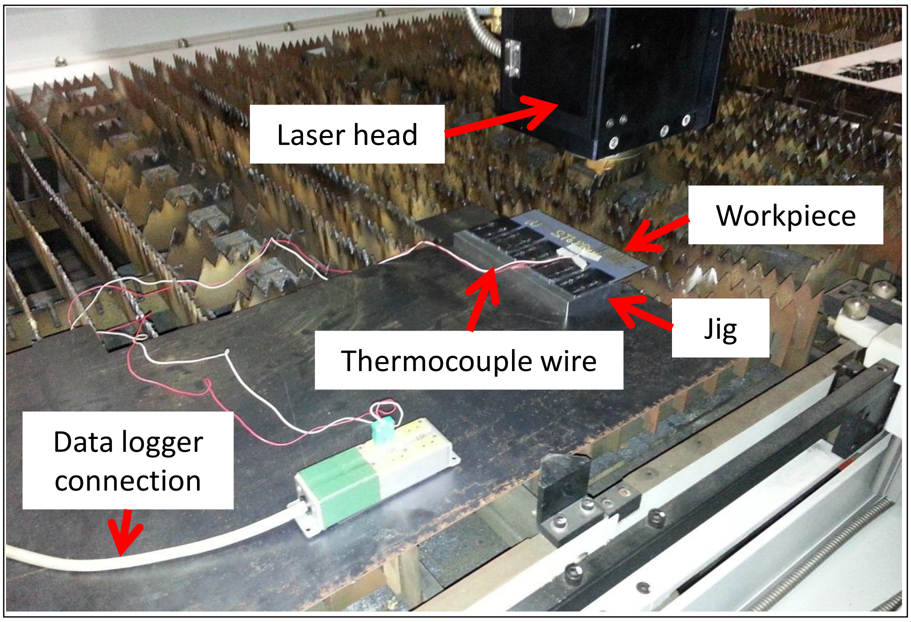


Figure 2. Experimental setup.

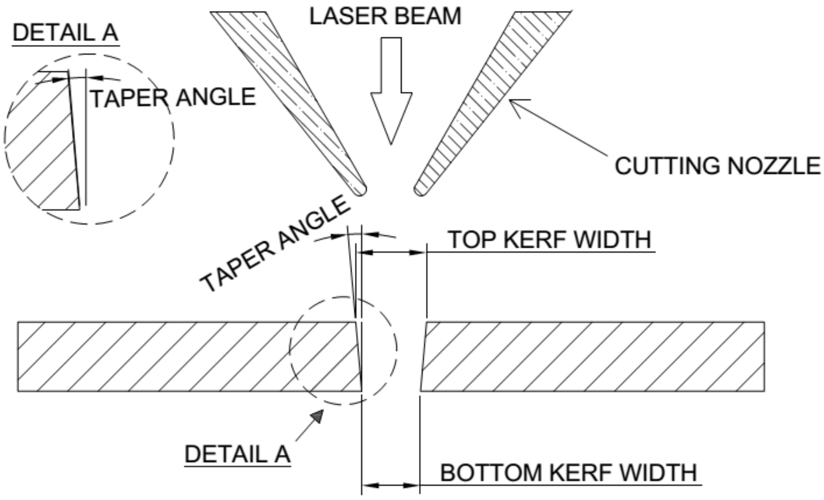


Figure 3. Kerf width and taper angle.

The interaction between the input parameters and kerf width can be seen in Figure 4 with the positive correlation observed between the laser power and kerf formation meanwhile the negative correlation occurred against the cutting speed. The effects of gas pressure on the kerf formation are insignificant and in agreement with the finding found by Cekic et al. [5] that concluded that a small variation of assist gas pressure has no significant influence on the cutting process. The interaction between the input parameters and kerf width formation is well agreed with [4, 9, 11, 14, 16, 17] and [26] where they all concluded that the wider kerf width can be observed at the higher laser power with slower cutting speed. The effect of laser power can be seen greatly as in Figure 5 with the increment of laser power resulting in the wider kerf formation. Hascalik [13] found that laser power contributes up to 26% of the kerf width ratio while studying on the Inconel 718 superalloy. The high laser power supplies more heat to the working material resulting in the high rate of the material removal process. The higher cutting speed means less heat concentrated at the workpiece surface as the laser beam is moving faster along the desired profile. This resulted in the less thermal effect applied to the working material thus producing narrower kerf formation [19]. The interaction between the laser power and kerf in this study shows that laser power proportionally interacts with the kerf formation. Contradicted to the laser power, cutting speed is inversely proportional with the kerf formation meanwhile the effect of the assisted gas pressure does not greatly influence the kerf with the formation.

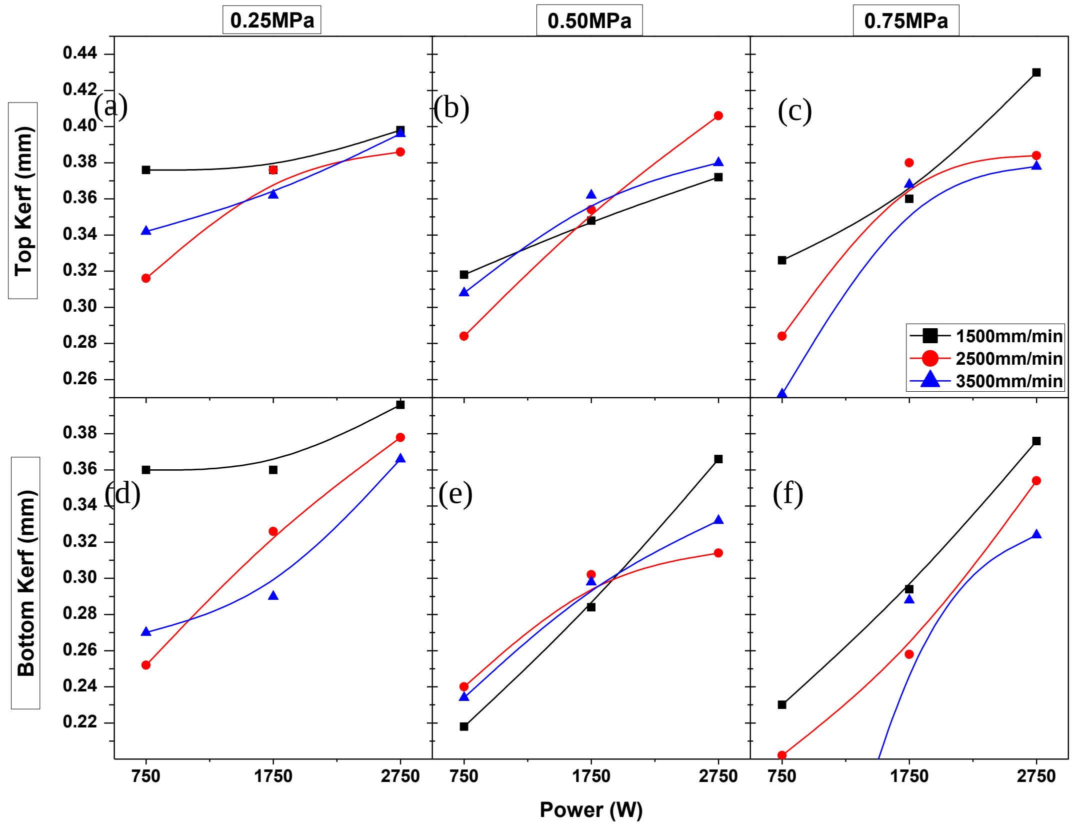
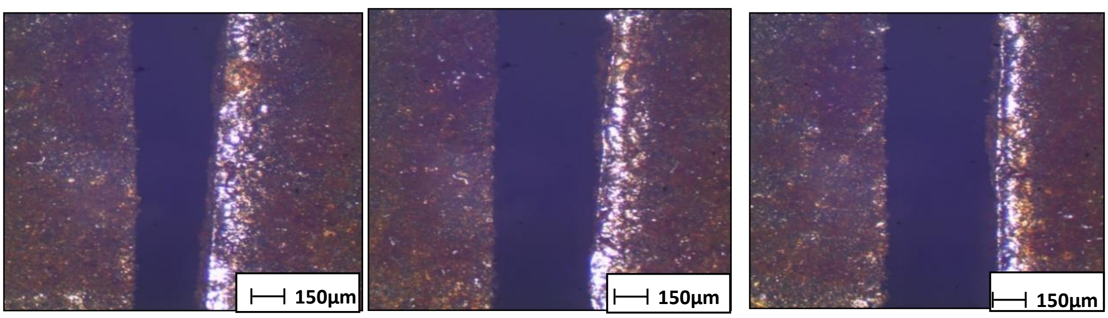


Figure 4. Tabulated graph of kerf width formation for top and bottom kerf at different gas pressures (a) top kerf at 0.25MPa; (b) top kerf at 0.50MPa; (c) top kerf at 0.75MPa; (d) bottom kerf at 0.25MPa; (e) bottom kerf at 0.50MPa; and (f) bottom kerf at 0.75MPa.



(a) (b) (c)

Figure 5. Cross-sectional views for the kerf width formation at 2500mm/min cutting speed and 0.25MPa assisted gas pressure and laser power of (a) 750 W; (b) 1750 W; and (c) 2750 W.

Taper angle

The evaluation on the taper angle was made in two aspects namely the actual measurement and calculated angle. The actual measurement was made based on the measurement obtained using the metrological equipment while the calculated angle was done according to Eq. 1. Figure 6 shows the result of the taper angle on laser processing 22MnB5 boron steel with a variation of the laser power, cutting speed and assisted gas pressure. From the graph, the actual and calculated taper angle was tabulated from 0.18 to 6.64 degree and 0.03 to 4.12 degree respectively. The smallest taper angle was recorded at run no. 3 with 2570 Watt of laser power, 1500 mm/min, and 0.25MPa assisted gas pressure. Meanwhile, the largest taper was obtained at 750 Watt, 3500 mm/min, and 0.75 MPa assisted gas pressure.

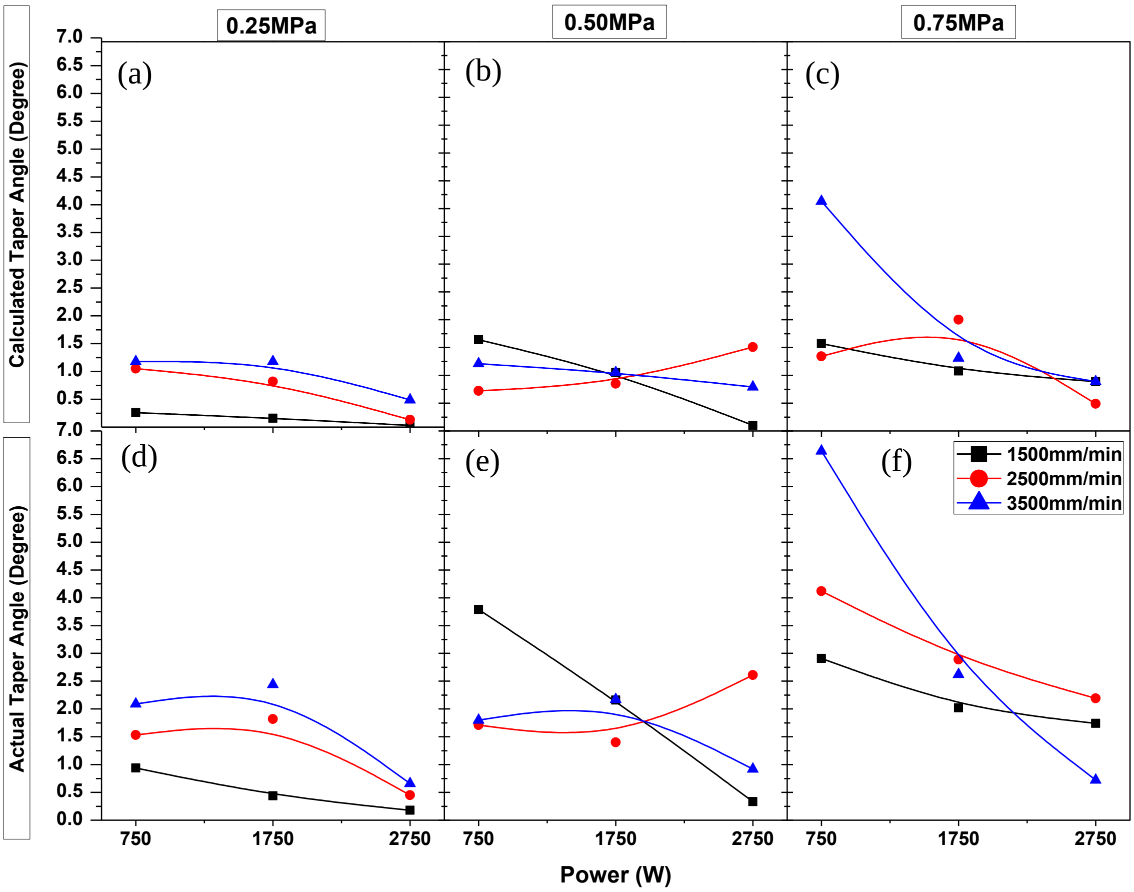
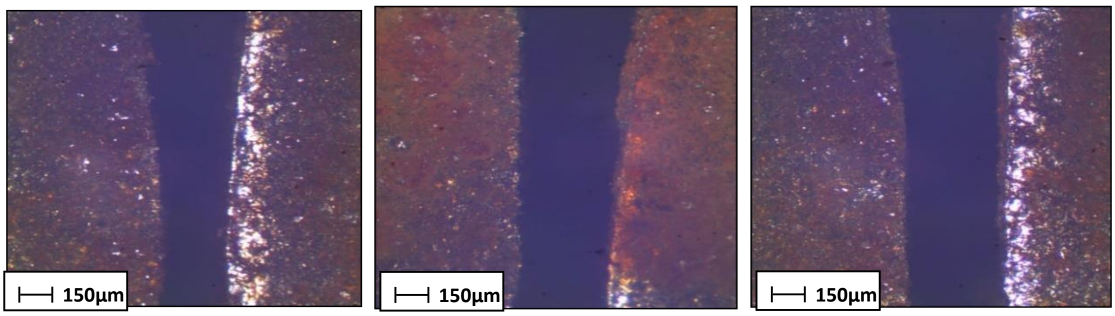


Figure 6. Tabulated graph of taper angle formation for calculated and actual taper at different gas pressure (a) calculated at 0.25MPa; (b) calculated at 0.50MPa; (c) calculated at 0.75MPa; (d) actual at 0.25MPa; (e) actual at 0.50MPa; and (f) actual at 0.75MPa.

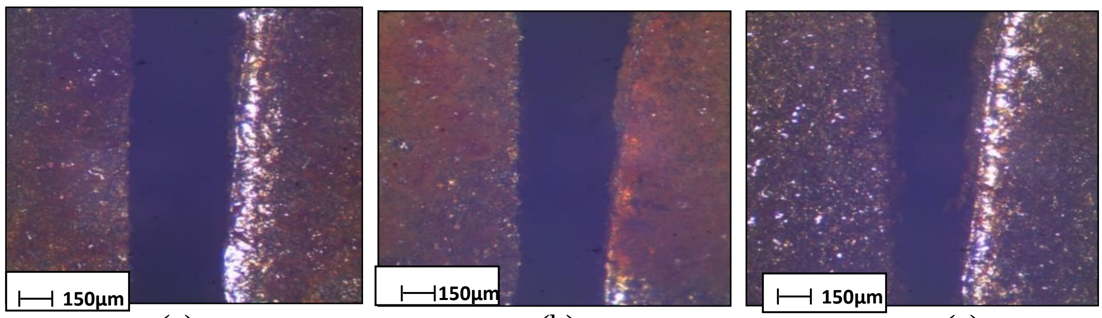
This result shows that the higher laser power has the capability to reduce the taper angle formation where the heat applied is able to penetrate fully down through the thickness of the working material. The higher laser power penetrated the material better hence the wider kerf with less taper were formed. As a consequence, the greater material removal rate was obtained by increasing the laser power hence reducing the taper formation. The high cutting speed mean that the laser beam movement is faster thus less time was spent at a single point location. As a consequence, the bigger taper angle was formed at the high cutting speed due to the less energy absorption time and this heat was not fully transmitted toward the thickness of working material. The interaction between the laser power and cutting speed obtained can be seen clearly in Figure 7 and is in agreement with the result obtained by Hascalik [13] while cutting the Inconel 718 superalloy, Yilbas [27] and Sharma [28] who developed an optimization for the taper angle on aluminium alloy. The relationship between each input parameter contradicts the kerf formation where the increment of power density helped to reduce the taper. The previous authors [13, 27, 29] concluded that by increasing the laser power while reducing the cutting speed will produce the smaller taper ratio.

The effect of the assisted gas pressure was found to be one of the significant factors influencing the taper angle formation. The high pressure of gas, especially nitrogen helps the cutting area to cool down faster thus, preventing the molten metal to be flushed away from the cutting region. Besides that, the higher pressure also produced a faster stream of gas thus preventing the heat to be conducted towards the bottom surface resulting in the smaller kerf hence producing the bigger taper angle. Figure 8 shows the taper angle formation at three different assist gas pressures. The result showed that the increment of gas pressure enhanced the taper angle formation. A similar result was obtained by Chen [12] and Yilbas [27] where both concluded that the high pressure of assisted gas could reduce the cutting quality and increase the taper angle formation. This positive correlation agreed with [14, 24].



(a) (b) (c)

Figure 7. Cross-sectional views for taper formation at 0.50MPa assisted gas pressure with (a) 750 W and 1500mm/min; (b) 1750 W and 2500mm/min; and (c) 2750 W and 3500mm/min.



(a) (b) (c)

Figure 8. Cross-sectional views for taper formation at 1750 Watt of laser power and 2500mm/min cutting speed and assisted gas pressure of (a) 0.25MPa (b) 0.50MPa; and (c) 0.75MPa.

HAZ region

Heat affected zone or known as HAZ is the region occurred at the cutting edges due to the thermal effect generated by the laser beam [19]. Figure 9 shows the result of the formation of HAZ while cutting the 22MnB5 boron steel. The HAZ region was measured according to the white band formed along the material thickness. The white band is the area where changes of the material properties happened [30]. From the result obtained, it was found that the bottom HAZ increased gradually along the material thickness and this can be seen clearly in Figures 9 and 10. A similar result was obtained by Thomas [31] where the author optimized the laser cut edge of DP600 high strength steel. The thinner HAZ at the top was due to the less thermal reaction at the top surface where cooled nitrogen was blown at the cutting edge. This results in the rapid cooling of the working area, especially, at the top surface. From the graph generated, the thickest HAZ region with the value of 326.42µm was recorded meanwhile the thinnest was 116.03µm.

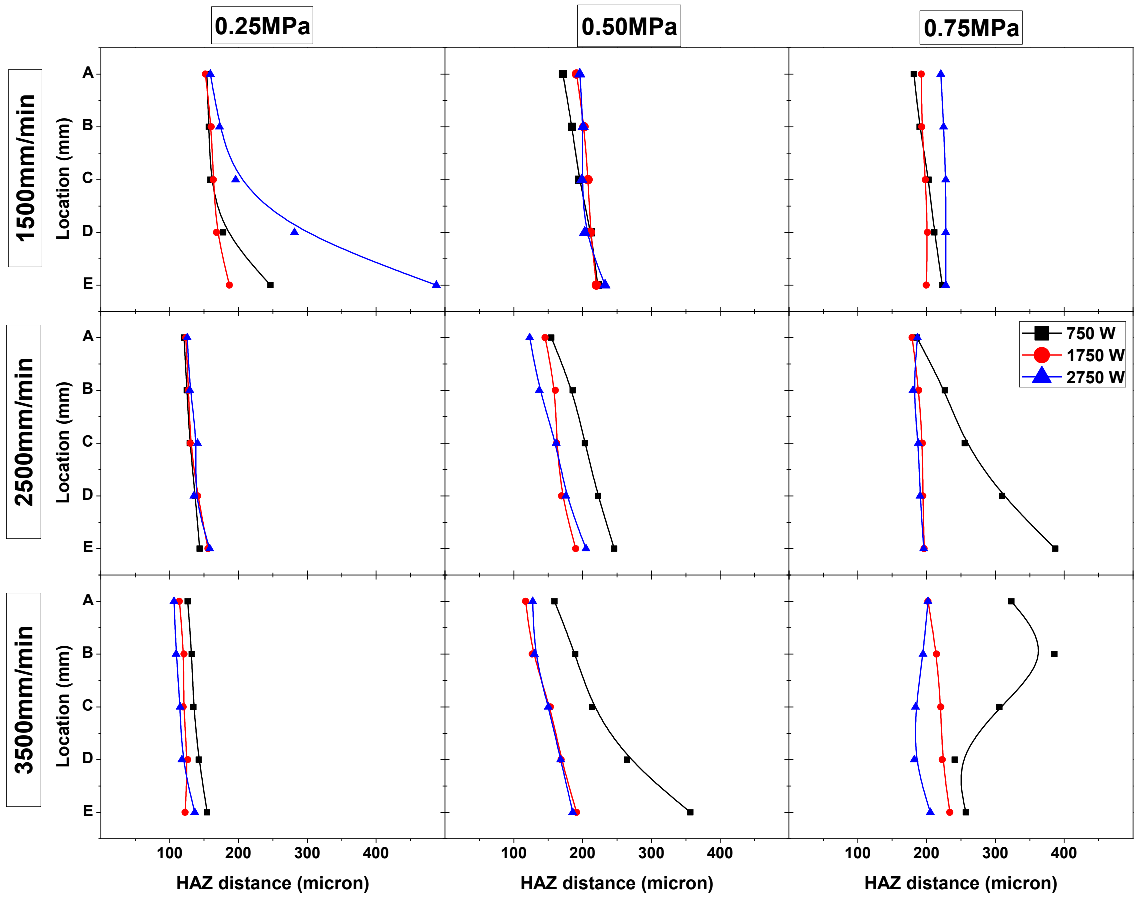


Figure 9. HAZ region along the material thickness.

The contribution of each factor on the HAZ region can be seen clearly in the graph illustrated in Figure 9. Various authors agreed on the effects of each input parameter and concluded that the HAZ region depends on the laser processing parameters [15, 30, 32, 33]. The laser power interacts proportionally with the HAZ region where the increment of the laser power will produce greater HAZ region. Bigger laser power means more heat is applied to the working material thus increasing the thermal effects at the working material. This resulting in the thicker HAZ region formed at the cutting edges. The effect of cutting speed is contradicted to the laser power where the higher cutting speed will produce a thinner HAZ region. The cutting speed represents the time allocated to a specific area thus the faster cutting speed represents less time allocated along the cutting path. This resulted in the less heat absorption rate thus reduced the thermal effect while weakening the HAZ formation. The interaction of both parameters with the HAZ region formation was similar to the result reported by researchers on the effect of the laser power and cutting speed to HAZ [11, 13, 14, 23, 30]. Even though the effect of gas pressure was not too significant, the interaction between the gas pressure and HAZ region showed that it is proportionally related. Increasing the gas pressure will slightly increase the HAZ region due to the dross creation. The result showed that the HAZ region at the top kerf was slightly thinner and thicker along the material thickness. It was reported that the HAZ formation increased from top to bottom and HAZ region was transformed back gradually in layers [34]. Figure 10 illustrated the cross-sectional view of the HAZ region for 0.25MPa at the magnifying of 100X. Different colour tones with dark boundaries showed the HAZ region along the cutting edges.

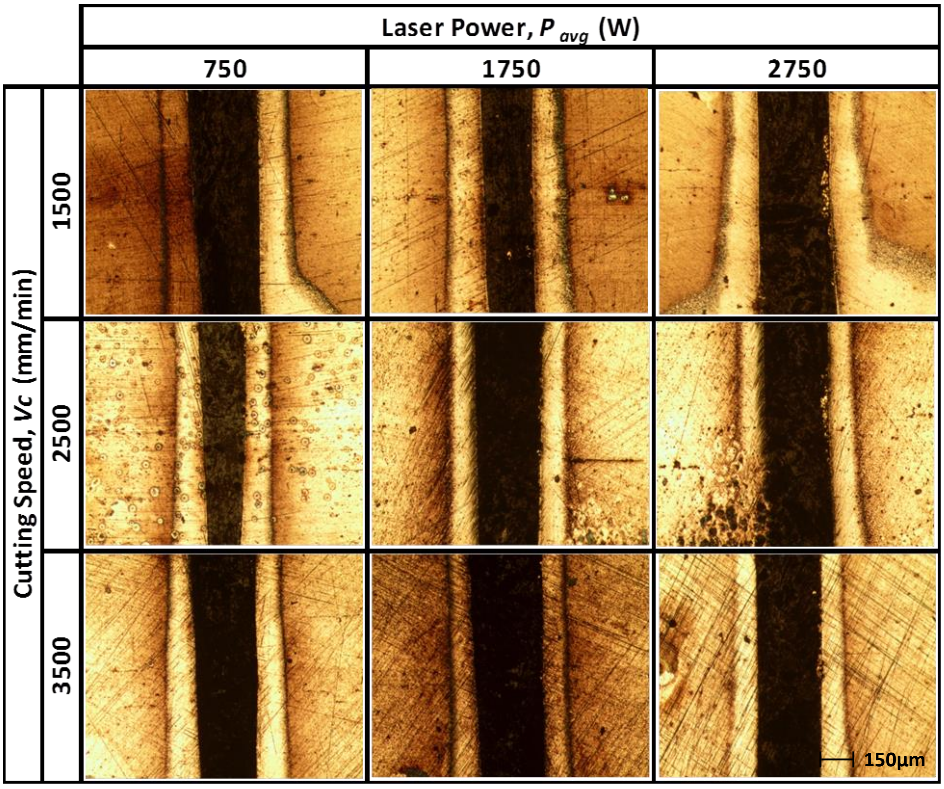
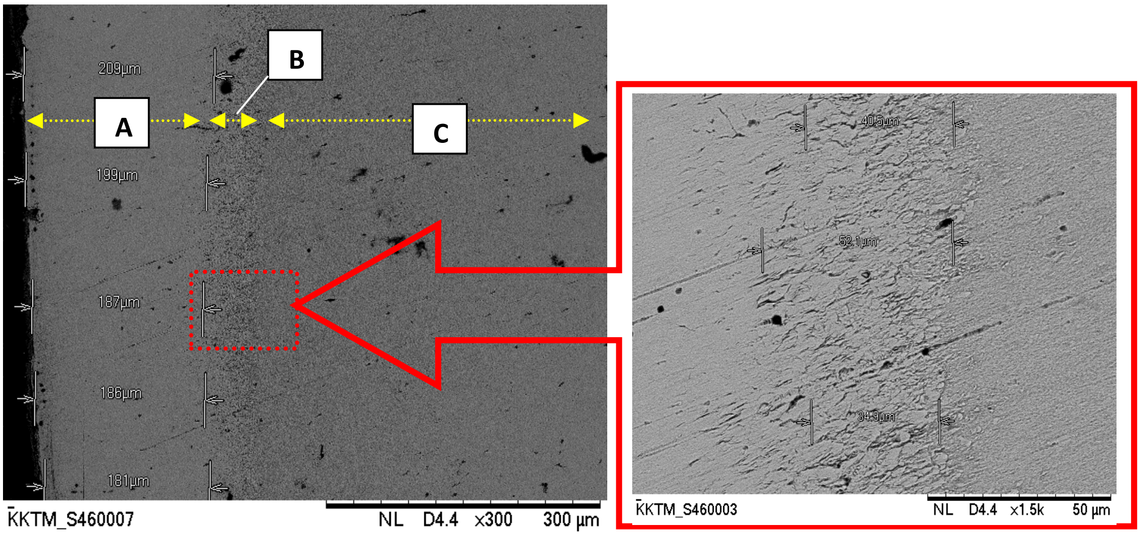


Figure 10. Cross-sectional view of HAZ region at 0.25MPa nitrogen assisted gas.

HAZ formation can be seen clearly in Figure 10 where the white band formation is beside the kerf width. It was found that the thicker HAZ was formed at the bottom side due to the assisted gas location. The power density consists of the laser power and cutting speed plays important roles in determining the HAZ formation. This was due to the HAZ formation related to heat and time exposure determined based on the proper selection of the laser power and cutting speed. Figure 11 illustrated the differences of the microstructure region, especially at the cutting edges. It was found that the changes of microstructure happened to start from the cutting edges to the base material. The confirmation of HAZ measurement was made using the Scanning Electron Microscope (SEM) and the measurement result was almost similar with the result obtained using the optical microscope. Three sections were defined based on the micrograph obtained from SEM namely the HAZ region (A), transition region (B), and base material (C). The HAZ region is where martensitic formation happened due to the rapid cooling of the nitrogen assisted gas. Babu et al. [35] and Thomas [34] concluded that the assisted gas pressure resulted in the formation of harder martensitic materials. The transition region (B) was developed due to the annealing process as reported by Bok et al. [36] who found the significant decreasing of hardness in the HAZ away zone due to the martensitic of 22MnB5 transformed to the soft bainite. The section named (C) is called the base material where the initial material properties from the hot pressed 22MnB5 boron steel were obtained.



(a) (b)

Figure 11. Micrograph of sample 16 operating at 750 W of laser power, 1500 mm/min cutting speed and 0.50MPa assisted gas pressure for; (a) microstructure transformation regions; and (b) detail on transition region.

CONCLUSIONS

This study was attempted to identify the relationship between the input parameters and cutting quality of the hot pressed 22MnB5 boron steel. The interaction of each laser parameter can be seen clearly affecting the kerf width, taper angle, and HAZ formation. Based on the result obtained, it was found that the laser power and cutting speed greatly influenced the cutting quality and mechanical properties whereas the gas pressure did not significantly influence the output. Conducting laser cutting at a low power with the high cutting speed produced much narrower kerf but significantly increase the taper angle formation. Meanwhile, operating at a high power with slow cutting speed will produce poor cutting quality in terms of the kerf width formation and dross adhesion. The selection of suitable cutting speed and laser power is crucial in determining the outcome needed either gaining the narrowest kerf or less taper formation. A similar effect happened to the HAZ region formation where the high energy density significantly increased the thickness of HAZ region. The effect of assisted gas also should be considered even it is not significantly affecting the kerf, taper, and HAZ formation. The selection of suitable pressure is able to enhance the cutting quality while reducing the operating cost. Meanwhile, the selection of suitable input parameters is crucial in determining the best cutting quality and mechanical properties whereas laser power plays the most important factor followed by the cutting speed and gas pressure in determining the cutting quality. These findings established an important relationship between the laser processing parameters in cutting the ultra-high strength steel to ensure the better cutting quality of automotive components.

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