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RESEARCH ARTICLE

Investigation of the effects of laser power and gas pressure on the top and bottom HAZ widths in AISI 1040 steels

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HIGHLIGHTS

- *Fiber laser technology was utilized.*
- *A different cutting method was applied for the HAZ.*
- *Especially top and bottom HAZ widths were investigated.*

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ABSTRACT

In this research, AISI 1040 steels, which are extensively used in different manufacturing industries, were used as workpieces to better comprehend the influences of laser beam cutting parameters on workpieces. In this context, such parameters as laser power, gas pressure and cutting speed were established as variable parameters. In present research, unlike the investigations available in the literature, the workpieces that started to be cut in a straight line were stopped 3 mm before the end of the cutting process. Thus, it could be possible to both see and investigate the top and bottom HAZ (Heat Affected Zone) widths occurring just outside the workpieces. Within the scope of the research, especially the top and bottom HAZ widths occurring in workpieces cut with a different method were investigated. At the gas pressure of 0.7 Bar, considering the largest and smallest bottom HAZ width values, it was studied out that the largest bottom HAZ width value (9.23 mm) was 32.83% larger than the smallest bottom HAZ width value (6.95 mm). On the other side, considering the largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (5.33 mm) was 71.39% larger than the smallest top HAZ width value (3.11 mm). At 1.4 Bar gas pressure, considering the largest and smallest bottom HAZ width values, it was found that the largest bottom HAZ width value (11.47 mm) was 28.19% larger than the smallest bottom HAZ width value (8.95 mm). On the other side, considering the largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (6.79 mm) was 42.95% larger than the smallest top HAZ width value (4.75 mm). Additionally, considering the largest and smallest average HAZ width values based on gas pressure of 0.7 Bar and 1.4 Bar, it was found that the largest the average HAZ width values were 33.29% and 44.75% larger than the smallest the average HAZ width values, respectively.

Keywords: *AISI 1040 steel, Fiber laser cutting, laser machining, Top and bottom HAZ widths, Kerf width*

I. INTRODUCTION

Contemporary manufacturing industries are conducting intensive research to provide better quality, more cost-effective and shorter delivery times in line with consumer demands. One of the research areas carried out in this context is the processing of materials with very different properties using laser beam technology (Guo & Singh, 2021; Salem, Mansour, Badr, & Abbas, 2008; Sargar, Jadhav, & Gautam, 2023; Steen & Mazumder, 2010). Laser beam technology is rapidly becoming widespread in contemporary manufacturing industries with its many advantages such as high production speed, cost-effectiveness and high processing quality. Laser beam is generally used for needs such as cutting, drilling, welding and surface treatment of materials with different properties (Batishcheva, Kuznetsov, Orlova, & Vympina, 2021; Kannatey-Asibu, 2023; Khdair & Melaibari, 2023; Wu et al., 2024; Wu, Wang, Zhang, Liu, et al., 2023). In recent years, the employment of laser beams in cutting chemically and physically very different materials such as metals and composites has become increasingly important. Laser beam cutting technology is used extensively in many different manufacturing industries, from the aerospace industry where high technology is used, to the electrical household appliance production industry where simple technologies are used (Guo & Singh, 2021; Steen & Mazumder, 2010; Wu et al., 2024). Research on this technology, which is used in such different fields intensively, has gained both importance and attention. However, when the usage rates of laser beam cutting technologies used in the contemporary manufacturing industries were compared, it was noticed that fiber and CO_2 lasers had the highest rates (Hilton, Lloyd, & Tyrer, 2016; Kannatey-Asibu, 2023). In particular, in recent years, indicators have been pointing entirely to fiber laser technologies.

The main reasons for this situation are that it has highly demanded features such as having a more advanced technology and lower maintenance costs (Amaral, Silva, Pinto, Campilho, & Gouveia, 2019; Guo & Singh, 2021; Kannatey-Asibu, 2023; Kardan, Levichev, Castagne, & Duflou, 2023; Steen & Mazumder, 2010). Despite all these superior features of fiber laser beam technology, as in other laser technologies, each processing parameter and its effects need to be intensively investigated in order to process each material with different properties in high quality. For this purpose, firstly, the influences of laser beam cutting parameters, for instances, cutting speed, laser power, assist gas pressure and cutting geometry on the workpiece should be investigated and optimized separately. Afterwards, the influences of other important agents such as laser technology, physical and chemical properties of the workpiece, and thickness of the workpiece should be examined. As a consequence, laser beam machining parameters will be optimized for each material individually, allowing manufacturing industries and therefore consumers to obtain high-quality and minimum-cost products (Amaral et al., 2019; Kannatey-Asibu, 2023; Steen & Mazumder, 2010).

In this research, AISI 1040 steels, which are extensively used in different manufacturing industries, were used as workpieces to better comprehend the influences of cutting parameters of laser beam on workpieces. In this context, laser power, gas pressure and cutting speed parameters were established as variable parameters. In the research, especially the top and bottom HAZ widths occurring in workpieces cut with a different method were investigated.

II. MATERIALS AND METHODS

A. Workpiece material

In this research, AISI 1040 steel materials were preferred (in order to guide manufacturing industries where these materials are used) as work pieces. AISI 1040 steel materials preferred as workpieces within the scope of this research are widely used in many different manufacturing industries from aerospace to automotive (Callister & Rethwisch, 2020; Gupta, Singh, & Sood, 2015). Pictures of the workpieces (four pieces) used in this research and their mechanical and melting temperature properties are presented in Fig. 1.

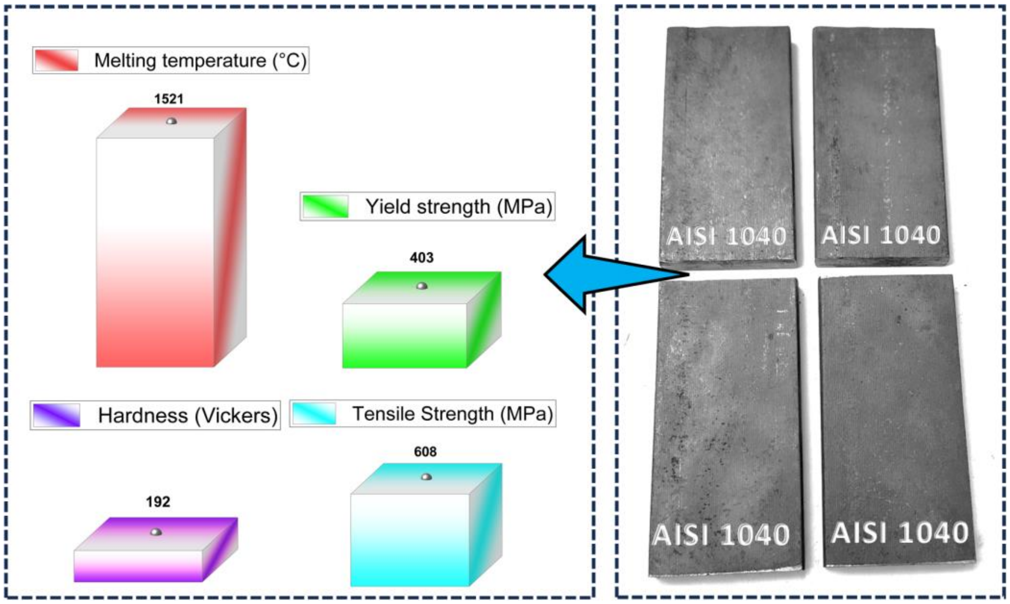

Figure 1. Pictures and properties of workpieces

The chemical compositions (as wt. %) of the AISI 1040 steel workpieces used in the research, which was carried out experimentally, are given in Fig. 2. As described in Fig. 2, the weight percentages of the elements found in AISI 1040 steel materials are within the lower and upper limits specified in the literature (Callister & Rethwisch, 2020; Dieter, 1997). The dimensions (length x width x thickness) of the workpieces used in this research are 100 mm, 50 mm and 10 mm (in the research, minimum dimensions were determined to achieve the goals of the experimental study in a cost-effective way), respectively.

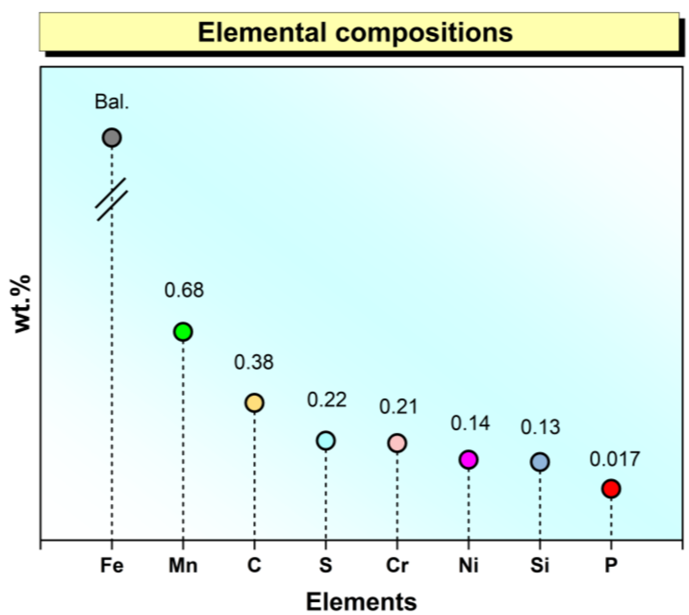

Figure 2. Chemical compositions of the workpiece

B. *Laser cutting experiments*

In this research, the cutting parameters and their levels determined (different values were determined, taking into account the upper and lower values.) for laser cutting experiments were selected as a result of intensive literature review (Guo & Singh, 2021; Kardan et al., 2023; Liu & Zhang, 2024a, 2024b; Steen & Mazumder, 2010), but the originality of the investigation was preserved by applying different values. In Table 1, the cutting parameters and levels applied to cut the workpieces with laser beam within the scope of this experimental research are given.

Table 1. Laser cutting parameters and levels

Parameter	Unit	Level 1	Level 2	Level 3
Gas pressure	Bar	0.7	1.4	-
Laser power	W	2400	2600	2800
Cutting speed	mm/min	380	480	580

In Table 2, the machining parameters of 18 laser cutting experiments performed according to the determined parameters and their levels (based on Table 1) are given. As displayed in Table 2, laser power, gas pressure and cutting speed were established as variable parameters. Also, as observed in Table 2, the increases in laser power, gas pressure and cutting speed were applied as 0.7 bar, 200 W and 100 mm/min, respectively. With these constant value increases in each parameter, the effects of each parameter and level have been provided with a clearer understanding. On the other side, parameters such as nozzle diameter and assist gas type were determined (since the workpieces are metal) as 2 mm and Oxygen gas, respectively, in line with literature investigations (Guo & Singh, 2021; Powell, Al-Mashikhi, Kaplan, & Voisey, 2011; Shin et al., 2018). The CNC fiber laser machine used in this research is HGStar 3015 (trademarked) with a wavelength and a power of 1064 nm and 6000 W, respectively.

Table 2. Laser machining parameters

Exp. no	Gas pressure (Bar)	Laser power (W)	Cutting speed (mm/min)
H1	0.7	2400	380
H2	0.7	2400	480
H3	0.7	2400	580
H4	0.7	2600	380
H5	0.7	2600	480
H6	0.7	2600	580
H7	0.7	2800	380
H8	0.7	2800	480
H9	0.7	2800	580
H10	1.4	2400	380
H11	1.4	2400	480
H12	1.4	2400	580
H13	1.4	2600	380
H14	1.4	2600	480
H15	1.4	2600	580
H16	1.4	2800	380
H17	1.4	2800	480
H18	1.4	2800	580

At the beginning, middle and end of the research (i.e., measured three times), the relative humidity and ambient temperatures in the experimental environment (considering the experimental results are known to be significantly impacted by it (Guo & Singh, 2021; Kannatey-Asibu, 2023; Steen & Mazumder, 2010) were measured with the HTC-1 brand device, then the arithmetic averages of them were computed. The measurements' results showed that the average relative humidity was 53% and the ambient temperature was 26°C. Within the scope of this research, a picture taken during the cutting process, the dimensions of the workpieces (Three-Dimensional, 3D) and the picture of the laser cutting method are presented in Fig. 3. In the research carried out experimentally, as displayed in Fig. 3, unlike the investigations found in the literature, the workpieces that started to be cut in a straight line were stopped 3 mm before the end of the cutting process. Thus, it became possible to both see and investigate the top and bottom HAZ widths occurring just outside (3 mm) the workpieces.

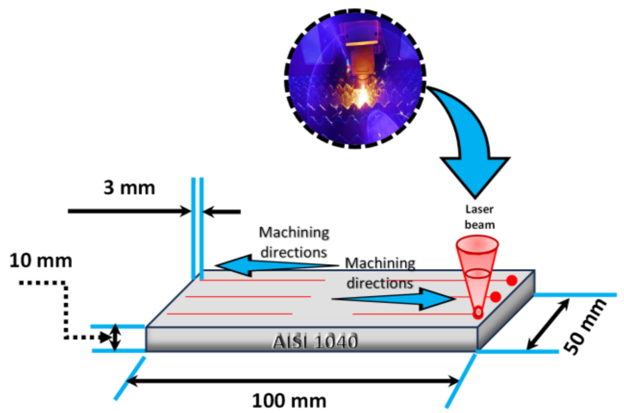

Figure 3. Dimensions of the workpieces and laser cutting method (also, an image taken during the cutting)

C. HAZ (top and bottom) and Kerf width measurements

In this research, although research was conducted especially on the top and bottom HAZ widths, the kerf widths that occurred during laser cutting processes were also measured. In Fig. 4, the locations of HAZ (top and bottom) and Kerf width measurements are shown.

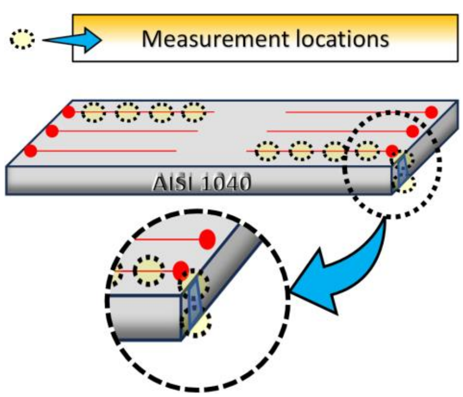

Figure 4. HAZ (top and bottom) and kerf width measurements

As displayed in Fig. 4, the kerf widths were measured at 4 (four) different locations and then their arithmetic means were calculated. On the other hand, HAZ widths were measured in the top and bottom regions where the HAZ occurred (Fig. 4). In order to precisely measure the HAZ and kerf widths, images were first taken with a Leica DM 750P microscope (for each laser cutting experiment separately. i.e., eighteen (18) experiments) and then measurements were made digitally on these images employing ImageJ software.

III. RESULTS AND DISCUSSION

A. HAZ (top and bottom) and Kerf widths

In this experimental research, as displayed in Fig. 5, unlike the investigations found in the literature, the specimens that started to be cut in a straight line were stopped 3 mm before the end of the cutting process. Thus, it is possible to both see and investigate the top and bottom HAZ widths occurring just outside (3 mm) the specimens.

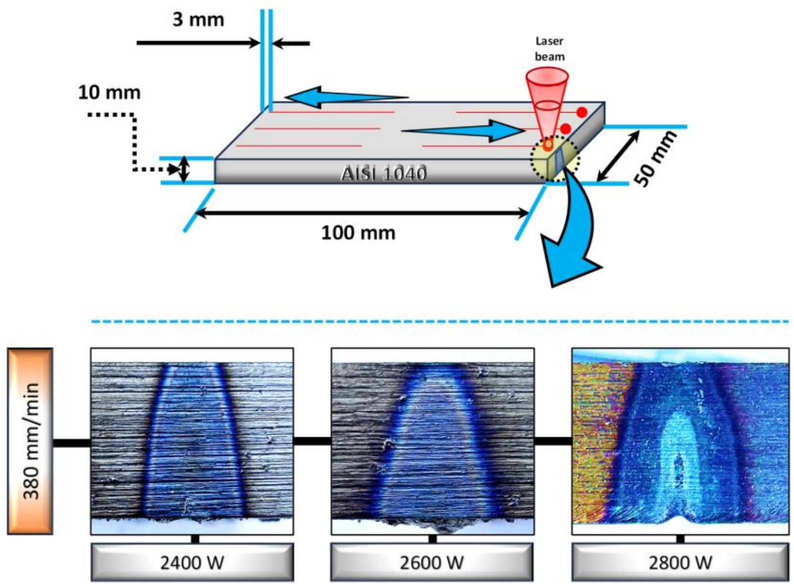

Figure 5. Change of top and bottom HAZ widths

The change of top and bottom HAZ widths depending on the increase in laser power at constant cutting speed is shown in Fig. 5. As displayed in Fig. 5, it is clearly observed that both top and bottom HAZ widths increase as the laser power increases. On the other side, as seen in Fig. 6, graphs of top and bottom HAZ width values obtained based on different gas pressure and laser power are given. As depicted in Fig. 6 a, at 0.7 Bar gas pressure, the largest bottom HAZ width value was studied out to be 9.23 mm and the smallest bottom HAZ width value was studied out to be 6.95 mm. This largest bottom HAZ width value was obtained at 2800 W laser power and 380 mm/min cutting speed parameters, while the smallest bottom HAZ width value was achieved at 2400 W laser power and 380 mm/min parameters. Considering these largest and smallest bottom HAZ width values, it was studied out that the largest bottom HAZ width value (9.23 mm) was 32.83% larger than the smallest bottom HAZ width value (6.95 mm). On the other side, as displayed in Fig. 6 b, at 0.7 Bar gas pressure, the largest top HAZ width value was studied out to be 5.33 mm and the smallest top HAZ width value was studied out to be 3.11 mm. This largest top HAZ width value was achieved at 2800 W laser power and 380 mm/min cutting speed parameters, while the smallest top HAZ width value was obtained at 2400 W laser power and 380 mm/min parameters. Considering these largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (5.33 mm) was 71.39% larger than the smallest top HAZ width value (3.11 mm).

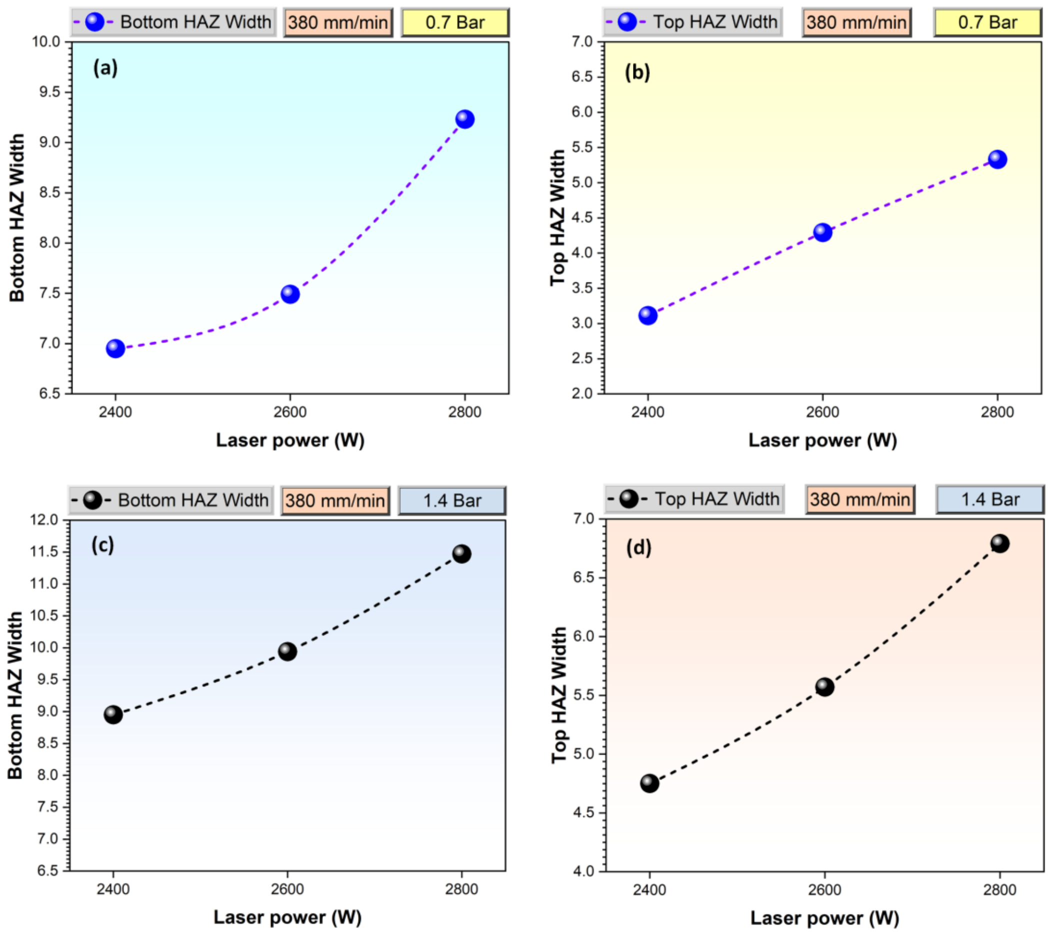

Figure 6. Top and bottom HAZ width values according to laser cutting parameters

As presented in Fig. 6 c, at gas pressure of 1.4 Bar, the largest bottom HAZ width value was studied out to be 11.47 mm and the smallest bottom HAZ width value was studied out to be 8.95 mm. This largest bottom HAZ width value was obtained at laser power of 2800 W and cutting speed of 380 mm/min, while the smallest bottom HAZ width value was achieved at the parameters of laser power of 2400 W and cutting speed of 380 mm/min. Considering these largest and smallest bottom HAZ width values, it was studied out that the largest bottom HAZ width value (11.47 mm) was 28.19% larger than the smallest bottom HAZ width value (8.95 mm). On the other side, as displayed in Fig. 6 d, at gas pressure of 1.4 Bar, the largest top HAZ width value was studied out to be 6.79 mm and the smallest top HAZ width value was studied out to be 4.75 mm. This largest top HAZ width value was obtained at parameters of laser power 2800 W and cutting speed of 380 mm/min, while the smallest top HAZ width value was achieved at parameters of laser power of 2400 W and cutting speed of 380 mm/min. Considering these largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (6.79 mm) was 42.95% larger than the smallest top HAZ width value (4.75 mm). Consequently, considering these largest and smallest top and bottom HAZ width values based on gas pressures of 0.7 Bar and 1.4 Bar, it was studied out that the largest bottom HAZ width values (i.e., 11.47 mm and 9.23 mm) were 141.47% and 196.78% larger than the smallest top HAZ width values (i.e., 4.75 m and 3.11 mm), respectively. In this experimental research, to better comprehend the HAZ widths, the arithmetic averages of the top and bottom HAZ widths obtained based on gas pressure and laser power were calculated and depicted in Fig. 7.

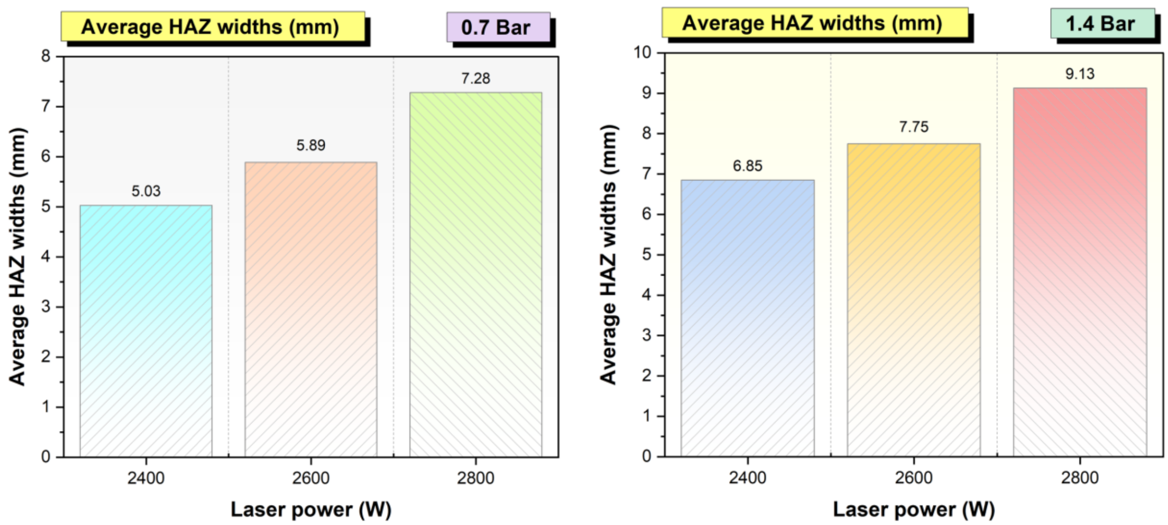

Figure 7. Average HAZ widths based on gas pressures

As displayed in Fig. 7, when the average HAZ width values obtained at gas pressure of 0.7 Bar were checked, it was understood that the largest average HAZ width value was obtained as 7.28 mm at 2800 W laser power. Additionally, it was inspected that at gas pressure of 0.7 Bar, the smallest average HAZ width of 5.03 mm was obtained at 2400 W laser power. On the other side, as depicted in Fig. 7, when the average HAZ width values obtained at gas pressure of 1.4 Bar were visually inspected, it was understood that the largest average HAZ width value was obtained as 9.13 mm at 2800 W laser power. Moreover, it was found that at gas pressure of 1.4 Bar, the smallest average HAZ width of 6.85 mm was obtained at 2400 W laser power. Consequently, considering these largest and smallest the average HAZ width values based on gas pressures of 0.7 Bar and 1.4 Bar, it was found that the largest the average HAZ width values (i.e., 9.13 mm and 7.28 mm) were 33.29% and 44.75% larger than the smallest the average HAZ width values (i.e., 6.85 m and 5.03 mm), respectively. Additionally, as a consequence of the experiments, it was revealed that the average HAZ widths were negatively affected by high gas pressure (based on the results obtained at 0.7 Bar and 1.4 Bar gas pressures). As depicted in Figs. 5, 6 and 7, it was understood that the HAZ widths were negatively affected by both high laser power and high gas pressure.

This can be explained by the fact that the laser beam concentrated on the metal material penetrates more into the metal material owing to the influence of high laser power, resulting in an increase in both the molten metal volume and the width of the HAZ. Moreover, because of high pressured oxygen penetrating into the same location for a longer period of time and reacting with the metal material, extra energy is generated and with the impact of this additional energy, both the HAZ width and the molten metal volume increase (Adin, 2024; Guo & Singh, 2021; Kannatey-Asibu, 2023; Karatas, Keles, Uslan, & Usta, 2006; Rao, Raju, Suresh, Ranganayakulu, & Krishna, 2024; Scintilla & Tricarico, 2012). As a matter of fact, when the results of the investigations in the literature on metal materials were examined, it was noticed that increases in gas pressure and laser power caused similar effects (Guo & Singh, 2021; Kannatey-Asibu, 2023; Steen & Mazumder, 2010; Wu et al., 2024; Wu, Wang, Zhang, Liu, et al., 2023; Wu, Wang, Zhang, Xue, et al., 2023).

In this research, although research was conducted especially on the top and bottom HAZ widths, the kerf widths that occurred during laser cutting processes were also measured. In Fig. 8, the kerf widths occurring at different cutting speeds at a constant laser power of 2800 W are displayed. As depicted in Fig. 8, it is understood that at constant laser power, kerf widths tend to decrease as the cutting speed increases. On the other part, it is observed that kerf widths are negatively affected due to the increase in molten metal volume at a cutting speed of 380 mm/min and its inability to be sufficiently removed (due to high laser power) (Steen & Mazumder, 2010; Wu, Wang, Zhang, Liu, et al., 2023) from the cutting area.

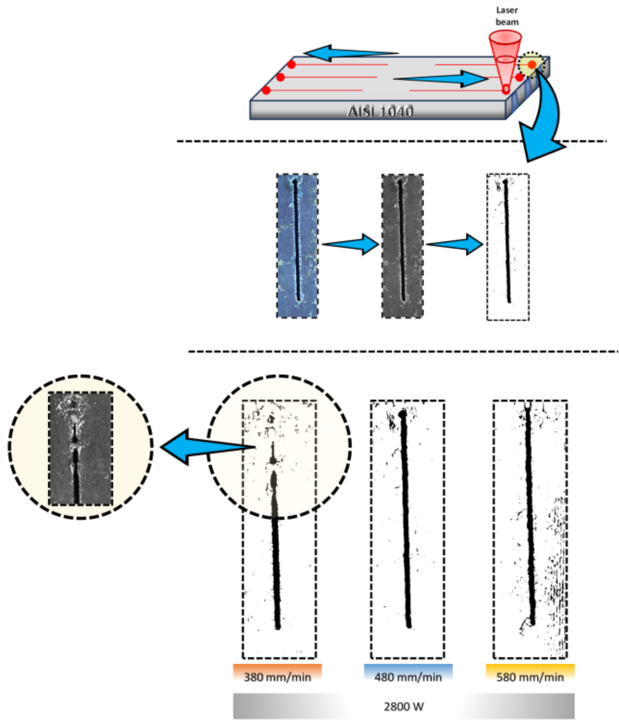

Figure 8. Kerf widths occurring at different cutting speeds at constant laser power

Fig. 9 shows the effects of laser power, gas pressure and cutting speed on the kerf width. When the graphs given in Figure 9 are visually examined, it is clearly understood that high laser power and gas pressures negatively affect the kerf widths.

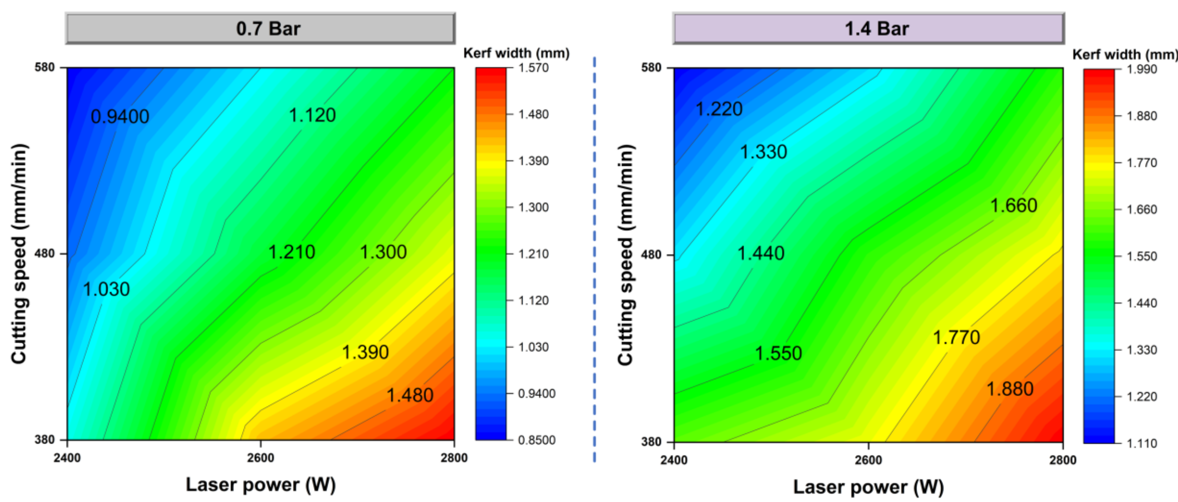

Figure 9. Influences of laser power, cutting speed, and gas pressure on the kerf widths

Moreover, it is inspected that the smallest kerf width values are concentrated (blue colored area) in the range of laser power of 2400 W and cutting speed of 580 mm/min, whereas the largest kerf widths are concentrated (red colored area) in the range of laser power of 2800 W and cutting speed of 380 mm/min. Additionally, it was understood that the largest kerf width values occurred at high gas pressure (i.e., 1.4 Bar). In order to better see the effects of high gas pressure (i.e., gas pressure 1.4 Bar) on kerf widths, a comparison graph was drawn and presented in Fig. 10.

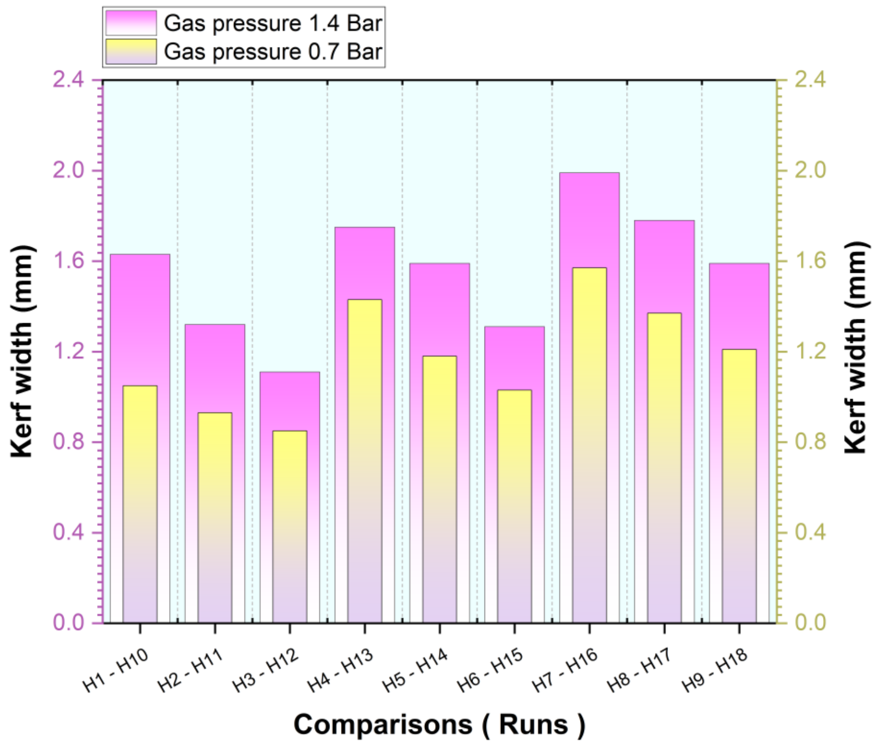

Figure 10. Comparison graph of gas pressures according to kerf width results

As displayed in Fig. 10, although the specimens were cut with the same processing parameters, it is evidently observed that the kerf width values are higher owing to the influence of high gas pressure, which may be explained by the fact that the laser beam concentrated on the metal material penetrates more into the metal material because of the influence of high laser power, resulting in an increase in the molten metal volume. Moreover, as a result of the high pressured oxygen gas penetrating into the same location for a longer period of time and reacting with the metal material, extra energy is generated and with the impact of extra energy obtained, not only HAZ width but also the molten metal volume increases. As a consequence of these situations, kerf widths are negatively affected, resulting in wider kerf widths compared to specimens cut with low gas pressure (i.e., 0.7 Bar). (Guo & Singh, 2021; Kannatey-Asibu, 2023; Steen & Mazumder, 2010; Yu, 1997). On the other hand, when the results given above are evaluated together, it is understood that the most optimum machining parameters for AISI 1040 steels used as workpieces within the scope of this article are gas pressure of 0.7 Bar, laser power of 2400 W and cutting speed of 580 mm/min, respectively.

IV. CONCLUSIONS

In present research article, the influences of laser cutting parameters applied during the machining of AISI 1040 steel workpieces, which are used extensively in contemporary manufacturing industries, were investigated. The results from the experimental research are summarized below:

- At 0.7 Bar gas pressure, the largest bottom HAZ width value was studied out to be 9.23 mm and the smallest bottom HAZ width value was studied out to be 6.95 mm. This largest bottom HAZ width value was obtained at the parameters of laser power of 2800 W and cutting speed of 380 mm/min, while the smallest bottom HAZ width value was achieved at the parameters of laser power of 2400 W and cutting spend of 380 mm/min.

Considering these largest and smallest bottom HAZ width values, it was studied out that the largest bottom HAZ width value (9.23 mm) was 32.83% larger than the smallest bottom HAZ width value (6.95 mm). The largest top HAZ width value was studied out to be 5.33 mm and the smallest top HAZ width value was found to be 3.11 mm. This largest top HAZ width value was obtained at the parameters of laser power of 2800 W and cutting speed of 380 mm/min, while the smallest top HAZ width value was achieved at the parameters of laser power of 2400 W and cutting speed of 380 mm/min. Considering these largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (5.33 mm) was 71.39% larger than the smallest top HAZ width value (3.11 mm).

- ❖ At gas pressure of 1.4 Bar, the largest bottom HAZ width value was studied out to be 11.47 mm and the smallest bottom HAZ width value was studied out to be 8.95 mm. This largest bottom HAZ width value was obtained at the parameters of laser power of 2800 W and cutting speed of 380 mm/min, while the smallest bottom HAZ width value was achieved at the parameters of laser power of 2400 W and cutting speed of 380 mm/min. Considering these largest and smallest bottom HAZ width values, it was studied out that the largest bottom HAZ width value (11.47 mm) was 28.19% larger than the smallest bottom HAZ width value (8.95 mm). The largest top HAZ width value was studied out to be 6.79 mm and the smallest top HAZ width value was studied out to be 4.75 mm. This largest top HAZ width value was obtained at the parameters of laser power of 2800 W and the cutting speed of 380 mm/min, while the smallest top HAZ width value was achieved at the parameters of laser power 2400 W and the cutting speed of 380 mm/min. Considering these largest and smallest top HAZ width values, it was studied out that the largest top HAZ width value (6.79 mm) was 42.95% larger than the smallest top HAZ width value (4.75 mm).
- ❖ Considering the largest and smallest top and bottom HAZ width values based on the gas pressures of 0.7 Bar and 1.4 Bar, it was studied out that the largest bottom HAZ width values (i.e., 11.47 mm and 9.23 mm) were 141.47% and 196.78% larger than the smallest top HAZ width values (i.e., 4.75 m and 3.11 mm), respectively.
- ❖ When the average HAZ width values obtained at the gas pressure of 0.7 Bar were checked, it was understood that the largest average HAZ width value was obtained as 7.28 mm at 2800 W laser power. Additionally, it was inspected that at the gas pressure of 0.7 Bar, the smallest average HAZ width of 5.03 mm was obtained at 2400 W laser power. On the other side, when the average HAZ width values obtained at the gas pressure of 1.4 Bar were visually inspected, it was understood that the largest average HAZ width value was obtained as 9.13 mm at 2800 W laser power. Moreover, it was found that at the gas pressure of 1.4 Bar, the smallest average HAZ width of 6.85 mm was obtained at 2400 W laser power.
- ❖ Considering the largest and smallest the average HAZ width values based on 0.7 Bar and the gas pressure of 1.4 Bar, it was found that the largest the average HAZ width values (i.e., 9.13 mm and 7.28 mm) were 33.29% and 44.75% larger than the smallest the average HAZ width values (i.e., 6.85 m and 5.03 mm), respectively. Additionally, as a consequence of the experiments, it was revealed that the average HAZ widths were negatively affected by high gas pressure.
- ❖ Although the specimens were cut with the same processing parameters, it is evidently observed that the kerf width values are higher owing to high gas pressure effect.
- ❖ When the results obtained are evaluated together, it is understood that the most optimum machining parameters for AISI 1040 steels used as workpieces within the scope of the present study are the gas pressure of 0.7 Bar, the laser power of 2400 W and the cutting speed of 580 mm/min, respectively.

STATEMENT OF CONTRIBUTION RATE

Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing-Original Draft, Writing-review & editing, etc. were performed by Mehmet Şükrü Adin.

CONFLICTS OF INTEREST

The author declares that I have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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