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Research Article

Experimental Research of the Influence of Fiber Laser Machining Parameters on HAZ Width in AISI 4140 Steels

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ABSTRACT

In present day, laser beam machining technology attracts great attention due to its cost-effectiveness, high machining quality, mass manufacturing velocity and broad areas of applicability throughout different manufacturing industries. However, intensive researches are required since many materials with different properties (chemical and mechanical) are used in the manufacturing industries; and there is need for high quality machining through newly developed laser technologies. In this context, in this experimental research, unlike most studies in the literature, an investigation was carried out on heat affected zone (HAZ) occurring in AISI 4140 steel machined by laser beam in different cutting geometries (triangle, square and circle cutting). In the present study, when the average HAZ widths calculated according to the laser cutting geometries were examined, it was understood that the highest average HAZ width (579 µm) was obtained in the triangle cutting geometry and the lowest average HAZ width (369 µm) was obtained in the circle cutting geometry. What is more, when the average HAZ widths obtained according to laser cutting geometries were compared, it was observed that the average HAZ widths of the specimens cut in triangle geometry were 31.61% and 56.93% larger than the specimens cut in square and circle cutting geometries, respectively. Furthermore, it was found that as the laser power increased, the HAZ widths were negatively affected (i.e., HAZ widths increased), but as the cutting speed increased, the HAZ widths were positively affected (i.e., HAZ widths decreased). From the ANOVA analyses, it was found that the cutting geometry (with a rate of 51.32%) was the most pivotal parameter influencing the HAZ width. When the regression analysis results (based on quadratic regression models) were checked, it was understood that R^2 value had a very high rate (96.79%) as desired. Thus, from these results, it was understood that the model developed to predict the HAZ width values has a high success rate and reliability.

Introduction

Nowadays, there is a great demand for machining materials with different properties (in terms of chemical and physical properties) using laser technologies. The most important reasons for this demand are their low costs and high-quality machining capabilities [1, 2]. Moreover, they have another advantage that no cutting tools are needed in machining operations [2]. Considering the laser technologies used in modern manufacturing industries, it is seen that especially CO_2 and fiber laser technologies stand out. However, in recent years, interest in fiber laser has been increasing day by day due to its relatively newer and more advanced features [3, 4]. Additionally, the fact that it is more cost-effective than CO_2 laser is seen as another advantage [5, 6]. In laser cutting processes, one of the most important factors affecting laser cutting efficiency is the absorption capacity of the material being machined. This factor is highly affected by many parameters such as the type of material (chemical and physical), the wavelength of the laser beam and the angle of incidence of the laser beam. Compared to CO_2 lasers, fiber lasers, due to their shorter wavelengths, provide higher absorption when processing metal materials. As a natural consequence of this situation (since it provides higher absorption), it provides higher quality machining [1, 5, 7, 8]. Although fiber laser is a newer technology than CO_2 laser, machining parameters need to be optimized separately for each material in order to achieve high quality machining of materials with different chemical and physical properties [4-6]. In the laser cutting process (to summarize briefly), local melting occurs in the workpiece (metal) under the influence of the laser beam focused on the workpiece and the molten metal is blown out from the operation area with the help of the assist gas used during the process. As a consequence of this continuous operation, the workpiece is separated (i.e., cutting occurs) from each other [4, 5]. In laser cutting processes, for a high-quality cutting, it is very important to take into account many parameters such as laser technology, cutting geometry, laser power, cutting speed, type of assist gas, gas pressure, chemical and physical properties of the workpiece, and thickness of the workpiece [5, 6]. Therefore, a lot of research needs to be carried out regarding these parameters. As a matter of fact, it is seen in the literature that investigations have been conducted regarding many of these parameters [3-5]. However, when the investigations in the literature are checked, it is observed that laser cutting geometries are generally in the form of a straight line. In other words, it is understood that a limited number of investigations have been conducted on different cutting geometries and their effects. Moreover, as a consequence of literature review, it was understood that there are very few investigations on the heat affected zone (HAZ) that occurs in metal workpieces during laser cutting process [3-6].

In this experimental research, unlike most studies in the literature, an investigation was carried out on HAZ occurring in AISI 4140 steel machined by laser beam in different cutting geometries (triangle, square and circle). In order to conduct the investigation cost-effectively and also for a comprehensive evaluation, one of the most widely used optimization methods was employed.

Materials and methods

Workpiece material

In this current research, AISI 4140 steel was utilized as the workpiece. AISI 4140 steel is a type of steel that stands out with its many features such as superior strength, wear resistance and good toughness. These steels are among the most demanded materials in the manufacturing industries due to their high durability [9, 10]. That is why it was specially selected within the scope of this research. In Table 1, the chemical compositions of AISI 4140 steel used as the workpiece in this research is given.

Table 1. Chemical compositions

Chemical composition (wt.%)			
C	0.41	Cr	1.04
Si	0.24	Ni	0.03
P	0.012	Mo	0.172
Mn	0.82	Cu	0.01
S	0.023	Fe	Bal.

As displayed in Fig. 1, images and dimensions (100 mm x 50 mm x 10 mm) of AISI 4140 steel materials machined with laser beam in different cutting geometries are given.

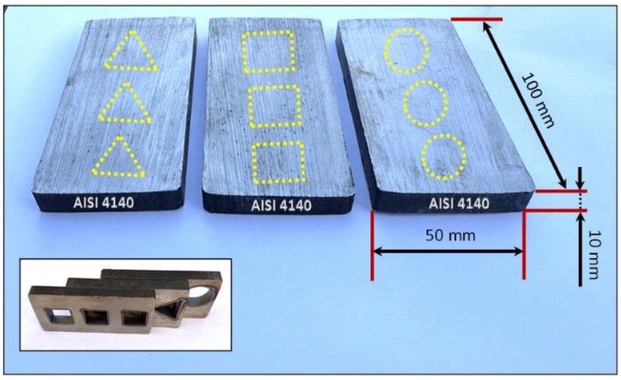

Figure 1. Images and dimensions of AISI 4140 test specimens

Use of Taguchi method

In the present day, many optimization methods are used in different manufacturing industries for high quality machining of workpieces with different characteristics (chemically and physically). The Taguchi method, which provides cost-effective solutions with a minimum number of experiments, is the most well-known of these optimization methods. That is why, in this research, this optimization method was utilized to obtain the most cost-effective solutions [11-13]. Moreover, variance (ANOVA) and regression analyses were also performed to make the study more comprehensive. ANOVA analysis was performed based on literature investigations at a confidence level of 95% and a significance level of 5%, and the most accurate results were achieved [11, 13, 14]. In this research, the "Smaller is better" approach (due to adverse effects on the workpiece) was adopted because the HAZ (the heat affected zone) width in laser-cut materials was required to be as minimum as possible [2]. In this context, for each experimental result obtained, signal-to-noise ratios (S/N ratios) were calculated using the formula (equation (1)) given below [11, 12].

Smaller is better:

$$S/N = -10 \log \left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

In this current research, Minitab statistical software (Fig. 2), which is widely used in investigations [15], was used to perform the analyses.

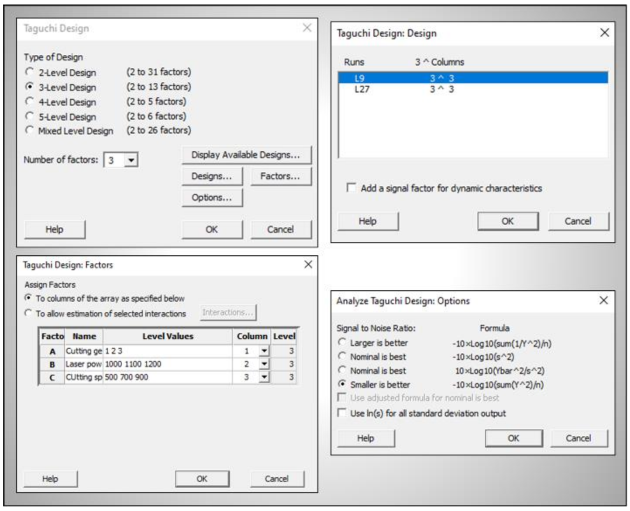

Figure 2. Step by step adjustments to perform analyses

Besides, as depicted in Fig. 2, the Taguchi L9 (3-level design) experimental design (DOE) was adopted (based on laser machining parameters and levels). In Table 2, the machining parameters and levels determined for laser cutting experiments within the scope of this research are given. The laser cutting parameters (gas pressure, laser power, cutting speed) used in this research were determined based on the investigations in the literature [2, 4, 16]. However, different values were determined (between the top and bottom values) in order to make this research original.

Table 2. Laser machining parameters and levels

Parameter	Unit	Level 1	Level 2	Level 3
Cutting geometry	-	1 (Triangle)	2 (Square)	3 (Circle)
Gas pressure	Bar	0.6	-	-
Laser power	W	1000	1100	1200
Cutting speed	mm/min	500	700	900

As displayed in Table 2, the levels of laser cutting parameters were increased according to the same increase rate (for each parameter separately), thus enabling more precise results to be obtained.

Laser beam machining experiments

In this current investigation, laser cutting experiments were conducted using a Senfeng brand CNC fiber laser machine with a maximum power of 2000 W. Since they have significant effects on the results of the experiments [4, 5], ambient temperature and relative humidity were measured three times using a Hubstein HTC-1 brand device and the averages of these values were calculated. The average relative humidity and ambient temperature throughout the laser cutting experiments were found to be 53% and 25°C, respectively. Fig. 3 depicts images of AISI 4140 steel materials machined in different laser cutting geometries (i.e., triangle, square and circle) taken during cutting experiments. Moreover, as seen in Fig.3, the laser cutting lengths were specifically ensured to be the same (96 mm) despite the different laser cutting geometries. Because, due to the nature of laser beam cutting processes, laser cutting lengths are very important [4]. As a matter of fact, this issue (laser cutting lengths) will be expressed in detail in the results and discussion section. The laser cutting geometries used in this research were specifically determined (for the purpose of an original research) because there is no similar study in the literature. In the laser cutting experiments performed with a fiber laser machine, a 2 mm diameter nozzle and O2 gas (as assist gas) were used [4-6, 16]. In the laser cutting experiments performed according to Taguchi's L9 DOE, the thickness (10 mm, i.e. thicker) of the workpieces was determined in the light of the studies in the literature in order to make the HAZ widths more apparent [4-6].

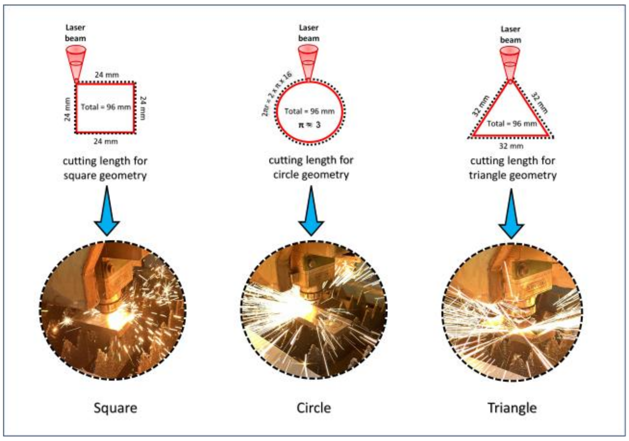

Figure 3. Laser cutting lengths (triangle, square and circle) and images taken during laser cutting experiments

HAZ width measurements

In this research, in order to investigate the effects of different cutting geometries and cutting parameters on the cut specimens, firstly the images of the edges of the cut specimens were captured with the help of a microscope (Leica DM 750P branded microscope) and then the HAZ widths were precisely measured on these images with the help of ImageJ software. As depicted in Fig. 4, the image taken of the cut edge of the steel material cut with a laser beam and a measurement process performed on this image are shown. In this research, since the negative effects of HAZ widths on the specimen are known [2, 4, 15-17], measurements were made at five different points of each cut (cut with different cutting geometries) specimen and then the arithmetic averages of these results were calculated.

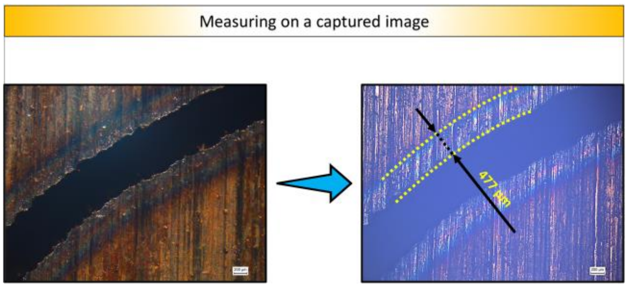

Figure 4. Measuring on a captured image

Results and discussion

HAZ width

Nowadays, in the manufacturing industries where laser-cutting processes are carried out, the surface roughness, cutting width and HAZ widths of the cut workpieces are taken into consideration as important aspects. The most important reason for this is that the machining quality of these manufactured parts directly affects their performance in their permanent use place [2, 4, 15-17]. For these reasons, in this research, measurements (HAZ widths) were made at five different points of each cut (cut with different cutting geometries) specimen and then the arithmetic averages of these results were calculated. In Fig. 5, the results of HAZ widths obtained as a consequence of this experimental study are given separately for different cutting geometries.

As illustrated in Fig. 5, when the specimens cut in triangle geometry with the laser beam were checked, it was seen that the highest HAZ width was 715 µm. On the other side, the lowest HAZ width was measured as 411 µm in specimens cut in triangle geometry with laser beam. When the highest (715 µm) and lowest (411 µm) HAZ widths obtained from these specimens cut in triangle geometries were compared, it was observed that the highest HAZ width was 73.96% larger than the lowest HAZ width.

On the other hand, as depicted in Fig. 5, when the specimens cut in square geometry with the laser beam were checked, it was observed that the highest HAZ width was 531 µm. On the other side, the lowest HAZ width was measured as 389 μm in specimens cut in square geometry with laser beam. When the highest (531 μm) and lowest (389 μm) HAZ widths obtained from these specimens cut in square geometries were compared, it was revealed that the highest HAZ width was 36.53% larger than the lowest HAZ width.

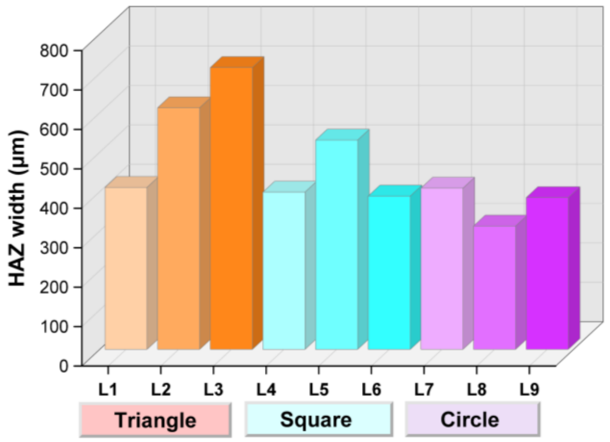

Figure 5. HAZ widths obtained based on different cutting geometries

Besides, as displayed in Fig. 5, when the specimens cut in circle geometry with the laser beam were checked, it was observed that the highest HAZ width was 409 μm. On the other side, the lowest HAZ width was measured as 313 μm in specimens cut in circle geometry with laser beam. When the highest (409 μm) and lowest (313 μm) HAZ widths obtained from these specimens cut in circle geometries were compared, it was seen that the highest HAZ width was 30.69 % larger than the lowest HAZ width. As illustrated in Fig. 6, the average HAZ width values calculated according to different laser cutting geometries (triangle, square and circle) are given.

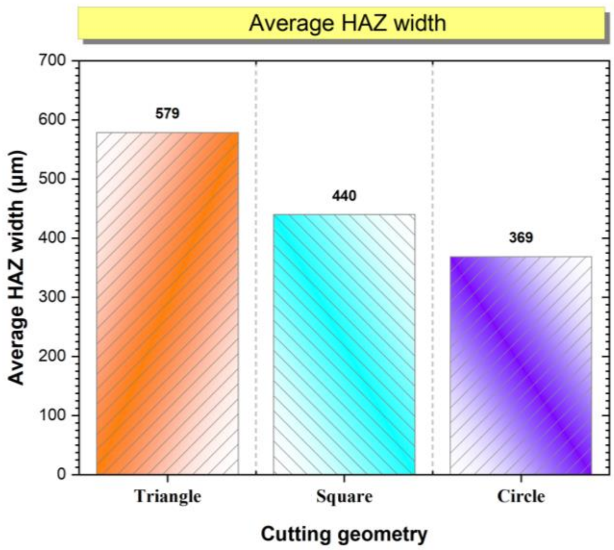

Figure 6. Average HAZ widths based on different laser cutting geometries

When the average HAZ widths calculated according to the laser cutting geometries given in Fig. 6 are examined, it is understood that the highest average HAZ width is obtained in the triangle cutting geometry and the lowest average HAZ width is obtained in the circle cutting geometry. What is more, when the average HAZ widths obtained according to laser cutting geometries were compared, it was seen that the average HAZ widths of the specimens cut in triangle geometry were 31.61% and 56.93% larger than the specimens cut in square and circle cutting geometries, respectively.

In this current investigation, analyses (based on Taguchi experimental design) were performed in the Minitab program in order to perform a more comprehensive analysis of the HAZ widths occurring in steel specimens cut in different cutting geometries. As a consequence of the analyses, the S/N ratios calculated for each HAZ width are illustrated in Fig. 7.

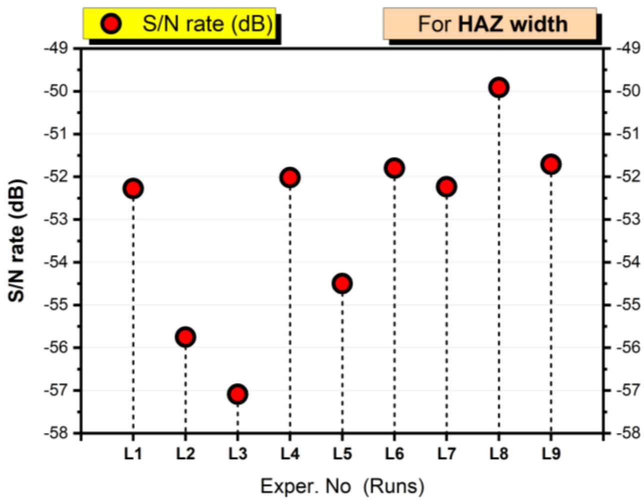

Figure 7. S/N ratios based on HAZ widths

As depicted in Fig. 7, when the analyses made according to the HAZ widths of the specimens cut in different cutting geometries were checked, it was understood that the highest S/N ratio was obtained in the specimen with experiment number L8 (- 49.9109). This highest S/N ratio was achieved in a circle cutting geometry and a HAZ width of 313 μm, respectively. On the other hand, when the analyses made based on the HAZ widths of the specimens cut in different cutting geometries were checked, it was found that the lowest S/N ratio was obtained in the specimen with experiment number L3 (- 57.0861). This lowest S/N ratio was achieved in a triangle cutting geometry and a HAZ width of 715 μm, respectively. As a consequence of the analyses carried out with the Minitab program, a main effect plot was also obtained according to the S/N ratios calculated based on the HAZ widths and illustrated in Fig. 8.

When the graph of the average of S/N ratios obtained according to the HAZ widths given in Fig. 8 is checked, it is clearly observed that the best result (i.e., the highest average S/N ratio) among different cutting geometries was obtained with the circle cutting geometry. Moreover, it was found that HAZ widths were negatively affected (i.e., HAZ widths increase) as the laser power increased.

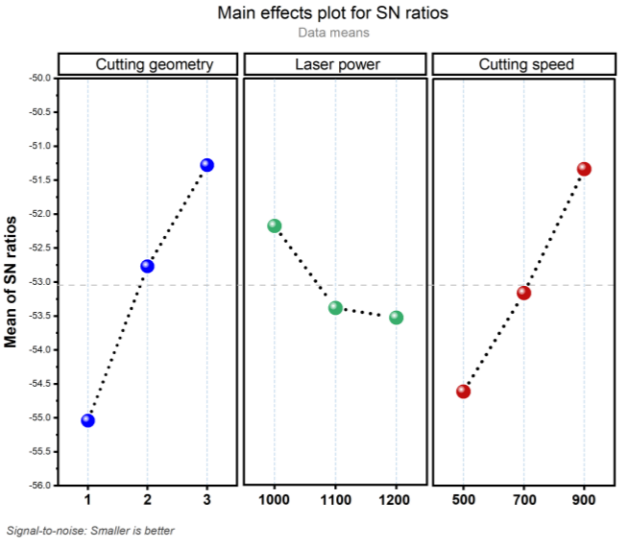

Figure 8. Main effects plot for HAZ widths

On the other hand, it was understood that HAZ widths were positively affected (i.e., HAZ widths decrease) as the cutting speed increased. In other words, it was found that the HAZ width had a directly proportional relationship with the laser power but an inversely proportional relationship with the cutting speed. As a matter of fact, when the results found in this research were compared with the results of investigations (regarding HAZ widths) in the literature, it was revealed that there were similar trends [2-4, 17, 18]. Additionally, in the light of the results obtained within the scope of this investigation, it can be stated that the most suitable machining parameters for the steel workpiece cut with fiber laser are circle cutting geometry, 1000 W laser power and 900 mm/min cutting speed, respectively. In this research, in order to investigate the effects (effects on HAZ widths) of different cutting geometries and cutting parameters on the cut specimens, firstly, the images of the edges of the cut specimens were captured with the help of a microscope and then the HAZ widths were precisely measured on these images with the help of ImageJ software. As depicted in Fig. 9, images taken of specimens cut with laser beam in different geometries are given for each experiment (i.e., between L1 and L9).

As displayed in Fig. 9, it is understood that the HAZ widths of the steel specimens cut with different geometries with the laser beam according to the Taguchi experimental design (DOE) vary according to the applied machining parameters. Moreover, it is observed that the HAZ widths of the specimens cut in triangle geometry with the laser beam are larger than the HAZ widths of the specimens cut in square and circle cutting geometries. Additionally, when the HAZ widths of specimens cut in different laser cutting geometries are compared, it is noticed that the lowest HAZ widths are in the specimens cut in circle geometry. As a matter of fact, when these visual inspections (Fig. 9) and statistical results (Figs. 8) are compared with each other, it can be clearly observed that the experimental and statistical results obtained confirm each other.

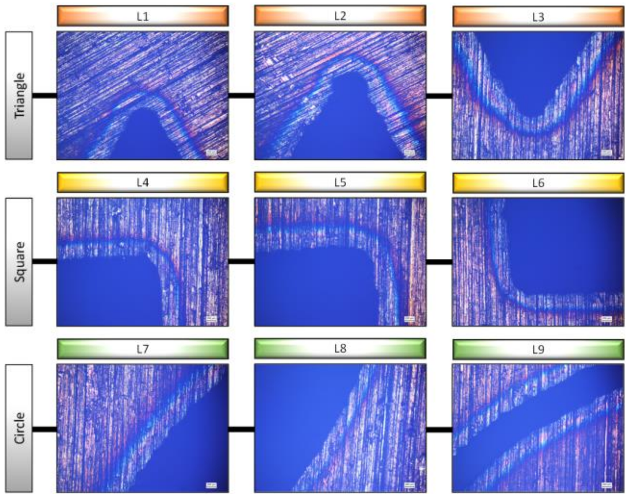

Figure 9. Images of specimens cut at different cutting geometries and cutting parameters

Moreover, it was found that HAZ widths were negatively affected (i.e., HAZ widths increase) as the laser power increased. On the other hand, it was understood that HAZ widths were positively affected (i.e., HAZ widths decrease) as the cutting speed increased. In other words, it was found that the HAZ width had a directly proportional relationship with the laser power but an inversely proportional relationship with the cutting speed. As a matter of fact, when the results found in this research were compared with the results of investigations (regarding HAZ widths) in the literature, it was revealed that there were similar trends [4, 17, 18]. Additionally, in the light of the results obtained within the scope of this investigation, it can be stated that the most suitable machining parameters for the steel workpiece cut with fiber laser are circle cutting geometry, 1000 W laser power and 900 mm/min cutting speed, respectively. In this investigation, the laser cutting lengths (see Fig. 3) were specifically ensured to be the same (96 mm) despite the different laser cutting geometries. Because, due to the nature of laser beam cutting processes, laser cutting lengths are very important [4]. As it is known, in laser beam cutting processes, the metal begins to melt under the effect of the laser beam focused on the workpiece (locally) and subsequently (i.e., after the continuous melting process) the workpiece is cut (i.e., the metal is separated from each other) [4, 5, 19]. During the laser cutting process of metals, O2 gas (assist gas) is used to both accelerate the cutting process (due to creating extra energy by reacting with the metal workpiece) and remove (i.e., throwing out) the molten metal [4-6, 16]. During this process, parameters such as the duration of the laser beam focused on the metal workpiece, laser power and cutting speed are very important because these parameters have direct effects on the HAZ widths [2, 6, 16]. Furthermore, it is observed that laser cutting geometries are quite effective on the HAZ width. This can be explained by the increase in the HAZ width that occurs because the metal starting to melt as a result of the laser beam focusing on the workpiece, but finding more penetration opportunity (i.e., since it penetrates for a longer time) in the same local area (i.e., especially at the corners where two edges meet) due to the effect of the cutting geometries (i.e., triangle and square cutting geometries) [4-6]. On the other side, since this negative situation, which increases the HAZ width, does not occur in the circle cutting geometry, it is less affected than the square and triangle cutting geometries (see Figs. 6 and 9).

Variance and Regression analyses

In this investigation, ANOVA analysis, which is referred to as analysis of variance, was also performed to reveal which machining parameter has the most important impact on the HAZ width. ANOVA analysis was performed based on literature investigations at a confidence level of 95% and a significance level of 5%, and thus the most accurate results were achieved [11, 13, 14, 20, 21]. As illustrated in Fig. 10, the results of the ANOVA analysis (percentage contribution rates) carried out using the HAZ width values obtained within the scope of this investigation are given.

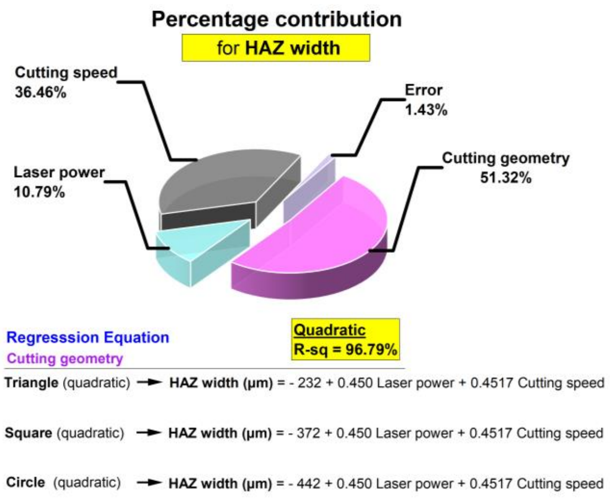

Figure 10. Percentage contribution rates and regression equations

When the ANOVA analysis results given in Fig. 10 are checked, it is clearly observed that the cutting geometry (with a rate of 51.32%) is the most important parameter influencing the HAZ width, in line with the experimental results mentioned above. Besides, the percentage contribution rates of other parameters were found to be 36.46% (cutting speed) and 10.79% (laser power), respectively. Additionally, within the scope of this investigation, regression analyses (in order to analyze the correlation between machining parameters and outputs) were performed for HAZ widths and as a consequence of the analyses, regression equations were developed according to different cutting geometries (Fig 10). As illustrated in Fig. 10, when the regression analysis results (based on quadratic regression models) were checked, it was understood that the R^2 value had a very high rate (96.79%) as desired (90% and above [11, 22]). As is known, the R^2 value (i.e., regression coefficient) is considered as an indicator of the effectiveness and success of the developed model [12, 22-25]. In Fig. 11, the comparison graph of actual and predicted HAZ width values is depicted.

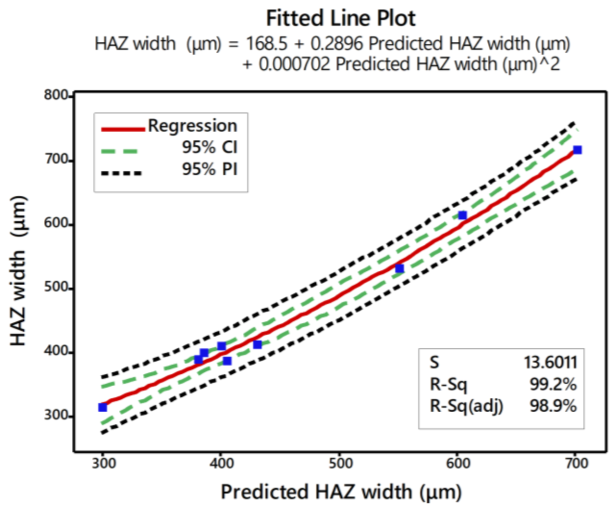

Figure 11. Comparison graph of actual and predicted HAZ width values

As illustrated in Fig. 11, it is understood that the results (comparison of actual and predicted HAZ width values) shown as blue dots are collected almost adjacent to the regression line (red colored line). Thus, from these results (Fig. 11), it is understood that the model developed to predict the HAZ width values has a high success rate and reliability [11, 12, 22]. Within the scope of this investigation, Fig. 12 was also drawn to visually demonstrate the success of the model developed to predict HAZ width values.

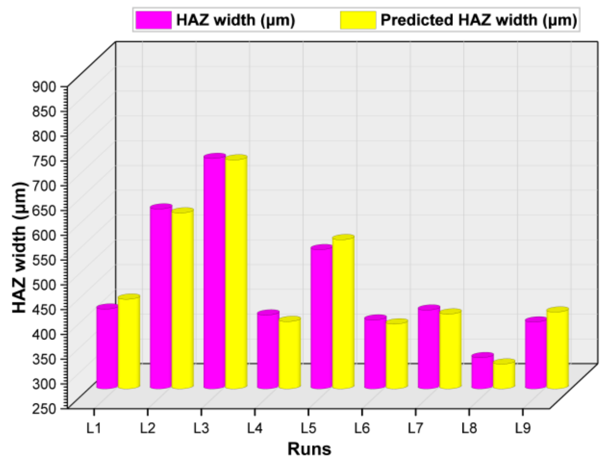

Figure 12. Actual HAZ width results vs predicted HAZ width values

As a matter of fact, as illustrated in Fig. 12, when the actual HAZ width results are compared with the estimated HAZ width values, it is observed that the estimated values are equal to or very close to the actual results. Considering these results (Fig. 12), it once again shows that the success rates and reliability of the models developed to predict the HAZ width values of samples cut with laser beam are quite high.

Conclusions

In this experimental research, an investigation was carried out on HAZ occurring in AISI 4140 steel machined by laser beam in different cutting geometries. The experimental findings and statistical results obtained from this current investigation are presented separately below as a summary:

When the average HAZ widths calculated according to the laser cutting geometries are examined, it is understood that the highest average HAZ width (579 μm) is obtained in the triangle cutting geometry and the lowest average HAZ width (369 μm) is obtained in the circle cutting geometry. What is more, when the average HAZ widths obtained according to laser cutting geometries were compared, it was seen that the average HAZ widths of the specimens cut in triangle geometry were 31.61% and 56.93% larger than the specimens cut in square and circle cutting geometries, respectively.

From the analyses of S/N ratios, it was found that the most suitable machining parameters (based on the cutting geometries applied in this research) for the steel workpiece cut by fiber laser were circle cutting geometry, 1000 W laser power and 900 mm/min cutting speed, respectively. Moreover, it was found that as the laser power increased, the HAZ widths were negatively affected (i.e., HAZ widths increased), but as the cutting speed increased, the HAZ widths were positively affected (i.e., HAZ widths decreased).

From the ANOVA analyses, it was found that the cutting geometry (with a rate of 51.32%) was the most pivotal parameter influencing the HAZ width. Besides, the percentage contribution rates of other parameters were found to be 36.46% (cutting speed) and 10.79% (laser power), respectively.

When the regression analysis results (based on quadratic regression models) were checked, it was understood that the R^2 value had a very high rate (96.79%) as desired. Thus, from these results, it was understood that the model developed to predict the HAZ width values has a high success rate and reliability.

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