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Investigating the Effect of Cutting Speed on Heat Affected Zone in Laser Cutting Process of Stainless Steel

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ABSTRACT
This research work investigated the effect of cutting speed, laser power and nozzle diameter on heat affected zone as well as surface roughness in laser cutting process of stainless steel. The practical experiment was carried out using laser cutting machine, while ANSYS finite element modeling (FEM) simulation software was employed in analyzing the responses of the laser beam machining parameters on stainless steel (SS316). The result showed that an inverse relationship exists between the cutting speed of the laser cutting machine and the heat affected zone (HAZ) depth as increasing the laser beam cutting speed consequently reduced the heat affected zone (HAZ) depth in the work-piece. Finally, it can be concluded that using appropriate machining parameters and ANSYS FEM technique could yield a reduction in overall machining costs and saves time for production companies through an economic analysis by applying the technique to predict the optimal machining parameters for their steel products.

1. INTRODUCTION

Machining is a subtractive manufacturing technique where the material is being removed from 3-dimensional objects to form a simple solid desired geometry (Dubey & Yadava, 2008). Subtractive manufacturing can be achieved through different ways: perforating, cutting, seaming, *etching, engraving, drilling, marking, or welding.*

Machining is the most important method of material removal processes as it offers excellent dimensional tolerances. Emergence of advanced engineering materials, stringent design requirement, as well as intricate shape and unusual size of work piece restricts the use of conventional manual cum CNC machining methods, leading to the development of nonconventional machining methods known as advanced machining processes, including Electron Beam Machining (EBM), Electro Chemical Machining (ECM), Electrical Discharge Machining (EDM), Ion Beam Machining (IBM),Abrasive Water Jet Machining (AWJM) and Laser Beam Machining (LBM) etc (Sifullah *et al.,* 2017).

Laser-beam machining is a non-traditional, subtractive, thermal material-removal process that utilizes a high-energy, coherent light beam to melt and vaporize particles on the surface of metallic and non-metallic work-pieces (Amal *et al.*, 2016).
Cutting is completed through a combination of pressure and heat that is directed via a nozzle. The heat from the laser melts and evaporates the work piece, thus forming the desired shape, and size of work piece (Asonganyi, 2020).

Lasers are widely used in industry for cutting and boring metals and other materials, in medicine for surgery, and in communications, scientific research, and holography (Martin *et al.*, 2019).
Catherine (2010) evaluated the performance of high power fibre laser cutting of thick-section steel and medium-section aluminium. The difficulty in achieving an efficient melt removal during high speed cutting of the 15mm mild steel work-piece with oxygen assist gas using the ytterbium fibre laser can be attributed to the high melting efficiency of the ytterbium fibre laser.

Imed *et al.*, (2016) studied high-power laser cutting of steel plates: heat affected zone analysis. The thermal effect of CO_2 high-power laser cutting on cut surface of steel plates was investigated. The effect of the input laser cutting parameters on the melted zone depth (MZ), the heat affected zone depth (HAZ), and the micro-hardness beneath the cut surface was analyzed. A mathematical model was developed to relate the output process parameters to the input laser cutting parameters.

Kaushal *et al.*, (2014) conducted an analysis of the effect of process parameters on heat affected zone in laser cutting using response surface methodology and Miraoui *et al.*, (2014) performed an analysis of roughness and heat affected zone of steel plates obtained by laser cutting, while Lim *et al.*, (2006) carried out a study on optimal cutting condition of a high speed feeding type laser cutting machine by using Taguchi method. These studies, however, addressed the problem of investigating the effect of machining parameters of the laser beam cutting machine on the Heat Affected Zone (HAZ) in laser cutting of stainless steel, but in a restricted manner.

2. MATERIALS AND METHODS

2.1 Materials

The machining tool used was the XTLaser G-series laser machine was used in the cutting process of the stainless steel material Fiber laser cutting machine with the CNC control operation was also simulated using ANSYS. The technical characteristics of the fiber Laser are radiation wavelength 10.6µm. The laser power ranged from 3000 to 5000W. The focusing system lens is of 28 mm in diameter and of focal distance is 125 mm. The nozzle con opening ranged from 1.0 to 3.0 mm in diameter. The cutting speed ranged from 700 to 2100mm/min. The material used for the practical experiment and simulation was Stainless Steel 316. The work process is carried out by the oxygen process of 98% in purity. Working conditions are the assisting gas O_2 with pressure of 13 bar, laser power (PL) ranged from 3.0 to 5.0kW; Laser spot is on top of the plate surface

2.2 Laser Beam Cutting Operation

Laser cutting is mainly a thermal process, in which a focused laser beam is used to melt material in localized area. Cutting is completed through a combination of pressure and heat that is directed via a nozzle. The heat from the laser melts and evaporates the work piece, thus forming the desired shape, size of work piece and creation of small kerf width as shown in Figure 2.1. Laser cutting is primarily used for metal cutting, as a laser can virtually cut everything thrown its way, be it cutting steel, nickel, or tungsten.

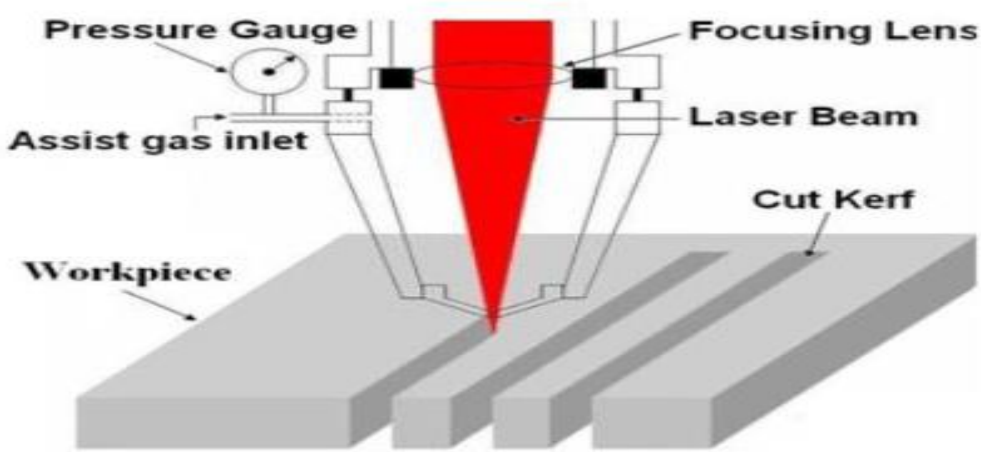

Figure 2.1 Laser Beam Cutting Operations (Catherine, 2010)

In several cases, the corrosion resistance steel 316 and 316L show similar performance. But to avoid inter-granular corrosion attack of welds and heat affected zone, alloy 316L should be utilized that has lower content of carbon. Steel type 316/316L can be conveniently welded and processed through standard fabrication.

The chemical compositions of the Stainless Steel (SS316) work-piece material are presented in Table 2.1

Table 2.1 Chemical Composition of the Stainless Steel (SS316) Work-piece

Element	Content
Carbon, C	0.03%
Manganese, Mn	2%
Silicon, S	0.75%
Phosphorus, P	0.045%
Sulfur, S	0.03%
Chromium, Cr	16 - 18%
Molybdenum, Mo	2 - 3%
Nickel, Ni	10 -14%
Nitrogen	0.10%

(Source: Krzysztof *et al.*, 2016)

The physical, mechanical and thermal properties of the Stainless Steel (SS316) work-piece material are presented in Table 2.2.

Table 2.2: Physical, Mechanical and Thermal Properties of the Stainless Steel (SS316) Work-piece

Physical, Mechanical and Thermal Properties	Value
Density	7870kg/m^3 (503.794lb/ft^3)
Bulk Modulus	152
Compressive Strength	310 MPa
Ductility	0.51
Tensile Strength	75ksi
Yield Strength	30ksi
Elastic Limit	310MPa
Endurance limit	307MPa
Hardness	2200MPa
Rupture Modulus	310MPa
Poisson Ratio	0.275
Shear Modulus	82GPa
Tensile Strength	620MPa
Young Modulus	205GPa
Latest Heat of Fusion	285KJ/Kg
Highest Operation Temperature	1198K
Melting Temperature	1673K
Lowest Operation Temperature	-459.7^{o}F
Specific Heat	30J/Kg.K
Thermal Conductivity	17 W/mK
Thermal Expansion	18 x 10^{-6}/K
Electric Resistivity	81 x 10-8 ohm.m

(Source: Krzysztof *et al.*, 2016)

The surface roughness was gotten during the theoretical analysis using equation 3.1 below; (Suraj *et al.*, 2021):

$$R_Z = 12.528 \ x \ \frac{D^{0.542}}{P_L^{0.451} \ x \ V^{0.322}} \quad (3.1)$$

where PL- the laser power (W), D-the nozzle diameter (mm), V- the cutting speed (mm/min)

2.2.1 Heat Affected Zone (HAZ) Performance Parameters

A heat-affected zone (HAZ) is the portion of the base metal that was not melted during cutting but whose microstructure and mechanical properties were altered by the heat. Reduced heat affected zone is necessary to have good quality of cuts. The depth of the heat affected zone was measured using is given in Equation (3.2) below (Imed *et al.*, 2016):

$$HAZ_d = 100.48 \ x \ P^{0.259} \ x \ V^{-0.146} \ x \ D^{0.04} \quad (3.2)$$

where P - the laser power (W), D- the nozzle diameter (mm), V- the cutting speed (mm/min)

3. RESULTS AND DISCUSSION

3.1 Results

The material of the work piece used in carrying out this study is the Stainless Steel 316 (SS316). All the specimens are of sheets with a thickness 8mm. The dimensions of the work-piece were 15mm in width and 30mm in length. The chemical composition of Steel 316 is shown in Table 2.1 while the physical, mechanical properties and thermal are revealed in Table 2.2. Stainless Steel 316 has superior corrosion resistance properties as well as elevated temperature prolong performance potential. It offers good resistance to pitting and crevice corrosion in the various chemical conditions, excellent aqueous corrosion resistance, and high oxidation resistance up to 870^{o}C. SS 316 is used in digesters, containers, evaporating systems, fabric production equipments, space jet engine parts, mining and medical apparatus and in welding applications.

Table 3.1: Result for the Machine Performance Indices

No. of Runs	Laser Power (W)	Nozzle Diameter (mm)	Cutting Speed (mm/min)	Surface Roughness (µm)		Heat Affected Zone (HAZ) depth (µm)	
				Theoretical	Experimental	Theoretical	Experimental
1	3000	1.0	700	0.04108	0.04500	307.09	315.20
2	3000	2.0	1400	0.04784	0.05100	285.34	279.65
3	3000	3.0	2100	0.05230	0.05300	273.33	282.45
4	4000	1.0	2100	0.02533	0.02800	281.82	288.28
5	4000	2.0	700	0.05253	0.05400	340.15	345.31
6	4000	3.0	1400	0.05235	0.05300	312.44	320.16
7	5000	1.0	1400	0.02609	0.02600	316.82	332.37
8	5000	2.0	2100	0.03335	0.04100	306.97	323.34
9	5000	3.0	700	0.05917	0.06200	320.89	327.56

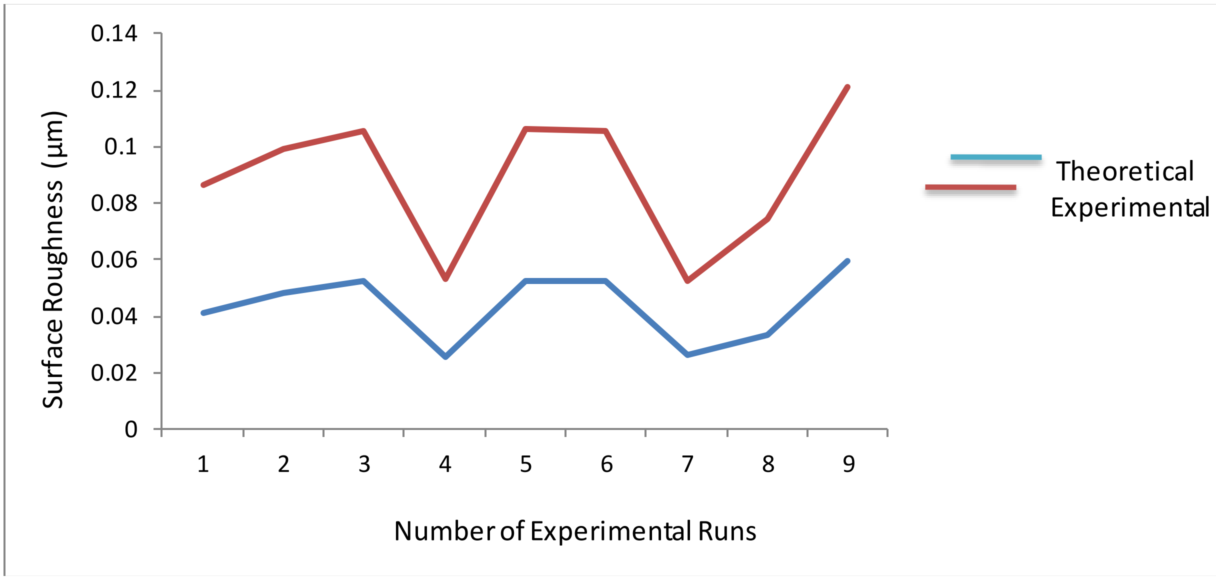

Fig. 3.1: Surface Roughness at different Experiment Runs

Figure 4.1: Reveals the results of the surface roughness on the work-piece for the nine (9) runs of experiments. The figure showed that the 9th experiment (laser power at 5000W, nozzle diameter 3.0mm, and cutting speed at 700mm/min produced the greatest surface roughness at0.05917µmwhile the 4th experiment had the lowest surface roughness at 0.02533µm with machining parameters (laser power at 4000W, nozzle diameter 1.0mm, and cutting speed at 2100mm/min) on work piece. The objective for quality cut is to minimize surface roughness response. Since the lowest surface roughness (0.02533µm) was obtained using larger cutting speed (2100mm/min), then larger is better-cutting speed for the operation.

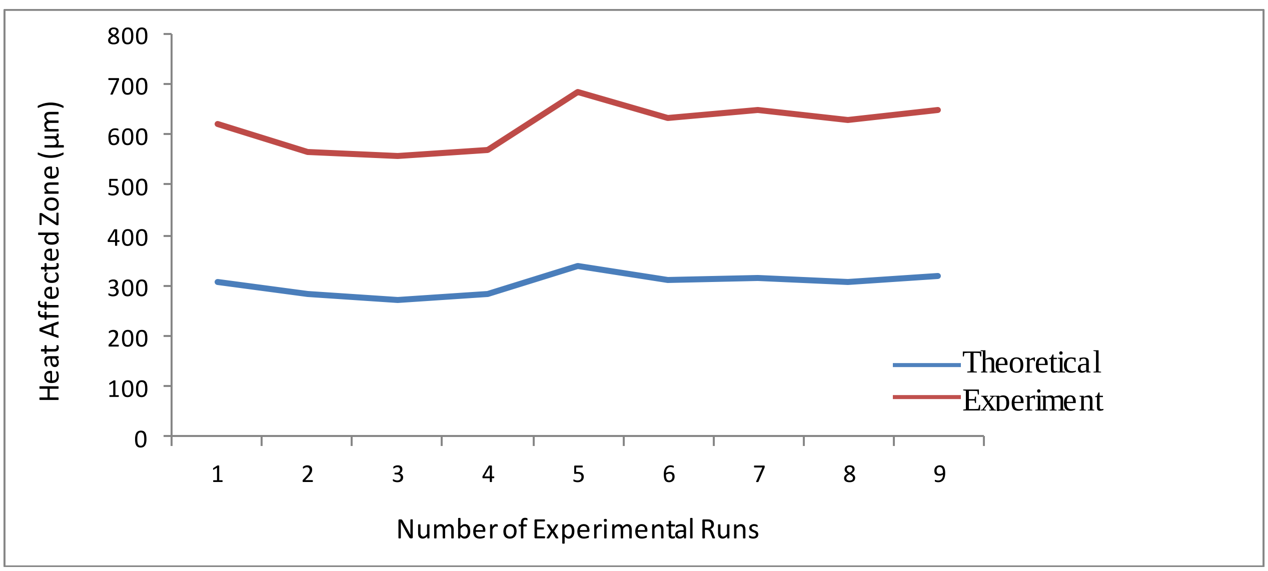

Fig. 3.2: Heat Affected Zone (HAZ) Depth at Different Experiment Runs

Figure 3.2: shows the comparison of results of both experimental and theoretical data of heat affected zone (HAZ) depth of the work-piece for the nine (9) runs of experiments. The figure showed that the 5th experiment (laser power at 4000W, nozzle diameter 2.0mm, and cutting

speed at 700mm/min had the greatest heat affected zone (HAZ) depth at 340.15µm while the 3rd run of experiment had the lowest heat affected zone (HAZ) depth at 273.33µm with machining parameters (laser power at 3000W, nozzle diameter 3.0mm, and cutting speed at 2100mm/min on work piece. The objective for quality cut is to minimize HAZ depth. Since the lowest HAZ depth (273.33µm) was obtained using larger cutting speed (2100µm) and so larger is better cutting speed to be chosen for the operation.

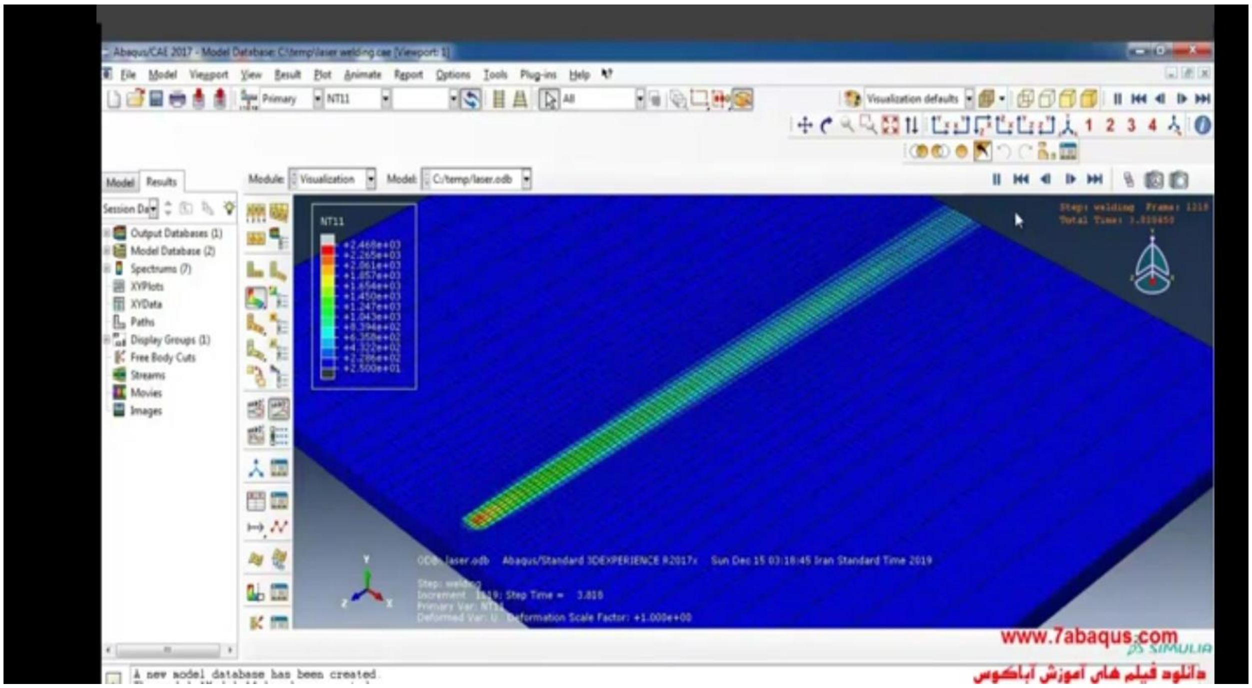

Figure 3.3: Simulation Results for Validation of Modeling.

Figure 3.3: shows the results of the model using ANSYS finite element dynamic explicit simulation with input cutting parameters data; laser power 3000W, nozzle diameter 1.0mm, and cutting speed 700mm/min for experiment 1. The heating temperature ranged from 20^{O}C-4000^{O}C.

4. CONCLUSION

The aim of this research which was on investigating the effect of Laser Cutting Speed, Laser Power and Nozzle Diameter were achieved by carrying out laser cutting process of stainless steel and using XTLaser G-Series Laser cutting Machine, also using optical microscope to measure the HAZ and Surface Roughness, and ANSYS computer simulation as presented in figure 3.3.

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