DEVELOPMENT OF ANFIS ALGORITHM TO PREDICT THE SHEET METAL CUT QUALITY OF CARBON DIOXIDE LASER

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DEVELOPMENT OF ANFIS ALGORITHM

TO PREDICT THE SHEET METAL CUT QUALITY

OF CARBON DIOXIDE LASER

by

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LIST OF ABBREVIATION

	TITLE
AHSS	Advanced high strength steels
AI	Artificial intelligence
ANFIS	Adaptive network based fuzzy inference systems
ANFIS-FCM	Fuzzy c-means clustering based FIS
ANFIS-GRID	Grid partition based FIS
ANFIS-SUB	Subtractive clustering based FIS
ANN	Artificial neural network
BP	Back-propagation
BPNN	Back-propagation neural network
CO_2	Carbon dioxide
CW	Continuous wave
DOE	Design of experiments
dsigmf	Built-in membership function composed of difference between two sigmoidal membership functions
FCM	Fuzzy c-means
FIS	Fuzzy inference system
FL	Fuzzy logic
GA	Genetic algorithm
gauss2mf	Gaussian combination membership function
gaussmf	Gaussian curve built-in membership function
gbellmf	Generalized bell-shaped built-in membership function
GD	Gradient descent
GUI	Graphical user interface
HAZ	Heat affected zone
HSLA	High strength low alloy
HTGLA	Taguchi-genetic learning algorithm
LBM	Laser beam machining
LM	Levenberg-Marquardt
LRT	Laser research team
MAPE	Mean absolute percentage error
$Nd:Y_3Al_5O_{12}$	Neodymium-doped yttrium aluminium garnet
NOR	Nano-optoelectronics research and technology

pimf	π-shaped built-in membership function
psigmf	Built-in membership function composed of product of two sigmoidally shaped membership functions
QFN	Quad Flat Non-Lead
QN	Quasi-Newton
R^2	Absolute fraction of variance
Radii	Cluster radius
RMSE	Root mean square error
SCG	Scaled conjugate gradient
SEM	scanning electron microscope
trapmf	Trapezoidal-shaped built-in membership function
trimf	Triangular-shaped built-in membership function

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PEMBANGUNAN ALGORITMA ANFIS UNTUK MERAMAL KUALITI KEPINGAN LOGAM YANG DIPOTONG DENGAN LASER KARBON DIOKSIDA

ABSTRAK

Keperluan utama dalam industri pemotongan laser adalah untuk menghasilkan kualiti pemotongan yang bermutu, yang melibatkan dengan kelebaran pemotongan, kekasaran pada permukaan, kekerasan dan kewujudan sanga sesuatu hasil produk selepas pemotongan laser. Keperluan ini memerlukan pembangunan model ramalan bagi mencapai dan meningkatkan kualiti yang tinggi dan produktiviti bagi proses pemotongan laser. Justeru itu, suatu kajian menggunakan aplikasi kecerdekaan rekaan (AI) iaitu rangkai saraf (ANNs), logik kabur (FL) dan pangkalan rangkaian suai sistem inferen kabur (ANFIS) telah dijalankan untuk meramal ciri-ciri kualiti kepingan logam Incoloy® 800 setebal 1 mm yang dipotong dengan operasi pemotongan laser karbon dioksida (CO_2). Model-model ini dibentuk dengan pengaplikasian MATLAB program. Eksperimen laser dijalankan bertujuan untuk mengumpul data bagi fasa latihan, fasa pengesahan dan satu set kaji data eksperimen yang baru digunakan untuk menentukan model rangkain yang terbaik dalam ramalan. Berdasarkan keputusan daripada kajian, walaupun keputusan yang diperoleh oleh ketiga-tiga teknik AI ini memberangsangkan dari segi purata peratusan ralat (MAPE) semasa fasa latihan dan pengesahan, namun, ANFIS dengan teknik sekatan grid (ANFIS-GRID) dipilih disebabkan ia mencapai MAPE yang terendah bagi fasa terakhir yakni fasa penentuan dalam ramalan pemotongan laser dengan nilai MAPE sebanyak 3.30% bagi kelebaran pemotongan, 12.41% bagi kekasaran pada

permukaan, 2.15% bagi kekerasan dan 12% bagi kewujudan sanga. Pendek kata, keempat-empat model ANFIS tersebut menghasilkan kejituan sebanyak 87% dan ke atas dalam membuat ramalan. Keputusan yang dicapai turut menujukkan bahawa model ANFIS boleh membuat ramalan bagi proses pemotongan laser dengan lebih mantap dan tepat berbanding dengan model ANN dan FL. Untuk memudahkan pengguna membuat ramalan, suatu anatara muka (GUI) bergandingkan laser dan ANFIS telah dihasilkan dengan menggunakan MATLAB. Dengan penghasilan GUI ini, pengguna bahkan bukan pakar dalam ANFIS atau operasi pemotongan laser CO_2 juga boleh melatih, mengesah dan menguji data-data eksperimen yang baru melalui GUI ini dan seterusnya memperoleh keputusan analisis dalam bentuk graf dan angka. Penemuan ini (pra-pembangunan model ANFIS diterbitkan daripada kajian) dijangka sudah pasti akan membawa manfaat kepada industri pemotongan laser dengan penjimatan masa dan kos berbanding dengan penggunaan kaedah cuba-jaya dalam membuat ramalan laser.

DEVELOPMENT OF ANFIS ALGORITHM TO PREDICT THE SHEET METAL CUT QUALITY OF CARBON DIOXIDE LASER

ABSTRACT

The major trend in laser beam cutting industry is to produce a good cutting quality, which involve with cutting geometry (kerf width), cutting surface quality (surface roughness), mechanical properties (hardness) and metallurgical characteristics (dross inclusion) of the end product. This trend has necessitated the development of predictive models in order to achieve and improve high quality and productivity of laser cutting process. Thus, an empirical comparative study has been carried out using the application of artificial intelligence (AI) approach, namely artificial neural networks (ANNs), fuzzy logic (FL) and adaptive network based fuzzy inference system (ANFIS) to predict the effect of carbon dioxide laser cutting quality based on laser cutting parameters onto 1 mm thickness of Incoloy® alloy 800. All the model developments were implemented on MATLAB toolbox. Experiments were performed to collect data for training and validation purposes, and a set of extra experimental data were used for the verification purpose in order to find out the best AI model architecture for prediction. Based on the results of the study, despite all the three AI approaches gave promising results in term of mean absolute percentage error (MAPE) during training and validation phase, but ANFIS with grid partition technique (ANFIS-GRID) was selected based on the least MAPE during testing phase in the final selection of prediction with the values of 3.30% for kerf width, 12.41% for surface roughness, 2.15% for hardness and 12% for dross inclusion. On the other hand, the prediction accuracy by the finalized four ANFIS models have yielded up to 87% and above proving the prediction stability. Results obtained reveal that the reliability and good predictability of ANFIS model outperforms the ANN and FL model for the laser cutting prediction in terms of training performance and prediction accuracies. An ANFIS laser graphical user interface (GUI) was developed on our own using MATLAB as an effort to avail the users even not an expert in both ANFIS and CO_2 laser cutting process can train, validate and test a new set of experimental data loaded into the GUI and easily obtain the numerical and graphical output from the ANFIS laser GUI analysis results. The findings (the practical pre-development of ANFIS models derived from the research study) were expected to benefit precision laser cutting industries in diminishing the setup time and cost as compared to the traditional way of trial and error method in predicting the laser cutting.

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CHAPTER 1

INTRODUCTION

This chapter discusses the background of research, its problem statements and objectives, scope of work, research approach, and the significance of the research.

1.1 Research background

Laser cutting is today the most common used of laser beam machining (LBM) process in industry for shaping and separating a workpiece into segments of desired geometry. Two of the most widely used lasers for cutting of sheet metals are carbon dioxide (CO_2) and neodymium-doped yttrium aluminium garnet ($Nd:Y_3Al_5O_{12}$). Apart from its fascination, which is rarely an enormous impetus for investment in hard metal industry, the reason is most probably that in cutting there is a direct process substitution into an established market and laser, in many case, happens to be able to cut faster and with a higher quality than the competing processes. Most manufacturers especially in the aircraft and automotive industries started to utilize laser cutting mainly because of the ability to cut complex contour with high level of precision, low cost of operation, rapid processing, online control and moreover the high quality components made by laser cutting process (Rajaram et al., 2003). Thus, this motivates researchers for the analysis and prediction of the laser cutting quality.

Laser cutting quality cannot be easily predicted due to the dynamic nature of the laser cutting process (Rajaram et al., 2003). The laser cutting quality is strongly determined by the laser cutting parameters. For laser cutting parameters, the energy input is controlled by the combination of laser power, frequency, cutting speed, duty cycle, and assist gas pressure **(**Olsen, 1983).

Many laser control parameters affecting laser cutting qualities have been investigated. Several studies have emerged to estimate and predict the characteristics properties of the laser cutting surface to describe quality. Kerf width, surface roughness, and size of heat affected zone (HAZ) are often used to be implied as laser cutting quality characteristic (Yilbas, 2004).

Modeling studies in laser cutting process are the scientific ways to study the system behaviours and helps us to get a better understanding of this complex process. Generally, models can be divided into three categories, experimental models, analytical models, and artificial intelligent (AI) based models (Avanish and Vinod, 2008). However, it is difficult to predict laser cutting quality via analytical formulae whose validity often applies to limited range of processes and cutting conditions due to the reason of the complication and process dependence of the mechanism behind laser cutting **(**Tsai et al., 2008**)**. Thus, the use of AI will be another useful method to allow a certain degree of prediction of the expected outcome of the laser processing.

For example, artificial neural networks (ANN) and fuzzy logic (FL) are AI applications which have recently been widely used to model the human keen on activities especially in the science and engineering areas, where both approaches express the interrelationship between the input and output of a complicated system for prediction.

Yet, nowadays the combination of ANN and FL has generated neuro-fuzzy systems. These systems have a great potential to assimilate the essences of both approaches in a single frame work. As a result, it can utilize linguistic information from human expert as well as measured data during modeling. Adaptive network based fuzzy inference systems (ANFIS) is one of the approaches in neuro-fuzzy development that has proven to be a powerful tool for many prediction applications

(Maren et al., 1990), where it has shown important results in modeling for non-linear functions.

In the following section, the major problems of the laser cutting process in term of the cutting quality are addressed. Then the research objectives, approach and significance are described followed by the entire presentation of the thesis outline at the end of the chapter.

1.2 Problem statement

Laser cutting quality can be defined, depending on the ultimate use of the manufactured parts, by considering many parameters, such as the wide of the kerf width size, surface roughness, extends of HAZ, dross adhesion and hardness change (Tani et al., 2003). A good quality cut can be defined in terms of a small kerf width, least amount of HAZ, minimum surface roughness and low striation frequency (Niku-Lari and Mordike, 1989). These laser cutting quality characteristics determine the economics of the machining and rate of the production. In order to save the energy and enhance the productivity, the prediction of CO_2 laser cutting qualities has become an important issue to the optimization of laser cutting parameters.

As mentioned in Section 1.1, it is not an easy job to predict the laser cutting quality owing to there is various adjustable machining parameters to be considered. Traditionally, the parameter of laser cutting process are usually adjusted (many tests have to be done) until a fine quality cut is obtained. This trial and error method will indeed increase the number of trial runs in obtaining a good cutting quality where not only time and cost consuming are being wasted but it also requires much effort and energy to procure the desired result in laser cutting process. Thus, the understanding of contribution of each cutting process parameters must be analysed independently.

The need to observe various interactions between each cutting parameters of the laser process must be considered before optimization can be performed to achieve an optimum cutting condition that will consequently give a good quality cut. Therefore, much effort has been dedicated in predicting and planning or monitoring and controlling the laser based process in order to improve the quality of the end product.

However, according to Sivarao et al. (2009[a]), mastering in both laser processing and AI programming are arduous tasks for most researchers, mainly for the difficulty to model the processes. Hence, a new approach needs to be undertaken (for example, creating a simple and user friendly user interface) in order to model the laser processing phenomenon, in which users can easily obtain the numerical and graphical output to interpret the results.

1.3 Research objectives

The main objective is to first understand and determine the AI approach that is used in the research and eventually evaluate the generated AI based models followed by selecting the best model in predicting the cutting quality of CO_2 laser cutting process based on a specified set of cutting parameters. The research attempts to achieve the following objectives:

1. To develop the AI based model using ANFIS approach in order to understand the relationship between laser cutting parameters and cutting output in quality prediction.
2. To investigate the accuracy of the developed ANFIS model in providing a satisfaction result in term of the lowest MAPE in order to become a reliable and practical pre-development predicting model.
3. To compare the developed ANFIS models with ANN model and FL model.

4. To develop a GUI integrating ANFIS variables for users to model other CO_2 laser cutting process in MATLAB platform.

1.4 Scope of Work

The research work was carried out with the aim of developing an AI based model by employing the ANN, FL and ANFIS approach in predicting the sheet metal laser cutting quality using various combination of cutting process parameter in CO_2 laser cutting operation. The three AI based models were undergone training, validation and verification model development process. However, this research study concentrates more on the development of ANFIS modeling while the other two AI approaches (ANN and FL) were used as comparison purposes. A comparison is also performed between the prediction results generated by the ANFIS model and the experimental results to investigate the accuracy of the predicting model that can obtain a satisfaction result in term of the lowest MAPE to become reliable and practical as an important decision support mechanism to assist user in the prediction with minor error rates.

1.5 Research approach

The research is commenced with the advanced engineering material namely Incoloy® alloy 800. CO_2 laser cutting is chosen to be evaluated using parametric studies of laser power, cutting speed, and assists gas pressure as input parameter. Each parameter will be conducted within the range that produces a through cut of the sample materials. The laser cutting qualities measured from the cut samples involve kerf width, dross inclusion, surface roughness, and hardness as output parameter.

Three case studies were carried out with the aim of developing the best predicting AI based model for the CO_2 laser cutting process. The entire program in developing the models was implemented by using MATLAB software package (MATLAB version 7.6). The predicting models generated for laser cutting output result is then verified by a set of confirmation testing data from the laser cutting experiment. Figure 1.1 shows the flow representation of the research methodology.

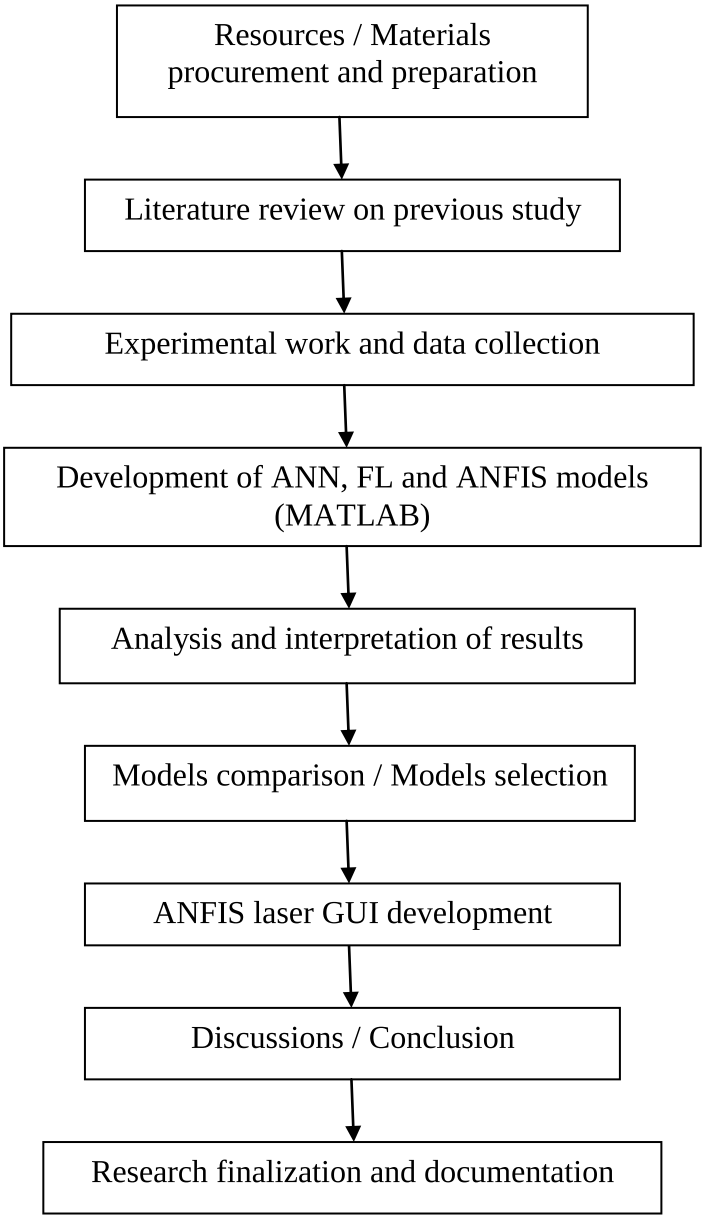


Figure 1.1: The flow of the research methodology

1.6 Research significance

It would be a significant benefit to student or even researchers in academic field involve with the laser application to have more information that will enable them to comprehend the technique whether is based on the practical experience gained from the laser processing or even with a breadth of their theoretical knowledge. The practical solutions derived from the study using AI based models (ANN, FL and ANFIS) which allow automatic output LBM prediction can provide an input for researchers and eventually encourage the use of laser to process engineering material. A realistic consequence from the AI approach could be exploited and yield good quality cut in the application of laser cutting process.

Apart from this, this research and development project will indeed enhance the confident of the component machining related industries. It also helps to promote utilizing and investing of this high technology application in order for the Malaysian industrialists to gain the competitive advantage in the global manufacturing sector.

1.7 Thesis outline

The thesis is organized in six chapters. Chapter 2 reviews the literature study of the CO_2 laser cutting process and fundamental theory about AI based on ANN model, FL model and ANFIS model. In Chapter 3, the method of approach including experimental details is given. This is followed by the preparatory works for ANN, FL and ANFIS model developments. Chapter 4 describes the development of the ANN, FL and ANFIS model using MATLAB command functions. The results for the models analyses and the detailed discussion for the result are highlighted in Chapter 5. The comparison of experimental results and predicting results are also presented in this chapter. Furthermore, the development of the ANFIS laser modeling GUI is discussed in Chapter 5 as well. To conclude the thesis, the conclusions of the research are drawn in Chapter 6. Recommendation and suggestions are also given for future work in this chapter.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The main fields that will be investigated in this research are the CO_2 laser cutting process and AI. These two fields are introduced and focused in this chapter. Basically, the literature survey focuses on three main sections in AI field, namely the ANN, FL and ANFIS. The related works which had been done by previous researchers are presented as well, based on the published literature.

2.2 Carbon dioxide (CO_2) laser cutting process

CO_2 laser is a process that uses CO_2 as the main lasing medium (Steen, 2003). CO_2 lasers use a mixture of gases such as helium and nitrogen, with CO_2 being the most predominant to create a cut quality and can operate in continuous wave (CW) or pulses mode (Steen, 2003). The efficiency of a CO_2 laser is fairly low; barely 10% of energy is lost as heat (Ready and Farson, 2001). CO_2 laser (10.6 μm wavelength) have higher efficiency of about 30% higher beam quality, higher depth of focus, smaller beam diameter and able to cut 12 mm of stainless steel using 2000 W continuous laser beam (Ready and Farson, 2001).

All materials cut with lasers are achieved by the translation of the spot along the desired cutting path. In CO_2 laser cutting, what matters is the end product quality. Hence, considerable experimental studies on CO_2 laser cutting process have been carried out by researchers to analyze the effect of its process input parameter such as laser power operating in continuous wave or pulse, type and flow rate of the cutting assisting gas pressure, cutting speed, cutting material composition and its thickness to understand the relationships between the laser cutting parameters and the process performance (Yilbas, 2004; Chen, 1998; 1999; Serruys, 2002; Rajaram et al., 2003; Lamikiz et al., 2005; Karatas et al., 2006; Al- Sulaiman et al., 2006; Shanjin and Yang, 2006). The process performance usually refers as the cutting geometry (kerf width), cutting surface quality (surface roughness), metallurgical feature (dross adhesion) and mechanical properties (hardness) (Avanish and Vinod, 2008). Figure 2.1 shows the laser cutting quality characteristics of sheets.

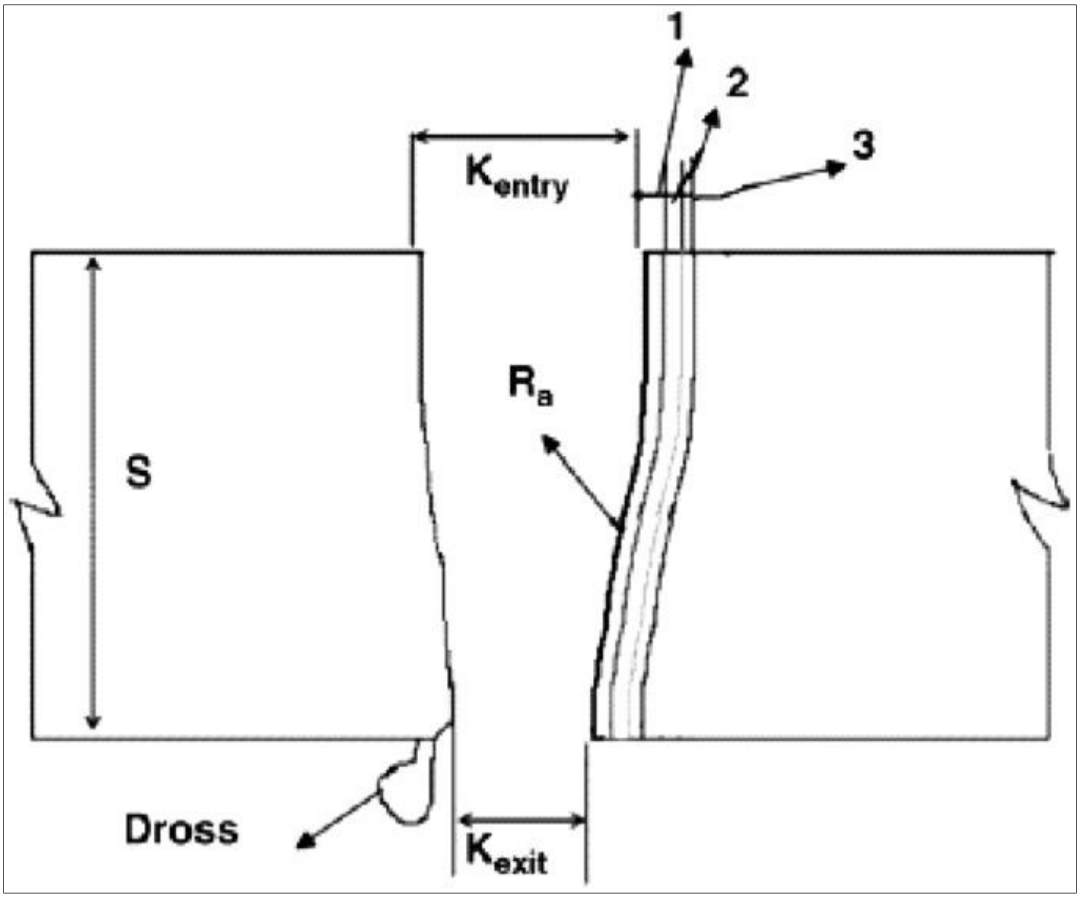


Figure 2.1: Schematic illustration of various cut quality attributes of interest (Li and Achara, 2004). K_{entry}: kerf width at entry side; K_{exit}: kerf width at exit side; R_a: surface roughness; S: thickness of material; 1: oxidized layer; 2: recast layer; and 3: heat affected zone (HAZ).

Avanish and Vinod (2008) produced an intensive review on laser beam machining. The main reviewed scope was about the recent developments of laser beam machining and the research study undertaken so far in this area with different materials and shapes. Avanish and Vinod also outlined the improvement of the laser process performance via experimental and theoretical studies and the future directions of the laser beam machining research. Several modeling and optimization based on experimental, analytical and AI approach had been emphasized in the review.

Almost all research studies reviewed in the literature on CO_2 laser cutting process were based on experimental works. And yet, majority of the experimental data analysis were based on conventional statistical methods such as linear and non-linear regression (Rajaram et al., 2003; Avanish and Vinod, 2008) to obtain an experienced mathematical model to express the relationships between the input laser cutting parameters and its cutting qualities results in laser cutting prediction. Rajaram et al. (2003) had utilized the regression analysis using first and second order main interaction effects to develop models that describe the effect of laser process parameters (power and feed rate) on the laser cutting quality. Ghoreishi et al. (2002) had developed the response model to analyze the effect of laser cutting parameters (peak power, pulse width, pulse frequency, assist gas pressure and focal plane position) on hole taper and hole diameter of stainless steel 304 sheet with 2.5 mm thickness. Kuar et al. (2006) have also applied the linear regression method to develop the mathematical model for predicting the HAZ and taper of Zirconia ceramic sheet with 1 mm thickness during micro-drilling using laser beam system.

However, this kind of conventional regression analysis method was no longer efficient and may lead to vast errant between predicted and real value especially when precisely describing the nonlinear and complex relationship between the process parameters and its performance characteristics (Avanish and Vinod, 2008).

Therefore, these kind of statistical methods have been taken over by the arising of AI based approach as the alternatives way for engineering problem solving. The literature demonstrated that AI model such as ANN (Oktem et al., 2006; Cus and Zuperl, 2006), FL (Hudayim and Haldun, 2009) and ANFIS (Lo, 2003; Ulas et al., 2009; Gao and Chen, 2006) are executable and applicable in machining process (to model the complex problems, avoiding the problem of approximating the complex unknown relationships by mathematical equation).

2.2.1 Process parameters in laser cutting process

Laser cutting is a process influenced by a large number of parameters (Avanish and Vinod, 2008). According to Rajaram et al. (2003), there are higher risks for a process to have higher error with a large number of the laser parameter. The error that occurred might disturbed the quality of a cutting process as well as the productivity of the process. Thus, ample of time, energy and cost were required just to overcome this problem. In laser machining, the basic parameters that will impact the quality of the laser cutting were (Chen, 1999 and Wang, 2000):

a. Nature and thickness of the material

b. Laser power operating in continuous wave or pulses

c. Cutting speed

d. Nature of the cutting assisting gas

e. Pressure and flow rate of the cutting assisting gas pressure

This parameters need to be set by selecting the appropriate operating window of cutting speed, gas pressure, laser power and stand-off distance **(**Olsen, 1983). Lamikiz et al. (2005) had carried out a study to demonstrate the optimum working area and cutting parameters for the CO_2 laser cutting on the quality and geometry of different types of advanced high strength steels (AHSS) sheet with certain thicknesses.

According to Serruys (2002), laser power and cutting speed are different for each type of cutting material. With applying a lower peak power, the cutting speed will be slow; however a higher cutting speed for the same material can be achieved by using a high peak power. Figure 2.2 shows how the cutting speed is determined by the average power level for three different materials, mild steel, stainless steel and aluminum. The higher the average power, the higher the cutting speed.

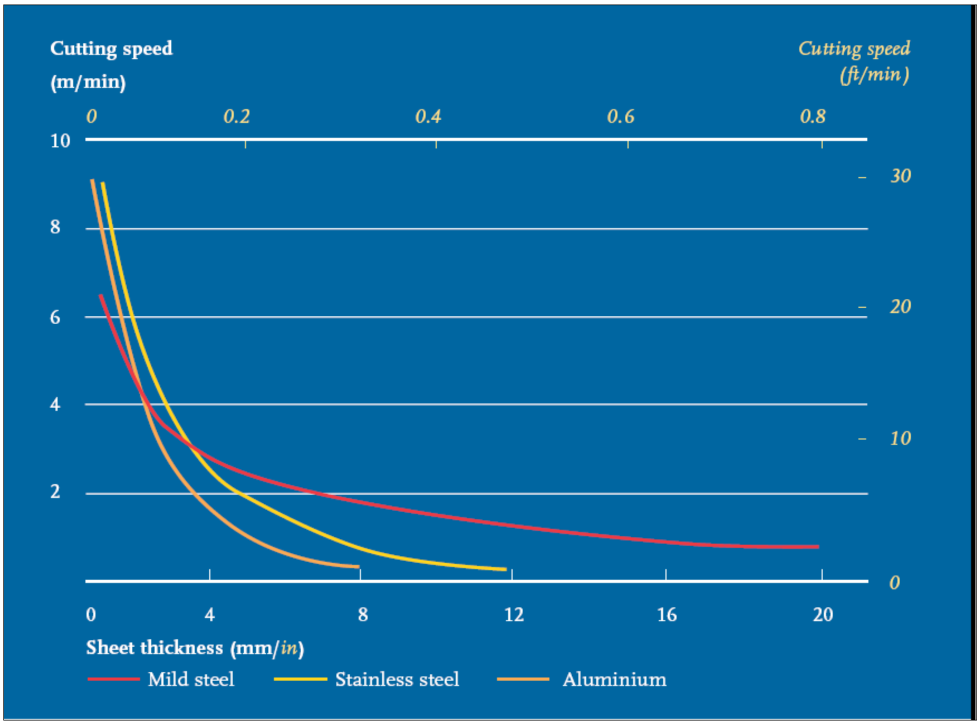


Figure 2.2: Typical cutting rates with approximate 3 kW of laser power (Serruys, 2002).

According to Chen (1999), the cutting gas used is crucial to the cutting result. Oxygen generally yields good performance in carbon steels and low alloyed steels. However, oxygen reacts with the base metal, and the cut edge is covered with an oxide layer. That is why nitrogen is also being used widely to cut high-alloy steels. The following rules of thumb apply to cutting pressure (Steen, 2003):

(a) General rule for cutting mild steel with oxygen:

- The thicker the material, the lower the pressure
- Maximum pressure at approximate of 6 bar.

(b) General rule for cutting stainless steel with nitrogen:

- The thicker the material, the higher the pressure.
- Minimum pressure at approximate of 8 bar.

2.2.2 Cutting geometry (kerf width)

One of the important parameters of laser cutting operation which decide the quality of machining is the size of the kerf width. Three different assist gases oxygen, nitrogen and argon at high pressure up to bar had been examined by Chen (1999) and had found out that kerf width increaser with increasing laser power and decreasing cutting speed during the CO_2 laser cutting of 3 mm thickness of mild steel sheet. Also, the oxygen or air gave wider kerf while the use of inert gas gives the smallest kerf. The combined effects of cutting speed and power on laser cutting quality was also considered by Rajaram et al. (2003). Based on the experimental results, size of kerf width increased with increasing laser power levels during CO_2 laser cutting of 1.27 mm thick 4130 steel. Figure 2.3 depicts the effect of feed rate and laser power on top kerf width. Rajaram et al. (2003) had concluded that power had a major effect on the kerf width, while feed rate played a minor role. Decreasing power and increasing feed rate generally led to a decrease kerf. At high power levels, increasing feed rate led to a greater decrease in kerf width while at low power levels, increasing feed rate led to a slight decrease in kerf width.

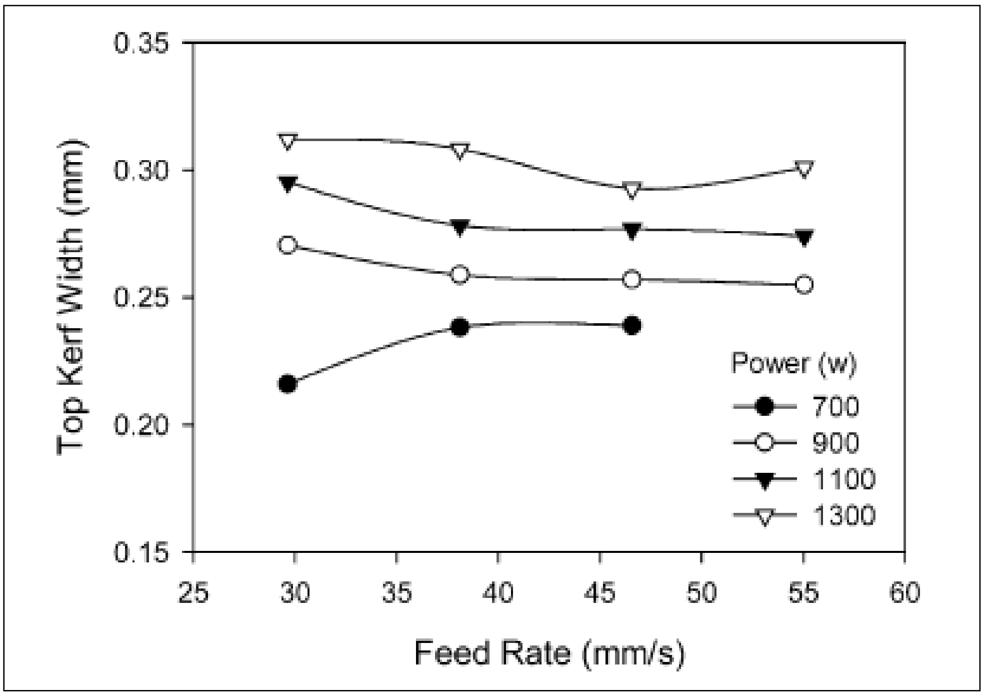


Figure 2.3: Variation of top kerf width with power and feed rate during CO_2 laser cutting (Rajaram et al., 2003)

Karatas et al. (2006) had investigated the effect of different focus setting and workpiece thicknesses on the kerf width during hot rolled and pickled high strength low alloy (HSLA) steel cutting using CO_2 laser. The results showed that as the workpiece thickness reduced, the relative location of beam waist position varies for the kerf width reduces to minimum, and vice versa.

Scaling laws to predict the kerf width during laser gas assisted cutting process was introduced by Kar et al. (1997) and had indicated that thick metal cutting performance could be improved by producing narrow widths.

Laser cutting parameters were investigated experimentally by Yilbas (1996) and results showed that smoothness of kerf surface deteriorate once the cutting speed increased to critical speeds and beyond the limits cutting ceases.

An experimental investigation based on the Taguchi methodology on the quality characteristics in CO_2 laser cutting of aluminum alloys has been carried out by Stournaras et al. (2009). Results reveal that cutting speed (67%), the laser power (11%) and assists gas pressure (21%) have strongest effect on the quality characteristics especially on the kerf width as shown in Figure 2.4.

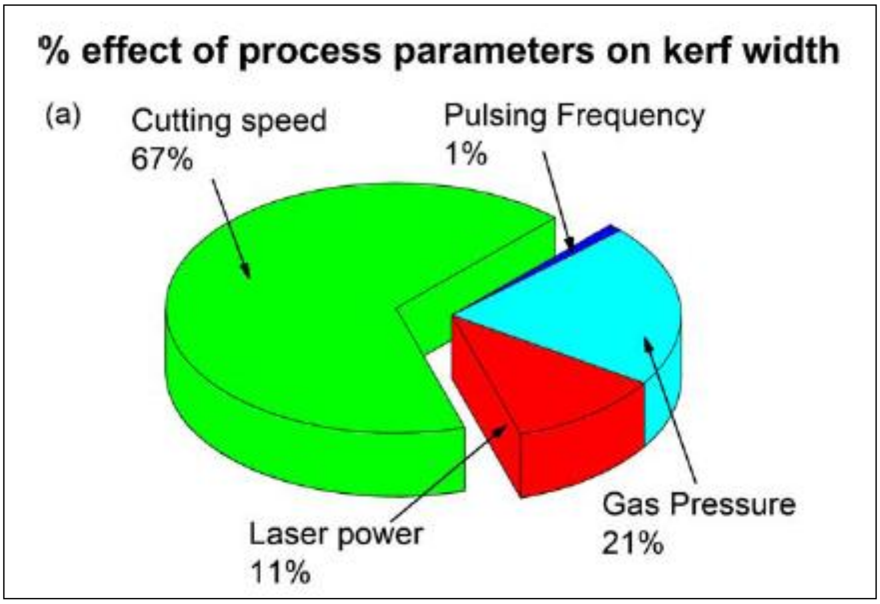


Figure 2.4: Effect of laser cutting parameters in kerf width (Stournaras et al., 2009).

To achieve the acceptable level of kerf quality characteristics, it is necessary to choose the optimum combination of input laser process parameters. Most of the experimental investigations so far, mostly researchers were considered the straight cut for analyzing the laser cut kerf. Generally, the kerf width is taken by the width of the top kerf (Sharma, et al., 2010). Figure 2.5 shows the better view and terminology of kerf width after laser cutting process.

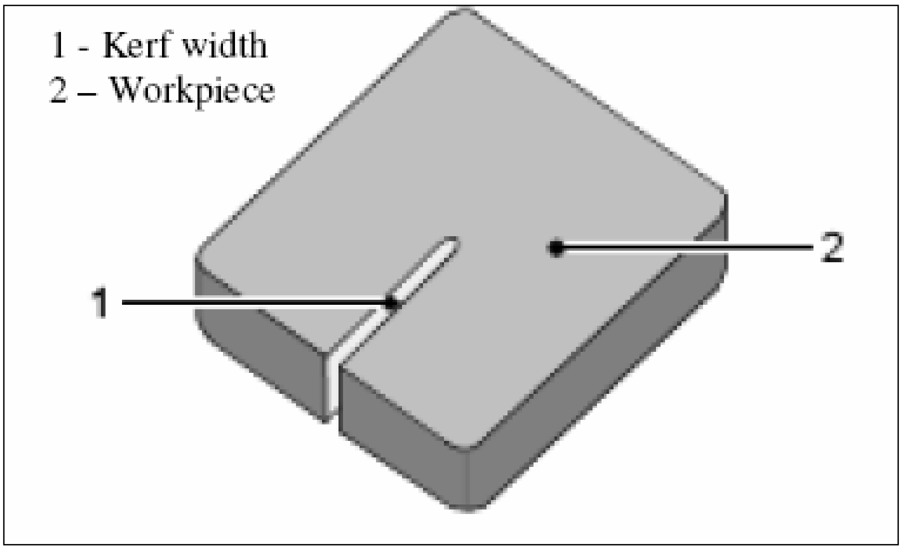
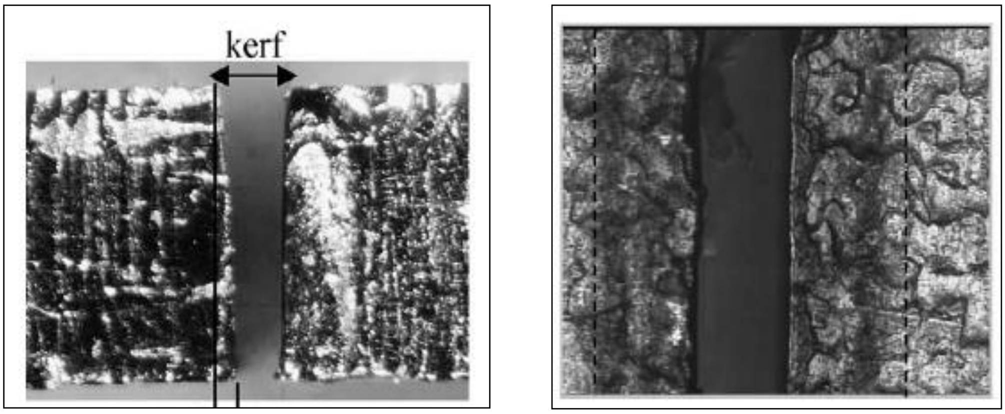


Figure 2.5: Kerf width in laser cut (Sivarao, 2007).

According to Lamikiz et al. (2005), in order to find out a good laser cut kerf, researchers need to ensure whether the cut is a valid cut, non-valid cuts or cut with pitting (dross occurred). Two criteria have been taken into account by Lamikiz et al. (2005) when considering the valid laser cut as shown as Figure 2.6. First, a visual inspection to ensure that no dross or uncut are present along the cutting area followed by checking that the top kerf variation is less that 10% of mean value.



(a) (b)

Figure 2.6: A valid laser cut: (a) section of the cut kerf; (b) top view of the cut kerf (Lamikiz et al., 2005)

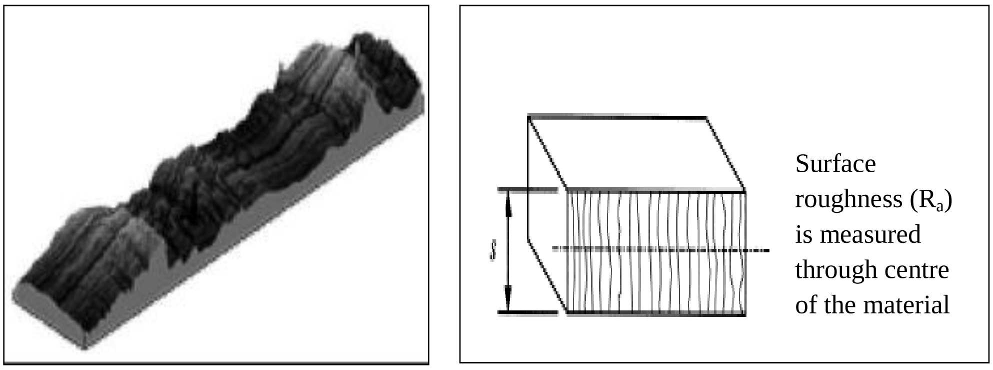
Sivarao (2007) had observed that after laser cutting process onto a 2.5 mm thickness of Managanese-Molybdenum pressure vessel plate using the laser power (1600 kW and 2300 kW), cutting speed (1800 mm/min and 2500 mm/min) and assisting gas pressure (0.5 bar and 0.8 bar), the observed values of kerf width (through cut) for laser cutting for the specified workpiece fall between 0.01 – 0.2 mm which is below the DIN Laser Standard of 0.2 mm.

A good laser cut kerf (valid cut) had been obtained by Lamikiz et al. (2005) ranging in between 0.15 – 0.3 mm onto the advanced high strength steel sheets (DP750, GXE450B and ZStE260 +ZE) with a thickness greater than 1 mm using cutting parameters of CO_2 laser power (200-600 W), assisting O_2 gas pressure (3-8 bars) and cutting speed (2000-8000 mm/min).

A considerable improvement in kerf quality had been carried out by Avanish and Vinod (2007) onto an aluminium alloy sheet with the thickness of 0.9 mm using pulsed Nd:YAG laser beam cutting. The optimum levels of process parameters for minimum kerf width was at gas pressure with 8 kg/cm^2, cutting speed with 17.5 mm/min, pulse frequency at 28 Hz and pulsed width with 1.2 ms. This kerf width had been reduced up to 0.2250 mm (optimum) against the initial value of kerf width as 0.2625 mm by employing the multi-objective optimization technique using Taguchi method.

2.2.3 Cutting surface quality (surface roughness)

Surface roughness is an effective parameter representing the quality of the machined surface (Avanish and Vinod, 2008). Parameter that are most often used for accessing the surface roughness are the standard roughness (ten point height of irregularities), R_z and the mean arithmetic profile deviation, R_a. However, R_a is the most common way of evaluating the surface quality and the unit of surface roughness is measured in micrometer (µm) (Lo, 2003). Figure 2.7 shows the edge topography of the cut surface after completion of the laser cutting and the surface roughness measurement from the centre of the cut edge. Same as kerf width, in order to find out a good laser cut surface quality, researchers need to ensure whether the cut is a valid cut, non-valid cuts or cut with pitting (dross occurred) followed by the surface roughness measurement.



(a) (b)

Figure 2.7: (a) Topography of the laser cut (through cut) (Lamikiz et al., 2005); (b) Measurement of surface roughness (Lum et al., 2000)

Rajaram et al. (2003) had proved that surface roughness value reduces on increasing cutting speed and decreasing laser power as shown in Figure 2.8. Rajaram et al. (2003) concluded that feed rate/cutting speed has a major effect in surface roughness and at optimum feed rate, the surface roughness is minimum. The word minimum for surface roughness can also be defined as the acceptable surface roughness values for a good laser cut. In this case, the acceptable surface roughness values obtained by Rajaram et al. (2003) to cut a 1.27 mm thickness of 4130 steel using CO_2 laser power (700-1300 kW), feed rate (29.6-55.0 mm/s) and gas pressure at 1.3 kgf/cm^3 falls in between 1.508 – 2.046 µm.

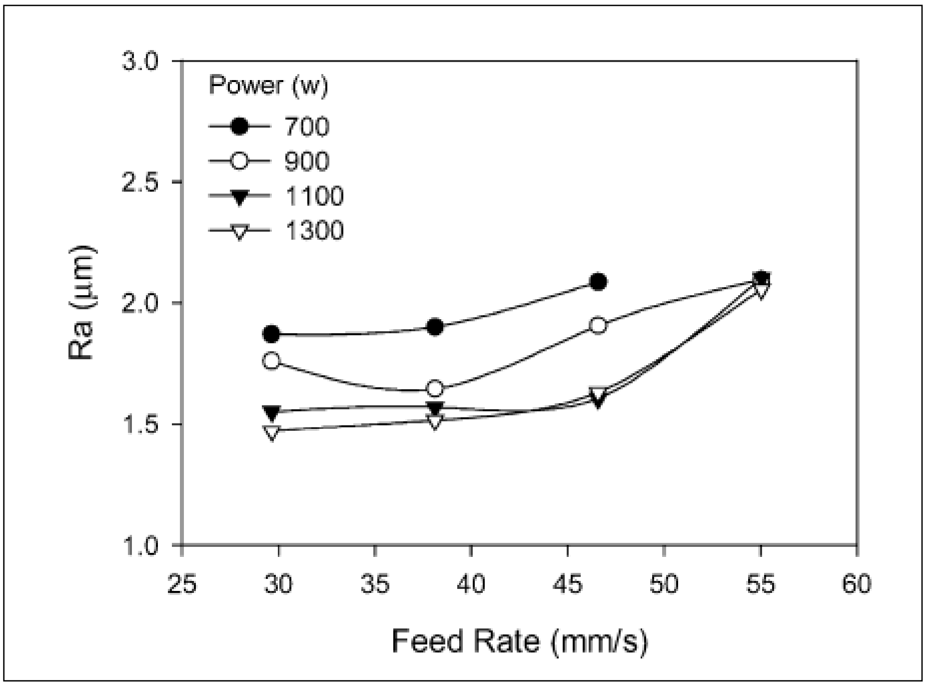


Figure 2.8: Variation of surface roughness with power and feed rate during CO_2 laser cutting (Rajaram et al., 2003)

A full through CO_2 laser cutting had been conducted by Lum et al. (2000) on a 6 mm thick of medium-density fibreboard to determine the range and the optimum laser cutting parameter to achieve a minimum surface roughness. Results revealed that higher cutting speed (3400-5800 mm/min) using CW laser cutting at 2.5 bar gas pressure (air) generated a good surface roughness in between 5.8-6.3 µm compared with lower cutting speed (800-1250 mm/min) using the same CW laser cutting at 2.5 bar gas pressure (air) generated poor surface roughness fall between 7.8-9.3 µm.

Chen (1998; 1999) observed that nitrogen and argon gave better surface finish than air beyond 6 bar pressure of a 3 mm thick mild steel during CO_2 laser cutting where it reduced the roughness (R_a) from 45 to 30 µm. Results also show that in order to produce a good-quality cut in term of the average roughness about 30 – 80 µm, the pressure range using pure oxygen should be in between 0.75 – 2 bar and cutting speed range should be 20-40 mm/s with a laser power of 1500 W.

Al- Sulaiman et al. (2006) presented parametric studies on CO_2 laser cutting of carbon multi-lamelled plain-weave structure. This works reported the use of nitrogen assist gas and low power levels tend to lessen the surface roughness value. An experimental investigation based on the Taguchi methodology on the quality characteristics in CO_2 laser cutting of aluminum alloys has been carried out by Stournaras et al. (2009). Results reveal that the laser power (66%), cutting speed (16%), and pulsing frequency (16%) have strongest effect on the quality characteristics especially on the surface roughness as shown in Figure 2.9.

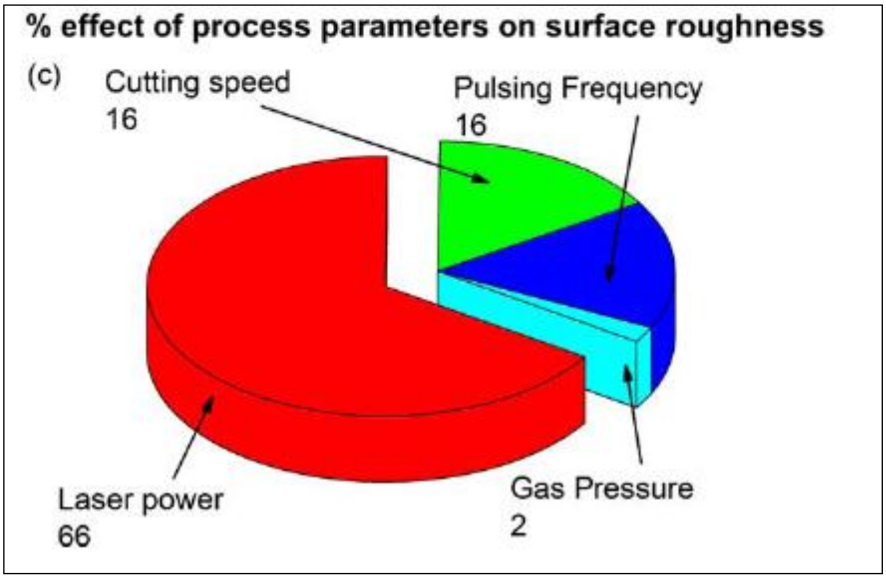


Figure 2.9: Effect of laser cutting parameters in surface roughness (Stournaras et al., 2009)

Ahn and Byun (2009) had performed the experimental work to investigate the influence of cutting parameters, including laser power (1.4-1.8 kW), cutting speed (3-10 m/min) and thickness (1.0, 1.6 and 2.0 mm) on the surface characteristics of the cut section in order to obtain the optimal cutting condition in the cutting of Inconel 718 super-alloy sheet using CW Nd:YAG laser cutting operation. According to the results of the experiments, it shows that the surface roughness decreases when the cutting speed increases. The optimal cutting condition was also being suggested in obtaining a good cutting surface through the experimental work as shown as Table 2.1.

Table 2.1: Surface roughness for each optimal cutting condition (Ahn and Byun, 2009).

Thickness, mm	Laser power, kW	Optimal cutting speed, m/min	Surface roughness, µm
1.0	1.4	7	14.1
	1.6	8	11.1
	1.8	8	11.3
1.6	1.4	5	21.4
	1.6	6	19.9
	1.8	6	19.1
2.0	1.4	4	23.2
	1.6	5	19.4
	1.8	5	20.7

2.2.4 Mechanical properties (hardness)

Based on the finding of the literature, it is observed that few researchers focused on hardness after laser cutting, mostly is on kerf width, surface roughness and dross inclusion. However, researchers have found out that the thermal damages and crack formations are the key elements that affected the strength of materials; whether is reducing or increasing the hardness of the material after laser cut (Avanish and Vinod, 2008). There is no standard value to determine how good the cutting quality is after laser cutting in terms of hardness; as long as there is no crack formation occurred as shown as Figure 2.10 and flexural strength reduction about 40% from its original strength after laser cutting that will definitely affect the strength of the materials (Avanish and Vinod, 2008).

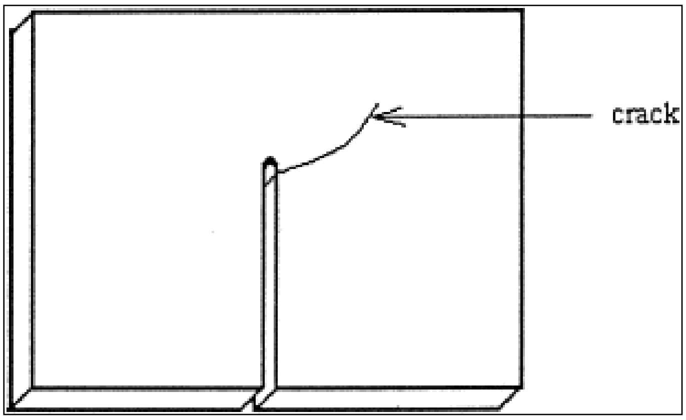


Figure 2.10: Sketch of a plate with a crack occurring during laser cutting (Lu et al., 1999)

Pulsed laser cutting of titanium alloy sheet was investigated by Shanjin and Yang (2006). They indicated that the hardness in HAZ was increased by 10% after the laser cutting and crack formation was found to be more by using oxygen or nitrogen assist gas pressure compared to argon. In spite of this, Zhang et al. (1996) have found out that the mean value of flexural strength reduced to 40% of the original material which means that a poor laser cutting quality occurred in term of hardness after laser cut.

2.2.5 Metallurgical feature (dross adhesion)

An investigation of the machine ability of metallic coated sheet steels Galvabond with three different thicknesses (0.55, 0.8 and 1 mm) using CO_2 laser has been presented by Wang and Wong (1998). Results revealed that assist gas pressure played an important role while the cutting speed did not show any observable effect in the formation of kerf geometry. At the pressure of 200kPa, most cuts on 0.55 and 0.8 mm specimens showed minimum or no dross at the exit. According to Wang and Wong (1998), the laser cutting quality are characterized based on the three classes of cut (for through cuts only) as shown in Figure 2.11. A good quality is referred to a clean through cuts with minimum or no dross at the exit. In this case, class III meets the requirements as the good laser cutting quality. Wang and Wong (1998) had also recommended the combinations of the parameters for cutting Galvabond for a good and fine laser cut as shown in Table 2.2.

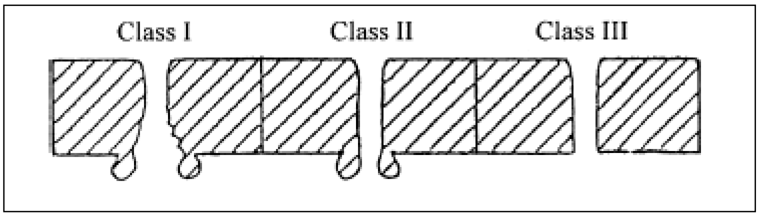


Figure 2.11: Three classes of laser through-cuts (Wang and Wong, 1998).

Table 2.2: Recommended combinations of laser parameters for cutting Galvabond. (Wang and Wong, 1998)

Thickness, mm	Assist Oxygen Pressure, kPa	Laser Power, W	Cutting Speed, mm/min
0.55	200	500	400
0.80	200	600	4500
1.00	200	700	5000

2.3 The background survey of artificial intelligence (AI)

Over the 60 years, AI has becoming useful as an alternate approach to conventional techniques where it used common assumptions and rules of thumb upon symbolic representations of knowledge and heuristic methods of reasoning (Pham and Pham, 1999). According to Barr and Feigenbaum (1981), AI is the part of computer science concerned with the design of intelligent computer systems, i.e. systems that exhibit the characteristics associated with intelligence in human