STUDY OF THE CARBON DIOXIDE (CO_2) LASER INERT GAS CUTTING ON INCONEL 718 USING EMPIRICAL APPROACH AND FINITE ELEMENT ANALYSIS

by

NYON KEN YOONG

Thesis submitted in fulfillment of the requirements

for the degree of

Master of Science

July 2011

ACKNOWLEDGEMENTS

I would like to express my deepest and sincere gratitude to my supervisor, Mr. Mohzani Mokhtar for his guidance and support throughout this project work. His wide knowledge and logical way of thinking have been of great value for me. His encouragement and personal guidance have provided a good basis for the present thesis.

I wish to express my warm and sincere thanks to my co-supervisor, Dr.-Ing Muhammad Razi bin Abdul Rahman for his grateful discussions, encouragements for their opinions and suggestions. I would like to express my indebtedness to my research team members, Mr. Chong Zhian Syn and Ms. Nyeoh Cheng Ying for their continued support. Also, I would like to thank all the staff members and technicians of School of Mechanical Engineering, Universiti Sains Malaysia for their continued cooperation. Thanks to you and all others who I have not listed here.

I gratefully acknowledged Universiti Sains Malaysia Science Fund project grant no. 6013362 provided by Ministry of Science, Technology & Innovation Malaysia and USM-RU-PRGS project grant no. 8031011 from Universiti Sains Malaysia for the financial support.

Nyon Ken Yoong

July 2011

TABLES OF CONTENTS

Page

CHAPTER 1 - INTRODUCTION

CHAPTER 2 – LITERATURE REVIEW

CHAPTER 3 – THEORITICAL FORMULATIONS OF AN INERT GAS LASER CUTTING PROCESS

CHAPTER 4 – IMPLEMENTATION OF FINITE ELEMENT ANALYSIS (FEA)

CHAPTER 5 – EXPERIMENTAL PROCEDURES

CHAPTER 6 – RESULTS AND DISCUSSIONS

CHAPTER 7 – CONCLUSIONS AND FUTURE WORKS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	**Description**
3D	Three Dimensional
APDL	ANSYS Parametric Design Language
BEM	Boundary Element Method
CO_2	Carbon Dioxide
CW	Continuous Wave
DOF	Depth of Focus
FDM	Finite Difference Method
FEA	Finite Element Analysis
FEM	Finite Element Method
HAZ	Heat Affected Zone
MRR	Material Removal Rate
PE	Polyethylene
PVC	Polyvinylchloride
PVM	Principle of Virtual Work
RPD	Relative Percentage Difference (RPD)3
SEM	Scanning Electron Microscopy
TC	Thermocouple

LIST OF SYMBOLS

Symbol	Description	Unit
$\{F^{th}\}$	Element thermal load vector	-
$[K_h]$	Surface convection matrix	-
$[K_c]$	Conduction matrix	-
$\{R_h\}$	Load vector associated with surface convection	-
$\{R_Q\}$	Load vector associated with internal heat generation	-
$\{R_T\}$	Conduction load vector	-
$\{R_q\}$	Load vector from specified surface heating	-
$\{\dot{T}\}$	Nodal vector of temperature derivatives with respect to time	-
$\{\varepsilon^{th}\}$	Thermal strain vector	-
h_{force}	convective heat transfer coefficient for the inert gas	$W.K^{-1}.m^{-2}$
$h_{free\ conv}$	Convective heat transfer coefficient of air	$W.K^{-1}.m^{-2}$
$\sigma_1, \sigma_2, \sigma_3$	principle stresses	N/m^2
A_f	Base of the cylinder	m^2
$[C]$	Capacitance matrix	-
C_s	Specific heat capacity of solid	J/kg.K
E_m	Energy required to melt the material	J

I_o	Laser intensity	W.m^{-2}
$[K]$	Element stiffness matrix	-
L_f	Latent heat of fusion	J/kg
M^2	Beam quality	-
Q_{forced}	Heat removal by forced convection	W
Q_{int}	Internal heat generation rate	W.m^{-3}
$S_o(x,y,z)$	Gaussian distributed volumetric heat source	Wm^{-3}
T_{amb}	Ambient temperature	K
T_{amb}	Ambient temperature	K
T_m	Melting temperature	K
T_s	Specified surface temperature	K
n_x, n_y, n_z	Direction cosines of the outward normal vector to the surface	-
q_s	Specified surface heat flux	W.m^{-2}
v_m	Melting speed	m/s
$\{\alpha\}$	Vector of coefficients of thermal expansion	-
σ_{m}	Von Mises stress	N/m^2
σ_{them}	Thermal stress	N/m^2
$[B]$	matrix for temperature-gradient interpolation	-

$[N]$	matrix of shape functions	-
$\{T\}$	vector of temperatures at nodes	-
A	Area	m^2
E	Young's modulus	GPa
f	Friction factor	-
Wd_{bottom}	Bottom kerf width	m
Wd_{top}	Top kerf width	m
α	thermal expansion coefficient	1/K
ν	Poisson's ratio	-
A	Absorptivity index	-
D	Beam diameter	m
Nu	Nusselt number	-
P	Laser beam power	W
Pr	Prandtl number	-
R	Reflection coefficient	-
Re	Reynold number	-
U	Internal Strain energy	J
V	Volume of the cylinder	m^3
V	External work	J

$c(T)$	Specific heat as a function of temperature	$J.kg^{-1}.K^{-1}$
d	Spot diameter	m
f	Focal length	m
k	Extinction coefficient of material	-
$k(T)$	Thermal conductivity as a function of temperature	$W.m^{-1}.K^{-1}$
m	mass of the material	kg
n	Refraction coefficient of material	-
r	Radius of the beam	m
s	Thickness of the material	m
t	Time	s
v	Cutting speed	m/s
x, y	Distance from center (0, 0) of the laser beam in x and y direction	m
δ	Absorption coefficient	m^{-1}
δ	Virtual operator	-
λ	Wavelength	m
ρ	Mass density	kg/m^3

LIST OF PUBLICATIONS AND SEMINARS

KAJIAN PEMOTONGAN LASER GAS LENGAI KARBON DIOKSIDA (CO_2) KE ATAS INCONEL 718 MENGGUNAKAN PENDEKATAN EMPIRIKAL DAN ANALISA UNSUR TERHINGGA

ABSTRAK

Pemotongan laser merupakan proses pemotongan panas di mana sinar laser yang kuat akan meleburkan bahan kerja melalui ketebalannya dan membentuk lebar alur. Di Malaysia, pemotongan laser merupakan salah satu industri yang paling umum diaplikasikan khususnya dalam industri pemprosesan kepingan logam. Inconel 718, sejenis aloi berdasarkan nikel yang berkekuatan tinggi, menjadikannya sukar untuk dipotong menggunakan kaedah pemotongan konvensional. Dalam kajian ini, pemotongan laser jenis gas lengai merupakan kaedah terbaik untuk memotong bahan ini dan dengan menggunakan gas Nitrogen. Pemotongan Laser untuk Inconel 718 dengan ketebalan 1 mm dan 2 mm disimulasikan dengan menggunakan perisian komersial iaitu analisis unsur hingga (FEA) kod ANSYS. Kaedah unsur hingga digunakan untuk meramalkan taburan suhu, tegasan haba, dan pembentukan lebar alur semasa proses pemotongan laser. Fluks panas dalam bentuk Gaussian digunakan sebagai model sumber panas dalam analisahaba peralihan tidak lelurus. ANSYS Parameter Design Language (APDL) digunakan untuk membentuk fluks panas dari sinar laser yang didistribusikan secara bentuk Gaussian benda yang dikerjakan. Pembuangan bahan cair semasa pemotongan laser untuk membentuk lebar alur dimodelkan dengan menggunakan elemen metodologi kematian dalam ANSYS. Selain itu, pemotongan laser disimulasikan pada gelombang berterusan dan kesan kuasa laser serta kelajuan potong pada lebar alur dikaji. Sementara itu, model disahkan dengan membandingkan hasilnya dengan

keputusan eksperimen dan yang diterbitkan dalam literatur. Hubungan yang baik ditemui antara keputusan simulasi dan keputusan dari eksperimen.

STUDY OF THE CARBON DIOXIDE (CO_2) LASER INERT GAS CUTTING ON INCONEL 718 USING EMPIRICAL APPROACH AND FINITE ELEMENT ANALYSIS

ABSTRACT

Laser cutting is a thermal cutting process in which a highly intense laser beam melts the material throughout the material thickness and form a cut kerf width. In Malaysia, laser cutting become one of the most common industrial application of laser especially in sheet metal processing industries. Inconel 718 is a type of high strength nickel-based alloy, thus makes it difficult to cut using conventional cutting methods. In this research, laser inert gas cutting was identified as the best method to cut the material and nitrogen gas is chosen as the inert gas. Laser cutting of Inconel 718 for 1 mm and 2 mm thicknesses were simulated by using commercial finite element analysis (FEA) code, ANSYS. Finite element method was used to predict the temperature distribution, thermal stress, and kerf width formation during laser cutting process. A moving Gaussian heat flux was employed as a heat source model for performing a non-linear transient thermal analysis. ANSYS Parameter Design Language (APDL) was used to model the Gaussian distributed heat flux from the laser beam acting on the workpiece. The removal of melted material during laser cutting to form the kerf width was modeled by employing the element death methodology in ANSYS. In addition, laser cutting was simulated at continuous wave (CW) and the effects of laser power and cutting speed on kerf width was investigated. Meanwhile, the model was validated by comparing the results with the experimental and results published in literature. A good correlation was found between simulation and experimental results.

CHAPTER 1

INTRODUCTION

1.0 Overview

This chapter provides an overview of the research work. The research background presents a brief introduction of laser cutting and the use of Finite Element Analysis (FEA) to predict the temperature and stress distribution, followed by problem statements. Then, it summarises the main objectives of this research. The chapter ends with the outlines of the thesis.

1.1 Research Background

Laser cutting is a non-contact thermal cutting process that uses a laser light to cut the workpiece into desired geometry. A narrow through cut kerf is generated by moving a focused laser beam along the surface of the workpiece (Ready, 2001). Laser cutting can be classified into using inert gas or with oxygen, depending on the material involved (Steen, 1991). Laser cutting is a well known technology used in sheet metal industry for materials processing. The main features of laser cutting are the ability to generate a highly concentrated heat power to perform high precision, fast processing and high quality end product.

A good quality cut characteristics are the cut having a narrow heat affected zone (HAZ) (Steen, 1991). High quality cutting is essential as it eliminates post machining and cleaning operations, improves productivity and significantly reduces the manufacturing costs. Besides, post machining operations such as grinding and brushing can damage the workpiece for its intended use. For example, thin intricate components can contain many small geometric features. This makes additional operation physically impossible, or economically unviable.

The cut quality of the laser cutting is influenced by the cutting parameters such as laser power, cutting speed, assisted gas pressure, and beam diameter. Besides, the thermo-physical properties and the thickness of the workpiece material will also affect the cut quality (Ready, 2001). Hence, the best quality of cut required optimum parameters setting which is depending on the thickness and thermo-physical properties of the workpiece material.

Apart from high quality, laser cutting systems interfaced with Computer-aided Design and Computer-aided Manufacturing tools (CAD/CAM) is capable of producing complex exteriors contours without the need of a die. These characteristics make laser suitable for cutting Inconel 718 which is a difficult material to machine due to its extreme toughness and work hardening characteristics (Rahman et al. 1997, Chen and Liao 2003, Sharman et al. 2008). Thus, it will overcome the serious tool wear and less material removal rate (MRR) problems in machining this material.

Although the laser systems are capable of achieving high quality cut, trial-and-error experiments are always required in order to find the optimum cutting parameters. Experimental research brings doubtlessly reliable and accurate results, but, at the same time, its shortcomings may be labeled as expensive and time consuming. This is especially true when using laser to cut advanced engineering material like Inconel 718. For this reason, a reliable simulation of the process might contribute to reduce the above shortcomings and provide a precise understanding of the physical mechanism governing these phenomena.

In the present years, a number of researchers have been working in the area of finite element-based numerical simulation techniques to predict the temperature fields and the thermal stress developed during laser cutting (Yu. 1997, Kim 2005, Arif and Yilbas 2008, Arif et al. 2008, Yilbas and Arif 2008, Yilbas et al. 2009, Yilbas et al. 2009, Yilbas et al. 2010). The study of temperature fields in the cutting region is important as excessive heat built up in the laser cutting area can cause poor quality in the form of widespread burning, increased dross, increased surface roughness and kerf widening. Meanwhile, the residual stress generated in the cutting edges limits the practical usage of the parts produced and will cause crack formation if the residual stress is higher than the yielding limit of the substrate material (Yilbas et al. 2009).

In this study, laser cutting of Inconel 718 for the thicknesses of 1 mm and 2 mm were simulated by using commercial finite element analysis (FEA) code ANSYS. Inconel 718 is a nickel alloy, thus nitrogen is suitable to be used as an inert gas to produce burr-free and oxide-free cuts. The inert gas nitrogen is used to eject the melt without causing chemical reaction with the material compared to those using oxygen as the inert gas (Ion, 2001). Thus, it is possible to predict the cut kerf width with sufficiently strong nitrogen jet to blow the molten material out of the cut kerf. The Gaussian distributed heat source produced by the laser beam can also be used to calculate the required cutting parameters mainly laser power and cutting speed to produce a through cut on the workpiece. These can reduce the number of trial and error in the real experiment to find out the optimum cutting parameters. This research is an extension from the previous model developed by Yilbas et al. (2009) which only consider the temperature fields and the thermal stress developed during laser cutting. This will be further discussed in chapter two.

1.2 Problem Statements

High quality cutting is essential in laser cutting as it eliminates post machining and cleaning operations, improves productivity and significantly reduces the manufacturing costs. This is especially true when using laser to cut advanced engineering material like Inconel 718. The quality problem may occur when the laser cutting parameters are chosen without any consideration.

Study of laser cutting processes in detail is essential in order to improve the quality and efficiency of the laser cutting process. This involves the study of heat transfer and the laser heat source for the development of thermal model by using finite element analysis (FEA). The developed thermal model can be used to understand the temperature and stress distributions which indirectly have an effect towards the kerf width size and other cut quality characteristics.

In order to achieve the understanding of the dynamic in laser cutting process, the numerical model must be able to simulate the actual environment of the laser cutting process. Consider a laser beam source cutting a workpiece of dimension L_x, L_y and L_z as shown in Figure 1.1. The laser beam moves over the workpiece with a constant velocity U and generates a continuous heat flux q_o that goes into the workpiece material. Heat is consumed to raise the temperature of the workpiece and thus, heat loses due to conduction and convection needed to be determined. In order to obtain the temperature fields as well as the thermal stress developed during the laser cutting process, the transient three dimensional heat conduction and convection equations must be solved numerically with appropriate boundary and initial conditions. In the present study, the FEA code, ANSYS 10.0 is utilized in the investigation. This work is expected to provide the improvement of the previous FEA model in analyzing CO_2 laser cutting and provide a guideline to the industry for the cutting parameters to obtain a good quality cut.

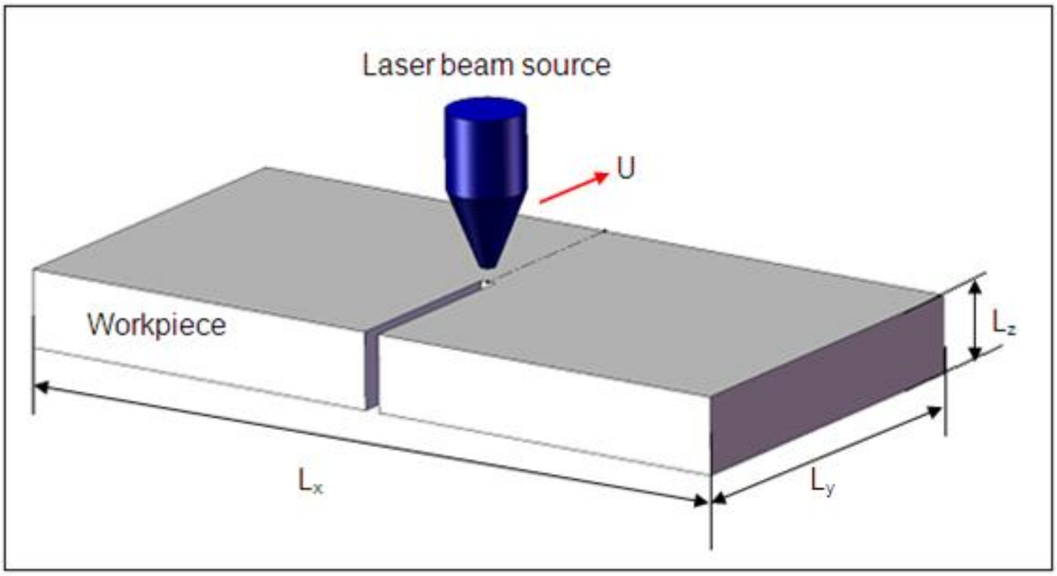

Figure 1.1: Schematic of the laser beam and the workpiece

1.3 Research Objectives

The purposes of the research are to predict the temperature fields and thermal stress developed during laser cutting as well as kerf width formation after the laser cutting of Inconel 718 for different cutting parameters and workpiece thicknesses.

There are three objectives involved to achieve the above research purposes:

1) To identify laser heat source characteristics, heat transfer mechanisms on the workpiece and the physical mechanisms involved in laser cutting.

2) To develop the thermal and structural models to predict temperature and stress fields during laser cutting by using commercial FEA code ANSYS with appropriate boundary and initial conditions.

3) To study the effect of laser powers and cutting speeds on the kerf width using FEA simulation and compare with experimental results.

1.4 Scope of Work

The primary aims of this research is to use finite element analysis (FEA) code, ANSYS to predict the temperature distribution, thermal stress, and kerf width formation during laser inert gas cutting of Inconel 718 for 1 mm and 2 mm thicknesses. A moving Gaussian heat flux was employed as a heat source model for performing a non-linear transient thermal analysis. ANSYS Parameter Design Language (APDL) was used to model the Gaussian distributed heat flux from the laser beam acting on the workpiece. The removal of melted material during laser cutting to form the kerf width was modeled by employing the element death methodology in ANSYS. Experimental verification is performed to validate the simulation model. Figure 1.2 depicts the general process flow of the research methodology framework. It consists of three fundamental phases where each phase occurred concurrently during the development of finite element model. Hence, the framework developed provides the guideline in developing the model for predicting the temperature fields, kerf width, and thermal stress developed during laser cutting of Inconel 718 for different cutting parameters.

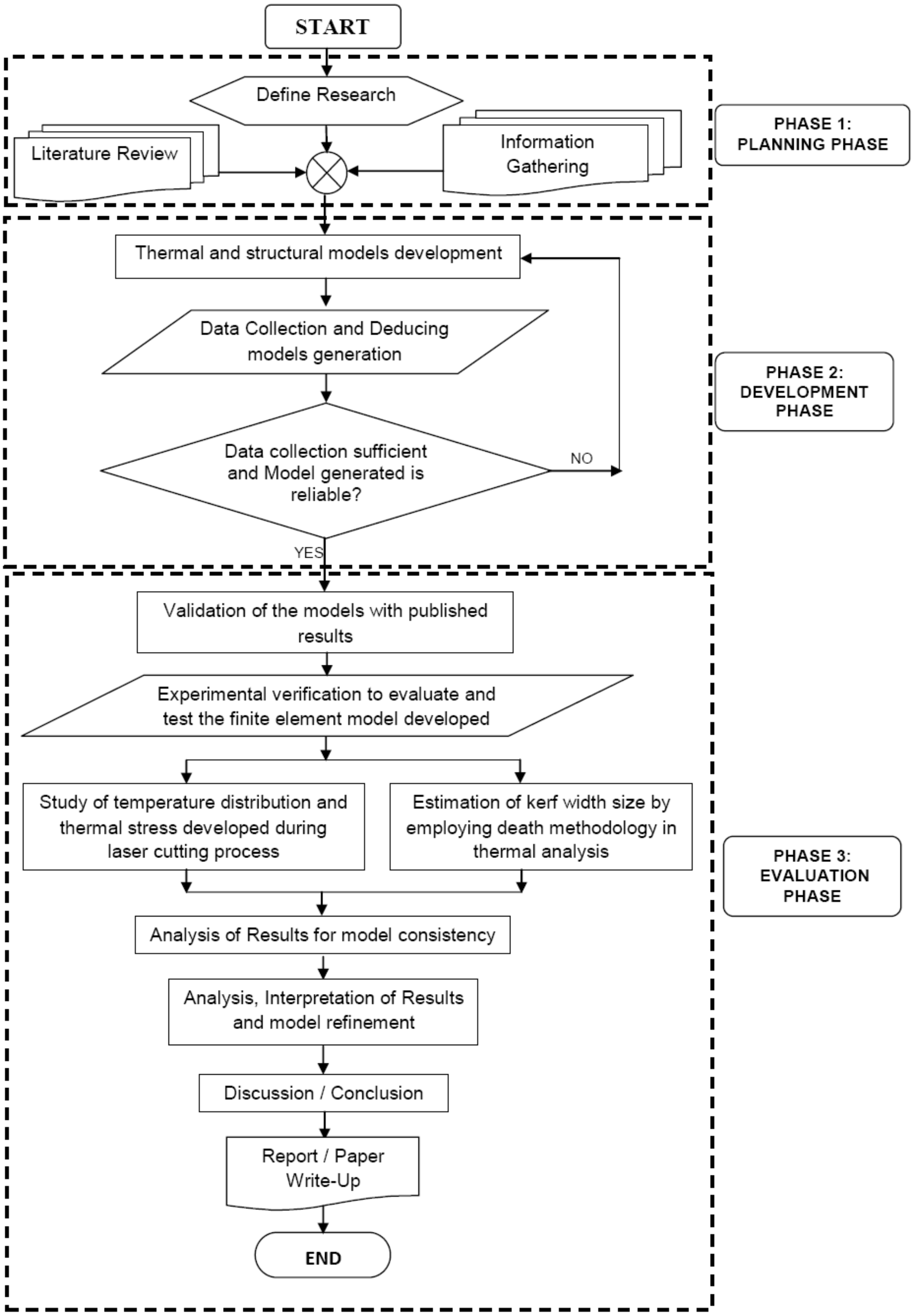

Figure 1.2: Process flow for the research methodology framework

1.5 Thesis Outlines

The presented thesis is served in seven primary chapters which connected with the introduction, followed by literature review, theoretical formulation, finite element analysis, experimental procedures, results and discussions and the last section draws the conclusion and future work.

Chapter 1	Summary of the research background and the importance of the research study in general. In addition, the problem statements, objectives, and the tasks involved in the current research were clearly highlighted
Chapter 2	Literature review of laser cutting process and its application, as well as the mechanism of laser cutting. Previous research works on analytical and numerical modeling of laser cutting process are discussed here
Chapter 3	Presents the theoretical formulations of inert gas laser cutting process which include thermal and structural analyses and the physical behaviors
Chapter 4	Introduces finite element analysis in solving transient and static stress analyses. Finite element formulations of heat transfer and thermal stresses as well as simulation using ANSYS are presented
Chapter 5	Describes the experimentations to validate the simulation model that are formed using ANSYS
Chapter 6	Provides the results for the simulation and experimentations followed by discussion of the simulation and experimental findings
Chapter 7	Outlines the conclusions and future research directions

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

In this chapter, research activities carried out in laser material processing is reviewed and discussed. Next, consideration is given to the basic concept of laser cutting process and its applications as well as the mechanism of laser cutting. This is followed by discussions on the major influences of laser cutting parameters towards to cut quality. Major quality issues including kerf width, striation, HAZ and cracks are comprehensively discussed. Previous research works on analytical and numerical modeling of laser cutting process are extensively discussed in the following section. The final section summarizes the chapter.

2.1 Laser Material Processing

Laser, an acronym for light amplification by stimulated emission of radiation, is a coherent, convergent, and monochromatic beam of electromagnetic radiation with wavelength ranging from ultra-violet to infrared. The principle of stimulated emission was found by Albert Einstein in 1916 and the first laser known as Ruby Laser was produced by Townes and Shawlow in 1957 (Ion, 2005).

Laser light are highly directional, high power density and better focusing characteristics because it has the photons of same frequency, wavelength and phase. The laser beam can deliver a very low (~mW) to extremely high (1-100KW) focused power with interaction time (10^{-3} to 10^{-15} s) on any kind of substrate material through any medium. These unique characteristics make high beam power laser suitable to be used in materials processing. As a result, laser has wide application in automobile sectors, aircraft industry, electronic industry, civil structural, nuclear sector, medical sectors and house appliances (Dubey and Yadava, 2008).

2.1.1 Type of industrial laser

Laser can be classified according to their operating mode (continuous wave (CW), pulsed mode or both); lasing mediums (gas, liquid or solid); wavelength (infrared, visible and ultraviolet).

In CW mode, the laser beam is emitted without interruption where else in pulsed mode; the laser beam is emitted periodically as shown in Figure 2.1. The main advantage of pulsed mode operation is the temporal limitation in energy coupling into the target material, resulting in a very limited depth of heat conduction into it, and thus reduces the size of the HAZ (Olsen and Alting, 1995). For example pulse mode is applied to cut materials that are sensitive to elevated temperature, i.e., polymers to minimize the HAZ. Also, deeper cutting or drilling depth can be achieved at a given beam power for pulsed mode operation. Meanwhile, continuous mode operation is used when high average power is required for achieving high material removal rate and resulting in smooth surface after machining.

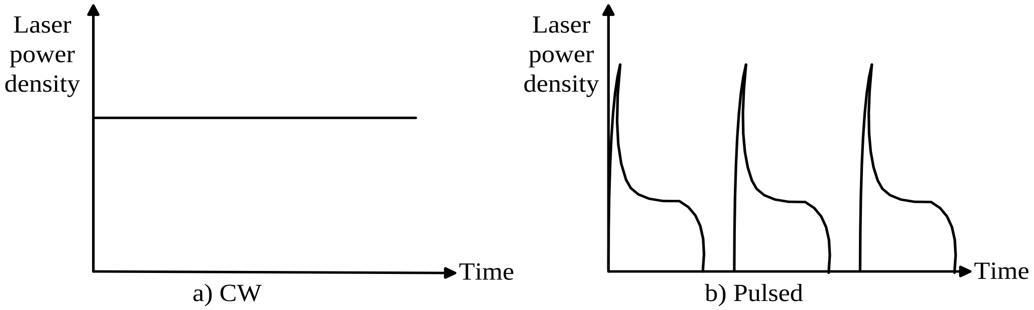

Figure 2.1: Temporal modes of laser operation (Narendra and Sandip, 2008)

There are many types of industrial laser used in laser material processing as shown in Figure 2.2 below. Carbon dioxide (CO_2) laser is an example of molecular lasing medium, which is widely used for laser material processing application i.e., laser cutting, welding and heat treating (Herzog et al. 2008, Ahn and Byun 2009). In the present work, CO_2 laser is chosen because it has high average beam power, better efficiency, and good beam quality. Hence, it is suitable for fine cutting of sheet metal (Norikazu et al. 1996).

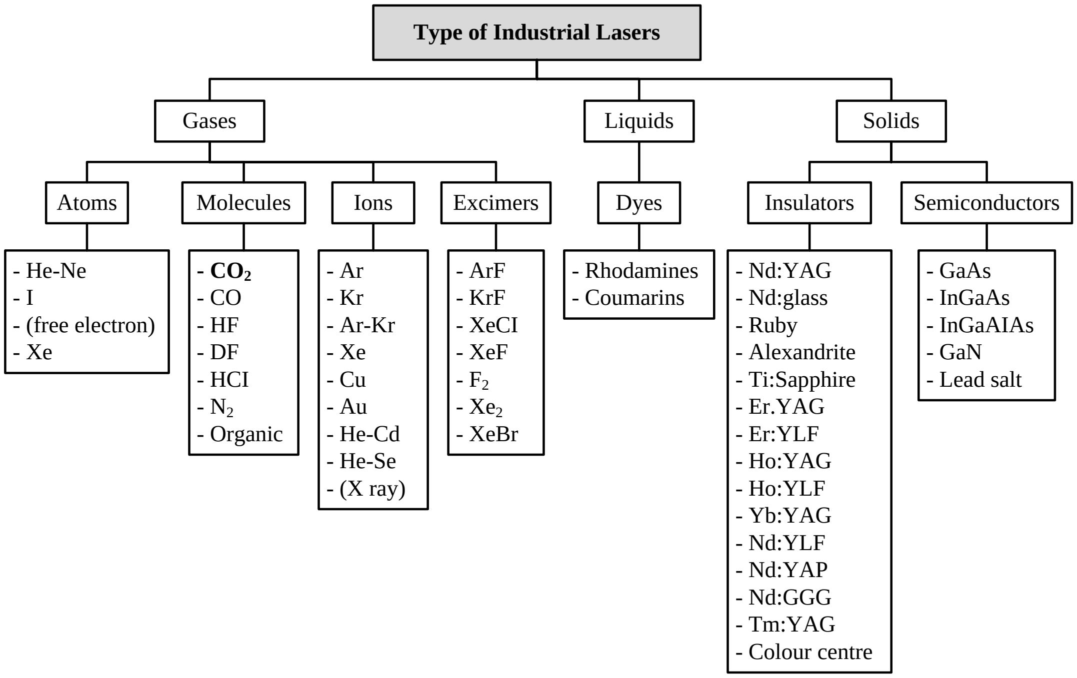

Figure 2.2: Type of industrial lasers (Ion, 2005)

2.1.2 Classification of laser material processing

Laser has been widely applied in many manufacturing applications including machining, joining, forming and surface engineering as shown in Figure 2.3 below. However, from the many different methods of laser materials processing listed in Figure 2.3, only few methods have industrial significance up to date as shown in Figure 2.4, measured in terms of sales figures of worldwide laser processing systems sold in 2004 (Belforte, 2004).

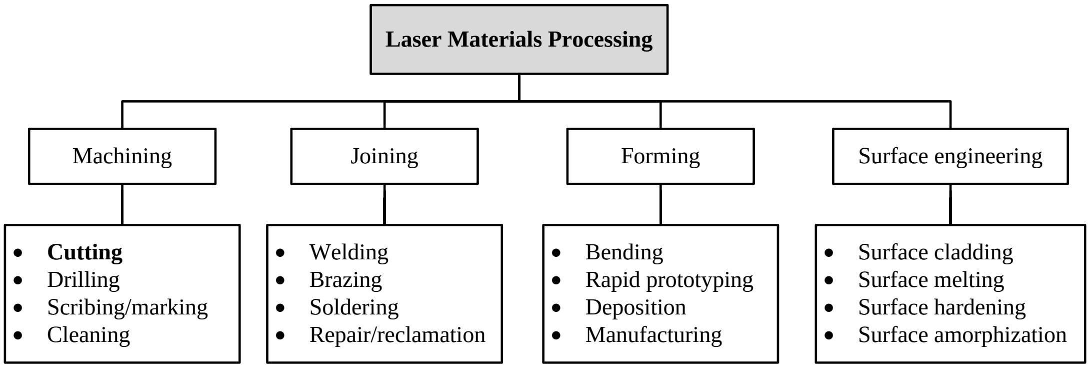

Figure 2.3: Classification of laser material processing

As shown in Figure 2.4, the most significant technology is laser marking, comprising 35% of the laser systems sold in 2004 followed by laser cutting with a share of 20% and laser engraving with 13%. Thus, laser cutting is one of the most important applications of laser technology in laser material processing. It is typically applied for small to medium batch sizes and for cutting the complex contours (Ahn and Byun 2009, Dubey and Yadava 2008, Tirumala et al. 2005). Compared with other processing techniques, i.e., punching, plasma arc cutting and sawing, laser cutting is superior in terms of contour precision, contour flexibility, reliability, cut edge quality and cutting speed. The types of laser cutting, its application and the influences of laser process parameters are discussed in the following section.

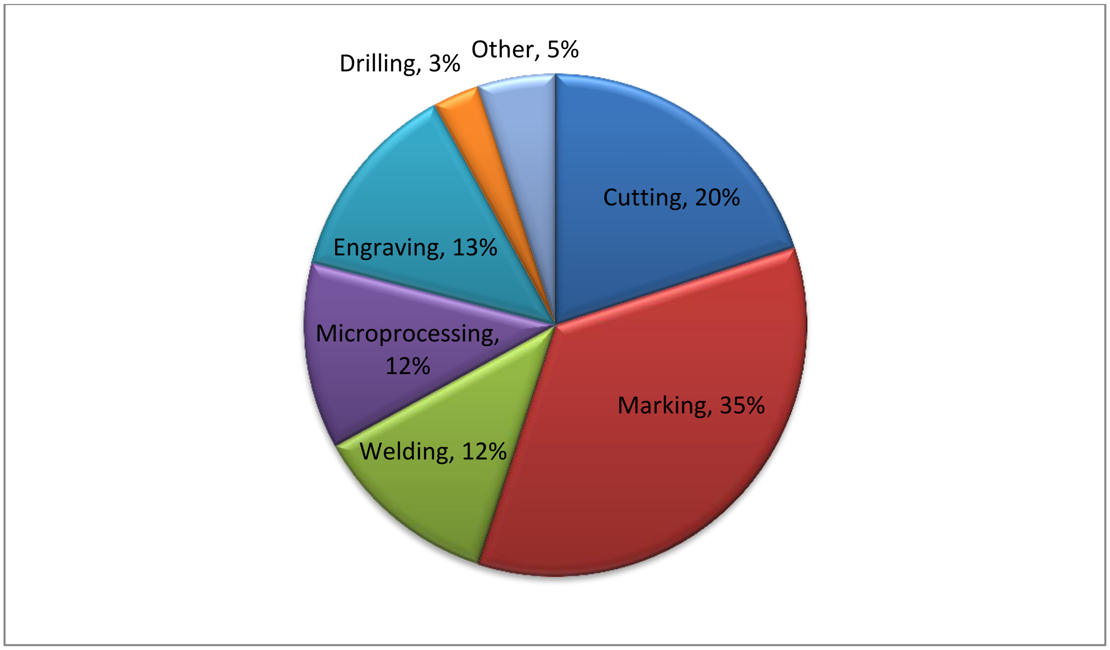

Figure 2.4: Worldwide applications for all lasers in 2004 (Belforte, 2004)

2.2 Laser Cutting

Laser cutting is one of the thermal cutting process in which a focused laser beam melts the material throughout the material thickness to form a cut kerf. Then, a pressurized gas jet which acts coaxially with the focused laser beam blows away the molten material from the cut kerf. Types of laser cutting are defined based on the governing transformation process, which include laser fusion cutting, laser oxygen cutting and laser vaporization cutting. Laser fusion cutting, also known as inert gas cutting is process used mainly in this research. Workpiece material is heated with the laser energy along the kerf into molten state. Then, high pressure inert gas jet, i.e., argon or nitrogen is responsible for ejecting the molten materials. This type of cutting is applicable to all metals especially stainless steels, aluminium, and alloyed steels (Narendra and Sandip 2008, Steen 1991). Usually the cutting speeds are relatively low compared to the other two methods, and the main concern of laser fusion cutting is to evade dross attachment at the bottom cut edges.

In laser oxygen cutting, workpiece material is heated by the focused laser beam in this exothermic condition and assist gas is responsible for blowing out the molten material from the cut kerf. Oxygen plays a vital role by providing exothermic oxidation reaction to the material while contributing additional heat input in the cutting zone. Because of this additional heat input, the cutting speed is higher compared to laser fusion cutting (Wandera, 2006).Although this type of laser cutting caused the formation of oxide layer on the cutting edges, it is suitable for cutting mild steel and low alloyed steel (Tirumala, 2005).

As its name implies, during laser vaporization cutting, the material is heated above its melting temperature and eventually vaporized. Gas jet is used to blow the material vapor out of the cut kerf to prevent the hot vapor steam from condensation within the formed kerf. This method is especially suitable for cutting precise and complex geometries of thin workpiece. However, this method requires high power and it is much dependent on the thermal properties of the cut material. Among the typical materials that are suitable to be cut by vaporization method are acrylic, polymers, wood, paper, and leather (Narendra and Sandip 2008, Caiazzo et al. 2008).

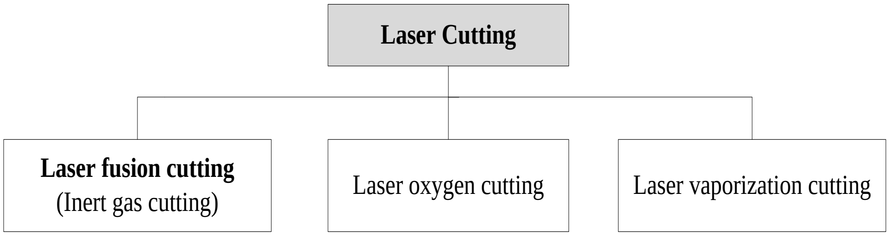

Figure 2.5: Types of laser cutting

2.2.1 Applications of laser cutting

Laser cutting has been used in industry since 1970's (Ion, 2005). Today, laser cutting become one of the most common industrial application of laser especially in sheet metal processing industries (Yilbas et al., 2009).Sheet metal is basically a metal that formed into thin and flat pieces that can be cut or bent into variety of different shapes. Sheet metal processing is one of the oldest manufacturing processes as reported by Fries-Knoblach, 1999. Laser cutting has developed over the past years and has diversified applications in the field of automobile sectors, aircraft industry, electronic industry, civil structures and house appliances (Graaf and Meijer 2000, Rajaram et al. 2003, Dubey and Yadava 2008) due to its high geometric flexibility and fast cutting speed in processing different types of engineering materials. Mild steel, stainless steel, aluminum, glass and plastics are examples of relatively easy to cut material using laser.

Applications of laser cutting in engineering materials, which can still be grouped into four general classes: metals and alloys; ceramics and glasses; polymers; and composites have grown considerably in many industries (Davim et al. 2008, Molian et al. 2008, Almeida et al. 2006, Shanjin and Yang 2006, Ion 2005). Titanium alloys, nickel-based superalloys, thermoplastics, such as polyethylene (PE), polyvinylchloride (PVC), thermoset plastics, modern engineering glass and monolithic ceramics, such as aluminium oxide and aluminium nitride are some of the examples of engineering material. Reasons such as high accuracy at high speed, non-contact process which eliminates tool wear and machine vibration, as well as the effectiveness of which this process depends on thermal properties rather than mechanical properties of the material make laser cutting a much better option as compared to other conventional techniques.

Laser cutting processes compete both technically and economically with conventional cutting processes such as mechanical and thermal machining, arc welding, wire cut, electric discharge machining (EDM), and abrasive water jet cutting (Dubey and Yadava 2008). CO_2 laser cutting is commonly used to cut hard materials such as titanium, Inconel 625, titanium alloys, advanced high strength steels (AHSS) (Arif and Yilbas 2008, Shanjin and Yang 2006, Rao et al. 2005, and Lamikiz et al. 2005). Hard material is the term used to signify a group of sintered, hard, and wear-resisting materials. Water jet cutting is another common method of cutting hard materials. However, water jet cutting is not as precise as laser cutting and due to high level of power and pressure used; small workpiece must be handled carefully. Although there is no thermal stress and burring in the cut, the surface of the material will appear sand-blasted as a result of the added abrasive to the water-jet (Standard metal cutting processes: laser cutting vs. water jet cutting). Hence, depending on the high accuracy required for cutting Inconel 718 which is applied in aircraft industry, CO_2 laser cutting is more appropriate for this application.

Automotive sectors and aircraft industry are two of the largest applications of laser cutting. High power density associated with small spot sizes results in small kerfs and straight walls even in thick metals make this process suitable to be applied here. Laser is used for cutting automotive hydroform tubes, cradles, side pillars and aircraft brakes as well as resizing silicon wafers for solar panels. Besides, laser is very useful for cutting apertures on printed circuit boards, trimming of circuit boards in electronic industry. For thick section metal cutting, laser has been applied to cut internal of core reactor, storage tanks, fuel channels, construction equipment, and concrete buildings (Dutta and Manna, 2005).

2.2.2 Mechanism of laser cutting

Laser cutting is a two-dimensional, non-contact machining process in which a cut kerf is formed by focusing a highly intense laser beam on the workpiece material. A typical laser cutting system consists of high power laser source, guidance mirror, focusing lens, gas jet muzzle, together with a CNC-controlled motion system. The general arrangement for laser cutting is shown in Figure 2.6 below. High power and low intensity laser beam is focused onto the workpiece material through a guided mirror from the laser source. A focusing lens will generates high intensity laser beam (about 10^6W/cm^2) which is sufficient for laser cutting by focusing the beam to a smaller spot. The laser cutting process is carried out by a CNC controlled system, moving the tiny focused laser beam (spot size diameter in the range of 0.2 mm to 4 mm or 5 µm to 100 µm) along the surface of a workpiece or to provide relative motion to the X/Y table.

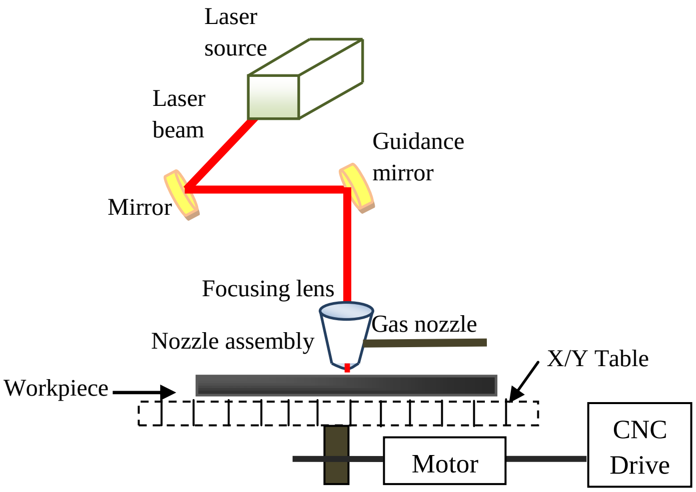

Figure 2.6: General arrangement of laser cutting

The cutting mechanism is as follow: The focused laser beam melts or vaporizes the material throughout the material thickness and a pressurized gas jet blows away the molten material from the cut kerf as shown in Figure 2.7 below. The mechanism is called laser fusion (inert gas) cutting if an inert gas, i.e., argon or nitrogen is used in the process. In contrast, if oxygen is used, which does not only eject the molten material but also causes chemical reaction with the material, it is called laser oxygen cutting. During laser vaporization cutting, material is removed by expansion in the gaseous state instead of ejection of the molten material. Basically, for all the methods mentioned, locally removed material forms the cut kerf as a result of relative motion between the laser beam and the workpiece material along the desired contour.

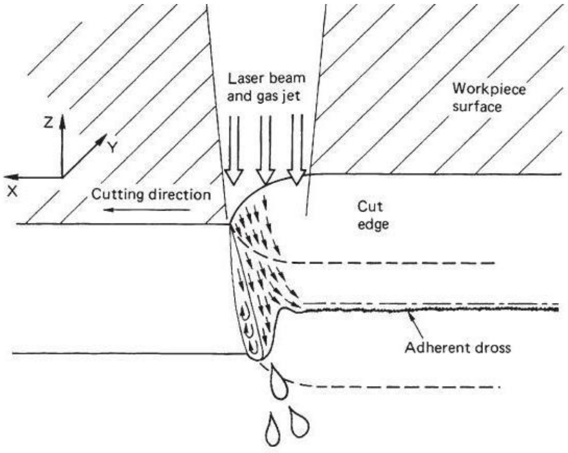

Figure 2.7: General schematic of a laser cutting process with a coaxial gas jet to blow the molten material (Narendra and Sandip, 2008)

2.2.3 Influence of the process parameters

Being a non-conventional machining process that involves high investment, selection of appropriate laser process parameter such as power, assist gas and its pressure, as well as cutting speed that have direct implication towards quality issues in laser cutting must be investigated and optimized. These parameters can be changed in order to improve the cutting performance and to achieve the desired cutting quality (Wandera, 2006). Basically, process parameters are unique for each material and thickness.

Laser power directs the energy input to the cutting process and it is rated by the power output in terms of watts. A high power continuous wave laser beam is preferred for smooth and fast cutting especially thicker materials because highest cutting speeds can be obtained with high power levels. Kerf width size, kerf taper and cutting efficiency increases with increasing laser power intensity (Al-Sulaiman et al. 2006 and Wang et al. 2010). However, at lower power, surface roughness can be improved. An optimum combination of cutting speed and laser power gives a maximum performance especially to cutting thick workpiece. This is illustrated in Figure 2.8 below and discussed by Li et al. 2007 for striation free laser cutting of 2mm mild steel using a 1 kW single mode fibre laser. The authors indicated that the maximum cutting speed of 80mm/s can be achieved at laser power of 800W to cut through the entire thickness of the material. However, through cut could not be formed when the power was set to maximum, i.e., 1kW and the cutting speed was set at 95 mm/s. The same situation happened when a lower power was set, i.e., at 600W and cutting speed at 60 mm/s. Hence, it can be concluded that if the process parameter was set at higher powers, and to produce a clean through cuts, it was necessary to reduce the cutting speed (Yilbas, 2008).

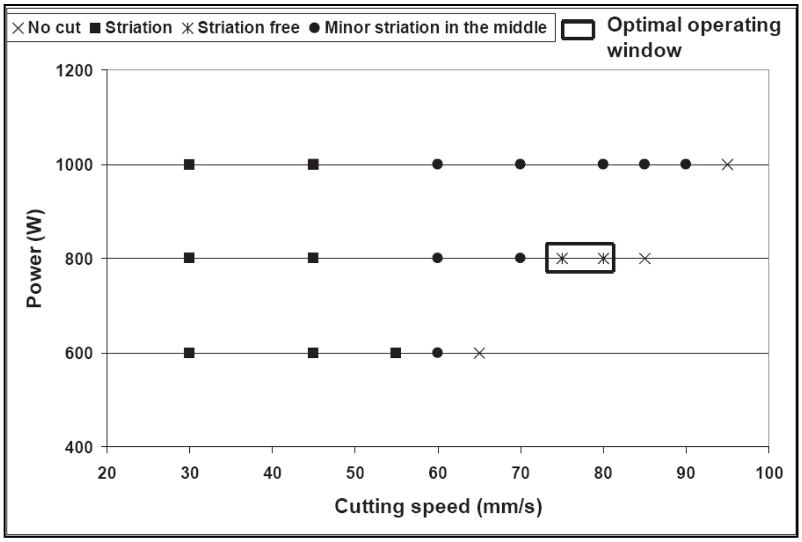

Figure 2.8: Operating windows for striation free laser cutting at a nozzle standoff distance of 1 mm and focal plane position of 4 mm above the workpiece with 2 bar O2 gas pressure (Li et al., 2007)

Besides laser power, the cutting speed or the feed rate is the most crucial parameters that must be considered during laser cutting process. Cutting speed is directly proportional to power density and inversely proportional to materials thickness. Therefore, it can be concluded that cutting speed will be increased with an increase in laser power. Cutting speed will also be increased with a decrease in material thickness (Yilbas 2008, Wandera 2006, and Caiazzo et al. 2005). In 2005, Caiazzo et al. pointed out that not always higher cutting speed was not always synonymous with good process efficiency. However, Wandera (2006) suggested that in order to increase the efficiency in the cutting process, a reduction in energy lost from the cut zone should be attained by increasing the cutting speed. Generally, increasing the cutting speed leads to increasing the roughness, striation frequency and tendency for cracking but will produce a narrower kerf. Wang et al. (2010) found that a high cutting speed as a result of applying the thermal load more rapidly, which will increase the temperature gradient, subsequently rising the thermal stresses which will induce the tendency of cracking. Both, Sharma et al. (2010) and Tani et al. (2004) explained that when the cutting speed has increased, the time of interaction of laser with sheet material will be reduced causing narrow kerf width. Basically, there is no standard cutting speed reference for different material at different thicknesses, it all depends on the material conditions and the quality of final products required in deciding on the appropriate speeds setting. Hence, in this research, the parameters setting, i.e., cutting speed and power is analytically (Appendix A) and experimentally determined before a range of parameters set is defined.

Assist gas such as oxygen, nitrogen, argon and helium are commonly used and chosen for laser cutting process based on laser cutting efficiency and quality of the cut desired. The choice of the process gas type also determines whether the process is a laser inert gas cutting (N_2, He, and Ar) or laser oxygen cutting. In general, an inert gas is used to eject molten material from the cut zone and to eliminate dross formation at the underside of the cuts. The gas pressure usually increases with an increase in material thickness. Meanwhile, for most metal, active gas, i.e., oxygen is employed to promote an exothermic reaction with the material. Nitrogen gas is normally used for cutting stainless steel, high-alloyed steels, aluminuim and nickel-based alloys because it is relatively cheap compared to pure argon and helium. Nitrogen gas requires higher working pressure (10-20 bar) to remove the molten material from the cut kerf (Wandera, 2006).In this experiment, nitrogen is identified as the most suitable inert gas for cutting Inconel 718, a type of nickel-based alloy and therefore was chosen in this study.

To conclude, laser cutting is a complex process involving various parameters and these parameters setting will determine the geometric and metallurgical quality of the cut material. Hence, the effect of some of the most important parameters, i.e., laser power, cutting speed, type of assist gas and its pressure must be determined and set correctly to produce a good quality laser-cut workpiece. In the next section, the influences of different combination of process parameters towards the cut quality are discussed.

2.2.4 Quality criteria

As mentioned, cut quality from laser cutting process is extremely important because this process is applied in the field of automobile sectors and aircraft industry. Characteristic properties which are important and usually being focused, includes, kerf width, dross adhesion, and metallurgical quality such as striation pattern and surface cracks. Figure 2.9below shows the schematic illustration of various cut quality attributes of interest. These characteristics are influenced by the process parameters and prediction of the cutting quality is difficult due to the dynamic nature of laser cutting process where it depends on the specific job requirements (Narendra and Sandip, 2008). Primary factors such as kerf width, dross adhesion and metallurgical quality are evaluated and further discussed in this research. Table 2.1 below summarized the quality criteria discussed in laser cutting process.

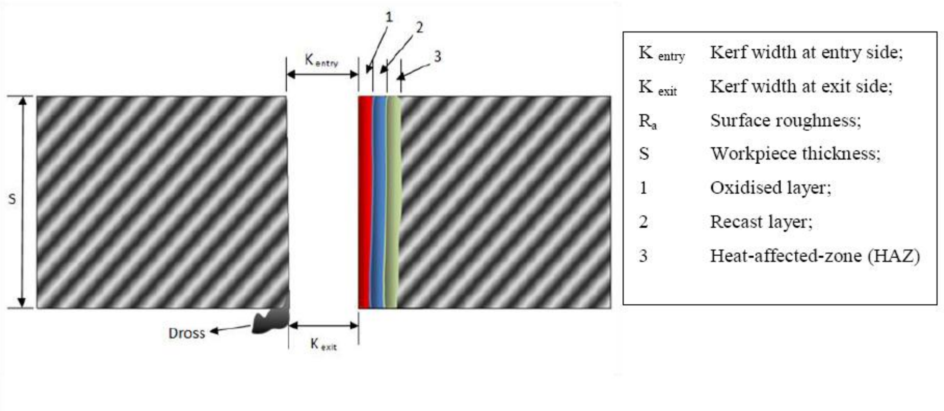

Figure 2.9: Schematic illustration of various cut quality attributes of interest (Thawari et al., 2005)

Kerf width refers to the width of the slot or the cut opening that is formed during laser cutting process. Also, this kerf width represents the total of material removed during the cutting. Usually, for laser cutting process, a narrow kerf width is preferred especially when cutting small and detailed part. As reported in the literature, power, cutting speed and assist gas have influence on the size of the cut kerf (Wang et al. 2010, Sharma et al. 2010, Yilbas 2008, Al-Sulaiman et al. 2006, and Tani et al. 2004). Wang et al. (2010) concluded that laser power density at the surface will affect the kerf width, kerf taper and cutting efficiency. Meanwhile, Sharma et al. (2010) examined the effects of cutting speed at the workpiece surface on the resulting kerf width. The authors commented that when the cutting speed increased, the time of interaction of laser with sheet material will be reduced, thus causing narrow kerf width at the top surface. The increase in cutting speedwell reduces the beam overlapping rate causing a narrower bottom kerf width, resulting in higher taper kerf. In conclusion, increasing laser power and lowering cutting speed increases kerf width size (Yilbas, 2008). However, as discussed, kerf width will vary depending on the material type and thicknesses. Kerf width variation lowers the end product quality significantly. Consequently, a study into the effect of laser process parameters on the resulting end products quality is essential. One of the objectives in this research is to measure and compare the kerf size formed during the laser cutting experiment and from the simulation.

Dross is related to solidify material that forms on the bottom kerf due to incomplete expulsion of the melt. Dross can be removed mechanically after cutting by using secondary process, such as sanding and electropolishing. As reported by Rao et al. (2005), cutting 1mm thick 99% pure titanium sheet using helium as the inert gas with pulsed mode, the fusion cutting of the CO_2 laser produced low dross, as compared to those produced with argon gas. The authors mentioned that laser cutting with high frequency and low-duty cycle pulse mode operation produced dross free cuts. However, no specific patterns were observed. Similar to Yilbas (2008), dross attachment and excessive melting were locally scattered around the cut edges but with no specific pattern. Analytical model of dross formation has been developed for AISI 304 stainless steel plates of three different thicknesses by considering mass, force and energy balances in evaluating the three - dimensional geometry of the cutting front, the geometry and temperature fields of the melt film (Tani et al., 2004). It was found that two different mechanisms which were dependent on the process parameters, i.e., cutting speed and assist gas pressure were responsible for the dross formation. The first mechanism is about the melt ejection speed of the molten material from the bottom of the kerf, and this critical melt speed depends on the characteristics of the material which is related to the ability of the melt film inertial forces to overcome surface tension and frictional losses at the kerf bottom. The second mechanism for dross adhesion is defined by the geometry of the melt film on the profile plane. Temperature distribution within the melt due to the effect of cutting speed and assist gas pressure are used to refine the dross adhesion conditions.

Striation is one of the most significant quality factors in laser cutting process as it was the most reported in literature (Yilbas 2008, Li et al. 2007, Karatas et al. 2006, Al-Sulaiman et al. 2006, Lee and Lin 2005, Tani et al. 2004). The presence of striations is undesirable since they may increase stress and cause unpredictable geometric changes to the workpiece material. Alternatively further finishing operations is required to achieve the smooth surface. A two-dimensional, analytical mathematical model on the effect of laser parameters such as power, scan speed and spot sizes for predicting striation formations was developed by Lee and Lin (2005). Striation width and depth increased with increasing of workpiece thickness (Karatas et al., 2006). However, no specific striation patterns were observed. Both, Li et al. (2007) and Yilbas (2008) concluded that striation effect increased with an increase of cutting speed. Besides cutting speed, the effect of laser power and gas pressure was experimentally investigated by Yilbas (2008). The author concluded that by increasing the cutting speed while decreasing laser power and oxygen pressure will reduce the striation depths and striation irregularities.

Surface cracks are another imperfections and major issues that need to be addressed as it will also lower the end product quality. High residual stress and cracks propagation at the cutting edge will cause failure to the products. These phenomena must be avoided as it will abbreviate the life time and cause failure to the components or end products. Rapid solidification of thin molten layer along the cutting edge and high thermal stress exceeding the elastic limit of material results in surface cracking (Ji et al.