MACHINABILITY ASSESSMENT WHEN TURNING AISI 316L AUSTENITIC STAINLESS STEEL USING UNCOATED AND COATED CARBIDE INSERTS

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MACHINABILITY ASSESSMENT WHEN TURNING AISI 316L AUSTENITIC STAINLESS STEEL USING UNCOATED AND COATED CARBIDE INSERTS

RUSDI NUR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

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JANUARY 2016

I declare that this thesis entitled "*Machinability Assessment when Turning AISI 316L Austenitic Stainless Steel Using Uncoated and Coated Carbide Inserts*" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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To my beloved mother and father,
Hj. Habesiah, and H. Muhammad Nur Pilo

To my honored mother and father in law,
Hj. Sitti. Marhamah, and Muh. Syabiruddin Abdolo

To my lovely wife and daughter
Asmeati and Ainayah Zalikhah Rusdy

Also to my brothers and sisters,
H. Ramli Nur, Rusli Nur, Rais Nur,
Ramlah Nur, Ramsiah Nur and Rosmiati Nur

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ABSTRACT

Austenitic stainless steel AISI 316L is mostly used as an implant material and is customarily applied as impermanent devices in orthopedic surgery because of its low cost, adequate mechanical properties, and acceptable biocompatibility. AISI 316L is an extra-low carbon type 316 (austenitic chromium nickel stainless steel containing molybdenum) that minimizes harmful carbide precipitation at elevated temperature. Machining is part and parcel during the fabrication of implants and medical devices made from stainless steels and thus it is of interest to evaluate the machinability of AISI 316L. In this study, austenitic stainless steel AISI 316L was turned using two commercially available cutting tool inserts at various cutting speeds (90, 150, and 210 m/min) and feeds (0.10, 0.16, and 0.22 mm/rev) and at a constant depth of cut of 0.4 mm. The turning of AISI 316L was implemented in dry cutting. The cutting tools used were an uncoated tungsten carbide-cobalt insert (WC-Co) and a multi coated nano-textured TiCN, nano-textured Al_2O_3 thin layer, and a TiN outer layer insert. The cutting forces, total power consumption, surface roughness, and tool life were measured/obtained and analyzed. The total power consumption of the turning process was obtained from direct measurements as well as using a combination of theoretical formulas and experimental cutting force data. The machining experiments and their responses were designed and evaluated using the three-level full factorial design and the analysis of variance (ANOVA). It was found that the cutting speed and feed significantly affect the various machining responses observed. The cutting force and total power consumption increased with increasing cutting speed, but the surface roughness and tool life decreased. With increasing feed, surface roughness and tool life decreased but the cutting force and total power consumption increased. The empirical mathematical models of the machining responses as functions of cutting speed and feed developed were statistically valid. Confirmation runs helped to prove the validity of the models within the limits of the factors investigated.

ABSTRAK

Keluli tahan karat austenit AISI 316L digunakan secara meluas sebagai bahan implan dan sering digunakan untuk peranti sementara dalam pembedahan ortopedik kerana kos yang rendah, sifat mekanikal yang memadai, dan biokeserasian yang boleh diterima. AISI 316L adalah versi karbon terendah-sangat bagi keluli jenis 316 (keluli austenit kromium nikel tahan karat yang mengandungi molibdenum) yang mengurangkan pemendakan karbida yang merbahaya pada suhu tinggi. Proses pemesinan digunakan dalam pembuatan implan dan peranti perubatan yang diperbuat daripada keluli tahan karat dan oleh itu adalah penting untuk menilai kebolehmesinan AISI 316L. Dalam kajian ini, keluli tahan karat austenit AISI 316L dilarik menggunakan dua mata alat sisipan komersial pada pelbagai kelajuan pemotongan (90, 150, dan 210 m/min) dan uluran (0.10, 0.16, dan 0.22 mm/putaran) dan pada kedalaman potongan tetap 0.4 mm. Larikan AISI 316L dijalankan dalam keadaan pemotongan kering. Mata alat sisipan yang digunakan adalah karbida tungsten-kobalt (*tungsten carbide-cobalt*, WC-Co) tak bersalut dan mata sisipan yang disalut berlapis dengan lapisan nano-bertekstur TiCN, lapisan nipis nano-bertekstur Al_2O_3 dan lapisan luar TiN. Daya pemotongan, jumlah penggunaan kuasa, kualiti permukaan, dan hayat mata alat diukur/diambil dan dianalisa. Jumlah penggunaan kuasa bagi proses larikan diperoleh secara pengukuran langsung dan juga gabungan formula teori dan data ujikaji daya pemotongan. Ujikaji pemesinan dan responnya telah direkabentuk dan dinilai menggunakan reka bentuk faktorial tahap tiga dan analisa varians (*analysis of variance*, ANOVA). Kelajuan pemotongan dan suapan didapati memberi kesan kepada pelbagai respon pemesinan yang diperhatikan. Daya pemotongan dan jumlah penggunaan kuasa meningkat dengan peningkatan kelajuan pemotongan, tetapi kekasaran permukaan dan hayat mata alat menurun. Dengan peningkatan uluran, kualiti permukaan dan hayat mata alat berkurangan tetapi daya pemotongan dan jumlah penggunaan kuasa meningkat. Model matematik empirikal bagi respon pemesinan sebagai fungsi kelajuan pemotongan dan uluran yang dibangunkan adalah sah secara statistik. Ujian pengesahan telah membantu dalam membuktikan kesahihan model dalam had bagi faktor-faktor yang dikaji.

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a_p	-	Depth of cut
b	-	Shank width
C	-	Constant
C_e	-	End cutting edge angle
C_s	-	Side cutting edge angle
E	-	Energy required for machining process
ε	–	Experimental error
f	-	Feed rate
F_C	-	Main cutting force
F_X	-	Radial force
F_Y	-	Feed force
F_Z	-	Cutting force
h	-	Shank height
I	-	Current
l	-	Tool length
k	-	Specific energy requirement
KI	-	Crater index
KT	-	Depth of the crater
n	-	Exponent varies
P	-	Power consumed by machining process
P_C	-	Power consumption
P_0	-	Idle power
r	-	Nose radius
Ra	-	Surface roughness
Rt	-	Surface profile
T	-	Tool life
V	-	Voltage

VB_B	-	Average of flank wear width in zone B
VB_{Bmax}	-	Maximum of flank wear width in zone B
VB_N	-	Maximum width of notch wear
Vc	-	Cutting speed
$\dot{v}$	-	Material removal rate (MRR)
x_1	-	Coded form for the cutting speed
x_2	-	Coded form for the feed rate
α_b	-	Back rake angle
α_s	-	Side rake angle
θ_e	-	End relief angle
θ_s	-	Side relief angle

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CHAPTER 1

INTRODUCTION

The first chapter begins with the background of the problem, which covers the problem statement. Following the problem statement are the objectives, scope and significance of the study, and the organization of the thesis.

1.1 Background

Machining processes are complex and dependant on many factors such as the process under consideration and its operating conditions, the workpiece material, and the cutting tool material. A particular combination of these factors will have an effect on machinability. In the case of the turning process, attempts have been made to measure or quantify machinability and it was done mostly in terms of:

1. Tool life which substantially influences productivity and the economics in machining. Investigations on the tool life as the response when cutting tool and cutting parameters are varied have been studied in several investigations, such as by Kurniawan *et al.* (2010), Rao *et al.* (2014), and Hu and Huang (2014).
2. Magnitude of cutting forces which affects dimensional accuracy. Cutting forces have been measured in several studies, such as by Kamely and Noordin (2011), Kadirgama *et al.* (2010), and Xie *et al.* (2013).
3. Surface finish which plays an important role on performance and service life of the product. Surface roughness at various machining conditions have been

investigated by several researchers, such as Devillez *et al.* (2011), Asiltürk and Akkuş (2011), Krishna *et al.* (2010), and Hwang and Lee (2010).

Nowadays sustainable development has been emphasized. In order to attain sustainable development, industries have resorted to sustainable manufacturing where the three pillars, namely; economic, social, and environmental were considered (Pusavec *et al.*, 2010; Westkämper *et al.*, 2000). Application of sustainability practices have been carried out in the various engineering fields, including manufacturing and design. It is known that industries gained financial and environmental advantages, produce products of best quality, became more competitive, have a larger market share and achieved increased profitability when these industries applied sustainable practices (Nambiar, 2010; Rusinko, 2007).

In manufacturing, sustainable practices include conserving energy and natural resources, implementing economically sound processes, and keeping negative environmental impacts to the minimum level, and simultaneously enhancing the safety of employee, community, and the products. Such practices can also be applied to machining processes which is part of the manufacturing system. Machining as an industry, is acknowledged as a production system, which is associated with the creation of economic wealth as well as the impact on the natural environment (Sarkis *et al.*, 2010; Warren *et al.*, 2001). Specifically for the turning process, sustainable machining can be implemented by taking into account the cutting conditions used during turning; such as the cutting parameters and cutting fluids, the cutting tool performance, the quality of machined surface, and the power consumed for cutting.

Use of cutting fluids is a common practice in machining, for increasing overall machinability, by reducing friction or temperature at the cutting region. However, their use has been recommended to be minimized whenever possible. Dry machining, without the use of any cutting fluid, has been investigated as a means towards sustainable manufacturing. Previous research was on dry turning was performed by Davoodi *et al.* (2012), Devillez *et al.* (2011), Kadirgama *et al.* (2010), Noordin *et al.* (2007), to name a few, with success to some extent. The use of proper cutting tools at suitable cutting parameters is determinant for optimal tool life, which in turn influences the sustainability of the turning process. The quality of machined surface, or sometime termed as surface integrity, reflects the performance of the machining process. This includes the surface roughness of the machined surface. The power consumption during the cutting process needs serious attention since it is related to various aspects of sustainable manufacturing. Some works have been done on some machining processes, such as Aggarwal *et al.* (2008), Bhattacharya *et al.* (2009), Hanafi *et al.* (2012), and Bhushan (2013), but works involving the turning process are still lacking. Combination of the first three considerations with power consumption in turning is a good way forward towards sustainable machining.

1.2 Problem Statement

The machining industry is an important and strategic industry for the manufacturing sector (Wang *et al.*, 2013). Based on the above, investigations have been carried out on machining processes by varying the cutting conditions and measuring the various machinability responses. Additionally, investigations involving newly developed cutting tools as well as newly developed workpiece materials were also undertaken. As mentioned previously; tool life, cutting forces and surface roughness are the responses normally investigated in machinability studies. The power consumption during machining is often neglected, and this holds true in the case of turning process. There was very limited research performed in investigating the power consumption machinability response. In line with making the turning process sustainable, there is a need to conduct a study on the turning process machinability, which also considers power consumption.

Stainless steel AISI 316L is the workpiece material of interest. Being highly corrosion resistant, this type of stainless steel is often used in medical devices, especially those in direct contact with the human body. Machining process is widely used in the manufacture of medical devices. However machinability data for this material is very limited. Therefore there is a need to evaluate the machinability during turning of stainless steel AISI 316L towards sustainable machining. The availability of machinability data obtained from the implementation of sustainable machining of turning process will benefit the manufacturer of these high value added products as guidelines to calculate and measure the total power consumption is available in addition to information on common machinability aspects of cutting forces, surface roughness, and tool life.

1.3 Objectives

The objectives of the research are as follows:

1. To examine the influence of cutting conditions on various machinability parameters during the turning of stainless steel AISI 316L using uncoated and coated carbide tools.
2. To develop the mathematical models for the various machinability parameters thus enabling the determination of the optimized as well as the feasible region of cutting conditions for a given set of machinability parameters' requirement.

1.4 Scope of Study

Considering the wide area of possible methods to achieve the objectives, some boundaries must be set and this research focuses within the following scope:

1. The cutting parameters were varied at 90, 150, and 210 m/min for cutting speed and 0.10, 0.16, and 0.22 mm/rev for feed, while the depth of cut was set constant at 0.4 mm. The turning process was performed dry (without cutting fluid).
2. Austenitic stainless steel AISI 316L was the workpiece material turned.
3. MC7025 coated carbide tool and UTi20T uncoated tool was the cutting tool materials used.
4. The machinability parameters investigated were the cutting forces, the total power consumption, the surface roughness and the tool life.
5. ALPHA 1350S 2-Axis CNC lathe was used to perform the cutting tests.
6. A three-component dynamometer, multi channel amplifier and the data acquisition system were utilized to obtain the cutting force data.

7. Mitutoyo Surftest SJ-301 was used to measure the surface roughness of the turned specimen.
8. Carl Zeiss Stemi 2000-C optical microscope was used to capture the wear of the cutting tool.
9. Portable power monitor ZN-CTX21 and its components were used to measure the power consumed on the main cable, spindle cable, and carriage cable which were installed in the box panel of the CNC lathe machine.
10. Wave Inspire ES software was used to display the total power consumed during turning.
11. The 3^2 or 3-level, 2-factor, full factorial design with 2 center points was used to develop the experimental plan.

1.5 Significance of Study

It was expected outcomes of this study would provide the followings:

1. By incorporating power consumption consideration together with the other machinability data, a reduction in energy consumption is expected thus making the machining process more sustainable.
2. Enhance our knowledge thereby providing a better understanding of the characteristics and application of the different cutting tools with the different cutting parameters when turning AISI 316L austenitic stainless steel.
3. The mathematical models developed will facilitate the optimization process.

1.6 Organization of Thesis

This thesis consists of six chapters, which begin with Chapter 1 as an introduction that contains the background, problem statement, objectives, scope and significance of study, and finally organization of thesis.

Chapter 2 provides the literature review for some topics, such as the definition of sustainability, sustainable production, power consumption, metal cutting and turning process, surface integrity, cutting insert, tool life and tool failure, and austenitic stainless steel. Chapter 3 describes the equipment and methodologies that were used and adopted.

The experimental results were presented in Chapter 4 and this includes the machining response data, such as cutting forces, total power consumption, surface roughness, and tool life. It also presents the data analysis and the development of the various mathematical models using the Design of Experiments (DOE) technique for predicting and optimizing the machinability parameters. Lastly, Chapter 5 provides the conclusion and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

The second chapter begins with a brief description on machinability and sustainability including sustainable manufacturing. This is followed by the theory of metal cutting, surface integrity, cutting inserts, tool life, and workpiece material.

2.1 Machinability in Turning

Machinability is the ability of a material to be machined. Machinability is a term indicating how the work material responds to the cutting process (Knight and Boothroyd, 2005). In the most general case, good machinability means that material is cut with good surface finish, long tool life, low force and power requirements, and low cost.

Some researchers have performed investigations on various aspects related to the turning process. Noordin *et al.* (2001) evaluated the performance, viz. cutting force and surface roughness, of three cemented carbides at a constant depth of cut and at various cutting speeds and feed rates when dry turning of AISI 1010 steel. Özel *et al.* (2005) studied the effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on machinability responses (i.e. surface roughness and resultant forces) in the finish hard turning of AISI H13 steel. Saglam *et al.* (2007) investigated the effects of rake angle and entering angle in tool geometry and cutting speed on cutting force components and the temperature generated on the tool tip in turning of AISI 1040 steel bars. Lalwani *et al.* (2008) observed the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces (feed force, thrust force and cutting force) and surface roughness in finish hard turning of MDN250 steel using coated ceramic tool. Philip Selvaraj *et al.* (2014) used the Taguchi method and studied the effects of cutting speed and feed rate on surface roughness, cutting force and tool wear when dry turning of two different grades of nitrogen alloyed duplex stainless steel. Davim *et al.* (2008) developed surface roughness prediction models using artificial neural network (ANN) to investigate the effects of cutting conditions (i.e. cutting speed feed, and depth of cut) during turning of free machining steel, 9SMnPb28k (DIN). Chavoshi and Tajdari (2010) studied the influence of hardness (H) and spindle speed (N) on surface roughness (Ra) in hard turning operation of AISI 4140 using CBN cutting tool. Zhou *et al.* (2011) presented their investigation of process factors (i.e. cutting speeds, feeds, and cutting depths) on surface roughness when turning of stainless steel. Thakkar and Patel (2014) used the Design of Experiment (DOE) technique to observe the influence of cutting parameters such as speed, feed, and depth of cut on surface roughness and material removal rate when turning stainless steel Grade 410 (UNS S41000).

Sharman *et al.* (2004) investigated other machinability responses such as the effects of varying cutting tool material, geometry, and operating parameters on tool life and surface integrity when turning Inconel 718. Noordin *et al.* (2012) developed the empirical model to measure the performance TiAlN-coated carbide by quantifying the influence of cutting conditions on tool life and surface roughness during hard turning of mild stainless steel (47-48 HRC). Aggarwal *et al.* (2008) observed the effects of cutting speed, feed rate, depth of cut, nose radius and cutting environment on power consumption when turning of AISI P-20 tool steel, and power consumption would be optimized by using response surface methodology (RSM). Bhushan (2013) investigated the effects of cutting speed, feed rate, depth of cut and nose radius on power consumption and tool life during turning of 7075 Al alloy 15 wt% SiC composite.

2.2 Sustainability

Sustainability is becoming an increasingly important issue to manufacturing companies worldwide. It has been regarded as a critical and timely topic; a major concern internationally over the last decade; a major competitive factor for many manufacturing companies (Seidel *et al.*, 2006); and an important concept to survive in a competitive environment (Bevilacqua *et al.*, 2007). Companies that adopt sustainability practices are able to achieve better product quality, higher market share, as well as increased profit (Nambiar, 2010). Sustainability has become an important issue in the manufacturing sector. The application of sustainability has been widely applied in various fields, such as design, manufacturing and engineering.

The Brundtland (1987) report by the World Commission on Environment and Development is the most commonly referred document for the definition of sustainability where it is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability has also been defined as the level of human consumption and activity which can continue into the foreseeable future, so that the systems which provide goods and services to humans persist indefinitely.

Most researchers have expressed sustainability based on the triple bottom line of planet, people, and profit (Rachuri *et al.*, 2009). Sustainability must address to the integration of all three indicators of environmental, social, and economic known as the three pillars of sustainability. The impact of industry can be determined in the triple bottom line, covering the three aspects of sustainability, which are environmental performance, social responsibility, and economic contribution (Pusavec *et al.*, 2010). It is desirable to strike a synergy between the sustainability pillars as shown in Figure 2.1. With a forecast on environmental sustainability in manufacturing, Alting (1995) presented a view on the meaning of sustainability as to design the human life cycle, namely production, supply, use and waste such that their affect on the environment is reduced (acceptable). In order to achieve sustainable development, industries should produce sustainable products (Westkämper *et al.*, 2000). One of methods to achieve environmentally sustainable products is by reducing the energy consumption during the manufacture and product use.

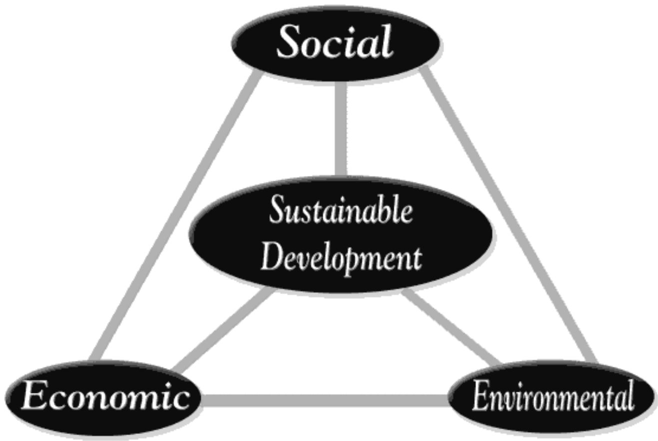

Figure 2.1 Sustainability pillars (Pusavec *et al.*, 2010)

2.3 Sustainable Manufacturing

Sustainable manufacturing can be considered to be related to the transformation of input materials and energy into finished goods for economic trade. The US Department of Commerce (2009) defined sustainable manufacturing as the creation of manufactured products that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound. The general principle of sustainable manufacturing is to reduce the intensity of materials use, energy consumption, emissions, and the creation of unwanted by-products while maintaining, or improving, the value of products to society and to organizations (OECD, 2009).

Sustainable manufacturing is currently a very important issue for governments and industries worldwide (Seliger *et al.,* 2008). Achieving sustainability in manufacturing activities have been recognized as a critical need due to diminishing non-renewable resources, stricter regulations related to environment and occupational safety, and growing consumer preference for environmentally-friendly products (Jayal *et al*., 2010). Sustainable manufacturing must respond to (Jovane *et al.*, 2008):