Faculty of Manufacturing Engineering

THE EFFECT OF CRYOGENIC CARBON DIOXIDE COOLING ON SURFACE INTEGRITY OF TITANIUM ALLOY IN TURNING

Muhammad Shahmi bin Razak

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MUHAMMAD SHAHMI BIN RAZAK

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled "The Effect of Cryogenic Carbon Dioxide Cooling on Surface Integrity of Titanium Alloy in Turning" 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.

Signature : ....

Name : Muhammad Shahmi bin Razak

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature : ……………………………………………..

Supervisor Name : Associate Professor Dr. Mohd Amri bin Sulaiman

Date : ……………………..………………………

DEDICATION

To my beloved mother, my family, my supervisor and my supportive friends that accompanying me along the difficult pathway in my university life.

ABSTRACT

High-speed turning is one of the most important methods in advanced manufacturing technology due to its speed which is three times the conventional speed value. The material that generally used in high speed turning is titanium alloy. The superior attractive properties of titanium alloy (Ti-6Al-4V) such as good mechanical and chemical properties, excellent corrosion resistance and high strength-to-weight ratio make it favorable in wide range of applications such as automotive, aerospace, medical and chemical industries. However, machining of this titanium alloy are known to cause the damaged of the surface due to their poor machinability as well as high cutting temperature using conventional cutting fluids as coolant. In this study, cryogenic carbon dioxide CO_2 cooling has been used during turning Ti-6Al-4V ELI (extra-low interstitial). The objective of this research is to analyse the effect of cutting parameters towards surface integrity such as surface roughness, surface hardness, and microstructure of the material. This research focuses on developing a mathematical model for surface roughness of machined surface. Then, the generated mathematical model was used to optimize the cutting parameters in producing the best surface roughness value. The Sandvik uncoated carbide insert, CNGG 120408-SGF-H13A was selected as a cutting tool in high speed turning of titanium alloy Ti-6Al-4V ELI with the hardness of 32 HRC by using 3-axis Computer Numerical Control (CNC) lathe Haas ST-20 lathe machine. The Response Surface Methodology (RSM) design of experiment using Box- Behnken was used to accommodate the turning experiment factors and levels towards surface roughness. Turning parameters studied were cutting speed (120, 170, 220 m/min), feed rate (0.1, 0.15, 0.2 mm/rev) and depth of cut (0.4, 0.5, 0.6 mm). There are 17 runs of machining parameters generated by Design Expert software using RSM Box-Behnken. The surface roughness values were measured for each 20 mm on the workpiece until flank wear (Vb) reaches the tool life criterion followed by JIS B4011-1971 standard. Based on the conducted investigation, it was found that the lowest surface roughness value 0.49 µm was achieved at the run 6; 220 m/min of cutting speed, 0.1 mm/rev of feed rate and 0.5 mm of depth of cut. The Analysis of Variance (ANOVA) shows that feed rate was the dominant factor that affects machining performance. The optimum parameter was achieved at 220 mm/min of cutting speed, 0.1 mm/rev of feed rate and 0.4 mm of depth of cut. The residual errors for surface roughness value of optimum parameters fell within 1.8% and 3.8% which are less than 10%. The microstructures of the surface and sub-surface have been changed in terms of volume fraction of β phase, compared to the as-received material. The surface hardness occurs due to hardening work caused by the low temperature at the cutting zone that comes from cryogenic cooling.

KESAN PENYEJUKAN KRIOGENIK KARBON DIOKSIDA PADA INTEGRITI PERMUKAAN ALOI TITANIUM DALAM PELARIKAN

ABSTRAK

Pelarikan berkelajuan tinggi adalah salah satu kaedah yang paling penting dalam teknologi pembuatan canggih kerana kelajuannya yang tiga kali nilai kelajuan konvensional. Bahan yang biasanya digunakan dalam pelarikan kelajuan tinggi ialah aloi titanium. Sifat-sifat yang sangat menarik pada aloi titanium (Ti-6Al-4V) seperti sifat mekanikal dan kimia yang baik, rintangan hakisan yang sangat baik serta nisbah kekuatan kepada berat yang tinggi dapat menggalakkan penggunaannya dalam pelbagai kegunaan seperti automotif, aeroangkasa, perubatan dan industri kimia. Walau bagaimanapun, pemesinan aloi titanium ini diketahui boleh menyebabkan kerosakan permukaan kerana oleh kebolehkerjaan yang kurang baik serta suhu pemotongan yang tinggi menggunakan cecair pemotongan konvensional sebagai penyejuk. Dalam kajian ini, penyejukan CO_2 karbon dioksida kriogenik telah digunakan semasa melarik Ti-6Al-4V ELI (extra-low interstitial). Objektif kajian ini adalah untuk menganalisis kesan parameter pemotongan ke atas integriti permukaan termasuk kekasaran permukaan, kekerasan permukaan, dan struktur mikro bahan. Kajian ini menumpukan kepada membangunkan model matematik untuk kekasaran permukaan permesinan. Kemudian, model matematik yang dihasilkan digunakan untuk mengoptimumkan parameter pemotongan dalam menghasilkan nilai kekasaran permukaan yang terbaik. Karbida tanpa salut Sandvik, CNGG 120408-SGF-H13A dipilih sebagai alat pemotong dalam pemesinan larik berkelajuan tinggi aloi titanium Ti-6Al-4V ELI dengan kekerasan sebanyak 32 HRC dengan menggunakan mesin larik CNC 3 paksi Haas ST-20. Rekabentuk Ujian Permukaan (RSM) menggunakan Box-Behnken digunakan untuk menampung faktor percubaan dan tahap percubaan terhadap kekasaran permukaan. Parameter proses larik yang digunakan ialah kelajuan pemotongan (120, 170, 220 m/min), kadar suapan (0.1, 0.15, 0.2 mm/pusingan) dan kedalaman pemotongan (0.4, 0.5, 0.6 mm). Terdapat 17 ujikaji parameter pemesinan yang dihasilkan oleh perisian Design Expert menggunakan RSM Box-Behnken. Berdasarkan kajian yang dijalankan, didapati bahawa nilai kekasaran permukaan terendah yang dicapai pada larian 6; 220 m / min kelajuan pemotongan, 0.1 mm/pusingan kadar suapan dan 0.5 mm kedalaman pemotongan iaitu 0.49 µm. Analisis Varians (ANOVA) menunjukkan bahawa kadar suapan adalah faktor dominan yang mempengaruhi prestasi pemesinan. Parameter optimum dicapai pada kelajuan pemotongan 220 mm/min, 0.1 mm/pusingan kadar suapan dan kedalaman 0.4 mm. Kesalahan sisa bagi nilai kekasaran permukaan parameter optimum jatuh dalam 1.8% dan 3.8% dimana kurang daripada 10%. Struktur mikro permukaan dan sub-permukaan telah berubah dari segi pecahan isipadu fasa β bertambah, berbanding dengan bahan yang diterima. Kekerasan permukaan berlaku disebabkan kerja keras yang disebabkan oleh suhu rendah di zon pemotongan yang dihasilkan daripada penyejukan kriogenik.

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LIST OF ABBREVIATIONS

α	-	Alpha
AISI	-	American Iron and Steel Institute
Al	-	Aluminum
ANOVA	-	Analysis of variance
β	-	Beta
BCC	-	Body centered cube
C	-	Carbide
C	-	Carbon
CAD	-	Computer-aided design
CAM	-	Computer-aided manufacturing
CBN	-	Cubic boron nitride
CNC	-	Computer numerical control
Co	-	Cobalt
Cp	-	Specific heat
CO_2	-	Carbon dioxide
CVD	-	Chemical vapour deposition
D	-	Diameter of material
Df	-	Degree of freedom
DoC	-	Depth of cut
DOE	-	Design of experiment

EDX	-	Energy Dispersive X-Ray
ELI	-	Extra low interstitial
F	-	Feed rate
Fe	-	Iron
H	-	Hydrogen
HCP	-	Hexagonal close pack
HF	-	Hydrofluoric acid
HNO_3	-	Nitric acid
HSM	-	High speed machining
HSS	-	High speed steel
ISO	-	International standard organization
LN_2	-	Liquid nitrogen
MQL	-	Minimum quantity lubrication
MWFs	-	Metalworking fluids
MQL	-	Minimum quantity lubrication
O	-	Oxygen
PCBN	-	Polycrystalline cubic boron nitride
PCD	-	Polycrystalline diamond
PVD	-	Physical vapour deposition
Ra	-	Surface roughness
RSM	-	Response surface methodology
S	-	Sulfur
SEM	-	Scanning Electron Microscopy
Si	-	Silicon
Ti	-	Titanium

TSI	-	Titanium Security International
v	-	Cutting speed
V	-	Vanadium
W	-	Tungsten
Y	-	Yttrium

LIST OF SYMBOLS

m/min	-	Meter per minute
%	-	Percent
°C	-	Degree celsius
mm	-	Millimeter
kgF	-	kilogram-force
µm	-	Micrometer
Nm	-	Nanometer
K	-	Kelvin
kg/m^3	-	Kilogram per cubic meter
g/cm^3	-	Gram per cubic meter
mm/rev	-	Millimeter per revolution
sfpm	-	Surface feet per minute
inch/min	-	Inches per minute
m/min	-	Meters per minute
N	-	Newton
kW	-	Kilowatt

kJ/kg	-	kilojoules per kilogram
kJ/kg. ^{0}C	-	kilojoule per kilogram per degree Celsius
kJ/m³	-	kilojoule per cubic meter
rpm	-	Revolution per minute
Nm	-	Newton meter
L/min	-	Liter per minute
HRC	-	Rockwell C hardness
HV	-	Vickers hardness
MPa	-	Megapascal
kPa	-	Kilopascal
GPa	-	Gigapascal
Psi	-	Pound per square inch

LIST OF PUBLICATIONS

Journal

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CHAPTER 1

INTRODUCTION

1.1 Research background

Over the last decade, the interest for titanium alloys, especially in the industry of aerospace has essentially extended due to their great strength to weight ratio, decreasing the formation of corrosion and capability in maintaining the strength at high temperatures (Arrazola et al., 2009; Sun et al., 2010; Pawar and Pawade, 2012; Pratap et al., 2015). They are also been used in shipbuilding industries, energy and power fields, and biomedical engineering due to their attractive properties (Hao et al., 2016; Karkalos et al., 2016). On the other hand, titanium and its alloys are difficult to change their shape as they represent a more challenge to machining processes because of high stresses and temperatures produced during machining (Ezugwu et al., 2005; Elshwain et al., 2013; Sulaiman et al., 2017). There are many types of titanium alloys. One of them is the Ti-6Al-4V extra low interstitials (ELI) alloy that has a greater purity grade than the Ti-6Al-4V alloy. This alloy compromises in high strength and its depth hardening ability which contains low oxygen, carbon and iron (Ibrahim et al., 2009; Sulaiman et al., 2014; Razak et al., 2017).

Some cutting processes, for example, turning and milling are utilize to machine this kind of titanium alloy. The machining process that generate a cylindrical shape or a complicated surface profile by removing the materials from the workpiece using a single-edge cutting tool is known as the turning process (Grzina et al., 2015). With a specific end goal to increase the productivity, whereas at the same time improving product quality and decreasing manufacturing costs, high speed machining is used in the machining operation.

High speed machining (HSM) is one of modern technologies and can be known as a metal removing process generally used in industry for manufacturing numerous machine parts (Da Silva et al., 2013; Krishnaraj et al., 2014; Rahaman et al., 2015). An excellent surface finish of the product can be achieved by using this machining process. It is also well appreciated because of its high removal rates, reduction in production dead-times and low cutting forces while at the same time it decreases costs and the machining time compared with conventional cutting (Velasquez et al., 2010; Sulaiman et al., 2014; Wang et al., 2016). The high speed machining of titanium alloys produces a high cutting temperature in the cutting zone, which diminishes tool life quickly. Besides, the machining also produces a bad surface finish of the product which is caused by the rapid tool failure and chipping at the cutting edge. It causes higher surface roughness values as well as higher microhardness values and severe microstructure alterations (Haron and Jawaid, 2005; Che Haron et al., 2011).

Titanium alloys are generally used for a component that requires the greatest reliability, and therefore the surface integrity must be maintained. However, the surfaces of titanium alloys are easily damaged during machining operations because of their poor machinability (Sun et al., 2015; Gupta and Laubscher, 2016). The damage usually occurs in the form of microcracks, phase transformations, plastic deformations, and residual stress effects. As far as the surface metallurgy of the machined component is concerned, the heat generated during cutting is the main source of damage (Che Haron et al., 2011; Ulutan and Ozel, 2011; Shokrani et al., 2016). The surface finish of the product is an important thing in manufacturing engineering. It is a typical thing that can impact the performance of mechanical parts and the production costs (Suhail et al., 2010; Costabile et al., 2017).

In order to improve the surface quality of the product in high speed machining of titanium alloys, the effectiveness of the cooling/lubrication provided must be considered