UNIVERSITI PUTRA MALAYSIA

EFFECT OF CUTTING PARAMETERS ON SURFACE INTEGRITY IN GROOVE MILLING OF HASTELLOY-C276 USING COATED CARBIDE END MILLS UNDER DRY AND WET CONDITIONS

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By

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May 2015

Chairman: B.T. Hang Tuah Bin Baharudin, P.Eng, PhD
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The development of novel materials (superalloys) is an evolving process towards improving the serviceability of their components in hostile industrial environments. Hastelloy-C276 is one variation of nickel-based superalloys which is a ductile corrosion-resistant superalloy that is widely used in chemical and nuclear industries. The superior properties of superalloys such as; the high-temperature strength, strain-hardening capacity, poor thermal conductivity and high chemical affinity hinder their machinability and therefore they are known as difficult-to-machine materials. Little studies were done on the machinability of Hastelloy-C276 particularly in term of surface integrity, therefore, this thesis aims to investigate surface integrity and tool wear in groove milling of Hastelloy-C276 using coated carbide end mills coated using different cutting parameters and conditions in the speed range of 24 m/min to 120 m/min. Two aspects of surface integrity were concerned; the arithmetic roughness and the micro-defects. Focus-variation microscope and scanning electron microscope (SEM) with the aid of energy dispersive x-ray spectroscopy (EDX) were used to measure the arithmetic roughness and the micro-defects of the machined surfaces respectively. Cutting speed of 50 m/min and below combined with the minimum feed and non-shallow depth of cut produced superior surface finish with average roughness below 50 nm. The dominant surface defects at low cutting speed were side flow, micro-chips re-deposition and long grooves. At cutting speed of 70 m/min and higher, cracks appeared on ploughed layers on the surface and these cracks are created by the brittle fracture due to the high strain-rate. Other surface defects at high cutting speed were smears, debris and side flow. The increase in surface defects at high cutting speed resulted in increase in surface roughness beyond 100 nm. Surface cavitation appeared at most of the runs and was probably caused by the breakage of the nucleated carbide phases. Tool-workpiece friction in dry machining resulted in large surface craters and large ploughing in addition to severe plastic flow, overlaps and voids created by the thermally induced deformation. Built-up edges formation on the tool faces can be avoided by increasing the cutting speed to 70m/min in wet machining for better chip disposal and only to 50m/min in dry

machining since the high oxidation reduces chips adherence tendency. The high oxidation promoted in dry machining resulted in less chips adhesion on groove's edges due to the poor adhesive capacity of the oxide compounds.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai memenuhi keperluan untuk ijazah Sarjana Sains

KESAN PARAMETER PEMOTONGAN KE ATAS INTEGRITI PERMUKAAN DALAM PEMESINAN ALUR HASTELLOY-C276 MENGGUNAKAN KARBIDA YANG BERSALUT MELALUI PEMESINAN KERING DAN BERPENYEJUK

Oleh

MUATH DHEAA ABDULRADHA AL-FALAHI

Mei 2015

Pengerusi: B.T. Hang Tuah Bin Baharudin, P.Eng, PhD
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Kajian dalam pemprosesan bahan aloi super yang semakin berkembang amatlah penting untuk penambahbaikan terhadap kegunaan super-aloi tersebut sebagai komponen dalam perindustrian. Hastelloy-C276 adalah salah satu aloi super yang berasaskan Nikel, berkemampuan untuk menahan hakisan terhadap karat dan digunakan secara meluas dalam industri kimia dan nuklear. Kehebatan sifat aloi super ini mampu bertahan kekuatannya pada suhu tinggi, kebolehannya dalam pengerasan terikan, dan konduksi terma rendah adalah penyebab aloi Nikel dikenali sebagai bahan sukar untuk diproses. Didapati tidak banyak maklumat kajian telah dibuat berkenaan integriti permukaan aloi Hastelloy-C276, oleh sebab itu kajian ini dilakukan bertujuan untuk menyiasat pemprosesan mesin menggunakan alat pemotong hujung rata di mana parameter pemotongan pada kadar yang berbeza dalam pelbagai kelajuan pemotongan antara 24 m/min dan 120 m/min. Mikroskop pelbagai fokus, mikroskop imbasan electron (SEM) dan mikroskop optik telah digunakan untuk mengukur kekasaran permukaan, kecacatan permukaan menganalisis dan menganalisis kehausan alat pemotong, masing-masing. Kekasaran permukaan di bawah 50 nm boleh didapati dengan kelajuan pemotongan 50 m/min dan bawah dengan kadar suapan yang minimum dan pemotongan axial yang tidak cetek. Kekasaran permukaan telah meningkat atas 100 nm dengan kelajuan pemotongan 70 m/min dan atas kerana kecacatan permukaan menjadi lebih teruk. Profil permukaan yang tidak sekata telah dihasilkan dalam pemposesan mesin kering kerana suhu tinggi semasa pemesinan yang meningkatkan pengoksidaan, ubah bentuk plastik yang teruk dan geseran antara alat pemotong dan aloi. Serpihan di pinggir alat pemotong adalah selalu kelakuan kehausan yang utama; lekatan haus dan kejadian *built-up edge* berlaku pada kelajuan pemotongan yang rendah. Dalam pemprosesan mesin kering, serpihan adalah lebih teruk terjadi kerana suhu tinggi dan rekatan adalah kurang kerana pengoksidaan tinggi. Untuk mendapat permukaan kasar yang rendah tanpa permukaan mikro-kecacatan yang teruk, hasil daripada kajian ini, berdasarkan kelajuan pemotongan

di bawah 50 m/min dengan kadar suapan yang minimum serta kedalaman pemotongan yang tidak cetek mesti digunakan.

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- Inttec Machine Sdn. Bhd.

I certify that a Thesis Examination Committee has met on 27th May 2015 to conduct the final examination of Muath Al-Falahi on his thesis entitled "**Effects of Cutting Parameters on Surface Integrity in Groove Milling of Hastelloy-C276 Using Coated Carbide End Mills Under Dry and Wet Conditions"** in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

ap	Axial depth of cut.
BUE	Built-up Edge.
CNC	Computer Numerical Control.
DOE	Design of Experiment.
EDM	Electrical Discharge Machine/Machining.
EDX	Energy Dispersive X-ray Spectroscopy.
f_z	Feed per tooth.
FESEM	Field Emission Scanning Electron Microscopy.
SEM	Scanning electron microscopes.
v_c	Surface cutting speed.
VP-SEM	Variable Pressure Scanning Electron Microscopy

CHAPTER 1

INTRODUCTION

Metallic alloys that have high strength, outstanding corrosion- and creep resistance and capable to retain their physical properties at high temperatures above 650°C are known as superalloys. These alloys have been developed mainly for air foils in the hot section of gas turbine engines and then they became widely used in several other applications such as; nuclear reactors, industrial furnaces, rocket components, heat exchangers, petrochemical equipment, petroleum production, automotive turbochargers and biomedical devices (Charre, 1997; Geddes & Leon, 2010). Machining processes such as turning, milling, grinding and broaching are vitally important in superalloys parts manufacturing. Superalloys machining is quite costly due to the very low allowable cutting speeds which are only 5-10% of those allowed for steel alloys. Low cutting speed is required due to the severe tool wear that is caused by the varying thermal and mechanical loads causing poor accuracy and surface deterioration. The properties that make superalloys difficult-to-machine are the high-temperature strength, high dynamic shear strength, hard carbide phases which make them abrasive, high strain hardening capacity and poor thermal conductivity which increases the tool tip temperature (Donachie & Donachie, 2002; Zhang, 2013). Due to the high importance of superalloys' surface condition on the machined part life, this thesis represents a study on the machined surfaces in groove milling of Hastelloy-C276 using carbide end mills with newly developed coating.

1.1. The Background of Hastelloy-C276

Hastelloy is a name for Ni-Cr-Mo-W superalloys which are wrought ductile superalloys that are known by their excellent performance in corrosive mediums and their very good weldability which make them preferred choice in aerospace engines, marine, petroleum, chemical and nuclear industries (Akhter *et al*., 2001; Guo *et al*., 2014). Due to their poor castability, the cast forms of Hastelloy are more susceptible to chemical attack and therefore they are available in wrought forms (Gossett, 1988). The strong corrosion resistance of Hastelloy is counted to high percentage of Chromium which improves the oxidation resistance and Mo and W which improve their corrosion resistance to non-oxidizing acids (Davis, 2000). The strong physical properties are counted for Cr which increase hardenability, Mo which improves strength and toughness and W which enhances the hot hardness (Cardarelli, 2008). Hastelloy-C267 is one variation of these alloys which is known by its versatility to several corrosive mediums such as chloride and seawater and due to their good formability they are produced in a variety of products such as; pipes, flanges, strips bars, etc. (Mehta *et al.* 2014). Hastelloy-C267 is used therefore for heat exchangers, reaction vessels, and piping in chemical industry and for stack liners, ducts, dampers, scrubbers and fans in pollution control industry (Davis, 2000).

1.2. The Machinability of Hastelloy-C267

The superior physical properties of Ni-based superalloys in general and their high temperature strength depress their machinability and therefore they are known as difficult-to-machine material. The following points summarize the dominant factors that make Ni-based superalloys intractable in machining:

- The heat generated by cutting is hardly dissipated into the workpiece due to the poor thermal conductivity of Ni-based superalloys and therefore the heat become concentrated in the cutting zone and become extremely high to extent that it can easily reach beyond 800° C (El-Wardany *et al.* 1996). Normal tools may not be able to withstand this extreme temperature due to oxidation in addition to the high chemical affinity of Ni-based superalloys which cause severe diffusion of their elements into the tool (Donachie & Donachie, 2002). The high cutting temperature also produce tensile residual stresses on the machined surfaces (Pawade *et al.* 2008) in addition to surface damages such as crack and plastic flow (Zhou *et al.* 2012).

- The high strain hardening capacity of Ni-based superalloys increases the stresses on the cutting tool which decrease tool life and thus machining at low feed rate is required which reduces the productivity (Lavella *et al.* 2008; Zhu *et al.* 2013).

- Welding of work material on the tool face and the formation of built-up edge (BUE) which can contribute to groove formation on tool face by peeling of some part of the cutting tool when the BUE is removed by progressive machining (Liao & Shiue, 1996).

- Difficult chip control and the formation of long continuous and serrated hard chips enhance the crater wear (Ezugwu *et al.* 2009).

The integrity of the machined surface is one of the main aspects of the machinability and it is crucially important due to its impact on the service life, performance and reliability of the components especially in aerospace and nuclear industries where the components are operating under high stresses, temperatures and corrosive environments (Field, 1973). Surface integrity includes several features of the surfaces which are mainly the arithmetic roughness, surface damages, surface hardness and residual stresses (Ulutan & Ozel, 2011). The low arithmetic surface roughness can't guarantee high quality of the machined surface as it can be associated with poor quality of other integrity features such as the micro-damages which could hinder some of the material properties such as fatigue strength and creep life (Zhou *et al.* 2012).

Due to the aforementioned difficulties, there is always a need to use special tools in machining Ni-based superalloys. NS Tool Corporation, Ltd has developed MUGEN-coating-premium which is meant to machine intractable superlloys. This study is aimed to investigate the effect of cutting parameters under on the surface arithmetic roughness, topology in milling Hastelloy-C276 using MUGEN-premium coated carbide end mills with and without the application of water-based fluid coolant. Focus variation microscope has been used to obtain the arithmetic surface roughness values and 3D surface topography of the machined surfaces. Scanning electron microscopes (SEM) with the aid of energy dispersive x-ray spectroscopy (EDX) have been used to investigate the surface micro-damages. Other issues such as the primary tool wear and edge cleanness has been also discussed.

1.3. Statement of the Problem

The development of novel materials keeps evolving by altering the percentages of alloying elements and applying different heat treatments to alter the micro-structures for the purpose of improving the alloys' serviceability in a very particular application. Despite some general common properties between Hastelloy-C276 and other difficult-to-machine materials in term of hardness, high temperature-strength, strain-hardening capacity and so on, it is not easy to predict the distinct issues associated with its machinability by relying on data obtained for other intractable materials especially at different machining conditions. Different manufacturing processes such as; turning, indexable milling, grinding and so on, and different workpiece properties such as phase structures and alloying elements are enough to make difference in the output particularly for surface finish and tool wear. Surface finish can be affected by the deformability of the material's micro-phases and tool wear by the diffusivity of the alloying elements and their tendency to adhere on the tool face in addition to the other factors such as work hardening. The majority of the studies in this field were concerned about hard Ni-based aerospace alloys such as; Inconel and Nimonic and there is lack of studies that were concerned about machining ductile corrosion-resistant superalloys (Hastelloy) particularly in groove milling. Little attention has been made also to the micro-surface abuse of the machined surfaces and the possible mechanisms of their formation, despite their impact on component's fatigue and creep life. Understanding the surface damages and their mechanism can help engineers to mitigate surface abuse by adjusting the machining parameters and conditions.

1.4. Objectives

This thesis aims to investigate the effect of cutting parameters (cutting speed, feed rate and depth of cut) and cutting condition (dry and with application of water-based fluid coolant) in full slot milling (grooving) of Hastelloy-C276 on surface integrity. The two aspects covered at surface defects and roughness which are important measures of the product quality. Furthermore, the high adhesive affinity of the workpiece and the high temperature produced during machining result in rapid tool wear by adhesion and oxidation, respectively. This thesis intends to highlight these issues and, therefore, its objectives are:

1- To study the surface roughness and the micro-features of the machined surfaces under different cutting parameters and cooling conditions and subsequently determine the most recommended parameters and conditions for finish milling.
2- To evaluate the dominant tool wear modes at the early stages machining and the effect of parameters on adhesion, oxidation and chipping wear.
3- To determine the mechanism of surface damages formation and the most influential parameters to their formation.

1.5. Research Scope

Surface integrity of the machined surface in machining nickel-based superalloys includes several aspects, in addition to arithmetic roughness and damages, such as; surface hardness, the thickness of the hardened layer, the formation of white layer, the formation of fine grains layer on the top surface, residual stresses and microstructural alteration. This thesis focuses on surface roughness and damages which are two aspects that deals with surface topography without taking into account the deformation beneath the surface. This thesis is also concerned only about oxidation and adhesion wear modes which occur at the early stage machining without taking into account the progressive flank wear and tool life.

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