RELATIONSHIP OF CHIP LOAD AND SPINDLE SPEED ON CUTTING FORCE AND SURFACE INTEGRITY FOR HIGH-SPEED DRY END-MILLING HASTELLOY X MATERIAL

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By

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Chairman : Associate Professor B.T Hang Tuah bin Baharudin, PhD, P Eng
Faculty : Engineering

The effect of the cutting force during high-speed machining (HSM) has been extensively focused on by many researchers and the existing literature mainly discuss the approaches that can be taken to reduce the cutting force when machining nickel-based superalloys, such as by reducing the chip load while increasing the spindle speed. Increasing the spindle speed can increase the cutting speed, which indirectly reduces the cutting force. While, a reduction in the chip load decreases the cutting force needed to remove the unwanted material. On the other hand, a decrease in chip load results in low material removal rate (MRR). Therefore, it is contrary to the principle of HSM, where increasing the spindle speed while reducing the chip load only reduce the cutting force, rather than reducing the cutting force and increasing the MRR. Furthermore, it has been proven that the surface integrity after machining directly affects the reliability and life of the product. Although the ultimate research goal of the cutting force is to improve cost-effectiveness and productivity, it is also crucial to maintain or improve the surface integrity of a product. Therefore, the main aim of this research is to study the influence of increases in spindle speed at constant chip load on the cutting force and surface integrity of high-speed end-milling of Hastelloy X material under dry conditions. The cutting force behaviour was simulated by using AdvantEdge, while dynamometer was used to measure the cutting force under experimental tests. The research then analysed the surface integrity of Hastelloy X. Surface integrity, that included surface roughness, surface hardness and sub-surface residual stress, was observed with the purpose of correlating it with the optimum combination of chip load and spindle speed under experimental conditions, and also the behaviour of cutting force components and resultant force. Results of the experimental tests revealed that the cutting force components and resultant force had quadratic behaviour. In addition, axial force was the dominant factor affecting the resultant force, followed by the normal force and feed force. In terms of surface integrity, the

surface roughness and sub-surface residual stress were in line with the behaviour of the cutting force components and resultant force. However, the behaviour of surface hardness did not necessarily correspond to the behaviour of the cutting force components and resultant force when the spindle speed was increased at a constant chip load. Finally, the ideal combination of chip load and spindle speed in order for the manufacturing industry to obtain the ideal cutting force, MRR and surface integrity during high-speed end-milling of Hastelloy X under dry conditions at 0.2 mm depth of cut was proposed at 0.016 mm/tooth and 21,400 rpm in half-immersion down-milling, 0.019 mm/tooth and 23,920 rpm in half-immersion up-milling, 0.016 mm/tooth and 23,560 rpm in full-immersion down-milling, and 0.016 mm/tooth and 24,640 rpm in full-immersion up-milling.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KEHUBUNGAN BEBAN SERPIHAN DAN KELAJUAN PENGUMPAR TERHADAP DAYA PEMOTONGAN DAN INTEGRITI PERMUKAAN BAGI PENGISARAN HUJUNG KERING BERKELAJUAN TINGGI BAHAN HASTELLOY X

Oleh

NOR AZNAN BIN MOHD NOR

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Kesan Pemesinan berkelajuan tinggi (HSM) telah banyak difokuskan oleh ramai penyelidik dan literatur yang sedia ada secara lazimnya membincangkan pendekatan untuk mengurangkan daya pemotongan semasa pemesinan superaloi berasaskan nikel, seperti dengan mengurangkan beban serpihan beserta meningkatkan kelajuan pengumpar. Meningkatkan kelajuan pengumpar dapat meningkatkan kelajuan pemotongan secara tidak langsung mengurangkan daya pemotongan. Manakala, mengurangkan beban serpihan dapat mengurangkan daya pemotongan yang diperlukan bagi menyingkirkan bahan yang tidak diingini. Sebaliknya, pengurangan dalam beban serpihan menghasilkan kadar penyingkiran bahan (MRR) yang rendah. Oleh itu, ianya bertentangan dengan asas HSM di mana peningkatan kelajuan pengumpar beserta pengurangan beban serpihan hanya mengurangkan daya pemotongan, bukannya mengurangkan daya pemotongan dan meningkatkan MRR. Selain itu, telah dibuktikan bahawa integriti permukaan selepas pemesinan secara langsung akan menjejaskan kebolehharapan dan hayat produk. Meskipun matlamat muktamad bagi penyelidikan daya pemotongan adalah untuk meningkatkan keberkesanan kos dan produktiviti, juga penting untuk mengekalkan atau meningkatkan integriti permukaan produk. Oleh itu, matlamat utama penyelidikan ini adalah untuk mengkaji pengaruh kelajuan pengumpar yang meningkat pada beban serpihan yang dikekalkan terhadap daya pemotongan dan integriti permukaan dalam pengisaran hujung berkelajuan tinggi bahan Hastelloy X di bawah keadaan kering. Sifat daya pemotongan disimulasikan dengan menggunakan AdvantEdge, manakala dinamometer digunakan untuk mengukur daya pemotongan di bawah ujian eksperimen. Penyelidikan diteruskan dengan menganalisis integriti permukaan Hastelloy X. Integriti permukaan, yang termasuk kekasaran permukaan, kekerasan permukaan dan tegasan baki bawah permukaan, diperhatikan dengan tujuan mengaitkannya dengan gabungan optimum beban serpihan dan kelajuan pengumpar di bawah keadaan eksperimen, dan juga sifat komponen daya pemotongan dan sifat daya paduan yang dihasilkan. Hasil ujian eksperimen mendedahkan bahawa komponen daya pemotongan dan daya paduan bersifat kuadratik. Disamping itu, daya paksi ialah faktor dominan yang mempengaruhi daya paduan, diikuti oleh daya normal dan daya suapan. Dari segi integriti permukaan, kekasaran permukaan dan tegasan baki bawah permukaan bersifat selari dengan sifat komponen daya pemotongan dan sifat daya paduan. Manakala, sifat kekerasan permukaan tidak semestinya selari dengan sifat komponen daya pemotongan dan sifat daya paduan apabila kelajuan pengumpar dipertingkatkan pada beban serpihan yang dikekalkan. Akhirnya, gabungan ideal beban serpihan dan kelajuan pengumpar untuk industri pembuatan bagi memperolehi daya pemotongan, MRR dan integriti permukaan yang ideal semasa pengisaran hujung berkelajuan tinggi Hastelloy X di bawah keadaan kering pada kedalaman pemotongan 0.2 mm dicadangkan pada 0.016 mm/gigi dan 21,400 rpm bagi separuh perendaman pengisaran bawah, 0.019 mm/gigi dan 23,920 rpm bagi separuh perendaman pengisaran atas, 0.016 mm/gigi dan 23,560 rpm bagi perendaman penuh pengisaran bawah 0.016 mm/gigi dan 24,640 rpm bagi perendaman penuh pengisaran atas.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

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LIST OF SYMBOLS

Sa	Arithmetical mean height
F_x	Feed force
F_y	Normal force
F_z	Axial force
F_r	Resultant force
N	Spindle speed
V	Cutting speed
D	Cutting tool diameter.
F	Feed rate
f_t	Chip load
n	Number of teeth
Fe	Iron
Co	Cobalt
W	Tungsten
Cr	Chromium
Mo	Molybdenum
r^2	Square of the correlation coefficient
D	Composite desirability
d	Individual desirability
2θ	Angle between incident and diffracted beam
d	d-spacing
ψ	Tilt angles
E	Young’s modulus
v	Poisson’s ratio
m	Slope

LIST OF ABBREVIATIONS

HSM	High speed machining
CM	Conventional machining
MRR	Material removal rate
FCC	Face centred cubic
WEDM	Wire electrical discharge machining
FEM	Finite element method
RMS	Root mean square

CHAPTER 1

INTRODUCTION

1.1 Background of Research

With the development of science and technology, the machining process has gradually become a main component in the manufacturing industry due to its ability to fulfil numerous criteria, such as having a variety of work materials, a variety of parts, shapes and geometric features, dimensional accuracy and surface finish. In fact, approximately more than 70% of the machining process is used in the manufacturing industry (Hidayah et al., 2015). Through this figure, it is clear that machining process is so important for the manufacturing of a part. Thus, it is vital for the manufacturing industry to identify the main factors affecting the efficiency of machining process and then overcome the effects of these factors, especially the cutting forces (Wan et al., 2016). In definition, cutting force is a natural phenomenon consisting of high compressive and frictional contact stresses on the cutting tool and machined material interfaces generated when cutting tools are used to mechanically cut the machined material during the machining process. On the other side, the imperative knowledge of cutting force research is the solution for practical problems associated with material surface quality, geometrical accuracy, tool-work material vibrations and chatter (Grossi et al., 2015). The research area on cutting force has provided a lot of benefits to the above problems and has long been established through development across time.

Since almost a century ago, the cutting force research has been developed at full speed worldwide through German patent number 523594 (Longbottom & Lanham, 2006; Ling et al., 2011). Dr. Carl Salomon who was also a researcher for the patent, said that the increase of cutting speed would lead to reduce cutting force (Longbottom & Lanham, 2006; Ling et al., 2011; Kadam & Pawade, 2017; Brinksmeier et al., 2017). Furthermore, high-speed machining (HSM) is one of the improvements found from the contributions of the patent to overcome the problems that cannot be overcome by conventional machining (CM), especially on cutting force (Ling et al., 2011; Kadam & Pawade, 2017). Significant differences between CM and HSM can be seen through cutting force behaviour when cutting speed is increased (Longbottom & Lanham, 2006; Al-Ghamdi & Iqbal, 2015), as indicated in Figure 1.1. Cutting force for CM will increase when the cutting speed is increased, then decreases after reaching a specific cutting speed, even when cutting speed continues to increase; this phase is known as HSM as stated by Kadam & Pawade (2017). Although the behaviour of cutting force in HSM is too complex to understand due to its fluctuating nature, it has positively impacted HSM nickel-based superalloys when high cutting speed is needed in order to achieve low cutting force as this material is difficult-to-machine (Thellaputta et al., 2017; Kumar et al., 2017).

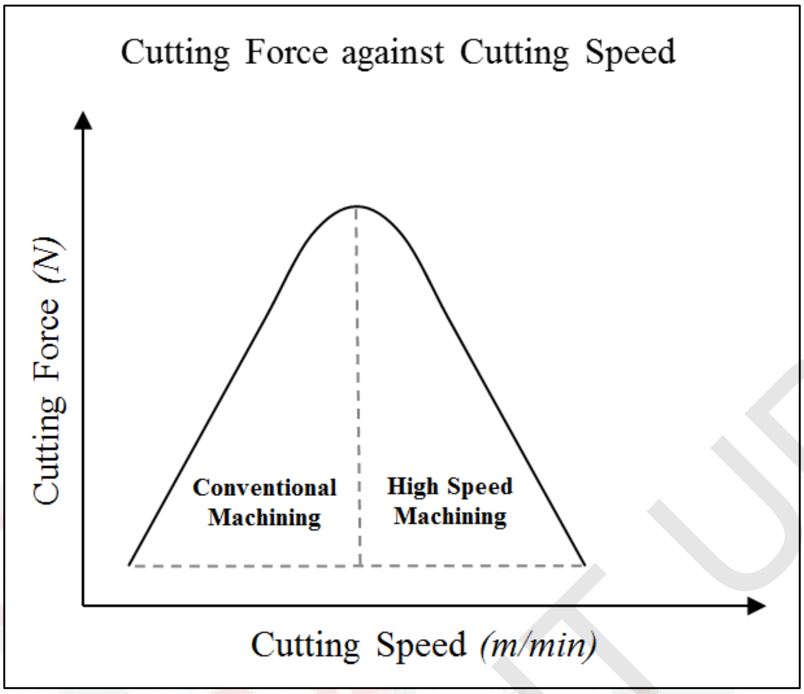

Figure 1.1 : Cutting force against cutting speed
(Modified from: Kadam & Pawade, 2017)

Nickel-based superalloys are frequently used materials for high-temperature applications due to their high-temperature strength (Yu et al., 2018; Sun et al., 2019). This alloy can withstand temperatures as high as 1200 °C (Han et al., 2018) and has high corrosion resistance (D'Addona et al., 2017; Thellaputta et al., 2017); due to this unique combination, the demand for these alloys for certain applications has rapidly increased. This alloy application can be seen through several examples, such as gas turbine engines (Qinghua Zhang et al., 2016), space vehicles (Thellaputta et al., 2017), nuclear reactors (Thellaputta et al., 2017) and rocket engines (Cheng et al., 2018). Referring back to HSM, machining is commonly recognised as the finishing process for achieving excellent surface finish and high-dimensional accuracy (Logins & Torims, 2015; Kadam & Pawade, 2017). Nickel-based superalloy parts are also no exception when it comes to achieving these two goals using HSM. However, it is vital to not only achieve excellent surface finish and high-dimensional accuracy, but also meet the requirement on the surface integrity for the reliability of nickel-based superalloy parts. Surface integrity of a machined part includes surface topography and metallurgy characteristic of the surface and sub-surface; for example, surface roughness, residual stress and surface hardness (Thellaputta et al., 2017). The transition from CM to HSM not only affects the cutting force, but also affects the surface characteristic of the machined parts. Based on the study conducted by Thakur & Gangopadhyay (2016b), surface roughness value decreases as the cutting speed increases. On the other hand, the residual stress and surface hardness values are found to increase with increase in cutting speed. It can be concluded here that the behaviour of cutting force and surface integrity in machining nickel-based superalloys are closely related to cutting speed variations.

1.2 Problem Statement

Hastelloy X material is one of the most widely used nickel-based superalloys for gas turbine engine parts because of its high strength at elevated temperatures and high oxidation resistance (Naik Parrikar et al., 2015; Jinoop et al., 2019). Also, Hastelloy X is principally noted as difficult-to-machine materials, and causes high cutting force. On the other hand, the effect of cutting force during HSM and especially high-speed milling has been widely focused on by many researchers and the result has provided the manufacturing industry an opportunity to reduce cutting force during machining (Arrazola et al., 2018). High-speed milling can be deduced as a transition from slow and heavy cuts to fast and light cuts, which is an innovative method that reduces cutting force. With high-speed milling in the manufacturing industry, productivity is continuously increasing, making businesses more and more efficient. In others words, high-speed milling has brought enormous benefits to the manufacturing industry. Through these approaches, reduction of cutting force when machining is done by reducing the rate of chip load while increasing the rate of spindle speed (Masmiati et al., 2016). Given that cutting speed is closely related to spindle speed, by increasing the spindle speed can reduce the cutting force (Selvaraj, 2017). Moreover, since the feed rate is tied to the chip load, as the chip load decreases, the feed rate also decreases. As a result, this allows for a reduction in the cutting force as the speed at which the cutting tool engages with the machined material is decreased (Selvaraj, 2017). Although cutting force has been reduced through this approach, there is still a concern that needs to be resolved whereby a decrease in chip load results in a reduction in material removal rate (MRR). Thus, it is contrary to the high-speed milling method in which the combination of high spindle speed and fast feed rate is the primary method used to increase MRR (Masmiati et al., 2016). Furthermore, it has been proven that the surface integrity after machining directly affects the reliability and life of the machined part (Masmiati et al., 2016; Thellaputta et al., 2017; Arrazola et al., 2018). Basically, the surface roughness decreases as the spindle speed increases. On the other hand, the sub-surface residual stress and surface hardness values are found to increase with the increase in spindle speed. Whereas, the increase in chip load led to increased surface roughness, surface hardness, and sub-surface residual stress. It is clear that the variation of spindle speed and chip load has significant impacts on surface integrity behaviour and cutting force behaviour. Although the ultimate research goal of the cutting force is to improve cost-effectiveness and productivity, it is also crucial to maintain or improve the surface integrity of a machined part. It is pointless when Hastelloy X parts are successfully produced at low cutting force through high MRR but have poor surface integrity. Since the influence of increased spindle speed at a constant chip load on the behaviour of cutting force and surface integrity remains undefined comprehensively, more accurate analysis should be focused on this approach as it has the potential to create a new dimension for reducing cutting force, while ensuring the desired reliability and life of the machined part as well as increased MRR. Apart from this, it is also intended to overcome the drawback from the existing approach, which is increasing spindle speed while reducing chip load during high-speed end-milling, in terms of MRR.

1.3 Objectives of Research

The main aim of this research is to study the influence of increases in spindle speed at constant chip load on cutting force and surface integrity of high-speed dry end-milling of Hastelloy X. Therefore, the objectives of this research are:

1. To analyse the behaviour of the cutting force components and the resultant force when spindle speed was increased at constant chip load under simulation and experimental conditions.
2. To determine the optimum combination of chip load and spindle speed, leading to the lowest value of cutting force components and resultant force, and subsequently correlate it with MRR and surface integrity.
3. To propose an ideal combination of chip load and spindle speed to the manufacturing industry in order to obtain the ideal cutting force, MRR and surface integrity during high-speed dry end-milling of Hastelloy X.

1.4 Scope and Limitation

This research was conducted to identify the ideal combination of chip load and spindle speeds that generated low cutting force at ideal MRR and surface integrity, in order to improve the existing cutting force reduction approaches. The method is done by increasing the spindle speed at constant chip loads, during high-speed end-milling of Hastelloy X under environmentally-friendly dry cutting conditions. The cutting force behaviour was simulated by using AdvantEdge version 6.4002, while dynamometer type 9129AA from Kistler was used to measure the cutting force under experimental conditions. A KYS40 solid ceramic with diameter 6 mm end-mill from Kennametal was employed in the simulation and experimental conditions during which the spindle speed was increased from 13,300 rpm to 37,600 rpm under three different chip loads (0.013 mm/tooth, 0.016 mm/tooth and 0.019 mm/tooth). Depth of cut was held constant at 0.2 mm, while the amount was selected to ensure it was greater than the work-hardened layer (more than 0.12 mm). In addition, the experimental tests were carried out in a vertical machining centre model Mori Seiki NV 4000 DCG. The behaviours of cutting force components (feed force, normal force and axial force) and resultant force for half-immersion up-milling, half-immersion down-milling, full-immersion up-milling and full-immersion down-milling were analysed using a curvilinear trend-line, while tool wear was not taken into consideration. The response optimizer was performed using the Minitab software version 18 to determine the optimum combination of chip load and spindle speed, leading to minimising the cutting force components and resultant force. Surface integrity consisted of surface roughness (Sa), surface hardness (HR_B) and sub-surface residual stress (MPa). Instruments used for the surface roughness, surface hardness and sub-surface residual stress evaluations were the LEXT OLS4100 3D measuring laser microscope, Wolpert UH930 universal hardness tester and PANalytical X'Pert Pro MPD PW 3040-60.

1.5 Significance of the Study

The proposed combinations of chip load and spindle speed are able to achieve low cutting force at ideal MRR and surface integrity during high-speed end-milling of Hastelloy X under environmentally-friendly dry cutting conditions. Here are some significant and beneficial achievements that the proposed combinations of chip load and spindle speeds are expected to provide:

1. Will enable the manufacturing industry to choose the ideal combinations of chip load and spindle speed, based on specification of the milling machine's spindle speed and the operation to be carried out in terms of direction of the cutting tool rotation and radial immersion amount. This is to enable them to achieve low cutting force and increase the productivity of Hastelloy X parts in addition to preserving surface integrity of the parts.
2. Furthermore, high-speed end-milling of Hastelloy X conducted under dry conditions can improve cost-effectiveness through loss of cutting fluid costs. In addition, it can minimise the negative impact on the environment.
3. Last but not least, the use of ceramic cutting tool during high-speed dry end-milling of Hastelloy X was the key to increase the MRR. Therefore, a new dimension was opened to encourage the use and study of this cutting tool.

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