STUDY OF TOOL ENGAGEMENT AND TOOL PATH STRATEGY IN HIGH SPEED END MILLING

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ABSTRACT

This thesis presents an investigation of the relationship between tool engagement, tool path strategy (TPS) and the machining output during pocketing operation to form a mould. For pocketing, the cutting tool is required to travel along a straight path and corner path by following the predefined tool path strategy. Variation of tool engagement occurs during the pocketing that leads to fluctuation of cutting force and cutting temperature that give a bad impact on surface quality. Although previous studies have demonstrated a relation between cutting force and tool engagement, the relation with cutting temperature has not given much attention. The aim of this study is to improve surface quality of mould through end milling process by considering tool engagement, tool path strategy, cutting force and cutting temperature.

Firstly, the tool engagement models for slot and peripheral cutting for different case of corner cutting were developed. From the model, relation between tool engagement and three different types of tool path strategy were analysed. The significant changes of tool engagement were observed during the corner when the tool changes direction for each tool path strategy. Then, experimental work was conducted to investigate the effect of variation engagement for the tool path strategies on cutting force and cutting temperature. The highest cutting force and cutting temperature were found in pocketing operation by using inclination tool path strategy compared to contour and zig zag tool path strategy. The variation of tool engagement is one of the attributed to high cutting force and cutting temperature.

Further investigation was conducted to evaluate the effect of cutting parameters on cutting force, cutting temperature and surface finish. The three key parameters are cutting speed, feed per tooth and depth of cut. Taguchi L_9 design of experiment and analysis of variance (ANOVA) was used to determine the significant factors that influence the result. Within the range of cutting parameters that have been selected, cutting speed and feed rate were the most significant parameters that influence cutting force, cutting temperature and surface finish. Meanwhile, it was found that the increasing of cutting speed and feed per tooth have shown increasing of surface roughness.

Finally, the relationship between cutting parameters (controllable factors) and machining output (uncontrollable factors) with surface roughness for different tool engagement angles were established. Pearson correlation analysis was used to explore the correlation between the controllable and uncontrollable factors. It was found that, most of the factors have positive relationship between each other. Then, multiple regression analysis was used to establish the correlation models. From the analysis, the model showed acceptable accuracy and are significant.

The main achievement of this study is improving surface quality of a mould, which the surface roughness obtained is in the range of surface quality of mould. In addition, it was found that cutting temperature is also closely related to cutting forces and tool engagement that affected surface quality.

خلاصة البحث

تقدم هذه الأطروحة التحقيق في العلاقة بين اشتباك أداة القطع، استراتيجية مسار أداة القطع (TPS) ومخرجات القطع لعملية الجيب لتشكيل القالب. يُتطلب من أداة القطع في عملية الجيب أن تتحرك على طول الطريق المستقيم والزاوي باتباع استراتيجية مسار أداة القطع المحددة مسبقاً. يؤدي التغير في اشتباك أداة القطع الذي يحدث أثناء عملية الجيب إلى تذبذب في قوة القطع ودرجة حرارة القطع التي تؤثر بشكل خطير على جودة سطح القالب. أثبتت معظم الدراسات السابقة العلاقات بين قوة القطع واشتباك أداة القطع. مع ذلك، لم تُمنح العلاقات بين قوة القطع، اشتباك أداة القطع وحرارة القطع الكثير من الاهتمام. إن الهدف من هذه الدراسة هو تحسين جودة سطح القوالب من خلال عملية الطحن النهائي وذلك من خلال النظر في اشتباك أداة القطع، استراتيجية مسار أداة القطع، قوة القطع ودرجة حرارة القطع.

من أجل تحقيق هدف هذا البحث، تم تقسيم الدراسة إلى ثلاث مراحل مرتبطة. أولاً، تم تطوير نماذج اشتباك أداة القطع لحالات مختلفة من القطع الزاوي. تم تحليل العلاقات بين اشتباك أداة القطع وثلاثة أنواع مختلفة من استراتيجيات مسار أداة القطع من هذه النماذج. لوحظت تغييرات كبيرة في اشتباك أداة القطع لكل استراتيجية مسار أداة القطع أثناء القطع الزاوي. بعد ذلك، أُجري العمل التجريبي لدراسة تأثير التغيرات في الاشتباك على قوة القطع ودرجة حرارة القطع لجميع الاستراتيجيات الثلاثة المختلفة لمسار أداة القطع. تم الحصول على أعلى قوة قطع ودرجة حرارة قطع في عملية الجيب من استراتيجية مسار أداة قطع الميل بالمقارنة مع استراتيجيات مسار أداة القطع المتعرج والمحيطي. إن التغير في اشتباك أداة القطع هو واحد من المساهمين لقوة قطع ودرجة حرارة قطع عاليتين.

تم إجراء المزيد من التحقيق لتقييم تأثير معاملات القطع على قوة القطع، درجة حرارة القطع ونهاية السطح. المعايير الأساسية الثلاثة التي دُرست هي سرعة القطع، التغذية في السن وعمق القطع. أُستخدم تصميم Taguchi L_9 من التجربة وتحليل التباين

(ANOVA) لتحديد العوامل الهامة التي تؤثر على النتيجة. وُجد من ضمن معاملات القطع التي تم اختيارها أن سرعة القطع ومعدل التغذية هما المعاملان الأكثر الأهمية اللذان يؤثّران على قوة القطع، درجة حرارة القطع ونهاية السطح. علاوة على ذلك، وُجد أن الزيادة في سرعة القطع والتغذية في السن تزيد من خشونة السطح.

أخيراً، تم تأسيس العلاقة بين معاملات القطع (عوامل يمكن التحكم بها) ومخرجات القطع (عوامل لا يمكن السيطرة عليها) مع خشونة السطح لزوايا اشتباك أداة القطع المختلفة. تم استخدام تحليل ارتباط Pearson لاستكشاف العلاقة بين العوامل التي يمكن التحكم بها وتلك التي لا يمكن السيطرة عليها. تبين أن معظم العوامل لها علاقة إيجابية مع بعضها البعض. تم استخدام تحليل الانحدار المتعدد لإنشاء نماذج الارتباط. أظهر النموذج من خلال التحليل دقة مقبولة وهي مهمة للاستجابة (خشونة السطح).

أنشأت هذه الدراسة بنجاح العلاقة الوثيقة بين درجة حرارة القطع، قوة القطع، اشتباك أداة القطع وجودة السطح. وفي النهاية، حققت هذه الدراسة هدفها في تحسين جودة سطح القوالب.

APPROVAL PAGE

The thesis of Roshaliza Hamidon has been approved by the following:

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATION

AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
ANN	Artificial Neural Network
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
FEM	Finite Element Method
HSM	High Speed Machining
TPS	Tool Path Strategy

LIST OF SYMBOLS

V_c	Cutting Speed (m/min)
f_z	Feed per tooth (mm/tooth)
f_r	Feed rate (mm/min)
D	Tool Diameter (mm)
r	Tool radius (mm)
N	Spindle speed (rpm)
n	Number of teeth
θ	Tool engagement angle
θ_{st}	Entry angle
θ_{ex}	Exit angle
l	length/ Distance (mm)
T_c	Cutting time
a_e	radial depth of cut/step over
a_p	axial depth of cut
F_x	Force in x-direction
F_y	Force in y-direction
F_z	Force in z-direction
$F_{r`}$	Resultant Force
$F_{r(meas)`}$	Measured Resultant Force
$F_{r(pred)`}$	Predicted Resultant Force
T_c	Cutting Temperature
$T_{c(meas)}$	Measured Cutting Temperature
$T_{(pred)}$	Predicted Cutting Temperature

K_{ac} axial shearing force coefficient in

K_{rc} radial shearing force coefficient in

K_{tc} tangential shearing force coefficient in

K_{ae} axial ploughing force coefficient in

K_{re} radial ploughing force coefficient in axial

K_{te} tangential force coefficient in axial

r tool radius

R_a Average surface roughness

$R_{a(meas)}$ Average measured surface roughness

$R_{a(pred)}$ Average predicted surface roughness

r Correlation

S/N Signal to Noise ratio

R^2 Correlation coefficient

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The mould and die industry is a rapidly growing industry with high demands especially in the aerospace and automotive parts. For this industry, improving production and at the same time providing the best quality of products is extremely essential. To fulfil these criteria, conventional machining is less favourable compared to high speed machining thus making the latter more relevant in today's fast moving world.

Previously, polishing is required as a finishing process for mould and die. However, the cost of labour and the time consumed for such process has encouraged the industry to alternatively switch to a better choice. According to Tsui & Chan, (2005) 30% of the total expense in mould and die making which comes from polishing process. For example in the automotive industry, hardened steel parts, gears and bearings need to go through the finishing process of grinding and polishing. If this need can be eliminated, the automotive industry can decrease capitals as much as 40% whilst at the same time improve productivity by 30% (Yan et al., 2005). One way of doing this is by employing high speed machining (HSM) which offers higher productivity, better quality and lower cost compared to polishing process especially in the long run. Though HSM has the potential to replace the polishing process, proper selection of cutting conditions such as cutting parameters, tool path strategy, cutting and workpiece is needed.

Cutting parameters play an important role to achieve optimum performance of HSM. The three key cutting parameters in machining is cutting speed, feed per tooth and depth of cut. However, to form a mould, end milling with tool path strategies is required for the process known as pocket operation. A pocket operation is a process in which an inner empty volume of a part is created. The machining process starts from the surface of the part to a pre-defined depth by following a particular tool path strategy.

An efficient and productive tool path strategy is determined by the tool engagement. Tool engagement can be defined as the percentage of the tool that engages with the material while the cutter is moving during machining (Kramer, 1992). In performing pocketing operation to a form a mould, tool needs to travel in straight and corner cuttings depending on the shape of the mould. This kind of actions leads to various engagements between the tool and workpiece. As a result, fluctuations in the cutting force occurs which in turn would affect the surface quality.

In addition, the heat generated during the engagement is another challenge during the pocketing process. The friction developed between the tool and the workpiece as well as the formation of chips during the machining process are related to the cutting force and the cutting temperature. Therefore in order to improve the quality of moulds, it is important to explore the relationship between tool path strategy and tool engagement cutting force and cutting temperature.

In this study, HSM was employed to perform pocket operation. Tool engagements model were developed for different tool path strategies. The relationship between tool engagement and cutting forces was analysed. Furthermore, the effect of cutting parameters on different machining strategies was investigated. Finally, the relationship between controllable factors and uncontrollable factors with surface roughness for different tool engagements was established.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

In a general milling operation, cutting tool travels along a straight path to remove material. For a pocketing operation, the tool is required to travel along a straight path and corner path by following the predefined tool path strategy on surface of the workpiece. In a straight cutting, radial depth of cut maintain at the same value along the path. When it turns to corner or curve shape, radial depth of cut is changing during the corner. Changing radial depth of cut causing the variation of tool engagement. As consequences, variations in cutting force causes more heat to be generated which can deteriorate the surface quality of the mould.

To solve the problem, some of researchers develop a cutting force prediction model during corner cutting. Han & Tang (2015), presented cutting force model that is based on tool engagement model during a corner. The model was verified experimentally by using titanium as work material. Another prediction model developed by Zhang et al., (2015). For verification, aluminium was used as work material and low cutting speed was utilized in the experiment. For both model, a good agreement was obtained between the prediction model and experimental result. However, it was only verified for low cutting speed process. In addition, the prediction model is a complex model to be implemented in a tool path strategy.

Another issue is the effect of tool engagement on machining output such as cutting force, cutting temperature and surface roughness. Not much study has been done which focuses on this issue. The study that was found on the related issue is only concerning on the effect of tool path strategy on the machining output. Among recent studies were conducted by Riza (2016) and Pinar (2013). From the result it was found that different tool path strategy has different effect on machining output. However, the studies were more focused on the optimization of tool path strategy and cutting parameters. The discussion of tool engagement that affected the result was not seriously discussed. Moreover, some of studies narrow down on soft material and low cutting speed only.

The empirical model developed from the previous researches focused on the relationship of three key cutting parameters (cutting speed, feedrate and depth of cut). The cutting parameters are the controllable factor that can be selected by machinist. However, machining output not only affected by controllable factors. According to Hou et al. (2014), the uncontrollable factors such as cutting force has relation on cutting temperature, surface roughness and tool wear. The study that focused on the relation of controllable factors and uncontrollable factors was done by Aguiar et al. (2013). The correlation of tool vibration and surface roughness was investigated. Tool vibration was assigned as the uncontrollable factor. The same area of study was done by Hessainia et al.(2013). The relationship of cutting parameter and tool vibration was presented in this study. It can be concluded that, surface quality not only affected by controllable factor, but same does for uncontrollable factor. However, not much study concerning on the issue.

By taking into account the importance of all of the above factors, there is still a gap that needs to be filled up. The objective of this study is discussed in the next sub chapter.

1.3 RESEARCH PHILOSOPHY

In mould and die making, milling operation is used to replace polishing operation for economical purpose. End milling operation with tool path strategy is usually used to perform pocket operation to form a mould. In order to meet surface quality requirement, selection of good process and cutting parameters is very important. However, in pocketing operation, tool engagement and tool path strategy is an additional criterion that needs to be seriously focused on as it can affect cutting force and cutting temperature. Since surface quality also affected by cutting force and cutting temperature, the relationship between the factors need to comprehensively study.

1.4 RESEARCH OBJECTIVE

The aim of this study is to enhance the surface quality of mould and die through end milling process. This is achieved through a series of objectives outlined as follows:

i. To develop a tool engagement models for different tool path strategies
ii. To analyse the relationship between tool path strategies, cutting force and cutting temperature
iii. To evaluate the effect of cutting parameters of different tool path strategies on cutting force, cutting temperature and surface roughness
iv. To establish correlation between cutting parameters and machining output with surface roughness