UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION OF TOOL GEOMETRY DESIGN FOR FREE CUTTING STEEL (AISI 12L14) IN TURNING OPERATION

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Chairman: Professor Mohd Khairol Anuar Mohd Ariffin, PhD
Faculty: Engineering

The need for major improvements in the design of cutting tools are due to the demands of delivering high dimensional accuracy and low surface roughness products in turning operation. An optimization of cemented carbide (WC) tool geometry design for AISI 12L14 free cutting steel in turning process was carried out with the emphasis on the optimal workpiece through the quality of surface roughness. In this work, the performance of cutting inserts in the market and the newly developed cutting tools was investigated in terms of cutting forces and surface roughness (R_y). In the first phase, the selection of currently available cutting tools were done and modeled. Cutting forces simulation using AdvantEdge software was performed in determining the cutting tool-workpiece force interactions. In the second phase, the cutting tool-force interactions were studied and results revealed that tool geometry's rake angle (γ) and cutting regimes such as depth of cut (a_p) and feed rate (f_r) gave significant impacts to the cutting forces (tangential force, radial force, and feed force) and R_y. A negative rake angle led to higher cutting forces compared to a positive rake angle. In third phase, a new proposed design of cutting tool was fabricated and tested according to rough and finish cutting conditions. Results showed that tool geometries of rake angle, inclination angle, and major (K_{r1}) and minor cutting tool's angle (K_{r2}) had significant influences on cutting forces and R_y. In the fourth phase, the tool's validation experiments were performed and the optimization was done by employing Taguchi method. The newly optimized tool cutter geometry was obtained at K_{r1} of 60° and 90°, K_{r2} of +3°, rake angle of +10°, and the inclination angle of -3°. It was revealed that a_p and f_r gave a significant impact on surface roughness. As a_p and f_r increased, R_y also increased except for setting parameters when a_p was below than minimum chip thickness (H_{min}). In the final phase, the performance of the newly developed cutting tool, in terms of R_y indicated that there was a significant

difference between travel lengths and the progression of surface roughness correspond to tool wear or tool's performance from 0 mm to 1560 mm (until tool breakage). However, none of the surface roughness results showed R_y more than 6.3. Additionally, cutting forces tend to increase with the increase of depth of cut (a_p) when a_p was higher than 1.15 mm. The feed force magnitude was almost similar to radial cutting force. However, the cutting force components started to deviate when the depth of cut was more than 1.15 mm whereby radial force slightly decreased with the increasing depth of cut. The effect of the combination of two cutting edges of the newly developed cutting tool could be the reason for radial force reduction. Hence, the newly developed tool was shown capable to produce final surface roughness within an acceptable range. The newly developed cutting tool demonstrated a great potential for turning operation market.

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

PENGOPTIMUMAN REKABENTUK MATA ALATAN UNTUK BESI (AISI 12L14) DALAM OPERASI MESIN LARIK

Oleh

ROSDI BIN MOHAMMAD

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Keperluan dalam menambahbaikan rekabentuk mata alatan adalah disebabkan oleh permintaan terhadap produk yang mempunyai ketepatan dimensi yang tinggi dan kekasaran permukaan yang rendah dalam operasi larik. Kajian pengoptimuman geometri mata alat karbida (WC) terhadap bahan campuran besi AISI 12L14 semasa proses larik telah dikaji dengan penumpuan kepada mekanisma kualiti permukaan larik. Dalam kajian ini, prestasi mata alat dalam pasaran dan juga cadangan baru mata alat telah diselidik dari segi daya pemotongan dan kualiti permukaan larik (R_y). Pada peringkat pertama, pemilihan mata alat sedia ada dipasaran telah dilakukan dan dimodelkan. Simulasi komputer menggunakan program pengatucaraan AdvantEdge telah dijalankan untuk menentukan interaksi daya pemotongan antara mata alat-bahan kerja. Pada peringkat kedua, kajian terhadap kaitan mata alat dan daya dijalankan dan keputusannya menunjukkan geometri mata alat sudut condong mata alat (γ) dan kondisi pemotongan seperti kedalaman potongan (a_p) dan kadar suapan (f_r) mempunyai kaitan yang signifikan dengan daya kekuatan pemotongan (daya tangen, daya radial dan daya suapan) dan R_y. Sudut condong negatif akan membawa kepada daya kekuatan pemotongan yang lebih tinggi berbanding dengan sudut condong positif. Pada peringkat ketiga, cadangan rekabentuk baru mata alat telah direka dan diuji mengikut keadaan pemotongan kasar dan pemotongan halus. Keputusan menunjukkan geometri mata alat sudut condong mata alatan, sudut condong potongan, dan sudut utama (K_{r1}) dan sudut kedua kemasukan pemotongan (K_{r2}) mempunyai pengaruh yang signifikan terhadap daya kekuatan pemotongan dan R_y. Pada peringkat ke empat, eksperimen pengesahan mata alat ini telah dijalankan dan pengoptimuman menggunakan kaedah Taguchi. Rekabentuk baru mata alat yang dioptimumkan telah diperolehi untuk K_{r1} pada 60° dan 90°, K_{r2} pada +3°, sudut mata alatan pada +10°, dan sudut condong potongan pada -3°. Kajian menunjukkan a_p dan f_r memberikan kesan

ketara ke atas kekasaran permukaan. Apabila a_p dan f_r meningkat, R_y juga meningkat kecuali bagi tetapan parameter bilamana a_p berada dibawah tahap kedalaman potongan (H_{min}) minima. Pada peringkat akhir, prestasi mata alat baru yang dibangunkan, dari segi R_y menunjukkan berlakunya perubahan ketara antara jarak pemotongan dan potongan kekasaran permukaan bersesuaian dengan kemerosotan mata alat atau prestasi mata alat dari 0 mm kepada 1560 mm (sehingga mata alat pecah). Walaubagaimanapun, tiada keputusan bacaan permukaan larik yang menunjukkan R_y melebihi 6.3. Di samping itu, kadar daya kekuatan pemotongan cenderung untuk meningkat dengan meningkatnya kedalaman pemotongan (a_p) bila a_p melebihi 1.15 mm. Magnitud daya suapan hampir sama dengan daya pemotongan radial. Walau bagaimanapun, komponen-komponen daya pemotongan mula menyimpang apabila kedalaman pemotongan adalah lebih daripada 1.15 mm dimana kadar daya potongan radial sedikit menurun dengan peningkatan kedalaman pemotongan. Kesan kombinasi dwi-mata alat pada cadangan baru mata alat berkemungkinan adalah penyebab kepada pengurangan kadar daya potongan radial. Justeru, mata alatan cadangan baru menunjukkan ianya mampu menghasilkan permukaan larik akhir di dalam julat yang boleh diterima. Mata alat yang baru telah membuktikan potensi yang besar untuk pasaran operasi larik.

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I certify that a Thesis Examination Committee has met on 4 December 2017 to conduct the final examination of Rosdi bin Mohammad on his thesis entitled "Optimization of Tool Geometry Design for Free Cutting Steel (AISI 12L14) in Turning Operation" 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 Doctor of Philosophy.

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LIST OF ABBREVIATIONS

3-D	Three dimensional
AISI	America Iron and Steel Institute
ANN	Artificial neural network
ANOVA	Analysis of variance
BCC	Body-centered cubic
BUE	Build-up edge
C0	Component of stress
C2	Surface angle of neck down material
CAD	Computer aided design
CCD	Central composite design
CVD	Chemical vapor deposition
DLC	Diamond-like coating
DOE	Design of experiment
ECR-CVD	Electron cyclotron resonance CVD
FCBPNN	Forward back propagation neural network
FCC	Face-centered cubic
FEM	Finite element method
FFBPNN	Feed forward back propagation neural network
GA	Genetic algorithm
GDP	Gross Domestic Product
HSS	High speed steel
IBAD	Ion beam assisted deposition
IBD	Ion beam deposition
JIS	Japan Industrial Standard
NC	Numerical control
OA	Orthogonal array
OFHC	Oxygen-free high thermal conductivity
PACVD	Plasma assistant CVD
PCBN	Polycrystalline cubic boron nitride
PE-PVD	Electron beam deposition
PLD	Pulsed laser deposition
PSO	Particle swam optimization
PVD	Physical vapour deposition
RBF	Radial basis function
RSM	Response surface methodology
TE	Thermal evaporation
TRS	Transverse rupture strength
UTS	Ultimate tensile strength
WC	Cemented carbide

LIST OF SYMBOLS

π	Pi
γ or Ra	Rake angle
λ	Inclination angle
μ	Friction coefficient between tool-workpiece
$A\alpha$	Flank-workpiece contact area
Cn	Material constants
D_w	Raw material original diameter
D_{w1}	Diameter of machined surface
F_c	Cutting force
f_c	Conventional feed rate
F_{ch}	Chip formation force
F_n	Normal force to shear
f_n	Applied feed rate
F_p	Passive force
fr	Feed rate
F_s	Shear force
f_w	Wiper feed rate
F_z	Feed force
F_x	Tangential force
F_y/F_t	Thrust/radial force
F_α	Force acting on flank
K_{r1}	Major cutting tool edge
K_{r2}	Minor cutting tool edge
L_{fr}	Axial length after fracture
L_{in}	Initial length
R_a	Arithmetic surface roughness
r_n	Tool radius
R_q	Root mean square (RMS) roughness
R_t	Maximum height of the profile
R_{tw}	Surface roughness finishing by wiper
r_w	Wiper nose radius
R_y	Maximum height
$r\varepsilon$	Nose radius
To	Room temperature
V_B	Flank wear
V_{BB}	Flank wear land
V_c	Cutting speed
β_{nec}	Surface angle of neck down material
γ_{eff}	Effective rake angle
ε	Strain
ε'	Strain rate
λn	Minimum chip thickness
ρ	Tool radius
σ	Effective flow stress
$\sigma 1$	Strength coefficient
τa	Shear strength
$\tau c\gamma$	Main shear stress

χ	Tool cutting edge angle
Cn	Material constants
F	Friction force
$F_{exp.}$	The experiment value
F_{sim}	The simulated value
N	Normal force to friction
n1	Strain-hardening exponent
R	Resultant force
T	Absolute temperature
To	Room temperature
Δ(%)	Absolute error

LIST OF NOMENCLATURES

Co	Cobalt
Cr	Chromium
Cr_3C_2	Chromium carbide
Fe	Ferum (Iron)
Hf	Hafnium
HfC	Hafnium carbide
Mn	Manganese
MnS	Manganese Sulphide
Mo	Molybdenum
Mo_2C	Molybdenum carbide
Nb	Niobium
NbC	Niobium carbide
Ni	Nickel
Pb	Lead
Ta	Tantalum
TaC	Tantalum carbide
Ti	Titanium
TiAlN	Titanium aluminium nitride
TiC	Cermet
TiC	Titanium carbide
TiCN	Titanium carbon nitride
Zr	Zirconium
ZrC	Zirconium carbide
C	Carbon
CBN	Cubic boron nitride
P	Phosphorous
S	Sulphur
V	Vanadium
W	Tungsten

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Total Malaysia's gross domestic product (GDP) growth in third quarter of year 2017 is at 6.2%. Manufacturing sector contributed the second largest of GDP growth after services sector (Department of Statistics, Malaysia, 2017). Thus, manufacturing sector is an important economic component to be explored. Manufacturing can be defined as the modification of low-value or non-value material into items of greater value by the means of appropriate process or processes (Groover, 2007). High productivity through the optimization of manufacturing processes is one of the elements that should be introduced in the manufacturing sector. An increase in productivity requires involvement of all technological operations where optimum technological processes, optimum tool selection, optimum combination of tool-workpiece material and determination of optimum cutting variables and tool geometry must be considered (Saglam, Unsacar, Yaldiz, 2006). Moreover, to attain satisfactorily high production rates at minimum cost, it is a necessity to optimize cutting tool geometry (Fang and Fang, 2007).

Among the most basic manufacturing processes performed by machine tools are drilling, milling, grinding and turning (Malagi and Rajesh, 2012). Typically, in turning the workpiece is rotated on the spindle and the tool is fed into it radially, axially or both ways simultaneously to give the required surface (Schneider, 2013). Turning offers significant advantages such as it is more flexible manufacturing method, capable to fabricate complex geometrical cylindrical features, has great ecological advantages as it is often used as a dry cutting process, yields good surface finishing that close to final tolerance, etc. Turning enables a broad variety of materials from metal and its metal alloys, plastic and their composites, and ceramic to be processed but ceramic can pose difficultly because of their high hardness and brittleness (Groover, 2007).

Metal is extensively used in machining process, from 'hard-to-machine steel' (with hardness 40 to 70HR) i.e. hot work steel, AISI D2 steel, AISI H13 steel, Hastelloy C-276, etc., to the 'easy-to-machine steel' such as free cutting steel (AISI 12L14 or JIS SUM24L) and non-ferrous materials e.g. brass, copper and aluminum alloy. A lot of researchers were interested in studying the hard-to-machine material due to its difficulty-to-machine, however, studies of 'easy-to-machine' material such as AISI 12L14 are scarcely available. According to America Iron and Steel Institute (AISI), AISI 12L14 free cutting steel are developed to offer good machinability of 160% which is considered easy-to-machine material (compared to AISI 1212). The AISI 12L14 or free cutting steel consists of carbon (C) 0.15 max, Manganese (Mn) 0.85 - 1.15, Phosphorus (P)

0.04 - 0.09, Sulphur (S) 0.26 - 0.35 and Lead (Pb) 0.15 - 0.35 (Japan Industrial Specification, 1994). The elements of Mn, S and Pb addition assists chip formation (reduces chip length, pattern, and size), friction and thus wear on cutting tool is reduced, which allowing higher feeds and/or speeds (Hashimura, Mizuno, Miyanishi, 2007). This enables AISI 12L14 or free cutting steel to be processed at minimum supervision while machining the products. Despite that, the presence of sulfide structure (MnS) in bulk grain size in material would lead to built-up edges (BUE), which repeatedly form irregular deposits and then fall off the tool, which is a factor in degrading the quality of the cutting surface as well as dimensional inconsistent. Moreover, Yaguchi (1986) reported that BUE which consist high concentration of MnS initiated on tool tip of high speed steel (HSS) would either harmful or beneficial depending on the condition. Insignificant quantity of BUE served as protecting layer to the tool therefore prolonged the tool life and affect adversely if BUE occurred at bulky amount. Chips formation/disposal, tool design and wear, and machine’s setting parameters during product machining are some of the factors that must be considered while using this free cutting steel material.

Numerous studies showed that tool geometry/parameters deviations, inhomogeneity in workpiece material, cutting conditions, machine tool parameters such as feed drive instabilities and dynamic behavior of the machine tool are the influencing factors in determining cutting forces in turning process (Sharma, Dhiman, Sehgal, Sharma., 2008; Nalbant, Altin, Gökkaya, 2007; Özel, Hsu, Zeren, 2005; Yang & Tarng, 1997). Subsequently, they influence the deformation of the machined workpiece, its dimensional accuracy, chip formation and machine system stability as well as their interaction forces (Chiou, Chung, Liang, 1995). In term of the importance of the relationship of forces and tool geometrical, Astakhov (2010) noted that the understanding of geometry is crucial, where a proper understanding in cutting tool geometry enables determination of the orientations of cutting edge, rake and flank surfaces with respect to the cutting conditions.

Cutting is a process of extensive stresses and plastic deformations where the high compressive and frictional contact stresses on the tool face results in a substantial cutting force. Cutting forces generated during cutting operation give a direct influence on the generation of heat, and thus tool wear, quality of machined surface and accuracy of the workpiece (Malagi and Rajesh, 2012). Cutting forces vary with the tool angles, and accurate measurement of forces is helpful in optimizing tool design and predicting tool life (Gutakovskis, Bunga, Pikurs, Brutans, Ratkus, 2012). An increased friction between cutting tool and workpiece consequently leads to a higher push-off force, the excessive heat created in cutting process will give a direct impact on the on the workpiece and could lead to workpiece damage, as well as deterioration of the tool life (Knufermann, 2003).

1.2 Problem Statement

Manufacturers presume to have higher and higher productivity in their machining processes and predictable tool wear change mechanism of their cutting tools. These call for major improvements in the design of cutting tools. Apart from considering the tool life, strict control on the quality of surface finishing during turning is extremely important too. The biggest challenge is to maintain the product within the specification throughout the mass production circumstances and the ability to foresee tool wear progression which would support them in predicting or change the tool before it would affect the final product (Zhang & Gou 2016; Waydande, Ambhore, Chinchanikar, 2016; Karim, Azuan, Yasir, 2013; Yanda, Jaharah, Haron, 2010; Dogra, Sharma, Dureja, 2011; Astakhov 2010; Storch and Zawada-Tomkiewics, 2012; Malekian, Mostofa, Park, 2012; Yuan, Zhou, Dong, 1996). To overcome those problems, one of the important keys to be considered is tool geometry optimization.

From previous report (Kandananond 2010; Xu, An, Chen, 2012; Wei, Liu, An, Chen, 2012), it is clear that turning of AISI 12L14 free cutting steel has not received extensive attention. Free-cutting steel refers to a specific kind of steel by adding some individual or composite elements (e.g. sulfur, phosphorus, lead, selenium, etc.) to improve its cutting performance and to satisfy the development demands of automatic processing (Tanaka, Yamane, Sekiya, Narutaki, Shiraga, 1977; Yaguchi, 1988). AISI 12L14 is a typical sulfured free-cutting steel which supposed to have excellent cutting performance owning to the embitter function on ferrite substrate from phosphorus and the sulfide internal notch effect (Xu et al. 2012). Using cemented carbide as a tool, the optimization of tool geometry using this free cutting steel material capable of delivering high dimensional accuracy and low surface roughness would be a significant improvement in turning operation. In order to achieve that, a better understanding on cutting forces are generated has to be gained. This also needs to take into account the various relevant factors and cutting parameters. Due to the complex tool configurations/cutting conditions of metal cutting operations and some unknown factors and stresses, an experimental measurement of interaction of cutting forces is unavoidable. Further, software helps in creating the database for manufacturing, to increase the productivity of the designer, and to improve the quality of the design. Hence, a computer aided simulation of cutting forces estimating of predicting achievable tool geometry/cutter rake angles for turning is then necessary. Finally the purpose of this research is to optimize cutting tool geometry for free cutting steel AISI 12L14 in turning operation.

1.3 Project Goals and Objectives

The overall aim of the study is to optimize the tool geometry design for free cutting AISI 12L14 steel using a cemented carbide (WC) tool for the optimal workpiece through the quality of surface roughness for turning operation, and to develop a cutting force simulation based on tool geometry designs. Therefore, this study will be commenced with the following objectives:

1) To develop a cutting forces simulation based on the commercial tool geometry cutting tool using AdvantEdge 7.1 software.

2) To verify the selected tool design (tool geometry) by tool's manufacturer versus their recommended setting parameters of cutting speed, feed rate, and depth of cut, using free cutting steel material (AISI 12L14) via numerical control (NC) lathe.
3) To design and fabricate several types of improved design tool geometry (at varied cutter geometry angles) using brazed cutting tool insert and to determine the tool-forces interactions with the workpiece according to objective number 2.
4) To validate and verify the newly developed cutting tool design (tool geometry) versus machine setting at controlled parameters of cutting speed, feed rate, and depth of cut on AISI 12L14 material, and to develop a cutting forces simulation based on the newly developed cutting tool using AdvantEdge 7.1 software.
5) To conduct a preliminary test for tool performance.

1.4 Significance of This Study

The study outcomes significantly contribute towards improvement in productivity and reduction in cost of manufacturing processes through the optimization of tool life. Hence, the results of the study will help the manufacturers to obtain their manufacturing productivity cost at an optimum level and at the same time maintain the part's quality at the best level. Moreover, it will benefit the manufacturers to be competitive in both national and global markets which indirectly will contribute to our national economic growth. Additionally, the development of a cutting simulation and the validation of the simulation based on the attained tool geometry designs and cutting forces data would help the manufacturer to improve their ability to expedite their selection process for appropriate tool.

1.5 Scope of Work

The scope of work is limited to experimental evaluations on the turning operation. The material used is limited to AISI 12L14 (or SUM24L). The project will be accomplished in the following five phases:

Phase	Content	Tasks
1	Cutting Simulation Development and Execution.	• Selection of tools geometry design. • Determine the recommendations of setting cutting regimes for cutting simulation. • Development of cutting simulation using AdvantEdge 7.1.
2	Commercial Tool Geometrical Design Verifications	• Tool purchase and material preparation. • Conduct Test Cut 1.
3	Design and Optimization	• Design and fabrication of new design tool geometry. • Conduct Test Cut 2.
4	Validation Experiments	• Test cut of develop tool geometry for process and cutting simulation validation. • Conduct Test Cut 3.
5	Tool Performance Study	• Conduct Test Cut 4

1.6 Thesis Organisation

This study has been divided into 5 phases; - Phase 1: cutting simulation, development and execution, Phase 2: commercial tool verification, Phase 3: design and optimization of cutting tool, Phase 4: the newly developed cutting tool's verification and cutting simulation and Phase 5: the performance (in term of tool life) of newly developed design tool. Phase 1 is for cutting simulation, the development and execution of simulation, the analysis of cutting forces and the comparisons of generated outcomes throughout the simulation. Phase 2, Phase 3, Phase 4 and Phase 5 is for analysis of cutting forces.

Chapter 1 provides with overviews of this study and the objectives derived from the problem statements. Chapter 2 presents a comprehensive literature reviews from the relevant areas associated with this topic in this research. Chapter 3 provides the overall research methodology applied in this research. Chapter 4 presents the comprehensive results and discussion from the experiments. And finally chapter 5 consists of the summary of this research. In this chapter, general conclusions are presented for each phase. Lastly, a recommended future research is presented.

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