ABSTRACT

Hardened D2 tool steel is widely used in the mold and die industry especially for injection molding tools, cold forming tools and precision engineering parts. Most of the applications require an excellent surface finish as it will reflect on the end product appearance. However, the high strength of these materials (>50 HRC) results in rough machined surface when using the conventional machining process, hence, special machining technique is required to maintain the part quality. In current industry practice, the machining tolerances are generally achieved by subsequent manual finishing process such as, polishing and grinding in order to realize both the required geometry and surface finish. Notably, the aforementioned manufacturing techniques for mould and die fabrication tend to decrease productivity and create uncertainty over the component accuracy. Hence, this thesis proposed a significant advancement on improving the mould fabrication process using a hybrid machining technique such as, combining two established machining processes into a new combined set-up known as Rotary Ultrasonic Assisted End Milling (RUAEM) whereby the advantages of each discrete process could be exploited synergistically. A total of 162 experimental runs based on statistical Response Surface Methodology matrix were executed comprising different level of machining parameter namely cutting speed, feed rate, depth of cut, frequency of vibration, amplitude vibration and alumina oxide slurry concentration towards surface roughness, cutting force and material removal rate. The investigation proceeded until a set of optimal machining parameter and satisfactory validation index were achieved. Based on the recommended optimized model, the best achievable surface roughness (Ra), resultant force (FR) and material removal rate (MRR) values was 0.12 µm, 4.98 N and 161.58 mg/min respectively. The results yielded that RUAEM process was able to improve 97% of the surface roughness, 92% of cutting force magnitude and 26% of material removal rate in comparison to the conventional machining processes within the same cutting conditions. For the multiple response optimization result, the combination of 111.45 rpm, 5.75 mm/min feed rate, 27.05 µm depth of cut, 20.91 kHz vibration frequency, 3 µm amplitude and 13.26% abrasive concentration yielded the highest desirability index of 0.87. Lastly, a good agreement value between the prediction and experimental validate the new proposed parameter optimization.

ABSTRAK

Keluli tahan karat, D2 digunakan meluas dalam industri acuan dan die terutama untuk alat pengacuan suntikan, alat membentuk dingin dan peralatan kejuruteraan ketepatan. Kebanyakan aplikasi memerlukan kemasan permukaan yang sangat baik kerana ia mencerminkan penampilan produk akhir. Walau bagaimanapun, pemesinan secara konvensional untuk bahan kekuatan tinggi (> 50 HRC) menghasilkan permukaan pemesinan yang kasar, maka teknik pemesinan khas diperlukan untuk mengekalkan kualiti pemesinan. Dalam amalan industri semasa, toleransi pemesinan dicapai melalui proses pemesinan akhir secara manual iaitu proses pengisaran dan pengggilapan berterusan untuk menghasilkan geometri dan kemasan permukaan yang diperlukan. Teknik pembuatan fabrikasi acuan dan die berpotensi untuk mengurangkan produktiviti dan mewujudkan ketidakpastian terhadap ketepatan komponen. Tesis ini mencadangkan teknik pemesinan terkini dalam proses fabrikasi acuan dengan menggunakan teknik pemesinan hibrid iaitu gabungan dua proses pemesinan ke dalam satu gabungan yang dikenali sebagai Pengisaran Akhir Berputar Berbantu Ultrasonik (RUAEM). Sebanyak 162 eksperimen telah dijalankan berdasarkan kaedah statistik Matrik Tindakbalas Permukaan yang berbeza parameter pemesinan iaitu kelajuan pemotongan, kelajuan suapan, kedalaman pemotongan, frekuensi getaran, getaran amplitude dan kecairan kepekatan alumina oksida terhadap kekasaran permukaan, daya pemotongan dan kadar penyingkiran bahan. Kajian diteruskan sehingga mencapai pemesinan yang optimum dan indeks pengesahan yang memuaskan. Berdasarkan model yang dioptimumkan, kekasaran permukaan yang dicapai (Ra), kekuatan pemangkin (FR) dan nilai penyingkiran bahan (MRR) adalah 0.12 μm, 4.98 N dan 161.58 mg/min masing-masing. Hasil kajian menunjukkan RUAEM mampu meningkatkan 97% kekasaran permukaan, 92% magnitud daya pemotongan dan 26% kadar penyingkiran bahan berbanding pemesinan konvensional dalam keadaan pemotongan yang sama. Keputusan Pengoptimuman Tindakbalas Pelbagai menunjukkan bahawa kombinasi 111.45 rpm, kadar suapan minuman 5.75 mm, kedalaman 27.05 μm, 20.91 kHz frekuensi getaran, 3 μm amplitude dan 13.26% kepekatan cairan menghasilkan indeks keinginan tertinggi 0.87. Nilai persetujuan yang baik di antara ramalan dan pengesahan melalui eksperimen telah menghasilkan pengoptimuman parameter yang baru.

ACKNOWLEDGEMENTS

Almighty Allah and peace be upon the beloved Prophet Muhammad s.a.w. Alhamdulillah. Thanks to Allah S.W.T for giving encouragement, strength, patience in completing this research and thesis writing. First and foremost, I would like thanks to my mother, my wife, daughters, sons, and my family for their constant prayer. Also, I sincerely thanks to my supervisor, Associate Professor Dr. Raja Izamshah Bin Raja Abdullah for his essential supervision, guidance, advice, encouragement and support. Also, the gratitude goes to Ir. Dr. Muhamad Arfauz Bin A Rahman as my co-supervisor for his time and support in giving advice and guidance towards the completion of this research and thesis. Not to forget, thanks to Mr. Hanafiah, Mr. Taufiq, Mr. Mazlan, Mr. Azhar, Mr. Hairul Hisham, Mr. Helmi and all the assistant engineer from Faculty of Manufacturing Engineering for their assistance and efforts in all the lab and analysis works. Lastly, thanks to Kementerian Pendidikan Tinggi for their financial support through the HLP scholarship.

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LIST OF ABBREVIATIONS

Al	-	Aluminium
adeq	-	Adequate
adeq Precision	-	Adequate Precision
Adj	-	Adjusted
Adj R-Squared	-	Adjusted Regression Squared
AutoCAD	-	Autodesk Computer-Aided Design
ASTM	-	American Society for Testing and Materials
Al_2O_3	-	Aluminium Oxide
AISI	-	American Iron and Steel Institute
AlCrN	-	Aluminium Cromium Nickel
ANOVA	-	Analysis of variances
Amp	-	Amplitude
BS	-	British Standard
BUE	-	Built Up Edge
B_4C	-	Boron carbide
CAM	-	Computer Aided Manufacturing
CNC	-	Computer Numerical Control
Cor Total	-	Total Corrected for the Means
DC	-	Direct Current
Df	-	Degree of Freedom

DOC	-	Depth of Cut
DIN	-	German Institute for Standardization
DOE	-	Design of Experiment
DOF	-	Degree of Freedom
EVA-L	-	Evaluation Length
EDM	-	Electrical Discharge Machining
EM	-	End Milling
EMF	-	Electromagnetic Fields
EPH	-	High precision and accuracy type cutting tools
FI	-	Function Interaction
FKP	-	Faculty Manufacturing Engineering
Fx	-	Feed Force
Fy	-	Feed Normal Force
Fz	-	Thrust Force
Freq	-	Frequency
HDD	-	Historical Data Design
HRUAM	-	Hybrid Rotary Ultrasonic Assisted Machining
HRC	-	Hardness Rockwell C scale
HSS	-	High Speed Tool Steels
ISO	-	International Organization for Standardization
JIS	-	Japanese Industrial Standard
MQL	-	Minimum Quantity Lubricants
MLS	-	Method of Least Squares
MRR	-	Material Removal Rate

N	-	Newton
NTB	-	Nominal The Best
PCBN	-	Poly-Crystalline Cubic Boron Nitride
PCD	-	Polycrystalline Diamond
Prob> F	-	Probability greater F
Pred	-	Prediction
Pred R-Squared	-	Prediction Regression Squared
p-value	-	probability value
RC	-	Rockwell Hardness measured on the C scale
RPM	-	Revolutions Per Minute
RUM	-	Rotary Ultrasonic Machining
RUAM	-	Rotary Ultrasonic Assisted Machining
RUAEM	-	Rotary Ultrasonic Assisted End Milling
RSM	-	Response Surface Methodology
R-Squared	-	Regression Squared
SAE	-	Society of Automotive Engineers
SEM	-	Scanning Electron Microscopy
SiC	-	Silicon carbide
TWR	-	Tool Wear Rate
TiAlN	-	Titanium Aluminium Nickel
USM	-	Ultrasonic Machining
UTeM	-	Universiti Teknikal Malaysia Melaka
UVAM	-	Ultrasonic Vibration Assisted Micro-Milling
WOC	-	Width of Cut

XRD	-	X-Ray Diffraction Analysis
3D	-	Three Dimentional

LIST OF SYMBOLS

A	-	amplitude vibration
df	-	Degree of freedom
f	-	frequency
f	-	feed rate
Fx	-	Feed force in x-axis
Fy	-	Feed normal force in y-axis
Fz	-	Thrust force in z-axis
Doc	-	depth of cut
Hz	-	hertz
kHz	-	kilohertz
Ln	-	Natural logarithm
HV	-	vickers pyramid number
μm	-	micrometer
mm	-	milimeter
mm^3	-	cubic milimeter
mm^3/s	-	cubic milimeter per second
mm/min	-	Millimeter per minute
min	-	minute
MRR	-	material removal rate
N	-	newton

R	-	regression
Ra	-	arithmetic average value of surface roughness
rpm	-	revolution per minute
Sqrt	-	square root
V	-	volt (voltage)
Vc	-	cutting speed
vs	-	versus
Vg	-	volume fractured per grit
%	-	percent
*	-	multiplication
ξ	-	size of particle
$\varphi(\xi)$	-	number of particles of size ξ
π	-	phi ($\pi = 3.142$)
rc^3	-	radius of the contact indentation zone
$\approx$	-	equivalent
$\leq$	-	less or equal
X	-	times

LIST OF PUBLICATIONS

Award:

1. Azlan, R., Izamshah, R., and Akmal, M., 2019. The Effectiveness of Rotary Ultrasonic Assisted End Milling (RUAEM) with Ultrasonic Frequency Controller for Increasing Material Removal Rate (MRR) for Machining Hardened D2 Tool Steel Material. *Symposium On Intelligent Manufacturing And Mechatronics 2019 (SIMM2019)*, Faculty of Manufacturing Engineering, UTeM, Malacca, Malaysia,8 July 2019. (Best Paper Award)
2. Azlan Bin Ramli, 2019. Improvement of Material Removal Rate (MRR) Through Ultrasonic Vibration Frequency In Machining Hardened Material. *Majlis Anugerah Kecemerlangan Staf PMS 2019, Politeknik Muadzam Shah, Pahang*, Malaysia, 14 November 2019. (Anugerah Terbaik Penyelidikan)
3. Azlan Bin Ramli, Raja Izamshah Bin Raja Abdullah, and Muhammad Akmal Bin Mohd Zakaria, 2019. New Vibro-Rotary Machining Technique For Achieving Superfine Surface Finish. *International Festival of Innovation On Green Technology 2019 (IFINOG) and IDEAS,* Universiti Malaysia Pahang, Malaysia, 19-21 April 2019. (Bronze Medal)
4. Azlan, R., Izamshah, R., Hadzley, M., Kasim, M. S., Arfauz, M., and Akmal, M., 2016. Surface Evaluation of Rotary Ultrasonic Assisted Machining Technique for Hardened Steel Material. *Advanced Processes and Systems in Manufacturing An*

International (APSIM 2016), Everly Hotel, Putrajaya, Malaysia, 28-30 August 2016. (3rd Winner in Best Paper Award)

Journal:

1. R. Azlan, R. Izamshah, M. S. Kasim, S. Ding, M. Akmal, 2019. Rotary Ultrasonic Assisted Machining Of Mould And Die Material. *Journal of Advanced Manufacturing Technology,* Vol. 13, No 2 (1) (2019), pp. 1-13, 2019. (Published)(Scopus).
2. R. Azlan, R. Izamshah, M.S. Kasim and M.S. Noorazizi, 2019. Effects of RUAEM Parameters Toward Cutting Force for Machining Hardened Steel Material. *International Journal of Mechanical & Mechatronics Engineering,* Vol. 19 No. 05, pp. 142-148, 2019.(Published)(Scopus).
3. Ramli, A., Raja Abdullah, R.I., Abu Bakar, M. H.,Kasim, M.S., Rahman, A., and Mohd Zakaria, M.A., 2017. Investigation on Improvement of Surface Roughness Using Rotary Ultrasonic Assisted Machining Technique for Hardened Steel Material. *Journal of Mechanical Engineering,* 3(1), pp. 119-134. (Published)(Scopus)
4. Azlan, R., Izamshah, R., Kasim, M. S., Akmal, M., and Nawi, M. A. H. M., 2017.Improvement of Machining Performance using Hybrid Rotary Ultrasonic Milling (HRUAM) for Hardened D2 Tool Steel Material.*International Journal of Applied Engineering Research*, 12(23), pp.13506-13513. (Published)(Scopus)

Proceedings conference paper:

1. Azlan, R., Izamshah, R., and Akmal, M., 2019. Improvement of Material Removal Rate (MRR) Through Ultrasonic Vibration Frequency In Machining Hardened

Material. *Symposium On Intelligent Manufacturing And Mechatronics 2019 (SympoSIMM 2019),* Faculty of Manufacturing Engineering, UTeM, Malacca, Malaysia, 4 July 2019. (Springer Nature Singapore Pte Ltd. 2020)

2. Azlan Ramli, Raja Izamshah Raja Abdullah, Linawati Razak@Ali, 2019. Application of Full Factorial Analysis Design For Determining Surface Roughness Model In End Milling of Hardened Steel Material Using Solid Carbide Niti Co 30 Standard End Mill. *Proceeding of the TVET on Research via Exposure 2019,* Politeknik Muadzam Shah, Pahang, Malaysia, 1-2 August 2019. Politeknik Muadzam Shah Pahang Publisher.

3. Azlan, R., Izamshah, R., Hadzley, M., Kasim, M. S., Arfauz, M., and Akmal, M., 2016.Improvement of Cutting Force Using Ultrasonic Vibration for Machining Mold and Die Materials. *Proceedings of Mechanical Engineering Research Day 2017 (MERD' 17),* Melaka, Malaysia, 30 March 2017. Universiti Teknikal Malaysia Melaka Publisher. (ISI)

4. Azlan, R., Izamshah, R., Hadzley, M., Kasim, M. S., Arfauz, M., and Akmal, M., 2016. The Effect of Rotary Ultrasonic Assisted Machining on the Thrust Force Generation of Cutting D2 Tool Steel Materials. *Proceedings of Innovative Research and Industrial Dialogue 2016 (IRID' 16),* Melaka, Malaysia, 20 Disember 2016. Universiti Teknikal Malaysia Melaka Publisher.

5. Azlan, R., Izamshah, R., Hadzley, M., Kasim, M. S., Arfauz, M., and Akmal, M., 2016. Surface Evaluation of Rotary Ultrasonic Assisted Machining Technique for Hardened Steel Material, *Proceedings of International Conference on Advanced Processes and Systems in Manufacturing An International (APSIM 2016),*Everly Hotel, Putrajaya, Malaysia, 28-30 August 2016. National University of Malaysia Publisher. (ISI)

6. Azlan, R., Izamshah, R., Hadzley, M., Kasim, M. S., Arfauz, M., and Akmal, M., 2016.Experimental Investigation of Surface Roughness Using Ultrasonic Assisted Machining of Hardened Steel. *Proceedings of Mechanical Engineering Research Day 2016 (MERD' 16),* Melaka, Malaysia, 31 March 2016. Universiti Teknikal Malaysia Melaka Publisher. (ISI)

eBook:

1. Azlan, R., Izamshah, R., and Akmal, M., 2019. Improvement of Material Removal Rate (MRR) Through Ultrasonic Vibration Frequency In Machining Hardened Material. *Symposium On Intelligent Manufacturing And Mechatronics 2019 (SympoSIMM 2019),* Faculty of Manufacturing Engineering, UTeM, Malacca, Malaysia, 4 July 2019. (Springer Nature Singapore Pte Ltd. 2020)