



**Ain Shams University
Faculty of Engineering**

An Investigation into High Precision Hard Turning of some Alloy Steels

A Thesis

**Submitted in Partial Fulfillment of the Requirements for
Degree of Ph. D. in Mechanical Engineering (Production)**

By

Mohamed Abdul Monim Abdu Asalam Shalaby

M. Sc. in Mechanical Engineering

Supervised by:

Prof. Dr. Sc. Techn. M. A. El Hakim

Prof. Dr. Magdy. M. Abdelhameed

2011



جامعة عين شمس
كلية الهندسة

دراسة عملية الخراطة عالية الدقة لبعض أنواع الصلب السبائكي المقسى

رسالة

مقدمة كمتطلب جزئي للحصول على درجة دكتوراه الفلسفة في الهندسة الميكانيكية (إنتاج)

مقدمة من:

مقدم مهندس/ محمد عبد المنعم عبدالسلام شلبي

ماجستير في الهندسة الميكانيكية

تحت إشراف:

أ.د. محمد علاء الدين سليمان الحكيم
أ.د. مجدي محمد عبد الحميد

2011

Summary

Grinding is used to produce hardened steel parts with high accuracy and surface quality. Due to the relatively high cost of the grinding process, hard machining has been suggested to partially replace grinding. According to previous research work, hard turning has been successfully used to produce accurate cylindrical parts from different hardened steels on CNC and high precision lathes. However, hard turning of high alloy steels still constitutes a challenge to the machining process due to the presence of very hard carbide particles in their microstructure. Some hardened alloy steels may also exhibit secondary hardening at certain temperatures that adds extra hardness, which leads to more machining difficulties. The choice of the proper tool materials to machine those workpiece materials is therefore of prime importance.

The effects of extremely small values of feed and depth of cut together with large tool nose radius, that are usually used in hard turning on the machining quantities, e.g. cutting forces, surface roughness.. etc., need more investigations. Conditions for chatter-free machining, which have not been previously considered in hard tuning have to be studied in order to attain the required quality.

The present study, aiming at the achievement of economic high precision hard turning of two types of high alloy tool steel, namely; T15 high speed steel (HSS), known to exhibit secondary hardening, and D2 cold work alloy tool steel, which has no tendency to secondary hardening and has been used for comparison with HSS. Annealed HSS has been also used to determine the effect of increasing the workpiece hardness on the different machinability criteria.

High precision hard turning has been performed on a conventional center lathe that has been modified to give a stepless variation of the spindle speed in the range of (5-1100) rpm. The feed drive has been also

modified to give low feeds down to 0.0125 mm/rev. The depth of cut in the order of micron(s) has been achieved through the implementation of a piezoelectric-based fast tool servo (FTS) on the used machine tool. The piezoelectric actuator is driven through a linear power amplification circuit. A PI controller has been designed and applied to control the required depth of cut.

In order to enable the selection of the most proper tool material, for machining the used workpieces four different tool materials have been used to perform the hard turning experiments, namely; sintered PCBN (60%CBN, TiN as a binder), PVD TiN coated sintered PCBN (60%CBN, TiN as a binder), mixed alumina ceramic (70%Al₂O₃+30%TiC), and (TiN- Al₂O₃- TiC) coated carbide.

The cutting force components have been measured using a three-component tool force dynamometer. The cutting temperature has been measured using the tool-workpiece thermocouple technique. Scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were used to investigate the wear patterns of each tool material. Tool wear has been measured using a tool room microscope, and surface roughness has been measured using a digital surface profilometer.

Both mechanistic and thermal analytical models have been established to explain the phenomena associated with the cutting force and cutting temperature measurements. The validity of each model has been proved using experimentally determined values of the cutting force components and cutting temperature.

An optimization technique has been developed for the roughing, semi-finishing, finishing, and high precision turning steps to obtain the optimum cutting speed that achieves minimum machining cost using a depth of cut and a feed that give the assigned accuracy and surface roughness.

A comparison has been made between the machining cost per piece in case of hard turning and cylindrical grinding.

The following results have been obtained:

1. High precision hard turning with relatively high accuracy (IT5) and good surface roughness ($R_z=1\mu\text{m}$) can be successfully carried out on the modified conventional general purpose lathe in case of hard machining of HSS.
2. The mechanistic model has shown that the ratio between the radial force component to the tangential force component (F_r/F_c) is >1 as the depth of cut (a) is $<$ the tool nose radius (r). This ratio was found to increase with the decrease of the depth of cut and/or the increase of the nose radius.
3. The values of the cutting force components when machining HSS in its hardened and annealed states, and when machining the D2 tool steel in its hardened state are remarkably affected by the type of the produced chips. Continuous chips cause larger cutting force components than those caused by discontinuous chips due to higher friction coefficient at the tool-chip interface. At relatively low cutting speeds (range of discontinuous chips for the hardened material), the annealed HSS produces larger cutting forces than the hardened HSS. However, as the cutting speed increases, the hardened HSS produces continuous chips and hence the cutting force components become considerably larger than those obtained in turning the annealed HSS.
4. Secondary hardening has been observed only during the turning of hardened HSS, which results in a sudden increase of both cutting force components and cutting temperature at a certain cutting speed. The shear plane temperature rise has been

calculated using the thermal model to detect the occurrence of secondary hardening.

5. Although both the HSS and D2 tool steel have been initially hardened to the same value of 52 HRC, the cutting force components produced when machining the hardened HSS, within a certain speed range are 10% higher than those produced when machining the hardened D2 tool steel under the same cutting conditions due to the tendency of the hardened HSS to undergo secondary hardening during cutting.
6. The cutting force components produced when machining the hardened HSS using the sintered PCBN cutting tool are found to be higher than those obtained when using the coated carbide and ceramic tools, which is attributed to the difference in the coefficient of friction (μ) at the tool- chip interface when using the different tool materials. The increase of (μ) leads to the increase the cutting force components as confirmed by the measurements of the chip compression ratio (λ_c) and the calculations of (μ) at the tool-chip interface using the proposed mechanistic model.
7. Empirical relationships have been established between the cutting force components (F_r , F_c , F_a) and the depth of cut (a), feed (s), nose radius (r), and tool flank wear land width (B) , which have the following validity ranges:

$$0.01 \leq a \leq 0.3 \text{ mm}$$

$$0.0125 \leq s \leq 0.1 \text{ mm/rev}$$

$$50 \leq v \leq 300 \text{ m/min}$$

$$B \leq 0.2 \text{ mm}$$

The obtained relationships are given in the following table:

Workpiece material	Used tool	Empirical relationships for the cutting force components (N)					
Annealed HSS	Coated carbide	$F_r =$	1100	$a^{0.5}$	$s^{0.5}$	$r^{0.5}$	$(1+5.5B)$
		$F_c =$	1160	$a^{0.55}$	$s^{0.55}$	$r^{0.4}$	$(1+3B)$
		$F_a =$	570	$a^{0.55}$	$s^{0.55}$	$r^{0.15}$	$(1+2B)$
Hardened HSS		$F_r =$	1220	$a^{0.5}$	$s^{0.4}$	$r^{0.55}$	$(1+8B)$
		$F_c =$	1260	$a^{0.55}$	$s^{0.45}$	$r^{0.5}$	$(1+5.5B)$
		$F_a =$	780	$a^{0.55}$	$s^{0.45}$	$r^{0.1}$	$(1+4.5B)$
	PCBN	$F_r =$	1340	$a^{0.5}$	$s^{0.4}$	$r^{0.55}$	$(1+8B)$
		$F_c =$	1360	$a^{0.55}$	$s^{0.45}$	$r^{0.5}$	$(1+5.5B)$
		$F_a =$	860	$a^{0.55}$	$s^{0.45}$	$r^{0.1}$	$(1+4.5B)$
	Ceramic	$F_r =$	1140	$a^{0.5}$	$s^{0.4}$	$r^{0.55}$	$(1+8B)$
		$F_c =$	1213	$a^{0.55}$	$s^{0.45}$	$r^{0.5}$	$(1+5.5B)$
		$F_a =$	740	$a^{0.55}$	$s^{0.45}$	$r^{0.1}$	$(1+4.5B)$
Hardened D2 tool steel	PCBN	$F_r =$	1220	$a^{0.5}$	$s^{0.4}$	$r^{0.55}$	$(1+8B)$
		$F_c =$	1240	$a^{0.55}$	$s^{0.45}$	$r^{0.5}$	$(1+5.5B)$
		$F_a =$	800	$a^{0.55}$	$s^{0.45}$	$r^{0.1}$	$(1+4.5B)$
	Ceramic	$F_r =$	1010	$a^{0.5}$	$s^{0.4}$	$r^{0.55}$	$(1+8B)$
		$F_c =$	1110	$a^{0.55}$	$s^{0.45}$	$r^{0.5}$	$(1+5.5B)$
		$F_a =$	700	$a^{0.55}$	$s^{0.45}$	$r^{0.1}$	$(1+4.5B)$

8. Mixed alumina ceramic (70%Al₂O₃+30%TiC), and (TiN- Al₂O₃-TiC) coated carbide cutting tools have outperformed both types of the used sintered PCBN in machining the hardened HSS, which can be attributed to the adaptive wear behavior of ceramic and coated carbide exhibited during machining due to the formation of tribologically protective oxide films protect both materials. TiN coated PCBN has not shown any significant

improvement in tool performance when compared to the uncoated PCBN.

9. Mixed alumina ceramic (70%Al₂ O₃+30%TiC) has outperformed both types of the used sintered PCBN in machining the hardened D2 tool steel.
10. Ceramic (70%Al₂ O₃+30%TiC) tools represent the proper choice in machining both the hardened HSS and the hardened D2 tool steel.
11. The cutting speed (v) -Tool life (T) relationships have been determined for the different used workpiece-tool materials for a specified flank wear land width (B) as follows:

Workpiece material	Tool material	Cutting speed relationships (m/min)
Annealed HSS	Coated carbide	$v = \frac{262}{T^{0.78} s^{0.44} a^{0.33}}$
Hardened HSS	Coated carbide	$v = \frac{261}{T^{0.65} s^{0.23} a^{0.16}}$
	Ceramic	$v = \frac{520}{T^{0.6} s^{0.25} a^{0.2}}$
	PCBN (BNX20)	$v = \frac{108}{T^{0.66} s^{0.19} a^{0.1}}$
	TiN coated PCBN(7020)	$v = \frac{101}{T^{0.56} s^{0.15} a^{0.09}}$
Hardened D2 steel	Coated carbide	$v = \frac{1054}{T^{0.29} s^{0.18} a^{0.12}}$
	Ceramic	$v = \frac{230}{T^{0.69} s^{0.26} a^{0.2}}$
	PCBN (BNX20)	$v = \frac{1727}{T^{0.71} s^{0.3} a^{0.21}}$

12. Using a cutting speed (v) of 120 m/min, feed (s) of 0.025 mm/rev, nose radius (r) of 1.6 mm, and depth of cut (a) of 0.1 mm, a minimum surface roughness (R_z) of 2 μm can be achieved in the precision turning of annealed HSS. In the case of precision turning of hardened HSS, a minimum surface roughness (R_z) of 1 μm can be attained by using a cutting speed (v) of 120 m/min, feed (s) of 0.0125 mm/rev, nose radius (r) of 2.4 mm, and depth of cut (a) of 0.1 mm. The decrease of the feed (s) below 0.025 mm/rev increases the surface roughness (R_z) in case of machining the annealed HSS due to material side flow. The decrease of the feed (s) below this value when machining the hardened HSS does not remarkably improve the surface quality.
13. Surface roughness of ($R_z=2 \mu\text{m}$) has been achieved using the optimum cutting conditions when machining the hardened HSS
14. A minimum depth of cut of 5 μm has been achieved by the application of piezoelectric-based fast tool servo (FTS) using the PI controller, with an error of 0.02 μm . The error increases with increasing the depth of cut and the flank wear land width due to the increase of the radial force component.
15. While the productivity has been increased by 100%, a cost reduction of 80 % has been achieved by high precision hard turning of HSS using the ceramic tool instead of grinding using the optimum machining variables (v , s , a) for nearly the same product surface roughness ($R_z=2 \mu\text{m}$) and dimensional accuracy (IT5) as obtained by cylindrical grinding. In precision hard turning of D2 tool steel, an accuracy level of IT6 can only be attained.

Contents

	Page
Chapter (1): Literature review	1
1.1 Competitive operations to hard machining	2
1.2. Chip formation in hard turning	3
1.3. Minimum undeformed chip thickness	5
1.4. Tool performance assessment in hard turning	7
1.4.1. Performance of Al_2O_3 as a cutting tool material	18
1.5. Cutting forces and surface roughness in hard turning	20
1.6. Cutting temperature in hard turning	25
1.7. Residual stresses in hard turning	27
1.8. Application of high precision positioning system in high precision machining	30
1.9. Statement of the problem	32
1.10. Objectives of the present work	34
1.11. Scope of work	34
1.12. Thesis outline	35
 Chapter (2): Theoretical background	 37
2.1. Basic concepts and definitions	37
2.2. Types of cutting tool materials used for hard machining of steel	38
2.3. Chip formation during metal cutting	40
2.4. Built-up edge	41
2.5. Cutting forces	42
2.6. Chatter in machining	43
2.6.1. Factors affecting chatter occurrence	44
2.7. Surface integrity	45

2.8. Cutting temperature	46
2.8.1. Methods of cutting temperature measurement	48
2.9. Cutting Tool failure	51
2.10. Tool wear mechanisms	53
2.11. Tool life	54
2.12. Strengthening mechanisms of alloy steels	55
2.12.1. Plastic deformation	55
2.12.2. Strain hardening	56
2.12.3. Recrystallization	57
2.12.4. Heat treatment of alloy steels	58
2.12.5. Hardenability	61
2.13. Dimensional errors in precision hard turning	62
2.13.1. Error due to tool flank wear	62
2.13.2. Error due to thermal expansion	62
2.13.3. Error due to flexibility of MFTW system	63
2.14. Machining economy	65
2.15. Optimization of the high precision hard turning process	67
2.15.1. Roughing step	67
2.15.2. Semi -finishing step	68
2.15.3. Finishing and high precision steps	69
2.16. Grinding	73
2.17. High precision turning requirements	73
2.17.1. Modeling of the FTS	75

Chapter (3): Modeling of the precision turning process

3.1. Mechanistic model for precision hard turning	77
---	----

3.1.1. Mechanistic model parameters	78
3.2. Thermal model for the precision turning	96
3.2.1. Temperature in the primary deformation zone	96
3.2.2. Temperature in the secondary deformation zone	97
 Chapter (4): Experimental Work	 103
4.1. Workpiece materials	103
4.2. Tempering tests	104
4.3. Cutting tool materials	106
4.4. Machine tool specifications	109
4.5. Workpiece preparation	110
4.6. Measurement of the cutting force components	111
4.6.1. Tool force dynamometer calibration	113
4.7. Cutting temperature measurement	118
4.8. Surface roughness measurement	123
4.9. Tool wear measurement	124
4.10. Cutting variables	125
4.11. High precision turning operation	125
 Chapter (5): Results and Discussion	 136
5.1. Cutting forces	138
5.1.1. Effect of cutting speed (v) on the cutting force components	138
5.1.2. Effect of depth of cut on the cutting force components in machining HSS	148
5.1.3. Effect of feed on the cutting force components in machining HSS.	151

5.1.4. Effect of nose radius on the cutting force components in machining HSS	154
5.1.5 Effect of flank wear on the cutting force components in machining HSS	155
5. 1.6. Empirical relationships	157
5.1.7. Chip compression ratio (λ_c).	158
5.2. Cutting temperature	162
5.2.1. Effect of cutting speed (v)	162
5.2.2. Effect of depth of cut and feed on the cutting temperature in machining the HSS	166
5.3. Tool wear	168
5.3.1. HSS workpiece	168
5.3.1.1. Tool wear mechanisms in machining the hardened HSS	173
5.3.1.2. Protection mechanisms	177
5.3.2. D2 tool steel	181
5.3.2.1. Tool wear mechanisms in machining the hardened D2 tool steel	184
5.3.2.2. Discussion	188
5.3.3. Effect of secondary hardening on tool wear	190
5.4. Tool life	192
5.4.1. HSS workpiece	192
5.4.2. D2 tool steel	199
5.5. Surface roughness	204
5.1.1. Effect of the cutting speed (v) on surface roughness	204
5.5.2. Effect of nose radius and feed on surface roughness	211
5.5.3. Effect of tool wear on surface roughness	214
5.5.4. Effect of chatter on surface roughness (R_z)	216

5.6. Chatter results	218
5.7. High precision turning system testing	221
5.7.1. System identification	221
5.7.2. High precision turning using open loop system	223
5.7.3. High precision turning using closed loop system	225
5.8. Optimization of the cutting variables in the hard precision turning	230
5.9. Calculation of total time consumed in the grinding of hardened HSS	237
5.10. Cost analysis	238
5.10.1. Variable cost/piece in the high precision hard turning of HSS	238
5.10.2. Variable cost/ piece in grinding	238
5.11. Accuracy analysis	240
5.12. Comparison between surface roughness produced by high precision hard turning and grinding	240
Chapter (6): Conclusions and recommendations for future work	242
References	249
Appendix (A): Grey cast iron machining	262
Appendix (B): Mechanistic model secondary results	263
Appendix (C): Thermal model results	269
Appendix (D): Accuracy Analysis	279
Appendix (E): Machining economy	281

List of Figures

	Page
Fig. (2.1) Turning operation	43
Fig. (2.2) Dissipation of heat during metal cutting	48
Fig. (2.3) Wear mechanisms vs. cutting temperature	53
Fig. (2.4) Development of flank wear land width vs. cutting time	54
Fig. (2.5) (v - T) relationship, indicating the Taylor's domain	55
Fig. (2.6) Effect of austenization and tempering temperatures on secondary hardening (AISI A2 tool steel)	60
Fig. (2.7) Tempering diagram of some HSSs and alloy steels indicating secondary hardening effect	60
Fig. (2.8) Effect of tool flank wear land width (B) on the reduction of the depth of cut (workpiece radial error)	62
Fig. (2.9) Error due to thermal expansion of the workpiece in turning	63
Fig. (2.10) Schematic of a turning operation	64
Fig. (2.11) Flow chart illustrating the optimization technique for the hard precision turning	72
Fig. (2.12) Types of flexural hinges	75
Fig. (2.13) (a) Structure of the flexure mechanism, (b) Equivalent model	76
Fig. (3.1) Proposed model for oblique cutting using a tool with nose radius (r)	78
Fig. (3.2) Estimation of the undeformed chip thickness for $a/r < 1$	80
Fig. (3.3) Variation of the undeformed chip thickness (h_i) within the contact angle (ϕ_i)	81
Fig. (3.4) The Chip flow direction angle (η_c)	82