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Faculty of Engineering

An Investigation into High Precision Hard Turning of some Alloy Steels

A Thesis

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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

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مقدمة من:

مقدم مهندس/ محمد عبد المنعم عبدالسلام شلبي

ماجستير في الهندسة الميكانيكية

تحت اشراف:

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

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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%Al_2O_3+30%TiC), and (TiN- Al_2O_3- 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=1µm) 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:

$0.01 \leq a \leq 0.3$ mm

$0.0125 \leq s \leq 0.1$ mm/rev

$50 \leq v \leq 300$ m/min

$B \leq 0.2$ 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%Al_2O_3+30%TiC), and (TiN- Al_2O_3-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 triboligically 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%Al_2 O_3+30%TiC) has outperformed both types of the used sintered PCBN in machining the hardened D2 tool steel.
10. Ceramic (70%Al_2 O_3+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**	$v = \frac{105.4}{T^{0.29} s^{0.18} a^{0.12}}$
	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 μm) has been achieved using the optimum cutting conditions when machining the hardened HSS
14. A minimum depth of cut of 5μm 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 μm) 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.

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