A study on Effect of Surface Finishing Processes on Surface Roughness of AISI D2 Tool Steel

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Abstract—**According to recent studies, dry hard turning is more beneficial practical process compared to a grinding operation, it increases quality, reduces cost and lead-time for machined parts. In this study, effects of workpiece hardness, feed rate, depth of cut and cutting speed on surface roughness were studied using chamfered and honed CBN inserts. Four factors (hardness, depth of cut, feed rate and cutting speed) were considered and - two level fractional experiments were conducted and analysis of the variance was performed. Furthermore this study shows that the effects of grinding of heat treated AISI D2 specimens on surface roughness were conducted and a comparison took place with hard turning.**

To investigate the effect temperature increase on both techniques, the machined surface of workpieces is examined using optical and scanning electron microscopy SEM. Practical results shows the lower workpiece hardness and lower cutting conditions resulted in a better surface roughness.

Finally results showed that in hard machining not only the machining parameters have an influence on the surface roughness but also the material hardness found effective factor in finishing process.

Index Terms: **hard turning, surface quality, CBN cutting tool.**

I. INTRODUCTION

S urface quality is one of the most specified customer requirements in machining of parts. Hard machining technique (hard turning) allows manufacturers to simplify their processes and still achieve the desired surface finish quality. The hard machining technique can be defined as the finishing of a hardened ferrous metal by hard turning into a finished component. When compared to the soft machining-hardening technique (grinding) hard turning offers a) higher productivity b) greater flexibility c) lower cost of machining and d) less energy consumption. However, finish dry hard turning is a challenging process and desired part quality requirements   are tough to achieve in conventional lathes [1-6].

II. HARD TURNING TECHNOLOGY

A. Factors Affecting Surface Quality In Hard Turning

This technique outlines major factors such as workpiece material (hardness), cutting tool (geometry), cutting conditions, and machine tool rigidity (vibration) and tool wear. These factors affect performance measures such as accuracy, surface roughness, integrity and productivity [7-9]. Hard turning has been a beneficial practice to metal component manufacturers that are in need of technologies to increase the quality of their products and overall competitiveness. Hard turning can be performed using cubic boron nitride (CBN) cutting tools because the heat generated during cutting is carried away with the chips from the cutting zone eliminating use of coolants, and due to workpiece hardness [10-12].
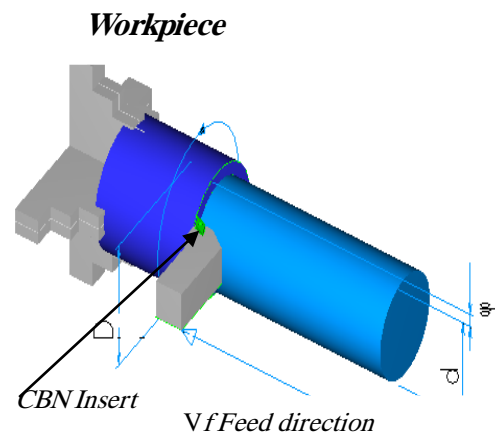

Figure 1. Hard turning components

B. Workpiece properties and hardness.

Workpiece properties such as high hardness, wear resistance and resistance to deformation were important in the field of application. Due to the difference in properties of hardened workpiece material, the metal cutting process and there conditions differ in hard turning. To obtain the desired surface quality and integrity, appropriate finishing conditions such as cutting speed, feed rate and depth of cut are selected. Since, the dealing with tool steels that are part of die and mold

material which are used to produce active components, suitable heat treatment greatly influences the component functionality and overall tool performance. The interaction between surface roughness and hardness influences the workpiece wear resistance and its life. Cold Work Tool steel AISI D2 is selected in this study to investigate its finishing process and wear resistance. Tugrul Özel, showed factors affecting surface finishing in hard turning [13]. Prior research showed that workpiece hardness has a profound effect on the performance of the CBN tools [14, 15, and 16] and also quality of finished machined surfaces [17]. S. N. Melkote, R. A. Peascoe, studied the effect of workpiece hardness on residual stresses [18].

C. Cubic Boron Nitride:

Cubic boron nitride is about twice as hard as aluminum oxide and is capable of withstanding cutting temperatures of up to 2500F (1371C) before breaking down. Manufacturing CBN is synthesized in crystal form with the aid of a catalyst, heat, and pressure. The combination of extreme heat 2725F (1496C) and tremendous pressure (947, 540, 0000 psi) on cubic boron nitride and the catalyst produces a strong, hard, blocky, crystalline structure. According to recent studies, it is evident that effect of edge geometry on surface quality is significant [19].

Theile et al showed that large hone radius tools produce more compressive stresses, but also leave "white-layers" [20]. Chou et al ,experimentally investigated the influence of CBN content on surface quality and tool wear in hardened steel [21]. Özel investigated the influence of edge geometry in CBN tools with respect to stress and temperature development through finite element simulations in hard turning [23]. Gerard Poulachon, B.P Bandyopahyay, investigated the flank and crater wear mechanisms of CBN cutting tools in finish hard turning of various heat treated steels, they showed the flank grooves have been correlated with hard carbide content of the workpiece. Hard turning components are shown schematically in Figure 1.

D. Cutting Conditions (Cutting Speed, Feed Rate and Cutting Depth.)

For hard turning processes, material hardness is usually between 50-65 HRC. Performance of CBN cutting tools is highly dependent on two factors a) heat treatment and properties of the workpiece, b) the cutting conditions i.e. cutting speed, feed-rate, and depth of cutting [21]. In particular the cutting speed and depth of cut significantly influence tool life [22]. The surface roughness increases as the feed rate increases and lower workpiece hardness resulted in better surface roughness in the finish of hard turning of tool steel, plotted and analyzed by Tsu-Kong Hsu, Erol Zeren [23].

Several studies on the effect of cutting conditions on surface quality of several types of steel using various finishing operations have been conducted and the results of these studies found that the greater the number of factors involved in the study increased the accuracy of the results [24, 25, 26].

E. Surface Finish Parameters

Some of the popular parameters of surface finish specification are described as follows:
• *Roughness average* (Ra): This parameter is also known as the arithmetic mean roughness value, AA (arithmetic average) or CLA (center line average). Ra is universally recognized and the most used international parameter of roughness.

Where Ra = the arithmetic average deviation from the mean line L = the sampling length, y = the ordinate of the profile curve It is the arithmetic mean of the departure of the roughness profile from the mean line.

$$Ra = 1/L \int |y(x)| dx = 1/N \sum |y_i| \qquad (1)$$

• *Root-mean-square* (rms): roughness (R*q*): This is the root-mean-square parameter correspon- ding to R*a*

$$Rq = [1/L \int y^2(x) \, dx]^{1/2} = [1/N \sum y_i^2]^{1/2} \qquad (2)$$

Since Ra and Rq are the most widely used surface parameters in industry, Ra was selected to express the surface roughness in this study.

F. Theoretical Model of Surface Roughness

It is well known that the theoretical surface roughness is primarily a function of the feed for a given nose radius and varies as the square of the feed rate [8].

In order to accurately model the surface roughness in hard turning machining, we need to first understand the current model, and investigate if it is necessary to take into account any imperfections in the process. The standard equation for modeling surface roughness is as follows:

$$Ra = f^2/32re \qquad (3)$$

Where,
Ra: Surface Roughness (mm)
f: Feed Rate (mm/rev)
re: Tool Nose Radius (mm)

III. EXPERIMENTAL TECHNIQUE AND PROCEDURES

A. Outlines of the Study:

For deep understanding of the finishing process technology in the field of tool manufacturing, especially in dies and molds which are exposed to repeated loads that influence on their function, workpiece hardness and finishing process conditions are studied carefully. Because of the importance of surface quality in tool life and its function, the effect of the finishing processes on the surface quality of hardened AISI D2 tool steel is considered as a major factor in this work. To investigate

this phenomenon on the produced surface, the impact of each of the above finishing process conditions is studied as well as the interactions between them, and are represented graphically.

B. Experimental Details

The cylindrical parts AISI D2 specimens that are used in these experiments have 30 mm diameters and 80 mm length. Two different processes to produce two different specimens are utilized, first s hard turning were the specimen hardened before the roughing and finishing operation, the other is soft machining-hardening technique, the specimens are annealed before rough machining then hardening to obtain the desired hardness values, last step will use grinding as a finishing process in this technique. Fig 2 illustrates a flow chart for these techniques. For both soft and hard techniques specimens are dived into 2 groups, one low hardiness value and high hardness value, and heat treated (through-hardened) in a furnace heat treatment in order to obtain the desired hardness values of 50 and 55 HRC. However, the subsequent hardness tests by using Future Tech Rockwell type hardness tester shows the actual hardness of each group was 51±1.0 and 56±2 HRC. Henceforth, the hardness values are defined by the mean values of the measured workpieces hardness (51 and 56 HRC), see Table 1.

TABLE 1. Thermal Cycling Used

Process	Temperature(C)	Time(min)	Medium	Hardness (HRC)
preheating	600	60		
austenizing	1040	2.5/1 mm	Oil	62-64
quenching	50-60			
washing	90		Hot water	
tempering	200	60	Cooling in air	51
	300			56

Soft machining-hardening technique

Hard machining technique

Figure 2. Illustrating hard and soft technic

C. Tooling and Insert Geometry

CBN cutting tools inserts from TIZIT of chamfered and honed edge as illustrated in Fig 3, Reference number (DCMX 150608SN TA201) insert is used in finishing hard turning for the hard machining technique experiments. The cutting tool geometry is as illustrated in the figure. The CBN tool fixed on SANDVICK (PDJNL 2525M15) lift hand tool holder and conducted on (PIGLIA) a precision CNC turning machine. For soft machining-hardening technique will use a CBN grinder stone is used and conducted on (TACILA) a conventional machine.

Type and Description	I	d	s	d1	r	a	TA201
DNMX150608SN	11.6	9.52	3.97	4.4	0.4	1.8	*

Figure 3. CBN Insert Geometry

D. Specimen Preparation for Microscopy Examinations.

Surface structure and microstructures will be analyzed by using optical microscopy and scanning electron microscopy (SEM), respectively. Samples were sectioned with an abrasive cutter, then mounted in a cold-setting epoxy with the machined surface .A fine grit mesh of 180, 240, 400, and 800 followed by polishing diamond paste on polishing paper was used until a mirror-like surface was obtained, which was cleaned by using acetone solvent to perform ultrasonic cleaning, then etching for a few seconds using 5% nital solution for observation of details in optical microscopy and SEM analyses. The samples will be immediately rinsed using running water and dried using hot air.

E. Experiments Design.

Experiments designed and analyzed by MINITAB software were used to determine the optimal machining parameters for a desired surface roughness. This method is used to identify the impact of various parameters on an output and figure out how to control them to reduce the

variability in that output. According to previous analysis, the most significant influences on surface quality were cutting speed, hardness, cutting depth, and feed rate. This found that the interactions between cutting conditions were all significant. The same design factors were chosen: cutting speed, feed rate, cutting depth, and hardness. In addition to these factors the interactions between these factors will be specifically investigated.

A four factor – two level factorial designs was used to determine the effects of the workpiece hardness feed rate, depth of cut and cutting speed on surface roughness and wear resistance in the finish hard turning of AISI D2 tool steel. The factors and factor levels are summarized in Table 2.

Longitudinal turning was conducted on a rigid, high-precision CNC lathe (PIGLIA) at conditions as represented. The workpieces were held in the machine with a hydraulic chuck to minimize run-out and maximize rigidity. The length of cut for each test was 80 mm in the axial direction. Due to availability constraints, fractional 8 was used for these experiments, which consisted of 16 replications. In this manner each workpiece was subject to the same number of passes and the same axial length of cut. Finally, surface roughness measurements were conducted randomly around the specimen diameter as represented.

Since dry techniques were used, surface examination of specimens gains more utilization. Specimens were cut by WCM (wire cut machining) to avoid increasing the specimen surface temperature. Optical and Scanning electron microscope (SEM) were used to investigate the effects of the finishing process and analyzing the surface texture for hard machining technique.

Finally, in order to obtain and understand the effect of hard machining technique on the applications of AISI D2 tool steel, the results will be compared with soft machining-hardening technique. The comparison will be done using EXCEL & MINITAB soft wares.

Table 2. The Factors and Factor Levels of the Experiments by (MINITAB) Software

FEED RATE 0.05-.15 mm/min	Cutting speed 100-200 (m/min)	Cutting depth 0.1-0.25 mm	Hardness 51-56 HRC	Mean of surface roughness (Ra) µ m
1	-1	1	1	.72
1	1	-1	1	.82
-1	1	-1	-1	.41
-1	-1	1	-1	.36
1	-1	-1	-1	.40
-1	-1	-1	1	.37
1	1	1	-1	.48
-1	1	1	1	.68

IV. RESULTS AND DISCUTION OF THE EXPERMENTS

A. MINITAB Software Results

MINITAB graphs for Ra surface roughness parameters are given in *hard machining technique*. Associated with each factor level, effect of workpiece hardness, depth of cutting, feed rate and cutting speed on surface roughness are shown in Figure 4. Figures 4 to 8 show the effect of the cutting speed and workpiece hardness interaction, feed rate and workpiece hardness interaction, depth of cutting, and workpiece hardness interaction and hardness on surface roughness. The interactions between feed rate and workpiece hardness are significant to surface roughness.

Feed rate is the dominant parameter associated with the surface roughness. This is expected because it is well known that the theoretical surface roughness (Ra) is primarily a function between nose radius and feed rate square.

B. Effect of main factors on surface roughness

The Graphs of surface roughness (Ra) are shown in Figure 4. Illustrates the effect of the cutting process conditions separately related to the surface roughness. The main effect of feed rate and workpiece hardness are more significant factors on surface roughness, where an increase in feed rate and hardness causes increases in surface roughness. Whereas cutting depth and cutting speed have less effecting factors on surface roughness, this means there is a small change in surface roughness due to the increases in cutting depth and speed. To gain more understanding, the effect of these factors interactions was analyzed.
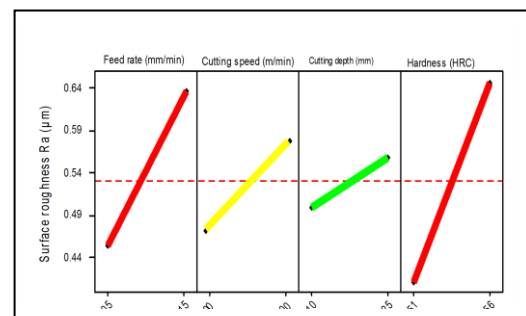

Figure 4. Illustrates of Effect of Cutting Condition Separately Related to the Surface Roughness in Hard Machining Technique.

C. Effect of Cutting Speed And Hardness On Surface Roughness.

The Graphs of surface roughness (Ra) are shown in Figure 5. This illustrates the effect of cutting speed and hardness on surface roughness (Ra). Based on the previous analysis, the main effect of the interaction between cutting speed and hardness is found to be statistically significant on surface roughness (Ra).

This figure shows that the cutting speed has a significant effect at higher hardness. However, the lower cutting speed and lower hardness resulted in better surface roughness, whereas it is opposite when higher hardness and higher cutting speed are used. Finally, the surface roughness increases as the cutting speed increases.
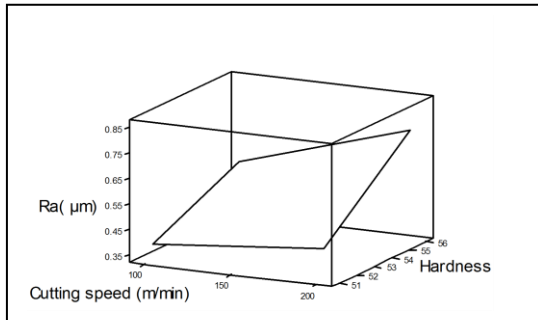

Figure 5. Effect of Cutting Speed and Hardness of Workpiece on the Ra Surface Roughness (for Cutting Length of 80 mm and 30 mm Diameter of *AISI D2)*

D. Effect of the Feed Rate and the Hardne -ss on the Surface Roughness.

Figure 6.has been done to illustrate the main effects of feed rate and hardness on the surface roughness. Based on the previous analysis, the main effect of the interaction between feed rate and hardness is found to be a more significant factor on surface roughness (Ra).

The graph shows that the feed rate has significant effect at higher hardness. However, the lower feed rate and lower hardness resulted in better surface roughness, while it is opposite at higher hardness and higher feed rate. Finally, it should be noted that the main effect due to the feed rate is quite clear for each hardness value (51 and 56 HRC).
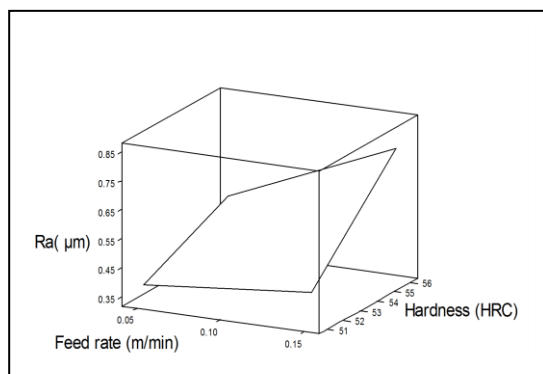

Figure 6. Effect of Feed Rate and Hardness of Workpiece on the Ra Surface Roughness (for Cutting Length 80 mm and 30 mm Diameter AISI D2)

E. Effect of the Cutting Depth and the Hard -ness On The Surface Roughness.

Figure 7. shows the effect of the cutting depth and the hardness on the surface roughness (Ra). Based on the previous analysis, the main effect of the interaction

between depth of cutting and hardness was found to be less significant on surface roughness (Ra).

Furthermore, it shows that the depth of cutting has a small effect at higher hardness. However, the lower depth of cutting and lower hardness resulted in a better surface roughness, while it is similar when higher hardness and higher feed rates were being used. Finally, it should be noted that the small effect due to depth of cutting is quite clear for each hardness value (51 and 56 HRC).
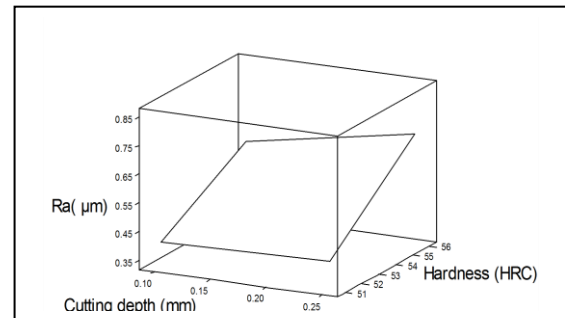

Figure 7. Effect of Depth of Cut and Hardness on Surface Roughness (for Cutting Length 80 mm and 30 mm Diameter AISI D2)

F. Micrographical Analysis

The experimental observations concerned the surface finish produced during hard and soft machining techniques of AISI D2 tool steel in its hardened conditions. Since surface finish is the only one of the parameters that could have affect on the wear resistance and performance of the AISI D2 tool steel products. And to enhance our results, it is important to examine the other parameters which influence surface quality.

G. Surface Examination

A close examination of the machined specimens was carried out under a scanning electron microscope. (SEM) shows that several distinguished features can be defined. These features exist relevant to the cutting technique. Fig 8 shows a selection of the surfaces generated under soft and hard techniques; at machined surface with soft machining hardening technique the resultant surface behaves as ductile material regardless of its hardness. Long, straight, well defined grooves parallel to the direction of the relative work-motion as shown in Fig 8a. Were observed additional features observed in the specimens were the presence of microchips attached to the workpiece surface. While fine grooves were observed during the hard machining technique indicating the existence of low material flow due to the occurrence of severe plastic deformation on the workpiece surface as shown in Figure 8b,
Transformation. The same observation was found when hard turning of H13 tool steel.

H. Metallographic Examination

The bulk material of AISI D2 tool steel is a fine tempered martensite. The high carbon contents in AISI D2 tool steel increased remarkably the stability of retained

austenite. This means that the material will require a high temperature and a longer time to undergo phase transformation. On the other hand, the grains growing under high temperature. These features of the AISI D2 material will influence the conditions of the surface microstructure produced during machining.

The surface structures of the machined specimens were examined under an optical microscope. The etched surface microstructures generated during different techniques are illustrated in Figure 9. The soft machining hardening technique shows a heat affected zone (white layer) the was observed in the surface region of the specimens, during progress of the grinding stone wear, the thickness of the white layer increased to almost 10 μm as shown in Figure 9a. The thickness of the white layer observed in this technique is much bigger than that which existed on the D2 tool steel surface produced by the hard machining technique. The main reason for the low penetration depth of surface changes in this case is the shorter instantaneous time of contact between the CBN cutting tool and the machined surface. Figure 9b illustrates a white layer of 2 to 3 μm was observed during hard turning only when the cutting tool was excessively worn .Figure 9c is an image of the workpiece cross-section within the first 30 mm from the surface, while Figure 9d shows an image of a cross-section at 2 mm from the surface. In both images no increase in the size and spacing of the precipitated carbides was observed, indicating the lack of over tempered martensite
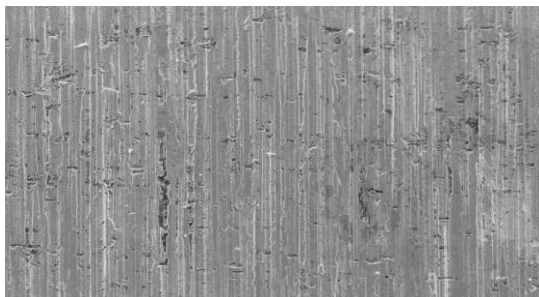
(a) Ssurface generated under the soft machining –hardening technique (1000x)

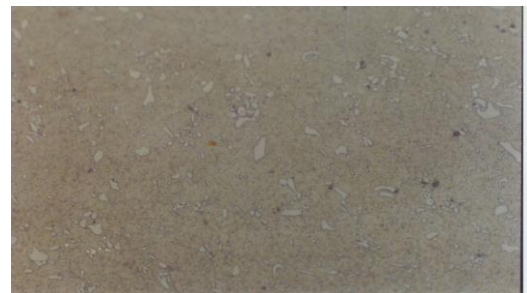(b) Surface generated under the hard machining technique (1000x)

Figure 8. SEM Images of Surface Structure Shows Effects of Machining Technique on Surface Quality.

(a)Heat treated grinding white layers

(b) Hard turning white layer.

c) Bulk material microstructure

(d) White layer microstructure

Figure 9. Optical Microscope Images of Machined Surface Microstructures Produced Under Soft Machining-Hardening Technique and Hard Machining Technique

V. CONCLUSION

A- By examination of surface roughness in hard and soft machining techniques, the results have indicated that the:

1- Results showed that in hard machining not only the machining parameters have an influence on the surface roughness but also the material hardness. As

hardness and feed rate decrease surface roughness improves and Ra of (0.36 μm) can be obtained.

2- Cutting speed has less effect on surface roughness, reducing cutting speed combined with decrease in material hardness result in better surface roughness.

3- Depth of cutting has almost negligible effect on surface roughness.

4- Comparing surface roughness in hard machining to that of soft machining-hardening technique (0.35 μm to 0.4 μm), it indicates better surface roughness is obtainable using hard machining at lower production time.

5- Results indicate that surface roughness increase as hardness increase from 51 HRC to 56 HRC, this goes in line with similar findings which reported surface roughness increase with hardness above 50 HRC.

B -The effect of material hardness and machining conditions on the surface structure and microstructure:

1- Long, straight grooves appear during soft machining hardening technique, in addition, a heat affected zone of thick white layer (10-13 μm) was observed on the surface. While in the hard machining technique it was found to result in fine grooves and a very thin (2-3 μm) white layer due to the short time of contact.

2- The breakage of the carbides particles and microcraks indicates that a very high temperature is generated during the soft machining technique due to a long cutting time.

C- As all the experiments of hard machining has been performed under dry cutting conditions, it can be concluded that in addition to quality and production time improvement, some environmental benefits are achieved. Avoiding cutting fluids, improve working environment and safety of operators and machineries.

VI. FUTURE WORK

1- Conduct Comparison between hard machining and soft machining techniques to find a percentage in reduction cost and time consuming.

2- Construct an engineering model depends on important hard turning conditions.

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