Influence of Surface Finishing Parameters on Wear Resistance of AISI D2 Tool Steel

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Abstract

Based on the several studies conducted, 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. Effects of surface roughness on wear resistance in finish hard turning of AISI D2 tool steel experimentally and analytically is investigated. 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. Further more 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. Due to wear rate being considered as an important factor of workpiece life, the block-on-ring wear test was used to evaluate the machined parts; the effect of surface roughness on wear resistance was investigated and plotted. To investigate the effect of 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 surface roughness and workpiece hardness found affectedin wear resistance. And the wear was graphically analyzed.

Keywords: *Hard turning, Surface quality, Wear resistance, CBN cutting tool.*

1. Introduction

In machining of parts, the surface quality is one of the most specified customer requirements. 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-technique (grinding) hard turning offers a) higher productivity b) greater flexibility c) lower cost of machining and d) less energy consumption. Most importantly, hard turning can be performed dry by using cubic boron nitride (CBN) cutting tools. Besides, dry finish machining is most beneficial in process realization due to increased Environmental regulation. However, finish dry hard turning is a challenging process and desired part quality requirements are tough to achieve in conventional lathes. 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. 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 the hardness of the workpiece (usually 50 to 65 HRC). Effects of hard turning surface quality on wear resistance of various hardness machined parts will be investigated and analyzed experimentally.

Factors Affecting Surface Quality in Hard Turning

To improve the efficiency of this technique, it is necessary to have a process understanding. To this end, a great deal of research has been performed in order to quantify the effect of various hard turning process parameters on surface quality. These factors can be divided into a) setup variables, b) tool variables, and c) workpiece variables. In order to gain a greater understanding of the hard turning process it is necessary to understand the impact of each of these variables, and the interactions between them. Hard turning components are shown schematically in figure 1.

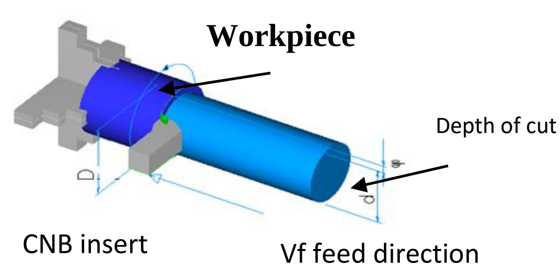


Fig. 1 Hard turning components

Cubic Boron Nitride CBN

Cubic boron nitride is about twice as hard as aluminum oxide and is capable of withstanding cutting temperatures of up to 1300C° before breaking down. Manufacturing CBN is synthesi-zed in crystal form with the aid of a catalyst, heat, and pressure. The combination of extreme heat 1496C and tremendous pressure on cubic boron nitride and the catalyst produces a strong, hard, blocky, crystalline structure. CBN contains the four main properties: hardness-cubic boron nitride next to diamond in hardness, wear resistance hereby increasing productivity, compressive strength- to withstand the forces created during metal removal, thermal conductivity- which allows greater heat dissipation.

Cutting Tool Geometry and Properties.

According to recent studies, it is evident that effect of edge geometry on surface quality is significant [19-22]. Theile et al showed that large hone radius tools produce more compressive stresses, but also leave "white-layers" [20, 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]. Chou et al experimentally investigated the influence of CBN content on surface quality and tool wear in hardened steel [22]. 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.

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 [25].

Surface Texture

In 1947, the American Standard B46.1-1947, "Surface Texture", defined many of the concepts of surface metrology and terminology which overshadowed previous standards. A few concepts are discussed and shown as follows [ASME, 1988]:

- *Surface texture*: Surface texture is the pattern of the surface which deviates from a nominal surface. The deviations may berepetitive or random and may result from roughness, waviness, lay, and flaws.
- *Roughness*: Roughness consists of the finer irregularities of the surface texture, usually including those irregularities that result from the inherent action of the production process.

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.

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

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. An example of the surface profile is shown in.

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

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

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

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

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

Wear of Tool Steel

AISI D2 is cold work tool steel. Most of group D (1.55% C, 0.6% Mn, 0.6% Si, 12% Cr, 0.3% Ni, 0.7 % Mo, 1.1%V, and 1% Co) is oil hardened and have high resistance to softening at elevated temperatures. These steels also exhibit excellent resistance to wear, the wear resistance of these groups is exceptional and increased with increasing carbon and vanadium content. This attribute is important for designers to choose the suitable tool material for its application, and typical applications of group D steels include long run dies for blanking, forming, dies for cutting and burnishing tool. And it is recommended wherever a high resistance to wear is required.

Wear Resistance and Surface Quality

Understanding the relationship between wear properties and surface quality can lead to the specification of optimized surface textures and manufacturing processes for various surface function needs. The surface of these components may require treatment, to enhance the surface characteristics. Thus they cannot be neglected in design. Friction occurs where two surfaces undergo sliding or rolling under load. Friction is a serious cause of energy dissipation, where wear is the main cause of material wastage. Wear is a process of removal of material from one or both of two solid surfaces in solid state contact, occurring when two solid surfaces are in sliding or rolling motion together. The rate of removal is generally slow, but steady and continuous. Table 1-1, shows the three main categories of wear and the specific wear mechanisms that occur in each category. There are various variables affecting in wear of surfaces of which hardness, toughness, composition of work surface, applied load, cross-sectional area or distance of contact and surface quality.

Engineering Models of Wear:

1- The most widely publicized equation is given by Archard in which the rate of wear γ (volume per unit of time), is:

$$\gamma = KWV/H \qquad (4)$$

Where:
W is the applied load, N
V is the sliding speed, cm/min
H is the hardness of the softest of a pair of the materials, HRC, and
K is a constant sometimes referred to as a wear coefficient.

2- Weight Loss per Unit of Sliding Distance.
This method uses weight loss for calculation of the wear rate as:

$$WR = \Delta W/SD \qquad (5)$$

Where:
WR =wear rate (gm/cm),
ΔW = weight loss during a time interval between two successive weight measurements (gm)
SD =sliding distance (cm)
The sliding distance is given by:

$$SD = SS.t \qquad (6)$$

Where SS = sliding speed (cm/sec)
t= time interval (min)

To show W.R = (gm/sec) may write equation (5) as:

$$WR = \Delta W.\ SS / SD$$

Since the two methods are the most widely used wear calculation in techniques, weight loss is selected to express the *wear rate* in this study.

Tabel 1-1 Wear categories

Wear by particles or Fluids	*Wear by Rolling, Sliding, or Impacting*	*Chemically Assisted wear*
Abrasive wear Polishing wear Solid particle erosion Slurry Erosion	Sliding and Adhesive wear Rolling contact wear Impact wear	Corrosive wear Oxidational wear

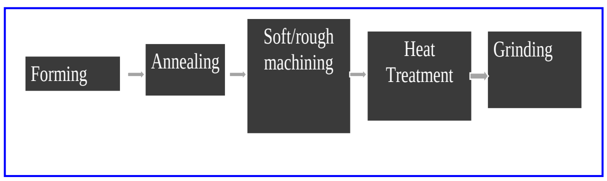
2. Experimental Technique and Procedures

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 there function, workpiece hardness and finishing process conditions are studied carefully. Because of the importance of wear resistance in tool life and its function, the effect of the surface quality on the wear resistance 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.

Experimental Details

Workpiece Preparation: 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 is 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. figure 2-1(a,b), illustrate a flow chart for these techniques. For both soft and hard techniques specimens are divided into 2 groups, one low hardiness and high hardness value, and heat treated 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). figure 2-1c, shows Thermal cycling used:



a- Soft machining-hardening technique

b- Hard machining technique

c- Heat treatment processes

Process	***Tempera ture(C)***	***Time (min)***	***Medium***	***Hardness (HRC)***
Preheating	**600**	**60**		
Austenizin g	**1040**	**2.5/1 mm**	**Oil**	**62-64**
Quenching	**50-60**			
Washing	**90**		**Hot water**	
Tempering	**200**	**60**	**Cooling in air**	**51**
	300			**56**

Tooling and Insert Geometry: CBN cutting tools inserts from TIZIT of chamfered and honed edge as illustrated in figure 2-1, 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 and used for hard machining technique. For soft machining technique grinder stone was used and conducted on (TACILA) a conventional machine. Wear Test System: After finishing surface roughness measurements and recording results data, the block on ring wear test system was selected and used. The block on ring system consists of a block (stationary specimen) positioned perpendicular to the ring (rational specimen), these rings prepared from hard turning and grinding workpieces, after cutting by wire cutting machine. The ring specimen revolves into the block with the sliding surface in constant speed (350 m/min). The plane of the block is vertical. The block is pressed against the ring at a specified load about (130 N) by means of an arm and attached weights. Prior to testing and measuring, cleaning and drying of all rings was required. Care was taken to remove all foreign particles from rings. For measurement of wear, a concept of concomitant methods was implemented by weight using a digital scale [+/-0.001g]. The amount of wear was determined by measuring, and weighing all rings before and after the test. In the research AISI D2 tool steel was used for both block and ring. The block specimen was hardened at the same value as the rings. A variable speed system with a motor able to maintain constant speed under load was used. The stationary block holder is attached to a lever arm that can add loads as an option of loading.

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.

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 2-1. 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. Wear resistance was examined using a (block-on-ring) wear test device to measure wear rate as weight loss versus time travel, and detect affected features in the finish hard turning process. 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 affects 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

3. Results and Discussion

Effect of main factors on surface roughness

The Graphs of surface roughness (Ra) are shown in figure 3-1 It was noted that 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 ofthese factors interactions was analyzed.

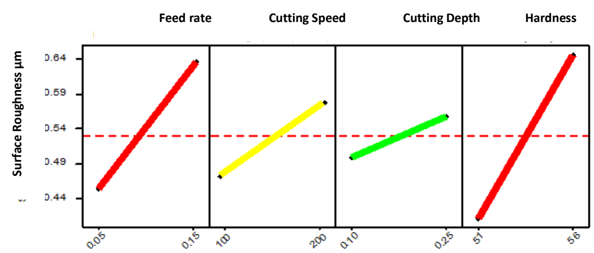


Fig. 3.1 illustrates of effect of cutting conditions related to the surface roughness in hard machining technique.

Effects of the Surface Roughness onWear Behavior (51 HRC).

Wear characteristics for hard turning group of (51 HRC) could be carefully observed in figure 3-2. This characteristic was caused by a lower value of the surface roughness that has effect at the first travel time of sliding tests, which resulted in lower weight loss due to the friction of block on ring, and better results were observed in wear resistance. Effects on the hardness that occurred were noted in these Specimens (51HRC), where higher loss rate was obtained at every travel time unit. Wear rates were close to zero and go up, itcould be notedthat the curve has changed to a horizontal straight line. This makes sure that the surface quality and Wear resistance are good enough.

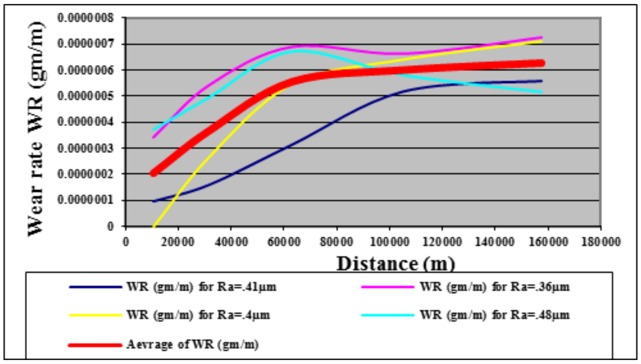


Fig. 3.2 Illustrates wear rate in relation to weight loss against time in (51 HRC) turning specimens.

Effects of the Surface Roughness on Wear (56 HRC Specimens).

Wear characteristics for turning group of (56 HRC) could be carefully observed in figure 3-3.These characteristics were caused by a higher value of surface roughness that has effect at the first travel time of sliding tests. A result of high loss in weight due to the friction of the block on ring resulted in poor Wear resistance. Effectiveness of hardness occurred and it was noted that higher hardness caused Wear resistance to increase dramatically.

High values of wear rate in this case, can be readily observed in the first travel. it can be observed that the curve has changed its position and turned to the up stream direction, which resulted in the surface quality and Wear resistance being poor.

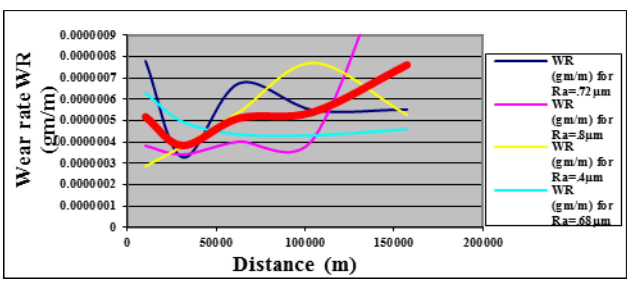


Fig. 3.3: Illustrates wear rate in relation to weight loss versus time in (56HRC) turning specimens.

Effects of the Surface Roughness on Wear Behavior (Grinding Specimens)

Wear characteristics for grinding specimens could be carefully observed in figure 3-4. These characteristics were caused by hardness of grinding specimens, and value of surface roughness, for 51 and 56 HRC were 0.35 and 0.4 µm respectively, effective from the first travel time of sliding tests which resulted in lower loss in weight due to the friction of block on ring and resulted in better wear resistance. Whereas effects of wear rate against distance that occurred were noted, the curve goes down in beginning, and then dramatically changed its way by going up. This makes sure that surface quality and wear resistance are poor. This technique detected high wear rate. Thus increasing the distance increased the wear in a dramatic way. These results noted that the hard machining technique in proper conditions could improve the surface quality and Wear resistance.

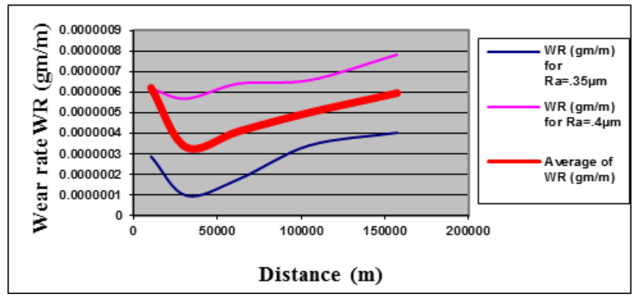
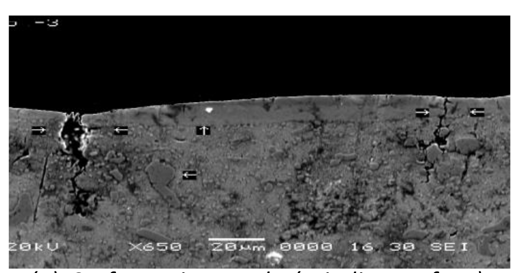


Fig. 3.4 Illustrates wear rate in relation to weight loss Versus time in (51-56HRC) grinding specimens

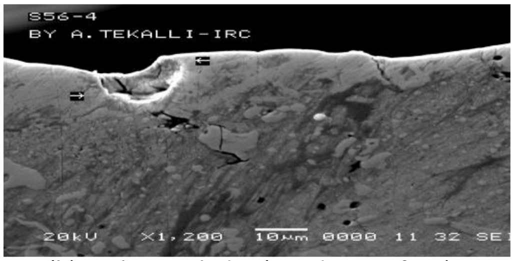
Micrographical Analysis

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. Microcracks and voids can be seen on the grinding surface, also brittle fracture as shown in figure 3-5 a and b. These cracks were observed more frequently as the white layer increased. The primary source of these defects is the nonhomogeneity of the workpiece material caused by the existence of carbide, chromium, manganese, and sulfide inclusions. Due to these inclusions the flow of the material during the cutting process will be interrupted because of their lower deformability and the cracks will be initiated.

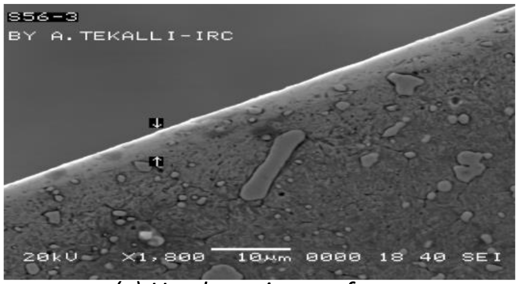
The results obtained from the preliminary experiments show that the cutting technique has significant effect on eliminating the existing cracks on the surface produced. Hard machining techniques with low feed rate and low cutting speed resulted in a regular surface. Cracks and voids cannot be clearly observed as shown in figure 3-5c.



(a) Surface microcracks (grinding surface)



(b) Broken carbides (grinding surface)



(c) Hard turning surface

Fig. 3.5 SEM images of machined surface microstructures produced under the soft machining-hardening technique and hard machining technique.

4. Conclusion

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

1- 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.

4- 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 sliding wear behavior of AISI D2 tool steel with different surface quality in hard machining technique had been evaluated:

1- At lower workpiece hardness (51 HRC) and lower surface roughness (0.36 μm), resulted in better wear resistance. While an increase in surface roughness for workpiece hardness of (56 HRC) caused high increases in wear rate.

2- The dramatic changes of the wear curve in the soft machining-hardening technique detected poor wear resistance.

C- 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.

D- 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.

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