Study of surface integrity AISI 4140 as result of hard, dry and high speed machining using CBN

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Abstract. The concept of hard, dry and high speed machining can be combined, to produce high productivity, with lower production costs in manufacturing industry. Hard lathe process can be a solution to reduce production time. In lathe hard alloy steels reported problems relating to the integrity of such surface roughness, residual stress, the white layer and the surface integrity. AISI 4140 material is used for high reliable hydraulic system components. This material includes in cold work tool steel. Consideration election is because this material is able to be hardened up to 55 HRC. In this research, the experimental design using CCD model fit with three factors, each factor is composed of two levels, and six central point, experiments were conducted with 1 replications. The experimental design research using CCD model fit.

1. Introduction

High-speed machining and hard machining are two methods that can be used to improve the productivity of manufacturing industries that produce products from metal cutting operations. Hard machining is more flexible, more environmentally friendly and performs better than grinding processes in terms of productivity [8] However, for surface quality especially surface packaging is still under grinding process. Until now high-speed machining and hard machining is still commonly done in wet machining conditions [3]. The cutting fluid that potentially distorts the environment can be eliminated so that the concept of dry machining has two benefits, namely saving the environment and reducing the cost of production because the contribution of 20% value of cutting fluids on production costs no longer need to be issued [7]. From the point of view of the process of cutting the metal, the distortion to the surface of the machined work piece is examined through the topic of surface integrity. An extensive surface integrity study involves the study of surface topography and surface metallurgy.

Study of surface integrity, reports that this study is so important to do, especially on the work piece that belongs to the product to be used as a high-reliability component. As an example Rech and Moisan [5] on hard steel alloys reporting problems related to surface integrity such as roughness, residual stress, white coating and surface integrity studies. Therefore, the material AISI 4140 is the material used for high-reliability hydraulic system components, when the concept of high, hard and dry machining is implemented to process the material AISI 4140. it is necessary to study the integrity of the surface to ensure the results of the surface of the engine can be produced by either fulfilling the aspects required by the concept of surface integrity.
2. Problem
Considering the above issue, it is necessary to conduct a study that can explain the machining condition that is done at high, hard and dry rate, this research needs to be done. From some previous researchers it was reported that a potential chisel can be used at high-speed machining and hard machining CBN chisel, ceramics and PCBN [8]. The high-heeled work piece selected in this study is alloy steel with AISI 4140. In the construction of engineering materials are commonly used as construction materials for aircraft landing gear, load bearing on rotary shafts, gears and armament components. From the physical nature of hardness, this work piece is at least as hard as it is 55 HRC. Therefore, the material AISI 4140 is the material used for high-reliability hydraulic system components, When the concept of high, hard and dry machining is implemented to process the material AISI 4140. A surface packaging study is needed to ensure that the surface of the engine can be produced properly which meet the aspects required by the concept of surface integrity.

3. Problem
The mechanics of the metal cutting process require parameters involving cutting and geometry conditions as well as the ability of cutting tool. The process of cutting the metal is the largest activity undertaken in the manufacturing industry. The process is capable of producing components that have complex shapes with high geometry and dimensional accuracy. Figure 1 is a schematic of a lathe process where $n$ is the main axis spin, $f$ is feeding, and $a$ is the depth of the cut.

![Figure 1. Lathe process scheme.](image)

There are three main parameters that affect the cut style, heat increase, wear and integrity of the work piece surface. The third parameter is the cutting speed ($V$), feeding ($f$), and the depth of the cut ($a$). Cutting speed is the speed around the work piece with the unit (m/min), speed of emphasize is the movement or mileage of each chisel of one work piece round by unit (mm/rev), The cut depth is the thickness of the wasted material in the radial direction with the unit (mm).

According to Rochim [9] in every machining process there are five basic elements that need to be understood, that are:

a. cutting speed : $V$ (m/min)
b. feeding speed : $Vf$ (mm/min)
c. depth of cut : $a$ (mm)
d. cutting time : $tc$ (min)
e. material removal rate : MRR (cm³/min)

The five basic elements mentioned above can be known using a formula that can be derived based figure 2.
Geometry of work piece, $d_0$ is the initial diameter (mm), where $d_m$ is the final diameter (mm), $lt$ is the machining length (mm), chisel geometry defined as $kr$ is the main cut corner (o), and $p0$ is the chip angle (o).

Machining conditions of cutting depth (mm), defined as

$$a = \frac{d_0-d_m}{2}$$ (1)

where $f$ is the feeding (mm/round) and $n$ is the main shaft rotation (rpm).

By knowing the above-mentioned quantities so that the cutting conditions can be obtained as follows. The Cutting speed, $V$ defined as

$$V = \frac{\pi \cdot d \cdot n}{1000}$$ (2)

where $d$ is the average diameter (in mm) and is defined as $d = \frac{d_0+d_m}{2}$. The feeding speed, $vf$ (mm/min) is defined as

$$vf = f \cdot n$$ (3)

where cutting time as $tc = \frac{lt}{vf}$ (min). While the rate of exhaust chips, $MRR$ (cm$^3$/min) is defined as

$$MRR = A \cdot V$$ (4)

where $A$ (mm$^2$) is the cross chip before cut off where it is defined as

$$A = f \cdot a$$ (5)

Then, it can be proved that

$$MRR = V \cdot f \cdot a$$ (6)

Principal cutting edge angle/$kr$ is the angle between the main cutting eye and the rate of feeding ($vf$), the magnitude of the angle is determined by the chisel geometry and the way of mounting on the lathe.
For feeding score \( (f) \) and cutting depth \( (a) \) that remains then this angle will affect the cut width \( (b) \) and thickness of chip before cut off \( (h) \) as follows:

The cutting width, \( b \) (mm) is defined as

\[
b = \frac{a}{\sin kr}
\]

(7)

where thickness of chip before cut off, \( h \) (mm) is

\[
h = \frac{f}{\sin kr}.
\]

(8)

Therefore, the cross chip before cut off is

\[
A = f \cdot a = b \cdot h
\]

(9)

Rech et.al [5] have found that cutting speed does not have a significant impact on surface roughness in steel machining 27MnCr5. However, the speed of feeding has an effect on surface roughness. When the speed of feeding increases from 0.05 mm / rev to 0.3 mm / rev at speed 150 m/min, surface roughness increased from 0.3 \( \mu \)m to 1.4 \( \mu \)m. On the other hand, when the speed increases from 50 m / minutes to 250 m/min at 0.1mm/revs constant feed, surface roughness values only between 0.2 to 0.4 \( \mu \)m. This proves that cutting speed does not affect surface roughness.

The working principle of ordinary lathe process is basically applied to the process of lathes. However, there are differences in characteristics as a result of the high hardness of the material to be cut. Hard material has abrasive properties, and high hardness or young modulus ratio. As a result of all that then on the process of lathes required a cutting tool much harder and resistant to abrasive than ordinary lathe process. Hard lathe process can be done on various types of metals such as alloy steel, bearing steel, hot and cold work tool steel, high speed steel, die steel, and hardened cast steel [1].

Hard lathe process can be a solution to reduce production time, considerations for the industrial world to use lathes is the ratio between the cost of equipment, especially the cutting tool used for the life of the chisel, should be low [4]. The special material used for hard lathe process is cubic boron nitride (CBN), ceramics, and mirrored [2]. CBN is the hardest material other than diamond, very suitable for hard lathe process. Insert CBN began to increase in popularity after General Electric found combination CBN with titanium nitride powder so as to increase the life of the chisel to five times [1].

In the field of manufacturing known type of chisel available is carbon steel, HSS, combine cobalt Cor, Carbide, Ceramic, Cubic Boron Nitride (CBN) and diamond. In order to set the right type of chisel, it is necessary to consider the selection based on the characteristics of the chisel which deals with the violence of strength and toughness as shown in figure 3, figure 4 and table 1.

![Figure 3. Heat hardness and chisel-wear resistance to strength and toughness.](image-url)
Figure 4. Degree of hardness and wear resistance of worm to temperature.

Table 1. Comparison of chisels.

| Chisel material          | Cutting speed (m/minutes) | Temperature hardness of heat (°C) | Hardness (HRA) |
|--------------------------|---------------------------|-----------------------------------|----------------|
| Carbon Steel             | 10                        | 300                               | 60             |
| HSS                      | 25 – 65                   | 650                               | 83 – 86        |
| Combined Cobalt Cor      | 50 – 200                  | 925                               | 82 – 84        |
| Carbide                  | 650                       | 1200                              | 90 – 95        |
| Ceramics                 | 330 – 650                 | > 2000                            | 91 – 95        |
| CBN                      | 500 – 800                 | 1300                              | 4000 – 5000 HK |
| Diamond                  | 300 – 1500                | > 650                             | 7000 – 8000 HK |

In this study, the type of chisel is focused on CBN (Cubic Boron Nitride) for hard machining process with high cutting speed. CBN including ceramic type, introduced by GE (USA, 1957, Borazon). Made with hot presses (HIP, 60 kbar, 1500°C) so white graphite powder Nitride Boron with hexagonal atom structure turned into a cubic structure. CBN inserts sculpting can be made by sintering the powder BN without or with material Al2O3 TiN or Co. Hardness of CBN is very high, CBN can be used for machining various types of hardened steel, cast iron, HSS or carbide cement. The affinity for steel is very small and resistant to changes in chemical reactions to the cutting temperature 1300°C (high cutting speed).

4. Research method

The object studied in this study is steel alloy machined surfaces AISI 4140 hardness ≥ 55 HRC which is generated on the operation of the latter by applying the concept of high-speed machining, hard and dry using chisel CBN. According to Rochim [9] a potential chisel that can be used at high-speed machining and hard machining is carbide chisel, ceramics and CBN. Chisel CBN price is relatively expensive compared to carbides and ceramics so that its use is still limited to machining. But, to achieve high dimensional precision and high surface smoothness, required a chisel made of a reliable material, that is in this case CBN. The main problem that will be discussed from the object in this study is the study of surface packaging of the engine AISI 4140. From the surface topography aspect, the study will be stacked on the surface of lay pattern, roughness, waviness and defect. When on surface metallurgy, the study is stacked to check for possible situations in the sub-surface layer.
Table 2. Chemical Composition AISI 4140.

| Element       | Chemical composition (%) |
|---------------|--------------------------|
| C             | 0.42                     |
| Si            | 0.32                     |
| Mn            | 0.85                     |
| S             | 0.004                    |
| P             | 0.009                    |
| Ni            | 0.16                     |
| Cr            | 1.08                     |
| Mo            | 0.25                     |
| Cu            | 0.2                      |

Table 3. Mechanical properties AISI 4140.

| Element          | Score |
|------------------|-------|
| Elastic (N/mm²)  | 864   |
| Tensile strength (N/mm²) | 976   |
| Flexible (%)  | 16.4  |
| Compressed (%)  | 61.6  |

Chisel used is CBN, this chisel is made with hot press (HIP, 60 kbar, 1500°C) so white graphite powder Nitride Boron with the structure of the hexagonal atom transformed into a cubic structure. Type of chisel CBN from SANDVIK Coromant, with the introduction of standardized products ISO that is TNGA160408S01030A 7015 with Geometry: \( r_e = 0.8 \) mm; \( A = 9.52 \) mm; \( T = 4.7 \) mm; \( od = 3.81 \) mm (see Figure 5), the chisel holders used are the type DTGNR 2020 M (91⁰).

The mechanical properties of chisels CBN can be seen on table 4 below:

Table 4. Mechanical properties of chisels CBN.

| Mechanical properties | Score |
|-----------------------|-------|
| Hardness (Gpa)        | 93    |
| Elastic Modulus (Gpa) | 900   |
| Wide Modulus (Gpa)    | 385   |
| Fracture toughness (Mpa) | 2.8  |

Optimization calculation of effect of cutting speed \( (V) \), feeding \( (f) \), and cutting depth \( (a) \) against surface roughness \( (Ra) \) using RSM with model match CCD.

The lathe used for testing is a conventional lathe with power 15 KW, maximum rotation 2500 rpm, maximum clamping diameter 158 mm and length of work piece 255 mm. The process of taking data by method CCF (cubic center of face) with 3 monoguard variable and 3 level + 0 -, data taken as many as 7 data with the following conditions: cutting speed \( v = 200 \) m/min and 250 m/min, while cutting depth \( a = 0.1 \) mm, 0.125 mm and 0.15 mm for cutting speed \( f = 0.3 \) mm/rev, 0.7 mm/rev and 1 mm/rev. The
required work surface roughness limit is 1.47 μm (semi finish for turning) or wear chisel is $VB < 0.3$ mm, in this case selected both of these criteria as parameters, whichever comes first and the machining process is dismissed. On the edge wear seen using USB Digital Microscope cameras DINO-R-LITE, which is equipped with dual Lens Axis 27x/W = 8 mm and 100x/WO = 2 mm microscope lens. Meanwhile, to see the microstructure of chisel damage seen by using test equipment SEM (Scanning Electron Microscope).

| Table 5. Measurement data design. |
|-----------------------------------|
| Run | $V$ (m/min) | $a$ (mm) | $f$ (mm/rev) |
|-----|-------------|---------|-------------|
| 1   | 200         | 0.1     | 0.3         |
| 2   | 200         | 0.1     | 1           |
| 3   | 200         | 0.125   | 0.3         |
| 4   | 200         | 0.125   | 0.7         |
| 5   | 200         | 0.15    | 0.7         |
| 6   | 200         | 0.15    | 1           |
| 7   | 250         | 0.1     | 0.3         |
| 8   | 250         | 0.1     | 1           |
| 9   | 250         | 0.125   | 0.3         |
| 10  | 250         | 0.15    | 0.7         |
| 11  | 267.045     | 0.125   | 0.7         |

5. Conclusion
The concept of high, hard and dry machining as described above can be integrated then the purpose of the manufacturing industry, to produce high productivity and environmental insight can be realized. Hard lathe process can be a solution to reduce production time through the reduction of the number of processes. The equipment setup and the time for inspection due to the loud lathe process can be performed on the same lathe where the conventional lathe process is performed, the same equipment can be used and without the need for an additional grinding machine. In this research will be used material of test object AISI 4140. where this material belongs to the of cold work tool steel. Election consideration is because the material is able to harden until it reaches 55 HRC. In this study, the experimental design using model fit CCD with 3 factors, each factor consists of 2 levels, and 6 center point, experiments performed with 1 repetition. The experimental design of the study with no coding uses model fit CCD. Optimization calculation of effect of cutting speed ($V$), feeding ($f$), and cutting depth ($a$) against wear ($VB_c$) using RSM with model match CCD.

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