Analysis of the effect of the cutting speed on specific cutting energy in turning process

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Abstract. In machining process, the cutting temperature and cutting force produced is an important parameter need to be control or reduce. The cutting temperature and cutting force will effect the tool life thus effect the tool cost. Metalworking fluids are essential coolants and lubricants used in material removal and deformation processes to improve manufacturing productivity. This Research will look the effect of cutting speed to specific cutting energy in workpiece on Turning Process using SCCO₂ as the coolant. The results of the analysis on this study will compare the results from simulations using Autodesk Software Simulation of Mechanical 2016 with the results of the journal as a reference. From theoretical calculations, the cutting forces decrease while the cutting speeds increase. Then the specific cutting energy will decrease with the increase of cutting speed. The specific cutting energy is 1,805 J/mm³ to cutting speed 50 m/min, 1,765 J/mm³ to cutting speed 65 m/min and 1,733 J/mm³ to cutting speed 80 m/min [8].

1. Introduction

Every machining industry is always use the machine tools. It’s been a lot of machining industry that use Titanium as a workpiece material. Because titanium material has special characteristics needed for the manufacture of aircraft engines, that is the strength of mechanical properties at high temperatures, the ratio between the strength of materials and the mass of good materials. But with some properties possessed by titanium material, it is not easy to cut the material into the desired engine component because titanium has a low engine capability. Therefore, titanium material is classified into materials that are difficult to machine, especially at higher cutting speeds. Although this titanium material is difficult to be machined there is a type of tool that is considered quite good to be used for the titanium machining process, that is carbide tool (WC-Co) with a note, the machining process is carried out in wet conditions (cutting using coolant) or with cryogenic machining [1]. High-speed machining of titanium with a note of machining processes carried out in wet conditions or with cryogenic machining can benefit greatly at the level of growling, machining time, cutting force, heat removal and tool life. Therefore, the determination of machining parameters on titanium is very important, such as cutting speed, feeding speed, cutting angle, depth of cut, and so on.

The use of high speed machining makes the specific cutting energy that occurs will be lower due to the increasing cutting speed [8]. Specific energy is the ratio between the consumption of energy used in machining operations and the volume of workpieces. The specific energy in this cutting is affected by the cutting speed, cutting style, and the growing speed. In addition, this specific cutting energy is usually used to calculate energy efficiency in the machining process [3].

Although this titanium material is difficult to ensure there is one type of machining with the concept of sustainable manufacturing (SM). One example of sustainable manufacturing (SM) is a machining
process where cooling techniques such as minimum quantity of lubrication (MQL) and cooling by cryogenic processes have shown promising performance especially in terms of cutting temperatures and cutting forces. At present, carbon dioxide has the potential to replace mineral-based cutting fluids using cutting fluids in the machining process causing negative effects especially on the environment, operator health and the machining costs themselves [8].

With this cryogenic machining, it allows us to be more energy efficient, clean in the process and reduce the safety and health factors in the process with the possibility of lower and higher production costs. The cryogenic machining process is a machining process in which traditional cooling fluids are replaced by jets of liquid nitrogen. Or also with supercritical carbondioxide (SCCO2). To increase tool life, cryogenic machining is also useful for machining processes carried out on materials that have high material strength or hard material properties such as titanium material (Ti-6Al-4V) and can be useful to maintain the integrity and quality of the workpiece surface in finishing process. Titanium is a relatively lightweight metal that provides excellent corrosion resistance, is strong, lightweight and has good heat conductivity [5].

2. LITERATURE REVIEW

2.1. Turning Process

Lathe is a machine that is used to cut cylindrical objects. In the process of turning the workpiece installed on the chuck which is located at the end of the main shaft (spindle). The process of feeding the workpiece on the lathe is done by rotating the workpiece which is then worn on the cutting tool which is moved in a translation parallel to the rotary axis of the workpiece and the rotational motion of the workpiece is called relative cutting motion [9].

In the turning process there are several parameters that must be considered, namely:
1. Cutting Speed
2. Feeding Speed
3. Depth of Cut
4. Cutting Time
5. Rate of Metal Removal

![Figure 1. Schematic Lathe Process][9]

2.2. Cutting Type

Cutting Style is a method used between aids (cutting tools) and objects to be used during the machining process. There are 2 types of cutting styles themselves, upright cutting (Orthogonal Cutting), and Oblique cutting [4].
2.2.1. **Orthogonal Cutting.** Orthogonal Cutting is a system of cutting with the relative movement between the tool's eye and the workpiece forming a 90° cutting angle or what is called the main cutting angle. The resulting chip direction will be perpendicular to the cutting edge and shaped like a short spiral coil. According to [9], the main cutting angle has a role, namely:

1. Determine the width and thickness material removal before cutting.
2. Determine the length of contact between material removal and the tool area.
3. Determine the amount of force.

![Figure 2. Orthogonal Cutting [4]](image)

2.2.2. **Oblique Cutting.** Oblique cutting is where the cutting edge of the work tool is not perpendicular to the cutting direction of the workpiece and will form a cutting angle of less than 90°. The resulting chip direction will deviate from the cutting edge and is shaped like a long spiral coil.

![Figure 3. Oblique Cutting [4]](image)

2.3. **Cutting Style**

In the cutting tool, it is known that the resultant force consists of three basic components, namely $F_T$ (Tangential force / force at cutting speed), $F_R$ (Radial force / force at the cutting depth), and $F_L$ (Longitudinal force / force at feeding or feeding). This tangential style is the highest force of the three styles [6].
2.4. Cryogenic Cooling System

2.4.1. Cryogenic Machining Process. In physics, cryogenics is the study of the production and properties of materials at very low temperatures. While cryogenic machining is a machining process in which coolant is usually replaced with cryogenics such as liquid nitrogen (LN2) and carbon dioxide (CO2) and so on. In this method the gas is usually liquefied, then directed to the cutting temperature zone to cool the tool's eyes or workpiece. Cryogenic media absorb heat from the cutting zone and evaporate into the atmosphere [2].

In this cryogenic machining process, coolant is needed or known as cryogenic cooling. Application of cryogenic cooling in the machining process in the 1950s. This cryogenic cooling is used for fast and effective temperature transfer from the heat generated during cutting operations and is used for almost all types of cryogenic materials which have very low temperatures of 100K (-173 °C) and absolute zero (0 K or -273 °C). Cryogenic words come from the Greek language, namely 'cryos' and 'genes', the word 'cryos' means cold ice and 'genes' means born. The ideal temperature is cryogenic, which is below temperature (-153 °C) or lower. Cryogenic cooling or cryogenic cooling variations such as helium, hydrogen, neon, nitrogen, oxygen, argon, krypton, xenon, methene, ethene, propane and carbon dioxide. But the most widely used in the machining process are carbon dioxide (CO2) and liquid nitrogen (LN2) [12].

Cryogenic cooling used in conventional machining processes can improve tool life, make the surface of the tool eye and workpiece better, dimensional accuracy, and reduce cutting temperature. Cryogenic cooling effects on engine performance steps such as cutting force cutting temperature, surface integrity, tool-wear, friction, etc.

2.4.2. Supercritical Carbon Dioxide (SCCO2). One of the most widely used fluids in its supercritical conditions is carbon dioxide (CO2). This substance is widely used especially in one of the separation processes namely extraction. Another advantage of carbon dioxide (CO2) is its relatively low critical point (critical temperature = 31.2 °C, critical pressure = 7.38 MPa) compared to other substances such as water. Carbon dioxide gas is cheaper than nitrogen gas and is available. Supercritical Carbon Dioxide (SCCO2) is selective in the process of separation, is environmentally friendly and not harmful to human health because this gas is non-toxic and has a very good solubility level with vegetable oil. SCCO2 is also widely used in dry cleaning processes because this solvent gas is environmentally friendly. In the food industry, SCCO2 is used as a solvent to remove caffeine from coffee beans. Because it has very high thermal efficiency so many nuclear plants use SCCO2 as reactor coolant.

Supercritical Carbon Dioxide (SCCO2) has great potential as a substitute for coolant used in the process of cutting workpieces and being one of the metalworking fluids used continuously [8].

Because of the good expansion which causes mechanical damage from the SCCO2 mixture and the oil that arises because the workpiece is homogenously cooled through a spray that sprays fine particles
in the form of dry ice and frozen oil in micron sizes. As a result, SCCO$_2$ as a metal fluids is quite good in heat dissipation and lubrication in replacing MWFs commonly used in machines that use MQL or LN$_2$ as coolant. High pressures from Nitorgen, Argon, and SCCO$_2$ have high heat dissipation rates and are very good at spraying coolant, but unlike high pressure Nitrogen and Argon, SCCO$_2$ gas can dissolve lubricants [7].

2.5. Specific Cutting Energy

According to [4] the amount of energy used in machining (P$_m$), including the cutting force component (F$_c$) is in the same direction as the cutting speed (V$_c$) of the machining operation that is derived in Equation (10). Furthermore, to look for specific energy cuts, the ratio between the energy used in machining (P$_m$) and the volume of material removal (Z), as released in Equation (11).

\[
P_m = F_c \cdot V_c \tag{1}
\]

Where:
- P$_m$ : Energy used (J)
- F$_c$ : Cutting force (N)
- V$_c$ : Cutting speed (m/min)

\[
P_s = \frac{P_m}{Z} \tag{2}
\]

Where:
- P$_s$ : Specific Cutting Energy (J/mm$^3$)
- P$_m$ : Energy used (J)
- Z : volume of material removal (mm$^3$)

\[
Z = f \cdot a \cdot v \tag{3}
\]

Where:
- Z : volume of material removal (mm$^3$)
- f : Feed movement (mm/round)
- a : depth of cut (mm)

2.6. The Relationship Between Specific Cutting Energy and Coolant (SCCO$_2$)

In titanium work, which has high material strength or hard material properties, it is difficult to machine. Then we need a special machining process in the process. The machining process is carried out in wet conditions (cutting using coolant) or cryogenic machining (Ginting 2006). This cryogenic machining process where ordinary coolant is replaced with cryogenic liquids such as liquid nitrogen (LN$_2$) or supercritical carbon dioxide (SCCO$_2$) [2]. Cryogenic machining process using coolant (SCCO$_2$) will affect the results of the titanium turning process such as cutting force, chip thickness, cutting temperature, surface quality, specific energy cuts and others. Specific cutting energy is affected by cutting speed, cutting force, and speed of producing growls [8]. This specific cutting energy is usually used to calculate efficiency in the machining process [3].

Specific cutting energy using coolant (SCCO$_2$) used will decrease or decrease compared to using dry machining. In other words, the specific energy of cutting using coolant (SCCO$_2$) is lower than using dry machining. This is because the specific energy of cutting using coolant (SCCO$_2$) can reduce the hardness of the material and the resulting thickness of the growl at low temperature spraying [10].
3. Research Methodology

3.1. Research Flow Chart

![Research Flow Chart](image)

Figure 5. Research Flow Chart

3.2. Stage of Research

In this study several stages of activities are carried out with the aim that research can run well, starting from preparation, data collection, data processing, and analysis of research results. These stages are explained as follows:

Study literature, study the intent and purpose of this study so that in the next stage it will be more efficient and no confusion occurs when analyzing by utilizing previous studies.

At the data collection stage related to the specific energy of the titanium turning process using cryogenic machining with the FEM Method (Finite Element Method) Simulation, the data needed include the types of materials, workpiece materials, and machining conditions.

Simulation of the machining process, after making a forecasting model of the titanium turning process using cryogenic machining performed FEA (Finite Element Analysis) to determine the stress in the titanium turning process.

The results obtained in this study are graphs of specific stresses and energies that occur in the titanium process using cryogenic machining.

The last stage is to validate the simulation results with experimental results.
3.3. Finite Element Analysis Flow Chart

![Finite Element Analysis Flow Chart](image)

Figure 6. Finite Element Analysis Flow Chart

3.4. Machining Limit Conditions

As for Machining Boundary Conditions, namely:

| Table 1. Machining Limit Conditions [11] dan [8] |
|-----------------------------------------------|
| **Boundary conditions** | **Description** |
| Machining Parameter | Cutting Speed, \( V_c \) (m/min) = 50, 65, dan 80 |
| | Feed Rate, \( F_r \) (mm/rev) = 0.12 |
| | Depth of cut, \( a \) (mm) = 1 mm |
| Coolant | SCCO₂ |
| Tools | Tools = Uncoated Carbide |
| | Rake Angle, \( \gamma = 10^\circ \) |
| Cooler Parameter | Temperature = -80°C |
| | Chamber pressure = 10.34 MPa |
| | Nozzle distance = 8 mm |
| | Nozzle angle = 45° |
| | Lubricant flow rate = 2.61 l/hr |

3.5. Analysis Steps

Finite Element Analysis is a way to get experimental results that approach the actual situation or situation with the help of a computer, where in conducting this research using the help of Autodek Simulation Mechanical 2016. The stages can be described as follows:

Making a forecasting model of the simulation of the titanium turning process using Autodesk Inventor 2016 needs to consider several parameters, such as geometry and mechanical properties of the
tool and workpiece as well as the load given in the form of cutting forces that arise at the contact angle between the tool and workpiece.

![Figure 7. Making Simulation Forecast Model Using Autodesk Inventor 2016](image)

Determination of boundary conditions is carried out after the forecast model is given a workload. In this writing the boundary conditions given are machining conditions in the titanium turning process.

![Figure 8. Mesh view and condition forecasts for simulation using Autodesk Simulation Mechanical 2016](image)

The results obtained in this study are stress graphs that occur in the titanium machining process. Validate simulation results with experimental results. Perform the calculation of specific energy cuts theoretically using existing equations.

4. Result and Discussion

4.1. Machining Parameter.
The machining parameter used in this simulation process refer to the research conducted by (Zheng et al. 2015) and (Rahim et al. 2016) as shown in Table 1.

4.2. Calculation Data
The cutting simulation data as shown in the previous chapter. To find the relationship between cutting speed, feed rate, and rake angle to cut force can be determined using equation (9). Then to obtain specific energy results, it is necessary to calculate using equations described in the previous sub-chapters, namely in equations (10), (11) and (12). Based on the equation above we can obtain the results of cutting forces and specific energy cuts in the machining parameters.
Table 2. Data from the calculation of cutting forces and specific cuts energy (12)

| Cutting Speed (v) | Rake Angle (θ) | Cutting Force (F_c) | Specific Energy (P_s) |
|------------------|----------------|---------------------|----------------------|
| 50 m/min         | 10°            | 216.675 N           | 1.805 J/mm³          |
| 65 m/min         | 10°            | 211.777 N           | 1.765 J/mm³          |
| 80 m/min         | 10°            | 208.005 N           | 1.733 J/mm³          |

Figure 9. Graph of the relationship between cutting speed and specific cut energy

Based on the graph above, a specific cutting energy ratio for different cutting speeds (v) with the same angular angle during the turning process of Ti-6Al-4V with a cutting depth of 1 mm using a carbide tool produces a specific energy cut with cutting speed (v) of 50 m/min, namely 1.805 J/mm³, while at cutting speed (v) of 65 m/min that is equal to 1.765 J/mm³, and at cutting speed (v) of 80 m/min which is 1.733 J/mm³. This means that there has been a decrease in the specific cutting energy for each cutting speed increase (v), the results are in accordance with the reference journal in [8], in the journal if the cutting speed is increased, the specific energy will be smaller or decrease.

5. Conclusion
The conclusions obtained from the study and discussion of the specific energy analysis of cutting and stress in the workpiece on the lathe machining process can be concluded as follows:
1. From theoretical calculations it appears that if the cutting speed increased, the specific cutting force and energy will slide down (decreased).
2. Based on the result, Stress will increase for each cutting speed.

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