MINIMIZING TEMPERATURE AND TOOL WEAR ON ROCK CUTTING WITH NEGATIVE RAKE ANGLE

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This research discusses the effect of negative rake angle, to the temperature and tool wear on rock cutting. The cutting process was conducted on marble rock material, without coolants and utilized tungsten carbide inserts with 0°, -5°, -10°, -15°, -25°, -30° and -40° rake angles; meanwhile, the feed rate, spindle speed and depth of cut were applied constantly. Temperature measurement used K-type thermocouples, and the scanning electron microscope observed the tool wear. The data collection was monitored in real time from initial conditions until cutting 150 mm in length. The tool wear data was observed after the turning process of 150 mm in length. The results show that at negative rake angle -25° produce the smallest temperature and tool wear compared to other negative rake angles. This phenomenon occurs because the cutting mode changes from brittle cutting mode to ductile cutting mode. The pile of chip powder in front of the cutting tool was implemented to protect the cutting tool from direct friction with the workpiece and enhance thrust force on the surface of the marble rock. It would greatly affect the cutting temperature and tool wear.

KEYWORDS

Rake angle, rock cutting, temperature, and tool wear

1 INTRODUCTION

Most of the rock materials are classified as brittle materials [Kaitkay 2004]. Rock cutting technology has been applied in many industries such as in gas drilling, mining, oil drilling, raw building materials, and handicrafts. The manufacturing can be done by the process of drilling, milling, sawing and turning [Che 2015]. Negative rake angles are used in machining because of their ability to form a large amount of pressure in front of the tool bit and change the cutting mode from a brittle to ductile cutting mode [Kaitkay 2004, Wilson 2003]. The application of negative rake angles to machining has several advantages, i.e., increasing tool strength, having slower tool wear [Hamade 2010], being capable of cutting very tough materials and creating a pressure effect in front of the cutting tool, thus producing a smooth surface for the workpiece. Requiring a large amount of force, generating high friction and high cutting temperatures are some of its drawbacks [Wilson 2003]. There have been only a small number of studies researching the effects of negative rake angles on temperature and tool wear on rock material longitudinal turning.

Research on temperature and tool wear on rock turning has been done by Che, et al. [2015] on the face turning of *Indiana Rock* with Polycrystalline Diamond Compact (PDC). The temperature was measured using a K-type thermocouple with a rake angle of -25°. It showed the highest temperature of face turning at 50°C for a length of 2.54 mm from the PDC tool edge. The other research conducted by Wilson, et al. [2003] includes longitudinal turning of granite with a diameter of 14.55 mm, a workpiece length of 254 mm and rake angle of -10°. The temperature measurement was conducted with K-type thermocouples from a distance of 2.54 mm, cutting depth of 1.4 mm and a feed rate of 0.185 mm/rev. From this research: the initial tool cuts the rock material, the temperature increases from 200°C until the tool would burn at temperatures above 500°C and the tool would start to break until it reaches 700°C. The tool wear is proportional to the chip volume.

The largest tool wear after the granite cutting was measured as big as 1.4 mm. Cools [1993] has investigated the effect of the positive rake angle of 36° on temperature and tool wear on rock cutting. The temperature measurement used a K-type thermocouple from a distance of 1 mm from the cutting tool. The result showed a maximum temperature of 800°C with the tool wear of 0.5 mm. These researchers discussed that the magnitude of the temperature occurred during cutting, and it should be noted that only one research study used a negative rake angle; therefore, it would require more research to determine the most optimal temperature for rock cutting.

Research on the analytical model on tool wear for rock cutting has been done by Chekina, et al. [1995]. In this research using a rake angle of 15°, cutting depth of 1 mm and cutting speed of 15 m/s, it was found that the tool wear increased in accordance with the cutting force. The tool wear gradually increased until the end of the cutting process. Ortega [1984] has done modeling of temperature on Tennessee Marble Rock that resulted in safe cutting with temperatures below 750°C. For cuts above 750°C, micro-chipping occurs, where grains would exfoliate from parent material of the tool. Researchers [Chekina 1995, Ortega 1984] conducted the modeling to determine the safe temperature at which to attend rock cutting. Further discussion on the research of negative rake angles to determine temperature and tool wear would be beneficial. Moreover, Hamade, et al. [2010] has researched the effects of the negative rake angle on the force and tool wear in the drilling process. The machining was using Basalt Rock as the working material, a PDC tool, and a negative rake angle. It showed that the wear decreased while increasing a negative rake. The research, however, mostly focused on the drilling process and did not discuss longitudinal turning and cutting temperature, and did not provide answers about negative rake angle circumstances in turning processes.

Nishimatsu [1971] was conducted research regarding orthogonal rock cutting with the rake angle ranging from 10° - 40° and a cutting speed of 5.2 m/min. The mechanism of chip formation is analogous to chip formation by metal cutting. Three zones of rock cutting are primary crushed zone, secondary crushed zone, and overcutting zone. Hough [1986] conducted an experiment of the effect of rake angles by 7°, 15°, 20° and 25° with a diamond tool bit with black marble as the working material and a spindle speed of 500 and 750 rpm. This research showed that the rake angle of 20° produced the maximum pressure. The optimum pressure and torsion acceleration were obtained from rake angles 7°and 20°. Verhoef, et al. [1996] have experimented with a tri-axial rock testing machine for changing mode from the brittle to ductile cutting mode by conditioning the pressure and surface of the workpiece. The research emphasized that the brittle-ductile cutting mode had a major role, as the cut from brittle to ductile would influence the crushed zone in which the larger area would into the ductile cutting zone, and the smaller would into the brittle cutting zone. Kaitkay and Shuting [2004] have experimented with the cutting force on face turning of the marble rock Chartage on hydrostatic pressure, a diamond tool bit and a rake angle from -5° to -25°. A feed rate of 0.8 mm/rev and cutting speed of 1 m/s were used. The experiment showed that the cutting force would increase the negative rake angle and hydrostatic pressure. The application of external hydrostatic pressure could influence the mechanism of chip formation. Research on a cutting mechanism, chip formation, and cutting force have also conducted by Nishimatsu [1971], Kaitkay and Shuting [2004]. However, it did not include cutting temperature and tool wear using a negative rake angle, even though the cutting temperature affects the cutting force, chip formation, tool wear and the quality of machining.

Negative rake angle has an essential role in brittle material machining because it made a large hydrostatic pressure in front of the tool, and in return, decreases the chance of crack initiation on the surface of the workpiece and changes the cutting modes from a brittle to brittle-ductile cutting mode [Che 2015, Kaitkay 2004, Verhoef 1996]. From the researchers [Cools 1993, Ortega 1984] who used positive rake angles, the results showed high-temperature responses between 750°C and 800°C. Further research [Che 2015, Wilson 2003] developed negative rake angles for rock cutting with lower temperature responses from 50°C to 200°C. However, this study only used a rake angle of -10° to determine the temperature response and did not discuss the tool wear if the negative rake angle was enlarged. These two statements have not revealed to researchers [Che 2015, Kaitkay 2004, Verhoef 1996]; with that, the author raised the topic of this research. This research discusses the effect of a negative rake angle on the cutting temperature and tool wear in the longitudinal turning process on marble rock. The rake angles were varied starting from a neutral rake angle (0°) to the most negative (-40°) to discover the temperature response and the tool wear. The result of this research could be applied for industries in manufacturing, oil and gas drilling, mining and making handicraft of marble ornaments, medallion bodies, statues, vases, and other decorations.

2 MATERIALS AND METHOD

The material used in the research includes marble rock (beige colored) obtained from Besuki Village Mining Area, Campurdarat Sub-District, Tulungagung District, Indonesia. Marble rock was tested X-Ray Fluorescence (XRF) to determine chemical composition. The marble rock has a chemical composition as shown in Table 1.

Ca	Mo	Lu	Fe	Er	Co	Cu
99.23	0.27	0.15	0.12	0.1	0.082	0.041

Table 1. Chemical composition (%) of marble rock

It was initially taken from the mine as a rectangular prism and divided into smaller blocks, where it was lathed to form the cylindrical testing specimens of 40 mm in diameter and 200 mm in length. The rock cutting process was conducted in a semi-automatic lathe machine with its specifications: Yamazaki machine type, power 4 kW, feed rate range: 0,045 up to 0,630 mm/rev, spindle speed range: 30 up to 2500 rpm.

2.1. Temperature Response Measurement

The temperature response on rock cutting with tungsten carbide inserts was performed without coolants. The workpiece was 40 mm in diameter, and the cutting length was 150 mm. The spindle speed uses a 350 rpm, 0.135 mm/rev feed rate and a cutting depth of 1 mm. Surface roughness of marble rock before machining process is 8.54 µm. The process parameters used in the longitudinal turning experimental summarized in Table 2. The tool used in this machining was a type of tungsten carbide, "Widia YG6". The tungsten carbide tool "Widia YG6" with characteristics: chemical composition (94% WC + 6% Co), density 14.95 g/cm^3, bend strenght 1900 N/mm^2 and hardness 90.5 HRA. The machining parameters: spindle speed, feed rate, and cutting depth made constant while the rake angle was varied from 0° to -40°. The variables observed in this research are cutting temperature and tool wear.

Parameters	Values
Spindle speed	350 rpm
Cutting speed	43.96 m/min
Rake angle	0°, -5°, -10°, -15°, -25°, -30° and -40°
Feedrate	0.135 mm/rev
Depth of cut	1 mm

Table 2. Process Parameters

In this research, temperature measurements was used the artificial thermocouple method because the fast temperature response, precise, compactible equipment and the measurement position on the tool can be adjusted. Temperature measurement can be directly right at the thermocouple position, thermocouple sensor can be placed until it approaches the heat source [Ceau 2010]. The closer the temperature sensor to the heat source, then the results are closer to reality, but this is difficult to do. The temperature of the tooltip was determined by conduction and extrapolation equations. The series of devices measurement includes thermocouples, ADAM 4018 data acquisition, USB converter, and ADAM Apax software. Thermocouples will obtain heat, and the analog data would be collected then processed in ADAM 4018 data acquisition to attain a digital signal. This signal would then be read in ADAM Apax Utility software and displayed in data graphs on the computer. The temperature measurement was conducted by a K-type thermocouple installed on the tool surface clamped by a plate. Two thermocouples were used to determine heat conduction. The distance between the tip of the tool and thermocouple 1 was 10 mm, while the distance between the tooltip to the thermocouple 2 was 15 mm, as shown in Figure 1. This arrangement was used to predict the heat at the tip of the tool and the propagation of heat through conduction with an extrapolation method [Che 2015, Cools 1993]. The temperature outcome at the tip of the cutting tool would utilize the conduction heat transfer equation [Incropera 1993]:

$$q_k = -\,k\,A\,\frac{dT}{dx} \qquad (1)$$

where:

q_k = Heat transfer rate (kJ/s, W)
k = Thermal conductivity (W/m, °C)
A = Cross-section area (m^2)
dT = Temperature difference (°C)
dX = Distance (m)

The cutting temperature at the tooltip was determined by thermocouple 1 and thermocouple 2. Extrapolation formula was used with the base of the cutting temperature read by thermocouple and distance between thermocouple. From this basis we can determine the temperature at the end of the tool with the extrapolation formula with the following equation:

$$\frac{T-T1}{T2-T1} = \frac{X-X1}{X2-X1} \qquad (2)$$

Where:

T = Tooltip temperature (^{o}C)
$T1$ = Temperature reading of the thermocouple 1 (^{o}C)
$T2$ = Temperature reading of the thermocouple 2 (^{o}C)
X = Distance in the position of the tooltip (mm)
$X1$ = Distance in the position of the thermocouple 1 (mm)
$X2$ = Distance in the position of the thermocouple 2 (mm)

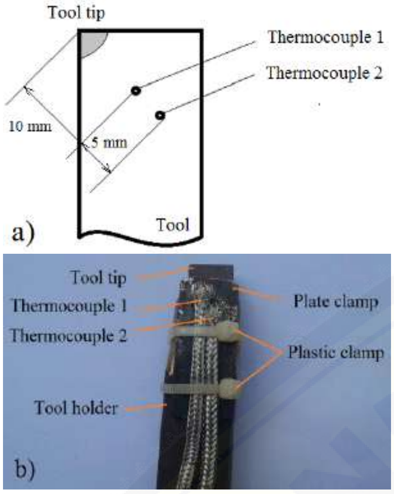


Figure 1. (a) Cutting tool thermocouple scheme; and (b) Thermocouple position at the cutting tool

2.2. Flank Wear Measurement

The tool wear observed in this particular research was the flank wear (VB) and observed by Scanning Electron Microscope "Hitachi TM 3000" with 100x – 2500x magnification. The value of flank wear can be analyzed by measuring the length of VB (µm), by measuring the distance between the cutting edge before the cut and the average line after wear on the main site. During the cutting process, the flank wear (VB) would increase parallel to the increase of cutting time t_c (min) and cutting length L (mm). Flank wear occurs on the main/major side, and the measurement flank wear (VB) was obtained by measuring the length of VB, the distance between the cutting tip before the wear to the average wear resultant at the main site [Chayeuski 2016, Naprstkova 2016].

Figure 2 shows the coordinate system on turning machine. The X axis was the direction of the cutting force, the Y axis in the direction of the thrust force and the Z axis in the direction of feeding. The observation position of tool wear that occurs in the major flank face and minor flank face.

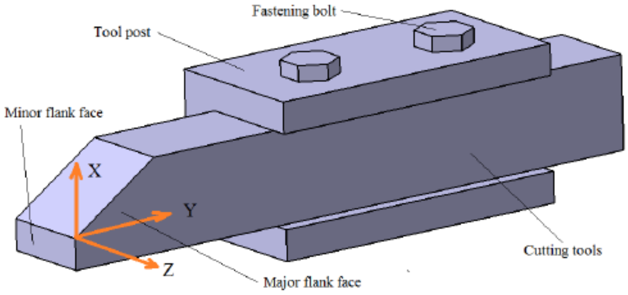


Figure 2. The coordinate system on turning machine.

3 RESULT AND DISCUSSION

There are two main discussions in this experiment of rock cutting, i.e. (a) The research of the temperature response of the rock cutting and (b) The analysis of tool wear in the rock cutting.

3.1. Temperature Response

The interaction between the rock and the cutting tool causes friction that produces heat; this heat would continue to increase until the cutting length finish. According to this condition, it appears that the temperature affects the cutting process of the rock. At the initial interactions between the objects, the heat starts propagating from the heat source (tooltip) and is recognized by thermocouple 1 (TC1) mounted 10 mm from the heat source, and the similar process occurs for thermocouple 2 (TC2) mounted 15 mm from the heat source. The temperature on tooltip was determined by using the heat transfer conduction equation and mathematical extrapolation.

Figure 3 shows all temperature responses have the same trend. Starting from the ambient temperature of 33.8°C then the temperature increases after the tool touches the workpiece, Temperature continues to increase until the end of the process after 350 seconds. Fluctuations in temperature response are almost all negative rake angle. This phenomenon shows the mechanism of cutting in a brittle material. In cutting the brittle material, the chips removal mechanism follows the crushing and friction mechanism so that the resulting chips were in the form of powder. The force increases at the initial crack formation and decreases when the crack has spread. Force Fluctuations will affect the friction between the tool and the marble rock. The magnitude of this friction will affect temperature response fluctuations. In Figures 3a and Figure 3c, there is a significant temperature response fluctuation. It shows the dominant brittle cutting mode whereas in figure 3b this small temperature response fluctuation shows the brittle-ductile cutting mode. The results of this research are in accordance with those obtained by Che, et al [2015]. which state that the maximum temperature on rock cutting is 50^{o}C, this occurs because in rock cutting occurs brittle cutting mode. The Chips generated in the form of chips powder that flow on the surface of the tool continues to be wasted.

The results of determining the temperature at the tooltip (conduction and extrapolation method) are as follows;

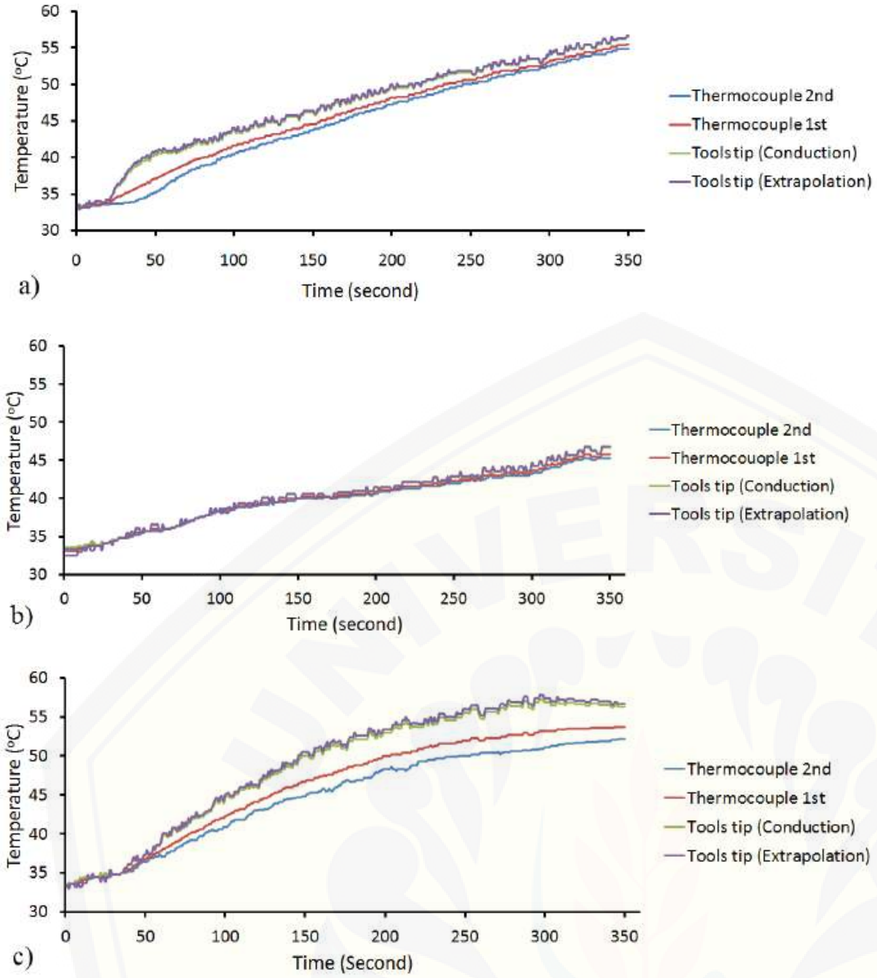


Figure 3. Temperature responses; a) rake angle 0°; b) rake angle -25° and c) rake angle -40°

Figure 4 shows the cutting temperature has decreased, starting from the rake angle 0° the temperature continues to decline until the temperature reaches the minimum at the rake angle of -25° after which the temperature increases to the rake angle of -40°. On the negative rake -25°, chips powder volume is more than the other negative rake. Chips powder volume in front of the cutting tool will protect the tool from friction directly with the workpiece so that the cutting temperature is low. The existence of the chips powder in front of the cutting tool, the chips powder will be crushed continuously during the cutting process. The advantage of this phenomenon will be to generate a large thrust force. This thrust force will produce a hydrostatic pressure that protects the surface of the workpiece from the initial crack formation. Hydrostatic pressure will change the cutting mode from brittle cutting mode to brittle-ductile cutting mode. This phenomenon can be proved by; the small fluctuations in temperature response (Figure 3b), more of the chips powder in front of the cutting tools (Figure 5e) and lower tool wear (Figure 9).

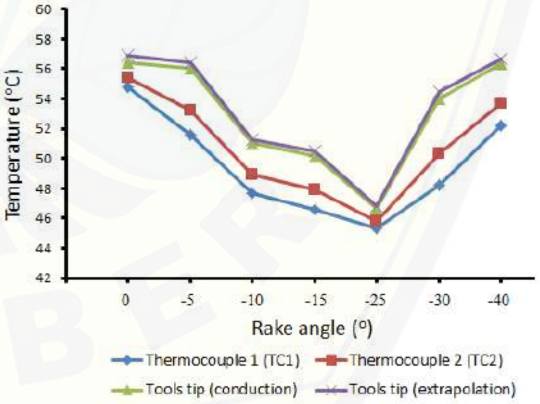
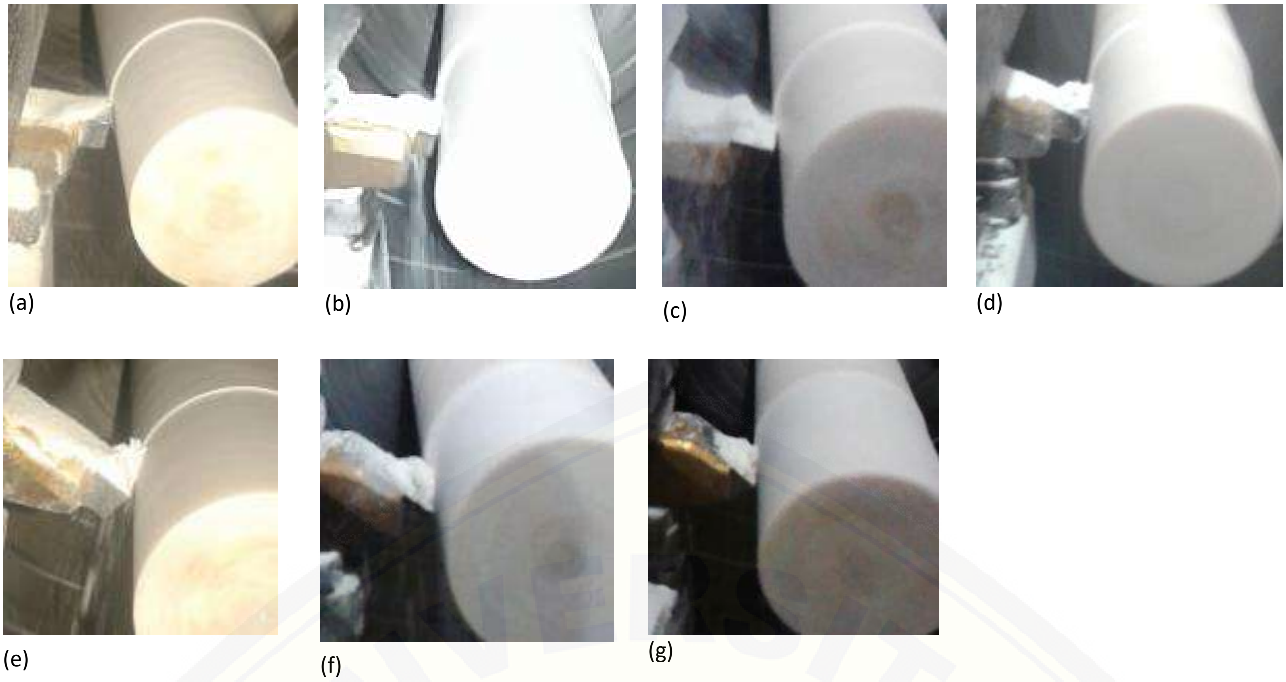


Figure 4. Rake angle and cutting temperature relationship.

The volume of chips powder in front of the cutting tool of various rake angles was shown in Figure 5. It can be seen in the rake angle of 0° the chips powder flowing out and immediately wasted. The tool will be rubbing directly with the workpiece so that the cutting temperature higher. On the negative rake -25° the chips powder will pile in front of the cutting tool. The results of this study are in line with the research Che, et al. [2017]. which states that chips from the rock cutting in powder form. The chips powder will pile in front of the cutting tool. The chips powder was in the form of; fine, coarse, and big chips depending on machining conditions.


(a) (b) (c) (d)

(e) (f) (g)

Figure 5. The pile of chips powder on rock cutting: (a) Rake angle 0º; (b) Rake angle -5º;(c) Rake angle -10º; (d) Rake angle -15º; (e) Rake angle -25º;(f) Rake angle -30º; and (g) Rake angle -40º

Che, et al. [2015] In metal cutting, the mechanism of chips formation begins in the cutting force of the tool until plastic deformation occurs. The chips will peel off from the parent metal because of the shear force that occurs in the sliding plane. As a result of plastic deformation, this will produce heat which will be passed to chips. The first heat source occurs in the primary shear zone. The cutting force of the tool will push the chisel and flow into the chisel cutting plane. Chips were flowing at high temperatures with the sliding mechanism and friction that occurs in the secondary shear zone then chips will be wasted. Heat conduction will propagate to the parent metal due to the mechanism of plastic deformation. This heat affected area was called the tertiary shear zone.

Meanwhile, the mechanism for the chips formation in metal cutting is very different from the mechanism of the chips formation on rock cutting. Nishimatsu [1971] suggested the rock cutting theorem, which classification three areas of cutting: the primary crushed zone, secondary crushed zone, and overcutting zone, as shown in Figure 6, in removal chip powder. The process of rock cutting starts from the tooltip, which begins to press the workpiece, and is where it will increase the crushed area around the tooltip, called the primary crushed zone. The tool will continue to press the workpiece and move forward, causing an initial macroscopic crack, called the secondary crushed zone. Afterward, the tool goes on into the overcutting zone, losing a great deal of energy. This process will take place continuously until the cutting process ends.

The chips produced in rock cutting are not hot because there is no plastic deformation during the brittle cutting mode. The heat that occurs during pure cutting comes from the friction between the tool and the rock. During the brittle cutting mode, chips powder would generate and flow over the surface of the cutting tool [Che 2015]. In this rock cutting, there is no sliding mechanism, but the phenomenon of crushing and sliding friction will occur. The heat that arises during cutting will be propagated from the tooltip towards the area around the tool in manner heat conduction and convection.

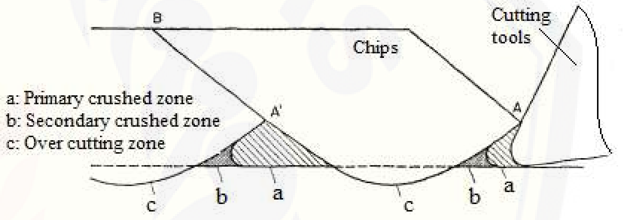


Figure 6. Chips formation mechanism on rock cutting [Nishimatsu 1971]

3.2. Tool Wear Measurement Result

From the SEM analysis, the tool wear seen on the major flank face and minor flank face due to damage to the coating parts of the tungsten carbide tool. Minor flank face wear is greater than the wear on the major flank face. At the rake angle 0º, the chips powder is immediately wasted so that direct contact occurs between the tool and the marble rock. The friction between the marble rock and the tool results in an abrasion process at the end of the tool so that it becomes worn. The irregular wear surface was caused by the mechanism of brittle fracture of marble rock. Figure 7 shows the tool conditions before cutting the rock. The tool surface visible that is still intact, without scratches and grooves.

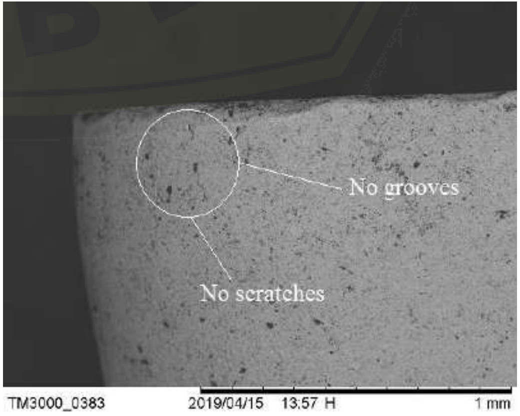


Figure 7. SEM image tool surface before marble rock machining

Figure 8 shows the particles structure seen was damaged due to friction. The grooves and scratches on the flank face were formed. The chips powder was sticking to tool surface and difficult to remove.

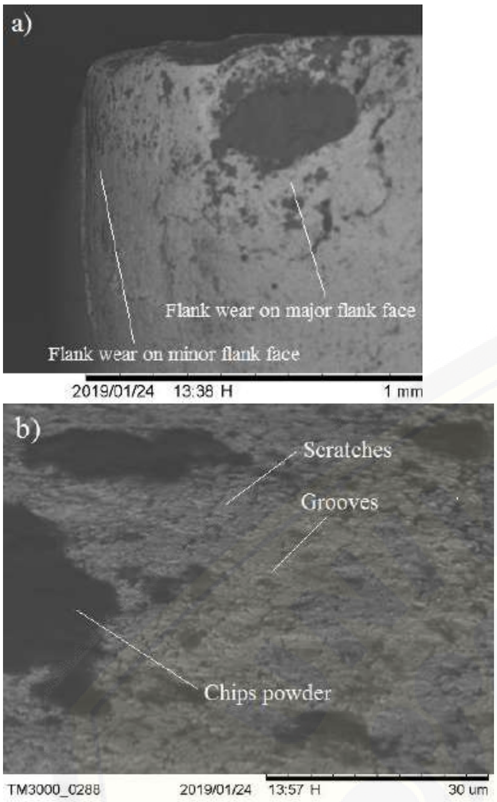
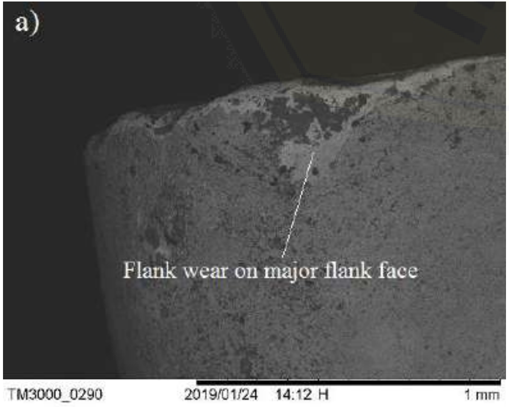


Figure 8. SEM image tool wear on rake angle 0° after marble rock machining a) Magnification 100x, b) Magnification 2500x

Figure 9 shows the SEM analysis for cutting tools with a rake angle of -25°, the tool does not occur minor flank face damage. The tool has occurred slight damage to the major flank face: slight scratches, no grooves, and no micro-pits. The pile of chips powder is crushed together during machining. The existence of piles of chips powder is also advantageous in brittle materials machining because it will increase the thrust force. This thrust force will form a hydrostatic pressure between the tool and the workpiece. This hydrostatic pressure will create the same pressure between the tool and the workpiece so that there is no stress concentration and cracking. The tool particles structure which is relatively intact compared to rake angle 0° and rake angle -40°.



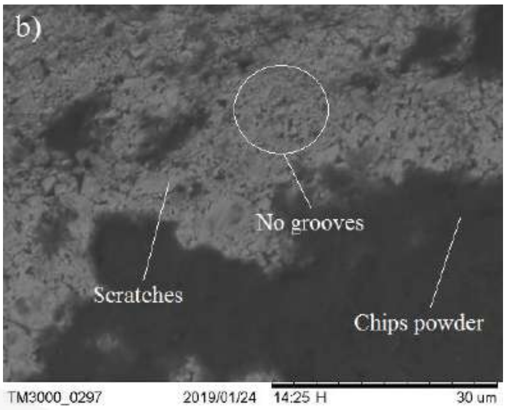


Figure 9. SEM image tool wear on rake angle -25° after marble rock machining a) Magnification 100x, b) Magnification 2500x

From SEM analysis for cutting tool with rake angle -40o, tool wear occurs on: major flank face and minor flank face. The tool wear on the major flank face is greater than wear that occurs on minor flank faces. This is due to the decrease in the pile of chips powder, so the tool area was less protected. The tool surface will rub against directly with the workpiece. The decreasing pile of chips powder will reduce the thrust force so that the hydrostatic pressure decreases. This phenomenon affected in the major flank face and minor flank face of the cutting tool being abrasion due to friction with the workpiece. This decrease in thrust force has an affected on the tool surface particles structure in the form of uneven grooves as shown in Figure 10. It appears that the structure of the particles is damaged by friction in the form: grooves, scratches and micro pits in the flank face. The results of this study are in line with the research Naprstkova, et al [2016]. which states that based on SEM analysis, tool wear occurs due to peeling off layers which occurs at the tooltip, tool front and back edge of the tool.

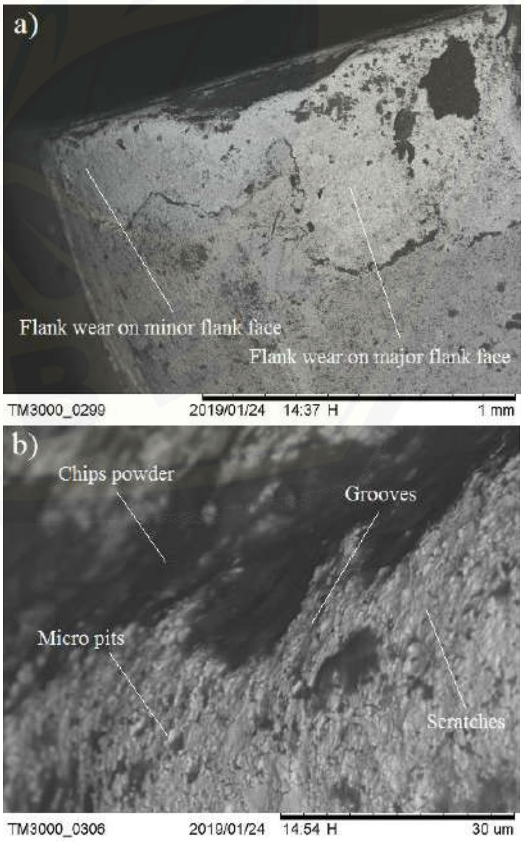


Figure 10. SEM image tool wear on rake angle -40° after marble rock machining a) Magnification 100x, b) Magnification 2500x

On the neutral rake angle (0°) was occurred the largest tool wear due to the absence of chip powder which protects the cutting tool and causes direct friction between the tool and the marble rock. This continuous cutting force increases the tool wear. Meanwhile, with the larger negative rake angle, the chips powder in front of the cutting tool becomes larger in volume as presented in Figure 11. This phenomenon can advantage for brittle material cutting process. The pile of chips powder can increasing thrust force. The thrust force can generate hydrostatic pressure which can change cutting mode from brittle to brittle-ductile cutting mode [Kaitkay 2004, Verhoef 1996].

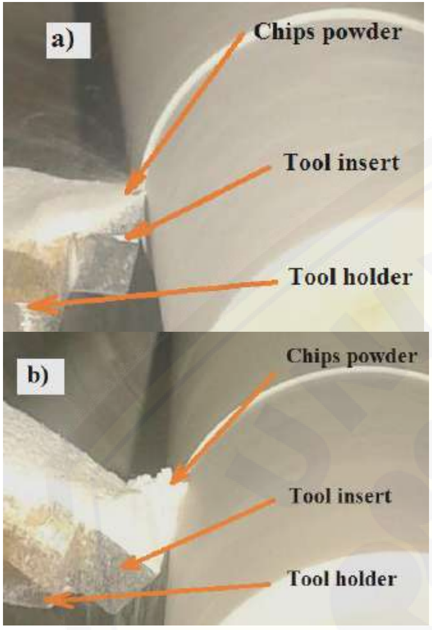


Figure 11. Comparison of the amount of chip powder in front of the tool rake face. a). Chip powder on rake angle 0°; and b). Chip powder on rake angle -25°

The tool wear was caused by plastic deformation due to pressure during cutting and abrasion from the friction between the marble rock and cutting tool. The phenomenon of tool wear can be explained due to plastic deformation at the tooltip rubbing against the workpiece [Cools 1983]. Cutting force will cause pressure on the tool. Pressure will generate stress on the tooltip area that rubs against the workpiece. As a result of this friction, it will produce heat. The heat was generated from friction and crushing force between the tool and rock material. Heat can form plastic deformation on the surface of the cutting edge of the tool. The difference in tool wear from various rake angle tools is due to differences in cutting force and the amount of friction between the tool and the rock material along the cutting path. The heat per unit time resulting from friction and crushing force will affect the tool wear width. The amount of heat per unit time will increase the temperature in the friction area. Increasing the temperature around the tool will weaken the tool and plastic deformation will occur at the tooltip. This process will cause the cutting tool to wear.

4 CONCLUSIONS

From this research on rock cutting, it can be concluded that:

1. The temperature response on rock cutting shows fluctuations. This fluctuation shows brittle material. In the cycle of rock cutting, the tool will touch the workpiece. The tool will enter pressing the rock material until a crushed area is formed. In this zone a great force was needed. The tool will continue to forward until there is a secondary crushed zone. This proses will produces crack initiation. After the crack propagates, with a small force the chisel will pass through it. This phenomenon has resulted in fluctuating cutting temperatures.
2. The Cutting marble rock using a negative rake angle produces a temperature that is low below 60°C. Chips produced from rock cutting in form chips powder. Chips powder produced in rock cutting before being removed from parent material is not hot because there is no plastic deformation during the cutting process. The chips powder only flows on the surface of the cutting tool after being removed it from the parent material. The heat source was pure comes from the friction between the tool and rock material, In this process, there is no sticking-sliding friction phenomenon.
3. Negative rake angle -25° produces the smallest tool wear. In rock cutting the source of heat pure comes from friction that occurs at the tooltip. The pile of chips powder will protect the tool surface from direct friction with the rock material. Chips powder will continue to crushing and sticking during the machining process and act as a new layer such as a built-up edge in metal cutting. Tool wear occurs because of the abrasion process due to pure friction between the tool and the rock material.

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