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Investigation of dry cutting performance in lathes machine using flat heat pipes as part of cooling system

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Abstract

This study aims to develop a cutting tool cooling system for lathe machines in dry machining using finned flat heat pipes. The heat pipe is equipped with fins placed at the cutting tool's edge to reduce the cutting tool's temperature. Tests were conducted on conventional lathes with spindle speeds varied from 250 rpm, 540 rpm, and 850 rpm for the 20 minute operation to reduce the workpiece diameter from 22 to 18 mm and 90 mm long. The testing was carried out in three methods: (1) dry cutting process without heat pipe and coolant, (2) cutting process without heat pipe but using coolant, (3) dry cutting process equipped with heat pipe without coolant fluid. The result shows that using heat pipes as a cooling medium significantly influences reducing the cutting tool temperature compared with the dry machining process. The cutting tool temperature can be maintained at 30–40ºC when using a heat pipe as part of the cooling system. Using heat pipes as a cutting tool cooling medium also positively affects the cutting tool's life. During the 20 minute with spindle speed 250 rpm machining process, the cutting tool assisted with the heat pipe has not shown wear, while the cutting tool in the dry machining process began to show wear. On the other hand, the cooling process using coolant liquid gives maximum results, so a combination of heat pipes and coolant fluid with a minimum capacity can be recommended as part of the cooling system to improve the cutting tool's performance.

Keywords: lathes machine cutting tool, dry cutting performance, flat heat pipe, temperature, cutting tool wear

1 Introduction

In recent industrial applications, producing products or components that are lighter, more precise, and use fuel efficiency is required. This need encourages the use of higher-strength and heat-resistant materials. A good quality product is a real challenge for manufacturers regarding tool life, productivity, and chip control systems. Machining processes on hard materials inherently produce high temperatures due to the hardness of the working part and high friction on the chip-tool surface and workpiece-tool surface. The tool life of complex machining and high cutting speed is usually increased by increasing the supply of more coolant. However, this machinery's liquid poses safety and health problems [1-3]. Therefore, improved performance of the cooling system with minimum fluid use is needed.

However, in dry operation, the friction between the chip and the tool becomes higher, leading to higher tool temperatures, higher wear rates, and shorter tool life. To solve the problem of the dry machining technique, the machining process with a minimum quantity of lubrication (MQL or the minimal fluid application (MFA) technique can be used. With the MQL method, the fluid volume is minimal, about 2 to 5 ml/m, and the liquid was applied in the critical zone as a pulsed jet. The use of MQL showed that the friction force between two surfaces could be reduced quickly, where the cooling chamber fills the gap separating the cutting tool and chip [1, 4, 5]. But further development is still needed to improve the cooling process through rapid heat removal. One of the heat exchangers that are very effective in moving heat is a heat pipe [6-8]. The heat pipe is a heat exchanger device with very high thermal conductivity and can transfer large amounts of heat with a small temperature difference [9-11]. The heat pipe structure consists of a closed tube with a wick structure and working fluid that acts under vacuum conditions. The heat pipe consists of evaporator, adiabatic, and condenser sides. The evaporator side is the area that receives heat which causes the working fluid in the pipe to evaporate and then flow through the adiabatic side and condenser. On the condenser, side heat will be released so that the working fluid will change from gas to liquid and return to the condenser [9-13]. The use of heat pipes in various applications [8, 11, 14-17] shows that heat pipes are one of the energy recovery devices that can provide significant energy savings.

The application of machining processes with minimum fluid cooling and heat pipes in manufacturing processes has been widely applied. The study used heat pipes equipped with fins mounted in a vertical position right at the end of the cutting tool at the point closest to contact with the workpiece to extract heat from the tool has been carried out as in reference [1]. The effect of heat pipes on cutting performance was analyzed using Taguchi. The test results showed cutting temperature, and tool wear were reduced to a maximum of 22% and 15%. Other studies [3] investigate the effectiveness of MQL compared to dry machining. Tests were carried out on thin disk-shaped workpieces with a diameter and thickness of 150 mm and 2 mm, using an uncoated carbide cutting tool.

The machining process is carried out with variations in cutting speeds, rates in dry machining conditions, and MQL technique. The fluid pressure of MQL was 0.2 MPa, and used Synthetic Ester as a lubricant. The test results showed that the cutting temperature was reduced by 10-30% in the MQL technique compared to dry conditions. These results indicate that the MQL machining technique is better than the dry condition. The utilize a heat pipe as a horizontally mounted cooler was conducted as in reference [18], where the evaporator side is located at the tool edge and the condenser side on the tool holder. Using heat pipes can reduce the tool's temperature significantly at high cutting speeds. Other studies [19] also investigated the use of cutters and workpiece materials with different thermal conductivities in dry machining techniques with heat pipe pipes embedded into the cutting tool. The result shows that using a heat pipe embedded into the cutting tool can decrease its temperature effectively. The thermal conductivity of the cutting tool and workpiece material affects the heat transfer from the workpiece to the cutting tool.

The literature review shows that heat pipes and minimal fluid use in machine tools have been widely carried out. But still separately on minimal fluid use only. Heat pipes have also been used but only placed at one end so that installation will be difficult in the field. In addition, it also uses a heat pipe that is not equipped with fins. This study aims to develop a cutting tool cooling system for lathe machines in dry machining using finned flat heat pipes. The heat pipe is a flat-shaped heat pipe that is easy to install on the cutting tool. In order to increase the heat release from the tip of the tool through the heat pipe, aluminum fins are added to the side of the heat pipe. The cutting tool cooling system equipped with this heat pipe is expected to reduce the tool's temperature during the machining process, increasing the cutting tool's life, and reducing the use of coolant.

2 Research Methods

2.1 Experimental setup

The tool cooling system on heat pipe-based machine tools is designed for hard-turning applications without fluid cooling. The evaporator of heat pipe is placed on edge of the tool, while the condenser side equipped with fins is cooled with ambient airflow. The placement schematic of the tool cooling system is shown in Fig. 1, and the detail of the cooling system with heat pipe is shown in Fig. 2.a

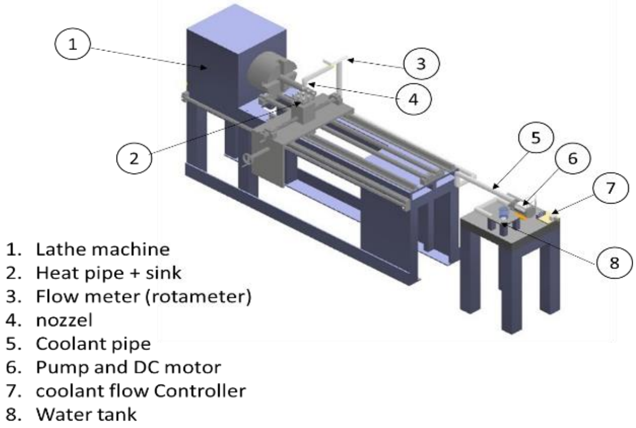
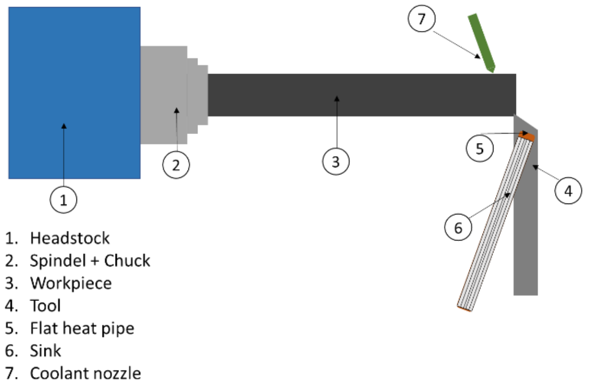
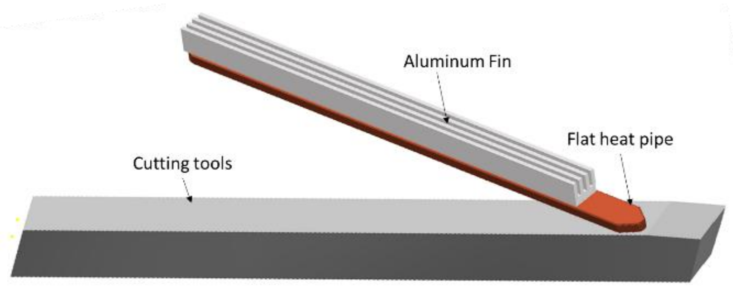


Fig. 1. The placement schematic of tool cooling system in the lathe machine



(a)



(b)

Fig. 2. The cooling system with heat pipe. (a) installation cooling system in the lathe machine (b) heat pipe assisted with heat pipe

A flat heat pipe equipped with fins is placed on the edge of the appliance, as shown in Fig. 2.b. The heat pipe placement at the tool's end is intended so that the heat caused by friction between the workpiece and the heat pipe can be directly transferred to the evaporator side of the heat pipe and then removed on the condenser side. In order to increase the heat release, an aluminum fin is added to the condenser side of a heat pipe. Heat-pipe was made of copper, in the inner surface of tube added a wick structure of sintered copper, and the working fluid is water with 50% filling ratio. The total length of the flat heat pipe was 130 mm, 2.5 mm thickness, and 8 mm wide. The evaporator section of 23 mm and condenser section of 107 mm. The geometry of the heat pipe is shown in Fig. 3.

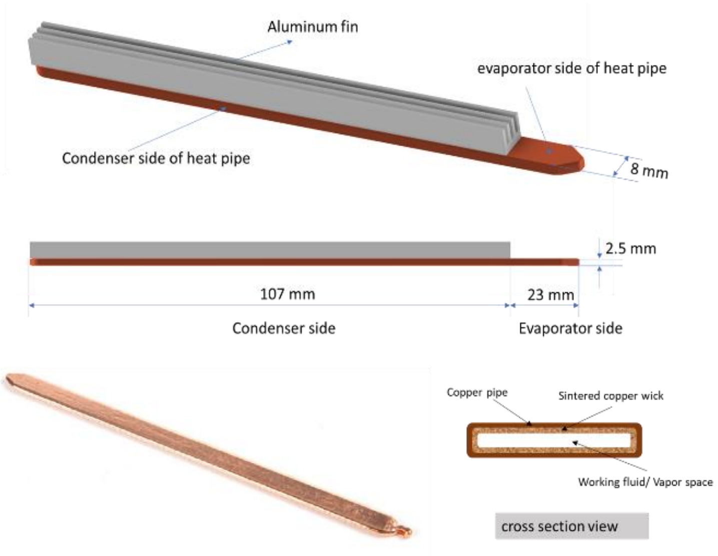
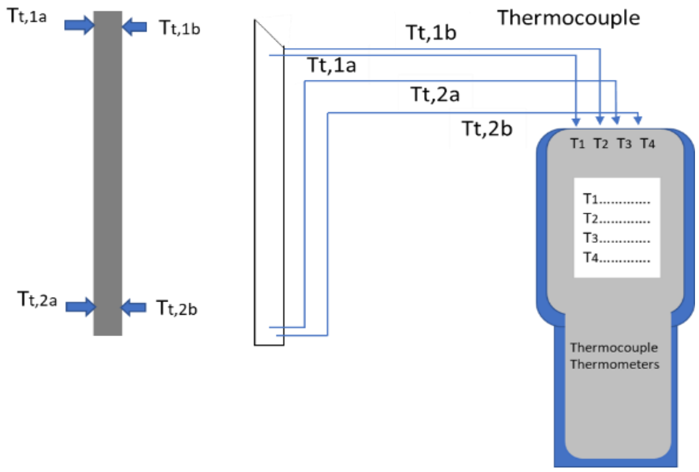


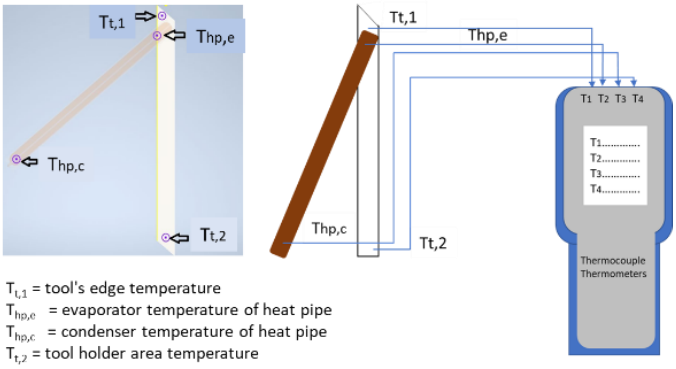
Fig. 3. The geometry of the heat pipe

The tool's edge is the contact area between cutting tool and workpiece, so the maximum heat will be in the area. Fig. 4 shows the setup of this experiment. Temperatures of tools and heat pipe were measured using K-type thermocouples which connected to a Digital thermometer HTI HT-981 with an accuracy ±0.1ºC.

Testing was conducted to investigate the using a heat pipe and it's effect on the tool's temperature. Temperature measurement is carried out at four measurement points using a type K thermocouple. Fig. 4.a shows the experiment setup for tool temperature measurement without a heat pipe during cutting, while Fig. 4.b experiment setup for tool temperature measurement which is coupled with heat pipe.



(a)



(b)

Fig. 4. Experiment setup of the cutting-tool (a) without heat pipe, (b) assisted with heat pipe

The testing was carried out in three methods: (1) a cutting process without heat pipe and coolant, (2) a cutting process without a heat pipe and with minimum coolant, and (3) a cooling system equipped with a heat pipe only. Tests were conducted on conventional lathes machine with spindle speed varied at 250, 540, and 850 rpm. Work is carried out with High-Speed Steel HSS-type tools (12,7 x 12,7 x 160 mm) and Steel ST-37 metal as a workpiece with a depth of cut 0.2 mm and longitudinal feed of 0.2 mm/rev at a spindle speed of 250 rpm, 540 rpm, and 850 rpm. The length of cutting is 90 mm for each test, reducing the pipe diameter from 22 mm to 18 mm with 10 times cutting for each depth of cut 0.2 mm in 20 minutes. The workpiece used for testing is shown in Fig. 5, and the machining testing process is shown in Fig. 6.

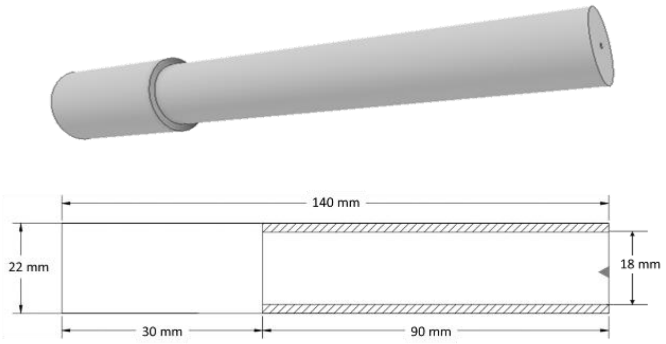


Fig. 5. The geometry of the workpiece

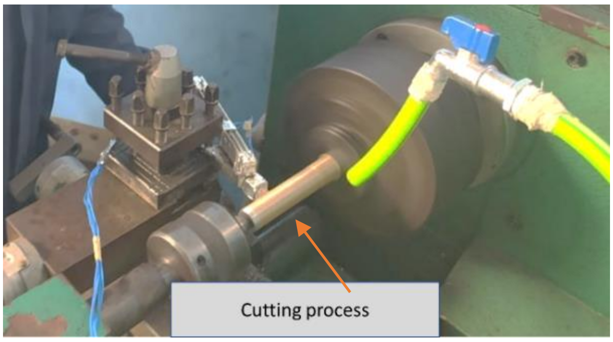


Fig. 6. Machining testing process

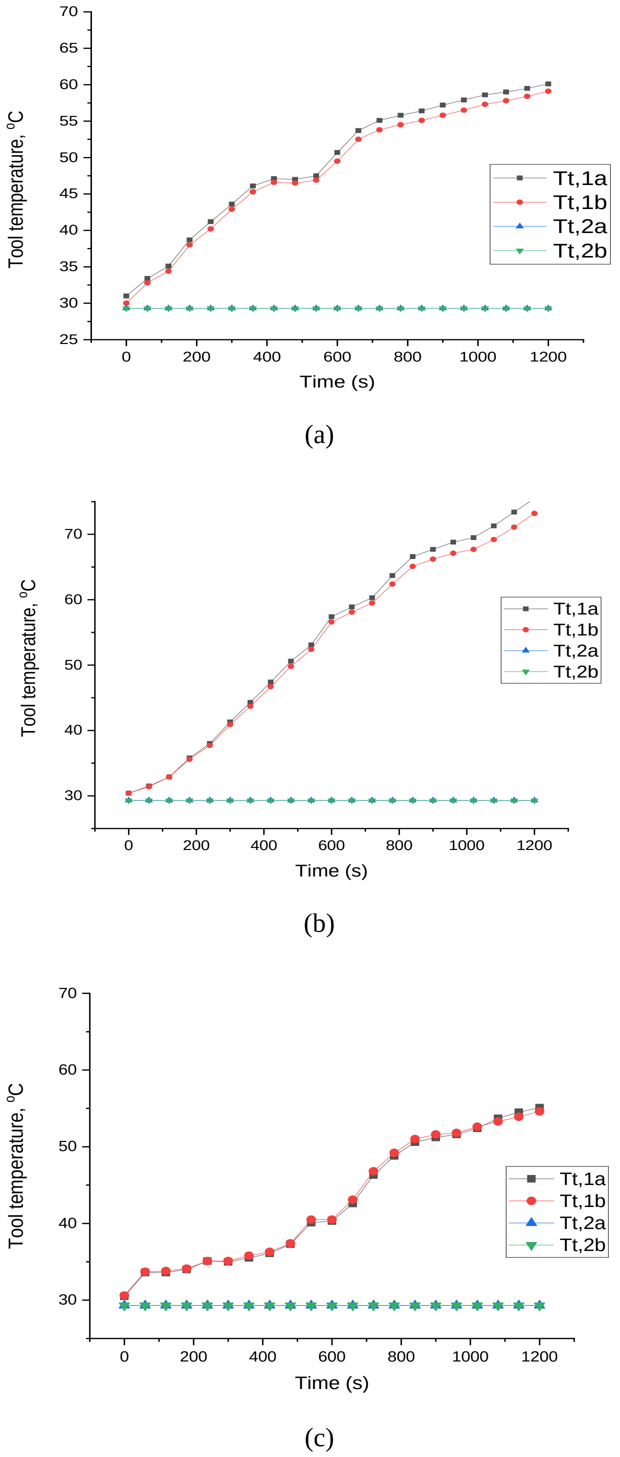
Heat pipe is a heat exchanger with has high thermal conductivity. The performance of a heat pipe can be determined by thermal resistance value. The lower thermal resistance of a heat pipe, the higher the ability to move heat. a heat pipe's thermal resistance can be written as Eq. 1 [12].

$$R=\frac{T_{hp,e}-T_{hp,c}}{\dot{Q}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where R is thermal resistance in °C/W and $\dot{Q}$ is heat source in W. In the heat pipe, different temperature between evaporator temperature ($T_{hp,e}$) and condenser heat pipe temperature ($T_{h\text{-},c}$) is very small compared with heat source in the evaporator side.

3 Results and Discussion

Testing was carried out on the feeding process with three variations in speed, and measurement time was carried out every 20 minutes. The temperature profile of the cutting tool in dry machining without a heat pipe and coolant liquid at 250 rpm, 540 rpm, and 850 rpm are shown in Fig. 7. While Fig. 8 shows the temperature profile of the cutting tool in the cutting process with coolant liquid at 250 rpm, 540 rpm, and 850 rpm.



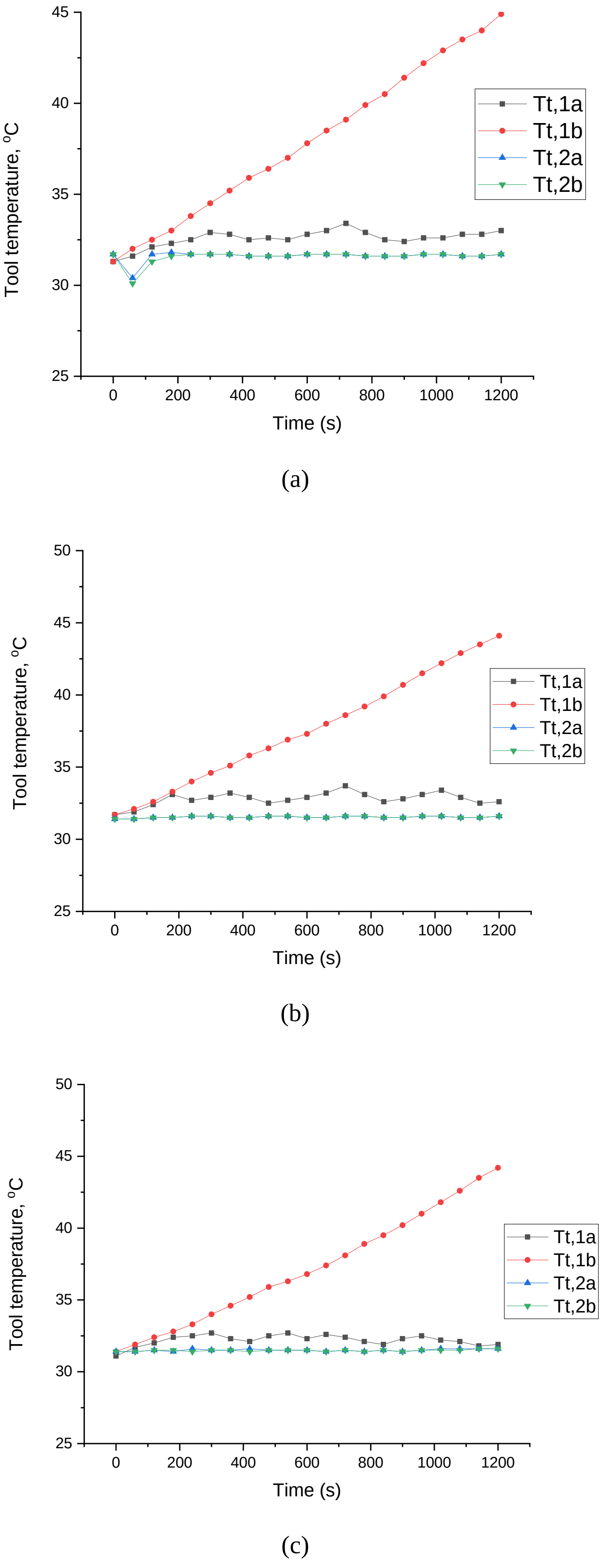
(a)

(b)

(c)

Fig. 7. Tool temperature profile without heat pipe and coolant (a) 250 rpm, (b) 540 rpm, (c) 850 rpm.

Fig. 7 shows that temperature increases with the machining time on the tool edge. Temperature increases with machining time ranging from 31–75ºC for 20 minutes. Fig. 7 also shows that at spindle speeds of 250 rpm and 540 rpm, higher speeds cause higher tool temperature.



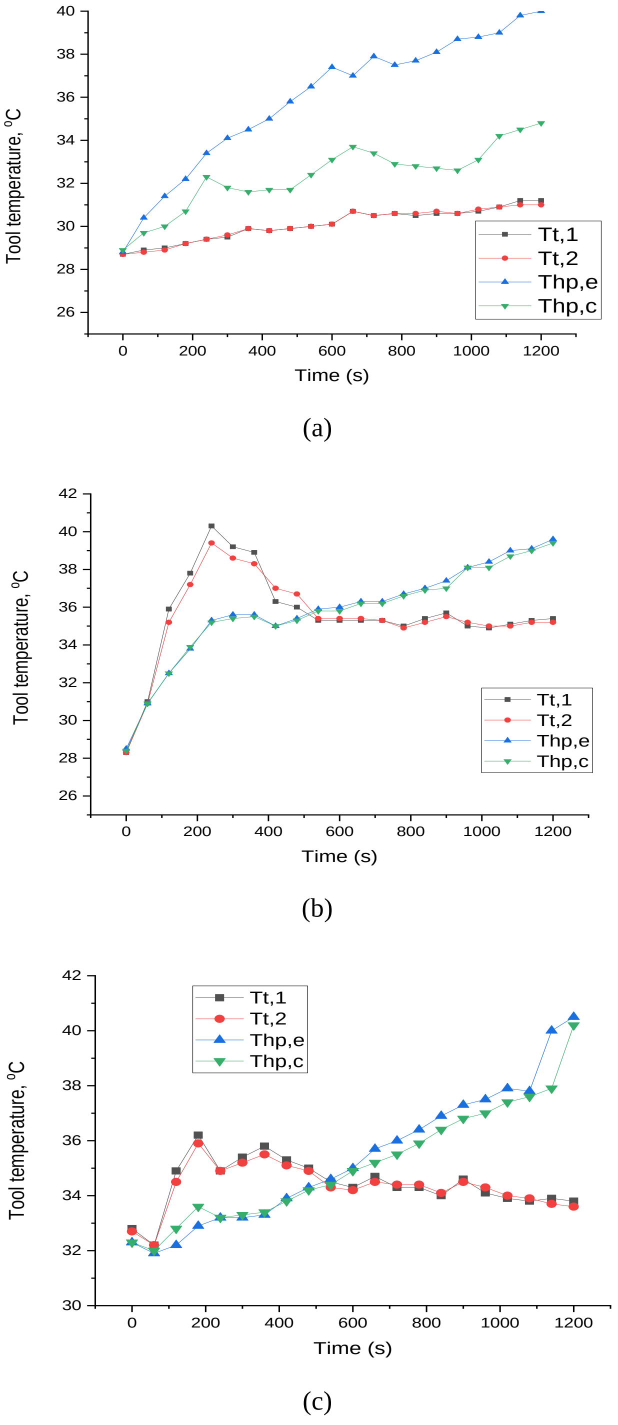
(a)

(b)

(c)

Fig. 8. Tool temperature profile with coolant (a) 250 rpm, (b) 540 rpm, (c) 850 rpm

Fig. 8 shows the temperature profile of coolant fluid used in lathes machining. The use of coolant liquid in the machining process has a positive impact on the cutting tool's temperature. The upper edge tool temperature ($T_{t,1a}$) becomes lower after the cutting process with coolant fluids. But tool cooling is only effective on the top side of the cutting tool. The bottom-edge cutting tool temperature ($T_{t,1b}$) increases with the machining time. This condition occurred because the coolant liquid is not evenly distributed and only hits the upper tool, so cooling only occurs at the upper edge of the cutting tool. The coolant cannot release heat quickly and can only cool the top of the cutting tool locally. Meanwhile, the bottom side of the cutting tool does not get cooling. The temperature of the upper edge cutting tool ranges from 31–33ºC for 20 minutes, while the temperature of the bottom end of the cutting tool ranges from 31-45ºC.



(a)

(b)

(c)

Fig. 9. Temperature profile of tool assisted with heat pipe (a) 250 rpm, (b) 540 rpm, (c) 850 rpm

The use of heat pipes as a cooling medium has a significant influence on reducing the tool temperature, as shown in Fig. 9. At the point of contact between the tool and workpiece, the average tool temperature ranges from 30–40ºC, and the maximum temperature occurs at a speed of 540 rpm. The heat from the tool is transferred to the heat pipe side from the evaporator side to the condenser indicated at $T_{hp,e} - T_{hp,c}$. This is very beneficial because no coolant liquid waste impacts the environment, and there is a decrease in the cost of procuring coolant liquid for the machining process.

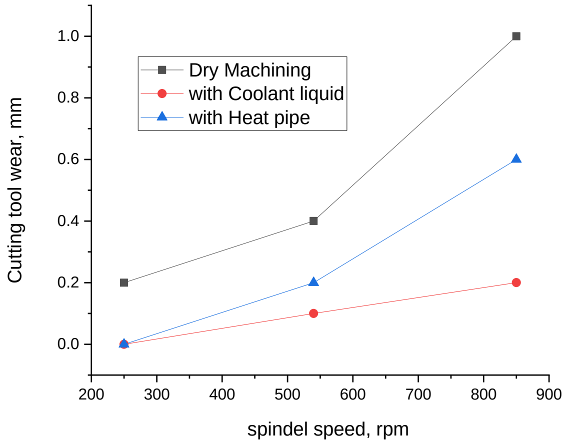


Fig. 8. Cutting tool wear graph

Fig. 9. The cutting tool condition before the cutting process

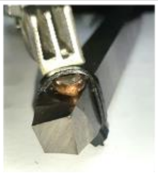
Machining	Dry Machining	With Coolant	With Heat pipe
250 rpm			
540 rpm			
850 rpm			

Fig. 10. The wear of cutting tool of each type opration

Fig. 8 shows the cutting tool wear graph in the dry cutting, cutting with coolant liquid, and cutting with heat pipe condition during a 20-minute operation with machining to reduce the workpiece diameter from 22 to 18 mm 90 mm long. While Fig. 9 shows pictures of the cutting tool before machining, and Fig. 10 shows the condition of the cutting tool after machining for each machining operation.

In the dry machining process, the cutting tool begins to wear out at a spindle speed of 250 rpm of 0.2 mm, at 540 rpm it is subjected to wear of 0.4 mm, and at 850 rpm, it wears 1.0 mm. The use of heat pipes as a cutting tool cooling medium also has a positive impact on the life of the cutting tool. At a spindle speed of 250 rpm, there has been no wear, at 540 rpm, it wears 0.1 mm, and at 850 rpm it is subjected to wear of 0.6 mm. The use of coolant liquid results in a cooling process and reduces wear to the maximum. At 250 and 540 rpm, wear has not been seen, while at 850 rpm wear by 0.2 mm. This result shows that as the cutting tool's temperature decreases, the cutting tool's life also becomes longer

Generally, cutting tool wear occurs at the end of the cutting tool, which is the contact point between the cutting tool and the workpiece. The cooling process using coolant liquid gives maximum results because coolant liquid can reduce friction and heat directly. Heat pipes provide better results than dry machining, but wear occurs at a very high spindle speed. The placement of heat pipes that are not placed right at the end of the tool affects the cooling performance. However, heat pipes generally positively impact the cooling of machining. The heat pipes and coolant fluids with a minimum capacity can be combined as a cooling medium to improve cooling performance.

4 Conclusions

The cutting tool cooling system using finned flat heat pipes has been applied in the cutting process of the lathe machine. Using heat pipes as a cooling medium significantly influences reducing the cutting tool temperature compared with the dry machining process. The cutting tool temperature can be maintained at 30–40ºC when using a heat pipe as part of the cooling system. The maximum temperature in 20 minutes of operation shows that in the dry machining reaches 75ºC. When using coolant liquid, the temperature of the upper edge cutting tool ranges from 31–33ºC, but the bottom edge cutting tool reaches 45ºC. Using heat pipes as a cutting tool cooling medium also positively affects the cutting tool's life. During the 20-minute with spindle speed 250 rpm machining process, the cutting tool assisted with the heat pipe has not shown wear, while the cutting tool in the dry machining process began to show wear. At a spindle speed of 540 rpm, it wears 0.1 mm, and at 850 rpm, it is subjected to wear of 0.6 mm when using a heat pipe. Heat pipes provide better results than dry machining, but wear occurs at a very high spindle speed. The cooling process using coolant liquid gives maximum results because coolant liquid can reduce friction and release heat directly. So a combination of heat pipes and coolant fluids with a minimum capacity can be recommended as a cooling medium to improve the cutting tool performance.

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