Sustainable Metal Cutting

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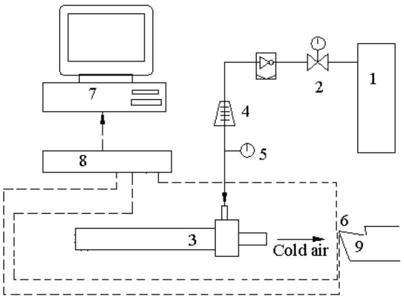
Abstract—**Metal cutting companies are being compelled to reduce their impact on the environment as more international and government environmental protection legislation is introduced. Ensuring appropriate waste disposal measures are in place will be essential to allow companies to operate. Particular attention must be given to liquid coolant used in metal cutting as this is a significant source of environmental pollution. Dry machining is obviously more ecologically desirable for metal cutting as there are no environmental issues or disposal costs for the coolant. Unfortunately though, there are issues that need to be resolved before manufacturing companies will adopt dry machining, mainly associated with the reduction of tool life. However, from previous research, it has been shown that the introduction of cold air directed at the cutting zone significantly increased tool life removing coolant waste disposal costs. To further improve the up take of air cooling the most sustainable and most efficient method of generating cold air suitable for machining must be sought. Comparing three methods of providing cold air has shown that the vortex tube is the most suitable method for providing cold air to the tool interface.**

Keywords-tool life; vortex tube; environmental; machining

I. INTRODUCTION

The need for optimum machining parameters has always been of great concern to the manufacturing industry, where the economy of the machining process plays a key role in the competitiveness of the product. Previous researchers [1] have shown that air-cooling can be effective at prolonging the life of tools during machining, so eliminating the cost of disposal of traditional liquid coolant. This research will compare three methods of providing cold air to the tool tip during machining, to establish the most effective method. In addition to operational effectiveness during machining the most sustainable method of producing the cold air must be found. Lian-yi Chen *et al.* [2] developed a prediction system for the environmental burden of machine tool operation based on life cycle analysis (LCA). This model enables the evaluation of the equivalent CO_2 emission during machining. The CO_2 emission is calculated from the electrical consumption of the machining process: in this case only the CO_2 emission produced by generating cold air will be considered. The CO_2 emission intensities factor for each cooling system is based on how much electrical energy is consumed in producing cold air (CO_2 emission intensity for electricity used was 0.304 kg-CO_2/kWh [3], and it should be noted that this value is dependent on local and country electrical generating facilities).

Fig. 1 shows the schematic diagram of the cold air cutting tests which consists of a computer, data logger to record the tool tip temperatures, air cooling nozzle, and air compressor to supply air to cooling nozzles. The temperature of the tool tip was measured by three imbedded thermocouples positioned 1mm from the tool interface which were able to determine the effectiveness of the cooling process during machining. Also, the volume of air directed at the tool tip was measured to determine the environmental cost of producing the cold air. These measured flow rates allowed the power contribution for each cold air system used to be calculated, enabling the most sustainable method of supplying cold air to the tool tip to be identified.



1. Supply of compressed air, 2. Control valve, 3. Air-cooling nozzle, 4. Flow meter, 5. Pressure gauge, 6. Thermocouples, 7. Computer, 8. Data logger, 9. Cutting tool.

Figure 1. Air-cooling test block diagram.

II. PERFORMANCE COMPARISON OF AIR COOLING METHODS

This air cooling comparison considers three air cooling methods. The first is impingement cooling, the second method considers the vortex tube, and the third method uses the semiconductor refrigeration effect to cool the air. Each cooling method will be examined for ease of use, and environmental burden contribution made during machining.

A. *Impingement Cooling*

Air is directed onto the tool face as close to the tool interface as possible as shown by the arrow in Fig. 2. It is known that the effectiveness of the air-cooling is improved by using jet-impinging jet Mao-Yu Wen *et al.* How effective this will be in metal cutting needs to be ascertained. A series of metal cutting tests were performed to determine how impingement air-cooling performed on cooling the tool tip. The most effective impingement cooling arrangement was found by changing jet parameters systematically, while keeping the cutting conditions constant throughout all the tests. Previous researchers Jung-Yang San *et al.* [4] have examined the aspect of determining the most suitable jet diameter with respect to the air gap between the jet nozzle and a flat object. However, in this application there are other factors that have to be considered such as the position of the jet. Selection of the jet diameter is important in order to find the correct gap between the jet and the tool, but it is now difficult to position the jet close to the tool tip. Basically there is a compromise between the theoretical ratio of the jet height and diameter to suit the machining application.

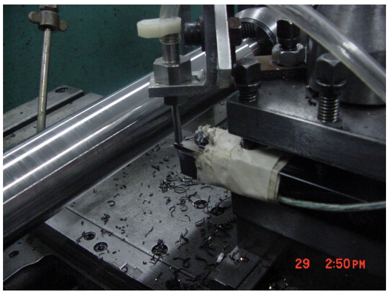


Figure 2. Adjustable Impingement nozzle holder.

The effect of varying the jet gap, with the different supply pressures of 1 MPa, 0.8 MPa and 0.6 MPa, is shown in Fig. 3 and 4, where it clearly shows that a jet height of 10 mm from the top face of the tool is the most effective cooling height. As the jet diameter is 2 mm the resulting optimum (diameter to jet gap) $\frac{G}{D}$ ratio is therefore 5 which is higher than the optimum $\frac{G}{D}$ ratio based on previous research of an impinging jet on a flat plate Lee *et al.* [5], Tong [6], proving that this previous theory may not be suitable for this machining application. A number of factors such as the shape of the surface of the tool or the effect of the rotating workpiece disturbing the air steam from the jet may have affected the performance of the impingement process.

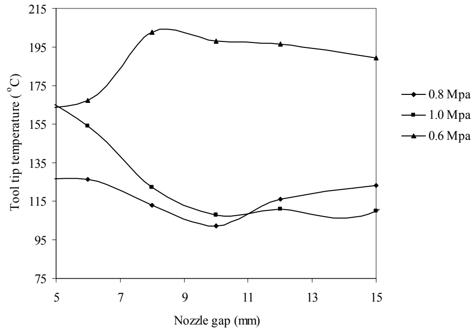


Figure 3. Jet optimum height from tool tip [7].

The temperatures of the three thermocouples in the tool tip showed the lowest temperature being recoded by channel 13 (Ch13), which is the position nearest to the tool tip, which indicates heat from the tool is being removed.

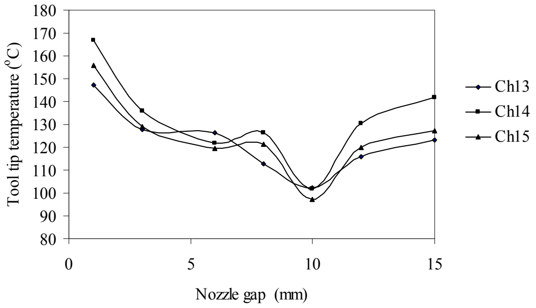


Figure 4. Recorded temperatures at the tool tip for a number of air gaps at 0.8 MPa [7].

The 2 mm diameter air-cooling jet at 0.8 MPa was able to cool the tool tip close to the conventional wet cooling cutting temperature (100 °C) as shown in Fig. 5. However, although this method is capable of cooling the tool tip, it was found that after a number of cutting tests the temperature in the workpiece became extremely hot. This therefore indicates that additional air-cooling needs to be applied to the workpiece to prevent dimensional inaccuracies occurring. Fig. 3 showed that there was no real benefit in increasing the pressure to 1 MPa from 0.8 MPa .

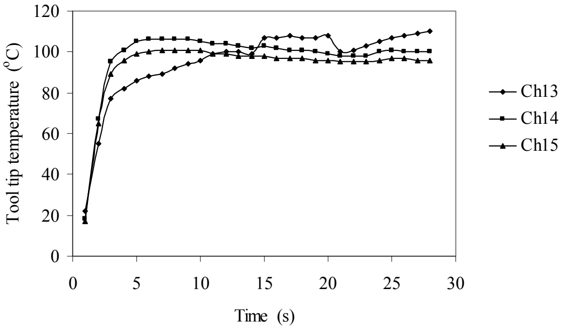


Figure. 5. Tool tip temperatures at 0.8 MPa with an air gap of 10 mm [7].

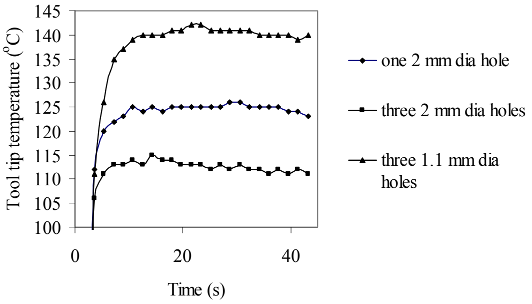


Figure. 6. Tool temperatures for thermocouple closes to the tool tip [7].

Fig. 6 clearly showed that the three 2 mm diameter holes of the jet produced the lowest tool tip temperature closest to the tool interface during machining. The volume of air used during this test was 849 SLPM at the maximum test pressure (1MPa) if it was necessary. This is not an extremely large supply of compressed air as a typical two-stage, two-cylinder air compressor can provide 1050 SLPM at a maximum working pressure of 1MPa with a Motor load of 7.5 kW. This would be relatively cheap to supply as can be calculated from (1). The cost of compressed air for one hour was calculated to be (AU) \$1.5 using this compressor.

$$\text{Cost (AU) \$} = \frac{(MLxOHxCxTxFL)}{ME} \tag{1}$$

Where:
ML = Motor full load in kW
OH = Number of operating hours
C = Cost per kWh (0.16kWh)
T = % of time running at this operating level
FL = % of full-load at this operating level
ME = Motor efficiency at this level

For air-cooling the main consideration for environmental consideration is the volume of air being passed over the tool tip, therefore the CO_2 produced cooling can be calculated from (2).

$$C_e = CUT \times CS \times CP_e \tag{2}$$

Where:
C_e = environmental burden of coolant (air) (\$/kg)
CUT = coolant usage time (s)
CS = cutting fluid discharge (l/s)
CP_e = environmental burden of coolant production (kg-CO_2/l)

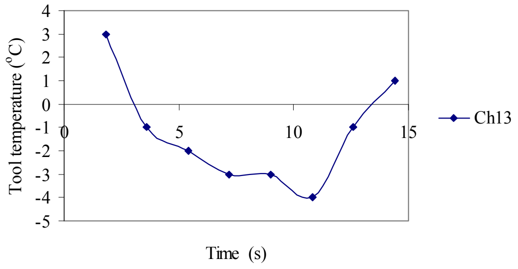


Figure. 7. Tool temperature before cutting using three – 2 mm diameter jet [7].

Figure. 8. Frost on impingement jet nozzle before machining.

The tool temperature in Fig. 7 was obtained before any machining had taken place and clearly indicates the effectiveness of the impingement cooling of the tool tip. Fig. 8 shows a build up of frost on the jet nozzle. In practice, however, the efficiency of the cooling of the tool tip is reduced due to the cutting action during machining.

B. Vortex Cooling

The Unlike the impingement cooling process there is no difference to the cooling effect by adjusting the distance that the cold tube nozzle is from the tool tip. The nozzle does not need to be perpendicular to the rake face - unlike the impingement jet nozzle - to be effective. Although, the closer the cold tube nozzle jet is to the tool face, the less time there is for the surrounding ambient temperature to begin to affect the cold stream of air. Fig. 13 shows the vortex tube directing the cold airflow onto the tool face as close as the machining restraints will allow. The vortex tube shown in Fig. 9 was produced for cooling the tool tip during machining, and was designed from the original concepts of the Ranque-Hilsch Tube [8]. A vortex tube consists of three important parts: the cold tube, hot tube and the vortex generator. When compressed air enters the inlet it is directed tangentially to the vortex generator, causing it to spin around producing a spiral airflow. Between the Vortex Generator and the cold tube there is a diaphragm fitted - with a central hole which can be easily altered - allowing diaphragms with large or small hole to increase or decrease the temperature obtained at the cold exit.

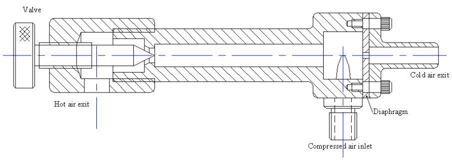


Figure. 9. Sectional view of the vortex tube showing the diaphragm.

The volume and temperature of these two air streams can be changed by adjusting the conical valve built into the hot air exhaust exit. It was possible to obtain temperatures as low as -46 °C and as high as +127 °C when using the vortex tube under test conditions. The compressed air pressure was set at 0.206 MPa, 0.275 MPa, and 0.344 MPa respectively to investigate how air pressures affect the vortex tube performance during machining [9]. Obviously, the higher the air pressure the higher the cost of producing the compressed air. Therefore the parameters that use the lowest pressure while producing the coldest temperature should be used to aid reductions in the operating cost of air-cooling. The coefficient of performance estimation for any cooling device can be used to give a good measure of the practical refrigeration performance of the cooling system. This can therefore be used in determining the performance of the vortex tube, which can in turn be compared with a conventional refrigeration system. The vortex tube's coldest airflow needs to be used in determining the coefficient of performance for this vortex tube. In this case, the lowest cold temperature is obtained from the vortex tube with a 3 mm diameter jet, and inlet air pressure 0.275 MPa. The lowest temperature measured was $T_c = -16.8\ ^oC$. The related values for this temperature are given in Table 1:

TABLE 1 Recorded readings from test

Parameter	Value
Cold Mass Fraction	0.605
Inlet Temperature (^oC)	22.4
Cold Outlet Temperature (^oC)	-16.8
Hot Outlet Temperature (^oC)	66.6
Inlet Volumetric Flow Rate (SLPM)	1095
Hot Outlet Volumetric Flow Rate (SLPM)	425
Cold Outlet Volumetric Flow Rate (SLPM)	651

To determine the coefficient of performance of the vortex tube for these conditions, it is necessary to calculate the compressor exit temperature T_2 (314 K) by using (3) when: $P_1 = P_{Ambient} = 101.325$ kPa, $T_1 = T_{Ambient} = 296$ K, $P_2 = 376.35$ kPa and n =1.4 and $\dot{W}$ in the present case is the work done to compress the air from atmospheric pressure, and temperature to the inlet conditions of the tube. Assuming reversible compression (isentropic, minimum work), $\dot{W}$ is then obtained from:

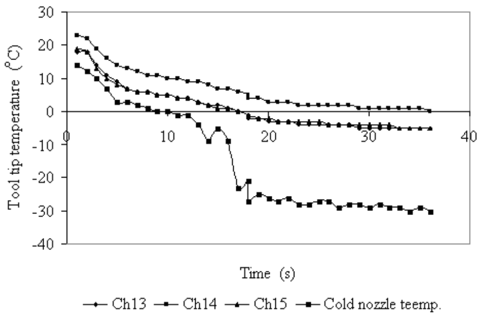
$$\dot{W} = \frac{\dot{m}R(T_2 - T_1)n}{n-1} \qquad (3)$$

$$COP = \frac{\Delta\dot{H}_c}{\dot{W}} \qquad (4)$$

where $\Delta\dot{H}_c$ is obtained from:

$$\Delta\dot{H}_c = \dot{m}_c(T_i - T_c) \qquad (5)$$

The coefficient of performance for the vortex tube can now be calculated by using (4), which gave a value of 1.38. The temperatures shown in Fig. 10 were recorded at the tool tip during adjustment of the conical valve on the vortex tube at an inlet pressure of 0.8 MPa. Setting the valve normally takes about thirty seconds to achieve the optimum cold exit air. Having obtained the minimum air temperature, machining can commence. During this time the cold air had already started to cool the tool tip down, with two of the thermocouples recording temperatures of approximately –5 ^oC. Reducing the inlet air pressure to 0.4 MPa the cold exit air temperature was approximately -15 ^oC, which correspondingly reduces the tool tip temperature down to approximately -3 ^oC in double the time achieve by 0.8 MPa. The time factor is important in cooling the tool tip, as the rise in temperature during machining is extremely fast. It is therefore imperative to be able to dissipate the generated heat in the tool tip as quickly as possible.



The vortex tube used a 3 mm diameter orifice plate at a pressure of 0.8 MPa

Figure. 10. Tool tip temperatures before machining [10].

When the vortex exit air has reached approximately -30 ^oC, machining is commenced. As indicated by the rise in the tool tip temperatures, the tip rises to a steady state temperature of 60 ^oC as shown in Fig. 11. The temperature drop at the end indicates the point when the feed is stopped with no more chips being generated. Allowing the cooling air to flow unimpeded across the tool tip gives a better heat dissipation from the tool reducing the temperature in the tool rapidly.

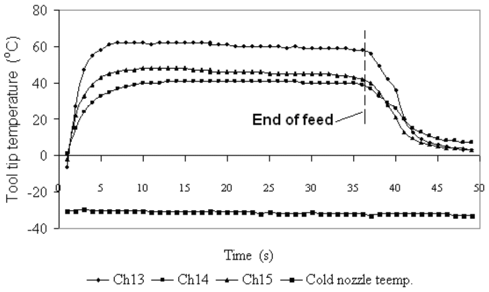


Figure. 11. The graph shows the tool tip temperatures during machining, and after the tool feed has stoped cutting [10].

Fig. 11 illustrates that a steady state temperature is reached in the tool tip in approximately 10 seconds during machining when being cooled by the vortex tube. Fig. 12 showed that the vortex tube used in these tests was able to generate very cold air at the exit of the cold jet. A temperature of -55 °C was obtained by using an inlet pressure 1MPa to the vortex generator.

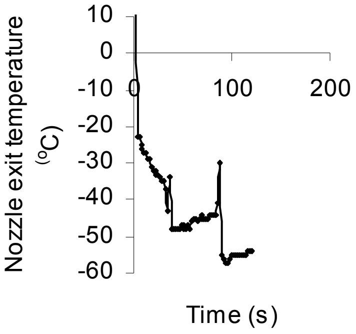


Figure 12. Vortex tube cold air outlet temperature [10].

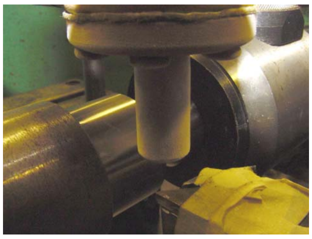


Figure. 13. Frost forming on vortex tube cold outlet.

C. *Refrigeration System*

A cooling system combining a vapour-compression refrigeration system, and semiconductor refrigeration effect was adopted by Y. Su *et al.* [1] to produce cold-air used for cooling tool tips when metal cutting. A vapour-compression refrigeration system was designed to reduce the temperature of water in order to improve the efficiency of semiconductor cooling. By applying a direct current to a thermopile heat energy is transferred from one side to the other side of the semiconductor due to the Peltier effect. The combination of the cold water and semiconductor cooling is now used to produce an effective heat exchanger to cool the air. This cooling system can provide cooling air of different temperatures by supplying the thermopile with different currents.

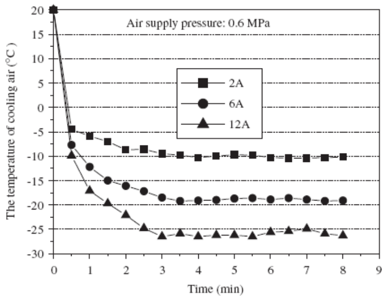


Figure. 14. The temperature of cooling air against time when supplying the thermopile with different current [1].

Fig. 14 shows the temperature of cooling air against time for different currents being supplied to the thermopile. From the graph it is shown that the temperature of cooling the air reaches a steady value after 3 minutes, indicating that this system has a high refrigeration speed and stability.

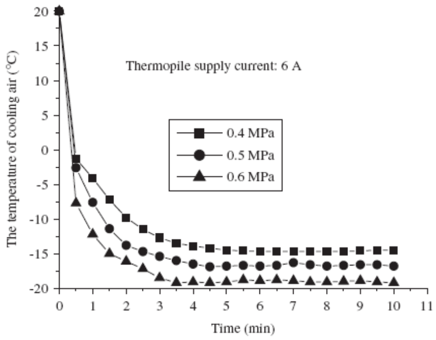


Figure. 15. The temperature of cooling air against time for various air supply pressure [1].

From the graph shown in Fig. 15 it can be seen that an increase in the air supply pressure leads to a reduction in the temperature of the cooling air. It is also shown in Fig. 16 that it only takes three minutes to adjust the temperature of the cooling air.

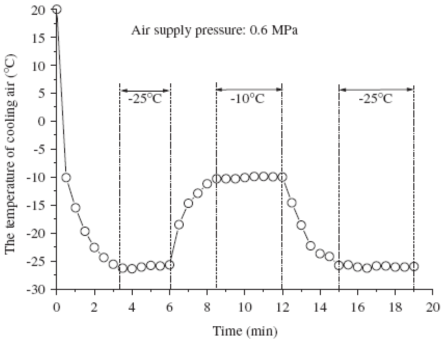


Figure. 16. Response curve of the new cooling gas equipment when adjusting the temperature of cooling air continuously [1].

III. CONCLUSION

Previous research has shown that cold air used in metal cutting improves the tool life to be just as effective as traditional cooling methods [11]. Current work investigated three separate methods of providing cold air to the tool tip, to determine the most sustainable and effective method of removing the heat generated during metal cutting. Even though the impingement cooling method removed heat from the tool tip, it was found to be impractical to be used in a manufacturing environment due to the necessary correct positioning of the nozzle. The vortex cooling method has no restrictions on the positioning of the cooling nozzle making this a more user friendly system for the machine operator to use in production. However, the high air mass flow rate of the vortex tube may in first instance be considered a disadvantage to this cooling method. This has been found not to be the case as the excess cooling air removes the heat from the machined part ensuring dimensional accuracy of the cutting process. The third cooling method considered used a vapour-compression refrigeration system and semiconductor thermopile to cool the compressed air that is directed at the tool interface. Y. Su *et al.* [1] have shown that heat is removed from the tool tip during metal cutting, however having less cold air presented to the cutting zone leads to heat not being removed as effectively from the machined part, which increases after each cut. The impingement cooling method of providing cooling air is rejected on two counts. Firstly it is unwieldy to use and uses the most energy, making it the least sustainable method of cooling the tool tip. The final two methods are both user-friendly in positioning the air flow or to make slight adjustments to the cold air temperature. Although, there is an additional cooling plant needed for the thermopile cooling system and the additional cost to the environment to manufacture the semiconductor materials used in this system. The most economical use of energy when these two cooling methods are used to produce cold air for cutting the same parameters needs to be used. The parameters that were taken for comparison were: cold air temperature of -16 ^{o}C at a flow rate of 650 SLPM, the resulting test and calculations revealed that the vortex tube used the least energy as it only needed a source of compressed air. While the thermopile cooling system needed additional energy for the auxiliary equipment used in cooling the compressed air. Therefore, for ease of use, no additional equipment was required and used the least power. The vortex tube is clearly an excellent method for cooling air for metal cutting purposes.

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