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ORIGINAL ARTICLE

Experimental analyses to investigate the feasibility and effectiveness in using heat pipe-embedded drills

Lin Zhu · Tien-Chien Jen · Cheng-Long Yin · Xiao-Ling Kong · Yi-Hsin Yen

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Abstract This paper presents an experimental investigation to verify the feasibility and effectiveness of heat pipe cooling in drilling operations. The basic idea is to insert a heat pipe at the center of the drill tool with the evaporator close to the drill tip and the condenser at the end of the drill. Consequently, the heat generated at the tool–chip interface can be removed by convection heat transfer. Experimental studies were involved in three cases, including solid drill without coolant, solid drill with coolant, and heat pipe drill. Drilling tests were conducted on a CNC machining center with full immersion cutting. The cast iron square block was used as the workpiece, and the high-speed steel was chosen for the drill tool material. Flank wear is considered as the criterion for tool failure, and the wear was measured using a Hisomet II Toolmaker's microscope. The tests were conducted until the drill was rejected when an average flank wear greater than 0.10 mm was recorded. The results demonstrate that using a heat pipe in the drilling process can effectively perform thermal management comparable to the flooding coolant cooling used pervasively in the manufacturing industry, extending the tool life of the drill.

Keywords Tool life · Heat pipe cooling · Feasibility and effectiveness · Drilling

1 Introduction

Mechanical work in machining processes is converted to heat due to deformation of the chip and friction between tool, chip, and workpiece. It is experimentally estimated that at least 98~99% of the input energy results from the mechanical work [1–3]. Some of this heat conducts into the cutting tool, incurring high tool temperatures near the cutting edge. Excessive tool temperature softens the tool material, especially promotes the formation of built-up edge (BUE) on the tool tip and, as a result, is detrimental to the tool life [4, 5].

For drilling, the high temperature is significant in the drill tip because the tool is constrained in a hole, causing the chips, absorbing much of the cutting energy, to remain in contact with the tool for such a long time compared with any other machining operation [6–8]. This results in the limited material removal rate, and, subsequently, low productivity and high cost in machining processes [9]. Currently, the most common cooling approach is the use of cutting fluids flooding through the cutting zone; however, the use of such fluids could adversely affect the health of the workers in the machine room [9, 10]. Metal chips (solid waste) in used cutting fluid are a source of pollution and must be disposed appropriately. Contaminants retained in the scrap often prevent the scrap from being recycled for an application similar to the original application. The cost to recover these contaminated materials consists nearly 30% of the total operational cost of the machining processes [9]. Therefore, it is critical and imperative for the manufacturing industries to look for new methods to remove heat efficiently.

Heat pipe is considered to be an effective alternative to conventional methods of removing heat from a drill tip allowing drilling operations to be carried out in a dry and "green" fashion [1, 4, 11], as illustrated in Fig. 1. The idea

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L. Zhu (✉) · C.-L. Yin · X.-L. Kong
School of Engineering, Anhui Agricultural University,
Hefei 230036, People's Republic of China
e-mail: zl009@mail.ustc.edu.cn

L. Zhu · T.-C. Jen · Y.-H. Yen
Mechanical Engineering Department, University of Wisconsin,
Milwaukee, WI 53211, USA

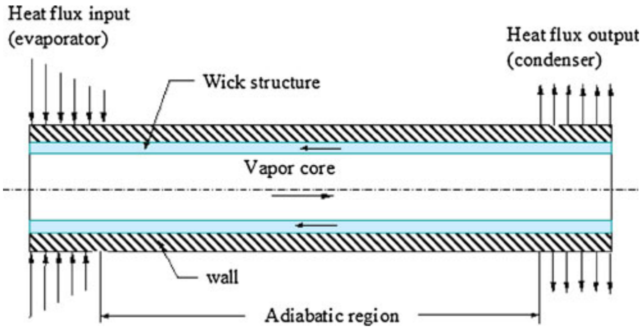


Fig. 1 Schematic of a heat pipe

of using a heat pipe for cooling a drill tool is inserting a heat pipe in the center of the drill [12] (see Fig. 2). Typically, the heat pipe can be divided into three sections: evaporator section, adiabatic (transport) section, and condenser section. The external heat load on the evaporator section causes the working fluid to vaporize. The resulting vapor pressure drives the vapor through the adiabatic section to the condenser section, where the vapor condenses, releasing its latent heat of vaporization to the low temperature environment. The condensed working fluid is then pumped back by capillary pressure generated by the meniscus in the wick structure [11]. Transport of heat can be continuous as long as there is enough capillary pressure generated to drive the condensed liquid back to the evaporator.

The main objective of this paper is that an experimental study is performed to verify the concept of thermal management and effectiveness of using a heat pipe in the practical drilling operations. Drill-tip temperature, tool wear morphology, and tool life were investigated in the experiments.

2 The physical model

For the practical drilling applications, inserting an internal heat pipe in the drill suffers from some manufacturing limitations due to the fact that there are geometric and stress constraints that require keeping the heat pipe smaller. The limitation is that the heat pipe location cannot get too close to the drilling tip due to the fact that the diameter of the heat pipe is affected by the maximum stress levels in the drill more than by the peak temperatures reached in the drill [4, 9, 10, 12, 13]. From the thermal viewpoint, however, the closer the heat pipe gets to the tip indicates the more effective it gets in taking the heat away from the drill tip [4, 13]. Consequently, it is critical to refine the geometry of the heat pipe inserted in the drill.

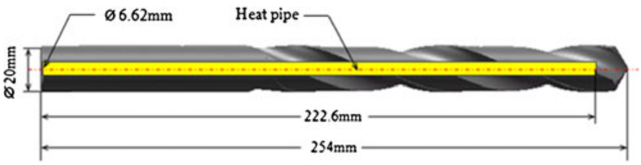


Fig. 2 Location of the heat pipe inside the drill

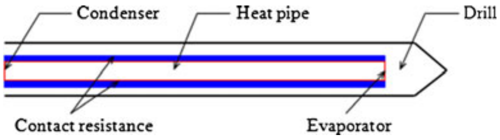


Fig. 3 Heat pipe drill fabrication

Based on the above analysis combined with the practical considerations that a certain distance has to be left if regrinds are required [1, 3, 4], the diameter of the heat pipe in this study was calculated as 7.62 mm, and the length of the heat pipe 222.6 mm (see Fig. 2).

3 Experimental procedures

The detailed approach on the drilling tests is that six drill bits were used to drill holes in the square blocks of cast iron until the drills failed. The drill tool material which was high-speed steel was provided by Arrow Tech, and 187–241 BHN Cast Iron block was used as workpiece [9]. Workpiece dimensions were 20.3 cm length×20.3 cm width×5.1 cm height. Three different kinds of cases, including solid drill, solid drill with coolant, and heat pipe drill, were investigated. Six drilling experiments were designated as SD_1 and SD_2, CF_1 and CF_2, and HP_1 and HP_2, respectively. Symbols SD, CF, and HP represented dry, cutting fluid supply and heat pipe supply drilling conditions, respectively. The number represented the amounts of the drills under the above drilling tests.

To fabricate the heat pipe drills, two of the drills were first gun drilled with a center hole, then the drills were heated to 600°F, and a certain amount of tin was put into the hole. When the tin melted, the tin material created a pool of a liquid metal at the bottom of the drill hole. After that, a

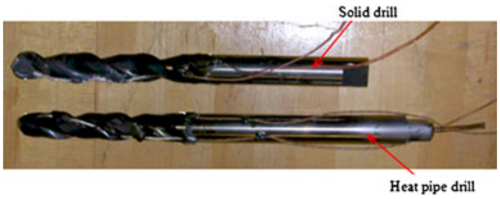


Fig. 4 Solid drill and heat pipe drill

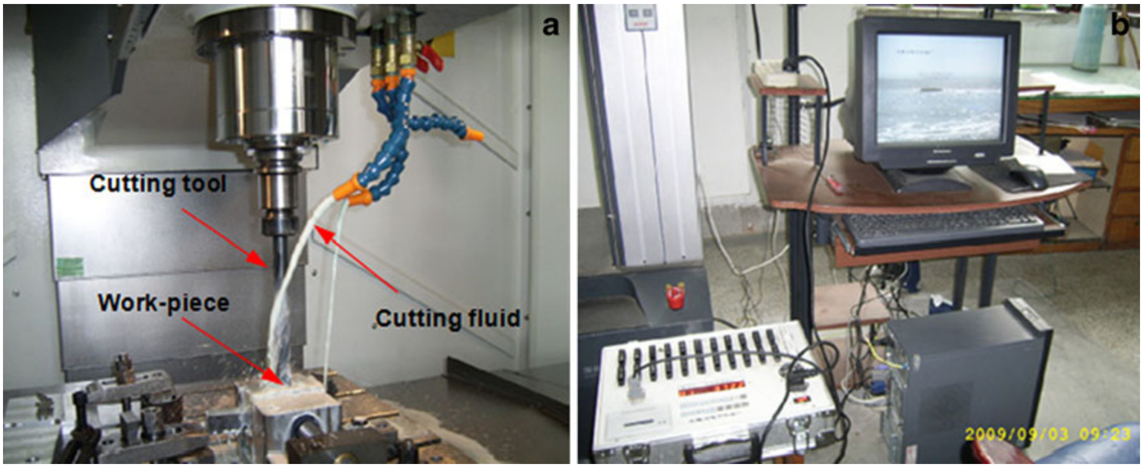


Fig. 5 **a** Drilling operations on the workpiece material and **b** data measure equipment used in the experiments

commercial heat pipe provided by Thermacore Inc. was slowly inserted into the hole until the drill tip (see Fig. 3). Note that the hole was 1.0 mm larger than the diameter of the heat pipe so that a clearance of 0.5 mm between the heat pipe and the drill could be obtained. In general, the smaller the clearance indicates the better heat transfer performance, but care must be taken to ensure the film distributes uniformly to minimize the contact resistance. For the purpose of creating a uniform film between the heat pipe and the drill in the region where most of heat is transported, portion of the drill that acted as the evaporator was reheated to approximately 600°F again and, as a result, a continuous film was formed uniformly to reduce the contact resistance.

Figure 4 shows the schematics of solid drill and heat pipe drill in the experiments.

The drilling experiments were conducted on a DECKEL MAHO DMU 60 P five axis CNC milling machine equipped with a maximum spindle speed of 12,000 rpm and a 15-kW drive motor (see Fig. 5). Selected test parameters for the experiment are presented as follows [9, 10]:

- Rotational speed of the spindle, 500 rpm
- Feed, 0.005 in. per revolution
- Depth of each strike, 2.000 in. (through hole)
- Number of holes, 49 holes per block
- Three blocks for each drill (if not failed)

Figure 6 shows a sketch of the test setup. The spindle served as a heat sink. During the experiments, the cast iron

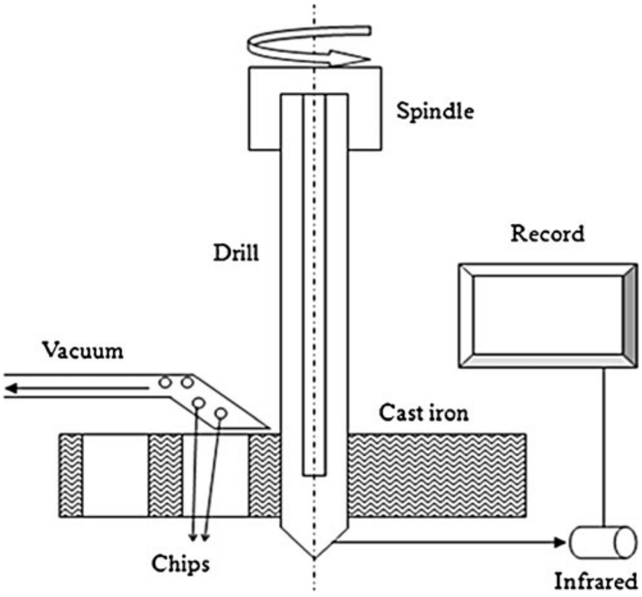


Fig. 6 A schematic sketch of the drilling operations

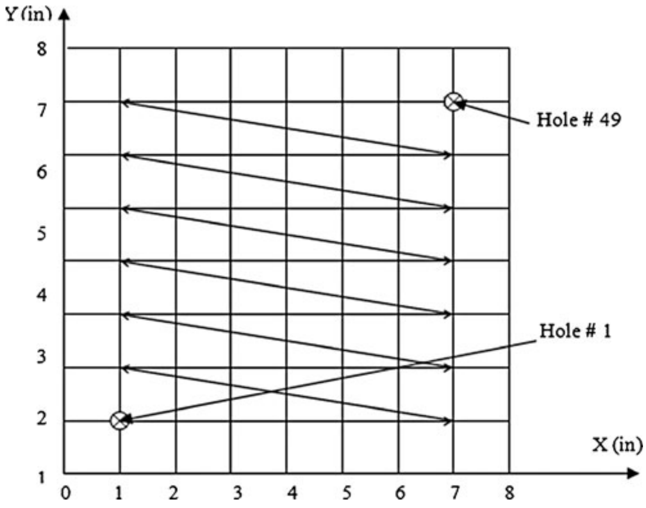
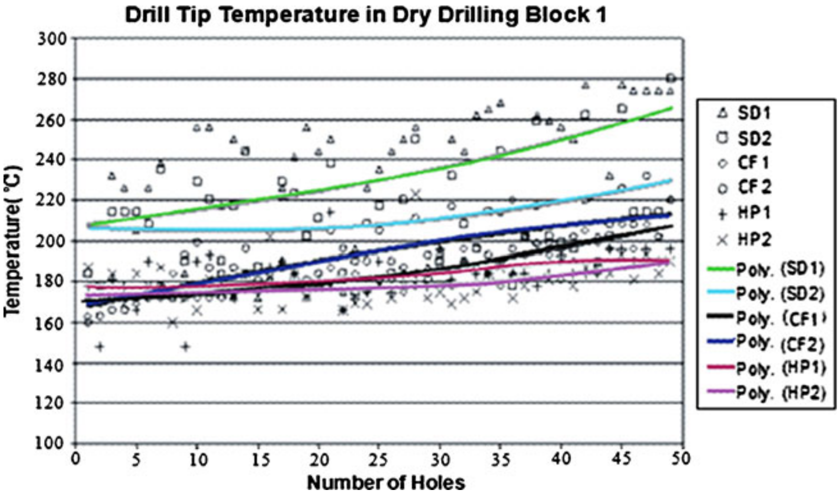


Fig. 7 Hole-drilling pattern for each cast iron block

Fig. 8 Temperature trend versus number of holes, block #1



block was first fixed firmly on the bench, and then the bench of the milling machine moved in the *X*–*Y* plane, and finally, the spindle, together with the drill, rotated and moved in the *Z* direction. The detailed machining process was depicted as follows:

On the 8.00-in. square block, hole #1 was located at 1.00 in. on the *X*-axis and 1.00 in. on the *Y*-axis. The *X*-axis dimension was first increased by 1.00 in. for each successive hole until 7.00 in. was reached, then the *X*-dimension was set to 1.00 in., and the *Y*-dimension was increased by 1.00 in. to begin the next row. Hole #49 was located at 7.00 in. on the *X*-axis and 7.00 in. on the *Y*-axis. Each hole was drilled through the 2.00-in.-thick block until the drill tool failed. The above-mentioned sequence was applied on all the tests, as shown in Fig. 7.

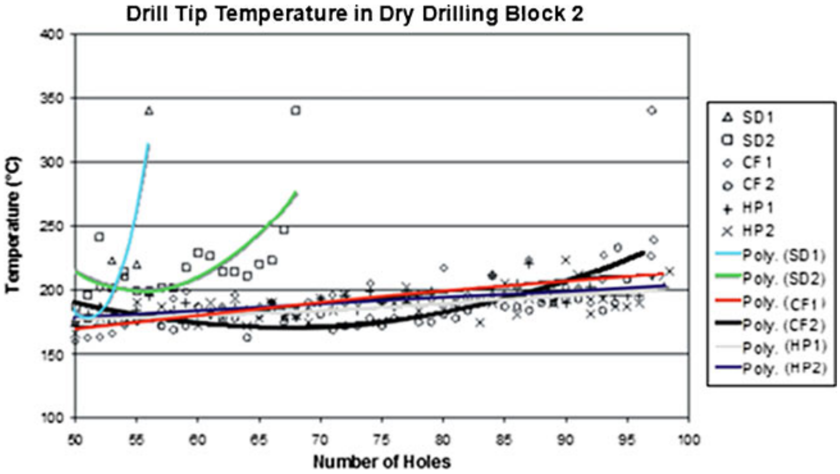
In order to measure the drill-tip temperature immediately the moment that the drill broke through, an infrared temperature meter was placed on a stand directly below the block [14, 15]. A chip vacuum was used for the purpose of chip removal to prevent the chips from accumulating in the hole or blocking the reading of the infrared meter. A vice was utilized to fix it to a stand and the intake tube was directly above the block surface, close to the drill (see Fig. 6). Flank wear is considered as the criterion for tool failure, and the wear was measured under a Hisomet II Toolmaker's microscope. Depending on the cutting conditions and wear rate, testing was stopped when an average flank wear exceeded 0.10 mm. Scanning electron microscope (SEM) was utilized to investigate tool wear and tool morphology [16].

4 Results and discussion

4.1 Drill-tip temperature analysis

Figure 8 shows the temperature trends of all the tool tips during drilling the first block. None of the drills failed in

Fig. 9 Temperature trend versus number of holes, block #2



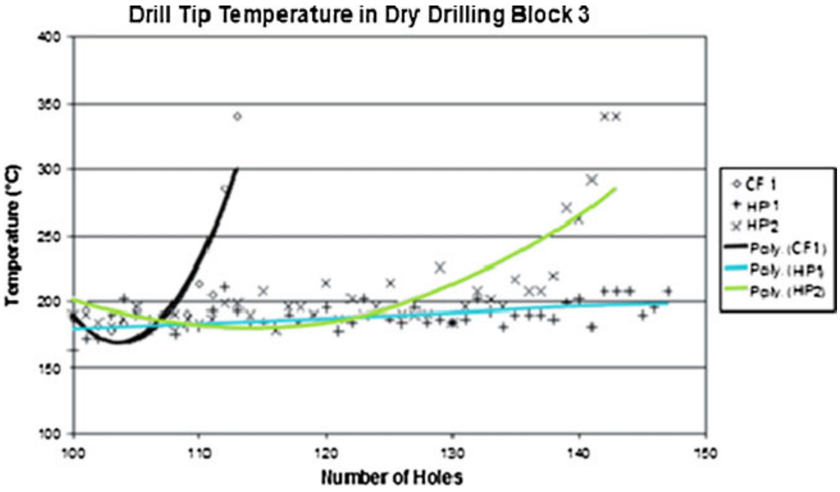


Fig. 10 Temperature trend versus number of holes, block #3

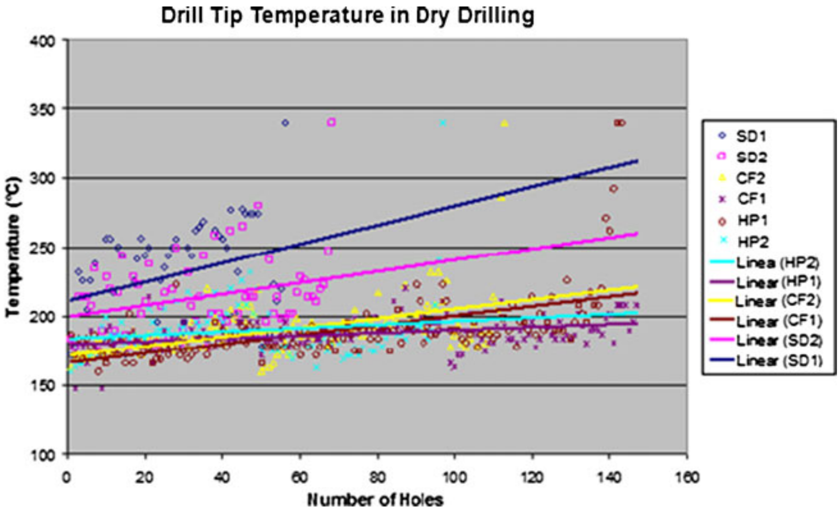


Fig. 11 Temperature trend versus time, all blocks

the above operations. However, the tip temperatures under dry drilling condition were higher than those under either cutting fluid supply or the heat pipe supply drilling conditions. Compared with the heat pipe drill-tip temperature, the tip temperatures under cutting fluid supply drilling conditions were also slightly higher, and displayed more of an upward trend.

Figure 9 presents the drill-tip temperature trends of all the tools in cutting the second block operations. It is observed that there were three failed drills, and that these failed drills displayed a sharp increase in the temperature trend. The failed drill-tip temperatures were measured as340°C. Note that 340°C was the maximum range of the infrared thermometer in this experiment. The measured temperature may not be the actual temperature of the failed

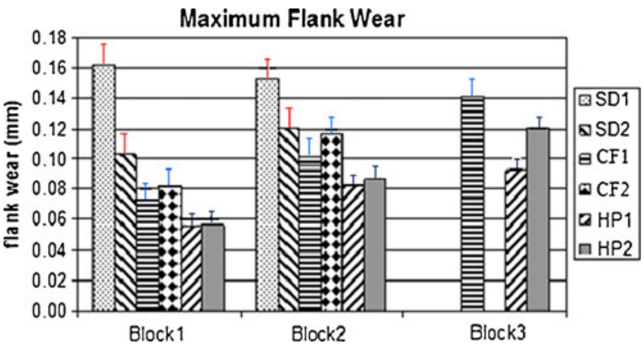


Fig. 12 Maximum flank wear after each block of drilling

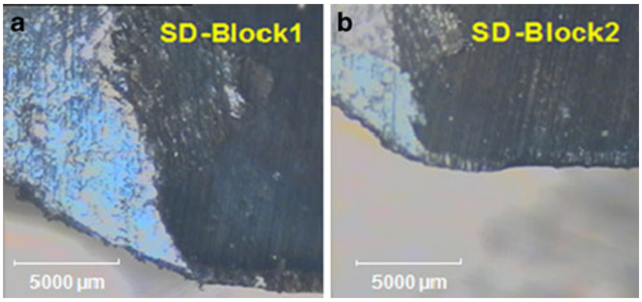


Fig. 13 Flank wear of solid drill

drill-tip, but it was the maximum temperature that could be recorded. The tip temperature was therefore at least 340°C. Seen in Fig. 9, the first solid drill (SD_1) failed at the seventh (56th overall) hole, the second solid drill (SD_2) at the nineteenth (68th overall) hole, and the second solid drill with cutting fluid supply (CF_2) at the 48th (97th overall) hole. Additionally, the first solid drill with cutting fluid supply (CF_1), the first heat pipe drill (HP_1), and the second heat pipe drill (HP_2) had slightly higher temperatures than in drilling the first block operations.

Figure 10 indicates the tool-tip temperature trends of the remaining non-failed drills during cutting the third block. It could be seen that the drills also failed when the drill-tip temperature reached 340°C. The failed drills displayed a much sharper increase in the temperature trend compared with that in drilling the second block applications. The first solid drill with cutting fluid supply (CF_1) failed at the 15th (113th overall) hole, the second heat pipe drill (HP_2) failed at the 45th (143rd overall) hole, but the first heat pipe drill (HP_1) survived with a slightly higher temperature in comparison with those in drilling the first two blocks operations.

Figure 11 presents the temperature trends of the six drills over the entire drilling time. It could be seen that the drill-tip temperature at failure was recorded as 340°C, and the temperatures increased sharply just before the drills failed. The experimental results show that experiments under heat pipe supply drilling condition resulted in approximately 120 min in tool life, which gives an improvement of tool life 2.2 and 1.6 times compared with those under dry and cutting fluid supply drilling conditions, respectively.

It is affirmed from Figs. 8, 9, 10, and 11 that using a heat pipe inside the drill could significantly reduce temperature in the cutting zone compared with solid drill and solid drill with cutting fluid supplied. Therefore, tool life is significantly influenced by heat pipe, which is responsible for increasing the tool life. This is because most of the heat generated on the drill tip could be removed effectively and quickly from heat pipe by convection heat transfer.

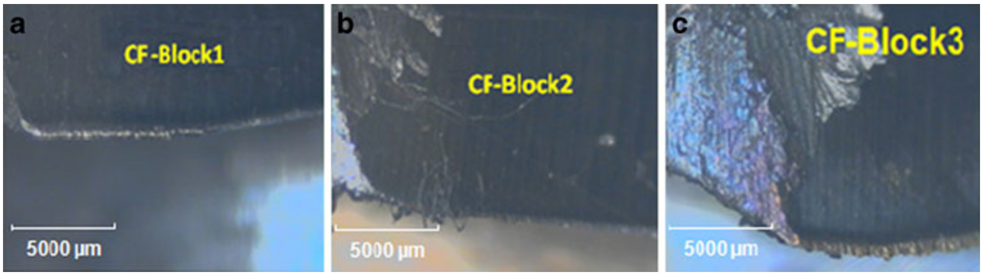
4.2 Tool wear morphology

For drilling, heat on the drill tool is significantly high, especially on the drill tip. Excessive temperature is known to cause various types of thermal damage to the cutting tool, e.g., rapid tool wear. Flank wear is considered as the criterion for tool failure in this study, and the wear was measured using a Hisomet II Toolmaker's microscope.

Figure 12 shows the maximum flank wear on each drill after drilling each block. From the picture, it could be seen that the drills SD_1 and SD_2 failed when drilling the first block, that the drill CF_2 failure occurred on the second block, and that the heat pipe drill did not fail until the third block. Therefore, it is inferred that heat pipe drill gives the longest cutting time before achieving 0.1 mm of flank wear compared with the experiments under either dry drilling condition or cutting fluid supply drilling condition.

Figure 13 shows the SEM micrograph of flank wear after drilling under dry machining conditions. As can be seen, solid drills both failed when cutting block 1 and 2, and extensive wear occurred in the tool flank face. Indications of abrasion and adhesion of cast iron along the worn edge are visible. In the area of the greatest flank wear, intense adhesion is observed, with material adhering to the top of the cutting edge. It can be attributed to the excessive drilling temperature due to the fact that the tool is constrained in a hole. In dry drilling, adhesion of workpiece material onto the tool flank covered the entire worn area, showing different thickness of the adhered layer, but no region free of adhesion. This is facilitated by the significantly high temperature. The adhered layer has a lower

Fig. 14 Flank wear of solid drill with cutting fluid supplied



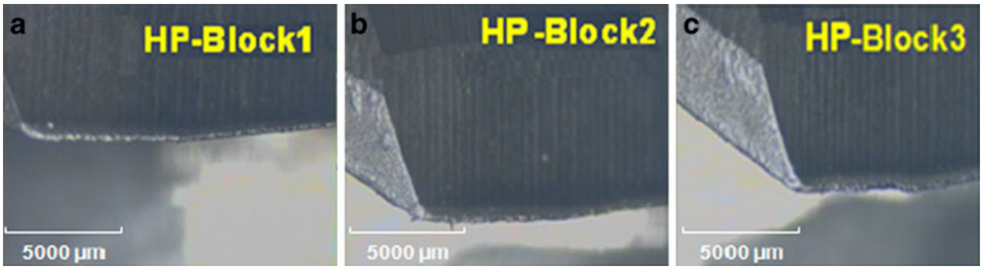


Fig. 15 Flank wear of heat pipe drill

mechanical resistance thanks to the sufficiently high temperature and, therefore, a lower capacity for removing tool particles [3]. Thus, it is likely that the tool particles in the severe drilling operations are pulled out due to mechanical fatigue, i.e., the large number of impacts between tool and workpiece.

Figure 14 shows the SEM micrograph of flank wear after drilling under cutting fluid supply conditions. The tool flank for drilling the first block did not exhibit much flank wear, but the drills for the block 2 and 3 both displayed a degree of flank wear exceeding the tool life criterion value. The less worn edge (Fig. 14a) showed homogeneous wear along the tool flank; however, it is apparent that the central areas of the worn regions (Fig. 14b, c) underwent intense wear. Compared with that in Fig. 13, the tool flank wear in Fig. 14b was found to be lower in the case of drilling with cutting fluid supply, which reflects that the cutting fluid supply has effects on the peak drill temperature. Due to the lower temperature, the adhered layer does not have the same plasticity as in dry drilling conditions [3], and is mechanically more resistant, thereby reducing the wear.

Figure 15 shows the SEM micrograph of tool flank after drilling under heat pipe supply conditions. As illustrated in Fig. 15, the heat pipe drill showed very little wear after drilling the first two blocks, and the minimal wear only appeared after drilling the block 3 with little or no adhesion. Compared with Fig. 15, BUE occurred under both dry drilling and cutting fluid supply conditions due to high reactivity of the material at elevated temperature, as shown in Figs. 13 and 14. BUE generally tends to grow until it reaches a critical size and then passes off with the chip. This gives rise to a cycle variation in the size of BUE and, consequently, BUE represents a major influencing factor on surface roughness in machining operations. For the wear in the case of heat pipe supply, this is basically related to more a result of flank wear due to mechanical wear than built-up edge [3, 9]. Generally, mechanical wear has a relatively low wear rate at any temperature [3]. Therefore, it is affirmed from the above analysis that a heat pipe could significantly lower the drill-tip temperature, makes it possible that it would not reach the required temperature to promote adhesive wear, curtailing the amount of BUE and extending the tool life.

4.3 Tool life

Figure 16 presents the tool life as a function of the cutting time. The solid drills resulted in 44.8 and 54.4 min (or 56 and 68 holes) in tool life, the drills with cutting fluid supplied had tool lives of 90.4 and 77.6 min (or 113 and 97 holes), and the heat pipe drills 117.6 and 115.2 min (or 147 and 143 holes). The experiment with heat pipe supply gives an improvement of tool life by 2.2 and 1.6 times under dry drilling and cutting fluid supply conditions,

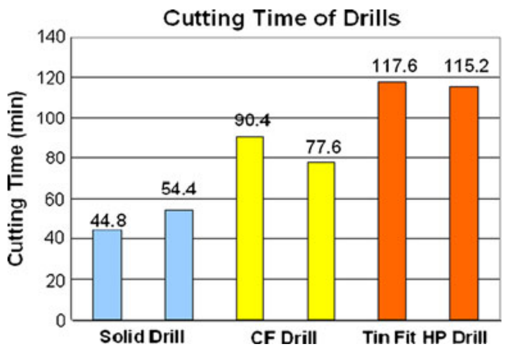


Fig. 16 Comparison of tool lives under various drilling conditions

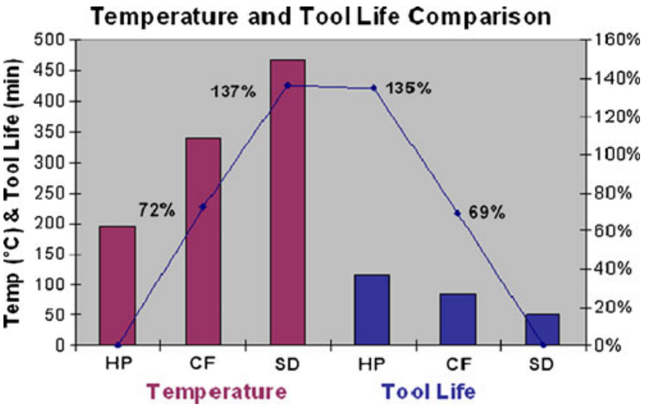


Fig. 17 Comparisons of tool lives and temperatures drill under various drilling conditions

respectively(see Fig. 17). Reducing the drill temperature was found to be critical in extending the drill tool life and, hence, most appreciable improvement of tool life takes place with heat pipe supply. This is basically because heat pipe can sufficiently help to prevent premature tool failure due to high drill temperature in the severe drilling operations.

5 Conclusions

For drilling operations, since the tool is constrained in a hole, the high temperature is significant in the drill tip. Excessive tool temperature softens the tool material and is detrimental to the tool life. This paper presented an experimental investigation to verify the feasibility and effectiveness of heat pipe cooling in drilling operations. The basic idea is that a heat pipe is inserted at the center of the drill tool with the evaporator close to the drill tip and the condenser at the end of the drill.

This study showed that the tin-fit heat pipe drill helped in substantially increasing tool life during drilling cast iron. Build-up edge is a big problem in the practical drilling processes. Evidence of build-up edge was found under either dry drilling or cutting fluid supply conditions, respectively. However, little or no adhesion appeared on the heat pipe drills. Experiment with heat pipe supply gave benefits in increasing tool life by 2.2 times and 1.6 times, respectively, compared with the experiments under both dry drilling and cutting fluid supply conditions. This is because large quantities of heat generated on the drill tip are removed along the drill axis effectively and quickly by means of a heat pipe.

The results demonstrate that using a heat pipe in the drilling processes can effectively perform thermal management comparable to the flooding coolant cooling used pervasively in the machining industry and, as a result, *indicates that the dry drilling can be achieved by using a heat pipe in the drilling operations*.

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