Effect of cooling methods on cutting temperature, cutting force and hole quality in drilling of three ferrous alloys

M N Islam and B Boswell
Department of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, Western Australia 6845

E-mail: m.n.islam@curtin.edu.au

Abstract. This paper presents the experimental results of an investigation into the effects of the cooling methods used on cutting temperature, cutting force and hole quality while drilling three ferrous alloys: alloy steel AISI 4340, medium-carbon steel AISI 1045 and stainless steel AISI 316L. HSS drill bits were used with different cutting conditions. Three cooling methods were compared: cryogenic, minimum quality lubrication (MQL) and flood cooling. The drilling operations were evaluated with respect to a number of evaluation parameters, such as cutting temperature (average and maximum temperature), cutting force (drilling thrust and torque) and hole quality (size variation, size tolerance, circularity and surface roughness). Results revealed that the cooling methods had a notable influence on the parameters investigated. However, the extent of the influence depended on the work material, and which coolant was being used. MQL produced the best results in terms of cutting force and surface roughness. With respect to the remaining parameters, they were similar to traditional flood cooling.

1. Introduction

The need to produce accurate round holes is critical in manufacturing. Indeed it is one of the most important machining processes, comprising approximately 25-30% of all metal-machining work [1, 2]. In many cases a drilled hole is the best option for assembling mechanical components and structures which use bolts or rivets. The relative motion of a drill bit is similar to all other cutting processes, with substantial heat being generated by the wedge cutting action of the drill bit. This increased temperature causes thermal distortion of the workpiece, and reduction of tool life. It is estimated that 10-35% of total heat generated is dissipated into the workpiece, which is greater than turning (1.1-20%), and milling (1.3-25%) [3]. Essential to improve the effectiveness of drilling operation the cooling fluid needs to be effective at the shear plain of the work material. Therefore, careful consideration needs to be given to the selection of cutting fluid, and the fluid delivery method in drilling operations. Traditionally, flood cooling has been used as it allows coolant to penetrate to the cutting edge of the drill, and helps in removing the swarf. This results in a high cost for the disposal of the contaminated cutting fluid which must now be considered [4]. For this alone it is imperative to discover a cooling method that is more sustainable but still as effective in cooling the cutting edge. In this research two alternative cooling methods, MQL and cryogenic cooling, have been investigated to establish their effectiveness in increasing tool life.

Investigations of the effect of various cooling methods have received considerable attention in the literature. However, most of the investigations focused on a single work material such as aluminium 6061 [5, 6], AISI 1045 steel [7], AISI 1020 steel [8], titanium alloys [9, 10], carbon fiber reinforced
polymer (CFRP) [11, 12], Kevlar composites [13], magnesium alloy AM60 [14], and aluminium silicon B319 cast alloy [15]. Experience has shown that the work material has considerable effect on the machining process. Consequently, to produce robust drilling data three work materials were selected to produce diverse machinability ratings for this research.

2. Experimental work

The drilling was performed on three ferrous alloys: alloy steel AISI 4340, medium-carbon steel AISI 1045 and stainless steel AISI 316L which are widely used in the industry. The chemical composition of the disks are compiled from Matweb [16], and are listed in Table 1. Three disks of each material, each 50 mm diameter and 24 mm thickness were prepared, with three 1 mm diameter holes for inserting the probes at different heights (Probe 1, 2 and 3 at 4.5, 12 and 19.5 mm respectively from the top) for temperature measurement. Holes were drilled on a vertical CNC machining centre with 5.5 kW spindle power and a maximum spindle speed of 4500 rpm. 12mm diameter high-speed steel (HSS) drill bits with 135° point angle were used. A spot drilling canned cycle (G81) was applied to simplify the analysis. The cutting parameters were varied only for the materials and not between cooling methods. The details of cutting conditions used are given in Table 2. Cutting conditions were selected as per recommendations of the drill bit supplier. Drilling was performed applying three cooling methods: cryogenic, flood and MQL. For cryogenic cooling liquid nitrogen (LN2) was sprayed directly on to the top of the disk via a single nozzle. For flood cooling, Robocol Long life soluble oil cutting fluid diluted with water to a concentration of 1:35 was used. This was applied to the disk by the CNC machines inbuilt coolant delivery system. For MQL drilling, Coolube 2210, a vegetable oil based metal cutting lubricant was applied in mist form by a UniMax cutting tool lubrication delivery system, manufactured by Unist, U.S.A.

| Component elements | AISI 4340 | AISI 1045 | AISI 316L |
|---------------------|-----------|-----------|-----------|
| Carbon, C           | 0.37 – 0.43% | 0.42 – 0.50% | <= 0.030% |
| Chromium, Cr        | 0.70 – 0.90% | 16 – 18%   |           |
| Iron, Fe            | 95.195 – 96.33% | 98.51 – 98.98% | 61.9 – 72% |
| Manganese, Mn       | 0.60 – 0.80% | 0.60 – 0.90% | <= 2.0%   |
| Molybdenum, Mo      | 0.20 – 0.30% | 2.0 – 3.0%  |           |
| Nickel, Ni          | 1.65 – 2.00% | 10 – 14%   |           |
| Phosphorous, P      | <= 0.035%   | <= 0.040%  | <= 0.045% |
| Silicon, Si         | 0.15 – 0.30% | <= 1.0%    |           |
| Sulphur, S          | <= 0.040%   | <= 0.050%  | <= 0.030% |

| Parameters | Unit | AISI 4340 | AISI 1045 | AISI 316L |
|------------|------|-----------|-----------|-----------|
| Spindle speed | rpm   | 400       | 800       | 250       |
| Feed rate   | mm/rev| 0.18      | 0.20      | 0.24      |
| Cutting time | s       | 20.00     | 9.00      | 24.00     |

Three hypodermic thermocouple probes (model HYP-2 manufactured by Omega, USA with a tip diameter of 0.81 mm, and temperature range of cryogenic to 200°C) were positioned precisely at desired locations. The temperature readings were recorded at the rate of 4 measurements per second using a data logger. The cutting force (drilling thrust and torque measured by a rotating cutting force dynamometer
Type 9125A, manufactured by Kistler, Switzerland) was taken at the rate of 20 Hz and recorded onto a computer via a data logger and associated computer software program. The size variation and circularity data were obtained using a coordinate measuring machine (Discovery Model D-8, manufactured by Sheffield, UK). The diameters of the holes were calculated using the standard built-in software package of the CMM. Eight points were probed to determine the diameter in the horizontal plane, and the diameter of each hole was checked at 1 mm height increments. The size variation was calculated as the measured diameter minus the design diameter (12 mm). The size tolerance was calculated as the difference between the maximum and minimum diameter of the hole. The circularity data was obtained from the CMM applying a similar probing scheme. The surface roughness parameter arithmetic average (Ra) was determined by a surface-measuring instrument (SurfTest SJ-201P, manufactured by Mitutoyo, Japan). For each hole, five surface roughness measurements were taken parallel to the hole axis at five axial positions excluding entry and exit positions.

3. Results and analysis
To provide an understanding of the effect on the cutting mechanisms for each cooling method, a comprehensive testing of different cooling mediums was conducted during drilling. Steel workpieces were subsequently inspected for accuracy, circularity and surface roughness. These parameters give an excellent indication of the quality of the holes produced. During the drilling process the thrust force, torque and temperature were continuously monitored, showing the effectiveness of the cooling medium on cutting. Each of the above parameters are indicators of the effectiveness of the drilling operation, and give a good indication of the drill bit life. As a consequence a substantial amount of data was obtained for subsequent analysis. Due to space constraints, minimum data, was included in this paper. However, the larger data set analysis findings and conclusions are presented. Unfortunately, the authors were unable to obtain reference material that provided a similar combination of data sets for comparison.

3.1. Cutting temperature
Examples of the cutting temperature measurement results are shown in Figure 1. A closer examination of the graphs reveals that in cryogenic drilling the minimum temperature was 17.23°C recorded by Probe 1 at 15.00 s on the time scale, and the maximum temperature was 57.34°C recorded by Probe 3 at 35.00 s. The difference (20s) equates to the machining time (Table 2). Since the highest temperature marks the end of the cutting process, the start of the cutting process can be determined by subtracting the cutting time from it. This gives a better understanding of the cutting process. The initial drop of temperature in cryogenic cooling was due to time laps between the starting of coolant supply and the beginning of actual cutting. No such drop in temperature was observed in flood or MQL cooling. The maximum temperature recorded for MQL (75.71°C) was comparatively higher that cryogenic (57.34°C), and flood (52.89°C) cooling. Contrasting only Probe 1 for all three cooling methods clearly shows flood cooling to be best nearest to drill entry point.
Figure 1. Temperature measurement results.

Figure 2 shows that the cooling method has the greatest influence on the average cutting temperature in drilling AISI 316L steel, whereas the lowest influence was in drilling AISI 1045 steel. The average temperature is highest when using MQL, followed by flood then cryogenic cooling. For the maximum temperature a similar trend is observed. Nevertheless, the difference between flood and cryogenic cooling is relatively small. The influence of a cooling method on the maximum temperature in drilling AISI 1045 is negligible.

Figure 2. Effect on cutting temperature.

3.2. Cutting force
Typical cutting force measurement results are shown in Figure 3. Results show a slight increase in trust force overtime in cryogenic and flood cooling, whereas a slight decrease in MQL. It is believed to be caused by a higher temperature, as noted in Figure 1 and 2. The thrust force and cutting torque are found to be larger when drilling the harder materials (4340 and 316L) due to increased efforts being required to overcome the shear strength of the material.

The average cutting force measurement results are shown in Figure 4. It illustrates that both thrust force and cutting torque are increased with the decrease in temperature as the low temperatures do not allow the material to soften, and requires more force to shear the workpiece.

3.3. Hole quality
Four hole quality characteristics were investigated: size variation, size tolerance, circularity and surface roughness (Figure 5). In all cases the average size error is positive, indicating oversizing of the holes, which is common in drilling operations [17]. It depends on the work material as well as the variation in relative lip heights of the drill, runout of the drill when attached to the machine, thermal distortion, a non-symmetric point angle and runout of the chisel edge [5]. Cryogenic drilling of AISI 316L produced the highest size variation and tolerance as a result of higher cutting force.
Figure 3. Typical cutting force measurement results.

Figure 4. Effect on cutting force.

For all materials tested, cryogenic cooling produced worst surface roughness. Surface roughness achieved by flood was considerably better than cryogenic cooling, whereas MQL produced the best surface finish. MQL also showed better performance on thrust force and cutting torque (Figure 4). The primary function of MQL is to lubricate the cutting zone, and not to dissipate the machining heat. The lubrication effect improves surface roughness whereas high workpiece temperature makes it more plastic, which reduces the effort for cutting.
6. Concluding remarks
The experimental and analytical investigations have indicated that the following conclusions can be made:

- Drilling thrust force and torque were found to be largest under cryogenic cooling for all materials tested. Due to the extreme decrease in material temperature, which does not allow any softening to occur at the tool interface with respect to the cutting temperature.
- As expected, the average and maximum temperatures were lowest under cryogenic cooling, followed by flood and MQL for all materials tested. This reduction of temperature did not however help to increase the quality parameters for the drilled holes.
- Comparing temperature from the probes indicated that flood coolant was best at penetrating the drilled hole, owing to the large volumes of coolant involved.
- It was also apparent form the temperature graphs that the rate of cooling, was surprisingly only slightly better for cryogenic, indicating inadequate penetration of liquid nitrogen.
- As there was higher thrust forces recorded when using cryogenic cooling which in turn caused an increase in temperature at the tool interface. This accounts to why cryogenic was not as effective in cooling as flood even with the substantial colder temperatures of liquid nitrogen.

References
[1] Tönshoff HK, Spintig W, König W, Neises A. Machining of holes developments in drilling technology. CIRP Annals-Manufacturing Technology. 1994 Jan 1;43(2):551-61.
[2] Black JT, Kohser RA. DeGarmo's materials and processes in manufacturing. John Wiley & Sons; 2017 Jul 5.
[3] Lin J, Lee SL, Weng CI. Estimation of cutting temperature in high speed machining. Journal of engineering materials and technology. 1992 Jul 1;114(3):289-96.
[4] Ginting YR, Boswell B, Biswas W, Islam N. Advancing environmentally conscious machining. Procedia CIRP. 2015 Jan 1;26:391-6.

[5] Islam MN, Boswell B. Effect of cooling methods on hole quality in drilling of aluminium 6061-6T. In: IOP Conference Series: Materials Science and Engineering 2016 Feb (Vol. 114, No. 1, p. 012022). IOP Publishing.

[6] Wakabayashi T, Suda S, Inasaki I, Terasaka K, Musha Y, Toda Y. Tribological action and cutting performance of MQL media in machining of aluminum. CIRP Annals-Manufacturing Technology. 2007 Jan 1;56(1):97-100.

[7] Govindaraju N, Shakeel Ahmed L, Pradeep Kumar M. Experimental investigations on cryogenic cooling in the drilling of AISI 1045 steel. Materials and Manufacturing Processes. 2014 Dec 2;29(11-12):1417-21.

[8] Boubekri N. An investigation in drilling 1020 steel using minimum quantity lubrication. International Journal of Applied. 2011 Sep;1(5).

[9] Rahim EA, Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. Tribology International. 2011 Mar 1;44(3):309-17.

[10] Ahmed LS, Govindaraju N, Pradeep Kumar M. Experimental investigations on cryogenic cooling in the drilling of titanium alloy. Materials and Manufacturing Processes. 2016 Apr 3;31(5):603-7.

[11] Xia T. Investigation of drilling performance in cryogenic drilling on CFRP composite laminates. Master's Thesis, University of Kentucky. 2014.

[12] Basmaci G, Yoruk AS, Koklu U, Morkavuk S. Impact of Cryogenic Condition and Drill Diameter on Drilling Performance of CFRP. Applied Sciences. 2017 Jun 29;7(7):667.

[13] Bhattacharyya D, Horrigan DP. A study of hole drilling in Kevlar composites. Composites science and technology. 1998 Jan 1;58(2):267-83.

[14] Bhowmick S, Lukitsch MJ, Alpas AT. Dry and minimum quantity lubrication drilling of cast magnesium alloy (AM60). International Journal of Machine Tools and Manufacture. 2010 May 1;50(5):444-57.

[15] Fox-Rabinovich G, Dasch JM, Wagg T, Yamamoto K, Veldhuis S, Dosbaeva GK, Taufiduzzaman M. Cutting performance of different coatings during minimum quantity lubrication drilling of aluminum silicon B319 cast alloy. Surface and Coatings Technology. 2011 May 15;205(16):4107-16.

[16] Matweb. Material Property Data [Internet]. Blacksburg VA: MatWeb LLC; 2018 [cited 2018 Mar 29]. Available from: http://www.matweb.com/

[17] Galloway DF. Some experiments on the influence of various factors on drill performance. Transactions of ASME. 1957;79:191.