Journal of Manufacturing Processes 29 (2017) 194–203

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

# The thermal modeling of deep-hole drilling process under MQL condition

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ARTICLE INFO

*Article history:*
Received 28 June 2016
Received in revised form 6 February 2017
Accepted 21 July 2017

*Keywords:*
Thermal modeling
MQL
Deep-hole drilling
CGI

ABSTRACT

This study investigates the temperature distribution of a compacted graphite iron (CGI) workpiece in minimum quantity lubrication (MQL) deep-hole drilling. The temperature distribution in the workpiece is predicted using the finite element method, in which the heat flux loads on the chisel and the cutting lip applied to the finite element model are determined using analytical equations. Additionally, heat flux loads on the margin and the heat convection coefficient of the air–oil mixture are considered and calculated using the inverse heat transfer method. The inverse method is validated experimentally, and the results demonstrate good agreement with the experimental temperature measurements. The importance of drilling time was demonstrated on the temperature distribution. The maximum temperature was observed on the chisel edge near the center of the hole instead of the outer surface of the hole.



## 1. Introduction

Drilling is the most common conventional machining process with the largest share of machining time, that is, 41% [1]. Increased tool life and material removal rates and decreased lubrication use in drilling can provide considerable cost reduction. In the interest of reducing drilling costs, companies desire to achieve high cutting speed with less lubricant use which generates high temperature problems. The residual stress, dimensional error and hardness of the machined surface are directly affected by high temperatures. Therefore, estimating temperatures of the final product is vital.

Traditional cooling technologies have been used to decrease disincentive effect of temperature on machined surface and tool material. New cooling technologies have been getting attractive in machining industry in order to decrease using coolant amount and increase cooling capacity. Currently, advanced cooling techniques including MQL, $CO_2$-assisted MQL, and cryogenic cooling have become popular mainly in grinding and deep-hole drilling for hard-to-machine metals [2]. MQL is the most popular among these technologies, using a minute amount of metal working fluid compared with other cooling technologies. Automotive powertrain production has been especially revolutionized by this technology in the last decade [2]. Nevertheless, the cooling capacity of MQL is limited compared with flood and cryogenic cooling techniques. In this study, the cooling capacity of MQL is quantified by the inverse heat transfer method.

The automotive industry aims to produce smaller, higher-performance, and more efficient diesel engines that meet the legal requirements of reduced emission levels while meeting customer expectations [3]. Owing to the development of diesel engines, CGI usage has increased in the last two decades. Engines operated at 135 bar in 1997; the target value of the peak firing pressure in next-generation diesel engines is expected to be 220 bar [4]. Considering this dramatic increase, a weight reduction of 10–30% can be achieved using CGI instead of grey cast iron, given the power and size of the engines [4]. CGI fulfills these requirements by providing reduced wall thickness, increased operating loads and reduced hot cracking (during shakeout) compared with grey iron in addition to improved castability, heat transfer and machinability compared with ductile iron [5]. CGI is capable of being 75% stronger than grey iron owing to the shape, size, and growth mechanism of graphite particles in the microstructure, which provide advanced thermal and mechanical properties [6]. To obtain and control these properties, additional alloy elements such as magnesium, titanium and chromium are added to the structure; yet these elements reduce the CGI machinability [7].

Several researchers have performed thermal modelling of the drilling process. Although most of these studies concentrated on

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http://dx.doi.org/10.1016/j.jmapro.2017.07.020

**Nomenclature**

| | |
|---|---|
| $\alpha$ | Rake angle |
| $\phi_c$ | Shear angle |
| $i$ | Inclination angle |
| $\eta$ | Chip flow angle |
| $v$ | cutting velocity of the ECT |
| $v_{chip}$ | Chip velocity |
| $v_f$ | Feed velocity of the drill |
| $\omega$ | Angular velocity of the drill |
| $r_{in}$ | Inner radius of the element |
| $r_{out}$ | Outer radius of the element |
| $q$ | Rate of total heat generation for an ECT |
| $q''_{wp}$ | Heat flux load applied to each element of the FEM |
| $q_{shear}$ | Rate of heat generation in shear for an ECT |
| $q_{friction}$ | Rate of heat generation by friction for an ECT |
| $T$ | Torque for each ECT |
| $F_z$ | Thrust force for each ECT |
| $F_t$ | Tangential force for each ECT |
| $F_f$ | Feed force for each ECT |
| $F_u$ | Friction force between chip and tool for each ECT |

drill temperatures, the number of studies focused on the prediction of workpiece temperature distribution is limited. Watanebe et al. developed a finite difference model that predicts workpiece temperatures to estimate thermal distortions in drilling [8]. Bono and Ni used thrust force and torque values as inputs in an oblique cutting to predict heat fluxes [9]. They then developed an advection heat partition model to calculate the temperature distribution of the workpiece in a finite element model in dry drilling. Kalidas et al. estimated heat fluxes in three distinct regions of the drill (drill body, cutting lips and chisel edge) by inverse heat conduction in dry and wet conditions [10]. Tai et al. calculated the heat flux both on the wall and on the bottom surface of the hole in dry and MQL conditions while using the inverse heat transfer method [11]. Biermann et al. also simulated the temperature workpiece distribution in the MQL condition by the finite element method [12,13]. Segurajauregui and Arrazola used the inverse heat transfer model to calculate the heat input to the workpiece and thermal distortions [14]. Most models assumed that the heat load on the cutting edge and chisel edge is constant.

In this study, the variation of heat flux on the cutting edge is considered, and heat fluxes on the chisel and the cutting lip are calculated analytically. Heat fluxes at the margin, accumulated hot chips on the spiral drill flute, and the heat convection coefficient of the air–oil mixture are calculated using the inverse heat transfer method. The inverse heat transfer method has three main steps: Collecting experimental data, direct problem, and inverse problem. Experimental data are collected by embedded thermocouples 1.5 mm from the hole on the surface. The direct problem is then solved via a commercial finite element program named Abaqus, and the inverse problem is solved using MATLAB. The goal of this paper is to determine the temperature distribution of a CGI workpiece in the MQL condition using a hybrid analytical and numerical heat transfer method.

## 2. Heat transfer in mql deep-hole drilling

Almost all mechanical energy is converted to heat, which is shared with the tool, chip and workpiece during machining. This energy is transferred to the workpiece from four regions during deep-hole drilling: chisel edge, cutting lip, drill margin, and drill flute, as illustrated in Fig. 1. The heat sources are the cutting and friction on the chisel edge ($q_c$) and cutting lip ($q_l$), the friction on

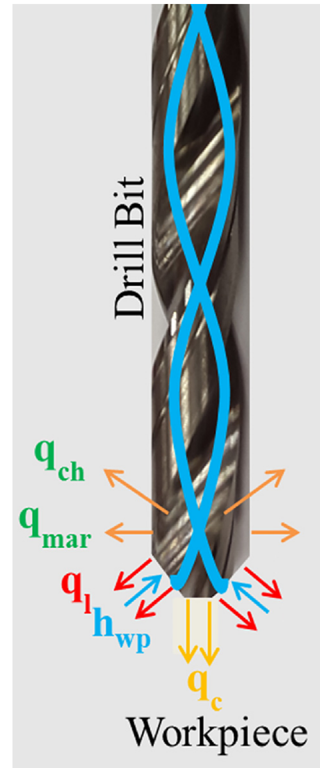


**Fig. 1.** The heat sources during deep-hole drilling.

the drill margin ($q_{mar}$), and accumulated hot chips ($q_{ch}$) on the drill flute.

Two major heat sources are precipitated from cutting on the cutting lip ($q_l$) and the chisel edge ($q_c$). Fig. 2 shows where heat is generated in the cutting process. A large amount of heat is generated in the shearing zone (zone a in Fig. 2) because of high thermomechanical deformation. In addition, the friction between the chip and tool rake face (zone b in Fig. 2) and the friction between the machined surface and tool flank surface (zone c in Fig. 2) are the other regions of generated heat. The friction between the tool margin and hole walls ($q_{mar}$) and accumulated hot chips ($q_{ch}$) through the flute are minor heat sources. In addition, lubrication fluid ($h$) is widely used to cool the drill and workpiece and evacuate the hot chips. In this study, MQL was used to cool the workpiece by convection during deep-hole drilling. The cooling effect of MQL on the bottom and on the hole surface is considered in the temperature distribution calculation. Heat generation loads at the cutting lip and at the chisel edge were calculated analytically. The convection coefficient of the air–oil mixture and the combination of heat generation at the margins and accumulated hot chips on the flutes were calculated by the inverse heat transfer method.

## 3. Heat flux calculations

The heat flux calculation procedure includes the geometric model of the drill, the prediction of the cutting force and the torque values at the cutting lip and the chisel edge. When estimating the cutting force, the cutting lip and chisel edge were divided into segments because of varying inclination and rake angles—namely, the Elemental Cutting Tools (ECTs). The advection heat partition model developed by Bono and Ni was applied to obtain the heat flux on the cutting surface for each ECT [9]. The total amount of heat gen-