A STUDY OF COMPUTER ASSISTED ANALYSIS OF EFFECTS OF DRILL POINT GEOMERICAL FEATURES ON FORCES AND POWER IN DRILLING WITH GENERAL PURPOSE TWIST DRILLS

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Abstract:
This paper presents results of a systematic – computer assisted – study focused on determining, and describing, from a mathematical point of view, the relationship between the drill point geometrical features and predicted performance measures as assessed by the cutting forces (thrust and torque) and cutting power when drilling a Type Bisalloy 360 steel work-piece material with general purpose twist (GPT) drills. The current study presents an innovative predictive strategy for eliminating the need of experimental testing when comparing drilling performance of GPT drills. It employs an advanced computer assisted model to analyse the rake angle distributions along the drill lips and the chisel edge regions when changing the six main individual drill point geometrical features (D, 2W, δ_O, ψ, Cl_O, and 2P) in the software input and looking at their effects on the generation of thrust, torque and power in drilling. It is expected that this sort of information may be used to assist in optimisation of the cutting performance of drills via advances through the modification of drill point geometrical features.

Keywords: *Computer assisted predictions, general purpose twist drills, geometrical features, drill point, lip region, chisel edge, rake angles, thrust and torque forces, cutting power.*

1. Introduction

In recent modern manufacturing environment drilling accounts for more than thirty percent of the many cutting tools used in finish machining [1]. In addition, there is an increasing demand on drilling performance and high process reliability. General purpose twist (GPT) drills are today's widely used tools in metal cutting industries. Their geometry is based on a design patented by Morse in 1863 [2]. It includes the six main drill point features, pictured in Figure 1, namely, the drill diameter D, lip spacing 2W, point angle 2P, clearance angle Cl_O, chisel edge angle ψ, and the helix angle δ_O. The later represents the lip rake angle.

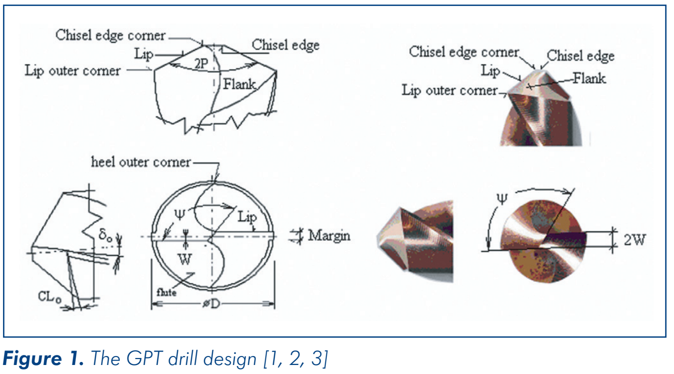

Figure 1. *The GPT drill design [1, 2, 3]*

It has been recognized that variability in the above drill point geometrical features can be responsible for large differences in cutting forces and power when drilling with nominally similar drills of identical GPT design. Because of this, considerable efforts have been expended on achieving optimum technological performance measures in terms of forces, power when drilling different work-piece materials. In 1970's the effects of several drill-point geometrical features on thrust and torque in drilling various work-piece materials with uncoated drills have been assessed 'experimentally' by some researchers who used a one variable to study the effect of the helix angle, point angle and clearance angle at a time approach. Their conclusions were briefly reviewed by Micheletti and Levi in source [3]. Some earlier research work [4] tried to predict drilling forces quantitatively using appropriate equations describing a relationship between forces, cutting conditions and drill point geometry for uncoated drills. A number of empirical equations in drilling with uncoated tools have been listed e.g. in the literature [5 and 6] for the power, P, thrust, Th, and torque, Tq, and are shown by Equations 1, 2 and 3, respectively.

$$P = C_1.T_q.n_{(=rpm)} + Th.f_{(=feed)}.n = C_1.T_q.n \quad (1)$$
$$T_h = C_2.f^{x1}.D^{y1} \quad (2)$$
$$T_q = C_3.f^{x2}.D^{y2} \quad (3)$$

Where empirical constants, C_1, C_2 and C_3 and exponents, x_1 and x_2, and y_1 and y_2, have to be found for each tool-work-piece material combination. Exponents such as x_1 and x_2, and y_1 and y_2 are curve-fitting constants. For uncoated drills the exponents y_1 and y_2 have been reported to be in the range from 1.8 to 2 [5 and 6], respectively while other two constants, C_1 and C_2, have been found to be associated with a type of work-piece material drilled.

It appears on the first sight that empirically derived thrust and torque equations for the uncoated drills may be a convenient method to quantitatively predict these drill performance measures. However, Armarego [5], Zhao [6], Wright [7] and Audy [8, 9 and 10] have shown that the specific drill point features vary within certain limits resulting in individual thrust and torque data for a particular drill examined. Empirical equations for reasonable force prediction have a limited range of use because they do not allow studying the effect of each drill design feature such as drill diameter, helix angle, web thickness, chisel edge angle, point angle and clearance angle individually with respect to other drill design features and different cutting speeds and feed rates.

It needs to be noted that many of nowadays drills are coated with TiN, TiCN, TiAlN, TiAlCrN coatings, and multilayer and nano-composite coatings based on TiN/TiAlN [8, 11 and 12]. Improvements sought are in increased machining productivity (due to better resistance to tool wear), and lower forces and power (due to smoother surface finish and hence lower friction at the tool rake / work-piece material interface). Audy [8 and 12] conducted an extensive literature survey on cutting tools and performance. The searched literature did not provide any empirical thrust and torque equations for coated drills with reference to the main drill point features, e.g. in a form shown below in Equations 4 and 5. Where the $C_{I\ and\ I}$, $c_{1\ to\ 6}$, as well as C1 to 6 are the empirically gained constants. The latter can be determined by computer simulations (i.e. running force and power predictions using a proprietary software equipped with database gained from orthogonal cutting tests and unified mechanics of cutting), or though time consuming experimental testing.

$$Th = C_I.f^{C1}.D^{C2}.(2W/D)^{C3}.2P^{C4}.\psi^{C5}.\delta_O^{-C6} \quad (4)$$
$$Tq = C_{II}.f^{C1}.D^{C2}.(2W/D)^{C3}.2P^{-C4}.\psi^{-C5}.\delta_O^{-C6} \quad (5)$$

Without such equations or proprietary software the users or researchers need to run expensive and time consuming experiments for different tool geometry/work-piece material/tool coating/cutting condition combination.

Moreover, it appears that there is only a limited awareness of effects of variances in drill point geometrical features on the rake angle distributions along the lips and chisel edge region and hence on forces and power generated when drilling with commercially available GPT drills. The experimental approaches are time consuming and expensive. In addition, they provide only limited knowledge into a complex relationship between the drill geometrical features and technology performance measures with respect to different tool material – surface coating – cutting process parameter combinations.

The present investigations were carried out with the aim of using computer assisted modelling and software for studying the effect of prominent drill point features on elemental cutting action along the lips and chisel edge region and hence on the cutting forces (thrust and torque) and cutting power when dry drilling into a Type Bisalloy 360 steel work piece material.

2. Experimental Method

Experimental Drills: Drill Point Geometry

A number of drills were randomly selected from different production batches and manufacturers for this investigation. There were nine sets of drills (marked as A to I, see Table 1) that were selected for the study. The average values of the five main geometrical – drill point – features (i.e. 2W, δ_O, ψ, Cl_O, and 2P) for a constant D=6.35 mm for each individual set were used for modelling the distribution of rake angles along the lip and the chisel edge regions prior studying their effect on toque, thrust and power in drilling.

ximum of 40RC (~400HB) and indicated that this particular work-material may not be easily machined with uncoated HSS tools. The reason for selecting this material was to run additional life tests on coated and uncoated HSS materials. These life data results were already published and they are not a part of this paper which focuses on forces and power in drilling.

The software for force prediction was developed at Melbourne University as a part of study [8]. The relevant flow chart of this computer assisted force prediction model was shown and explained in source [13 and 20]. The software validity was tested via prediction of a large number of computer simulations (i.e. 729 for GPT) and compared with data gained from real experimental tests. The simulations were run using the two different databases – one for the uncoated tools and one for the coated tools. The coated tools were treated as one group i.e. the combined database has been employed, since the orthogonal tests showed no statistically significant differences in forces and drilling power between the coatings themselves. The effect of the three coatings – TiN, Ti(C, N) and Ti(Al, N), M35 HSS tool substrate material, and drill point geometry on the thrust and the torque characteristics has been studied first qualitatively and then quantitatively to distinguish differences between the uncoated and the coated drills for this GPT drill design. The general information about coating deposition details can be found in literature source Audy et al [20], and as such it is not repeated in this paper. It however, needs to be noted that the coatings produced for testing had their thickness up to 1micron in order to minimise the residual stresses.

When drilling the Bisalloy 360 steel work-piece material at a constant feed of 0.1mm/rev and a tangential velocity of 12.5m/min the computer assisted force model showed that the predicted thrust and torque values increased with increases in drill diameter D, and web thickness to drill diameter ratio 2W/D. Increases in the helix

Table 1. Reported experimental data on drill point geometrical features of GPT – 6.35 mm diameter – drills from different manufacturers. Adopted from sources [6, 8, 9, 10, 15, and 16] with reference to sources [7, and 17 to 19].

Drill Point		Actual Data reported for 6.35mm diameter GPT drills								
Geometry		[17]	[15]		[6, 7 and 15, 16]			[18]	[19]	[9]
Drill Set		A	B	C	D	E	F	G	H	I
2P	average	119.6°	118.5°	121.2°	120.8°	118.9°	115.2°	116.8°	116.4°	118.3°
[deg]	range	±5.6°	±1.5°	±1.7°	±2°	±3.65°	±2.3°	±3.5°	±4.1°	±0.48°
Ψ	average	124.8°	128°	130.5°	119.2°	129.6°	123.3°	125.3°	125.0°	124°
[deg]	range	±7.3°	±3°	±3.8°	±4.3°	±7.35°	±8.9°	±5.9°	±6.3°	±1.15°
δ_o	average	25.3°	31.8°	25.3°	26.8°	27.1°	26.3°	25.6°	25.9°	28.46°
[deg]	range	±1.1°	±0.75°	±2.05°	±1.6°	±2.35°	±2.15°	±0.65°	±1.35°	±0.37°
Cl_o	average	12.6°	15°	12.9°	12.6°	14.7°	12.3°	13.3°	12.3°	13.3°
[deg]	range	±4.8°	±1°	±3.75°	±3.55°	±3.45°	±3.7°	±4°	±3.15°	±0.57°
2W	average	1.092	1.041	1.117	1.117	1.092	0.965	1.117	1.092	1.115
[mm]	range	±0.165	±0.165	±0.101	±0.127	±0.051	±0.279	±0.101	±0.152	±0.019

Predictive approach

A computer program allowing firstly to calculate the distribution of elemental rake angles along the lip and the chisel edge region and secondly to predict the thrust, torque and power when drilling a Type Bisalloy 360 steel with uncoated and coated – GPT – drills has been used to carry out investigations associated with the experimental drill sets (A to I). The chemical composition of Bisalloy 360 steel plate of 50 mm thickness is given as: 0.18%C, 0.015%P, 1.15%Mn, 0.04%Si, 0.003%S, 0.85%Cr., 0.2%Mo, 0.030%Al, 0.03%Ti and 0.0015%B. It was water quenched at 900°C and subsequently quenched and tempered at 450°C. The relatively high amount of additives namely manganese, chromium and molybdenum combined with subsequent heat treatment created a noticeable hardness ranging from minimum of 39RC (~360HB) to ma-

angle δ_O resulted in lower thrust and torques. Increases in the thrust and decreases in the torque where observed when the point angle 2P was increased. Increases in the chisel edge angle resulted in a small decrease in the torque and a slight increase in the thrust. Some of these findings were published in sources [13 and 14] and as such they are not repeated here. It should be noted that the thrust and torque trends gained from this predictive force model for coated and uncoated GPT drills [8, 13, 14] exhibited qualitative patterns similar to those published in the literature [5 and 6]. This allowed employing the model for studying the effects of elemental rake angle distributions along the lips and chisel edge regions on forces and power in drilling with drills listed earlier in Table 1. The most important results obtained from this study are summarised and discussed in the following section 3.

3. Results and Discussion

Rake Angle Distribution

Figure 2 shows the trends for rake angle distributions along the lip and chisel edge regions for the experimental drill sets A to I. It was made according to information described in paper [13] by Audy (2006). In order to compare the qualitative trends and quantitative differences in the elemental rake angle distributions it was decided to treat the lengths of the lip region and the chisel edge region as a number of individual elements Mi with i ranging from 1 to 25 [6 and 8]. From Figure 2 (a) it appears that for the GPT twist drill design the normal rake angles, γ_n, will vary from negative value(s) of γ_{ni} at i=1 close to the outer chisel edge corner to highly positive value(s) of γ_{ni} at i=25 close to the lip outer corner radius. The chisel edge, pictured in Figure 2 (b), represents series of negative rake angles that cut from the smallest negative γ_{ni} at i=1 close to the drill axis to the highest negative γ_{ni} at i=25 close to the outer chisel edge corner. Comprehensive stresses created by the chisel edge will contribute to the large percentage of the total thrust force in drilling, while the drilling torque will, however, be not as great. The observations associated with the above trends showed a good agreement with the trends published for different drills and different point angles in literature sources [8, 13 and 14].

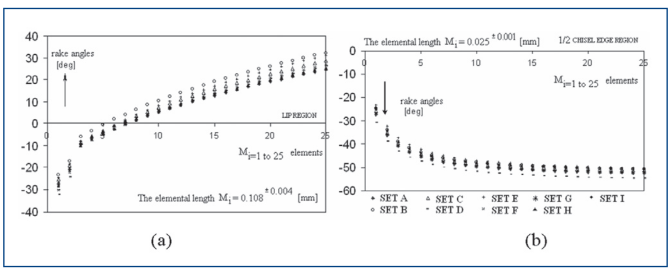

Figure 2. *The elemental rake angle distribution along the lips (a) and the chisel edge (b) of experimental GPT drill sets A to I.*

The comparison of patterns for the nine different experimental drill sets (A to I) shows qualitative similarities and quantitative differences. These differences are listed in Table 2.

From Figure 2 and Table 2 it is evident that the drill set B showed the most favourable rake distributions along the lips with –23.6 degrees at the chisel edge corner to 32 degrees at the lip outer corner. The worst were sets D and G with their degrees ranging from –32.7 to 25.8 and –28.2 to 24.8 respectively. The rake angle distributions along the chisel edge region were the most favourable for sets B and E with their degrees ranging from –24.6 to 50.8 and –24.5 to 50.6 respectively. The worst was the set D with rake angle distributions along the chisel edge ranging from –30.9 to –54.8 degrees.

Drilling Forces and Power

Table 3 shows the drilling thrust and torque forces predicted using the computer software [8, 13] when using the average values of the five main geometrical – drill point – features (i.e. 2W, δ_O, ψ, Cl_O, and 2P) for each individual set as the input data. It should be noted that the predicted thrust and torque values are without dispersion range, because no dispersion ranges in drill point features were included into the input data. It was because the intentions of this paper were to study the effect of coatings for nominally identical, geometrically similar, drills without having batch to batch interference. This was possible by employing the mechanics of cutting approach in predictive force models for drilling with a variety of drill point designs [20]. It involved using database obtained from the orthogonal cutting tests for predicting forces, power and deformation in classical oblique cutting as well as various practical machining operations including drilling. This avoided the needs of running experimental testings and selections of drills with exact geometries for proper comparison of effects of coatings without having any unwanted influence of variability in drill point geometry.

From this table 3 it is evident that the lowest torque and thrust force values were exhibited by the drill set B while the highest values were exhibited by the drill sets G, D and E, which confirmed the finding and conclusions drawn earlier from Table 2.

The grand mean values were used to quantify the overall benefit of coated tools against uncoated tools. The percentage deviations between the thrust and toque forces, for the coated and uncoated tools, were calculated using Equation 4.

$$deviation = \frac{[Th \text{ or } Tq \text{ (coated)} - Th \text{ or } Tq \text{ (uncoated)}]}{Th \text{ or } Tq \text{ (uncoated)}} \ x100 \quad (4)$$

The calculations showed that the coated tools reduced the thrust by about 6.7% and the torque by about 8.4%. Moreover it appears that the differences between the drill point geometrical features of experimental drills (on average) can cause 'unpredictable' drill performance variability in forces and power up to about 10%. It would be interesting to run a similar study to investigate the effect of variability in drill point geometry on thrust and torque individually for each drill set.

Table 2. The values of minimum and maximum rake angles along the lip and chisel edge regions obtained for experimental GPT drill sets (A to I).

Rake angles	Experimental GPT Drill sets								
Values in degrees	A	B	C	D	E	F	G	H	I
LIP (min)	–27.8	–23.6	–21.9	–32.7	–23.1	–30.6	–28.2	–28.6	–28.4
LIP (max)	24.3	32	24.1	25.8	26.5	26.4	24.8	25.3	28.1
CHISEL (min)	–27.4	–24.6	–26.2	–30.9	–24.5	–23.4	–24.9	–24.6	–26.8
CHISEL (max)	–52.6	–50.8	–51.6	–54.8	–50.6	–50.4	–50.9	–50.8	–52.2

Table 3. Thrust and torque values predicted for experimental GPT drill sets (A to I) in coated (CC) and uncoated (UC) conditions.

Technological	Experimental GPT Drill sets								
measures	A	B	C	D	E	F	G	H	I
Thrust [N] – UC	755.3	705.3	774.9	745.5	748.9	701.4	753.4	743.4	738.2
Torque [Nmm] – UC	1621.3	1473.9	1597.6	1608.9	1566.9	1595.7	1632.9	1623.5	1567.6
Thrust [N] – CC	702.9	659.3	726.2	690.7	701.9	647.7	704.4	693.9	687.7
Torque [Nmm] – UC	1490.1	1333.7	1470.6	1473.8	1434.9	1455.4	1501.5	1490.2	1431.7

4. Conclusions

This study revealed that the changes in drill point geometry are responsible for elemental rake angle distributions along the lip and chisel edge region, which in turn influences drilling forces and power. The experiments showed qualitative similarities and quantitative differences in definite patterns of actual rake angle distributions along the lips and chisel edge regions for the nine experimental drill sets investigated in this study. The pattern for lips was one in which the elemental rake angles increased 'on average' from around negative 27 degrees at the chisel edge corner to around positive 26 degrees at the lip outer corner. The pattern for chisel edge was one in which the rake angles ranged 'on average' from around negative 26 degrees close to the drill axis to around negative 52 degrees at the chisel edge corner. Interestingly it was found that the quantitative differences in 2W, δ_O, ψ, Cl_O, and 2P values for 9 sets of GPT drills were responsible for drill performance variability in torque and thrust forces (including the drilling power) up to about 10%. The software prediction employed in this study allowed quantifying the overall benefit of coated tools against uncoated tools by reducing the thrust forces by about 6.7% and the torque by about 8.4%. Referring to the sources [3, 5, 6, 8 to 10, and 19] the variability in as manufactured drill point geometry must be taken in account for example when using experimental forces as a criterion in quality assure of coatings.

Acknowledgement

The author wish to express his appreciation to Professor Armarego from the University of Melbourne for his comments and suggestions within the industrial consortium of the project [8] and development of computer assisted software for force and power predictions. Furthermore the author would like to thank the University of Melbourne and Advanced Engineering Centre for Manufacturing (AECM) for providing a Postgraduate Research Scholarship and to the Department of Mechanical and Manufacturing Engineering for providing all the necessary testing facilities for the research work [8]

References

1. TONSHOFF, H. K. et al. Machining of Holes, Developments in Drilling Technology. *Manufacturing Technology*. Vol. 43, CIRP Annals, 2/1994, p. 551.
2. MORSE, S. A. American Patent. No. 38, USA, 1863, p. 119.
3. MICHELETTI, G. F., LEVI, R. The Effect of Several Parameters on Twist Drill Performance. Published in: *Advances in Machine Tool Design and Research 1967, Part 2, 8th International M.T.D.R. Conference*. Edited by Tobias S. A., Koenigsberger F. Pergamon Press, Great Britain, 1968, pp. 864–865.
4. BERA, S., BHATTACHARYYA, A. On the Determination of Torque and Thrust During Drilling of Ductile Materials. Published in: *Advances in Machine Tool Design and Research 1967, Part 2, 8th International M.T.D.R. Conference*. Edited by Tobias S. A., Koenigsberger F. Pergamon Press, Great Britain, 1968, pp. 879–892.
5. ARMAREGO, E. J. A. *Material Removal Processes – Twist Drills and Drilling Operations*. Manufacturing Science Group, Department of Mechanical and Manufacturing Engineering, The University of Melbourne, 1996.
6. ZHAO, H. *Predictive Models for Forces, Power and Hole Oversize in Drilling Operations*. Ph.D. Thesis. The University of Melbourne, 1994.
7. WRIGHT, J. D. *A Study of the Conventional Drill Point Geometry Its Generation, Variability and Effect on Forces*. Ph.D. Thesis, University of Melbourne, 1981.
8. AUDY, J. *The Influence of Hard Coatings on the Performance of Twist Drills*. Thesis for Master of Engineering Science in Research, The University of Melbourne, June 2002.
9. AUDY, J., AUDY, K., DOYLE, E. D. Estimation of Sources of Variations and the Toleration Ranges in the Manufactured Point Geometry of General Purpose Twist Drills, *2nd Asia-Pacific Forum on Precision Surface Finishing and Deburring Technology, PSFDT, Seoul. Korea, July 2002*, pp. 194–202.
10. AUDY, J. Experimental Study of Deviations in Geometrical Features of General Purpose Twist Drills. *Manufacturing Engineering (Journal)*. May 2007, No. 2, Vol. VI,
11. SUBRAMANIAN, C., STRAFFORD, K. N. Review of Multi-component and Multi-layer Coatings for Tribological Applications, *Wear*. 1993, 165, pp. 95–95.
12. AUDY, J. *Assessment of Metal Machining Process Parameters and the Development of Adaptive Control*. Ph.D. Thesis, The University of South Australia, June 1996.
13. AUDY, J. Exploring the Role of Computer Modelling and Image Analysis in Assessing Drill Design Features and Performance. *Journal of Manufacturing Engineering, (Strojnicky časopis)*. December 2006, 57, Vol. 6, pp. 322–338.
14. AUDY, J. A Study of the Effect of Variations in Drill Point Geometry on the Experimental and Predicted Cutting Forces Generated by Uncoated and Coated Drills. *Materials Engineering (Journal)*, 2006, Vol. 13, No. 4, pp. 8–15. WWW informations-http://fstroj.utc.sk/journal-mi. ISSN 1335-0803.
15. ARMAREGO, E. J. A., WRIGHT, J. D. Manufactured General Purpose Twist Drill Point Geometry-I and II. Preliminary Appraisal of Variations. *J. Engg*. Prod. Vol. 2, No. 1, pp. 1–19, India, Dec. 1977, p. 2.
16. ARMAREGO, E. J. A., WRIGHT, J. D. Manufactured General Purpose Twist Drill Point Geometry-II. Sources of Variations and Process Capability Estimates. *J. Engg*. Prod. Vol. 2, No. 2, pp. 59–76, India, Dec. 1977.
17. HARIS, D. *Some Aspects of Machining with Twist Drills*. M. Eng. Sc. Thesis, University of Melbourne, 1974.
18. ABD-EL-SAYED, M. L. *Geometrical and Force Variability of as Brought Twist Drills*. M. Eng. Sc. Thesis, University of Melbourne, 1977.
19. MALKIEWICZ, H. *An Investigation of Geometric Variables Affecting the Drilling Process*. M. Eng. Sc. Thesis, University of Melbourne, 1973.
20. AUDY, J. et al. Performance Evaluation of Cathodic arc Evaporated (CAE) TiAlCrN Coated General Purpose Twist Drills When Dry Machining Grey Cast Iron. In *5th International Conference on Behaviour of Materials in Machining, Chester UK*. IoM Communications Ltd, 2002, p. 140.

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