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A STUDY OF COATINGS ON EXPERIMENTAL THRUST AND TORQUE IN DRILLING

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Abstract:
The paper presents results of a systematic study of tool coatings on drilling performance of twist drills. It looks at data reported in open literature sources as well as the author's own experimental results. The findings are discussed in terms of cutting forces, namely thrust, torque (and power) in drilling and advantages of advanced surface coatings from a competitive point of view. Moreover the searched literature did not provide any empirical thrust and torque equations for coated drills. An alternative way to solve this problem has been offered through analytical approach based on the mechanics of cutting analysis, and required to carry out the fundamental approach to the effects of coating in machining which is considered further in this paper with reference to cathodic arc evaporated TiN, TiCN and TiAlN coated general purpose twist drills when dry machining a Type Bisalloy 360 steel work-material.
Key Words:
Drills, Surface Coatings, Thrust, Torque, Drilling

1. INTRODUCTION

The thrust force, torque and power in drilling with general purpose (standard) drill designs have been reported [1 to 3, 7, 10, 12, 15] to be dependent on drill point geometrical features, drill-coating-workpiece material combinations and cutting conditions. The literature survey relating experimental drilling force and power trends with changes in the drill geometrical variables and cutting conditions have shown that the qualitative trends could be considered to be similar for a wide range of tool-workpiece material combinations, while quantitative data vary from one tool-workpiece material combination to another.

Well-accepted qualitative trends are that speed has negligible effect on the drilling forces, while increases in feed cause the drilling forces to increase linearly. Pramanik [13], for example reported that thrust, *Th,* and torque, *Tq*, did not change much while drilling a Type 1020 steel work-material under various speeds ranging from 12.2 to 36m/min. Similar effect has been reported by Armarego [1]. Information has been found in the literature [1, 3 and 13] showing that drilling forces increase with both drill diameter, *D,* and the web thickness to drill diameter ratio, *2W/D*, and decrease with increases in both the helix angle, δ_o, and chisel edge angle, ψ. Armarego [1] further showed that the increases in point angle, *2P*, decreased torque and increased thrust. Not significant effect of clearance angle, Cl_o, on drilling forces and power has been reported by many researchers [1, 3 and 13] and is well accepted.

A number of sources indicated that most quantitative information on forces and power are from the uncoated HSS general purpose drill design [1, 3 to 5, and 10 to 13], while less has been published for TiN coated drills [4, 5, 11 and 12] and only a little information has been found for the Ti(AL, N) coatings [5], and almost no relevant data has been found for other coatings and drill designs.

2. REPORTED DATA ON MACHINING PERFORMANCE OF COATED AND UNCOATED DRILLS

Table 1 shows various experimental thrust, torque and power data for uncoated and coated general purpose twist drills for different cutting conditions with reference to five different papers [5, 7, 11 and 12].

Table 1. Reported performance measures of uncoated and coated drills examined at different cutting conditions [5, 7, 11 and 12]

Symbols: UC and ( ) data reported for uncoated drills, ( )* data reported for TiN coated drills, ( )' data reported for Ti (Al)N coated drills, I. the initial, II steady and III final stage of tool wear. DIN34 is equal to AISI 4340 steel (Cr-Ni-Mo6) type, DINX210 is equal to AISI D3 Steel (CrW12) type, UNI C 40 is 38NiCr2Mo4 steel normalised to 750Nmm^{-2}

CUTTING TOOL DRILL								WORK MATERIAL		MACHINING CONDITIONS			PERFORMANCE MEASURES			REF
Tool substrate material	Diameter [mm]	Geometry	Coating	Hardness x10^3	Thickness of the coating [μm]	Coating unit used	Coating method	TYPE	Hardness	SPEED [m/min]	FEED [mm/rev]	Hole Depth [mm]	THRUST [KN]	TORQUE [Nm]	Work-material removed [cm^3]	
AISI	6.35	-	TiN	-	1.5	PVD	Reactive				0.08	-	1.3 (0.75)*	2.2 (1.2)*	57 (447)*	
M7							Ion Plating	AISI	32	28	0.11	-	1.6 (0.9)*	3.2 (2)*	12 (398)*	
HSS	6.35	-	UC	-	-	-	-	4340	[RC]		0.15	-	2.1 (1.3)*	3.7 (2.4)*	1.6 (440)*	[12]
uncoated drills versus coated drills										46	0.11	-	1.7 (0.8)*	2.7 (2.1)*	0 (48)*	
OTHER DATA	(1) Reliability analysis was made using Weibull statistical distribution for the tool-life of five drills in total tested individually for each new cutting condition. (2) There was no mention about a type and accuracy of measuring technique employed. (3) Torque and thrust data was monitored from only new drills (P I.) enabling comparison for tool life/wear distribution (P II. -& P III).															
AISI M2	6	-	TiN	2HV$_{1N}$	-	PVD	-	AISI	190	22.6	0.254	22.25	I. 2.2 (2.2)*	I. 20 (35)*	- -	
HSS	6	-	UC	58HRC	-	-	-	1045 S	[HB]	const.	const.	const.	III. 6 (6)*	III. 50 (50)	35 (133)*	[7]
OTHER DATA	(1) The four uncoated and one coated drill were tested in total, reliability analysis was not made. (2) Strain gauge transducers were used to record thrust and torque signals. (3) Nothing was mentioned on the accuracy and reliability of the measuring technique used.															

Tool substrate material	Diameter [mm]	Geometry	Coating	hardness [HB]	Thickness of the coating [μm]	Coating unit used	Coating method	TYPE	Hardness	SPEED [m/min]	FEED [mm/rev]	Hole Depth [mm]	Tool-flank wear [μm]	Power [%]	Work-material removed [cm^3]	REF
	6	-	TiN	-	-	PVD	Ion Plating	Low carbon					~100	-	(77)*	
DIN 34	6	-	Ti(Al)N	-	-	PVD	Ion Plating	steel	-	35	0.2	20	~100	-	(158)'	
	6	-	UC	310HB	-	NO	-						~300	-	1	[5]
	6	-	TiN	-	-	PVD	Ion Plating	Low carbon					-	I.-II. (20-30)*	(6 - 85)*	
X-210	6	-	Ti(Al)N	-	-	PVD	Ion Plating	steel	-	20	0,2	15	-	I.-II. (20-30)'	(6 - 211)'	
	6	-	UC	-	-	-	-						-	I.-II. 35-40	1.6 - 8.2	
OTHER DATA	(1) The mean and standard deviations of tool/life were not calculated. (2) The type and accuracy of cutting force measurement system was not reported															

Tool substrate material	Diameter [mm]	Geometry	Coating	hardness [HB]	Thickness of the coating [μm]	Coating unit used	Coating method	TYPE	Hardness	SPEED [m/min]	FEED [mm/rev]	Hole depth [mm]	Drill-life [min.]	Drilling cost [Lit./min.]	Work-material removed [cm^3]	REF
AISI	8.5	-	TiN	-	-	PVD	-			23			55, (79)*	800, (850)*	427, (676)*	
M 2								UNI C 40	normalised	33	0.18	25	30, (50)*	800, (850)*	356, (619)*	[11]
HSS	8.5	-	UC	-	-	NO	-			50			5, (25)*	1600, (1300)*	64, (498)*	
OTHER DATA	(1) The mean and standard deviations of tool/life were calculated and reported. (2) Thrust and torque data were not monitored.															

Additional information is provided in the same Table 1 with reference to source [11], about work-material removed to drill generated power, drill-life and drilling cost/expenses for TiN (PVD) coated drills and uncoated drills. The effect of coatings on the thrust and torque appear to be quite often studied as indicated by some research workers [2, 5, 7 to 9, and 11 and 12]. A relatively large variability in the thrust and torque quantities has been observed, for example, in the paper [12], for a set of nominally identical – uncoated and TiN coated - twist drills tested at the same drilling conditions. The first and second set of TiN coated drills was able to reduce the thrust by a factor of 1.7 (1.3kN/0.75kN) and 1.8 (1.6kN/0.9kN) and the torque by a factor of 1.8 (2.2Nm/1.2Nm) and 1.6 (3.2Nm/2Nm), respectively in comparison with the uncoated tools. After plotting the maximum thrust and maximum torque as a function of the number of holes drilled, the pattern of thrust and torque produced by the TiN coated drills were much smaller than those produced by the uncoated drills. What however was not mentioned in the paper [12] was the relatively high scatter in the thrust and torque data. Another source [19] also showed a relatively large variability in drilling forces for nominally identical drills and tried to explain this occurrence due to variances in the manufactured drill point geometry and differences in coatings. However, it did not provide any quantitative evidence about drill point geometrical features nor about additional data relating the coating conditions. Armarego and Wright [14 and 15], for example, stated that if we reduce the geometrical variability in the 'as manufactured' drills we can have a same mean value of the thrust and a same mean value of the torque for all drills in the batch.

Subramanian *et al* [7] examined drilling forces of TiN (PVD) coated and uncoated – 6mm diameter – general purpose - twist drills made from AISI M2 HSS tool material in drilling AISI 1045S steel (190HB) at drilling speed of 1200rpm, feed rate of 0.254 mm/rev and depth of hole of 22.25mm. The authors tested five drills in total - four uncoated and one TiN coated until their total failure. They found that the TiN coated - M2 HSS - drill outperformed the drill-life of the uncoated M2 HSS drills by at least four times (~200holes/~50holes). In moderate – steady state wear region – up to about 30 holes for the uncoated drills and up to about 180 holes for the TiN coated drill the force patterns appeared to have qualitatively similar linear increases. The quantitative comparison of force results in the range of 0 to 30 holes drilled showed that both the uncoated and coated drills produced similar thrust(s), ~2000N at the beginning and ~2500N after drilling of ~30 holes. For the same range of holes drilled the TiN coated drill produced torque values higher by a factor of 1.6 (35Nm/22Nm) in comparison with the uncoated drills. It is evident from the above study that the authors compared the performance of only one coated drill against four uncoated drills, which is not enough to make any scientific comments. To study the effect of coatings on thrust and torque in drilling it seems to be necessary to use either more drills from a same batch for testing at one or more cutting conditions, as reported for example in literature [3, 12, 13, 16].

Figure 1 (a and b) shows a relationship of 'as measured' drilling thrust and torque values on the drilling speed and feed [12] for the uncoated and TiN coated twist drills.

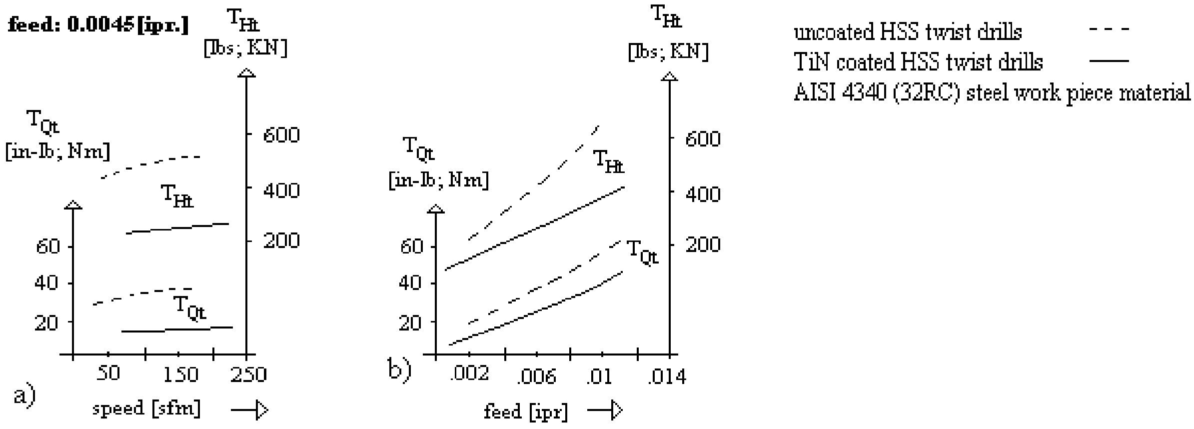

Figure 1. Some 'as measured' effects of thrust T_{Ht} and torque T_{Qt} on the drilling speed and feed [12]

The speed has been found to have an insignificant effect on both the thrust and torque values, Figure 1 (a), while the feed has been reported to have a linear relationship with T_{Ht} and T_{Qt} values, Figure 1 (b), as described also in the literature [1].

The above survey showed that some researchers preferred to compare the thrust and torque of the coated drills with those from the uncoated drills to show quantitatively benefit, if any, of their coatings against uncoated tools. Because of this a short literature review has been carried out to summarise the most important results that have been reported on the thrust, torque and power for the uncoated drills.

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 [17], and are shown in Tables 2 and 3 for the helix angle and the point angle, respectively for the uncoated – twist design – drills of different diameters ranging from 0.15 to 1 inch.

Table 2. Effects of a 10° increase in the helix angle (from 25° to 35°) on the percentage decrease in the experimental thrust and torque values of uncoated drills [17]

Drill Diameter	Work-piece material	Percentage decrease [%]		Note
1 inch	Cast-iron	T_h by 12-13	T_q by 10-12	Benedict B.W. and Hershey A.V.
5/32 inch	Mild steel	T_h by 15-25	T_q by 8-16	Boston O.V. and Gilbert W.W.
1 inch	Cast iron	T_h by 30	T_q by 20	Galloway D.F. and Morton I.S.
1 inch	Axle steel	T_h by 20	T_q by 20	Galloway D.F. and Morton I.S.
9/16 inch	Alloy steel	T_h by 10-20	T_q by 5-7	Curtis V.C.
1 inch	Cast iron	T_h by 20	Not-reported	Galloway D.F.
1 inch	Mild steel	T_h by 50	Not-reported	Galloway D.F.
½ inch	Alloy steel	T_h by 8	T_q by 6	Shaw M.C. and Oxford C.J. Jr.

Table 3. Effects of a 40° increase of the point angle (from 80° to 120°) on the percentage increase and decrease in the experimental thrust and torque values, respectively [17]

Drill Diameter	Work-piece material	Percentage		NOTE
		Increases[%]	Decreases [%]	
1 inch	Cast-iron	T_h by 43	T_q by ~16	Benedict B.W. and Lukens W.P.
5/8 inch	Cast-iron	T_h by 36	T_q by ~8	Benedict B.W. and Lukens W.P.
5/8 inch	Steel	T_h by 18	T_q by ~16	Galloway D.F.
5/8 inch	Cast-iron	T_h by 42	T_q by ~14	Kowstubhan M.V. and Philip P.K.

Table 2 shows that a 10° increase in the helix angle from 25° to 35° decreased both thrust and torque values of the uncoated drills, while Table 3 shows that a 40° increase in the point angle from 80° to 120° increased the thrust but decreased the torque values of the uncoated drills. Literature [17] reported no effect of the clearance angle on the cutting forces. Similar information has been published in literature [1, 3 and 13].

Micheletti and Levi [17] examined the thrust and torque values produced by uncoated - 12mm diameter and general purpose twist design – drills in drilling grey cast iron and mild steel work-piece materials under dry and mineral oil coolant conditions, respectively, at drilling speed of 806rpm and various feeds ranging from 0.075 to 2mm/rev. The authors investigated 14 drills in total. They found that when drilling steel work-piece material the thrust and torque increased linearly 'on average' from a minimum ~1440N (std 380N) and 4430Nmm (std 410Nmm) to a maximum ~3960N (std 110N) and 10790Nmm (std 860Nmm) for a feed range from a minimum 0.075 to a maximum 0.2mm/rev, respectively. When drilling the cast-iron work-piece material, but at higher feeds ranging from a minimum of 0.125 to a maximum of 0.3mm/rev, the thrust and torque increased linearly 'on average' from a minimum ~1680N (std 290N) and 5260Nmm (std 250Nmm) to a maximum ~3480N (std 680N) and 10400Nmm (std 490Nmm), respectively.

From the above it is evident that there are some experimental results for providing sufficient qualitative and quantitative information about the thrust, torque and power in drilling for the uncoated drills [1, 3 to 5, and 10 to 13], but only a little has been published for the coated drills [4, 5, 12 and 13]. Although some quantitative prediction is possible for several drill point geometrical designs [1, 3, 13, 16] for the uncoated drills and S1214 steel work piece material, no published information has been found for the coated drills and different work piece material combinations.

Some earlier research work [18] 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 [1 and 3] for the power, P, thrust, T_h, and torque, T_q, and are shown by Equations 1, 2 and 3, respectively.

$$P = C_1.T_q.n_{(=rpm)} + T_h.f_{(=feed)}.n = C_1.T_q.n \quad (1)$$

$$T_h = C_2.f^{x1}.D^{y1} \quad (2)$$

$$T_q = C_3.f^{x2}.D^{y2} \quad (3)$$

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 [1 and 3], 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 [1, and 14 to 16], Wright [20] and Zhao [3] 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. Moreover the searched literature did not provide any empirical thrust and torque equations for coated drills.

An alternative way to solve this problem has been offered through analytical approach based on the mechanics of cutting analysis, and required to carry out the fundamental approach to the effects of coating in machining which is considered further in the following Section.

3. FUNDAMENTAL APPROACH TO THE EFFECTS OF COATINGS IN MACHINING

A literature search has shown that there have been extremely few investigations of the effects of coatings on the cutting process and machining performance measures based on the 'fundamental' or mechanics of cutting approach. This is in stark contrast to the corresponding research investigations of machining with uncoated cutting tools, where this 'fundamental' approach represents a major approach which has led to predictive force, torque and power models for the wide spectrum of complex practical machining operations such as turning, drilling and milling [21 and 22]. The first investigations based on the 'fundamental' approach considered the effect of the popular TiN coating and HSS and carbide substrates on the tool-chip friction, forces, power on the cutting process as a whole in the 'classical' orthogonal cutting operation. Later studies considered TiN and TiCN as well as the effect of TiN on the three force component trends and magnitudes in turning operations with circular corner radius plane faced lathe tools [23 to 26].

Effect of Coatings on Orthogonal Cutting Process

Armarego, Verezub andf Samaranayake [23] reported that the TiN and TiCN coatings on HSS tools resulted in similar quantitative drops in F_{Pt} and F_{Qt} as well as β of about 13%, 50% and 30% 'on average', respectively, the deposition of these two coatings on a steel cutting grade of carbide tool material results in no statistically significant differences in the forces, power and friction angle as shown in Table 4 [23]. Thus, the TiN and TiCN coatings have been shown to be effective in reducing the forces, power and tool-chip friction angle when applied to a HSS substrate but not effective when deposited on a steel cutting grade of carbide when machining S1214 free machining steel.

Table 4. Comparison of Orthogonal Cutting Force Components and Friction Angles for Coated and Uncoated HSS (M2) and Carbide (DX-25 - Japan) Tools Machining Different Work Materials; After source [23].

Tool / Work piece Combination	Power Force Reduction (F_{Pt})	Thrust Force Reduction (F_{Qt})	Friction Angle Reduction (β)
TiN HSS versus Uncoated HSS machining S1214	20%	50%	30%
TiCN HSS versus Uncoated HSS machining S1214	12.7%	48.1%	29.2%
TiN Carbide versus Uncoated Carbide machining S1214	Not statistically significant	Not statistically significant	Not statistically significant
TiCN Carbide versus Uncoated Carbide machining S1214	Not statistically significant	Not statistically significant	Not statistically significant
TiCN Carbide versus Uncoated Carbide machining 1020	Not statistically significant	Not statistically significant	Not statistically significant

Audy [27 and 28] run comprehensive 'classical' orthogonal cutting tests over a wide range of cut thickness t, rake angle γ and cutting speeds V for TiN, TiAlN and TiCN coated and uncoated HSS substrates machining a Bisalloy 360 steel work piece material. The two force components F_{Pt} and F_{Qt} as well as the chip length ratio r_l have been measured for each cut from which it has been possible to evaluate the edge forces and basic cutting quantities (*i.e.* the shear angle ϕ, tool chip friction angle β, and shear stress τ in the shear zone) based on the modified mechanics of cutting analysis [27]. This study showed that when comparing the effects of different coatings, one with another, there were no qualitative or quantitative differences between the three coatings i.e. their performance measures, namely forces, power, friction angle, shear angle, shear stress and chip length ratio values were statistically equal at 95% and greater confidence level. Moreover the group of coated tools reduced F_{Pt} by 14.5%, F_{Qt} by 24.9%, β by 16.4% and drilling power by 14.5%. The greatest reduction was in thrust force F_{Qt} not in the power force F_{Pt}.

Development of Predictive databases for the Coated and Uncoated Tools

It has been confirmed by the orthogonal test results that the orthogonal cutting tests can show the effects of coatings for a given work-piece material (Bisalloy 360 grade steel) and tool substrate (M35 HSS) material. Moreover, the following databases, shown in Tables 5 and 6 were found from the orthogonal cutting tests for each particular tool-work piece material combination.

Table 5. Database for continuous chip formation of uncoated and coated HSS M35 tool material and a Bisalloy 360 steel work-material.

Tool Conditions	Continuous Chip Formation $r_l, \beta, \tau, C_{ep}, C_{eq}$	Tool Conditions	Continuous Chip Formation $r_l, \beta, \tau, C_{ep}, C_{eq}$
Uncoated Tools	$r_l = 0.506 + 0.0045\gamma_n$ $\beta = 29.129 + 0.71\gamma_n$ $\tau = 970.35 - 11.05V_w - 12.807\gamma_n$ $C_{ep} = 6.15V_w$; $C_{eq} = 6.006V_w$	Coated Tools	$r_l = 0.387 + 0.0022V_w + 0.0068\gamma_n$ $\beta = 28.5 - 0.141439V_w + 0.361\gamma_n$ $\tau = 619.286 + 1.964V_w - 3.384\alpha\gamma_n$ C_{ep}=50.96 and C_{eq}=30.256+0.3966V_w

Note: γ_n [degree]; t [mm], V_w [m/min]; β [degree]; τ [N/mm²]; C_{ep} [N/mm]; C_{eq} [N/mm]

Table 6. Database for discontinuous chip formation of uncoated and coated HSS M35 tools and a Bisalloy 360 Grade steel work-material.

Tool Conditions	Discontinuous Cutting (C_P, C_Q)
Uncoated	$C_p = 1.016x10^7 . t^{0.602} . \gamma_n^{(-1.767)}$ $C_q = 14.26 . t^{0.7249} . \gamma_n^{(0.945)} . V_w^{0.45}$
Coated tools (COMBINED DATABASE)	$C_P = 4.225x10^8 . t^{0.402} . \gamma_n^{(-2.682)}$ $C_q = 30.9 . t^{0.445} . \gamma_n^{0.709} . V_w^{0.157}$

Note: C_P and C_q represent F_{Pt}/b [N/mm] and F_{Qt}/b [N/mm], respectively, γ_n [degree]; V_w [m/min]; β [degree]; τ [N/mm²]

The equations for databases of the coated and uncoated tools are tabulated in Table 5 (for continuous chip formation relating r_l, β, τ, C_{ep} and C_{eq} variables to γ_n and possibly V_w); and in Table 6 (for discontinuous chip formation relating C_p and C_q variables to t, γ_n and possibly V_w). Since the earlier orthogonal cutting trends and statistical test results showed that the basic derived cutting quantities were not affected by the different coatings, the Tables 5 and 6 present combined database for all the three - TiN, Ti(Al,N) and Ti(C,N) - coated Type M35 HSS tools. Moreover, the database equations indicate that in some cases the effects of tool rake angles (γ_n) and cutting velocity (V_w) were not always significant for each basic cutting quantity. The databases were incorporated into a computer software described in sources [28 and 29] and used for running simulations that allowed establishment of empirical-type equations for twist drills.

Input Data and Establishment of Empirical Type Predictive Equations

The computer program for the thrust, torque and power prediction when drilling with the coated and uncoated GP-twist drills has been developed [28] and was presented in source [29]. An outline of this computer flow chart, including references to relevant equations, can be found in source [29] where the main inputs and steps required for predicting the thrust, torque and power for a particular drill or drilling conditions are given. The main input data include *firstly* the drill geometry (D, 2W, δ_o, ψ, Cl_o, 2P), *secondly* the drilling conditions (f-feed, n-revolutions per unit time), *thirdly* the databases (for the basic cutting quantities τ, r_l, β and coefficients C_{ep}, C_{eq} and C_p, C_q) for different tool-coating-work piece material combination – specified in the early stage of the software program.

The input values involved D = 6mm, 8mm and 12mm; 2W/D = 0.12, 0.16, and 0.20; ψ = 100°, 120° and 140°; 2P = 100°, 120° and 140°; δ_o = 10°, 25° and 40°, Cl_o=15°, f = 0.1, 0.2 and 0.3 mm/rev. Thus for the GP-twist drill force model the six variables (D, 2W/D, ψ, 2P, δ_o and f) were considered giving the total 3^6 or 729 combinations of thrust and torque values individually for a particular database used.

The empirical type equations are shown below:

Uncoated M35 HSS GP drills and Bisalloy 360 steel work piece material

$$Th = 101.892 f^{0.67}.D^{0.967}.(2W/D)^{0.379}.2P^{0.397}.\psi^{0.265}.\delta_o^{-0.233} \quad (4)$$

$$Tq = 28010.23.f^{0.732}.D^{2.004}.(2W/D)^{0.202}.2P^{-0..388}.\psi^{-0.282}.\delta_o^{-0.427} \quad (5)$$

Coated M35 HSS GP drills and Bisalloy 360 steel work piece material

$$Th = 56.625 f^{0.519}.D^{0.971}.(2W/D)^{0.461}.2P^{0.308}.\psi^{0.405}.\delta_o^{-0.216} \quad (6)$$

$$Tq = 22223.13.f^{0.692}.D^{2.0037}.(2W/D)^{0.159}.2P^{-0..383}.\psi^{-0.297}.\delta_o^{-0.366} \quad (7)$$

Quantitative Study of Effects of the three Coatings on the Predicted Thrust and Torque values Produced by the GP-Twist Drills

The quantitative reductions in the predicted thrust and the torque values of the combined coatings against a Type M35 uncoated HSS drills were also estimated in terms of the percentage deviation for 3^6 combinations of the thrust and the torque values for the GP-twist drills using the following relationship (8).

%Deviation E =100 x {Th or Tq (coated drills) – Th or Tq (uncoated drills)} /
Th or Tq (uncoated drills) (8)

For comparison purposes the coated drills were treated as one group. This followed because it was statistically shown earlier that in orthogonal cutting tests all the quantities – the forces (F_{pt}/b and F_{qt}/b), the machining power (P), and the basic cutting quantities r_l, ϕ, β and τ for the three different coatings – TiN, Ti(Al, N) and Ti(C, N) – were statistically equal at the 95% and higher confidence level.

The resulting average percentage deviations and the distributions are shown in Figure 2 in details (a) and (b), respectively, in the form of histograms individually for the thrust and for the torque.

The histograms in Figure 2 showed that 'on average' the coated GP-twist drills reduced the thrust by ~15.9% and the torque by ~17.3%.

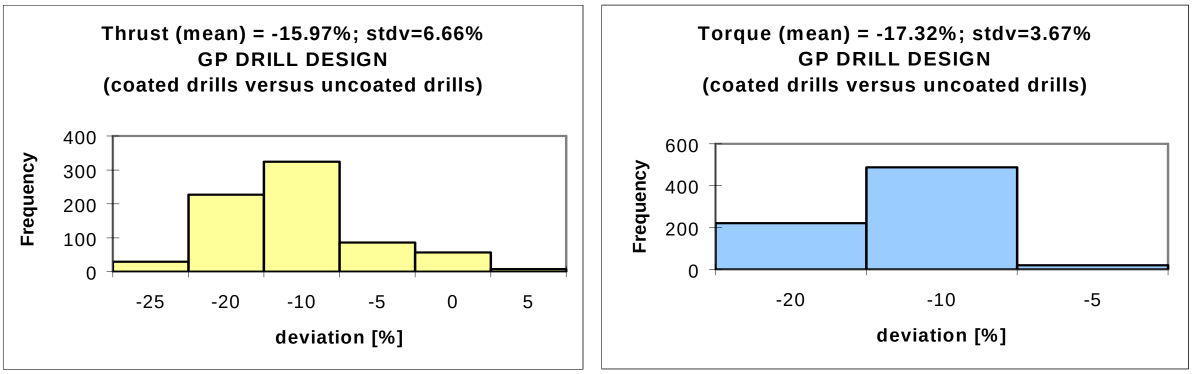

Figure 2. Histograms of percentage deviations between the predicted values of the thrust and the torque for the coated and the uncoated drills for each individual cut. Negative values indicate lower levels for the coated drills.

4. CONCLUSIONS

The most important conclusions that can be drawn from this study are summarised as follows:

- When comparing the effect of different coatings, one with another, the quantitative differences in various performance measures namely forces, power, friction angle, shear angle, shear stress and chip length ratio values were statistically equal at 95% C. L, *i.e.* there were no qualitative or quantitative differences between the three coatings.
- The group of coated tools reduced F_{pt} by 14.5%, F_{qt} by 24.9%, β by 16.4%, ϕ by 11% and P by14.5% in comparison with the uncoated tools. The highest reduction was in the thrust force F_{qt} not in the power force F_{pt}.
- Databases for the force predictive models in drilling were established and used for prediction purposes when incorporated into adequate force predictive models. This allowed to determine the empirical-type equations for the thrust, torque and power prediction for the coated and uncoated drills when drilling Bisalloy 360 steel work piece material.
- Comparison of the predicted total thrusts and the total torques has shown that the coated GP-twist drills reduced the thrust by ~15.9% and the torque by ~17.3%.

Overall Conclusions on Effect of Coatings

- No qualitative or quantitative differences in the chip formation, cutting process as a whole, mechanics of cutting analyses, forces, power and tool-life have been found between the three popular and modern coatings, namely, TiN, Ti(C, N) and Ti(Al, N).
- The coated HSS tools improved the machining performance compared to uncoated tools by reducing the forces and power.

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