An Investigation in Drilling 1020 Steel Using Minimum Quantity Lubrication

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Abstract

The current trend in the metal-cutting industry is to find ways to completely eliminate or drastically reduce cutting fluid use in most machining operations. Recent advances in tool and machine technology have made it possible to perform some machining without cutting fluid use or with minimum-quantity lubrication (MQL). Drilling takes a key position in the realization of dry or MQL machining. Economical mass machining of common metals (i.e., tool and construction- grade steels) requires knowledge of the work piece characteristics as well as the optimal machining conditions. In this study we investigate the effects of using MQL and flood cooling in drilling 1020 steel using HSS tools with different coatings and geometries. The treatments selected for MQL in this study are commonly used by industry under flood cooling for these materials. A full factorial experiment is conducted and regression models for both surface finish and hole size are generated. The results show a definite increase in tool life and better or acceptable surface quality and size of holes drilled when using MQL.

Keywords: Minimum Quantity Lubrication, MQL, Mist Cooling, 1020 Steel, Drilling.

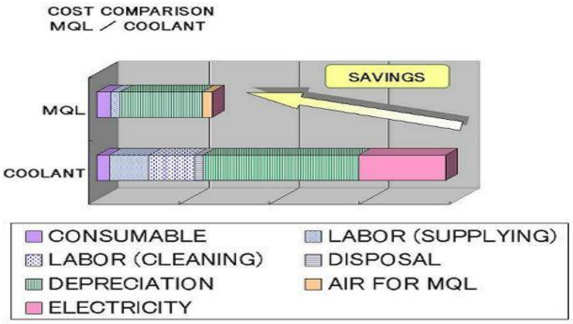
INTRODUCTION

The current trend in the metal-cutting industry is to find ways to completely eliminate or drastically reduce cutting fluid use in most machining operations. In fact, an increasing number of countries view the use of coolants in machining ferrous and nonferrous components as undesirable for economical, health, and environmental reasons. Heins (1997) reported that coolant and coolant management costs are between 7.5% and 17% of the total manufacturing cost compared to only 4% for cutting tools. Ngoi & Sreejith (2000)stated that lubrication represents 16-20% of the product cost. Quaile (2000) reported that the coolant cost is approximately 15 percent of the life-cycle operational cost of a machining process. Chalmers (1999) reported that more than 100 million gallons of metalworking fluids are used in the U.S. each year and that 1.2 million employees are exposed to them and to their potential health hazards. The savings in cutting fluid and other related costs would be very significant if micro-lubrication (Minimum-Quantity Lubrication or MQL) is adopted, particularly in common machining operations (i.e., milling and drilling) which are currently conducted with flood application.

MINIMUM QUANTITY LUBRICATION

Minimum-quantity lubrication administers traditional metal removal fluids (oils and water miscible) at very low levels (.02 gallons/min or lower). These are once-through systems; there is no need to collect the applied fluid. MQL systems are considerably more cost-effective than flood application systems. McCabe (2002) reported that according to automakers, the annual operating cost of a flood-application-based machining system is estimated to be between $350,000 and $1,000,000. The cost for an MQL system is between $100,000 and $300,000. In the same study, he reported that the machining cost was reduced by 45% when minimum-quantity lubrication was used as compared to flood cooling in drilling aluminum. Horkos (2006) compared the cost of flood coolant versus MQL performed by a cutting tool manufacturer. As depicted in figure 1, a sharp cost reduction using MQL is realized compared to flood cooling.

Figure 1: Cost Comparison of Coolant and MQL (Source: Horkos Corp)



The challenge for machining using MQL is to provide substitutes for the four critical functions of flood cooling. While it is generally thought that MQL systems can supply excellent lubrication, results on acceptable cooling are not conclusive. Moreover recent advances in tool and machine technology have made it possible to perform some machining without cutting fluid use or with Minimum-Quantity Lubrication (MQL). Drilling takes a key position in the realization of some dry machining. The main problem in dry drilling of steels is the reliable removal of the chips from the drilled hole. Another problem is the tendency of the drill to jam in the hole if its diameter expands too much as a result of high tool temperature as reported by Lung, Klocke, Eisenblatter & Gerschwiler (1995).

The integration of hard coatings with cutting tool substrate materials has been found out to be the most successful innovation in improving wear resistance for various tools as reported by Quinto (1996)&Sahoo,Chattopadhyay A.K& Chattopadhyay A. B. (2002). McCabe (2001)reported that coating drills with a variety of standard products raised the hole-producing capability of twist drills from 25 to approximately 225 holes when cutting aluminum. The tool geometry and cutting conditions were further optimized, which raised its drilling capacity to 5000 holes. Nouari,List, Girot & Coupard (2003) reported that with large cutting speeds and low feed; good surface quality and dimensional accuracy can be obtained with optimum drill geometry when machining aluminum under dry conditions. They also reported that tool life was increased significantly when optimized drill geometry was coated with a diamond film in the same experiment.

Klocke & Eisenblatter (1996) reported that dry drilling was not possible due to the high tendency of the aluminum to adhere to the tool. It was found that even a minimum quantity of cutting fluid that is fed towards the contact zone suffices to achieve a drilling operation that meets the stipulated quality characteristics. Braga(2003) conducted a study where the objective was to test the MQL technique in the drilling of aluminum silicon alloy with a solid carbide drill. They showed that drilling aluminum can be successfully achieved with MQL. One concern of MQL is that the metal working fluids mist themselves are potential health hazards. The standard advisory committee convened by the United States Occupational Health and Safety Administration (OSHA) in 1997 found that exposure to metalworking fluids may result in asthma, hypersensitivity pneumonitis, other respiratory disorders, dermatitis and other health conditions including cancer.

The costs associated with procurement, filtration, separation, disposal and records keeping for coolant are increasing. Already the costs for disposal of coolant are higher than the initial cost of the coolant, and they are still rising. Even stricter regulations are under consideration for coolant usage, disposal and worker protection. As a result, coolant in wet machining operations is a crucial economic issue. An alternative, machining with "Minimum Quantity Lubricant," or MQL, is gaining acceptance as a cost-saving and a potential environmentally friendly option in place of some wet machining processes.

EXPERIMENTAL TESTS

RESEARCH OBJECTIVES

There is a definite need to understand the effects of MQL in all metalworking processes. This study aims to study the effects of feed, speed, and cutting when drilling a 1-inch deep hole into a block of 1020 steel.The drilling is performed on a CNC Bridgeport milling machine under Minimum Quantity Lubrication.

The objectives of this research are:

- Evaluate the effects of cutting speed and feed rate on surface finish, hole size and tool life in drilling 1020 steel under minimum quantity lubrication.
- Make recommendation of feasible solutions based on the study results.

DESIGN OF EXPERIMENTS

This study was conducted using a randomized factorial design as shown in

Table 1. The two independent variables were cutting speed and feed rate. The depth of the hole was 1” throughout for all drilling operations. The two dependent variables were surface finish and hole size (inner diameter, I.D.). The cutting speed and feed rate are reported in square feet per minute, (SFM) and inch per revolution (IPR) respectively.

Table 1:Factorial Experiment for 1020 steel

Drill Number	Speed=80SFM	Speed=100SFM	Speed=120SFM
Feed= 0.006IPR	Treatment 1	Treatment 2	Treatment 3
Feed=0.008IPR	Treatment 4	Treatment 5	Treatment 6
Feed=0.01IPR	Treatment 7	Treatment 8	Treatment 9

CUTTING TOOLS

The tools used were high-speed steel (HSS) and cobalt drill bits manufactured by Guhring Inc. with the following specifications/dimensions as shown in Table 2.

Table 2: Tool specification

Tool Specification	Diameter (in)	Coating	Cutting Angle (deg)
Drill 205	0.500	No coating	118
Drill 305	0.500	Cobalt	118
Drill 651	0.500	Titanium	118
Drill 657	0.500	Titanium	130

DRILLING EQUIPMENTS AND PROCESS

A computer numeric-controlled Bridgeport vertical milling machine, Discovery Torq-Cut 22, is used to perform the drilling operations for this study.

The work piece material is 1020 steels billets flame cut to a workable size of 7”× 6” × 2” as shown in, Figure 2.

Figure 2: Drilled Work Pieces

DATA COLLECTION AND ANALYSIS

The analysis of variance and the regression models were developed after the omission of the outliers from the data based on the Cook’s distance method which is a scaled measure of the difference between the fitted values with and without the k^{th} observation in the model. That is:

$$D_k = \frac{1}{p+1} s^2 \sum_{i=1}^{n} (\hat{y}_i(k) - \hat{y}_i)^2 \qquad (1)$$

D_k = Cook’s distance
p = number of regressor variable in the model
s = standard deviation
$\hat{y}_i(k)$ = fitted value for i^{th} observation when k^{th} observation is omitted.
$\hat{y}_i$ = i^{th} observation

The analyses of variance and the results are reported in Tables 7 through 14. The F-statistics test was performed to insure that the model is significant at 5% confidence level. The analysis of variance was conducted and the important factors and interactions at the 5% confidence level are identified. The following are the prediction models for surface finish and inner diameter deviation using the four different HSS drill bits. The regression model is of the form:

$$S_f(S,F) = A_0 + A_1S + A_2F + A_3S^2 + A_4F^2 + A_5SF \ (2)$$

$$H_s(S,F) = B_0 + B_1S + B_2F + B_3S^2 + B_4F^2 + B_5SF \ (3)$$

Where S and F are speed and feed, respectively. S_f and H_s are the surface finish as measured by R_a and hole diameter, respectively. The coefficients regression models A's and B's are reported in Table 3. The R-squared and Adjusted R-squared values as shown in Table 4 indicate that a significant variation is predicted by the resulting regression models.

Table 3: Coefficients of the regression models for 1020 steel

Tool	Surface Finish					Hole Size				
	A_1	A_2	A_3	A_4	A_5	B_1	B_2	B_3	B_4	B_5
Drill 205	-5.89327	192805	0.05207	-5967869	-913.47936	0.00053769	-4.50992	-0.00000249	268.06685	0.00493
Drill 305	24.48854	-203150	-0.15593	9090213	657.34356	0.00053366	-5.25426	-0.00000204	465.53860	-0.01950
Drill 651	1.41061	97789	-0.04029	-10052562	579.54642	0.00002852	1.65497	-8.62163E-7	-214.71018	0.01429
Drill 657	0.61765	90841	-0.01119	-5935234	-15.32430	0.00021732	-1.15854	-0.00000148	-12.25764	0.00999

Table 4: The R-squared and Adj R-squared values for the regression models for 1020 steel

Tool	Surface Finish		Inner Diameter Deviation	
	R-squared	Adj R-squared	R-squared	Adj R-squared
Drill 205	0.9783	0.9780	0.9276	0.9245
Drill 305	0.9708	0.9701	0.8630	0.8541
Drill 651	0.9456	0.9449	0.9474	0.9455
Drill 657	0.9286	0.9278	0.9069	0.9038

RESULTS

SUMMARY OF THE STUDY RESULTS

Table 5 shows the maximum tool life, surface finish, and hole size for the four drills used in this study under MQL cooling. Note that if the first, second and third best surface and hole size were close, then they were also reported. Otherwise only the best case was reported. Table 6 shows the feed and speed for maximum tool life, surface finish, and hole size reported in Table 5.

Table 5: Maximum Tool Life, Surface Finish, and Hole Size Using MQL

	Drill 205	Drill 305	Drill 651	Drill 657
Maximum Tool Life	1320	1260	900	900
2nd Best Tool Life	960	N.S.T.R.[*]	660	840
3rd Best Tool Life	N.S.T.R.	N.S.T.R.	570	N.S.T.R.
Best Average Surface Finish (micro inches)	287.85	234.5	238.27	175.0
2nd Best Average Surface finish (micro inches)	308.64	N.S.T.R.	238.76	N.S.T.R.
Best Average Hole size (in)	0.5050	0.5050	0.5030	0.5030
2nd Average Best Hole Size (in)	0.5065	N.S.T.R.	N.S.T.R.	N.S.T.R.

[*] Not Significant To Report

Table 6: Feed and Speed for Maximum Tool Life, Surface Finish, and Hole Size under MQL

	Drill 205		Drill 305		Drill 651		Drill 657	
	Speed (SFM)	Feed (IPR)	Speed (SFM)	Feed (IPR)	Speed (SFM)	Feed (IPR)	Speed (SFM)	Feed (IPR)
Best Maximum Life	100	0.008	100	0.008	80	0.006	80	0.006
2nd Best Maximum Life	80	0.008	N.S.T.R.	N.S.T.R.	100	0.006	80	0.008
3rd Best Maximum Life	N.S.T.R.	N.S.T.R.	N.S.T.R.	N.S.T.R.	80	.010	N.S.T.R.	N.S.T.R.
Best Average Surface Finish	100	0.006	100	0.010	120	0.006	100	0.008
2nd Best Average Surface finish	120	0.008	N.S.T.R.	N.S.T.R.	100	0.010	N.S.T.R.	N.S.T.R.
Best Average Hole size	100	0.008	100	0.008	80	0.010	80	0.010
	N.A.	N.A.	120	0.006	N.A.	N.A.	N.A.	N.A.
	N.A.	N.A.	120	0.008	N.A.	N.A.	N.A.	N.A.
2nd Average Best Hole Size	120	0.008	N.S.T.R.	N.S.T.R.	N.S.T.R.	N.S.T.R.	N.S.T.R.	N.S.T.R.

[!] Not Applicable

Table 7: Analysis of variance for surface finish; Drill 205

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Analysis of Variance
                    Sum of            Mean
   Source                DF          Squares           Square              F Value          Pr > F
   Model                 5           43251930          8650386    2        673.21           <.0001
   Error                 296          957843           3235.95732
   Uncorrected Total     301         44209773
        Root MSE                     56.88548          R-Square    0.9783
        Dependent Mean               376.55150         Adj R-Sq    0.9780
        Coeff Var                    15.10696

                    Parameter Estimates
                    Parameter        Standard
      Variable           DF          Estimate          Error               f Value          Pr > |f|
      speed              1           -5.89327          2.52072             5.4756           0.0201
      feed               1           192805            27908               47.7481          <.0001
      feedsq             1           -5967869          1938789             9.4864           0.0023
      speedsq            1           0.05207           0.01646             9.9856           0.0017
      speedfeed          1           -913.47936        210.04699           18.9225          <.0001

Response 1=         (-5.89327*Speed)+(192805*Feed +(-5967869*Feed*Feed)+(0.05207*Speed*Speed)
        +(-913.47936*Speed*Feed)
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Table 8: Analysis of variance for surface finish; Drill 305

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Analysis of Variance
                    Sum of            Mean
   Source                DF          Squares           Square              F Value          Pr > F
    Model                5           23080009          4616002             1597.30          <.0001
    Error                185          534627           2889.87711
    Uncorrected Total     190        23614637
            Root MSE                 53.75758          R-Square    0.9774
            Dependent Mean           345.90263         Adj R-Sq    0.9767
            Coeff Var                15.54125

                    Parameter Estimates
                    Parameter        Standard
      Variable           DF          Estimate          Error               t Value          Pr > |t|
      speed              1           24.48854          4.41177             5.55             <.0001
      feed               1           -203150           60406               -3.36            0.0009
      feedsq             1            9090213           3574171            2.54             0.0118
      speedsq            1           -0.15593          0.02546              -6.12           <.0001
      speedfeed          1           657.34356         202.38869           3.25             0.0014

Response 1 = (24.48854*Speed) + (-203150*Feed) + (9090213*feedsq) +  (- 0.15593*speedsq) +
(657.34356*speedfeed)
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Table 9: Analysis of Variance for Surface Finish; Drill 651

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                                       Analysis of Variance
Source                 DF          Sum of Squares          Mean Square       F Value    Pr > F
Model                  5                39537233          7907447           1355.64    <.0001
Error                  390              2274873           5833.00664
Uncorrected Total      395              41812106
                 Root MSE                   76.37412      R-Square     0.9456
                 Dependent Mean             313.50380     Adj R-Sq     0.9449
                 Coeff Var                  24.36147

                                       Parameter Estimates
Variable         DF        Parameter       Standard
                           Estimate        Error             f Value            Pr > |f|
speed            1         1.41061          2.53685          31.36              0.5785
feed             1         97789           32229             9.18.9             0.0026
feedsq           1         -10052562       2036736           24.4036            <.0001
speedsq          1          -0.04029       0.01487           7.3441             0.0070
speedfeed        1         579.54642       131.12447         19.5364            <.0001

Response 1= (1.41061*Speed) + (97789*Feed) + (-10052562*Feed*Feed) +
(-0.04029*Speed*Speed) + (579.54642*Speed*Feed)
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Table 10: Analysis of Variance for Surface Finish, Drill 657.

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   Analysis of Variance
                 Sum of             Mean
    Source                 DF       Squares             Square            F Value           Pr > F
    Model                  5        33034275             6606855          1116.51           <.0001
    Error                  429     2538564              5917.39827
    Uncorrected Total      434      35572839
            Root MSE                76.92463            R-Square     0.9286
            Dependent Mean          273.99885           Adj R-Sq     0.9278
            Coeff Var               28.07480

                  Parameter Estimates
      Parameter            Standard
     Variable              DF      Estimate             Error             f Value           Pr > |f|
     speed                 1         0.61765             2.09643           0.0841           0.7684
     feed                  1          90841             26049             12.1801           0.0005
     feedsq                1        -5935234            1697212           12.25             0.0005
     speedsq               1        -0.01119            0.01270           0.7744            0.3789
     speedfeed             1        -15.32430           133.55110          0.0121           0.9087

     Response 1 = (90841*Feed) + (-5935234*Feed*Feed)
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Table 11: Analysis of Variance for hole size deviation, Drill 205

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Analysis of Variance
                  Sum of           Mean
    Source                  DF       Squares            Square           F Value          Pr > F
    Model                   5        0.00399            0.00079889       294.84           <.0001
    Error                   115      0.00031160         0.00000271
    Uncorrected Total       120      0.00431
            Root MSE                 0.00165            R-Square    0.9276
            Dependent Mean           0.00571            Adj R-Sq    0.9245
            Coeff Var                28.84692

                            Parameter Estimates
                  Parameter          Standard
       Variable             DF       Estimate           Error            f Value          Pr > |f|
       speed                1        0.00053769         0.00010559       25.9081          <.0001
       feed                 1         -4.50992          1.19894          14.1376          0.0003
       feedsq               1        268.06685          80.93303         10.9561          0.0012
       speedsq              1        -0.00000249        6.942304E-7     12.8881           0.0005
       speedfeed            1        -0.00493           0.00844          0.3364           0.5601

Response= (0.00053769*Speed) + (-4.50992*Feed) + (268.06685*Feed*Feed) +
       (-0.00000249*Speed*Speed)
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Table 12: Analysis of Variance for hole size Deviation, Drill 305

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Analysis of Variance
                  Sum of           Mean
    Source                  DF       Squares            Square           F Value          Pr > F
    Model                   5        0.00235            0.00047074       97.04            <.0001
    Error                   77       0.00037354         0.00000485
    Uncorrected Total        82      0.00273
            Root MSE                 0.00220            R-Square    0.8630
            Dependent Mean           0.00528            Adj R-Sq    0.8541
            Coeff Var                41.71108

                            Parameter Estimates
                  Parameter          Standard
       Variable             DF       Estimate           Error            f Value          Pr > |f|

       speed                1        0.00053366         0.00020828       6.5536           0.0124
       feed                 1         -5.25426          2.67230          3.8809           0.0529
       feedsq               1        465.53860          156.07624        8.8804           0.0038
       speedsq              1         -0.00000204       0.00000121       2.8224           0.0974
       speedfeed            1        -0.01950           0.00974          4.00             0.0487

Response= (0.00053366*Speed) + (-5.25426*Feed) + (465.53860*Feed*Feed) + (-0.01950*Speed*Feed)
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Table 13: Analysis of variance for hole size deviation Drill 651

Analysis of Variance

		Sum of	Mean		
Source	DF	Squares	Square	F Value	Pr > F
Model	5	0.00316	0.00063220	497.46	<.0001
Error	138	0.00017538	0.00000127		
Uncorrected Total	143	0.00334			

Root MSE	0.00113	R-Square	0.9474
Dependent Mean	0.00459	Adj R-Sq	0.9455
Coeff Var	24.53487		

Parameter Estimates

	Parameter	Standard			
Variable	DF	Estimate	Error	f Value	Pr > |f|
speed	1	0.00002852	0.00006125	0.2209	0.6422
feed	1	1.65497	0.77911	4.4944	0.0354
feedsq	1	-214.71018	49.38948	18.9225	<.0001
speedsq	1	-8.62163E-7	3.599665E-7	5.76	0.0180
speedfeed	1	0.01429	0.00323	19.5364	<.0001

Response= (0.00002852*Speed) + (1.65497*Feed) + (-214.71018*Feed*Feed) + (-8.62163*Speed*Speed) + (0.01429*Speed*Feed)

Table 14: Analysis of variance hole size deviation; Drill 657

Analysis of Variance

		Sum of	Mean		
Source	DF	Squares	Square	F Value	Pr > F
Model	5	0.00314	0.00062880	292.30	<.0001
Error	150	0.00032269	0.00000215		
Uncorrected Total	155	0.00347			

Root MSE	0.00147	R-Square	0.9069
Dependent Mean	0.00444	Adj R-Sq	0.9038
Coeff Var	33.00762		

Parameter Estimates

	Parameter	Standard			
Variable	DF	Estimate	Error	f Value	Pr > |f|
speed	1	0.00021732	0.00006628	10.758	0.0013
feed	1	-1.15854	0.82577	1.96	0.1627
feedsq	1	-12.25764	53.85238	0.529	0.8203
speedsq	1	-0.00000148	4.033727E-7	13.4689	0.0003
speedfeed	1	0.00999	0.00427	5.4756	0.0207

Response= (0.00021732*Speed) + (-0.00000148*Speed*Speed) + (0.00999*Speed*Feed)

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