# OPTIMIZATION OF CUTTING TEMPERATURE IN FINISH TURNING SMALL HOLES ON HARDENED X210CR13

## TỐI ƯU HÓA NHIỆT CẮT KHI TIỆN TINH LỖ NHỎ THÉP X210Cr13 ĐÃ TÔI CỨNG

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## ABSTRACT

*This paper presents a development of predictive models for cutting temperature optimization when finish hard turning small holes (HRC 55-62) under dry cutting conditions. Since cutting temperature is a major problem when hard turning for dimensional and lubricant limitations of small holes, it needs to be minimized. In this study, Response Surface Methodology (RSM) was used in developing thermal models in relation to primary machining variables such as cutting velocity and depth of cut. Response surface contours were constructed in speed-depth planes and then used to determine the optimum cutting conditions for cutting temperature. It has been shown that small holes of 6-10 mm diameter can be produced by finish hard turning at below 300 Celsius degrees of cutting temperature. The machined surface roughness of Ra is as low as 0.6 micrometers. The results have been verified and applied successfully in machining commercial products.*

## TÓM TẮT

*Bài báo này trình bày cách thức phát triển mô hình dự đoán nhằm tối ưu hóa nhiệt cắt khi gia công tinh các lỗ nhỏ đã tôi cứng (55-62 HRC) trong điều kiện không sử dụng dung dịch trơn nguội. Nhiệt cắt là một trong các vấn đề cần giảm thiểu nhất khi tiện cứng lỗ nhỏ do những khó khăn, hạn chế về kích thước không gian và khả năng cung cấp dung dịch trơn nguội. Trong nghiên cứu này, phương pháp quy hoạch thực nghiệm "bề mặt chỉ tiêu" được khai thác để phát triển mô hình hồi quy về nhiệt cắt, phụ thuộc các thông số gia công cơ bản như vận tốc và chiều sâu cắt. Các đồ thị đường mức trong không gian nhiệt cắt – vận tốc – chiều sâu cắt đã được xây dựng và khai thác để xác định chế độ cắt tối ưu cho ra nhiệt cắt thấp nhất. Thực nghiệm chỉ ra rằng có thể gia công bằng tiện cứng các lỗ nhỏ có đường kính cỡ 6-10 mm mà chỉ sinh nhiệt cắt dưới 300 độ C. Nhám bề mặt khi gia công ở chế độ tối ưu có thể đạt tới 0,6 micromet. Các kết quả nghiên cứu đã được kiểm chứng và đã áp dụng để sản xuất các khuôn dập thương phẩm.*

## I. INTRODUCTION

Precision-machined mechanical parts have been typically made by grinding and hard turning technologies. Hard turning is the name used for a process of turning materials with hardness greater than HRC 45 [1]. Since the late 1970s, hard turning has become a very competitive alternative finishing process compared to grinding. Hard turning is used in finish machining for many kinds of precision mechanical elements, such as bearing races, shafts, tools, mold and dies... Compared with grinding, hard turning has the potential to reduce capital investment by about 40%, increase production rate by approximately 30%, and reduce production time by 25 to 30% [2], while maintaining equivalent surface finish characteristics of the components.

In turning, similar to other methods of metal cutting, the processes without utilization of cutting coolants (usually named dry or green machining) are an important goal in order to reduce environmental and production expenses. Dry machining has several advantages [3-5], such as: non-pollution of the surrounding environment or water; no remains on the chip composites; no danger to health, and being non-injurious to skin and allergy free. Dry machining is becoming more popular in many industrial factories throughout the world.

In dry machining, there may be more friction and adhesion between the cutting tool, chips and work pieces. This may not only result in increased tool wear and hence reduction in tool life, but also increase cutting heat. Therefore, dry cutting is able to decrease forming precision, dimension accuracy and surface roughness of the machined parts. Simultaneously, this heat cutting resource may be able to reduce hardness and to change surface integrity of the parts. Several studies have focused on temperature issues in hard turning, especially under dry cutting conditions. Ueda at al. [6] presented the fact that the temperature increased with cutting speed and with the hardness of the parts. Fleming and Bossom [7] also estimated that the self – inducted heat generation at cutting zone exhibits temperatures in the range of 700 $800^0$C, and it is enough to reduce the hardness of the material in contract with the cutting edge. X.L Lui et al. [8] published the influence rules of the bearing steel GC15 with the hardness HRC 30, 40,50, 60, 64 on the cutting temperature while changing cutting data and the part hardness under the condition of dry machining.

Despite a lot of work in the area of cutting temperature in hard turning, efforts to finish turning hardened small holes have been limited. When hard turning small holes, cutting temperature may is one of major problems for its dimensional and coolant restrictions.

This paper presents an experimental method to develop predictive models for cutting temperature optimization when finish hard turning small holes (HRC 55-62) under dry cutting.

## II. EXPERIMENTAL PROCEDURES

### 2.1 Experimental setup

Due to the dimensional restrictions of the machining holes, a special structure of thermal measurement system has been manufactured to measure the cutting temperature. Figure 1 shows a detailed schematic diagram of the experimental setup used in this study.

In Figure 1, workpiece 1 was clamped in a chuck 3 via an isolating jig 2. A rolling 4 was kept in contact with the workpiece to conduct the current into the thermometer 5, a natural thermocouple model Nr 83 – 6280 (Poland) with 0-1200 Celsius degrees of measurement range. The second terminator of the thermometer was connected to the cutting tool holder 6. The tool was also isolated from the tool clamp. The measurement system was calibrated and verified on normal and well understood external hard turning experiments.

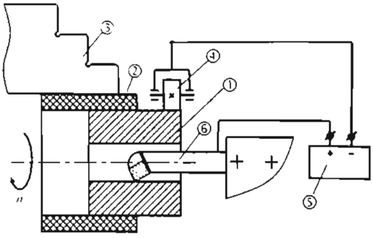


*Figure 1. Experimental schematic for temperature measurement*

### 2.2 Experimental materials

The sample workpieces were made from steel X210Cr13, hardened at HRC 55 to 62. Initial holes were tapped at different diameters ranging from 6 mm to 10 mm.

The machine tool employed was a turning lathe model Takizawa (Japan), having a rotational speed range of 360 to 1650 revolutions per minute (rpm) and a feed rate range of 0.03–0.25 mm/min. The cutting tools used were K01 inserts with rake angle $\gamma = -10^\circ$, clearance angle $\alpha = 15^\circ$; plane approach angle $\varphi = 35^\circ$, mounted in a tool holder of 30 mm in length and 5.2 mm in diameter (See Figure 2). All experiments were carried out in dry cutting conditions. Figure 3 shows some of experimental samples used in this study.

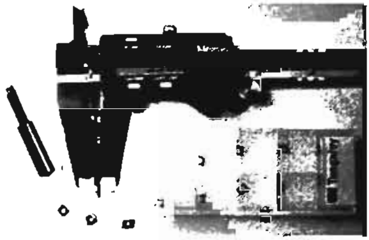


*Figure 2. Tool inserts and holder*

In Figure 3, the samples with diameter of 6mm-8 mm are numbered according the experiments performed. Since the machine tool is of conventional type, experimental cutting speeds were achieved at different workpiece diameters.

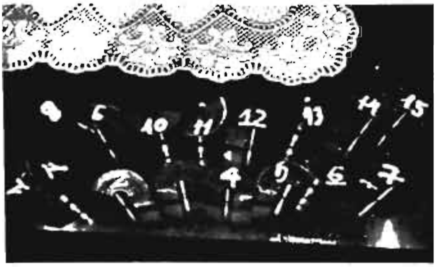


*Figure 3. Experimental samples*

### 2.3 Experimental plan

In order to obtain more information in the extended observation region, the central composite design (CCD) was used as the design of experiment. The distance between center points and star points α = 1.4142, was calculated according to theoretical concepts in Response Surface Methodology [9].

With a view to exhaust all possible combinations, individual experiments were conducted from 5 various cutting speeds and 5 various cutting depths. Sets of cutting parameters used in the study are shown in table 1 below.

*Table 1. Level of experimental variables*

| Level | Lowest | Low | Middle | High | Highest |
|---|---|---|---|---|---|
| Coded | -1.414 | -1 | 0 | 1 | 1.414 |
| Cutting speed V (m/min) | 31,76 | 33 | 36 | 39 | 40,24 |
| Depth of cut, t (mm) | 0,009 | 0,05 | 0,15 | 0,25 | 0,29 |

The experimental plan was designed using Minitab®, which was also deployed for the analysis of mathematical models.

According to CCD design recommendations, at least 9 experiments, including 4 corner and 4 axial points, plus 1 center point, need to be performed. In order to reduce noise effects, the center point of experiment was replicated 5 times. In total, 13 experiments were performed, as shown in Table 2. In each experiment, a combination of cutting speed, $V$, and cutting depth, $t$, is implemented, and then the corresponding cutting temperature was measured and recorded. The values of cutting temperature obtained from all planned experiments are depicted in column *To* of Table 2.

## III. RESULTS AND DISCUSSION

### 3.1. Development of regression models

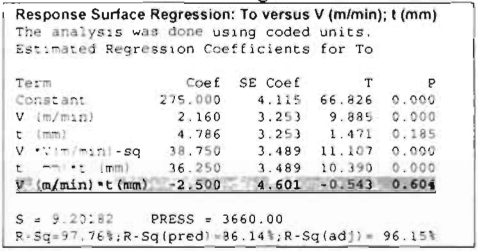
It can be assumed that the relationship between the response variable, *To*, and the independent variables cutting speed, $V$, and cutting depth, $t$, can be demonstrated by a second order equation as below.

$$T_o = b_0 + b_1V + b_2t + b_3V^2 + b_4t^2 + b_5V\cdot t \quad (1)$$

*Table 2. Plan and results of CCD experiments*

| Std Order | Run Order | Point Type | V (m/min) | t (mm) | To |
|---|---|---|---|---|---|
| 1 | 13 | 1 | 33.00 | 0.050 | 320 |
| 2 | 10 | 1 | 39.00 | 0.050 | 390 |
| 3 | 9 | 1 | 33.00 | 0.250 | 330 |
| 4 | 6 | 1 | 39.00 | 0.250 | 390 |
| 5 | 2 | -1 | 31.76 | 0.150 | 300 |
| 6 | 4 | -1 | 40.24 | 0.150 | 390 |
| 7 | 12 | -1 | 36.00 | 0.008 | 330 |
| 8 | 8 | -1 | 36.00 | 0.291 | 350 |
| 9 | 7 | 0 | 36.00 | 0.150 | 280 |
| 10 | 3 | 0 | 36.00 | 0.150 | 275 |
| 11 | 11 | 0 | 36.00 | 0.150 | 270 |
| 12 | 5 | 0 | 36.00 | 0.150 | 280 |
| 13 | 1 | 0 | 36.00 | 0.150 | 270 |

The regression coefficients $b_0$, $b_1$... $b_5$ were calculated from the experimental data by Minitab®, as shown in Figure 4.



**Response Surface Regression: To versus V (m/min); t (mm)**

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The analysis was done using coded units.
Estimated Regression Coefficients for To

Term                   Coef  SE Coef       T      P
Constant            275.000    4.115  66.826  0.000
V (m/min)             2.160    3.253   9.885  0.000
t (mm)                4.786    3.253   1.471  0.185
V *V(m/min)-sq       38.750    3.489  11.107  0.000
t (mm)*t (mm)        36.250    3.489  10.390  0.000
V (m/min)*t (mm)     -2.500    4.601  -0.543  0.604

S = 9.20182     PRESS = 3660.00
R-Sq=97.76%;R-Sq(pred)=86.14%;R-Sq(adj)= 96.15%
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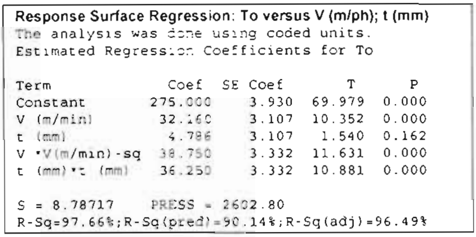
*Figure 4. Regression model of the response*

It can be seen in Figure 4 that the coefficient $b_5$ of the term *V.t* (shadowed row), with a p-value of 0.604 (much bigger than the common α-level of 0.05), is not statistically significant. Hence, the term *V.t* should be omitted from the model.

Figure 5 shows the regression calculated after the term *V.t* was neglected.

In Figure 5, the coefficients of both terms V*V and V*t have a p-value smaller than 0.001

(shown as 0.000 in the figure). Hence, these terms are significant. Despite the p-value of the coefficient of $t$ ($p$=0.162) being bigger than 0.05, the term $t$ could not be omitted, since the term $t*t$ has to be included.



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Response Surface Regression: To versus V (m/ph); t (mm)
The analysis was done using coded units.
Estimated Regression Coefficients for To

Term                 Coef  SE Coef       T      P
Constant          275.000    3.930  69.979  0.000
V (m/min)          32.160    3.107  10.352  0.000
t (mm)              4.786    3.107   1.540  0.162
V *V(m/min)-sq     38.750    3.332  11.631  0.000
t (mm)*t (mm)      36.250    3.332  10.881  0.000

S = 8.78717    PRESS = 2602.80
R-Sq=97.66%;R-Sq(pred)=90.14%;R-Sq(adj)=96.49%
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*Figure 5. The second regression model*

Table 3 presents the analysis of variance (ANOVA) results for the regression obtained.

*Table 3. ANOVA table of To*

| Source | DF | Seq SS | Adj SS | Adj MS | F-ratio | P-value |
|---|---|---|---|---|---|---|
| Regression | 4 | 25790.0 | 25790.0 | 6447.49 | 83.50 | 0.000 |
| Linear | 2 | 8457.3 | 8457.3 | 4228.64 | 54.76 | 0.000 |
| Square | 2 | 17332.7 | 17332.7 | 8666.35 | 112.24 | 0.000 |
| Residual Error | 8 | 617.7 | 617.7 | 77.21 | | |
| Lack-of-Fit | 4 | 517.7 | 517.7 | 129.43 | 5.18 | 0.070 |
| Pure Error | 4 | 100.0 | 100.0 | 25.00 | | |

The ANOVA table summarizes the linear terms and the squared terms of the model. The small p-values for the interactions (p = 0.000) and the squared terms (p = 0.000) suggest there is curvature in the response surface. For the new model, the p-value for lack of fit being 0.070 (Greater than 0.05) suggests that this model adequately fits the data.

The final regression model is rewritten (see Figure 5) as:

$$T_o = 275 + 32.16\cdot V + 4.786\cdot t + 38.75\cdot V^2 + 36.25\cdot t^2 \quad (2)$$

Alternatively, in the form of real (uncoded) values:

$$T_o = 5543.47 - 299.28\cdot V - 1039.64\cdot t + 4.31\cdot V^2 + 3625.00\cdot t^2 \quad (3)$$

### 3.2 Surface and contour plots

Based on the mathematical model of Equation (3), plots of response surface and contour lines can be made, as shown in Figures 6 and 7. The effects of cutting speed $V$ and depth of cut $t$ on cutting temperature can be well understood by inspecting a surface plot. This plot, which is shown in Figure 6, presents the response of cutting temperature versus $V$ and $t$ in a 3-dimension space.

In Figure 6, it can be seen that the surface of temperature has a "valley" towards the middle of the graph.

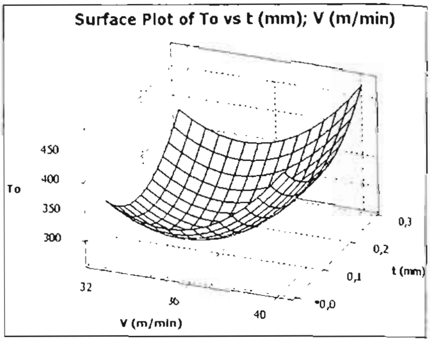

*Figure 6. Surface plot of cutting temperature*

A minimum value of cutting temperature at a particular cutting speed and depth of cut is observed on the contour plot of Figure 7.

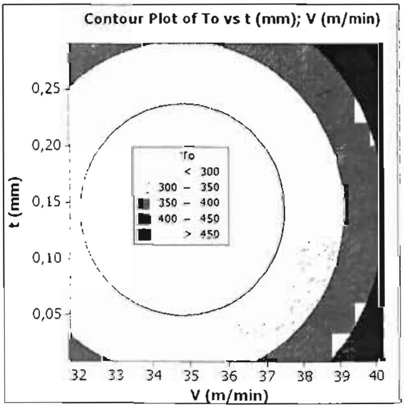

*Figure 7. Contour plot of cutting temperature*

In Figure 7, the cutting speed is selected for the horizontal axis, and the depth of cut is presented on the vertical axis. It can be seen that there has a large area where the temperature is lower than 300 °C.

This area is presented in the lightes shade of green and located next to the left of the center of the graph. The values of temperature less than 300 °C and lower have been known t be safe for cutting tools and beneficial to surface quality of the machined workpiece. The optimum cutting parameters then have been verified by machining samples with hardness of HRC 55-59. Several types of commercial molds hardened at HRC 57-59, with 6-10 mm in diameter of holes, have been produced using the cutting parameters found here. It has been found that, the surface roughness, Ra, of products obtained are as small as about 0.6 micrometers. These can be seen as a validation and useful result of the study.

## IV. CONCLUSION

In this paper, a thermal model for predicting and optimization of temperatures generated when hard turning small holes has been experimentally developed and verified.

It is found that for holes with diameter as small as 6 millimeters, hardened at common levels of HRC 55-59, can be precision-machined by hole-turning. The cutting temperature, below 300 °C, is safe for extending tool life as well as for surface integrity of the parts.

In addition, the model was developed for a normal conventional lathe. Hence, the results can be applied in machining small holes on any other lathes. It would be noted that, CNC lathes usually have machining abilities and stiffness much higher than conventional lathes.

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