Empirical Modelling for Prediction of Work piece Surface Roughness and Cutting Tool Temperature in Turning Carbon Steel

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ABSTRACT

To increase cutting tool life and improve workpiece surface quality, an empirical model was proposed to predict workpiece surface roughness and cutting tool temperature by discovering an empirical equations that depends upon the experimental results of turning carbon steel. These empirical equations predict values; and describe the behaviour of workpiece surface roughness and cutting tool temperature. The experimental work involves turning carbon steel (ASTM Standard A105) by measuring workpiece surface roughness and cutting tool temperature at different cutting speed, feed rate, and depth of cut that consider the major cutting parameters. The results indicated that cutting speed and feed rate has a major effect on workpiece surface roughness and cutting tool temperature. Also, a comparison between experimental and predicted results was made, which show a good agreement, i.e the correlation coefficients reached to 0.9894 for surface roughness and 0.9943% for temperature.

نمذجة تجريبية لتنبؤ خشونة سطح قطعة العمل ودرجة حرارة أداة القطع خلال عملية الخراطة للصلب الكربوني

الخلاصة

لغرض اطالـة عمر اداة القطـع ولتحسين نوعيـة سطح قطعـة العمل فقد تـم ايجـاد نمـوذج تجريبـي للتنبـؤ بقيمـة كـل مـن خشـونة سـطح قطعـة العمـل ودرجـة حـرارة اداة القطـع عـن طريـق التوصـل الـى معـادلات تجريبيـة تعتمـد علـى نتـائج العمـل المختبـري المتمثـل بخراطـة الصـلب الكربوني. المعـادلات التجريبيـة تتنبأ بقيم وتصـف سلوك خشـونة قطعـة العمل ودرجـة حـرارة اداة القطـع. يتضـمن العمـل المختبـري عمليـة الخراطـة لسـبيكة مـن الصـلب الكربـوني (ASTM Standard A105) عـن طريـق قيـاس خشـونة سـطح قطعـة العمـل ودرجـة حـرارة اداة القطـع المستخدمة وبقيم مختلفة لكل مـن سـرعة قطـع والتغذيـة وعمق القطـع والتـي تعتبـر مـن المتغيـرات الرئيسية لعملية القطع. أظهرت النتائج بأن لكل من سرعة القطـع والتغذيـة تـأثير كبيـر علـى خشـونة

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سطح قطعة العمل ودرجة حرارة اداة القطع. تم اجراء مقارنة بين القيم العملية والقيم التي تم التنبؤ بها (النظرية) والتي اظهرت توافق كبير بينهما.

INTRODUCTION

With the development of cutting processes and increasing demands for economic efficiency, higher productivity, and surface quality; workpiece surface roughness and cutting tool temperature were predicted to develop and improve tool life and the surface quality of the products. The empirical model proposed in this study is a useful prediction tool to help analysis of the relationship between cutting parameters (cutting velocity, feed rate, and depth of cut) and the work-piece surface roughness and cutting tool temperature without embarking on laborious time consuming and often expensive machining trials.

The discovered empirical equations were feasible to make the prediction of workpiece surface roughness and cutting tool temperature. The constants and coefficients of these equations was calculated by multiple regression method using data-fit software.

Prediction of cutting tool temperature give a good indication to life of the cutting tool and reducing cost. Several sources of heat appear during the metal cutting process; they are associated with the plastic deformation in the different shear zones, and the frictional dissipation energy generated at the tool-chip interface and at the interface between tool and workpiece. The generated temperatures have a significant influence on the friction conditions at the tool-chip and at the tool-workpiece interfaces and, as a consequence, on the level of cutting forces. The increase in the workpiece material temperature softens the material, and thereby decreases cutting forces and cutting energy to cause further shear. Temperature at the tool-chip contact affects the seizure and the sliding conditions at this interface. These conditions play an important role on the tool wear and then on the limitation of tool life [1,2]. High temperatures at the tool-workpiece interface accelerate the flank wear mechanisms and promote plastic deformation on the machined surface. That leads to a significant thermal load of the subsurface which may induce phase transformation, generate surface alterations and produce high tensile residual stresses values which have a negative effect on fatigue life of the machined parts [3]. Several techniques have been developed over time for the measurement of temperature in various manufacturing processes. They include principally thermocouples (the embedded thermocouple and the dynamic thermocouples or the chip-tool thermocouple), infrared thermography and optical radiation pyrometers. Two papers by Komanduri and Hou [4] and Davies et al. [5] reviewed an important number of measuring techniques.

Surface quality is one of the specified customer requirements for machined parts [6]. Surface roughness is classified among the most important technological parameters in machining process. It is in relation to many properties of machine elements such as wear resistance, the capacity of fit and sealing [7]. Surface roughness has received serious attention of manufacturers for many years. It has been an important design feature and quality measure in many situations, such as parts subjected to fatigue loads, precision fits, fastener holes and aesthetic requirements. In addition surface roughness provide adequate tolerances, which imposes one of the most critical constraints for cutting parameter selection in process planning [8].

Many researchers proposed surface roughness of workpiece in turning process. Kumar et al [6] conduct statistical model of surface roughness in turning process to study the effects of turning process parameters on surface roughness. Abdullah et al [9], used a sensitivity analysis method to identify the optimal machining conditions with respect to surface quality. Dawson et al [10], developed an empirical model based on metal cutting experiments using Taguchi designs, and it included the feed, speed, and depth of cut as input variables. Hamdan et al [11], presented an optimization method of the machining parameters in high-speed machining of stainless steel to achieve minimum cutting forces and better surface roughness.

Modern instrumentation allowing the experimental results to be directly forwarded to a computer for data processing makes it possible to compile a model for any material in a very short time [12].

In the present work, carbon steel (ASTM Specification A105) was used as a workpiece. It is the most widely used metallic material, account for more than 80 million tons, or approximately 98% of the annual steel production in the United States. Carbon steel is a popular material of choice because they can be manufactured relatively inexpensively in large quantities to very precise specifications. They also provide a wide range of mechanical properties, from moderate yield strength levels (200 to 300 MPa, or 30 to 40 ksi) with excellent ductility to yield strengths exceeding 1400 MPa (200 ksi) with fracture toughness levels as high as 110 MPa $m^{0.5}$. [13]

EXPERIMENTAL THEORY

Turning is a machining process for generating external surfaces of revolution by the action of a cutting tool on a rotating work-piece. The experimental theory includes the principle of measurements cutting tool temperature and workpiece surface roughness:

Measurements of cutting tool temperature: The cutting tool temperature was picked up by infrared thermometer based on Steffen-Boltzman law by the following equation [14]:

$$E = \varepsilon\sigma T^4 \quad (W/m^2) \qquad \text{... (1)}$$

Where, ε is the emissivity of the material radiation element, σ the Steffen-Boltzman constant, 5.67×10^{-8} $W\ m^2\ K^4$, T the surface temperature of radiation element (K) and E the radiation energy of radiation element (W).

The radiation energy could be received and measured on the radiation element of the material by an infrared thermometer and then the surface temperature of the radiation element could be calculated according to the Steffen-Boltzman law if the emissivity of the radiation element was known. This was a visual, simple and non-contact method to measure the temperature by an infrared thermometer. [14]

Measuring of Workpiece Surface Roughness: There are various simple surface roughness amplitude parameters used in industry, such as roughness average (*Ra*), root-mean square (rms) roughness (*Rq*), and maximum peak-to-valley roughness (*Ry* or *Rmax*). Since *Ra* and *Rq* are the most widely used surface parameters in industry, *Ra* was selected to express the surface roughness in the present study. The average roughness (*Ra*) is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length.
The *Ra* is specified by the following equation [15]:

$$Ra = \frac{1}{L}\int_{0}^{L}\left|Y(x)dx\right| \text{ (µm)} \qquad \text{... (2)}$$

Where *Ra* is the average roughness or it is a deviation from the mean line (µm), *L* is the sampling length, and *Y* is the ordinate of the profile curve, it is the arithmetic mean of the departure of the roughness profile from the mean line as shown in Figure (1) below:

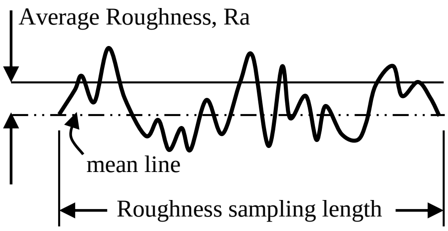

Figure (1) Designations of average surface roughness, Ra.

EXPERIMENTAL WORK

A serious of turning carbon steel tests were carried out to measure workpiece surface roughness (*Ra*) and cutting tool temperature (T_{CT}) at different cutting parameters. The parameters are the cutting speed denoted as(*V*), the feed rate denoted as (*f*), and the depth of cut denoted as (*t*).

The workpiece specimens were carbon steel (ASTM Specification A105), 300 mm long and 40 mm diameter. The chemical composition (wt.%) and the mechanical properties of the material selected for the present study are shown in Tables (1) and (2). The cutting tool material used in this work was Tungsten Carbide (ISO grade P10) .

The lathe used for turning operations is ANDRYCHOWSKA; type TUE40.

A roughness meter surface type Qualitest TR-110, US was used to measure surface roughness factor (average roughness) *Ra* in (µm) according to ISO 4287:1997 Standard.

For cutting tool temperature measurement, handheld infrared thermometer type UNI-Trend (UT303) with built-in laser circle to do switchable and <1mW output used.

The infrared thermometer have been used in more reports than any other method and there are advantages in the use of infrared sensor [16]:

- Non contact
- Can respond to rapid changes in temperature
- Enable the easy measurement of high temperatures without distributing the heat distribution
- Not affected by cutting process.

RESULTS AND DISCUSSION

The direct method of measuring workpiece surface roughness and cutting tool temperature are impractical during machining process. The indirect methods represented by empirical equations are more practical for measurements. The multiple regression analysis method has been used in developing empirical models for predictions the workpiece surface roughness and cutting tool temperature in turning process under dry cutting conditions to reduce environmental problem as there is no use of cutting fluid.

The empirical model was developed using multiple regression method to predict of workpiece surface roughness and cutting tool temperature using data-fit software as follow:

Data – fit for surface roughness

During analysis of experimental results, the relation between roughness factor (*Ra*) and cutting speed (*V*) was power relation while the relation between (*Ra*) and feed rate (*f*) was linear. In the same time there was no effect to the depth of cut on the behaviour of *Ra*. Therefore, depending on the above relations, *Ra* model is given by equation (3) which describe the behaviour and predict the value of workpiece surface roughness under the effect of cutting speed (in/s) and feed rate (mm/rev.). Its coefficient of correlation *R* is 0.9894.

$$Ra = A * B^{V} * f^{C} + D \qquad \text{... (3)}$$

The values of constants are:

A	B	C	D
13.706	0.9875	-0.149	0.1976

The experimental results of workpiece surface roughness were compared with the predicted (theoretical) values of eq. (3) as shown in Figure (2). There is a good agreement was obtained between experimental and predicted values of (*Ra*), with *R*=0.9894.

Figure (3) shows the effect of cutting speed on roughness factor at different feed rates. As the values of cutting speed increase, roughness factor values were decreased. It was clearly that roughness factor improved when the cutting speed increases and feed rate increase. This mean that if the cutting speed and feed rate increase, the workpiece surface roughness will improve and become more smooth.
The improvement on workpiece surface roughness was obtained at the highest feed rate of 1.5 mm/rev.

The experiments had proved that higher feed rate results in lower value of surface roughness [17].

Also, the relation between roughness factor and feed rate at different cutting speed of 100, 150, and 200 in/s was shown in Figure (4). Therefore, workpiece surface roughness will improve with increasing values of feed rate. From Figures (3) and (4) it was observed that workpiece surface roughness decreases more considerably with increase in cutting speed than that of feed rate.

Data – Fit For Temperature

Discovering of cutting tool temperature equation was analysed in the same manner of discovering empirical equation for surface roughness. From analysis of experimental results, the relation between cutting tool temperature (T_{CT}) and cutting speed (V) was logarithmic while the relation between (T_{CT}) and feed rate (f) was linear. Also, there was no effect to the depth of cut on the behaviour of cutting tool temperature. Using the above relations, cutting tool temperature model is given by equation (4) which describe the behaviour and predict the value of cutting tool temperature under the effect of cutting speed (in/s) and feed rate (mm/rev.). Its coefficient of correlation R is 0.9943.

$$T_{CT} = A\ f^{B} Ln(V + C) - D \qquad ... (4)$$

The values of constants are:

A	B	C	D
20.02	0.0462	16.93	52.79

The experimental results of cutting tool temperature were compared with the predicted values of eq. (4) as shown in Figure (5). The results obtained of cutting tool temperature by empirical equation were shown to be agreed well against experimental values, the correlation coefficient (R) reaches to 0.9943Figure (6) shows the effect of cutting speed and feed rate on the values of cutting tool temperature. From this figure, cutting tool temperature increases directly with increasing of cutting speed and feed rate.

Also, the relation between cutting tool temperature and feed rate at different cutting speed of 100, 150, and 200 m/s was shown in Figure (7). It is clear that cutting speed was more effective on the value of cutting tool temperature than feed rate.

The results of Korkut et al [18], showed that increasing cutting speed and feed rate resulted in increase in the temperature of cutting tool. However, cutting speed had the most influence on the temperature.

CONCLUSIONS

The present work develops an empirical model to predict workpiece surface roughness that represented by roughness factor (Ra) and cutting tool temperature (T_{CT}) in terms of cutting parameter (cutting speed and feed rate). From this work, the following conclusions could be reached:

1. Cutting speed and feed rate are the dominant cutting parameters factors in controlling cutting tool temperature and workpiece surface roughness.
2. The surface roughness of the workpiece is develop and improve (become more smooth) with increasing of cutting speed and feed rate.
3. There is no effect to depth of cut on workpiece surface roughness and cutting tool temperature.
4. The empirical model of the present study is more accurate than other mathematical models.
5. The empirical model results show that workpiece surface roughness and cutting tool temperature can be used as an indicator of the cutting performance.

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Table (1) chemical composition of ASTM Specification A105 Carbon Steel.

Contents	Weight %
Carbon, max.	0.35 max.
Manganese	0.6-1.05
Phosphorus	0.035 max
Sulfur	0.040 max
Silicon	0.10–0.35
Copper	0.40 max
Nickel	0.40 max
Chromium	0.30 max
Molybdenum	0.12 max
Vanadium	0.05 max
Columbium	0.02 max

Table (2) Mechanical properties of ASTM SpecificationA105 Carbon Steel.

Yield Strength (MPa)	250
Tensile Strength (MPa)	485
Elongation %	22
Hardness, HB, max.	187

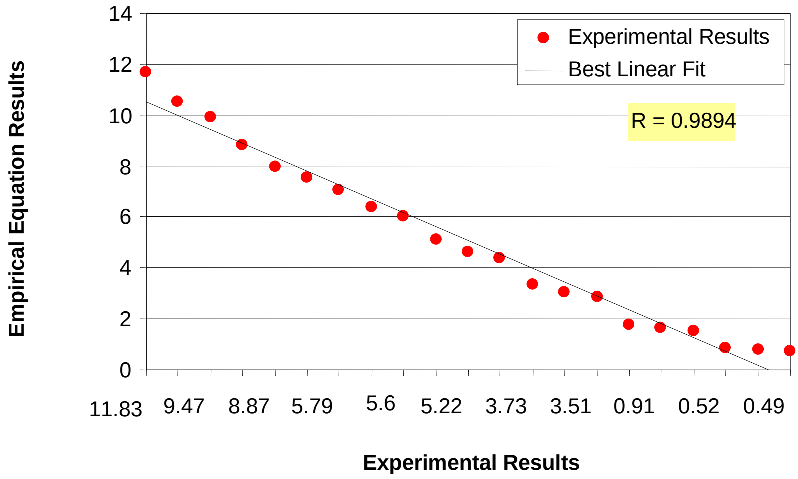
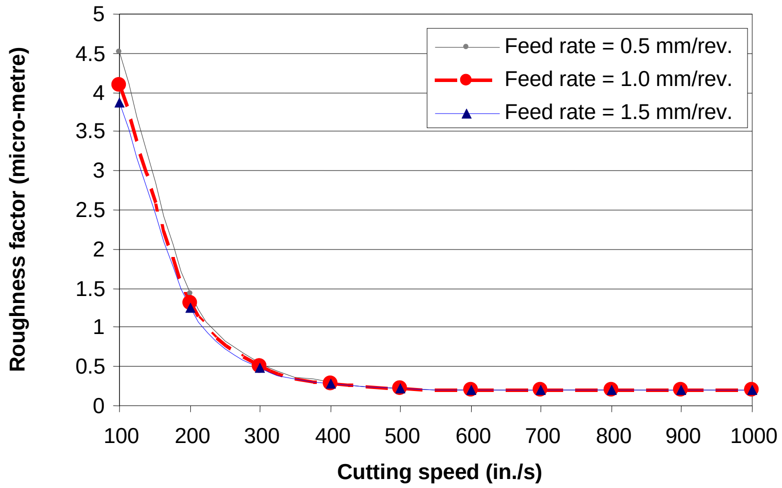


Figure (2) Comparison between Empirical Equation Results and Experimental Results of Workpiece Roughness Factor.



feed rate

Figure (3) Effect of cutting speed on roughness factor at different.

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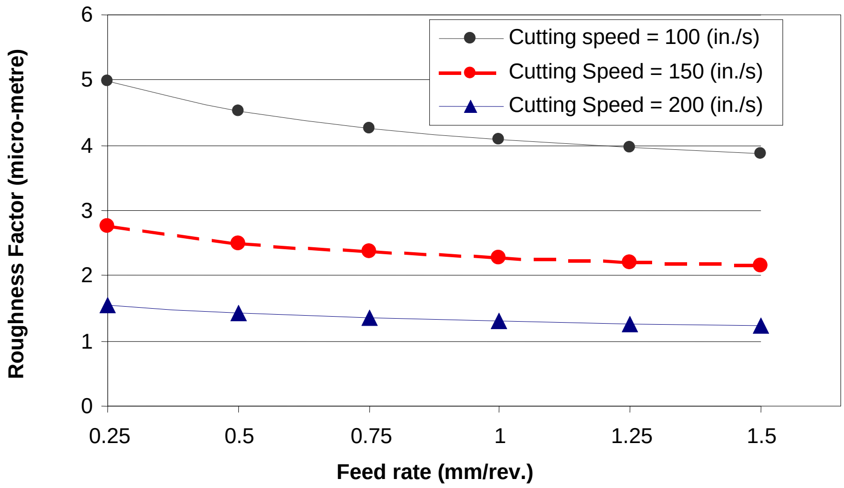

Figure (4) Effect of feed rate on Roughness factor at different Cutting speed.

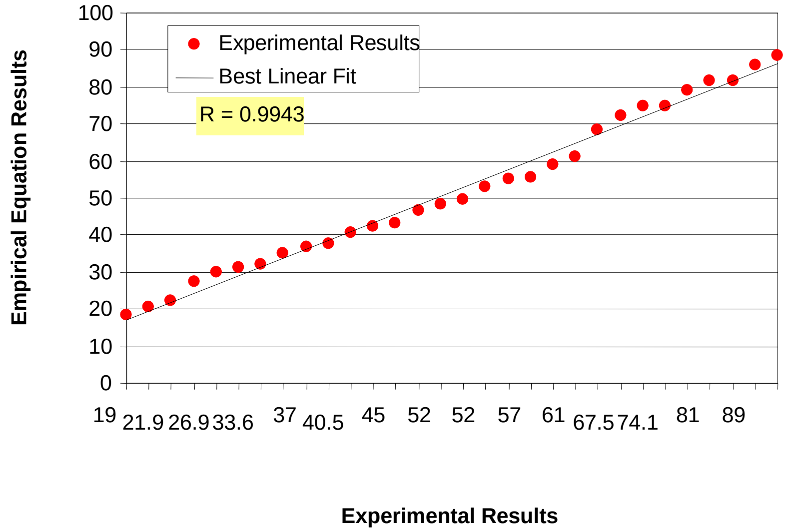

Figure (5) Comparison between Empirical Equation Results and Experimental Results of cutting tool temperature.

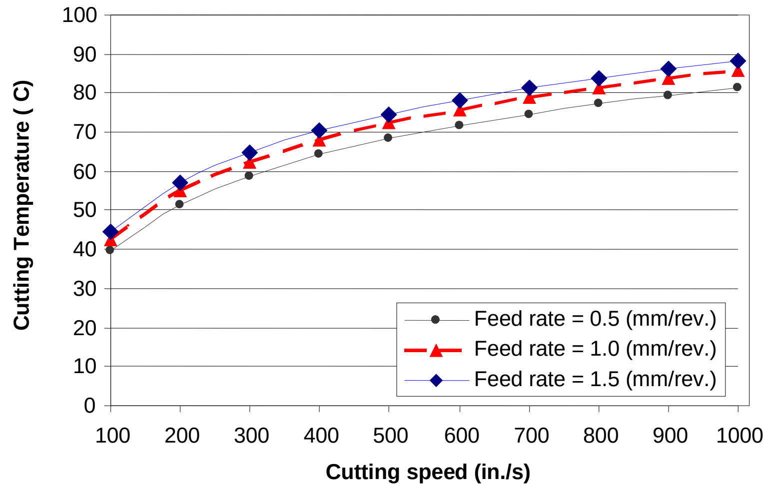

Figure (6) Effect of cutting speed on cutting temperature at different feed rate.

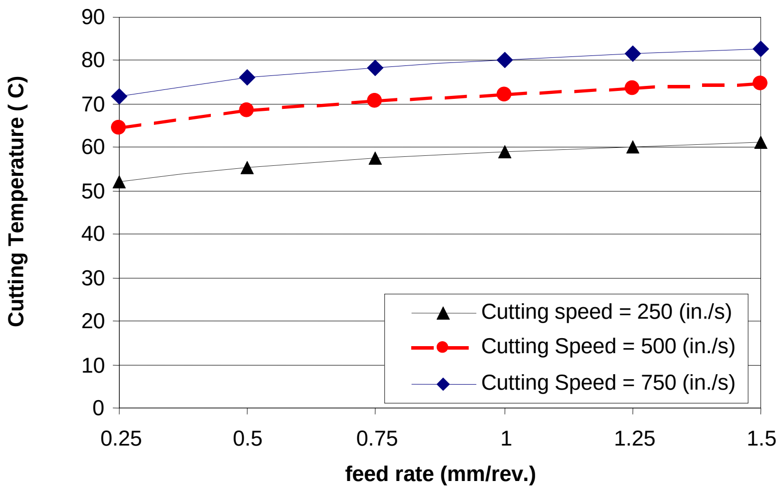

Figure (7) Effect of feed rate on cutting tool temperature at different cutting speed.