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Relationship Between Measurement of Cutting Force and Sensor Location in Turning Process

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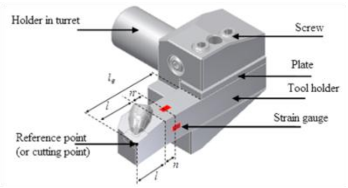
Graphical abstract



Abstract

Turning process is widely used in the production of components for automotive and aerospace applications. The machinability of a work material is commonly assessed in terms of cutting tool life, surface finish, and cutting force. These responses are dependent on machining parameters such as cutting speed, feed rate, and depth of cut. In this study, the relationships between cutting force, cutting speed, and sensor location in the turning process were investigated. Strain gauge was chosen as the sensor for the detection of cutting force signal during turning of hardened plain carbon steel JIS S45C. Two strain gauges were mounted on a tool holder at a defined location of I, II, or III at a distance of 37, 42, or 47 mm, respectively, from the cutting point. Only one set of machining experiments was conducted at spindle speed $\boldsymbol{N}$ = 1000 rpm, feed $\boldsymbol{f}$ = 0.25 mm/rev, and depth of cut $\boldsymbol{d}$ = 0.80 mm. The turning process was stopped and the insert was discarded when average flank wear $\boldsymbol{VB_m}$ reached 0.30 mm. The main cutting force $\boldsymbol{F_y}$ and the feed force $\boldsymbol{F_x}$ for each cycle measured by the strain gauges at location I, II, and III were collected and analyzed. Results show that when cutting speed $\boldsymbol{V}$ was increased, the main cutting force $\boldsymbol{F_y}$ and the feed force $\boldsymbol{F_x}$ were decreased accordingly. The change of $\boldsymbol{F_y}$ was inversely proportional to the change of cutting speed, but the $\boldsymbol{F_x}$ did not decrease continuously and behaved contrarily. A strain gauge placed at a distance of approximately 43 mm from the cutting point was found to be the best and most suitable for sensing accurate force signals.

Keywords: Turning process; strain gauge; sensor location

Abstrak

Proses larik digunakan secara meluas untuk menghasilkan komponen automotif dan aeroangkasa. Kebolehmesinan suatu bahan biasanya dinilai daripada hayat mata alat, kemasan permukaan dan daya pemotongan. Perkara itu bergantung kepada parameter pemesinan seperti laju pemotongan, kadar suapan dan kedalaman pemotongan. Dalam kajian ini kehubungan antara daya pemotongan, laju pemotongan dan letak penderia akan diselidik. Tolok terikan dipilih sebagai penderia untuk mengesan isyarat daya pemotongan semasa melarik keluli karbon terkeraskan JIS S45C. Dua tolok terikan dilekatkan pada pemegang mata alat yang dinamakan lokasi I, II dan III pada jarak 37, 42 dan 47 mm daripada titik hujung mata alat. Hanya satu set ujikaji pemesinan yang dijalankan iaitu pada putaran spindel, $\boldsymbol{N}$ = 1000 rpm, suapan, $\boldsymbol{f}$ = 0.25 mm/pusingan, dan dalam pemotongan, $\boldsymbol{d}$ = 0.80 mm. Proses larik dihentikan dan mata alat dibuang ketika haus rusuk mencapai $\boldsymbol{VB_m}$ 0.30 mm. Daya pemotongan utama, $\boldsymbol{F_y}$ dan daya suapan, $\boldsymbol{F_x}$ bagi setiap pemotongan diukur dengan tolok terikan pada lokasi I, II dan III yang kemudian dianalisis. Hasilnya menunjukkan bahawa ketika laju pemotongan, $\boldsymbol{V}$ meningkat, maka daya pemotongan $\boldsymbol{F_y}$ dan daya suapan $\boldsymbol{F_x}$ menurun. Perubahan daya pemotongan $\boldsymbol{F_y}$ berkadar songsang terhadap perubahan laju pemotongan, tetapi $\boldsymbol{F_x}$ tidak menurun secara berterusan dan berkelakuan berlawanan. Didapati bahawa tolok terikan yang diletakkan pada jarak kira-kira 43 mm dari titik hujung mata alat adalah yang terbaik dan sesuai untuk penderiaan daya pemotongan dengan tepat.

Kata kunci: Proses larik; tolok terikan; lokasi penderia

■1.0 INTRODUCTION

Machining is a general term for a group of processes involved in removing unwanted material from the work material in the form of chips, so that the remaining material has the desired shape. To perform this process, relative motion is required between the work and the tool. Thus, tool wear is inevitable under machining conditions. Machinability of a particular material is commonly assessed by the tool life of the cutting tool used, material removal rate (MRR), cutting force generated, chip formation, and so forth. According to Qian and Hossan [1], cutting force and feed force increase with increasing feed rate, tool edge radius, negative rake angle, and workpiece hardness. This increase is due to the increased energy required for the cutting process [2]. More heat is generated when cutting speed is increased; consequently, the maximum temperature experienced on the tool and workpiece surfaces is higher. This may be because most of the heat or generated temperature is carried away by the chip [3].

According to Ghani *et al*. [4], cutting speed and feed rate most significantly affect tool life, followed by depth of cut. Ghani *et al*. [5] found that the surface finish of the work part is not influenced by tool wear, which contradicts the metal cutting theory and the findings of other researchers. However, they found that increasing the cutting speed, feed rate, or depth of cut affects the surface finish. Dry machining is becoming popular because of the increased awareness of environmental and health concerns [6]. The additional 16% to 20% of the total manufacturing cost due to the cutting fluid application also influenced scientific interest. Jaharah *et al*. [7] found that the temperature and effective stress (caused by the cutting force) generated on the cutting edge are most affected by cutting speed, followed by feed rate and tool geometries.

The current study will present the relationships between cutting force, cutting speed, and sensor location in the turning process. The aim is to investigate how sensor location will affects the cutting force signals generated in the turning process.

■2.0 METHODOLOGY

In this study, hardened plain carbon steel JIS S45C with a diameter size of 85 mm and a length of 210 mm was chosen as the work material because it is widely used in the automotive industry. A rhombus-shaped titanium nitride coated carbide insert using the CVD process was used. The nose radius of the insert was 0.80 mm. Two pieces of strain gauges were mounted on the horizontal and vertical surface of the tool holder shank, as shown in Figure 1. These strain gauges were used to detect the deflection of the tool holder due to the main cutting force and the feed force, respectively. The detected signal was then transmitted to the data acquisition and shown graphically using QuickDAC and Microsoft Excel software on a computer monitor. The deflection was caused by the cutting forces and the unit was in volt (V), which must be converted to newton (N). Signal de-noising was carried out before data analysis was conducted.

The strain gauge was mounted on the tool holder at location I, II, or III, respectively, with a distance $(l + n)$ from the cutting point, where l = 32 mm and n = 5, 10, and 15 mm (Figure 1). At every location I, II, or III, the average flank wear VB_m was measured using a three-axis microscope every time after turning at a length of 60 mm (or 65 mm). The experiment was continued until VB_m reached 0.30 mm, according to ISO 3685:1993. The experiment was conducted at spindle speed N = 1000 rpm, feed f = 0.25 mm/rev, and depth of cut d = 0.80 mm.

■3.0 RESULTS AND DISCUSSION

3.1 Cutting Force and Cutting Speed

As shown in Figures 2 and 3, as cutting speed V increases, the main cutting force F_y and the feed force F_x decrease. This result was also stated by Shaw [8] and Silva *et al*. [9]. Temperature is directly proportional to the increase in cutting speed, which caused both F_y and F_x to be reduced as depicted in Figure 2. F_y was inversely proportional with the increase in cutting temperature, but F_x did not decrease continuously and behaved contrarily. F_x increased at the cutting speed of 75 m/min and decreased after 175 m/min. The increase and decrease of F_x were also stated by Lin *et al*. [10]. This observation is believed to be a result of the increase of friction force.

During the experiment, the formation of built-up edge (BUE) was observed. In general, BUE occurs at low-medium cutting speed. Initially, as the cutting speed increases, the effects of friction or rubbing at the tool-chip interface will also increase, therefore increasing the temperature and pressure at the secondary zone. The strong bond between the tool and the chip was formed due to the adhesive effects. BUE started to form as the bonding force between the tool and the chip exceeded the shear strength of the metal chip body. In Figure 3, BUE size is believed to be at its maximum at point A. At a certain speed, the BUE will break away due to either the resultant force exceeding the bonding force or the temperature being sufficient to soften the deposited material. During the process, more hard particles enter the space between the chip and the tool face, which causes an increase in friction force. Therefore, BUE size is believed to decrease from point A to B. In Figure 3, the cutting speeds at points A and B are about 75 m/min (predicted value) and 175 m/min, respectively, which means maximum BUE is about 75 m/min and minimum BUE size is about 175 m/min.

3.2 Development of Mathematical Model

The developed mathematical model consists of the distance between the strain gauges and the reference point $l + n$, the main cutting force F_y, and the change in main cutting force ΔF_y, where ΔF_y is a function of the average flank wear VB_m and the specimen original diameter D_0. The unit of F_y is volt (V) while the unit of $l + n$, VB_m, and D_0 is millimeter (mm). The new developed mathematical model (Equation 1) and its functions (Equations 2 and 3) are shown below:

$$F_y\text{-}0.00021800\,(l+n)^2 + 0.018778\,(l+n) - 0.35604 + \Delta F_y, \quad (1)$$

where

$D_0 \leq 85$ mm,

$$\Delta F_y = 0.0000015297\,(90 - D_0)^2 + 0.000054169\,(90 - D_0) + 0.00018121 + 0.036080\,(VB_m - 0.05) \quad (2)$$

$D_0 > 85$ mm,

$$\Delta F_y = 0.036080\,(VB_m - 0.05) + 0.000023333. \quad (3)$$

The development of this mathematical model is based on one concept, that is, the tool wears gradually in similar cutting conditions. This mathematical model was found capable of predicting real data correctly because the average error between experimental and predicted values is very small (0.0179 or 1.79 %). Equation (1) has a maximum value of $(l + n)$, which is 43.07 mm. The decrease of F_y in the range $(l + n) > 43.07$ mm is believed to indicate that the signal is no longer accurate.

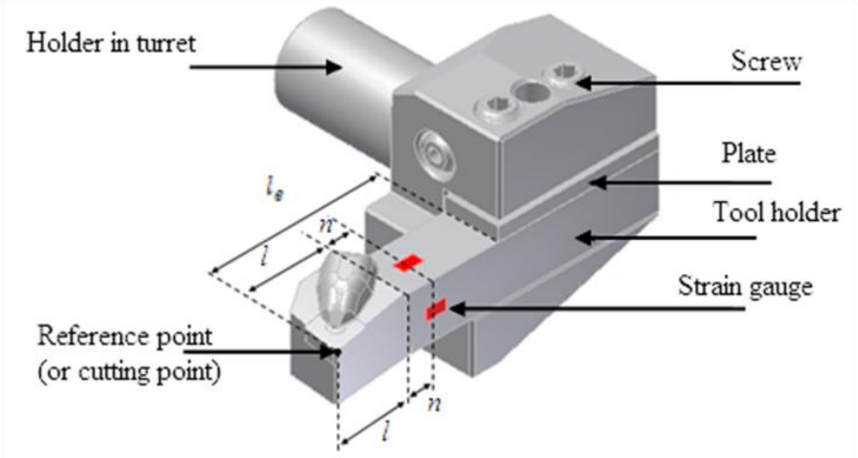


Figure 1 Experimental preparation

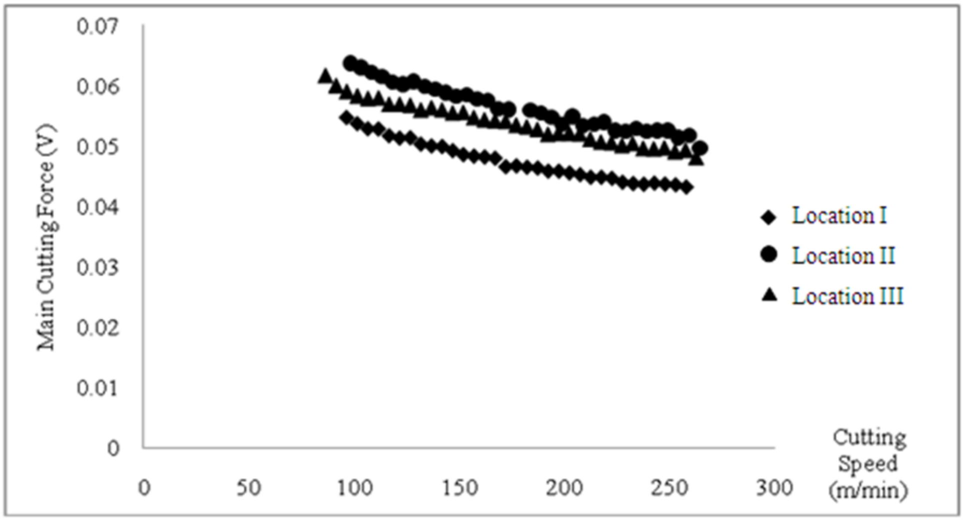


Figure 2 Main cutting force versus cutting speed (*VB* in the range of 0.099 mm to 0.173 mm) at locations I, II, and III

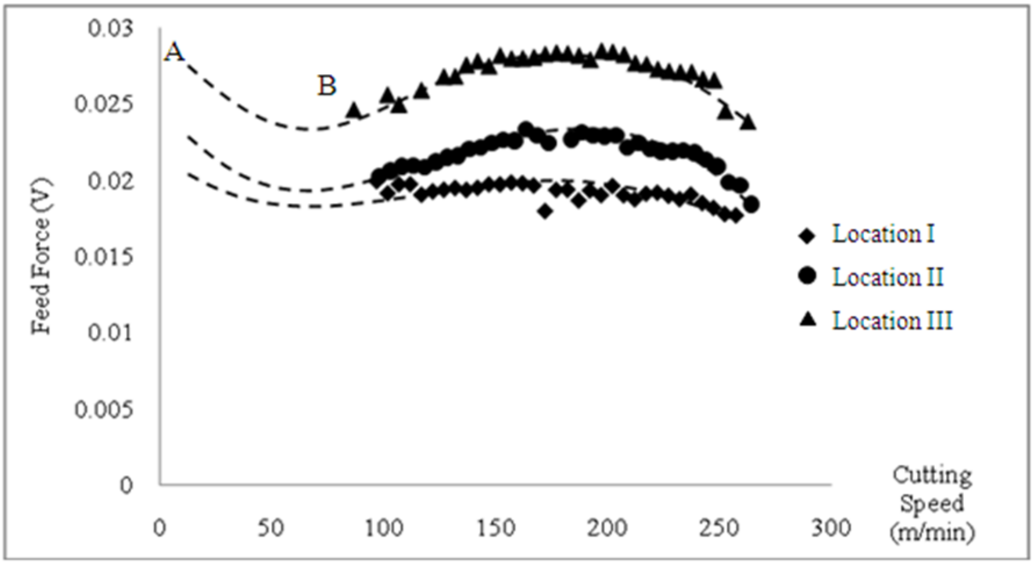


Figure 3 Feed force versus cutting speed (*VB* in the range of 0.099 mm to 0.173 mm) at locations I, II, and III

■4.0 CONCLUSIONS

Increasing the cutting speed V caused the main cutting force F_y and the feed force F_x to decrease accordingly. The change of F_y was inversely proportional to the change of cutting temperature, but F_x did not decrease continuously. But the resultant force (Fy + Fx) decreasing with an increasing in cutting speed. A strain gauge placed at a distance of approximately 43 mm from the cutting point was found to be the best and most suitable for sensing accurate force signals.

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