Team No. - 25

Determination of material dependent parameters and friction in ultrasonic-vibration assisted turning by inverse modelling

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1. Introduction

- Ultrasonic-vibration assisted machining of metals was first carried out in late 1950s for machining of difficult to machine parts. (Skelton, 1969; Brehl and Dow, 2008)
- **Ultrasonic-vibration assisted turning (UAT)** is a cutting technique in which a certain frequency (in ultrasonic range) of vibration is applied to the cutting tool or the work-piece (besides the original relative motion between the work piece and the tool) to achieve better cutting performance.

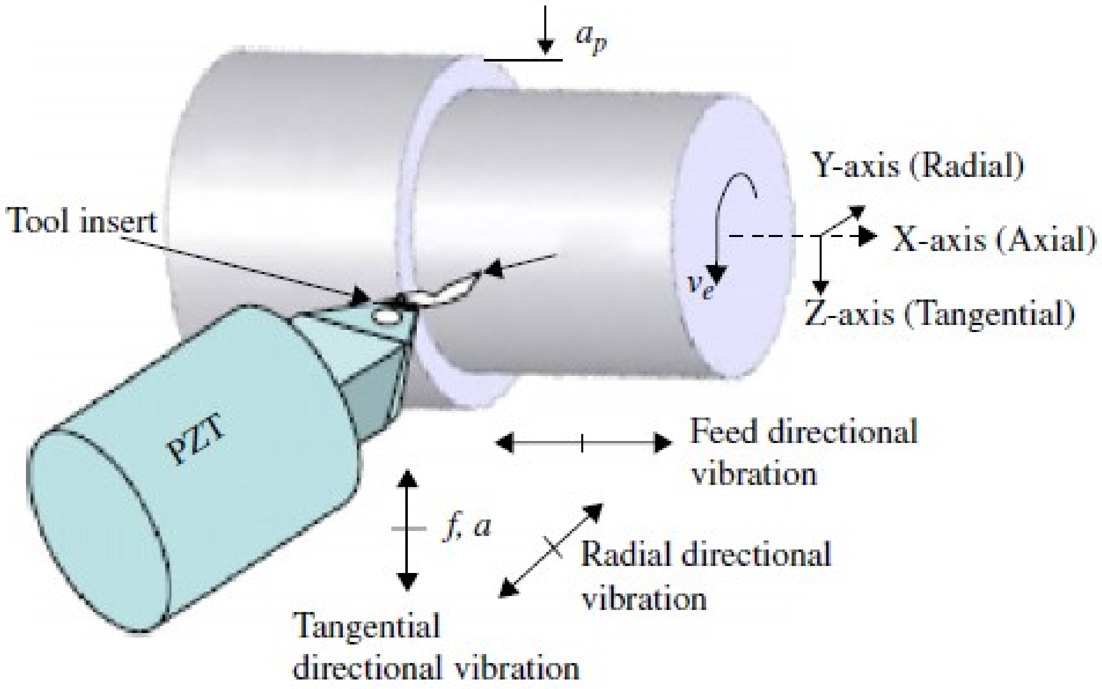


Figure 1 Schematic diagram of Ultrasonic vibration assisted turning (UAT) process

1. Introduction contd.

- The ultrasonic-vibration assisted turning setup comprises **piezoelectric transducer**, **horn** and **tool** which are shown schematically in Fig. 2.
- The forces in cutting can be represented with the Merchant's force circle (Fig. 3). The resultant force **R** can be resolved into components acting along different axes into the following forces.
  - cutting force $\mathbf{F_x}$ and feed force $\mathbf{F_y}$ *or*
  - friction force $\mathbf{F_{fr}}$ and normal force $\mathbf{F_n}$

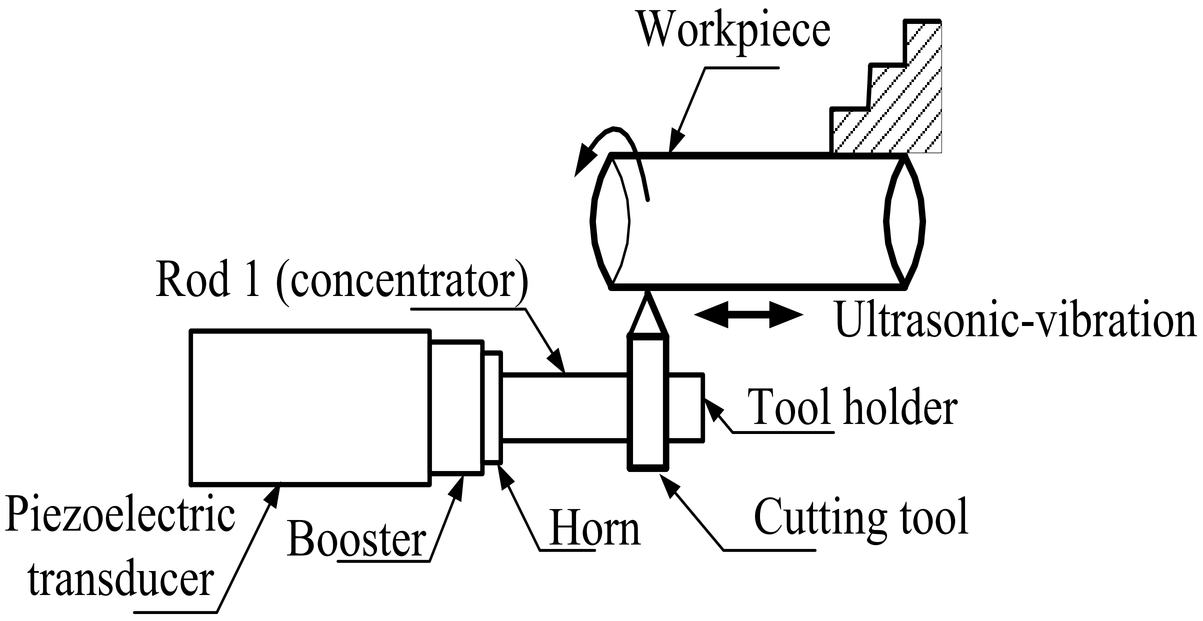


Figure 2 Schematic representation of UAT system

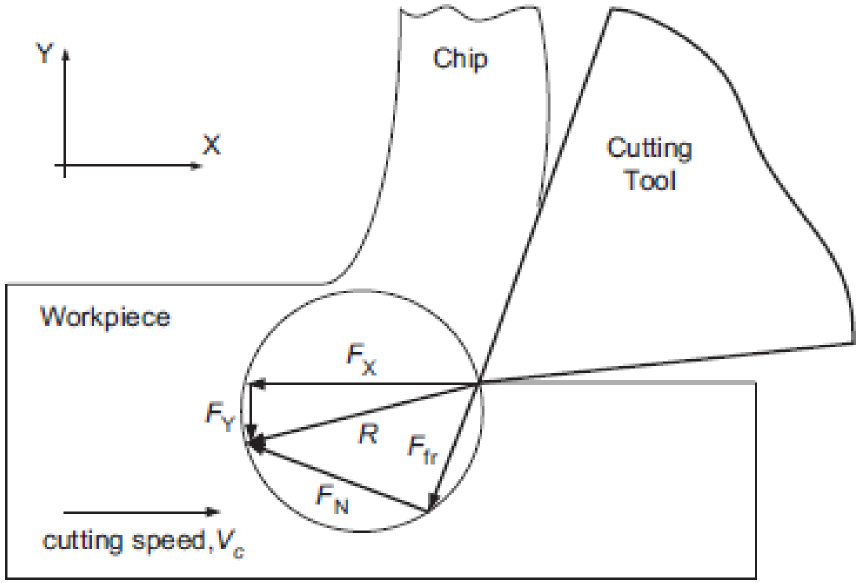


Figure 3 Merchant's force circle

2. Direct Model of UAT

- The tool-chip contact length is divided into **two zones** viz., **sticking and sliding**. (Astakhov, 2006)
  - ➢ The frictional and normal stresses are a function of time and the distance between the separation point of chip on the rake face and the tool-chip contact.
  - ➢ The length of sticking and sliding zones are a function of time only.

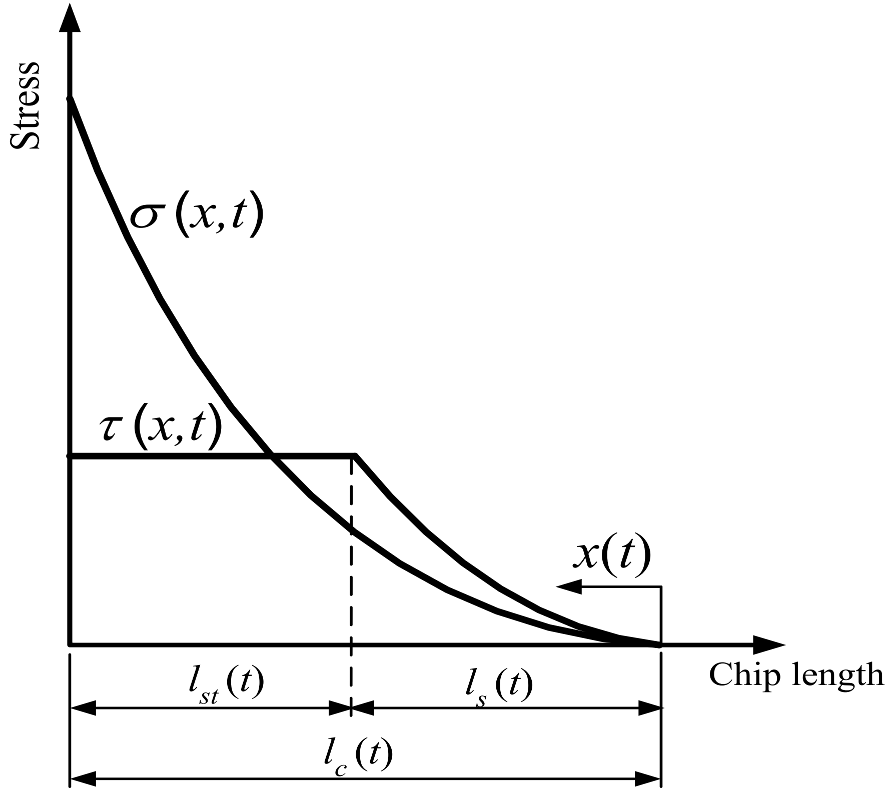


Figure 4 Schematic diagram of Ultrasonic vibration assisted turning (UAT) process

2. Direct Model of UAT contd.

2.1 Determination of normal and frictional stresses

The expression of the normal stress, $\sigma(x,t)$ over the two distinct zones is given by (Jamshidi and Nategh, 2013)

$$\sigma(x,t) = \sigma_{\max}\left(\frac{x}{l_c}\right)^{y} f(t),$$

y is the constant dependent on cutting tool and work piece materials

f(t) is a function indicating the effect of cutting speed variation on the normal stress.

The expression of the frictional stress, $\tau(x,t)$ over the two distinct zones is given by

$$\tau(x,t) = \begin{cases} \mu\sigma(x,t) & \text{if} \quad 0 \le x \le l_c(t) - l_{st}(t) \\ \tau_{st} & \text{if} \quad l_c(t) - l_{st}(t) \le x \le l_c(t) \end{cases}.$$

τ_{st} is the yield stress of the work piece material.

The tool-chip contact length (lc) is calculated as a function of time

$$l_c(t) = l_c g(t),$$

g(t) is the function of time dependent on the variation in relative cutting speed.

2. Direct Model of UAT contd.

2.2 Determination of cutting time and functions f(t) & g(t)

In the one-dimensional ultrasonic-vibration assisted turning cutting of the tool is perpendicular to the direction of tool traveled. The position of the tool tip and the tool's velocity is given by (Brehl and Dow, 2008)

$$x_t = a_1 \sin(\omega t), \qquad \omega = 2\pi f, \qquad V_\omega = a_1 \omega \cos(\omega t).$$

The relative speed between the tool and work piece is calculated as

$$V_{t-\omega} = V_c + a_1 \omega \cos(\omega t)$$

The functions f(t) and g(t) are determined for the specific materials of the work piece based on the experimental data obtained in **Conventional Turning (CT)** process. (U.S. Dixit, 2018)

f(t) represents the variation of normal stress and tool-chip contact length with the cutting speeds.

$$f(t) \approx \sigma_{CT} = a \exp(-bV_c)$$

where, **a** and **b** are the material parameters dependent on cutting speed

g(t) represents the variation of tool-chip contact length as a function of cutting speeds

$$g(t) \approx l_c = c \exp(-dV_c)$$

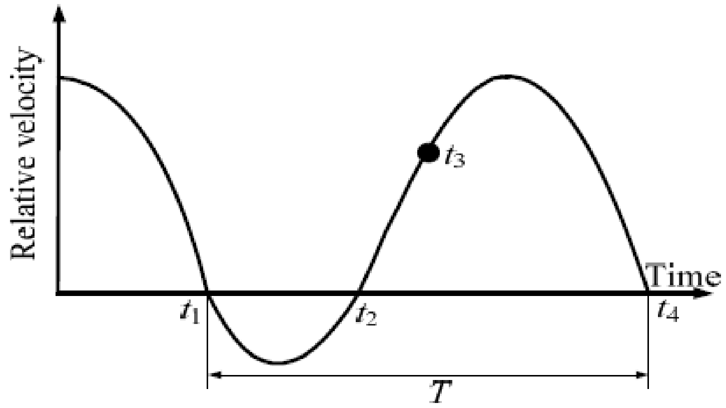
where, **c** and **d** are the cutting speed dependent material parameters

2. Direct Model of UAT contd.

2.3 Determination of averaged coefficient of friction

Expression for **normal force** (Jamshidi and Nategh, 2013; U.S. Dixit, 2018)

$$N = \frac{N_{CT}}{(t_4 - t_3)} \int_{t_3}^{t_4} g(t)^{y+1} f(t)\mathrm{d}t \qquad N_{CT} = \frac{d_c \sigma_{\max} l_c}{(y+1)},$$



The averaged normal force is

$$N_{\mathrm{UAT}(avg,T)} = \frac{t_4 - t_3}{T} N,$$

Expression for **friction force** (Jamshidi and Nategh, 2013; U.S. Dixit, 2018)

$$F = \frac{F_s}{(t_4 - t_3)} \int_{t_3}^{t_4} f(t) g(t)^{(y+1)} \mathrm{d}t + \frac{F_{st}}{(t_4 - t_3)} \int_{t_3}^{t_4} g(t)\mathrm{d}t \qquad F_{st} = \tau_{st} d_c l_{st}. \qquad F_s = \frac{\tau_{st} d_c (l_c - l_{st})}{2(y+1)},$$

The averaged friction force is

$$F_{\mathrm{UAT}(avg,T)} = \frac{t_4 - t_3}{T} F.$$

The **averaged coefficient of friction** in UAT is obtained as per Coulomb's model:

$$\mu_{avg} = \frac{F_{\mathrm{UAT}(avg,T)}}{N_{\mathrm{UAT}(avg,T)}}.$$

3. Parametric Study

Parametric study was carried out to obtain the **normal and friction forces for different values of cutting speed** and dependent material parameters (**y, b and d**). The other two cutting speed-dependent material parameters viz., **a and c** were kept **constant**.

The **direct model** of UAT process is required the data of friction force, normal force and tool-chip contact length at different cutting speeds in CT process.

Table 1 Tool-chip contact length, normal force and friction force in CT process measured experimentally at dc=2.25 mm, rake angle =0° and feed rate = 10 mm/min (Jamshidi and Nategh, 2013)

Cutting speed (m/min)	Tool-chip contact length, (mm)	Normal force (N)	Friction force (N)	Normal stress assuming y=0 (MPa)
15.198	1.430	515	112	160
21.277	1.330	385	100	129
27.356	1.132	375	109	147
33.435	1.125	255	93	101
39.514	1.041	244	82	104

3. Parametric Study contd.

3.1 Dependency of normal and friction force on y

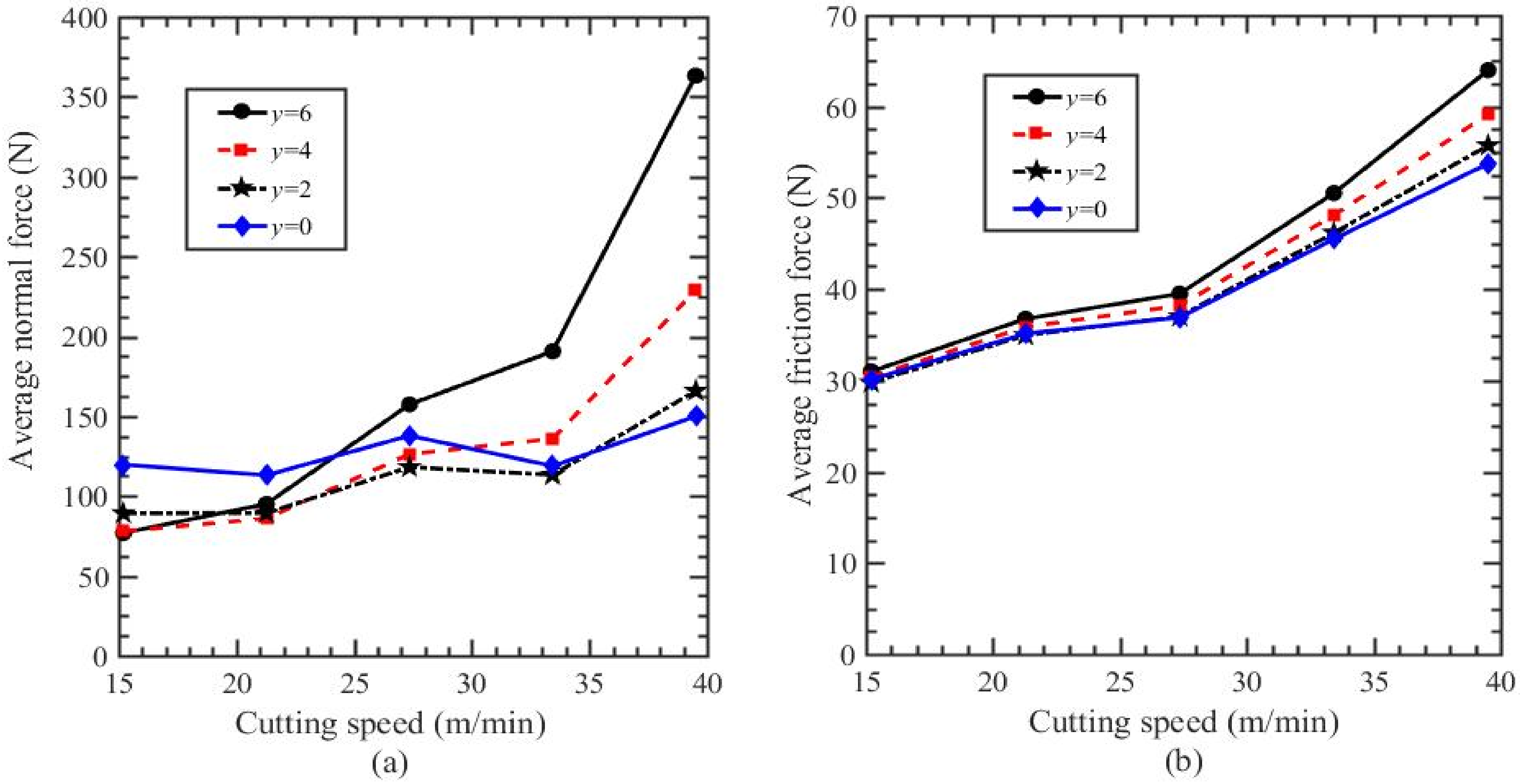


Figure 5 Effect of material parameter (y) normal (a) and friction (b) forces at different cutting speeds (dc=2.25 mm, feed rate=10 m/min, f =20 kHz, a1=6 μm, a = 0.01 and d = 0.01)

3. Parametric Study contd.

3.2 Dependency of normal and friction force on b

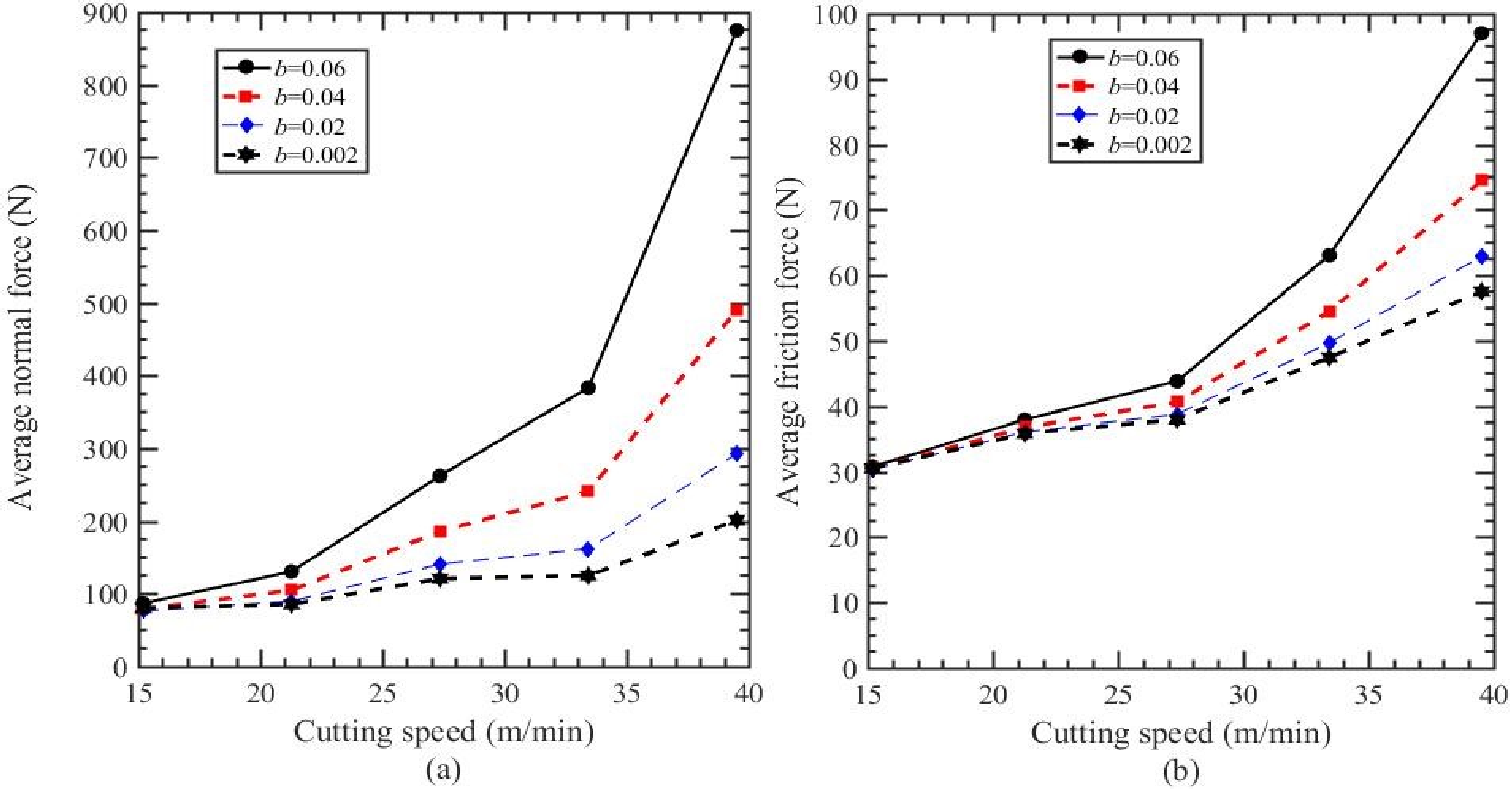


Figure 6 Effect of material parameter (a) normal (a) and friction (b) forces at different cutting speeds (dc=2.25 mm, feed rate=10 m/min, f =20 kHz, a1=6 μm, y = 4 and d = 0.01)

3. Parametric Study contd.

3.3 Dependency of normal and friction force on d

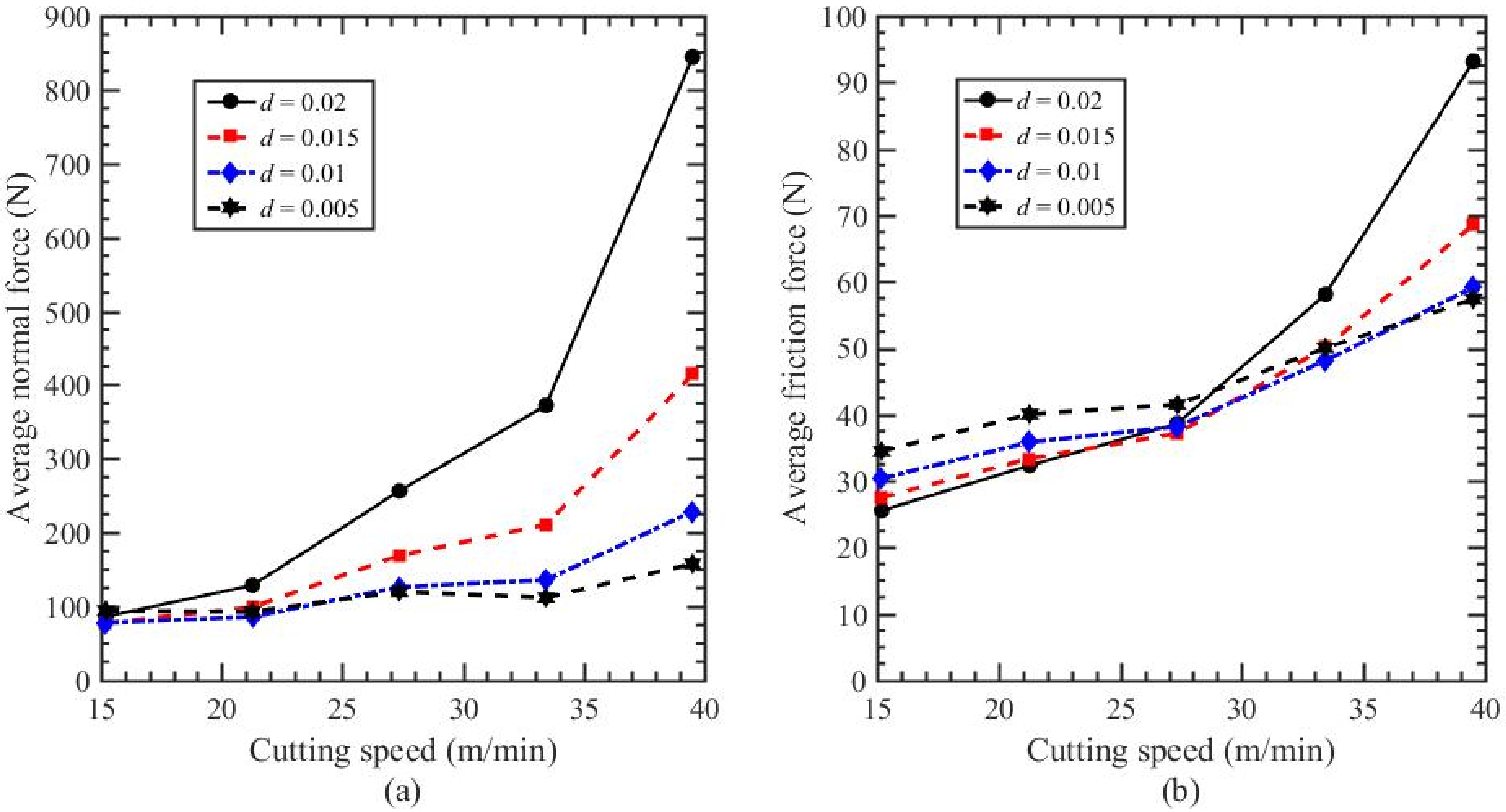


Figure 7 Effect of material parameter (d) normal (a) and friction (b) forces at different cutting speeds (dc=2.25 mm, feed rate=10 m/min, f =20 kHz, a1=6 μm, a = 0.01 and y = 4)

4. Inverse Methodology

Methodology to **estimate the cutting speed dependent material properties (a, b, c and d)** and the coefficient of friction (μ) is based on the measurement of normal force, friction force and tool-chip contact length in CT

a and b

Normal Stress at specified cutting speed

$$\sigma_1 = a\exp\left(-bV_{c1}\right)$$

$$\sigma_2 = a\exp\left(-bV_{c2}\right).$$

Taking logarithm on both sides

$$\ln\sigma_1 = \ln a - bV_{c1}$$

$$\ln\sigma_2 = \ln a - bV_{c2}$$

Solving the above equations

$$b = \frac{\ln\sigma_1 - \ln\sigma_2}{V_{c2} - V_{c1}}.$$

The value of b is substituted in the above equations to find the value of a.

c and d

Values of c and d can be found using **similar procedure** as used for calculating a and b but using the equation

$$g\left(t\right) \approx l_c = c\exp\left(-dV_c\right)$$

y

Knowing the sped-dependent parameter a, b, c and d we can calculate the normal and friction force for different values of y.

$$N = \frac{N_{CT}}{(t_4 - t_3)}\int_{t_3}^{t_4} g(t)^{y+1} f(t)\mathrm{d}t$$

$$F = \frac{F_s}{(t_4 - t_3)}\int_{t_3}^{t_4} f(t)g(t)^{(y+1)}\mathrm{d}t + \frac{F_{st}}{(t_4 - t_3)}\int_{t_3}^{t_4} g(t)\mathrm{d}t$$

The value of y is obtained by **reducing the error** between the estimated and measured normal and friction force.

e.g., bisection method.

5. Results from Inverse estimation

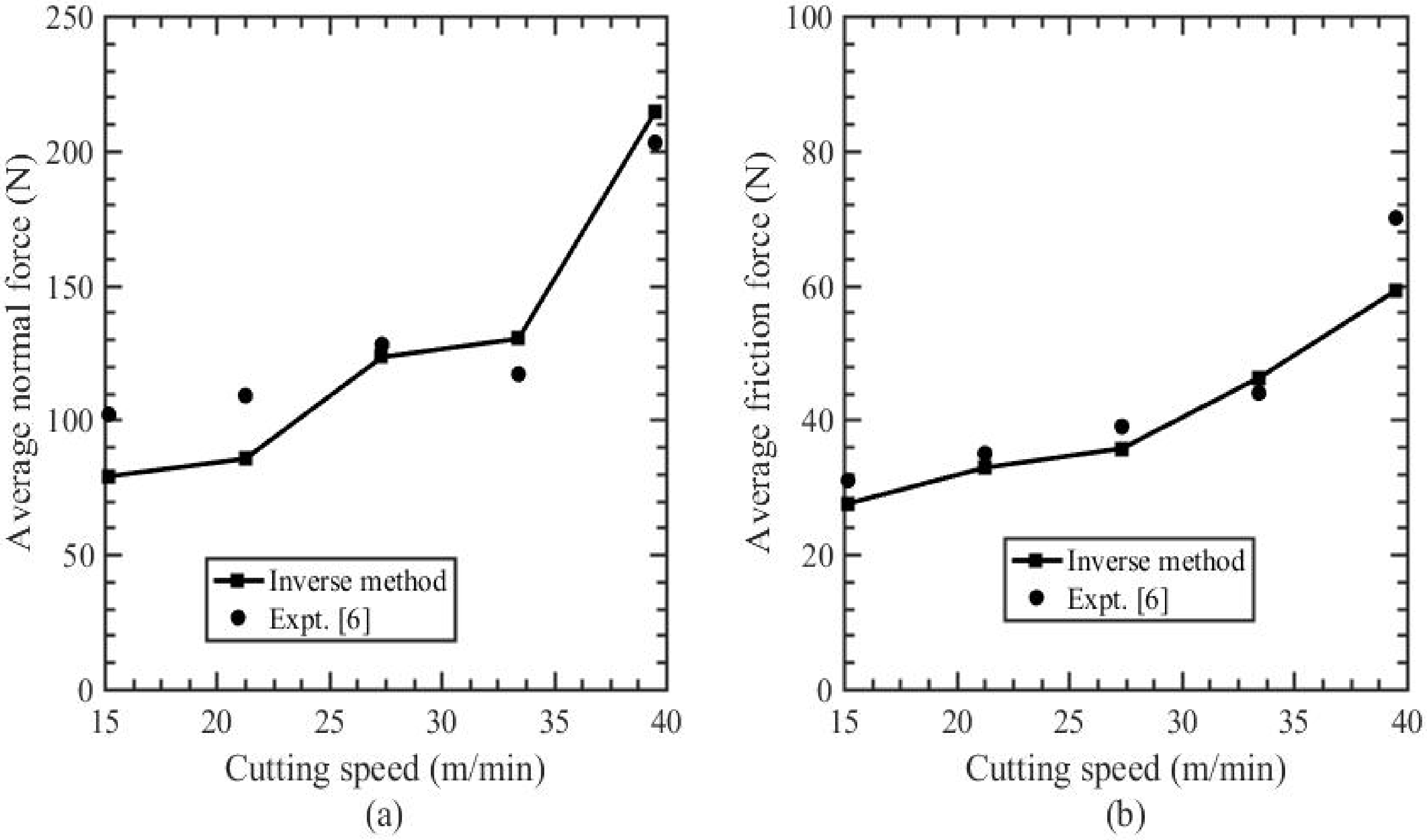


Figure 8 Validation of inversely estimated normal (a) and friction (b) forces with the experimental results of the different cutting speeds (dc=2.25 mm, feed rate=10 m/min, f =20 kHz and a1=6 μm)

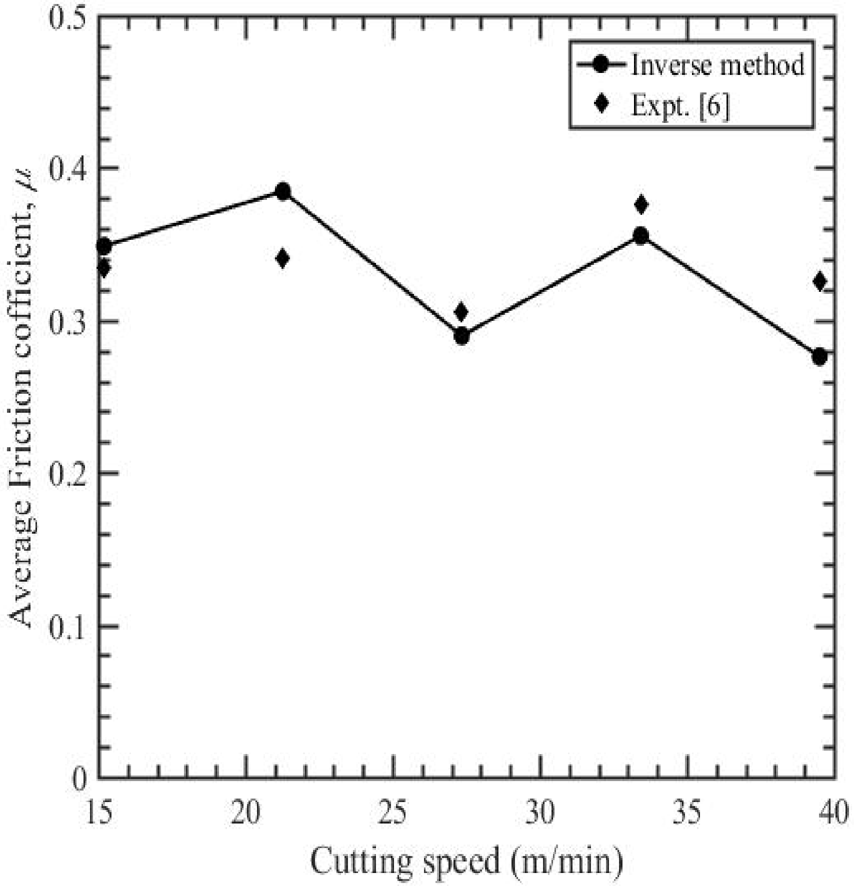


Figure 9 Validation of coefficient of friction obtained using inverse method with the experimental results of the different cutting speeds (dc=2.25 mm, feed rate=10 m/min, f =20 kHz and a1=6 μm)

5. Results from Inverse estimation contd.

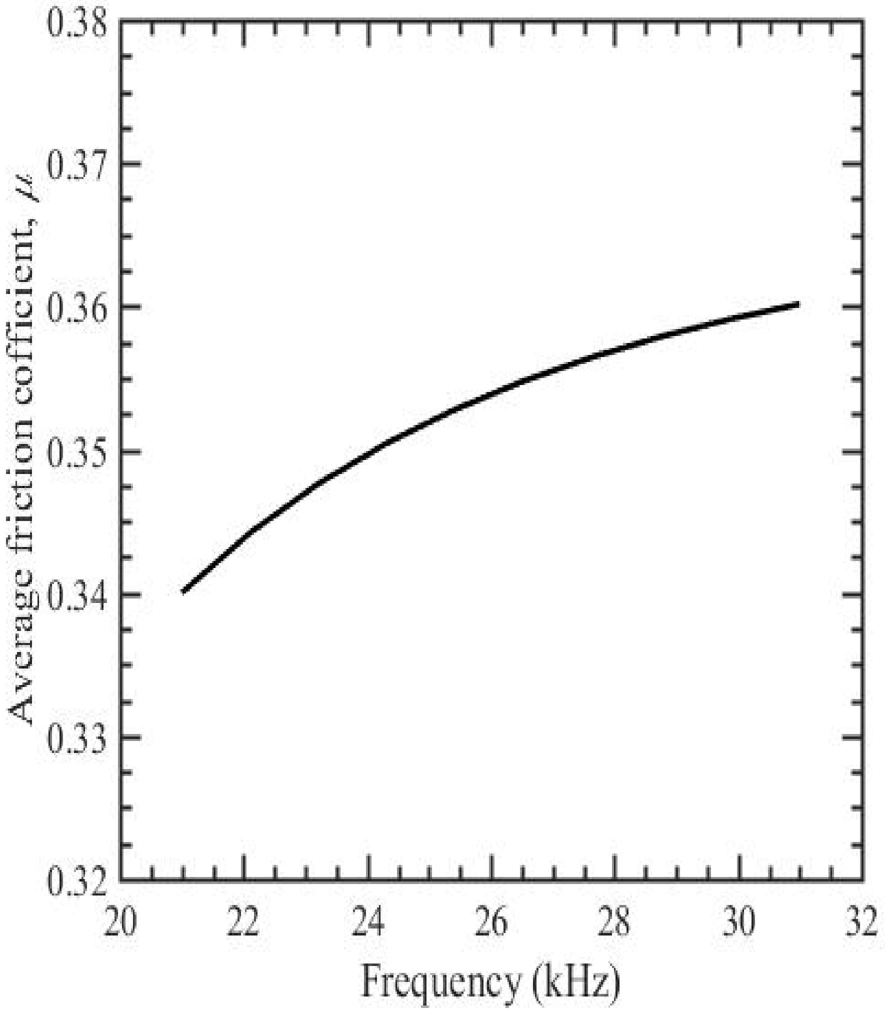


Figure 9 Variation of coefficient of friction obtained using inverse method at different vibration frequencies (dc=2.25 mm, feed rate=10 m/min and a1=6 μm)

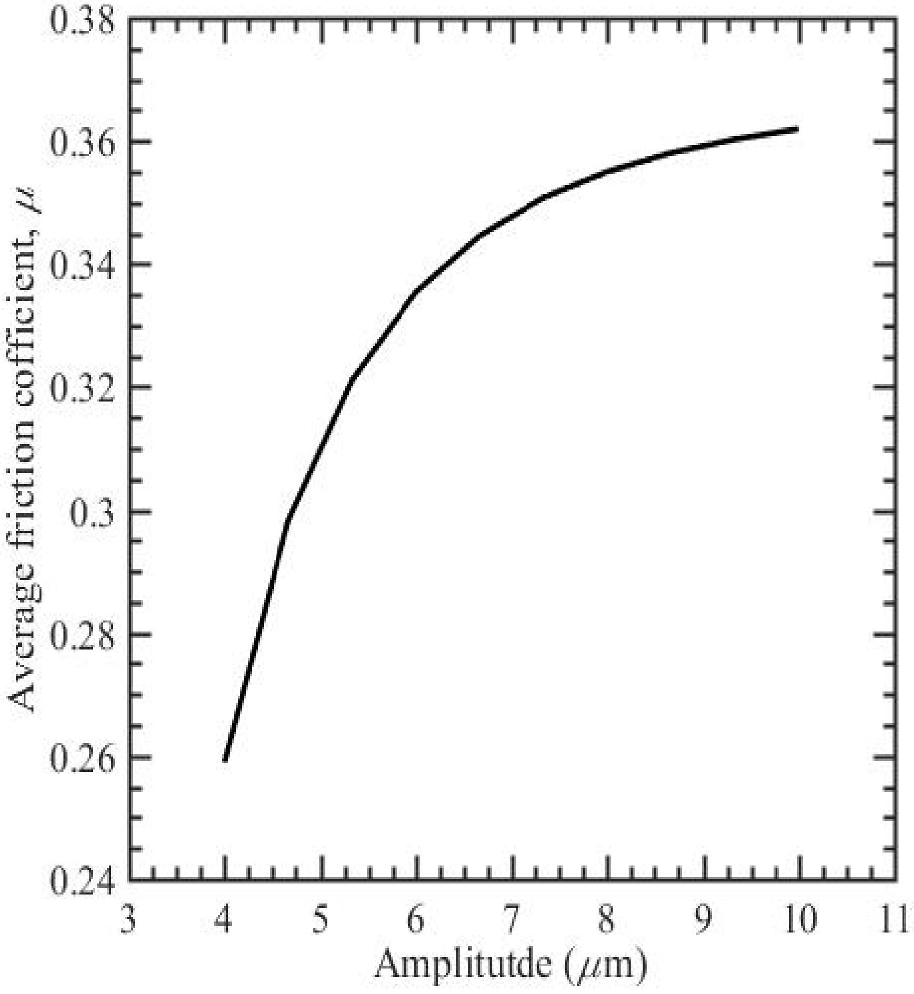


Figure 10 Variation of coefficient of friction obtained using inverse method at different vibration amplitudes (dc=2.25 mm, feed rate=10 m/min and f =20 kHz)

6. Conclusions

Inverse Methodology Requirements

The inverse methodology requires the measurement of the following in a Conventional Turning (CT) process:

1. normal force,
2. friction force
3. tool-chip contact length

Inverse Methodology Determines

The inverse methodology determines the following in an Ultrasonic-vibration assisted turning (UAT) process:

1. material parameters
2. the coefficient of friction

Inverse Methodology Estimates

The inverse methodology estimates the following in an Ultrasonic-vibration assisted turning (UAT) process:

1. normal force
2. friction force

It was observed that an **inverse model results are in-line with the experimental results** available in the literature. Hence, the proposed methodology can be implemented in industry for the on-line estimation of cutting speed-dependent material parameters and friction in UAT.