



HAL
open science

The influence of cutting force on surface machining quality

Xinmin Fan, M Loftus

► **To cite this version:**

Xinmin Fan, M Loftus. The influence of cutting force on surface machining quality. International Journal of Production Research, 2007, 45 (04), pp.899-911. 10.1080/00207540600632208 . hal-00512894

HAL Id: hal-00512894

<https://hal.science/hal-00512894>

Submitted on 1 Sep 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



The influence of cutting force on surface machining quality

Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	TPRS-2005-IJPR-0352.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	10-Feb-2006
Complete List of Authors:	Fan, Xinmin; The University of Warwick, Warwick manufacturing group Loftus, M; University of Birmingham, School of Mfg and Mech Engineering
Keywords:	FLEXIBLE MANUFACTURING, CNC MACHINING, ADVANCED MANUFACTURING PROCESSES, CAM, ADVANCED MANUFACTURING TECHNOLOGY
Keywords (user):	Ball-end mill, cutting force model, machining quality



The influence of cutting force on surface machining quality

X. FAN* and M. LOFTUS†

Keywords:

Ball-end mill, cutting force model, machining quality

Abstract

Appropriately controlled cutting forces can contribute not only to the safety and efficiency of machining but also to the quality of machined surfaces. It is even more important when hardened material is cut. The correlation between the cutting force and the surface quality in ball-end milling operations has been investigated by machining P20 steel (HRC 30) work-pieces using solid carbide ball-end cutters. Plane surfaces with different depth of cut were machined using two different cutting strategies. The first strategy cut the test-piece using a cutting force model, whereas the other machined with a feed rate optimisation product, which uses the removal rate as an analogue of cutting force to control the feed rate. The test results show that constant surface quality is possible when the cutting forces are controlled through feed rate adjustment. Conversely, a desired surface quality can also be maintained by controlling the cutting force in a predetermined manner.

Nomenclature a_0, a_1, a_2, a_3 b_0, b_1, b_2, b_3 c_0, d_0 constants for model parameters calculation, D_a depth of cut, dF_{xj}, dF_{yj} differential cutting force in x and y directions on the infinitesimal cutting element j , AF_x, AF_y average cutting force components, AF Average cutting force on the cutter, dF_{tj}, dF_{rj} differential cutting force in tangential and radial directions on the infinitesimal cutting element j , dz thickness of the infinitesimal disc, E_j cutting element of j , f feed per tooth, F_x, F_y resultant cutting force in x and y directions on the cutter, i_0 helical angle of the flute, K_t, K_r cutting force parameters in tangential and radial directions, m_t, m_r size effect parameters in tangential and radial directions, MF maximum resultant cutting force on the cutter, N_f numbers of flute on a cutter, R_o radius of the cutter, t_j undeformed chip thickness of element cutting edge on flute j , $d\theta$ rotation angle increment, t_j undeformed chip thickness on flute j , z axial distance of the infinitesimal cutting element measured from the cutter tip,

Formatted: Line spacing: Double

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- θ cutter rotation angle measured from the referenced flute at cutter tip,
- ϕ lag of the cutting element on referenced flute, distanced z from cutter tip,
- ψ_j angular position of the cutting element on flute j , distanced z from the cutter tip,
- δ_j engagement indicator of cutting element on flute j ,

For Peer Review Only

1 Introduction

Research initiatives to investigate the correlation of the cutting parameters within the milling process have been conducted over the years. Merchant (1945) pioneered this work and reported the fundamental relationship between the cutting parameters and the cutting force in orthogonal cutting application. Martelloti (1941, 1945) demonstrated that feed per tooth is one of the most important cutting parameters to determine the removed chip volume and other milling parameters. Sabberwal (1960) suggested the empirical relationship between the cutting force and undeformed chip volume in end milling operations. Lin and Yang (1995) and Sarhan *et al* (2001) reported that the variable cutting force can cause quick tool wear, and may be dangerous in high speed machining applications. Devor (1998), Gadalla and Elmaraghy (1998) and Bouzakis *et al* (2003) commented on the requirements for a constant cutting force during the machining operation for a satisfactory surface quality. Research on feed rate optimisation to obtain appropriate cutting conditions have also been reported. Bergs and Altintas (1996), Chu *et al* (1997) proposed an approach of feed rate optimisation in ball-end milling applications.

Cutting force is considered to be one of the most important physical output variables in a machining process (Bayoumi A E, at el 1994), because it affects the machining quality (Yun W S, at el 2002), and compromises the efficiency and safety of the whole machining process. It is even more important in die and mould machining where the material is hard and the component shapes are complicated. Cutting force controlled machining has attracted interest from industry, with commercial software available to control the cutting forces when cutting conditions vary. For example, PSOptiFeed (developed by Delcam International plc) is a feed rate optimisation

Deleted: ¶

¶
¶
¶

Page Break

Formatted: Font color: Red

1
2 product which attempts to maintain a constant cutting load by adjusting the feed rate
3 as cutting conditions vary.
4
5

6
7
8 The effect of cutting force on machining quality in ball-end mill machining is
9 presented in this paper, which is organised into four sections: cutting force model
10 parameter calibration, plane surface machining with a cutting force model, plane
11 surface machining with feed rate optimisation software and a concluding section.
12
13
14
15

16 Deleted: s
17 Plane surface machining trials were conducted to assess the effect of cutting force on
18 the machining quality in P20 tool steel. The test-pieces have three stepped surfaces
19 with different depths of cut on each surface. The machining trials were conducted
20 using two different cutting force control strategies. The first maintained the cutting
21 force at a constant value in the variable depth of cut surfaces using a cutting force
22 model. The second employed commercial feed rate optimisation software in the
23 variable depth of cut conditions. The principle of the feed rate optimisation software
24 is to maintain a constant cutting load, but instead of cutting force, it uses the removed
25 chip volume as an analogue of the cutting load. An existing infinitesimal flute ball-
26 end mill cutting force model (Feng and Meng, 1994) was used to calculate the cutting
27 force. The model parameters of this cutting force model for machining of P20 tool
28 steel using solid carbide ball-end mill were determined by a set of calibration tests. In
29 model parameter calibration, a modified method is used to evaluate the model
30 parameters using the slot milling test data. In the plane surface machining with a
31 cutting force model section, the feed rates derived from the cutting force model, in a
32 variable depth of cut situation, are considered. The actual cutting forces generated
33 during the machining trials were recorded and compared with the simulated values.
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51 The results of the machining quality and the cutting force during the surfaces
52
53
54
55
56
57
58
59
60

1
2 machining are analysed. In the plane surface machining by feed rate optimisation
3 software section, the machining quality and the recorded cutting force during the
4 machining trial for a similar test-piece is presented along with a comparison of the
5 machining quality from the cutting force model.
6
7
8
9

10
11
12 The material of the test-pieces used in the machining trials was P20 steel with a
13 hardness value of HRC30. The cutters were 8 mm diameter, 2-flute with 30° helical
14 angles, solid carbide ball-end mills.
15
16
17

20 2. Calibration of a cutting force model for milling P20 steel

21
22 Many cutting force models have been developed over time, but the practical
23 application of cutting force models is limited due to their empirical characteristics and
24 the model parameters being restricted to a few popular work-piece materials. As
25 addressed by Lutervelt Van (1998), the kernel of the empirical cutting models is the
26 calibration of the model parameters for the specific work-piece material and cutter
27 combination. The infinitesimal flute cutting force model of Feng and Meng (1994)
28 was developed for ball-end mill cutting force calculation. It has a simpler system to
29 calibrate the model parameters than other ball-end mill cutter models (Yang and Park
30 1991, Lee and Altintas 1996). The curved cutting edges of the ball-end mill cutter are
31 considered as a series of infinitesimal cutting elements, as shown in Figure 1.
32
33
34
35
36
37
38
39
40
41
42

43
44
45 Suppose the reference of the cutter rotation is at the tip point of flute 1, and the cutter
46 has a number of helical flutes, N_f , Figure 1 (c). Owing to the helix angle, i_0 , of the
47 flute, Figure 1 (a), the lag of a cutting element, z , on flute 1, Figure 1 (b) and (c), can
48 be given as:
49
50
51
52
53
54

$$\Phi = \theta - \frac{z}{R_0} \tan i_0 \quad (1)$$

Deleted:

Therefore, the angular position of a cutting element of flute j on a disc z , Figure 1 (b),

from the cutter tip can be calculated by:

$$\Psi_j = \theta - \frac{z}{R_0} \tan i_0 + (j-1) \frac{2\pi}{N_f} \quad (2)$$

Deleted:

Formatted: Font color: Auto

where θ is the rotation angle of the reference flute 1 at the tip of the cutter. The

undeformed chip thickness t_j of a cutting element, E_j , can be given by:

$$t_j = |f \sin \Psi_j| \quad (3)$$

Formatted: Indent: First line: 36 pt

Formatted: Lowered by 8 pt

Considering the size effect, the differential tangential and radial cutting forces dF_{ij}

and dF_{rj} on an element can be calculated by:

$$\begin{aligned} dF_{ij} &= K_t t_j^{m_t} dz \\ dF_{rj} &= K_r t_j^{m_r} dz \end{aligned} \quad (4)$$

Formatted: Indent: First line: 36 pt

where, m_t , and m_r are the size effect parameters. K_t and K_r are the tangential and

radial specific cutting pressures. dz is the thickness of the disc. The differential

tangential and radial cutting forces on the element can be resolved into the cutting

forces in x (normal) and y (feed) directions as (Figure 1 (d)):

$$\begin{aligned} dF_{xj} &= -dF_{ij} \sin \Psi_j + dF_{rj} \cos \Psi_j \\ dF_{yj} &= dF_{ij} \cos \Psi_j + dF_{rj} \sin \Psi_j \end{aligned} \quad (5)$$

Deleted:

The resultant cutting forces on the cutter in the x and y directions at cutter rotation

angle θ are obtained by summing the cutting force over all the cutting elements by:

$$\begin{aligned} F_x &= \int_0^{D_0} \left\{ \sum_{j=1}^{N_f} \delta_j [K_t t_j^{m_t} (-\sin \Psi_j) + K_r t_j^{m_r} (\cos \Psi_j)] \right\} dz \\ F_y &= \int_0^{D_0} \left\{ \sum_{j=1}^{N_f} \delta_j [K_t t_j^{m_t} (\cos \Psi_j) + K_r t_j^{m_r} (\sin \Psi_j)] \right\} dz \end{aligned} \quad (6)$$

It has been found that the size effect parameters m_t and m_r can be assumed to be constant for a specified material. K_t and K_r change with the depth of cut and can be approximated by the polynomial (Feng and Meng, 1994) as;

$$K_t(z) = a_0 + a_1\left(\frac{z}{R_0}\right) + a_2\left(\frac{z}{R_0}\right)^2 + a_3\left(\frac{z}{R_0}\right)^3$$

$$K_r(z) = b_0 + b_1\left(\frac{z}{R_0}\right) + b_2\left(\frac{z}{R_0}\right)^2 + b_3\left(\frac{z}{R_0}\right)^3$$

where a_0, a_1, a_2, a_3 and b_0, b_1, b_2, b_3 are constants. Therefore, the average cutting forces on the cutter can be written as:

$$AF_x = -f^{m_t} (a_0 A_0 + a_1 A_1 + a_2 A_2 + a_3 A_3)$$

$$AF_y = -f^{m_r} (b_0 B_0 + b_1 B_1 + b_2 B_2 + b_3 B_3)$$

where,

$$A_n = -\frac{1}{2\pi} \sum_{\theta=0}^{2\pi} \sum_{z=0}^{D_n} \sum_{j=1}^{N_f} \left(\frac{z}{R_0}\right)^n |\sin \Psi_j|^{m_t+1} \Delta z \Delta \theta$$

$$B_n = \frac{1}{2\pi} \sum_{\theta=0}^{2\pi} \sum_{z=0}^{D_n} \sum_{j=1}^{N_f} \left(\frac{z}{R_0}\right)^n |\sin \Psi_j|^{m_r+1} \Delta z \Delta \theta$$

$n = 0, 1, 2, 3$

The model parameters, m_t , m_r , K_t and K_r can be evaluated using the slot milling test data.

The cutting conditions of the model parameters calibration tests are presented in Table 1, where a brand new cutter was restricted to six cuts to minimise the effect of tool wear on the cutting force. In the first set of tests (CT1 to CT6), the depths of cut are the same while the feed rates are different. In the second and third set of tests (CT7 to CT12, CT13 to CT18), different depths of cut and fixed feed rates were used. The tests were carried out on a Hermle C600U 5-axis machining centre. The instantaneous cutting forces in the feed (F_y) and the normal directions (F_x) were measured using a 3-component dynamometer, as seen in Figure 2. To avoid the effect of noise on the

Deleted: ¶

Formatted: Font color: Black, Lowered by 35 pt

Formatted: Justified

Deleted: ¶

Deleted: ¶

cutting force signals, samples of 20 cutter revolutions were used to calculate the average cutting forces (AF_x, AF_y) in Equation 8 as presented in Table 1.

A method was developed to evaluate the size effect parameters based on the assumption that the size effect parameters are constant for a specific work-piece. Suppose the average cutting forces on the cutter for constant depth of cut can be expressed as:

$$\begin{aligned} \ln|AF_x| &= c_0 + m_t \ln f \\ \ln|AF_y| &= d_0 + m_r \ln f \end{aligned} \quad (10)$$

The plot of the log function of the cutting forces against the log function of feed rate is shown in Figure 3. It can be seen that the log function of the cutting forces has linear relationship with the log function of the feed rate. Using the linear regression method, the cutting force can be resolved as:

$$\begin{aligned} \ln|AF_x| &= 6.35 + 0.693 \ln f \\ \ln|AF_y| &= 3.5 + 0.574 \ln f \end{aligned} \quad (11)$$

Comparing Equation (10) with Equation (11), the size effect parameters were obtained as:

$$m_t = 0.693, m_r = 0.574 \quad (12)$$

The model parameters constants a_0, a_1, a_2, a_3 and b_0, b_1, b_2, b_3 in Equation 7 were obtained using the least squares technique from Equation (8) and Equation (9). And the specific cutting pressures were given as:

$$\begin{aligned} K_t &= 5120 - 25719\left(\frac{z}{R_0}\right) + 46678\left(\frac{z}{R_0}\right)^2 - 25433\left(\frac{z}{R_0}\right)^3 \\ K_r &= 231 + 2303\left(\frac{z}{R_0}\right) - 4630\left(\frac{z}{R_0}\right)^2 + 2551\left(\frac{z}{R_0}\right)^3 \end{aligned} \quad (13)$$

Formatted: Lowered by 18 pt

Deleted: ¶

Deleted: .

Formatted: Font: 12 pt, Font color: Black, Lowered by 32 pt

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

In the ball-end milling applications, where the tests-piece is P20 (AISI), the cutting forces on the cutter can be calculated using Equations 6, 12 and 13.

3. Machining with a cutting force model

The infinitesimal cutting force model, which has been used by Kline (1982), Kim et al (2000) and Bouzakis et al (2003) for cutting force control in cornering and sculptured surface quality machine research, was used to investigate the influence of the cutting force on the surface quality of ball-nose milled parts. A cutting force, on a randomly selected surface, can be calculated using the cutting data supplied by the cutter tool manufactures, and the cutting conditions are usually kept constant through the machining process. However, the feed rate must be adjusted, when the cutting conditions vary, according to the calculated cutting force on a specified surface. The feed rate would be reduced when the calculated cutting force is larger than the target value, or increased when the calculated cutting force is smaller. It is convenient to machine a freeform surface using a ball-end mill cutter, but it is difficult to maintain the surface roughness over the whole free form surface. To reduce this complexity, the cutting process can be considered incrementally, and the cutting force on the cutter at a specific location can be determined by the cut geometry, cutter immersion condition and cutting parameters at each location point (Feng, 2001). Understanding the cutting force and its affect on simple plane surfaces is important, because plane surface machining can simplify the cutting force calculation and ease the surface roughness measurement. Therefore, a test-piece with three plane surfaces S1, S2 and S3 was machined with different depths of cut on each surface, as shown in Figure 4.

Formatted: Font color: Red

Formatted: Font color: Red

Formatted: Font color: Red

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

The cutter was fed to the work-piece in the negative y direction (raster tool passes in down milling mode) with a spindle speed of 2000 rpm. The first tool path was half immersion down milling with subsequent passes having a step-over value of 0.3 mm. Each surface was, therefore, machined with a fixed width of cut of 0.3 mm and a specified depth of cut of 2.0 mm, 1.2 mm and 0.8 mm for surfaces S1, S2 and S3 respectively. The cutting force for surface S1 was calculated from the cutting force model using the supplier recommended feed rate. This cutting force was considered as the target value, which would be maintained during the machining process. Likewise, when surfaces S2 and S3 were machined, the cutting forces were calculated using equation 1 and compared with the target value for surface S1. The feed rate was decreased when the cutting force was larger than the target value, and increased when the cutting force was smaller. Therefore, in this way, a constant cutting force could be maintained through the machining operation. The cutting conditions and the measured average *AF* and maximum *MF* cutting forces on the cutter are listed in [Table 2](#). The measured surface textures and machined surface roughness values are shown in [Figure 5](#).

Formatted: Body Text, Left

Deleted: ¶
¶

It can be seen that the surface roughness changed very slightly across the surfaces S1, S2 and S3 from 9 μm to 10 μm , though the depth of cut varied significantly from 2.0 mm to 0.8 mm. The larger cutting force of 71 N on surface S2 produced a slightly larger surface roughness value of 10 μm , compared with the target value of 9 μm on surface S1. The surface roughness value of surfaces S1 and S3 are the same. These results support the view that the cutting force model can be used to predict a feed rate to maintain a constant force and, therefore, ensure a constant surface quality.

4 Machining with feed rate optimisation software

In this test, the shape shown in Figure 4 was machined using feed rates generated by commercial feed rate optimisation software, in which the removed chip volume is used as an analogue of the cutting force. In variable cutting conditions, the feed rate is adjusted based on the anticipated variation in the removed chip volume. The target feed rate is determined from the cutting data recommended by the cutting tool supplier. The cutting conditions and the recorded cutting forces are listed in Table 3.

Though the depths of cut are the same as those in Table 2, the feed rates differ significantly. In this test, the feed per tooth was increased from 0.117 mm/tooth on S1 to 0.406 mm/tooth on S3, with corresponding depth of cut changes from 2.0 mm to 0.8 mm. It is apparent from a comparison of the data in Tables 2 and 3 that the cutting forces in the latter test are larger than those in the cutting force machining trial, and that the cutting forces change considerably in variable cutting conditions. It is considered that the chip volume can not represent the actual cutting force precisely, especially in varied cutting conditions. The measured surface textures and roughness values of the machined surfaces are shown in Figure 6.

The surface roughness values produced by the optimisation software are significantly greater than those produced by the cutting force model, and also have a wider range of values. The roughest surface S3 (48 μm) was machined with the largest cutting force (175 N), whereas the least rough surface S1 (17 μm) had the smallest cutting force (84 N).

5 Conclusion

In ball-end milling applications, the cutting force and the surface machining quality have a strong positive correlation. Larger cutting forces produce rougher surfaces than smaller cutting forces. The infinitesimal flute cutting force model, which controls the cutting accurately, can be used for cutting force control. Similar to all mechanistic cutting force models, it requires considerable effort to calibrate and ascertain the parameters for specific combinations of material and cutting media. The machining trials demonstrated that the cutting force model was able to maintain a relatively constant surface quality between 9 μm and 10 μm , whilst maintaining the average cutting force in the range 62.8N to 71.7N. Using the chip volume removal rate as an analogue of cutting force does not control the cutting force precisely. The average cutting force varied by 104%, and the machined surface roughness values ranged from 17 μm to 48 μm . The results of the investigation supports the view that consistent surface finishes can be produced by maintaining the cutting forces at desired levels with feed rate control strategies.

Formatted: Font color: Red

Formatted: Font color: Red

Acknowledgements

The authors wish to thank Delcam International and the School of Engineering at the University of Birmingham for their financial support of the project.

References

1. BERGS, T. and ALTINTAS, Y., 1996, Tool path optimisation for finish milling of die and mold surfaces- software development, *Transactions of NAMRI/SME*, XXXIV.

Formatted: Numbered + Level: 1 + Numbering Style: 1, 2, 3, ... + Start at: 1 + Alignment: Left + Aligned at: 18 pt + Tab after: 36 pt + Indent at: 36 pt

2. BAYOUMI, A.E., YUCESAN, G. and KENDALL, L. A., 1994, An analytic mechanistic cutting force model for milling operations: a theory and methodology, *ASME Journal of Engineering for Industry*, 116, 324-330.
3. BOUZAKIS, K. D. AICHOUH, P., 2003, Efstathiou, K., Determination of the Chip Geometry, Cutting Force and Roughness in Free Form Surfaces Finishing Milling, with Ball-End Tools, *International Journal of Machine Tools & Manufacture*, Vol. 43, p. 499-514.
4. CHU, C. N., KIM, S. Y., LEE, J. M. KIM, B. H., 1997, Feed-Rate Optimisation of Ball-End Milling Considering Local Shape Features, *Annals of the CIRP*, Vol. 46 (1), p. 433 - 436.
5. Devor, R. E., 1998, Mechanistic Model for the Force System in End Milling with Application to Machining Airframe Structures, *Manufacturing Engineering Transactions*, p. 297-300.
6. GADALLA, M. AND ELMARAGHY, W. H., 1998, Parametric Surface Offsetting Using Surface Subdivision with Application to Free Form Surface Machining and Accuracy Improvement, *The International Journal for Manufacturing Science & Production*, Vol. 1 (2).
7. FENG, H. Y. AND SU, N., 2001, A Mechanistic Cutting Force Model for 3-D Ball-End Milling, *Journal of Manufacturing Science and Engineering*, Vol. 123, p. 23-29
8. FENG, H. Y and MENG, C. H, 1994, The prediction of cutting forces in the ball-end milling process-I. Model formulation and model building procedure, *International Journals of Machine Tool Manufacturing*, 34(5), p. 697-710.

Formatted: Font: Not Bold

Formatted: Justified

Formatted: Bullets and Numbering

- 1
2
3 9. KIM, G. M., CHO, P. J. AND CHU, C. N., 2000, Cutting Force Prediction of
4 Sculptured Surface Ball-End Milling Using Z-Map, *International Journals of*
5 *Machine Tool Manufacture*, Vol. 40, p.277-291.
6
7
- 8
9 10. KLINE W. A, DEVOR, R. E. and LINDBERG, J. R, 1982, The prediction of
10 cutting forces in end milling with application to cornering cuts, *International*
11 *Journals of Machine Tool Design and Research*, 22(1), 7-22.
12
13
- 14 11. LUTTERVELT VAN, C. A, CHILD, T. H. C, JAWAHIR, I. S, KLOCKE, F.,
15 VENUVINOD, P. K.,1998, Present and Future Trends in Modelling of
16 Machining Operations, *Progress Report of the CIRP Working Group*
17 *'Modelling of Machining Operations'*, *Annals of the CIRP*, Vol. 47(2), p. 587-
18 625.
19
20
21
22
23
- 24 12. LEE, P. AND ALTINTAS, Y., 1996, Prediction of Ball-end Milling Forces
25 from Orthogonal Cutting Data, *International Journals of Machine Tool and*
26 *Manufacturing*, Vol.36 (9), p. 1059-1072.
27
28
29
- 30 13. LIN, S. C. AND YANG, R. J., 1995, Force-Based Model for Tool Wear
31 Monitoring in Face Milling, *International Journal of Machine Tools &*
32 *Manufacture*, Vol. 35, p. 1201-1211.
33
34
35
- 36 14. MARTELLOTTI, M. E., 1945, An Analysis of the Milling Process Part II-
37 Down Milling, *Trans. ASME*, Vol. 67, p. 233-251.
38
39
- 40 15. Martellotti, M. E., 1944, An Analysis of The Milling Process, *Trans. ASME*,
41 Vol. 63, p. 677-700.
42
43
44
- 45 16. MERCHANT, M. E., 1945, Mechanics of the Metal Cutting Process, *Journal*
46 *of applied physics*, Vol. 16, No. 5, P267, and No.6, P318,
47
48
- 49 17. SABBERWAL, A. J. P., 1960, Chip Section and Cutting Force During the
50 Milling Operation, *C.I.R.P. Annul*, p. 197- 203.
51
52
53
54

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
18. SARHAN, A. SAYED, R. NASSR, A. A. EL-ZAHRY, R. M., 2001,
Interrelationships Between Cutting Force Variation and Tool Wear in End-
Milling, *Journal Of Materials Processing Technology*, Vol. 109, p. 229-235.
19. YANG, M. AND PARK, H., 1991, The Prediction Cutting Force in Ball-End
Milling, *International Journals of Machine Tool and Manufacturing*, Vol. 31
(1), p. 45-54.

For Peer Review Only

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

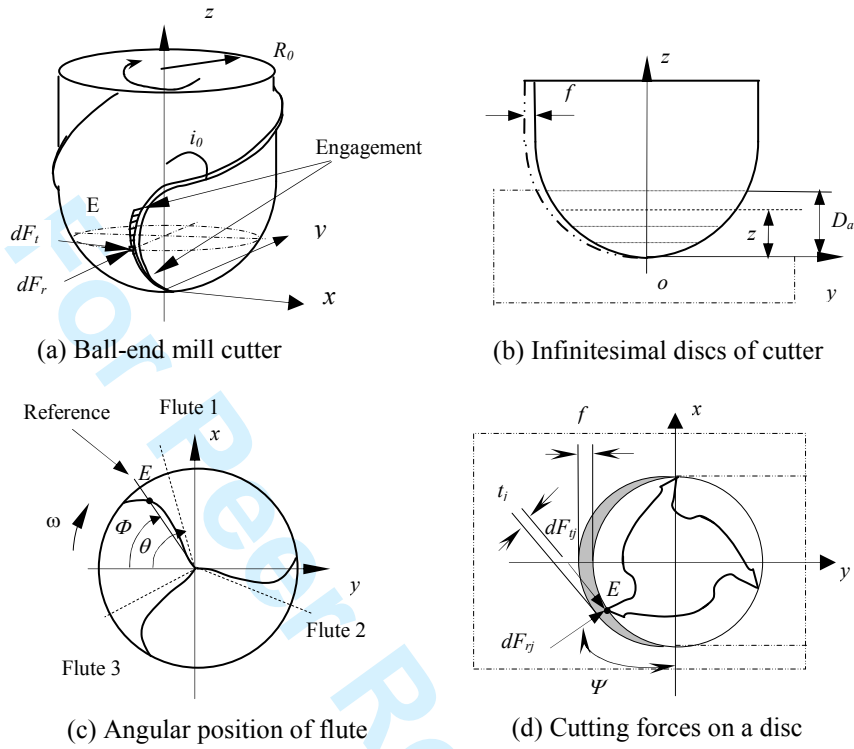


Figure 1 Infinitesimal cutting force model for a ball-end milling cutter

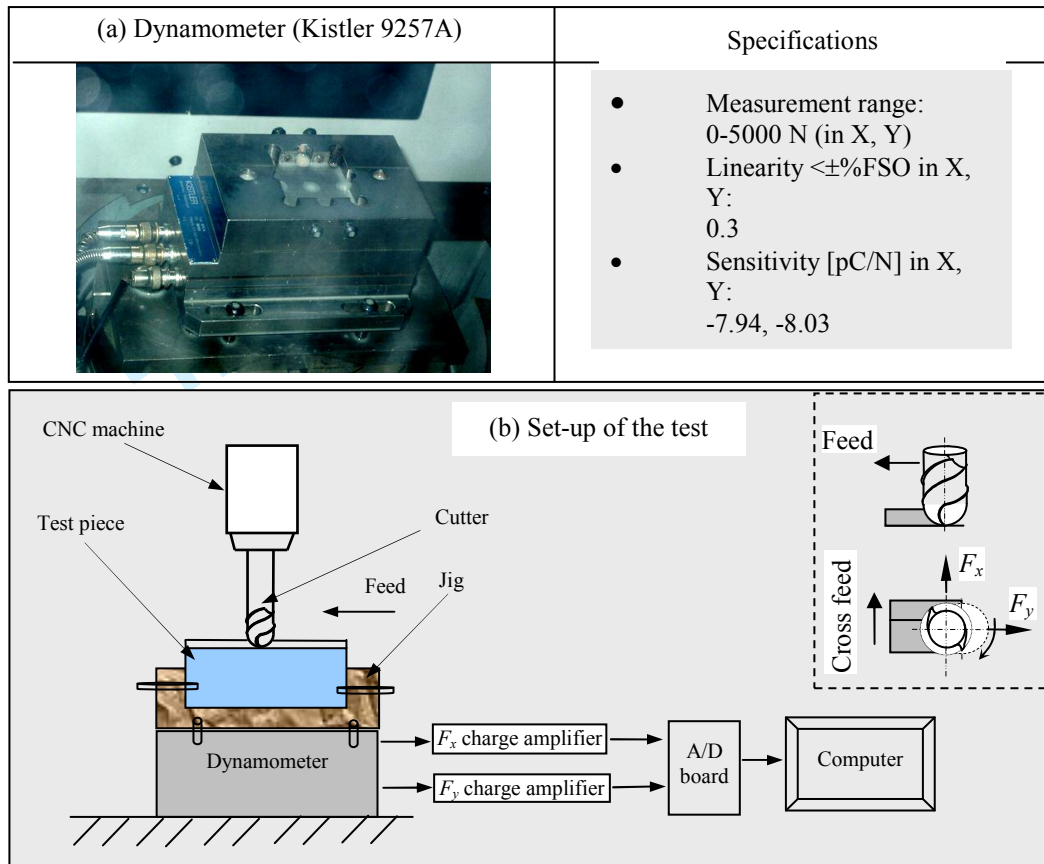


Figure 2 Dynamometer and test set-up arrangement

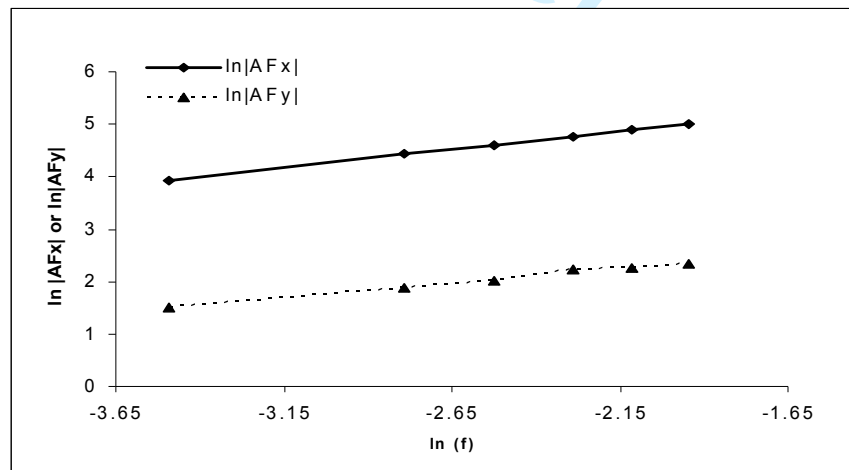


Figure 3 Relationships between cutting forces and feed rate

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

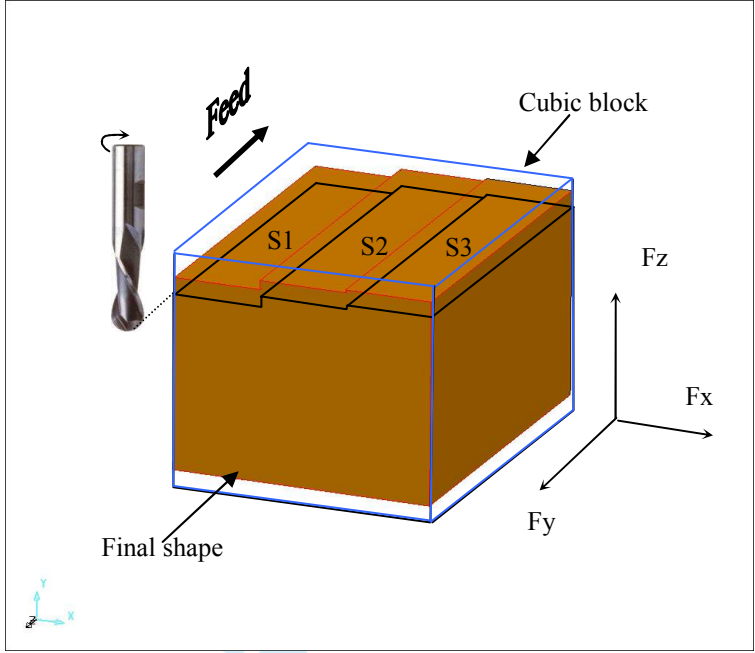


Figure 4 Three plane test-piece

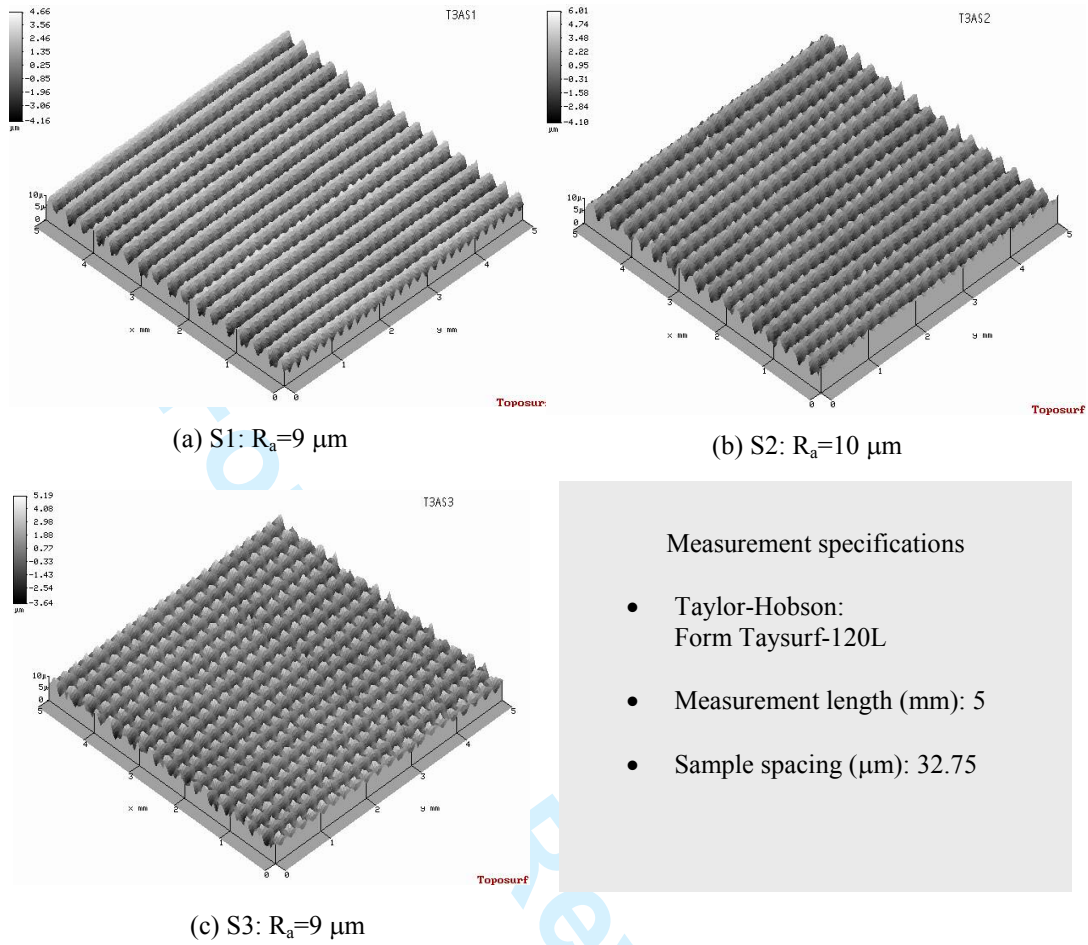


Figure 5 Surface roughness values from the cutting force model tests

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

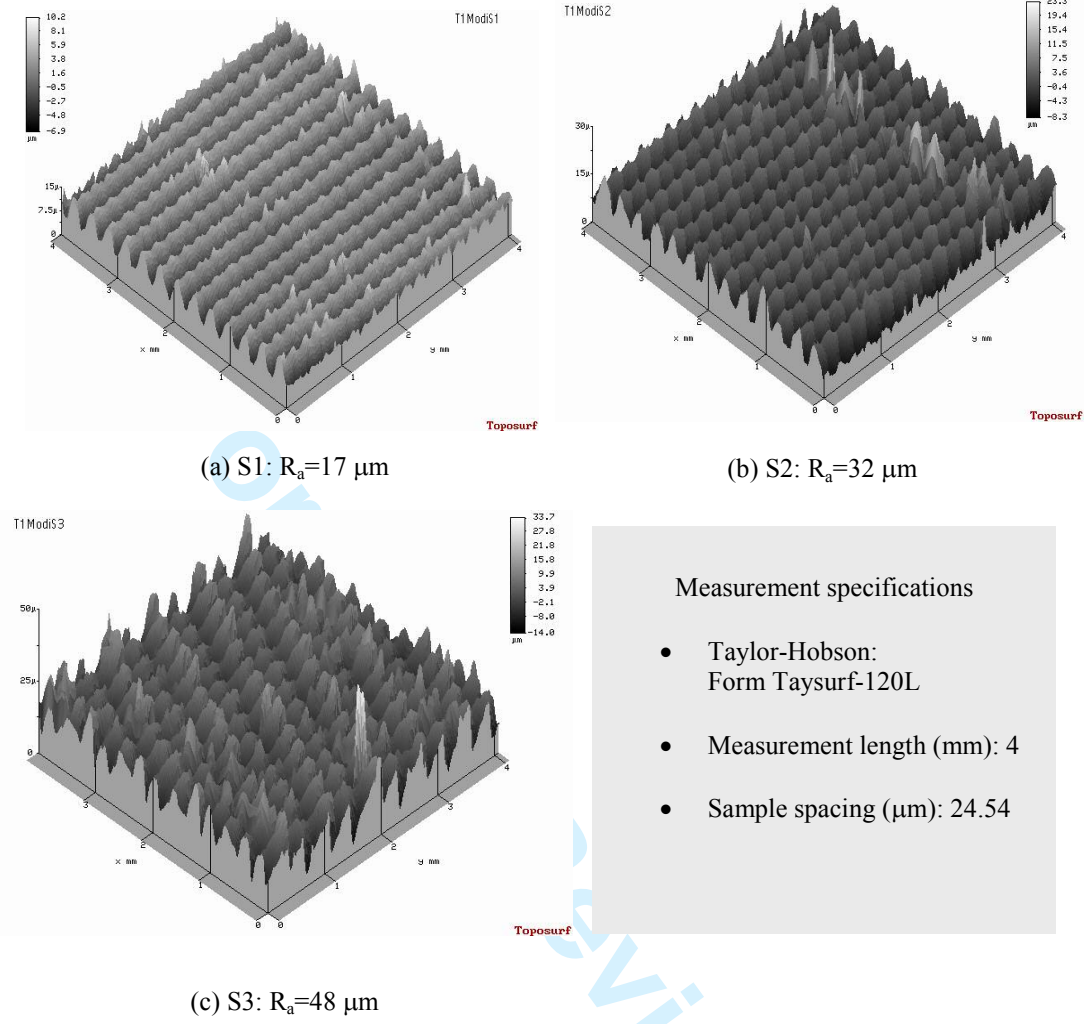


Figure 6 Surface roughness values from the feed rate optimisation software

No	Depth mm	Feed rate mm/tot	Spindle speed rpm	Measured cutting force	
				AF_x	AF_y
CT1	0.24	0.0304	2000	-51.2	4.5
CT2	0.24	0.0614	2000	-83.6	6.5
CT3	0.24	0.0802	2000	-99.8	7.6
CT4	0.24	0.1016	2000	-115.9	9.4
CT5	0.24	0.1205	2000	-134.9	9.6
CT6	0.24	0.1431	2000	-149.8	10.5
CT7	0.24	0.0304	2000	-49.2	4.5
CT8	0.92	0.0304	2000	-138.3	31.2
CT9	1.43	0.0304	2000	-166.2	56
CT10	1.98	0.0304	2000	-160.7	62.9
CT11	2.13	0.0304	2000	-175.5	73.3
CT12	2.82	0.0304	2000	-211	95
CT13	0.24	0.0614	2000	-81.3	6.5
CT14	0.77	0.0614	2000	-172.6	36
CT15	1.22	0.0614	2000	-221.1	60.9
CT16	1.98	0.0614	2000	-276.4	114.6
CT17	2.53	0.0614	2000	-333.4	162
CT18	2.82	0.0614	2000	-341.1	161.4

Table 1 Cutting conditions and measured cutting forces for the model parameter calibration tests

Surface	Depth of cut (mm)	Feed rate (mm/tooth) (From model)	Measured cutting force (N)	
			AF	MF
S1	2	0.088	62.8	406
S2	1.2	0.104	71.7	425
S3	0.8	0.117	68.9	403

Table 2 Measured cutting forces from the cutting force model tests

Surface	Depth of cut (mm)	Feed rate (mm/tooth) (From Software)	Measured cutting force (N)	
			AF	MF
S1	2.0	0.117	84	359
S2	1.2	0.235	128	460
S3	0.8	0.406	175	554

Table 3 Measured cutting forces from the feed rate optimisation software