ISSN 2347-4289

# An Experimental Investigation Of Micromilling

**V. S. Kathavate, P. R. Cheke, A. S. Adkine**

COLLEGE OF ENGINEERING, PUNE 05.
CSMSS' COLLEGE OF ENGINEERING, AURANGABAD 431003
HITECH INSTITUTE OF TECHNOLOGY, AURANGABAD 431133
kathavate_vaibhav@rediffmail.com, prcheke@rediffmail.com, amoladlkine@rediffmail.com

**ABSTRACT:** This study was carried out to understand micro-milling of MILD STEEL material with flat end mill and consisted of three stages: experimental work, analysis and multi objective optimization. In the first stage (experimental work), micro-milling experiments were carried out using Taguchi method. The effects of spindle speed, feed per tooth and depth of cut on MRR and surface roughness were investigated. The effect of control factors on responses was determined by analysis of variance. In the third stage (multi objective optimization), responses were optimized simultaneously using by MINITAB (VERSION 16. 0) analyzing software.

**Key words**: Depth Of Cut (DOC), Feed Rate, Metal Removing Rate, Spindle Speed, Surface Roughness.

## INTRODUCTION:

Nowadays, there have been increasing demands for micro components in many industries such as electronics, optics, aerospace, and medicine and biotechnology. Non-traditional fabrication methods such as laser machining, focused ion beam machining, electrochemical machining and electro discharge machining (EDM)are used to produce micro components, but these methods have limited potential due to the limited work piece material selection, poor productivity and high cost [1]. Apart from these non-traditional methods, micro mechanical machining (micro milling, micro drilling, micro turning, and micro grinding) has gained increasing interest in recent years since it is capable of producing two dimensional structures with a third dimension (2½D) [2] and real three dimensional (3D) microstructures [2, 3], but some drawbacks such as unpredictable tool life [4], burr formation [5–7], chatter [8–10], tool alignment error, high friction due to rubbing at the work piece tool interfaces, poor surface quality restrict its performance. One of the micro mechanical machining processes is micro-milling. Micro milling uses miniature cutting tools which have been adopted from macro tools and many works have been conducted to design and fabricate micro-milling tools [6]. Manufacturing of complex 2D and 3D shapes is possible with micro-milling and micro-components made from a great variety of engineering materials such as polymer [15], aluminum[16], steel [17], copper [18], silicon [19], brass [20], tungsten carbide, glass, composite and NiTi were machined successfully with micro-milling. However, micro-milling of hardened steels is a challenging task due to the unpredictable tool life. The tool deflection and tool edge radius greatly affect the micro-milling performance as compared to macro-milling. Although a lot of researches have been conducted about micro-milling process, there is very little study about optimization of machining parameters in micro-milling. The optimization of surface roughness in micro-milling has been reported by Cardoso and Davim. In some micro milling studies, different design of experiment methods such as response surface, full factorial and Taguchi were used. In macro-machining Taguchi method and grey relational analysis were used to optimize machining performance. Micro-milling, one of the mechanical micromachining methods, is a process that utilizes end mills that typically vary in diameter from 100 to 500 μm and have edge radii that vary from 1 to 10 μm. additionally, the micro-milling process has several Salient features that differentiate it from the macro-end-milling process. [11] Many of the researchers and manufacturers have studied end milling operations to design better tools, to perform machining operations at the optimal cutting condition to monitor tool condition. [7]Cutting forces in micro-milling is the serious problem as it produces undesirable effects on the tool geometry and its wear. [1 and 2] Micromachining is increasingly continuing to have significant impacts on national security, defence, energy, healthcare and domestic manufacturing base. Micro parts being utilized in the electronic and drive system for unmanned reconnaissance planes, for high precision parts used in missile guided systems, for medical devices to deliver medicines in tumors located in fragile internal organs. [12] Micro-milling using a sub millimetre range with end mills diameter, a process of creating features measured in micro meters, is rapidly growing in advance industries. The micro-milling process is the flexible process and used to manufacture more complex microstructures where surface topography and cutting forces are dependent on the cutting parameters [5]. Micro-milling is the capability of producing tedious geometric surfaces with good surface finish and higher accuracy. Material removal rate is one of the most important aspects [17]. Material removal rate greatly having variance with change of cutting parameters in micro-milling operation. Material removal rate indicates the processing time of work piece and it is important factor influencing on production rate and cost [1]. Reliable prediction of cutting forces in micro-milling is essential for design of cutting tool in micro-milling operation as well as planning and machining operation for achieving maximum productivity and quality [4]. Micromilling is a flexible method of fabricating three-dimensional (3-D) features [8]. Increasing popularity of micro/meso milling has sparked the researcher to study the micromilling for quality improvement and for reduction in lead time for achieving the higher productivity including the end use of product. The ratio of feed per tooth to the radius of cutter is much greater than in micromilling than conventional milling which often leads to error prediction in cutting forces. The run out of the tool tip even in small microns also greatly affects on the accuracy of end milling operation in micro scale than conventional milling. Miniature systems can provide probability, disposability, lower material, lower power consumption, lower sample requirements, higher heat transfer and the capability of better process integration and automation. [6]

ISSN 2347-4289

Micro-fabrication requires reliable and accurate process technology and tools. Now a day in present scenario micro-end-milling process is very useful as it produces three dimensional forms of various micro sizes in a wide range. In micro-end-milling the speed of spindle should be very high to maintain the acceptable productivity since the small tool diameter decreases the chip removal rate. In micro milling process High Speed Milling has become a versatile operation in industry full filling the requirements of high productivity and better quality. High geometrical accuracy, reduction in undesirable cutting forces are the advantages of High Speed Milling which finds the application mainly in aerospace and die and mould industry. Micromilling is an intermediate cutting process performed by multi point cutting tool, where the chip formation process is more complex compared to turning operation in continuous cutting action. The uncut chip thickness in micromilling process varies as in one tooth pass in trajectory of trochoid. High Speed Milling can be milling at higher speed or at higher feed rates. The first concept of High Speed Milling in 1931 was presented by Cari J. Salomon who is the father of High Speed Milling and other micro machining process[20]. The fundamental differences in micromilling and conventional milling process arise due to scale of operation, while they are kinematically the same. Micro-milling offers many advantages, such as fast material removal rate and the ability to manufacture parts with true 3D features in a broad range of work piece materials, including hardened tool steels. In current study spindle speed, feed per tooth and axial depth of cut were chosen as machining factors in order to investigate their effects on METAL REMOVING RATE (MRR) and SURFACE ROUGHNESS. So the important point of measurement used in this study was to investigate a relationship between the micro-milling parameters and machinability, performance, including MRR and SURFACE ROUGHNESS. This study presented the optimization of micro-milling for MILD STEEL so as to minimize surface roughness simultaneously using Taguchi based $L^9$ array.

### 1.1. WORKING OF MICROMILLING: (THE STATE-OF-ART PHENOMENON)

In a operation study of micromilling, this concept is demonstrated by modelling of the AMB spindle micromilling machine. This is a state-of-the-art AMB spindle from EAAT GmbH Chemnitz (Elektrische Automatiserungs- und Antriebstechniek), with a relatively high maximum rotational speed of 120, 000 rpm. The rotor length is 250 mm and the rotor mass is 1. 1 kg. The displacement sensors used in the bearings have a resolution of 0.1 μm. The AMB controller hardware also provides measurements of the currents through the coils with an accuracy of 1 mA. The magnetic bearings are controlled by analogue PID controllers.

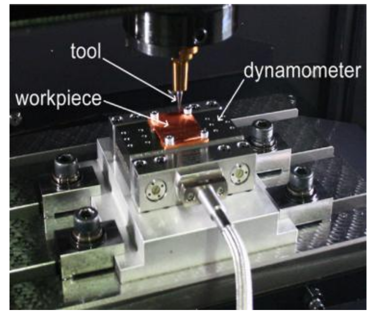


***Fig. No. 1*** *Photograph of dynamometer on the CNC machining centre*

The high rotational velocities of this spindle are required to achieve recommended cutting velocities for good process performance for the machining of most steel and irons (100–500m/min) with miniature End mills of diameters less than 1 mm. In order to select appropriate levels for the tool edge condition, the geometry of the micro-end mills was examined. Here the micro milling set up is shown in following figure

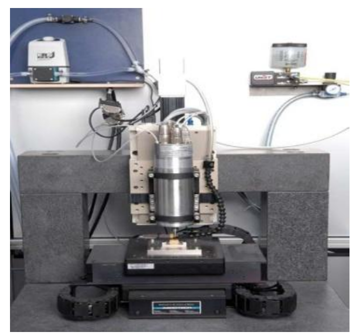

***Fig. No. 2*** *Micro milling set up*

The pictorial view below gives the idea about force measuring in micro milling process

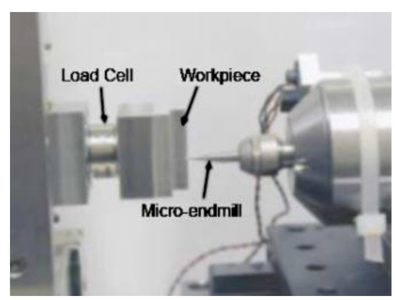


***Fig. No. 3*** *Cutting force measurement in micro milling*

## 2. DESIGN OF EXPERIMENT:

According to Taguchi method of experimentation the procedure of Experimentation is generalized in following manner; 1] Selecting Input parameters 2] Selection of material 3] Proper tool selection 4] Construction of Taguchi $L^9$ array 5] Performing of Experiment

### 2.1 Material Selection:

The micro-milling tests were conducted on the machine of HEARTFORD (E-2 SERIES) VMC milling machine. In the micro- milling experiments, MILD STEEEL (M. S. BAR) material with a Vickers hardness of 120 was used as a workpiece material, which had a dimension of 65mm×35 mm×15 mm. The static run out of tool shaft was measured via dial gauge before each experiment and the values were found to be smaller than 5 µm. Distance between the cutting tool tip and end of tool holder (over hang length)was fixed about 20mm for each experiment. All micro-milling experiments were conducted as down milling method and dry conditions. For each experiment, the tests were carried out on 65mm×35mmblocks of work piece and surfaces were machined at two times (with surface grinding) and tolerance is maintained up to 2µ. The materials used MILD STEEL has shown below in the fig.

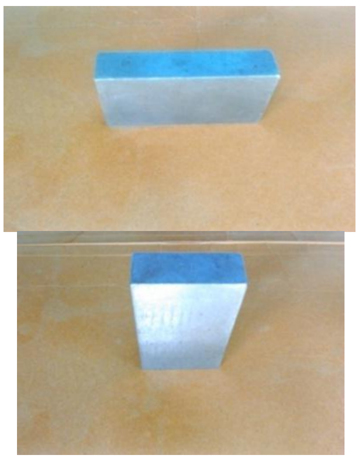

***Fig. No. 4:*** *Mild Steel Material*

### 2.2 Selection of Input Controlled Variables:

Input controlled variables such as Spindle speed (rpm), feed rate (mm/min) and Depth of cut (mm) are designed according to the highest permissible values that the material can withstand with and according machine specifications so as to achieve optimum values of MRR and SURFACE ROUGHNESS. So here the different set of values for different levels is shown below in Table no. 1

***Table no. 1*** *(Input controlled variables with different levels)*

| INPUT VARIABLES | LEVELS | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Spindle Speed (rpm) (X1) | 2800 | 3000 | 3200 |
| Feed Rate(mm/min)(X2) | 600 | 800 | 900 |
| Depth of Cut (mm) (X3) | 0.03 | 0.05 | 0.07 |

### 2.3 Design with Taguchi Method:

Taguchi method uses specially constructed tables named as ''orthogonal array'' to design the experiments and using of these orthogonal arrays diminishes the number of experiments. As a result, experimental cost, effort and time will reduce. Taguchi's L9 orthogonal array was used for the experimental design in order to achieve the aims of how the controlled factors affect the output factors and what the optimal micro-milling controlled parameters to obtain lower tool wear, MRR and Surface Roughness. Spindle speed, feed rate and depth of cut were considered as controlled factors and MRR and Surface Roughness were selected as output factors.

***Table no. 2*** *Taguchi ($L_9$orthogonal array)*

| Experiment | X1 | X2 | X3 |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

### 2. 4 Selection of Tool Materials:

***Table no. 3*** *Tool Material Specifications*

| Sr. No. | Particulars | Specifications | Remarks |
|---|---|---|---|
| 1 | Flat end milling cutter | 1] 3 mm diameter<br>2] 40 mm end mill length<br>3] 5mm shank diameter | With dry/wet conditions |

## 3. EXPERIMENTATION:

Experiment was carried out on the machine Heart ford series or E-2 and all the work is done according to construction of Taguchi $L_9$ ORTHOGONAL ARRAY in pre deterministic way: here the fig. No. 6 below gives the idea about an VMC machining and through all of experiments width of cut and machining time was kept constants.

***Fig. No. 5*** *Micro Milling Process*

The whole experiments were carried out at Pravin Engineering Pvt. Ltd. Ranjangaon M. I. D. C. Aurangabad. Again for experimental analysis the table no. 5 shown below conceptualize the experimentation and final results matrix:

ISSN 2347-4289

***Table no. 5** Final Design Matrix And Results*

| Sr No. | Spindle Speed $X_1$ | Feed Rate $X_2$ | Depth of Cut $X_3$ | MRR gm/min | Surface Roughness Value (µm) |
|---|---|---|---|---|---|
| 1 | 2800 | 600 | 0.03 | 0.175 | 0.68 |
| 2 | 2800 | 800 | 0.05 | 0.3741 | 0.35 |
| 3 | 2800 | 900 | 0.07 | 0.5283 | 0.77 |
| 4 | 3000 | 600 | 0.05 | 0.3016 | 0.59 |
| 5 | 3000 | 800 | 0.07 | 0.5441 | 0.31 |
| 6 | 3000 | 900 | 0.03 | 0.2366 | 0.94 |
| 7 | 3200 | 600 | 0.07 | 0.3166 | 0.80 |
| 8 | 3200 | 800 | 0.03 | 0.167 | 1. 18 |
| 9 | 3200 | 900 | 0.05 | 0.341 | 0.48 |

### 3. 1 Evaluation of MRR:

The material MRR is expressed as the ratio of the difference of weight of the work-piece before and after machining measured by precision weight balance to the machining time.

$W_{JB}$-$W_{JA}$ MRR =-------------T

Where as

$W_{jb}$ = Weight of work-piece before machining
$W_{ja}$ = Weight of work-piece after machining.
T = Machining time (constant T = 12 min)

## 4. RESULT AND DISCUSSION:

### 4. 1 Analysis of Surface Roughness:

### 4. 1. 1 Model Analysis of Surface Roughness in Micromilling:

***Table no. 6** Estimated Regression Coefficients for Surface Roughness Value*

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 0.676786 | 0.09744 | 6.945 | 0.001 |
| Spindle speed($X_1$) | 0.110000 | 0.11829 | 0.930 | 0.395 |
| Feed Rate($X_2$) | 0.08929 | 0.11616 | 0.077 | 0.942 |
| Depth of cut($X_3$) | -0.15333 | 0.11829 | -1.296 | 0.252 |

S = 0.289756 PRESS = 1.60336 R-Sq = 93.78% R-Sq(adj) = 90.00%

**Regression Equation:** SF = 0.676786 + 0.110000($X_1$) +0.008929($X_2$) - 0.15333($X_3$)

***Table no. 7** Analysis of Variance for Surface Roughness Value (µm)*

| Source | DOF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 3 | 0.214163 | 0.214163 | 0.071388 | 0.85 | 0.523 |
| Linear | 3 | 0.214163 | 0.214163 | 0.071388 | 0.85 | 0.523 |
| Spindle speed | 1 | 0.072600 | 0.72600 | 0.072600 | 0.86 | 0.395 |
| Feed rate | 1 | 0.000496 | 0.000496 | 0.000496 | 0.01 | 0.942 |
| Depth of cut | 1 | 0.141067 | 0.141067 | 0.141067 | 1.68 | 0.252 |
| Residual Error | 5 | 0.419793 | 0.419793 | 0.083959 | | |
| Total | 8 | 0.633956 | | | | |

### 4. 1. 2 Residual Plots for Surface Roughness:

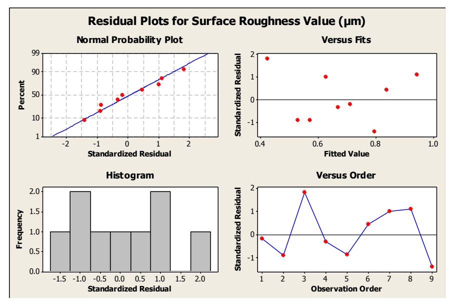


***Fig. no. 6** Residual plots for Surface Roughness (4 in 1)*

### 4. 2 Analysis for Metal Removing Rate:

### 4. 2. 1 Model Analysis of metal removing rate in Micromilling:

***Table no. 8** Estimated Regression Coefficients for MRR*

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 0.32561 | 0.01388 | 23.466 | 0.000 |
| Spindle speed($X_1$) | -0.04190 | 0.01684 | -2.487 | 0.055 |
| Feed Rate($X_2$) | 0.05521 | 0.01654 | 3.338 | 0.021 |
| Depth of cut($X_3$) | 0.13493 | 0.01684 | 8.010 | 0.000 |

S = 0.0412610 PRESS = 0.0328294 R-Sq = 94.22% R-Sq (adj) = 90.75% **Regression Model:** MRR = 0.32561 – 0.04190($X_1$) + 0.05521($X_2$) + 0.13493($X_3$) Table no. 9Analysis of Variance for MRR

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 3 | 0.138745 | 0.138745 | 0.046248 | 27.17 | 0.002 |
| Linear | 3 | 0.138745 | 0.138745 | 0.46248 | 27.17 | 0.002 |
| Spindle Speed | 1 | 0.010534 | 0.010534 | 0.010534 | 6.19 | 0.055 |
| Feed rate | 1 | 0.018969 | 0.018969 | 0.018969 | 11.14 | 0.021 |
| Depth of cut | 1 | 0.109242 | 0.109242 | 0.109242 | 64.17 | 0.000 |
| Residual Error | 5 | 0.008512 | 0.008512 | 0.001702 | | |
| Total | 8 | 0.147257 | | | | |

#### 4.2.2 Residual Plots for Metal Removing Rate:

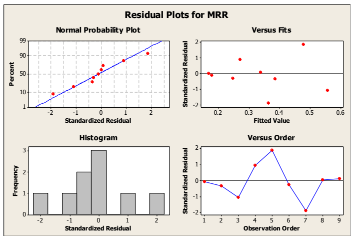


***Fig. no. 7*** *Residual plots for MRR (4 in 1)*

#### 4.3 Multi Objective Optimisation in Micro-milling: 4.3.1 Optimisation Graph:

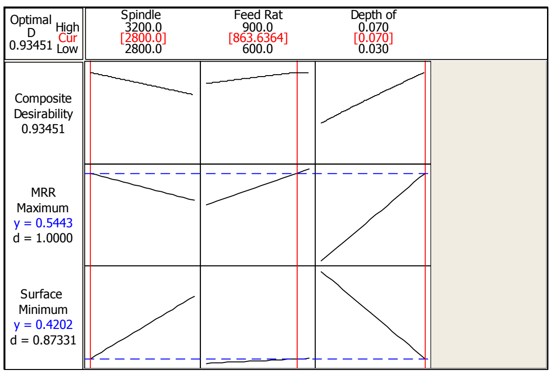


***Fig. no. 8*** *Optimization Graph*

The graph above shown indicates that the values for response optimization for achieving maximum MRR and minimum surface roughness. It was found that the increment of the spindle speed decreased surface roughness. The decreasing surface roughness with the increase in spindle speed was explained by the built up edge on the flank surface of the cutting tool and by the tool deflection orthogonal to the feed direction. On contrary it was found that surface roughness increased with an increment of spindle speed. In this study surface roughness increases with an increment of feed rate and depth of cut. It was found that surface roughness decreased largely as feed rate increases 600 to 800 mm/min. thus, using a larger axial depth of cut is an effective way in order to increase the machining efficiency without affecting tool breakage and tool life. Surface roughness can be minimized by utilizing lower value of feed rate and depth of cut with higher spindle speed.

#### 4. 3. 2 Response Optimization:

***Table no. 10*** *Response Optimization Table*

| Parameters | Goal | Lower | Target | Upper | Weight | Import |
|---|---|---|---|---|---|---|
| MRR | Maximum | 0.5441 | 0.5441 | 0.5441 | 1 | 1 |
| Surface Roughness | Minimum | 0.3100 | 0.3100 | 1.1800 | 1 | 1 |

- Starting Point
  Spindle Speed = 2800 (rpm)
  Feed Rate= 600 (mm/min)
  Depth of Cut = 0.03 (mm)
- Predicted Responses

MRR = 0.544272, desirability = 1.000000
Surface Roughness =0.420216, desirability = 0.873314, Composite Desirability = 0.93451 From the above response optimization table it reciprocates in the final optimized solution of the maximum metal removing rate and minimum surface roughness by controlling three different parameters according to Taguchi $L^9$ array. The predicted responses with composite desirability are 0.934513 having actual desirability of 0.873314. For the spindle speed of 2800 rpm and feed rate of 863. 63 mm/min with axial depth of cut 0.07 mm the maximum metal removing rate is 0.54427 gm/min by keeping time 12 min. constant. The minimum roughness indicated as 0.3100 µm.

## 5. CONCLUSION:

In this study, the effects of spindle speed, feed rate and depth of cut on MRR and surface roughness during micro-milling of mild steel were investigated using Taguchi experimental design method. All data gathered in the experimental studies were used to formulate and analysed using MINITAB 16. 0 software. Responses were used alone in optimization study as an objective function. From multi-objective optimization it was concluded that the optimal values for minimizing tool wear were spindle speed of 2800 rpm, feed rate of 800 mm/min and depth of cut of 0.07mm. With these values maximum metal removing rate (MRR) and minimum Surface Roughness can be achieved. Tool wear increased with spindle speed and depth of cut. Initially an increment of tool wear with increasing of feed per tooth was observed however as feed rate was further increased, tool wear eventually decreased. Multi objective optimization is carried out by using analysis of variance ANOVA to optimize two responses simultaneously (to maximize MRR and minimize surface roughness) in one set of input variables. It is observed that, maximum MRR and minimum surface roughness was obtained simultaneously when the work piece was employed to the spindle speed of 2800 rpm, feed rate of 800 mm/min and depth of cut of 0.07mm. It is also observed that, to obtain maximum MRR (0.5441) and minimum surface roughness (0.31) simultaneously when employ low range of axial depth of cut and optimum range of spindle speed with moderate feed rate. Thus to optimise the responses depth of cut eventually contributes up to 44. 38%, following feed rate up to 35% and spindle speed having the contribution of 18% approximately.

## ACKNOWLEDGMENTS:

We want to deliberate the sincere thanks to Pravin Engg. Ltd. , Aurangabad and Micronix Callibration Centre, Aurangabad. We are also indebt thankful to Prof. P. R. Cheke of CSMSS'College of engineering, Aurangabad. Our sincere gratitude is to Prof. R. S. Pawar for his continuous encouraging support.

ISSN 2347-4289

## REFERENCES:

[1] Emel Kuram , Babur Ozcelik, "Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill", Measurement 46 (2013) pp 1849–1864.

[2] J. L. Liow, "Mechanical micromachining: a sustainable micro-device manufacturing approach", Journal of Cleaner Production 17 (2009) pp 662–667.

[3] C. J. Morgan, R. R. Vallance, E. R. Marsh, "Micro machining glass with polycrystalline diamond tools shaped by micro electro discharge machining", Journal of Micromechanics and Microengineering 14 (2004) pp 1687–1692.

[4] M. Rahman, A. Senthil Kumar, J. R. S. Prakash, "Micro milling of pure copper", Journal of Materials Processing Technology 116 (2001) pp 39– 43.

[5] F. Z. Fang, Y. C. Liu, "On minimum exit-burr in micro cutting", Journal of Micromechanics and Microengineering 14 (2004) pp 984–988.

[6] Ch. Horsch, V. Schulze, D. Löhe, "Deburring and surface conditioning of micro milled structures by micro peening and ultrasonic wet peening", Microsystem Technologies 12 (2006) 691–696.

[7] A. J. Mian, N. Driver, P. T. Mativenga, "A comparative study of material phase effects on micro-machinability of multiphase materials", The International Journal of Advanced Manufacturing Technology 50 (2010) pp 163–174.

[8] B. A. Mascardelli, S. S. Park, T. Freiheit, "Substructure coupling of microend mills to aid in the suppression of chatter", ASME Journal of Manufacturing Science and Engineering 130 (2008) pp 011010.

[9] R. Rahnama, M. Sajjadi, S. S. Park, Chatter suppression in micro end milling with process damping, Journal of Materials Processing Technology 209 (2009) pp 5766–57

[10] S. S. Park, R. Rahnama, "Robust chatter stability in micro-milling operations", CIRP Annals – Manufacturing Technology 59 (2010) pp 391–394.

[11] M. B. G. Jun, K. Bourne, R. E. DeVor, S. G. Kapoor, Estimation of effective error parameters in high-speed micro-endmilling, International Journal of Machine Tools and Manufacture 47 (2007) 1449–1454.

[12] A. Marcon, S. Melkote, K. Kalaitzidou, D. DeBra, An experimental evaluation of graphite nanoplatelet based lubricant in micro-milling, CIRP Annals – Manufacturing Technology 59 (2010) 141–144.

[13] T. Schaller, L. Bohn, J. Mayer, K. Schubert, Microstructure grooves with a width of less than 50 mm cut with ground hard metal micro end mills, Precision Engineering 23 (1999) 229–235.

[14] C. R. Friedrich, M. J. Vasile, Development of the micromilling process for high-aspect-ratio microstructures, Journal of Microelectromechanical Systems 5 (1996) 33–38.

[15] C. Li, X. Lai, H. Li, J. Ni, "Modeling of three dimensional cutting forces in micro-end milling", Journal of Micromechanics and Micro engineering 17 (2007) pp 671–678.

[16] X. Lai, H. Li, C. Li, Z. Lin, J. Ni, "Modelling and analysis of micro scale milling considering size effect, micro cutter edge radius and minimum chip thickness", International Journal of Machine Tools and Manufacture 48 (2008)1–14.

[17] T. Yun, S. Heo, M. K. Lee, B. K. Min, S. J. Lee, "Ploughing detection in micromilling processes using the cutting force signal", International Journal of Machine Tools and Manufacture51(2011)pp377–382.

[18] H. Li, X. Lai, C. Li, J. Feng, J. Ni, "Modelling and experimental analysis of the effects of tool wear, minimum chip thickness and micro tool geometry on the surface roughness in micro-end-milling", Journal of Micromechanics and Microengineering 18(2008) pp 025006.

[19] Rusnaldy, T. J. Ko, H. S. Kim, "Micro-end-milling of single-crystal silicon", International Journal of Machine Tools and Manufacture 47 (2007) pp 2111–2119.

[20] Rusnaldy, T. J. Ko, H. S. Kim, "An experimental study on microcutting of silicon using a micromilling machine", The International Journal of Advanced Manufacturing Technology39(2008) pp85–91.