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A Summary Note On Micro-Turning

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The present paper emphasized comprehensible texts on some important aspects relating to the micro-turning (micromachining) process and on the chip formation mechanism during micro-turning of metallic alloys. Conventionally processed material, when subjected to conventional machining, is unable to produce the necessary surface quality characteristics for certain important applications. For an item to function as a miniaturized part, its machined surface must be free of any defects. The micro-turning process can be the suitable process route to produce miniaturized components (micro-pins, micro-shafts, etc.) with superior precision and accuracy. The miniature components need absolute surface perfection to function. To resolve the matter, some unusual consideration is needed for the process parameters during micro-turning. For example, to introduce a higher negative rake tool during micro-turning. Use of a sharp tool provides better accuracy for conventional machining. But this condition is not applicable for micro-turning since the uncut chip thickness (micron) is comparable to the edge radius of the micro-tool. The present study will be helpful to understand the reasons for the attainment of better surface and sub-surface quality characteristics of micro-turned components.

Keywords: Quality characteristics, machining, micro-turning (micromachining)

Introduction

The micro-machining process is usually for the production of micro-injection moulds, watch parts, optical devices, biomedical and electronic parts, etc. The effect of higher negative rake on the tool plays a vital role during micro-turning. Micro-turning is performed with a tool having a higher negative rake angle that may be beyond the usual range. The conventional machining process as such occurs with a tool having a rake angle between -10^{o} and +10^{o}. The value of the negative rake angle of the tool for micro-turning has been larger beyond the conventional range. For that, the tool used in micro-turning possesses a round curvature (the radius of curvature is on a micro scale) at the cutting edge in order to present a higher negative rake effect to the work-piece during micro-turning [1]. The purpose of selecting the higher negative rake angle is to cause a plasticity transition of the work material due to higher heat generation on the surface as well as the region just beneath the surface up to the depth of a few microns from the surface of the work material. Plasticity transition of the work material at higher temperature causes the release of internal residual stress (defect) as well as helps to minimize the chance of crack formation in the work material (surface and sub-surface). The nature of the tool used in micro-turning is schematically shown in Fig. 1.

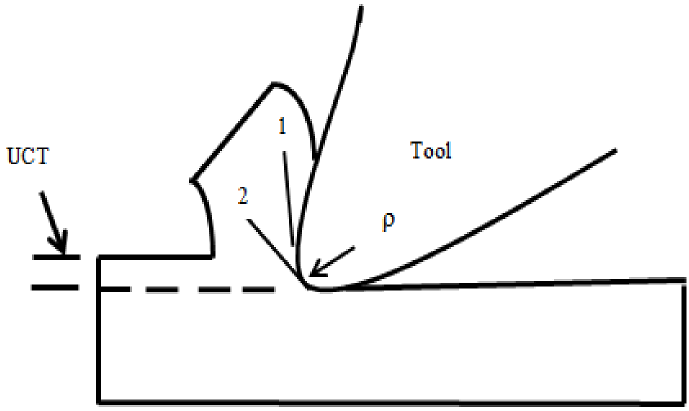


Fig. 1 ρ is the radius of curvature of the tool in micro scale (UCT: uncut chip thickness).

Different tangents to the curved profile (Fig. 1) indicate variations of negative rake values to the higher order from tangent 1 to tangent 2. But, unlike grinding, micro-turning occurs with a tool having specific tool geometry. In the case of grinding, tool (grit) geometry changes throughout the process. Such changes in tool (grit) geometry during grinding with a higher negative rake effect cause a number of adverse effects, like the introduction of residual stress, metallurgical structural changes of the ground surface, etc.

A critical UCT exists in micro-turning that is the minimum UCT at which a chip starts forming. Material removal in the case of micro-turning occurs at a lower UCT just exceeding the critical (minimum) UCT. In this condition, the spring-back phenomenon of the micro-turned surface does not occur, and this causes dimensional stability of the work-piece. At this machining condition also, plasticity transition of the work material takes place due to higher temperature generation on the work surface and at the region just beneath the work surface up to a depth of a few microns. The plasticity transition at the surface of the work-piece causes the release of residual stresses (defects). The micromachining occurs under the following conditions:

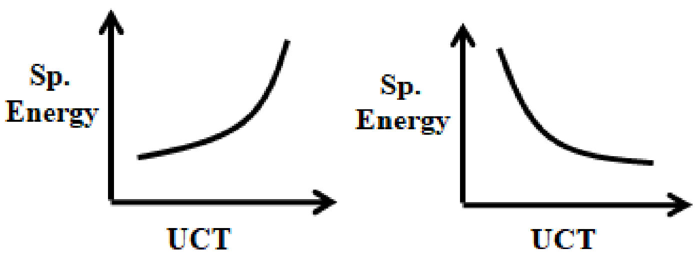
1) During micro-turning, the UCT is always less than the radius of curvature of the tool.

2) The uncut chip thickness is less than the average of the smallest grain sizes of the work material.

3) The uncut chip thickness must be greater than the critical (minimum) uncut chip thickness.

4) The uncut chip thickness should be less than 999 μm [2-4].

The specific energy is defined by the amount of energy required to remove a unit volume of material. Usually the specific energy requirement (during conventional machining) is higher at higher UCT and lower at lower UCT (Fig. 2a). This is justified by the cutting force requirement, which is always higher at higher UCT and lower at lower UCT. But in the case of micro-turning, a higher specific energy requirement is for lower UCT, and a lower specific energy requirement is for higher UCT (Fig. 2b). The size effect in micro-turning is a different phenomenon that happens during micro-turning. There is always some depth beneath the surface at which defects (dislocations, etc.) are present. In order to remove the material during micro-turning, the elastic stress field has to travel to the depth to encounter a defect. But when the UCT is less, more energy is required to encounter a defect. Thus, the specific energy requirement is higher at lower UCT during micro-turning. But when the UCT is higher, then the elastic stress field can encounter defects easily, and the specific energy requirement decreases (Fig. 3). This phenomenon of increased specific energy requirements at lower UCT and lower specific energy requirements at higher UCT is known as the size effect in micro-turning. The obtained results on measurement of depth of plasticity transition (subsurface deformation) (δ) versus uncut chip thickness (UCT) showed that the ratio (δ/UCT) is about 200 at UCT = 0.01 μm. But the same ratio was two orders of magnitude smaller at UCT = 1 μm. The mean defect spacing for the work material (Te/Cu alloy) was 1 μm. Thus, the elastic stress field penetrates very deep to encounter a defect (dislocation) for plastic flow to take place at UCT = 0.01 μm. This caused a higher specific energy requirement at UCT = 0.01 μm than when UCT = 1 μm or greater. This showed a higher specific energy requirement at a lower UCT (0.01 μm). This finding illustrated the size effect in micromachining [5]. A very high specific energy requirement (≈ 11 GPa) at (UCT/ρ) ≈ 0.1 and a very low specific energy requirement (≈ 2.8 GPa) at (UCT/ρ) ≈ 1 occurred during micro-cutting of an aluminium alloy. A similar trend was also available for micro-cutting of copper alloy. This observation further showed the size effect in micro cutting [6]. The micro-turning is not influenced by the bulk properties of materials. Micro-turning is influenced by the individual grain type of the material. [7-9].



(a) (b)

Fig. 2 Specific energy requirement (a) Conventional machining (b) Micro-turning.

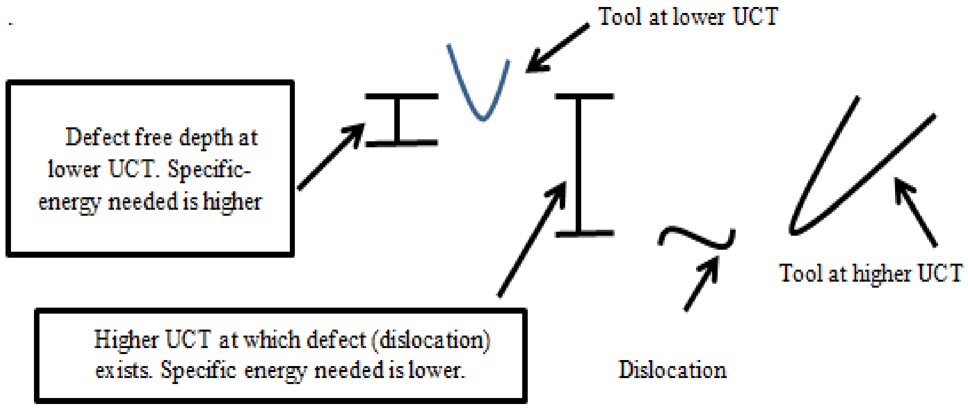


Fig. 3 Schematic diagram showing the tool to pass through defect free region during micro-turning. Tool at higher UCT encounters defect easily.

Ploughing is an adverse effect that occurs when the UCT is less than the minimum UCT (critical). Ploughing occurs by side flow of the material during micro-turning (Fig. 4). At this micro-turning condition, the higher negative rake effect of the tool further attributes to severe heat generation, causing severe thermal damage to the work surface. The extensive ductility transition of the material at this machining condition is also a cause for the size effect in micro-turning. The strain gradient effect may also be another cause of the size effect in micro-turning [10–16].

At the lower uncut chip thickness, a higher specific energy requirement is also due to the material strengthening effect of high strain and higher strain rate hardening during micro-turning. This phenomenon also contributes to the size effect observed in micro-turning [17].

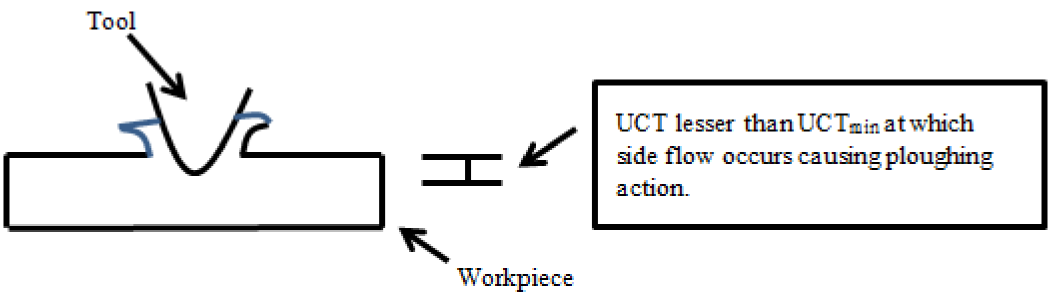


Fig. 4 Ploughing phenomenon.

Usually during a conventional machining process, main cutting force is always greater than the thrust force. However, during micro-turning, thrust force is greater than the main cutting force, which is again somewhat different. There are some specific considerations during micro-turning that leads to the occurrences that are somewhat different. The micro-turning is performed at a condition at which the UCT just exceeds the critical (minimum) UCT and at this machining condition the thrust force drops slightly (greater than main cutting force) indicating an ideal condition for micro-turning to take place (Fig. 5). Under such a condition heat is developed just beneath the tool, and a small volume of material at the surface undergoes plasticity transition that helps to eliminate the chance of any defect formation. Chance of crack formation at this condition is reduced due to the compressive hydrostatic stress generation at the surface and subsurface. A severe hydrostatic stress (compressive) generates with reduced UCT in comparison to the radius of curvature. Such stress resulted in chip formation by the extrusion process. The Fig. 6 schematically shows the extruded chip formation process. The micro-turning in fact occurs in the ductile regime mechanism [18, 19, 20 and 21]. When UCT is less than the radius of the tool, the effective rake angle for the tool attains such a large negative value that a large volume of material attains a fully plastic state to escape as a chip through micro-extrusion during single-point diamond (precision) turning [22]. The experimental determination of minimum UCT is also possible based on surface roughness (Ra) measurement. The authors turned (precision) Al 6082 alloy with a CBN (cubic boron nitride) tool and determined the surface roughness (Ra) value as a function of the ratio of UCT to the cutting edge radius (ρ), i.e., (UCT/ρ). The study indicated that the minimum value of surface roughness (Ra ≈ 0.06 μm) occurred at (UCT/ρ) = 0.08. Thus, the machining at threshold (UCT/ρ) = 0.08 will generate superior surface finish. The (UCT/ρ) ratio represents the normalized UCT. The ratio (UCT/ρ) = 0.08 (threshold) represents the normalized minimum UCT. The Ra value increased below the threshold value and above the threshold value. A higher value of Ra below the threshold clearly indicated the occurrence of the ploughing phenomenon [23, 24]. Shimada et al [25] performed molecular dynamic simulation to predict the surface finish using edge-radius tooling in diamond turning. They claimed that minimum UCT was the major limiting factor on accuracy as the generated surface finish deteriorated due to ploughing process when the UCT is less than the minimum UCT. They showed that minimum UCT during chip formation was (1/20) of the cutting edge radius for diamond turning of copper and aluminium with edge radii of 5 to 10 nm.

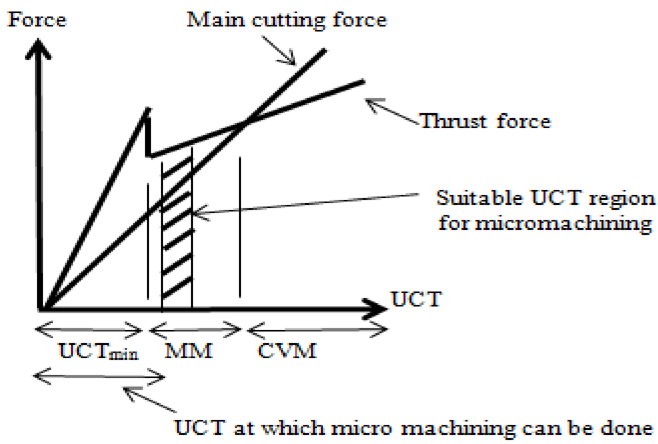


Fig. 5 Schematic diagram to show different machining regions, (MM: micro machining, CVM: conventional machining).

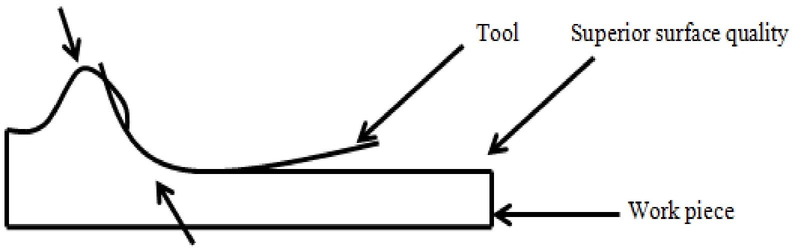


Fig. 6 Schematic representation of extruded chip formation.

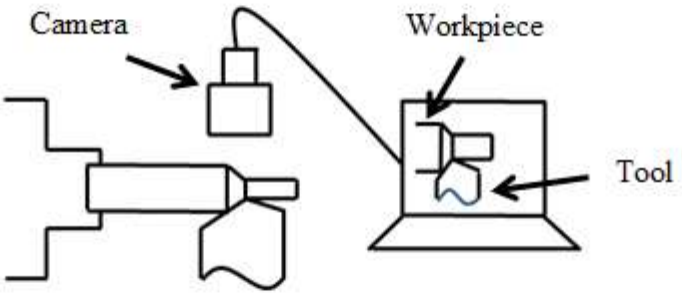


Fig. 7 The micro machining process in the computer screen.

Since micro-turning occurs at micro scale, the formed chips are not visible like the case with conventional machining. A camera connects the computer to view the chips during micro-turning (Fig. 7). The monitoring device helps to understand the UCT_{min}, and subsequently the process occurs with little incremental increase of UCT from UCT_{min}.

The chip formation mechanism for micro-turning can be explained by considering the micro-turning of pearlitic steel. The Fig. 8(a) shows the schematic diagram of pearlite. In case of micro-turning, the tool is actually moving through the individual phases (Fig. 8(b)) since the size of the UCT is comparable with the size of the individual smallest grain during micro-turning. As a result, individual phases (Fe_3C, α-Fe etc.) behave like pure material. Although Fe_3C is very hard and brittle conventionally, even then it bends as shown in Fig. 8(b) indicating the ductile behaviour of the Fe_3C. This happens because property of material is actually the function of the scale of deformation. Since the material removal in case of micro machining is taking place at micro scale, all these different kind of deformation behaviour of the material occurs. One more phenomenon occurs during micro-turning because of squeezing effect of softer (α) ferrite between bent cementites. The softer ferrite gets squeezed and forms plumes through quasi-shear extrusion process (Fig. 9) of α ferrite between bent cementites during micro machining. From this illustration it is clear that the behaviour of a material depends much upon the scale of deformation. Harder material may behave like softer material depending upon the scale of deformation. The identity of a material can be known during the processing since a harder material may behave like softer material. In-situ behaviour of the material is very important. The quality characteristics of the machined surface are very much depending on to the in-situ behaviour of the material. A micro machined component can have superior quality characteristics of the surface (devoid of any defects) and subsurface [26, 27].

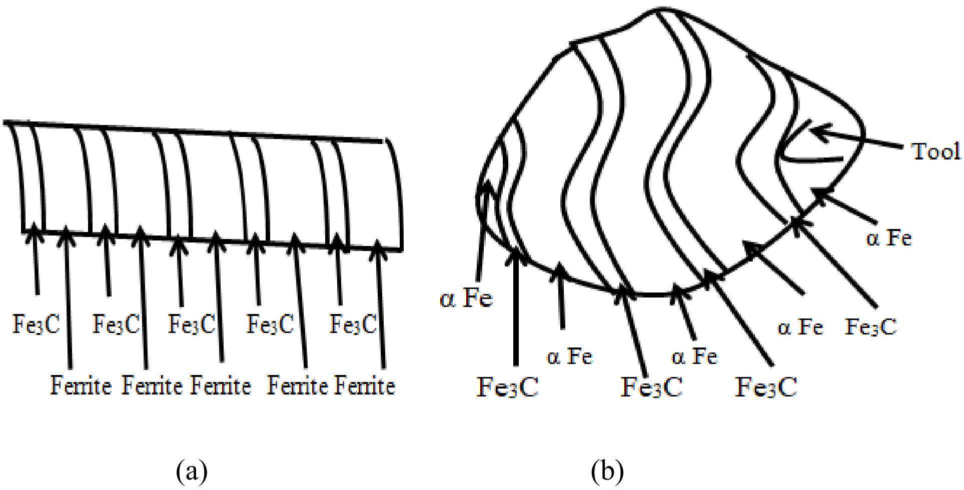


Fig. 8 Schematic representation of (a) pearlite (b) path of tool through individual phases during micro-turning, causing bending of Fe_3C.

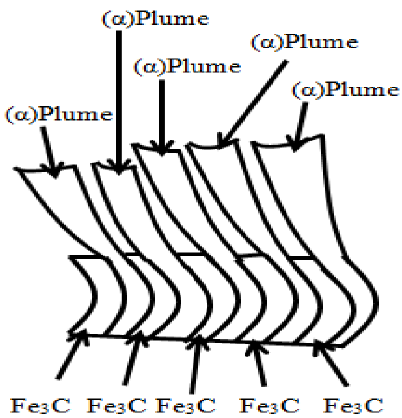


Fig. 9 Deformation behavior of pearlitic phase during micro-turning (schematic).

High-energy laser beams are sometimes used during micro-tool fabrication. The method is not very suitable, as the thermal energy from the photons falling on the work surface can change the properties. Additionally, initial costs and energy consumption are higher. Presently, mechanical machining is very effective for micro-tool fabrication. A specific computer numerically controlled machine tool is used and material removal takes place in a controlled way during mechanical machining. Higher dimensional accuracy attainment is also possible during mechanical machining [28].

The present text implies that the study emphasizes the following salient factors of micro-turning:

i) Use of a higher negative rake tool.

ii) Micro-turning condition.

iii) Specific energy requirement during micro-turning.

iv) Critical factor (UCT_{min}) to understand an ideal condition of micro-turning to take place.

v) Reasons for attainment of superior surface characteristics.

vi) Chip formation mechanism during micro-turning of pearlitic steel.

vii) The role of micro-scale deformation to cause material property transition during chip formation in micro-turning that influences the attainment of superior surface characteristics.

viii) Effectiveness of mechanical machining for micro-tool fabrication.

Conclusion

Micro-turning is a process route to generate surfaces that are devoid of any defects. Micro-turning is usually applied to work pieces to generate superior quality characteristics of the surface. The effect of higher negative rake angle is the dominating factor for attainment of superior quality characteristics of the micro turned component. The next dominating factor for the superior quality characteristics is the micro-scale deformation during the chip formation process in micro-turning. The basic difference between conventional machining and micro-turning is that conventional machining occurs at the macro scale (average bulk property of the material influences) and micro-turning occurs at the micro scale (property of individual phase influences). The machining process as such is a deformation-based process. The quality characteristics of the machined surfaces depend upon the in-situ behaviour of the material during processing. The most important feature in this context about material properties is that the property of material (e.g., strength, toughness, hardness, etc.) is a function of scale of deformation. The superior quality characteristics of the micro-turned component are also attributed to the deformation of the material during micro-turning at a much smaller scale (micro scale). The present study will be helpful for easier understanding of the micro-turning process behaviour, especially in respect of the chip formation process during micro-turning.

References

[1] M. A. Rahman, M. Rahman, M. Mia, M. K. Gupta,, B. Sen, A. Ahmed, Investigation of the specific cutting energy and its effect in shearing dominant precision micro cutting, Journal of Materials Processing Tech. 283 (2020) https://doi.org/10.1016/j.jmatprotec.2020.116688

[2] J. J. Wang, Y. Liao, Critical depth of cut and specific cutting energy of a microscribing process for hard and brittle materials, J. Eng. Mater. Technol. 130(1) (2008) 011002, https://doi.org/10.1115/1.2806253

[3] M. P. Vogler, R. E. DeVor , S. G. Kapoor, On the modeling and analysis of machining performance in micro-end milling, Part I: Surface generation. J. Manuf. Sci. Eng. 126(4) (2004) 685-694. https://doi.org/10.1115/1.1813470

[4] M. Agmell , D. Johansson, S. V.A. Laakso, A. Ahadi, J.E. Stahl. The influence the uncut chip thickness has on the stagnation point in orthogonal cutting, 16th CIRP conference on modelling of machining operations, Procedia CIRP. 58 (2017) 13 – 18.

[5] M.C.Shaw, Precision finishing, Annals of the CIRP. 44/1(1995) 343-348.

[6] M. A. Rahman, M. Rahman, M. Mia, M.K. Gupta, Investigation of the specific cutting energy and its effect in shearing dominant precision micro cutting, Journal of materials processing technology. 283 (2020) 116688, https:// doi.org/10.1016/j.jmatprotec.2020.116688

[7] X. Liu, R. E. DeVor, S. G. Kapoor, K. F. Ehmann, The mechanics of machining at the microscale: Assessment of the current state of the science, J. Manuf. Sci. Eng. 126(4) (2004) 666-678. https://doi.org/10.1115/1.1813469

[8] S. Subbiah, N. Shreyes, Melkote, Evidence of ductile tearing ahead of the cutting tool and modeling the energy consumed in material separation in micro-cutting, J. Eng. Mater. Technol. 129(2) (2007) 321-331. https://doi.org/10.1115/1.2712471

[9] A. Simoneau, E. Ng, M.A. Elbestawi, Grain size and orientation effects when microcutting AISI 1045 steel, Annals of the CIRP. 56 (2007) doi:10.1016/j.cirp.2007.05.016

[10] K. Liu, N. Shreyes, Melkote. Effect of plastic side flow on surface roughness in micro-turning process, International journal of machine tools and manufacture, 46(14) (2006) 1778-1785. https://doi.org/10.1016/j.ijmachtools.2005.11.014

[11] P.K. Basuray, B.K. Misra, G.K. Lal, Transition from ploughing to cutting during machining with blunt tools, Wear. 43 (3) (1977) 341-349.

[12] A.C. Ramos , H. Autenrieth , T. Strau , M. Deuchert , J. Hoffmeister , V. Schulze**,** Characterization of the transition from ploughing to cutting in micro machining and evaluation of the minimum thickness of cut, Journal of Materials Processing Technology. 212(3) (2012) 594-600.

[13] S. Subbiah, N. Shreyes. Melkote, Evaluation of Atkins' model of ductile machining including the material separation component, Journal of materials processing technology. 182 (1–3) (2007) 398-404.

[14] S. Subbiah, N. Shreyes. Melkote, The constant force component due to material separation and Its contribution to the size effect in specific cutting energy, J. manuf. sci. eng. 128(3) (2006) 811-815. https://doi.org/10.1115/1.2163363

[15] P. Michael, Vogler, R. E. DeVor , S. G. Kapoor, On the modeling and analysis of machining performance in micro-endmilling, Part I: Surface generation, J. manuf. sci. eng. 126(4) (2004) 685-694. https://doi.org/10.1115/1.1813470

[16] S. S. Joshi, N. Shreyes N. Melkote, An explanation for the size-effect in machining using strain gradient plasticity, J. Manuf. Sci. Eng. 126(4) (2004) 679-684. https://doi.org/10.1115/1.1688375

[17] K. Liu, S. N. Melkote, Material strengthening mechanisms and their contribution to size effect in micro-cutting, J. Manuf. Sci. Eng. Aug 2006, 128(3) (2006) 730-738. https://doi.org/10.1115/1.2193548

[18] X. Liu, R. E. DeVor, S. G. Kapoor, An analytical model for the prediction of minimum chip thickness in micromachining, J. Manuf. Sci. Eng. 128(2) (2006) 474-481. https://doi.org/10.1115/1.2162905

[19] N.P. Wayne, Hung, M. Corliss, Micromachining, Chapter 1, Micromachining of advanced materials (2019) DOI: 10.5772/intechopen.89432

[20] S. Wojciechowski, Estimation of minimum uncut chip thickness during precision and micro-machining processes of various materials—A critical review, Materials. 15 59 (2022) https://doi.org/10.3390/ma15010059

[21] K.S. Woon, M. Rahman, F.Z. Fang, K.S. Neo, K. Liu, Investigations of tool edge radius effect in micromachining: A FEM simulation approach, journal of materials processing technology. 195 (2008) 204-211

[22] M.C. Shaw, A new theory of grinding, Mech and chem engg, Trans. Inst, Engrs. (Australia), (1972) MCB: 73-78.

[23] S.Wojciechowski, Estimation of minimum uncut chip thickness during precision and micro-machining processes of various materials- A critical review, Materials. (2022) 1-22, https://doi.org/10.3390/ma15010059is
[24] M. A. Rahaman, M. rahman, A.S.Kumar, Chip perforation and burnishing like finishing of Al alloy in precision machining , Precis. Eng. 50 (2017) 393-409.
[25] S. Shimada, N. Ikawa, H. Tanaka, G. Ohmori, J. Uchikoshi, H. Yoshinaga, Feasibility study on ultimate accuracy in microcutting using molecular dynamics simulation, CIRP Ann. 0007-8506, 42 (1993) 91-94.
[26] Simoneau, E. Ng, M.A. Elbestawi, Grain size and orientation effects when microcutting AISI 1045 Steel, CIRP Annals. 56 (1) (2007) 57-60.
[27] A. Simoneau, E. Ng, M.A. Elbestawi, Chip formation during microscale cutting of a medium carbon steel. International journal of machine tools and manufacture. 46 (5) (2006) 467-481. https://doi.org/10.1016/j.ijmachtools.2005.07.019
[28] O. John, F. Fengzhou, Advances in micro-cutting tool design and fabrication, International journal of extreme manufacturing, 1 (2019) 032003, 1-29, DOI: 10.1088/2631-7990/ab3e7f