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EDITORIAL COMMENTARY

Miniaturization by precision micro cutting

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Abstract

The trend of increasing miniaturization for various industrial applications serves the basic progress of precision micro cutting adopted for wide variety of materials and alloys. Different from conventional metal cutting, the precision micro cutting deals with some important process parameters along with cutting edge geometry, material property, microstructure, and material removal phenomena. Significant research on micro cutting mechanics, an established science in metal cutting, has been conducted to explore the basics of micro manufacturing towards miniaturization. This article, thus, becomes a chronological presentation of the critical analysis of breakthrough research in precision micro cutting process.

Keywords: Miniaturization; Precision micro cutting; Material behavior; Cutting edge effect; Surface finishing.

Miniaturization by precision micro cutting

Miniaturization of products and components, the recent trend in industrial and manufacturing process, is widely spreading for various applications such as silicon chips for computation/information technology (Jahan et al., 2011), micro channels for micro fluidics in biotechnology (Perveen et al., 2012), micro lens array for automobiles and optical instruments (Arif et al., 2011; Neo et al., 2012), micro spinneret for textile microfibers (M Rahman et al., 2007), microshaft in micromotor for electromechanical drives (Mustafizur Rahman et al., 2007), micro tools for single/compound micro machining (Habib et al., 2009; Mustafizur Rahman et al., 2010) and micro electrodes for measurement probes (Rahman et al., 2019). Micromachining is the vital technology to augment such increasing demand of product miniaturization. A collective push on the technology development of miniature machine, micro cutting process and on-machine metrology, thus, contributes to micromachining as depicted in Fig. 1(a) (M Rahman et al., 2010). Moreover, hybridization of conventional cutting processes (such as milling, drilling, turning) with non-conventional machining processes (such as EDM, EDG, ECM) can realize micro parts and features on almost all kind of materials (Asad et al., 2007). In this respect, better understanding of cutting dynamics helps the adoption of tool based micro cutting in the rapid miniaturization of a variety of precision products for the electronics, aerospace and biomedical industry (Ng et al., 2006; Rahman et al., 2001). By adopting CNC microturning, which is a miniaturized version of conventional material removal process, compound shaped micropin was produced for biomedical application (Rahman et al., 2005), as shown in Fig. 1(b). Thus, micro turning can be used to realize complex 3D shape by using a solid cutting tool (Rahman et al., 2003). However, several factors which are trivial in conventional machining become noteworthy in micro cutting to fabricate complex features and to impart high quality finishing surface required for micro parts (M. A. Rahman, M. Rahman, et al., 2018b; M. A. Rahman, M. Rahman, A. S. Kumar, et al., 2018). These critical factors-cutting edge radius effect, material property and microstructural effect-will be discussed here.

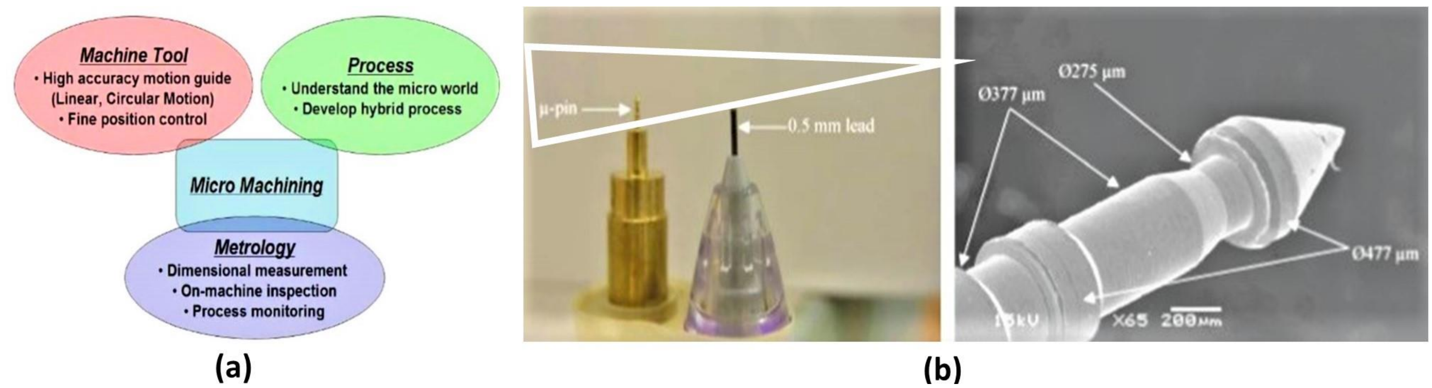

Fig. 1. (a) Collective push on technologies required for micromachining (M Rahman et al., 2010), (b) miniaturized compound shaped pin (Rahman et al., 2005). Reprinted with permission.

Edge radius effect in micro cutting: Since the product miniaturization progresses through mechanical micro cutting, much attention is required towards the understanding of cutting mechanics as micro cutting is not just scaling down the conventional macro cutting. This is due to the increased proportion of the cutter participating in the micro cutting process than in conventional cutting as a result of higher depth of cut (d) to tool diameter (D) ratio as illustrated for end milling in Fig 2(a). Moreover, assumption of perfectly sharp cutting tool in conventional machining is not valid for micromachining as the undeformed chip thickness (*a*) becomes comparable to the cutting tool edge radius (*r*) as shown in Fig. 2(b) (Woon et al., 2008). In micro cutting, as the undeformed chip thickness (*a*) is reduced, the material removal characteristics changes at a particular ratio of *a*/*r* when the material flow occurred in the opposing direction of tool motion similar to the 'extrusion-like behavior'. Finite element analysis (FEA) of micromachining of AISI 4340 showed extrusion-like chip formation (at *a*/*r*=0.2625) differing completely with conventional chip formation in shearing mechanism. Transformation of effective positive rake angle ($+\gamma_{eff}$) to effective negative rake angle ($-\gamma_{eff}$) is a remarkable characteristic of extrusion-like mechanism which produces high quality surface (Woon & Rahman, 2010). Therefore, micro cutting mechanics is significantly affected from the evolution of cutting-edge radius effect as the material removal scale is lowered to micrometer level.

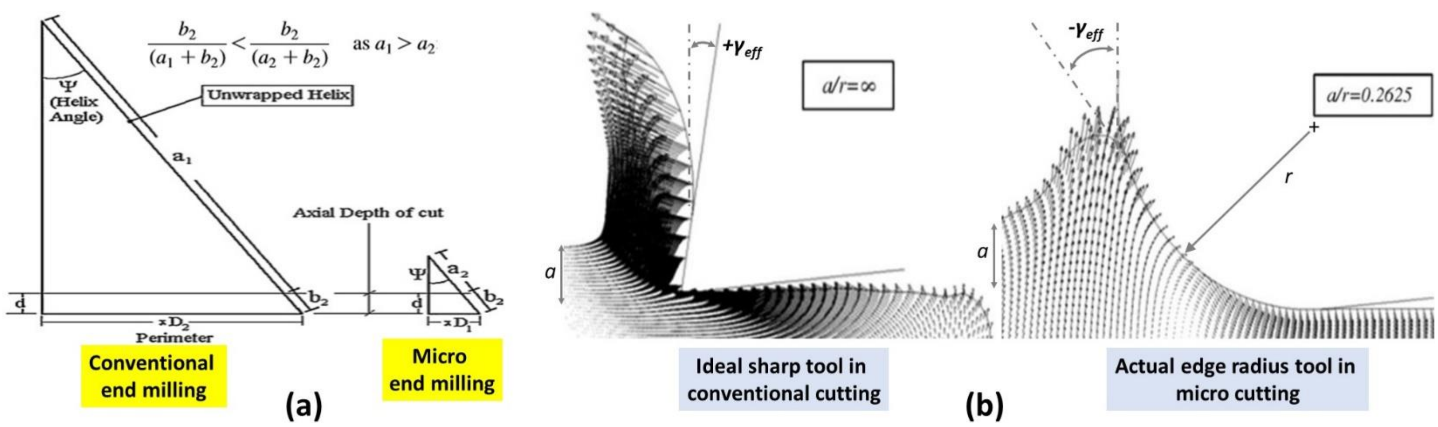

Fig. 2. Illustration of the difference between (a) conventional and micro end milling (Zaman et al., 2006), (b) ideal sharp tool (r = 0) in conventional cutting and actual tool with edge radius (r) in micro cutting (Woon et al., 2008). Reprinted with permission.

Material behavior in extrusion-like cutting: Currently, almost all metallic materials and alloys are adopted for micro cutting applications. However, different materials have different characteristics and properties for which the micro cutting process parameters will vary especially for the critical threshold value of *a*/*r* in extrusion-like cutting. An innovative experimental technique for the rapid characterization of 'extrusion-like' finishing surface is established based on material hardness as illustrated in Fig. 3(a) (Rahman, Amrun, et al., 2017). It can be concluded that the harder the material, the smaller is the threshold value of $(a/r)_{critical}$ for achieving best surface finishing. Additionally, it is found that the location of the 'extrusion-zone' moves away further from the machined surface for softer material (AZ91D) than harder material (AISI 1045) as illustrated in Fig. 3 (b) (M. A. Rahman, M. Rahman et al., 2018a). Thus, the critical ratio *a*/*r*, % engagement of cutting-edge radius with undeformed chip thickness, for a cutting tool changes with the behavior of workpiece material properties in micro cutting.

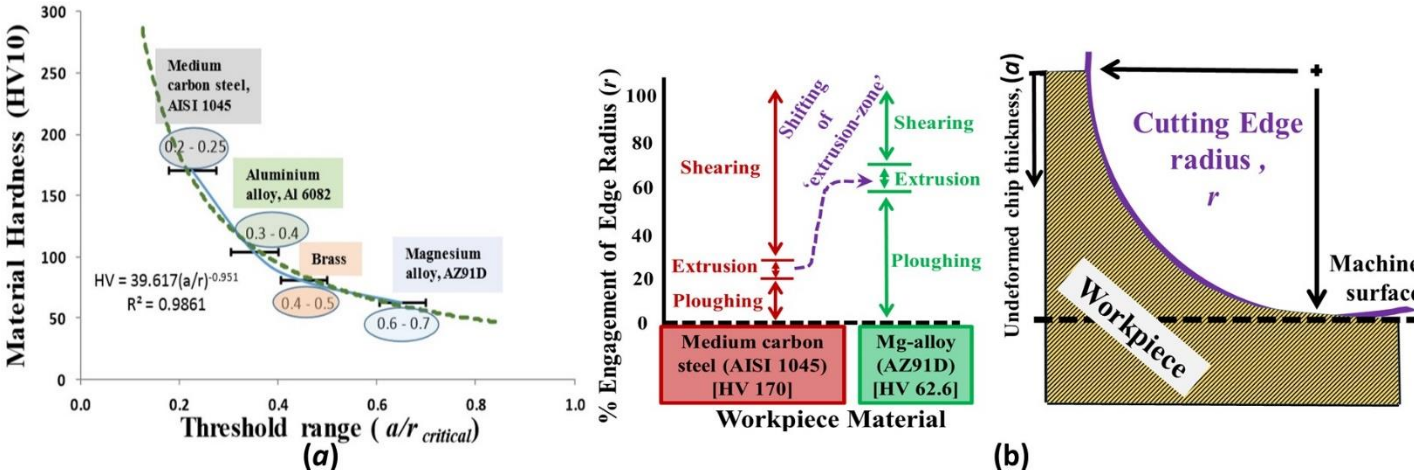

Fig. 3. Illustration of the (a) variation of material hardness with *a/r* for achieving 'extrusion-like' finishing (Rahman, Amrun, et al., 2017), (b) Shifting of 'extrusion-like' machining zone for different materials of AISI 1045 and AZ91D as a function of (*a/r*) (M. A. Rahman, M. Rahman, et al., 2018a). Reprinted with permission.

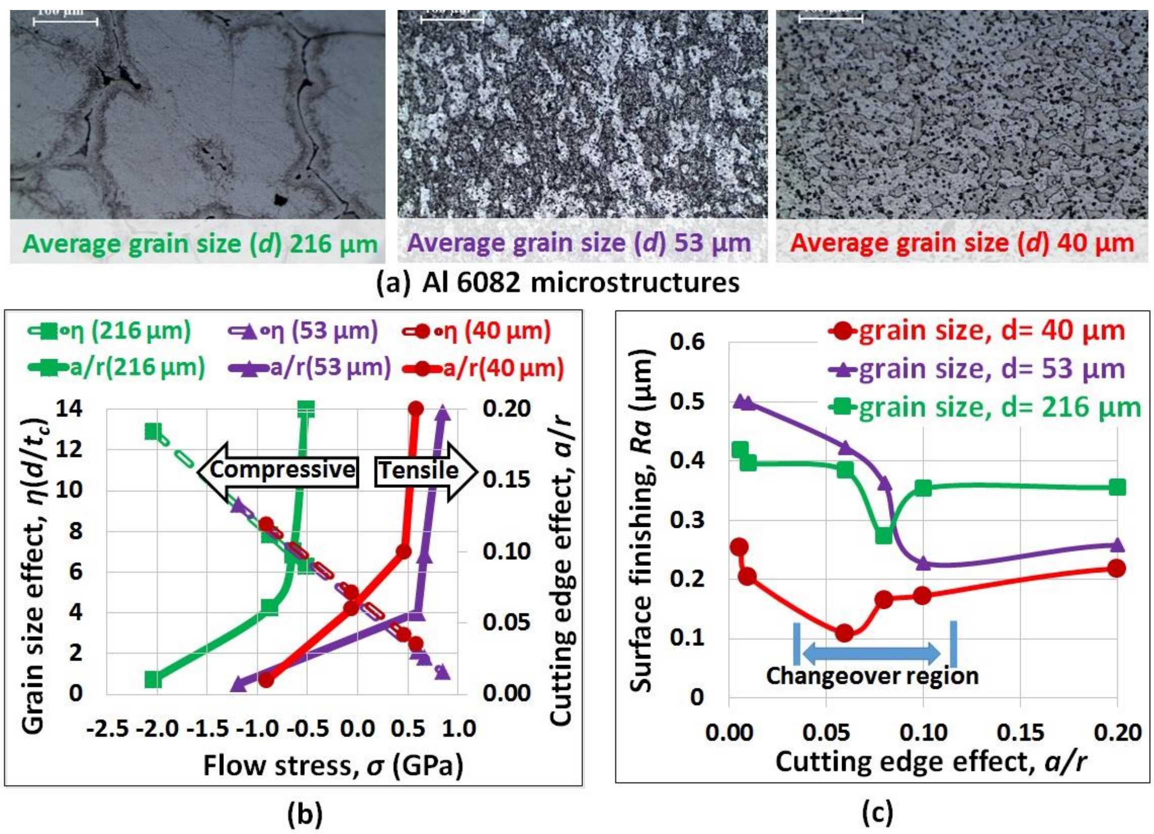

Fig. 4. For Al 6082 alloy, variation of (a) microstructures, (b) flow stress with grain size and cutting edge effect, (c) cutting edge effect with surface finishing as function of grain size (M. Rahman et al., 2018). Reprinted with permission.

Microstructure effect: It is known that the variation of material properties arises from its microstructural properties, grain size and structure. Most of the materials and alloys used for micro cutting process are polycrystalline materials where the grain size varies in the range from micro to nano meter. Additionally, single phase material behaves differently than multiphase materials due to the presence of secondary phase. Thus, micro cutting mechanics is affected by materials microstructures when material removal scale is reduced to micron-scale. Hence, material flow stress model is developed to analyze the machining performance by incorporating the material 'grain size effect' in ultra-precision machining (Rahman, Rahman, et al., 2017). The model is experimentally validated with Al 6082 material with different grain sizes of varied microstructures achieved by heat treatment. Moreover, the results of the combined cutting edge and microstructural effect is illustrated in Fig.4 (M. Rahman et al., 2018). The microstructural (grain size) effects are observed as smaller material grains lead to the transition from tensile to compressive stress as shown in Fig. 4(b). This is due to the reduction of *a/r* towards the extreme condition which yields highly compressive stresses on the machined surface. Additionally, a 'changeover region' is observed for cutting edge effect to achieve higher surface finishing as shown in Fig. 4(c). Thus, micro cutting phenomena changes from material separation (tensile stress) to material deformation (compressive stress) mechanism which has been captured from the combination of material microstructure and cutting-edge effect with surface finishing results.

Conclusion and outlook: Precision micro cutting, a dominant process in micro manufacturing, has been discussed to understand the effects of notable factors on the micro mechanics of material removal and surface generation. Future outlook of micro cutting very much relies on towards the combination of resources on miniature machine tool development, material behavior, characterization and process mechanics to realize miniature products in wide variety of industrial applications. Customized cutting tool geometry and on-machine metrology can also advance the micro cutting technology.

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