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Characteristics and Formation Mechanism for Stainless Steel Fiber with Periodic Micro-fins

TANG Tao, WAN Zhenping*, LU Longsheng, and TANG Yong

School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

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Abstract: Metal fibers have been widely used in many industrial applications due to their unique advantages. In certain applications, such as catalyst supports or orthopedic implants, a rough surface or tiny outshoots on the surface of metal fibers to increase surface area are needed. However, it has not been concerned about the surface morphologies of metal fiber in the current research of metal fiber manufacturing. In this paper, a special multi-tooth tool composed of a row of triangular tiny teeth is designed. The entire cutting layer of multi-tooth tool bifurcates into several thin cutting layers due to tiny teeth involved in cutting. As a result, several stainless steel fibers with periodic micro-fins are produced simultaneously. Morphology of periodic micro-fins is found to be diverse and can be classified into three categories: unilateral plane, unilateral tapering and bilateral. There are two forming mechanisms for the micro-fins. One is that periodic burrs remained on the free side of cutting layer of a tiny tooth create micro-fins of stainless steel fiber produced by the next neighboring tiny tooth; the other is that the connections between two fibers stuck together come to be micro-fins if the two fibers are finally detached. Influence of cutting conditions on formation of micro-fins is investigated. Experimental results show that cutting depth has no significant effect on micro-fin formation, high cutting speed is conducive to micro-fin formation, and feed should be between 0.12 mm/r and 0.2 mm/r to reliably obtain stainless steel fiber with micro-fins. This research presents a new pattern of stainless steel fiber characterized by periodic micro-fins formed on the edge of fiber and its manufacturing method.

Keywords: stainless steel fiber, periodic micro-fins, burrs, chip morphology

1 Introduction

Metal fibers have been greatly developed due to their high performance of elasticity, wear ability, good electrical, and thermal conductivity. Currently, a wide range of methods is used to manufacture metal fibers including bundle-drawing[1], die less drawing[2], melt extraction[3–4] and cutting method. Since NAKAGAWA, et al[5], produced short length steel fibers for composite materials on a milling machine, cutting methods were extensively developed and can now be used to manufacture both long and short fibers for different materials. LI, et al[6], developed vibration cutting to manufacture short metal fibers. KANEKO, et al[7], proposed coiled sheet shaving for production of metal fibers. CHEN, et al[8], suggested rotary cutting to fabricate metallic fibers using advanced industrial materials. LIU, et al[9], used a combined method of microsaw turning and pulling to produce long metal fibers. TANG, et al[10], proposed peripheral milling process with an end-milling cutter to manufacture aluminum fibers. WAN, et al[11], proposed chip-splitting method to manufacture slim long red copper fibers.

This work presents a new pattern of stainless steel fiber—stainless steel fiber with periodic micro-fins manufactured using a specially designed multi-tooth tool. Micro-fins and born jagged surface of stainless steel fibers provide a higher specific surface area, hinder primer particles aggregation at high temperature and promote adhesive strength of the primer to the metal fiber support while using porous sintered stainless steel fiber substrates as combustion catalyst supports to disperse active phase[12–13]. Micro-fins structure is useful in orthopedic applications as they favor bone anchoring and improve mechanical interlocking at bone-implant interface when stainless steel fiber networks are used in bioimplants[14]. A critical problem associated with manufacturing of stainless steel fibers is related to the formation of the micro-fins. Available metal cutting theories and references focus on chip control[15], chip flow, chip curl and chip breaking[16] and radius prediction of curled chip[17]. These theories and references on chip formation can be hardly applied to elucidating the formation of stainless steel fiber with periodic micro-fins.

This paper presents the characteristics of stainless steel fiber with periodic micro-fins. In addition, mechanisms contributing to the formation of micro-fins are investigated

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* Corresponding author. E-mail: zhpwan@scut.edu.cn

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along with the influence of cutting conditions on micro-fin morphologies.

2 Experimental Procedures

2.1 Design of special multi-tooth tool

To manufacture stainless steel fibers with periodic micro-fins, a special multi-tooth tool was designed. This special multi-tooth tool is shown in Fig. 1. A row of tiny teeth with 45° inclination angle and triangular cross-section were machined on the nominal flank face of the multi-tooth tool. Every tiny tooth was composed of a cutting edge S_1, S_2 and line l. Controlled parameters for the tooth include width m and height h. Machining was carried out using wire electrical discharge machining. In Fig. 1, γ_o and α_o are nominal rake angle and clearance angle respectively. Multi-tooth tool was installed by rotating it an angle θ=45° counterclockwise and is shown in Fig. 2. As seen in Fig. 2, several stainless steel fibers can be manufactured from this setup as several tiny teeth are involved in cutting process simultaneously. The line l interferes the cutting process, as line l is parallel to the axis of workpiece.

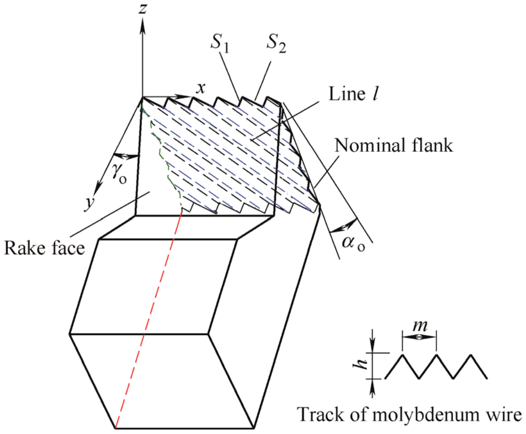


Fig. 1. Schematic drawing of multi-tooth tool

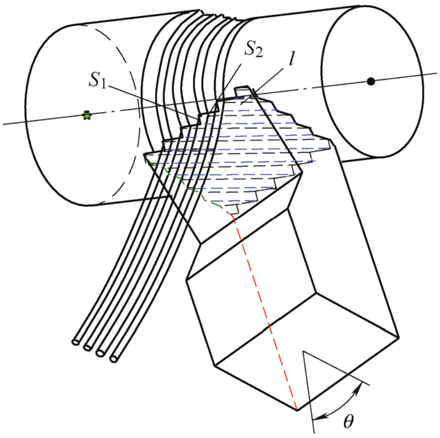


Fig. 2. Geometric cutting model of the multi-tooth tool

2.2 Cutting conditions

Dry cutting experiments were carried out using a precise lathe C6132A. Stainless steel 1Cr18Ni9Ti was used as workpiece with diameter 65 mm. A tungsten carbide tool was used to machine workpiece under different cutting conditions. According to mass experimental results, parameters for the special multi-tooth tool used in this study were m=0.3 mm, h=0.2 mm, γ_o=30°, α_o=8°.

3 Characteristics of Stainless Steel Fiber with Micro-fins

Fig. 3 shows micrographs for front and back of the stainless steel fiber with micro-fins. From Fig. 3, micro-fins appear to be periodic on the edge of fiber. Moreover, the micro-fins and fiber regions form an integral entity. Shear-induced lamella structures can be observed on the free surface of the micro-fins and fiber. Striated marks on the joints between micro-fins and fiber are continuous. Micro-fins appear as outshoots integrated with the stainless steel fiber body. Shape mutations on the free surface are joints between chip and micro-fins.

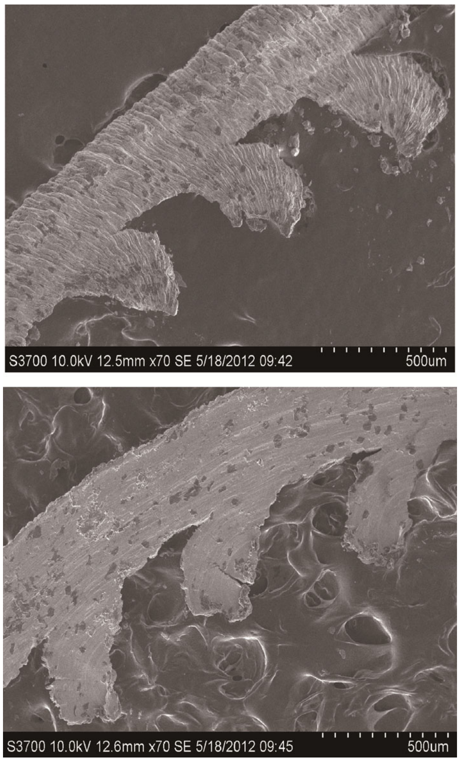


Fig. 3. Micrographs of stainless steel fiber with micro-fins

Lamella structures are known to form the basic feature of free surface of chip. Although, chips generated using high-speed cutting and in the machining of difficult-to-cut materials typically present saw-tooth shape[18–20]. However, periodic micro-fins generated on the edge of stainless steel fibers are different from lamella structures and saw-tooth shape chips. Therefore, the stainless steel fiber with periodic micro-fins is a new pattern of chip. As mentioned previously, a critical problem related to the manufacturing of this type of stainless steel fiber is associated with control of the micro-fin formation process. Understanding mechanisms associated with the micro-fin formation along with the influence of cutting conditions is critical for this kind of stainless steel fiber manufacturing.

4 Mechanism for Formation of Stainless Steel Fiber with Periodic Micro-fins

4.1 Cutting mechanism of the multi-tooth tool

Several stainless steel fibers can be produced simultaneously as shown in Fig. 2. The multi-tooth tool can bifurcate the entire cutting layer into several thin cutting layers. Fig. 4 illustrates this mechanism used for cutting layer bifurcating with the special multi-tooth tool. As shown in Fig. 4, if all tiny teeth are disregarded, the special multi-tooth tool becomes a tool with single-straight cutting edge denoted by line *AC*. In Fig. 4, b_D represents contact length between line *AC* and the workpiece; a_p and *f* are cutting depth and feed respectively. Points *E*, *F* and *G* indicate apexes of discretional three teeth of the multi-tooth tool. Cutting layers of the three discretional teeth *E*, *F* and *G* correspond to the hatched sections on the reference plane *YOX*. Thus, the entire cutting layer is bifurcated into several thin cutting layers due to the tiny teeth. As a result, several slim long stainless steel fibers are produced. This is known as chip bifurcating. In Fig. 4, *Δ* denotes cutting depth for a tiny tooth of the multi-tooth tool to distinguish it from a_p.

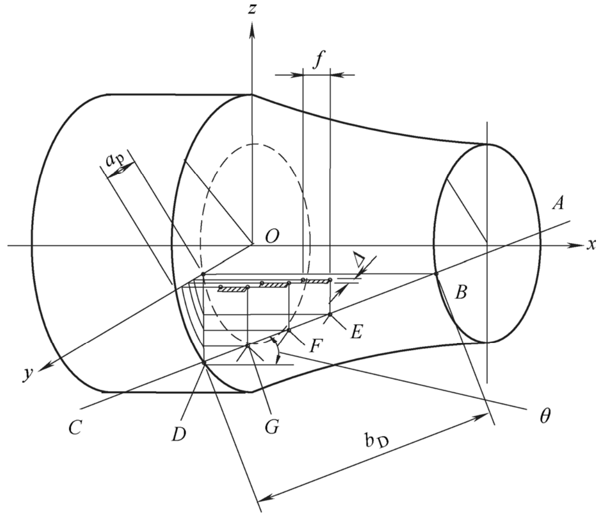


Fig. 4. Cutting layer bifurcating model for a multi-tooth tool

4.2 Mechanism of micro-fins formation

It is suggested by mass experiments that micro-fins formation results from burrs that remain on the machined surface of a tiny tooth and critical chip bifurcating.

4.2.1 Burr formation on machined surface of a tiny tooth

When the entire cutting layer is bifurcated into several pieces of fibers completely, cutting process of every tiny tooth involved in cutting operates independently. Each tiny tooth in the multi-tooth tool is composed of cutting edge S_1, S_2 and line *l* (shown in Fig. 1). As shown in Fig. 2, line *l* is parallel to the reference plane and the included angle between *X*-axis and line *l* is α_o at a counterclockwise angle of 45°. Nominal cutting layer for a tiny tooth (e.g., tooth *G*) is divided into two sections by cutting edge S_2: section I and section II (as shown in Fig. 5). The stainless steel fiber is produced when section I is removed by the cutting edge S_1 and S_2. At the same time, section II is also removed under the joint action of cutting edge S_2 and line *l*.

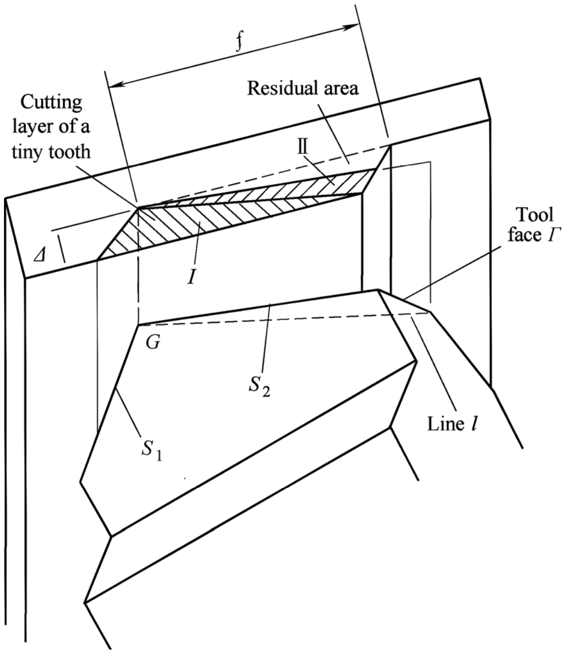
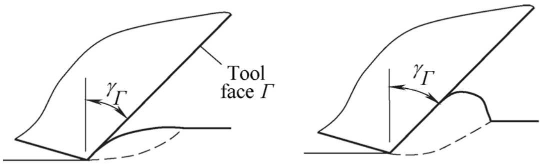


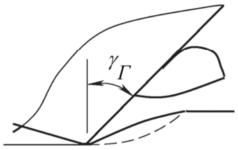
Fig. 5. Cutting layer of a tiny tooth of multi-tooth tool

Cutting edge S_2 and line *l* constitute the tool face *Γ* as indicated in Fig. 5. From Fig. 5, tool face *Γ* is seen to have a large negative rake angle when cutting section II. For example, if m=0.3 mm, h=0.2 mm, γ_o=30°, α_o=8°, rake angle of tool face *Γ* γ_Γ is –51.5°. When, tool face *Γ* enters the workpiece, cutting begins at a normal shear angle as shown in Fig. 6(a). As cutting proceeds, this process resembles an extrusion process rather than concentrated shear in orthogonal cutting. This is related to the large negative rake angle. In this case, tool face *Γ* extrudes the deformed metal in the cutting zone and it accumulates ahead of the tool face *Γ* as shown in Fig. 6(b). Thus, a chip in form of ribbon shape cannot be formed. At the same time, material accumulated in the front of tool face *Γ* flows towards the free side of the cutting layer (as shown in Fig. 7). This is the velocity vector of the finite element mode used for analyzing effect of tool face *Γ* on metal flow of section II in extrusion deformation. The side flow materials are the embryo of burrs. When, strain in the accumulated chip reaches a critical value, a chip fracture occurs as shown in Fig. 6(c). In this way, discrete chip segments form as illustrated in Fig. 8. When, accumulated chip fractures and moves away from the bulk, side flow ceases. As a result, discrete burr is formed. Subsequently, the process begins again. Therefore, a series of discrete burrs form on the free side of cutting layer of a tooth (shown in Fig. 9). With the cutting process being continued, series of discrete burrs left on the machining surface of a tooth, e.g., tooth *G* turns into part of cutting layer of the next neighboring tooth, e.g., tooth *F*, as shown in Fig. 10 since several tiny teeth take part in cutting simultaneously. Thus, a series of discrete burrs remaining on the machining surface of a tooth become periodic micro-fins on stainless steel fiber, which are produced by the next neighboring tooth.



(a) Tool face Γ enters workpiece

(b) Deformed metal accumulating and flowing towards free side



(c) Accumulated chip fracturing and burr formation

Fig. 6. Sketches of discrete burrs formation

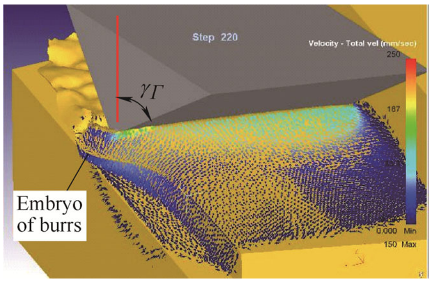


Fig. 7. Side flow of materials accumulated in the front of tool face Γ

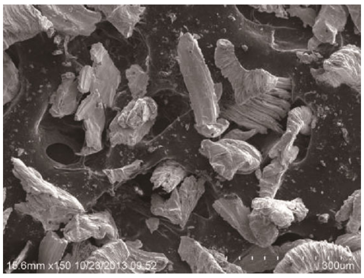


Fig. 8. Photograph of discrete chip segments

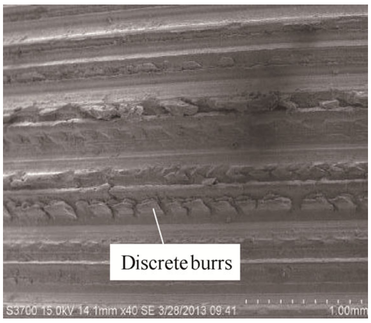


Fig. 9. Discrete burrs formed on the free side of cutting layer of a tooth

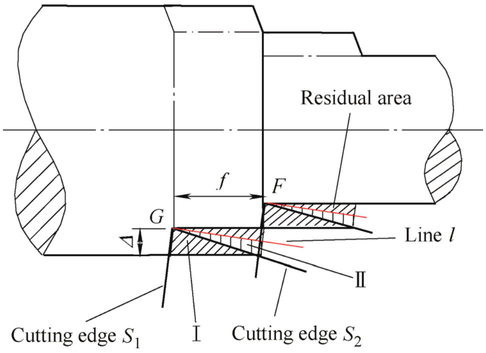
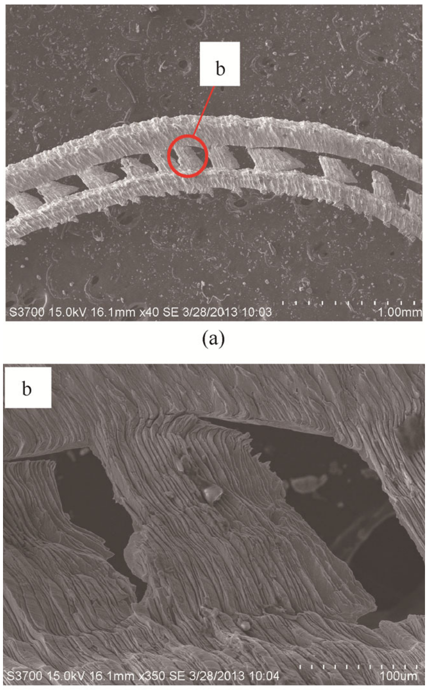


Fig. 10. Cutting layers of two neighboring tiny teeth of multi-tooth tool: Burrs left on machining surface of tooth *G* will turn into part of cutting layer of the next neighboring tooth *F*

4.2.2 *Critical chip bifurcating*

As shown in Fig. 11, several fibers produced simultaneously are prone to stick together when the chip bifurcating approaches or is in critical chip bifurcating state. The connections between two fibers are also the embryos of periodic micro-fins. If the two fibers stuck together are finally detached due to differences of chip flow direction and chip flow speed, unilateral plane micro-fins or bilateral micro-fins form on the edge of stainless steel fiber. Fig. 11(b) clearly presents the tearing action between two fibers since the chip flow direction and speed of the two fibers are different. Furthermore, the micro-fins and stainless steel fiber are monolithic and shear deformation occurs on the free surface of micro-fins as shown in Fig. 11(b). In practice, bilateral micro-fins cannot be obtained. Moreover the process is not stable as it is difficult to control chip bifurcating completely in the critical state or in the vicinity of critical state.



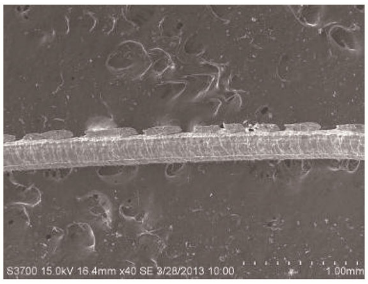
(b)

Fig. 11. Critical chip bifurcating state

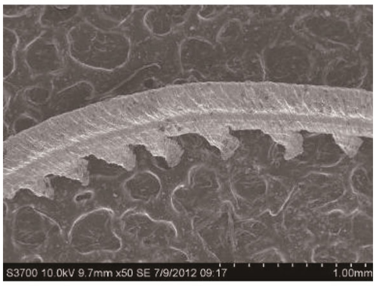
5 Effects of Cutting Conditions on Micro-fin Formation

5.1 Morphological classification of stainless steel fiber with periodic micro-fins

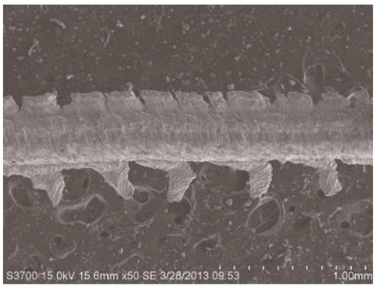
Morphologies of the stainless steel fiber with periodic micro-fins are various. Micro-fins can be classified into three different categories based on their shape: unilateral plane micro-fin, unilateral tapering micro-fin and bilateral micro-fin according to shape of micro-fins, which is shown in Fig. 12. The height of micro-fins ranges from 50 μm to 300 μm and width of fins is between 100 μm and 400 μm. Considering shear-induced lamella structures on the free surfaces of stainless steel fiber, the stainless steel fiber with periodic micro-fins are multi-scale in feature size. Therefore, stainless steel fibers with periodic micro-fins possess multi-scale rough surface morphologies.



(a) Unilateral plane micro-fins



(b) Unilateral tapering micro -fins



(c) Bilateral micro-fins

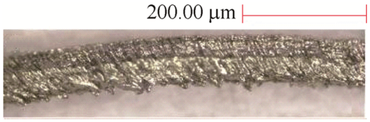
Fig. 12. Morphological diversity of stainless steel fiber with periodic micro-fins

5.2 Influence of cutting conditions on micro-fin formation

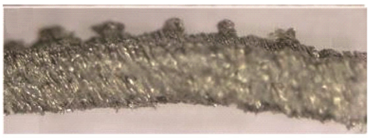
It is suggested by mass experiments that cutting depth α_p has no significant effect on micro-fin formation unless cutting depth is big enough to result in unstable chip bifurcating or incomplete chip bifurcating. This is because the entire cutting layer is split into several thin cutting layers due to multiple tiny teeth simultaneously participating in the cutting process. Typically, cutting depth a_p can be selected as 0.2–0.5 mm.

5.2.1 Influence of cutting speed on micro-fin formation

Fig. 13 presents morphologies of stainless steel fiber produced at cutting depth of 0.2 mm, feed of 0.17 mm/r at different cutting speeds. It can be seen form Fig. 13 that no micro-fins form when cutting speed is 5.1 m/min. Micro-fins are formed at cutting speed of 10.2 m/min. Shape of micro-fins is planar, when cutting speed is below 36.7 m/min. Tapering shape for micro-fins is observed when cutting speed exceeds 53.1 m/min. From Fig. 5, it can be concluded that high cutting speed is conducive to micro-fin formation. Considering, tool wear, cutting speed should be selected in the range of 10 to 53 m/min.



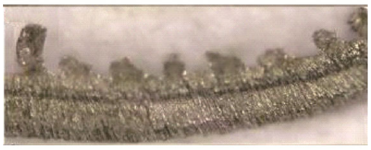
(a) 5.1 m/min



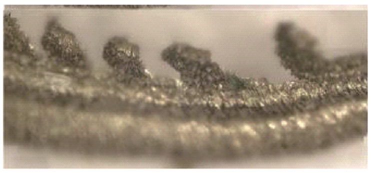
(b) 10.2 m/min

(c) 21.4 m/min

(d) 36.7 m/min



(e) 53.1 m/min

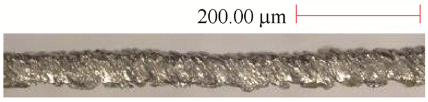


(f) 73.5 m/min

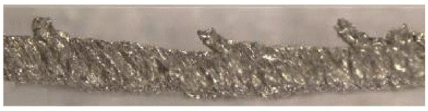
Fig. 13. Morphologies of stainless steel fiber at different cutting speed

5.2.2 Influence of feed on micro-fin formation

Fig. 14 shows morphologies of stainless steel fiber at different feed with cutting speed of 10.2 m/min and cutting depth of 0.2 mm. From Fig. 14, no micro-fins form when feed is 0.05 mm/r. Sparse micro-fins were observed at feed of 0.1 mm/r. When, feed ranges from 0.12 mm/r to 0.21 mm/r, periodic micro-fins were observed. Cutting using the multi-tooth tool is close to critical state of chip bifurcating when feed is 0.21 mm/r. In this case, micro-fins result from connections between two fibers as indicated in Fig. 11. Therefore, shape of micro-fins is unilateral plane as shown in Fig. 14(d). If feed keeps on increasing, the entire cutting layer cannot be bifurcated completely and the cutting operation by multi-tooth tool would turn into single-straight oblique cutting with a large inclination angle. Thus, feed should be selected in the range between 0.12 mm/r to 0.2 mm/r for reliable formation of stainless steel fiber with micro-fins.

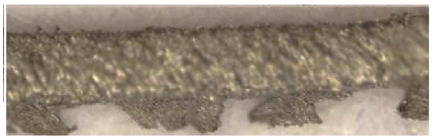


(a) $f=0.05$ mm/r



(b) $f=0.1$ mm/r

(c) $f=0.12$ mm/r



(d) $f=0.21$ mm/r

Fig. 14. Influence of feed on morphologies of stainless steel fiber

6 Conclusions

(1) A new pattern of stainless steel fiber characterized by periodic micro-fins formed on the edge of chip was produced using a special multi-tooth tool. The stainless steel fiber with periodic micro-fins is also a new pattern of chip.

(2) Morphology for these micro-fins was found to be diverse and can be classified in three categories based on their shape: unilateral plane, unilateral tapering and bilateral; and this new pattern of stainless steel fiber possesses multi-scale rough surface morphologies.

(3) There are two mechanisms for formation of micro-fins. The first method is associated with the periodic burrs remaining on the free side of cutting layer of a tiny tooth come to be micro-fins on the stainless steel fiber and produced by the next neighboring tooth; the other mechanism is formed when connections between two fibers are stuck together. Micro-fins are formed when the two fibers detach.

(4) Shape of micro-fins is planar when cutting speed is below 36.7 m/min. The shape become tapering, when cutting speed exceeds 53.1 m/min. Periodic micro-fins are formed, when cutting speed was in the range from 10 to 53 m/min, feed was 0.12–0.2 mm/r and cutting depth was 0.2–0.5 mm.

References

[1] ROGER DB. Bundle-drawn metal fibers[J]. *Advanced Materials and Processes*, 1995, 147(6): 33–34.

[2] HUH Y, H A BK, KIM J S. Dieless drawing steel wires using a dielectric heating method and modeling the process dynamics[J]. *Journal of Materials Processing Technology*, 2010, 210(13): 1702–1708

[3] BAIK N I, CHOI Y, KIM K Y. Fabrication of stainless steel and aluminum fibers by PDME method[J]. *Journal of Materials Processing Technology*, 2005, 168(1): 62–67.

[4] CRAMER A, GERBETH G. Melt extraction of short metallic filaments: Fibre formation process revisited[J]. *Journal of Materials Processing Technology*, 2008, 204(1–3): 103–110.

[5] NAKAGAWAT, UCHIDA T, SUZUKI K. Production of short length steel fiber for composite material on a milling machine[J]. *International Journal of Machine Tool Design & Research*, 1980, 20(3–4): 251–264.

[6] LI Jiazhong. The forming mechanism of metal fiber and its cutting principle[J]. *Manufacturing Technology & Machine Tool*, 1994(3): 46–49. (in Chinese)

[7] KANEKO M, YANGISAWA A, NAKAGAWA T. On fiber sticking phenomenon incoiled sheet shaving for metal fiber production[J]. *Journal of the Japan Society for Precision Engineering*, 1995, 61(5): 692–696. (in Japanese)

[8] CHEN Ping. Fabrication of metallic fibers of advanced industrial materials by rotary cutting[J]. *Journal of the Japan Society for Precision Engineering*, 1995, 61(9): 1280–1284.

[9] LIU Wangyu, ZENG Zhixin, MING Donglan. Production of long metal fibers using a combined method of microsaw turning and pulling[J]. *Journal of Materials Processing Technology*, 2003, 142(2): 562–568.

[10] TANG Yong, HE Zhanshu, PAN Minqiang, et al. Fabrication and characterization of aluminum fibers by peripheral milling[J]. *Materials and Manufacturing Processes*, 2010, 25(10): 1052–1058.

[11] WAN Zhenping, LIU Yajun, TANG Yong, et al. Cutting model of multi-tooth tool and its chip splitting mechanism[J]. *Chinese Journal of Mechanical Engineering*, 2005, 41(3): 211–215. (in Chinese)

[12] ZHANG Ting, CHEN Min, GAO Yuanyuan, et al. Preparation process and characterization of new Pt/stainless steel wire mesh catalyst designed for volatile organic compounds elimination[J]. *Journal of Central South University of Technology*, 2012, 19(2): 319−323.

[13] TANG Yong, ZHOU Wei, XIANG Jianhua, et al. An innovative fabrication process of porous metal fiber sintered felts with three-dimensional reticulated structure[J]. *Materials and Manufacturing Processes*, 2010, 25(7): 565–571.

[14] MALHEIROVN, SKEPPERJN, BROOKSRA, et al. In vitro osteoblast response to ferritic stainless steel fiber networks for magneto-active layers on implants[J]. *Journal of Biomedical Materials Research Part A*, 2013, 101(6): 1588–1598.

[15] JAWAHIR I S, VAN LUTTERVELT C A. Recent developments in chip control research and applications[J]. *CIRP Annals-Manufacturing Technology*, 1993, 42(2): 659–685.

[16] RAHMAN M, SEAH KHW, LI X P, et al. Three-dimensional model of chip flow, chip curl and chip breaking under the concept of equivalent parameters[J]. *International Journal of Machine Tools & Manufacture*, 1995, 35(7): 1015–1031.

[17] KHARKEVICH A, VENUVINOD P K. Basic geometric analysis of 3-D chip forms in metal cutting. Part 1: determining up-curl and side-curl radii[J]. *International Journal of Machine Tools &*

Manufacture, 1999, 39(5): 751–769.

[18] YANG Qibiao, LIU Zhanqiang, SHI Zhenyu, et al. Analytical modeling of adiabatic shear band spacing for serrated chip in high-speed machining[J]. *International Journal of Advanced Manufacturing Technology*, 2014, 71(9–12): 1901–1908.

[19] WAN Z P, ZHU Y E, LIU H W, et al. Microstructure evolution of adiabatic shear bands and mechanisms of saw-tooth chip formation in machining Ti6Al4V[J]. *Materials Science and Engineering A*, 2012, 531: 155–163.

[20] WANG Minjie, GU Liyao. Fracture criterion for adiabatic shear localization during high speed cutting process[J]. *Journal of Mechanical Engineering*, 2013, 49(1): 156–163. (in Chinese)

Biographical notes

TANG Tao, born in 1990, is currently a master candidate at *Key Laboratory of Surface Functional Structure Manufacturing of Guangdong Higher Education Institutes, South China University of Technology, China*. She received her bachelor degree from *South China University of Technology, China*, in 2008. Her research interests include metal cutting and heat transfer enhancement.

Tel: +86-20-87114634; E-mail: tangtaoscut@126.com

WAN Zhenping, born in 1971, is currently a professor and a PhD candidate supervisor at *South China University of Technology, China*. He received his PhD degree from *South China University of Technology, China*, in 2003. His research interests include modern machining theory, technology and machined surface quality control; and advanced manufacturing technologies of functional surface structure.

Tel: +86-20-87110684; E-mail: zhpwan@scut.edu.cn

LU Longsheng, born in 1982, is currently an associate professor at *South China University of Technology, China*. He received his PhD degree from *South China University of Technology, China*, in 2009.His research interests include heat management of microelectronic/optoelectronic chip and carbon fiber processing.

E-mail: meluls@scut.edu.cn

TANG Yong, born in 1962, is currently a professor and a PhD candidate supervisor at *South China University of Technology, China*. His main research interests are microelectronics manufacturing and its digital design.

E-mail: ytang@scut.edu.cn