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Study on machining characteristics with variable distribution density micro-texture tools in turning superalloy GH4202

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Abstract

Micro texture tool (MTT) with variable distribution density was proposed, and the novel MTT can adapt to different friction states in the tool chip contact area and maintain good anti-friction and wear resistance. The novel MTTs were composed of two regions with different groove width and distribution density which were prepared on the rake face by femtosecond laser technology. The cutting process were carried out in turning superalloy GH4202. According to the machining characteristics (rake wear, tool wear volume, workpiece material adhesion volume and the chip morphology), the role of variable distribution density in turning were analyzed. The experimental results show that the texture parameters of the texture region near and away from the edge have different effects and mechanisms on the machining characteristics. Compared with non textured tool and uniform textured tool, the proper design of texture parameters of variable distribution density texture can make the MTT have better wear resistance and chip breaking ability when turning superalloy GH4202.

Keywords: Micro-texture tool, Variable distribution density micro-texture, Tool wear, Superalloy GH4202, Machining characteristics

Nomenclature	
KB	Wear width of rake face
VB	Wear width of flank face
W_{RM}	Volume of material lost on the tool after machining
W_{AM}	Volume of material adhered to the tool after machining
W_A	Width of each micro groove in Part A
W_B	Width of each micro groove in Part B
D_A	Distribution density of micro texture in Part A
D_B	Distribution density of micro texture in Part B
dW/dt	Tool wear rate
V	Sliding velocity at the interface between the tool and chip
σ	Contact pressure at the interface between tool and chip
T	Tool temperature at the interface between the tool and chip
E	Activation energy (75.35kJ/mol)
R	Gas constant (8.314 kJ/mol·K)

1 Introduction

Nickel base superalloys are widely used in aerospace, petrochemical, nuclear engineering and other fields with harsh processing environment and strict technical requirements because they can still maintain good oxidation resistance, thermal stability and good physical and mechanical properties at a high temperature of nearly 1000 °C. However, due to its many hard spots, small thermal conductivity and serious work hardening, it is easy to form serrated chips in the cutting process, large fluctuation of cutting force, fast tool wear and low machining efficiency[1–4].

Studies on micro-texture technology has been increasing in recent years. Micro texture (MT) technology is to prepare a certain microstructure on the surface of the friction pair, which can effectively reduce the friction. At present, it has been widely used in mechanical seals, bearings, computer hard disks, cylinders, piston rings, guide rails and other mechanical parts. As an application field of surface texture technology, MTT can reduce cutting force and cutting heat, reduce tool wear and vibration, and improve tool life and workpiece quality by increasing texture on the rake face and flank of the tool.

Sugihara et al.[5] studied the effect of CBN tool on high-speed turning of nickel base superalloy. They conducted a wide range of orthogonal cutting experiments (20-300m/min) on Inconel 718 Alloy, and studied the wear mechanism of CBN tool cutting nickel base alloy. The results show that when the cutting speed is increased to more than 100m/min, the initial micro defect morphology on the rake face of the tool before machining affects the crater wear process of CBN tool. In order to verify this conjecture, several tools with different surface morphology are prepared and their cutting performance is evaluated. The experimental results show that the polished rake face reduces the crescent pit wear by about 40% compared with the unpolished tool.

Zhou et al.[6] carried out milling experiments on titanium alloy with uncoated texture tools, and used nano fluid cutting fluid as cooling and lubricating medium for auxiliary machining. A series of experiments were carried

out to study the coupling effect of MT and nano fluid cutting fluid on the cutting performance of milling cutter under different cutting conditions. The results show that the cutting force is significantly reduced, the surface roughness is decreased by 38.4%, and the tool wear rate is decreased by 63.3%. In addition, the mechanism of the coupling effect between microstructure and nanofluid is also revealed. In the cutting process, the tool wear mainly occurs on the rake face and flank face. The use of cutting fluid on cutting area can reduce the tool wear. However, the friction state is usually in the state of boundary lubrication and mixed lubrication due to the huge contact stress between tool-chip contact area[7, 8]. Pang [9] et al. considered that the tool-chip contact area is still boundary lubrication under flooding cutting fluid.

For the cutting process of nickel base superalloy, Kang[10] et al. processed the MT on the rake face of the bit with nanosecond laser. It was found that the MT reduced the cutting heat and cutting force, but there was secondary cutting phenomenon. Peng[11] et al. applied high-speed ultrasonic machining technology and MT technology to the machining process of turning Inconel 718. It was found that the use of texture tools can effectively improve the microhardness of parts, which can help improve the service life and fatigue resistance of parts.

Texture size and density play an important role in the tribological properties of texture. Tang[12] found that MT plays an important role in reducing friction and wear. The change of concave area fraction can significantly reduce friction and wear. Obikawa[13] et al. studied the cutting performance of MT tool in turning A6061-T6. It was found that parallel and dot type micro-textures reduced more effectively friction force and the coefficient of friction. With the decrease of MT size or the increase of texture depth, the MT was more effective. Because the contact stress on the tool chip contact surface is gradual, the friction state is also related to the contact stress.

In this paper, some novel micro texture with variable distribution density were prepared on the rake face. These novel micro textures were prepared on the inserts by femtosecond laser technology and applied to the turning process of nickel-based superalloy GH4202. Rake wear, wear volume, workpiece material adhesion volume and chips morphology were analyzed to evaluate the effect of micro textures with different distribution density and groove width.

2 Experimental setups

A turning experiment was carried out on the Lathe DOOSAN PUMA GT2100M as Fig.1(a) shown. The cutting speed, feed rates and cutting depth were 70m/min, 0.1mm/r and 2mm, respectively. The workpiece material is superalloy GH4202. GH4202 has many hard spots, small thermal conductivity and serious work hardening. It is easy to form serrated chips in the cutting process. The harsh tool wear leads to the low machining efficiency. The cutting law is different from other ferrous metal materials, making it one of the most difficult materials in machining. The material elements were shown in the Table.2.

Fig. 1: Rectangular groove type micro-texture is composed of 2 parts and parallel to the blade

In this study, CNMG120404E-SC3 inserts from Achtek were selected as shown in Fig.1(b). The texture processed on the rake face will weaken the tool strength to some extent. To avoid the strength-weaken phenomenon, the distance between the micro-texture and the blade is 0.05mm. The distance between the micro-texture and the tool tip is 0.5mm. The cutting distance of each insert is 100m except the severe tool tip breakage occurs.

The variable distribution density micro-texture is composed of 2 parts: (1) Part A close to the insert blade (2) Part B away from the insert blade. Both of the 2 Parts are parallel to the blade. The 2 Parts have different size and distribution density as Table.1 shown. The micro textures were prepared on the rake face of the insert by femtosecond laser processing equipment, and the dimensional parameters are shown in Table.1. 1# insert is non-textured insert. 2#~10# are variable distribution density textured inserts designed by orthogonal experiment of four factors and three levels. 11#~13# are uniformly distributed textured inserts. The design diagram of micro texture and the position on the rake face are shown in Fig.1(b)(c).

3 Results

3.1 Rake wear

The 2# insert has cut 50.4m and the 3# insert has cut 76.2m, and the others have cut 100m. Fig.2 shows the tool wear profile of the carbide insert after turning GH4202. The wear pattern includes:

- the crater wear occurs on rake face (Fig.2(a))
- burns occur on the flank face (Fig.2(b))

Table 1: The dimension parameter and different wear parameters of micro-texture inserts

No.	Width/mm		Distribution density		KB/ μm	VB/ μm	W_{RM}/mm^3	W_{AM}/mm^3
	Part A	Part B	Part A	Part B				
1#	-	-	-	-	240.92	-	108.7	
2#	0.05	0.05	50%	20%	240.39↓	101.28	1.734	0.0059
3#	0.05	0.04	40%	15%	433.45↑	955	1.769	0.107
4#	0.05	0.03	30%	10%	507.27↑	1164.57	3.309	0.1526
5#	0.04	0.05	40%	10%	220.80↓	116	3.311	0.0144
6#	0.04	0.04	30%	20%	232.04↓	109.91	0.2137	0.0059
7#	0.04	0.03	50%	15%	374.90↑	124.15	2.625	0.0064
8#	0.03	0.05	30%	15%	237.33↓	89.99	0.0383	0.0187
9#	0.03	0.04	50%	10%	348.38↑	162.57	4.76	0.0098
10#	0.03	0.03	40%	20%	243.83↑	96.27	5.031	0.0136
11#	0.03	-	10%	-	243.51↑	125.02	4.228	0.0074
12#	0.03	-	30%	-	281.49↑	202.7	0.0944	0.0133
13#	0.03	-	50%	-	496.43↑	140.71	0.0734	0.0207

Table 2: Chemical composition of GH4202

Component	Ni	Cr	W	Mo	Fe	Ti	Al	Si	Mn	C	P	B	Ce	S
Content (%)	rest	17~20	4~5	4~5	≤4	2.2~2.8	1~1.5	≤0.6	≤0.5	≤0.08	≤0.015	≤0.01	≤0.01	≤0.01

- a certain degree of edge collapse at the tool tip (Fig.2(b))
- the coating on flank face is peeling (Fig.2(c))

Fig. 2: Rectangular groove type micro-texture is composed of 2 parts and parallel to the blade

For variable density textured tools, Fig.3 shows the index analysis of rake wear factors in groups 2#~10# orthogonal experiments. It can be seen that the wear of Part A is the smallest when the width and distribution density are 0.04mm and 40%, respectively, while the wear of Part B is the smallest when the width and distribution density are 0.05mm and 20%. The rake wear increases with the increase of Part A texture width, but decreases with the

increase of Part B texture width. For the distribution density, the distribution density of part a has little effect on the rake face, while the distribution density of Part B is negatively correlated with the rake wear. According to Table.1, the rake wear KB of uniformly distributed textured inserts (11#~13#) increase with the increase of the distribution increase.

Fig. 3: Effects of texture dimension parameters on rake wear

Fig.4 shows the rake wear profile of the micro-texture inserts after cutting. Among them, 3#, 4#, 12#, 13# there are adhesions and built-up edge. 2#, 5#, 8#, 9#, 10# have mild rake wear, while 8#, 11# coating peeling occurs. The maximum wear width KB of the rake face is shown in the picture, where the wear of the rake face is close to or less than that of the non-textured tool, including 2#, 5#, 6#, 8#, 10#, 11#, 12#.

3.2 Wear and adhesion volume

FVM (Alicona, model Infinite Focus G5, Fig.5) was used to quantitatively evaluate three-dimensional tool wear parameters. The volume of material adhered to the tool after machining is recorded as W_{AM} . The volume of material lost on the tool after machining is recorded as W_{RM} . Both volume are recorded in Table.1.

Fig.6 shows the analysis on the influence factors of volume of adhered material on the tool in relation to the reference surface. When the width of Part A is 0.04mm, the adhesion volume is the smallest. In addition, the adhesion volume decreases with the increase of the width of Part B and the distribution density of the two parts.

As Fig.6(b) shown, when the width of Part B increases, the wear volume decreases; when the width of part a and the density of Part B take the middle

Fig. 4: The rake wear profile of the micro-texture inserts after cutting GH402. The serial number of the picture is the number of the insert.

value, the wear volume is the smallest; When the density of part a takes the middle value, the wear volume is the largest. For the uniformly distributed density textured tool, the edge collapse occurred at 11# and 12# the tool tip, as shown in Fig.7.

3.3 Chips morphology

The chip when cutting superalloy GH402 with a non-textured tool is shown in Fig.8. Due to the severe plastic deformation in the cutting process, the chip strength is higher than that of the original workpiece material. Under the cutting parameters in this paper, the higher strength causes the chips continuous. The continuous chips will not only scratch the machined workpiece surface, but also easily entangle in processing, resulting in greater danger. And the rapidly rotating chips are also easy to pose a threat to the personal safety of

Fig. 5: Three-dimensional tool wear based on FVM quantitatively evaluate

Fig. 6: Effects of texture dimension parameters on tool wear and adhesive material volume

operators. Fig.8 shows 2#~13# the chip when machining superalloy GH4202 with the inserts. Among them, 9#, 13# chip breaking occurs, and the chip is fragmented; While 7#, 8#, 10#, 12#, 13# in the initial stage of cutting, chips are broken, then short chips are processed, and finally continuous chips emerged before reaching the predetermined processing distance; All the other inserts are continuous chips. The blade with chip breaking has smaller chip inclination angle and tighter curl than that of continuous chip, as shown in Fig.9(8)(9)(13).

4 Discussions

4.1 Analysis of rake wear

For the turning of nickel base superalloy GH4202 with non-textured inserts, the main wear form is crater wear on the rake face, which is caused by the strong plasticity of nickel base alloy. GH4202 material has high strength and hardness, which makes the cutting force very large. The contact pressure in the tool chip contact area can reach more than 1GPa. The environment of high temperature and high pressure makes the bonding wear more and more intense.

Fig. 7: Tool tip breakage after turning superalloy GH4202 (a) 11# insert after turning (b) 12# insert after turning

Fig. 8: The continuous chip with non-texture tool at the cutting speed, feed rates and cutting depth were 70m/min, 0.1mm/r and 2mm

The rake wear of uniform texture (11#~13#) is positively correlated with texture density. As shown in Fig.4, 11#~13# the main form of wear is adhesive wear. The increase of texture density will lead to the formation of micro blades at the edge of texture pits and secondary cutting of chips. The pit structure of texture makes it easier for chips to accumulate on the rake face, resulting in the increase of adhesive wear[14].

By adding reasonably designed texture on the surface, the cutting fluid can easily penetrate into the tool chip contact area[15], reduce the contact pressure and cutting temperature, so as to reduce the crater wear of the rake face[16, 17]. According to Fig.6, the following conclusions can be obtained: (1)The width of part a is positively correlated with the wear amount. This is because the decrease of distribution density reduces the contact area, resulting in insufficient curl of chips at the initial stage of formation, and increases the tool chip contact area. (2)The width of Part B is negatively correlated with the wear amount. Because the increasing width improves the capacity of holding cutting fluid and reduces the contact area ratio of boundary lubrication / fluid lubrication. (3)The distribution density of part a has nothing to do with the wear amount, which is because the actual contact length is greater than the

Fig. 9: Chip morphology of experimental group 2#~13#

width of part a and the contact stress near the tool tip is too large. At the beginning of cutting, a large number of chip materials adhere to the texture and paste the groove of the texture. So that the wear of rake face is not sensitive to the distribution density of Part A. (4)The distribution density of Part B has a negative correlation with the rake wear. This is because the larger the distribution density, the larger the texture area, the larger the fluid lubrication area and the smaller the friction coefficient. Moreover, the real contact area between tool and chip is reduced and the tool-chip friction stress is reduced.

The influence of variable density texture and traditional texture on tool wear is different. When the average distribution density of variable distribution density texture is greater than that of uniform distribution texture, the wear of rake face can be smaller. This is because at the entrance where the cutting fluid penetrates into the tool tip (Part B away from the edge), the texture has smaller distribution density and larger width, which can increase its dynamic

pressure lubrication, increase the curl degree of chips and reduce the tool chip contact length. However, in part a close to the edge, the texture must have smaller width and larger distribution density. This is because although the texture is processed by femtosecond laser, there are still molten pool and heat affected zone at the edge. The height of the texture edge is slightly higher than the tool surface, resulting in secondary cutting. Smaller texture width will reduce the probability of chip fragments falling into the texture groove to avoid aggravating secondary cutting, while larger texture distribution density can reduce the real contact area and friction stress, so as to reduce wear.

4.2 Analysis of wear and adhesion volume

As shown in Fig.6(a), except for the width of Part A, the other three are negatively correlated with the adhesion volume. This is because the increase of both width and distribution density will improve the storage capacity of cutting fluid, shorten the tool chip contact length, and reduce the cutting heat, so as to reduce the overall wear of the tool. Because Part A is close to the cutting edge, the wider texture will increase the probability of broken chips falling into the texture groove, resulting in micro cutting edge on the tool rake face and secondary cutting, so that the material accumulates on the rake face to form chip accumulation.

According to Fig.6(b), it can be found that the texture size also affects the wear volume of the tool. Because the texture weakens the strength and structure of the tool, and because of the accuracy of laser processing, the texture cannot be processed at the tool tip, and the wear at the tool tip cannot be directly affected by the antifriction effect of texture. According to Ref[18], the wear rate can be expressed as Eq.1. Where dW/dt is the tool wear rate (unit is millimeter per second); E is the activation energy (75.35kJ/mol); R is the gas constant (8.314 kJ/mol·K); σ is the contact pressure at the interface between tool and chip (in megapascals); V is the sliding velocity at the interface between the tool and chip (in millimeter per second); T is the tool temperature at the interface between the tool and chip (in Kelvin). G , A_1 , and B_1 are the material constants.

$$\frac{dW}{dt} = GV + A_1\sigma V \exp\left(\frac{-B_1}{\theta}\right) + D(T) \exp\left(\frac{-E}{R\theta}\right) \quad (1)$$

The $D(T)$ term of Eq.(1) was defined according to Ref[19], a third-order polynomial function of the temperature T .

$$D(T) = aT^3 + bT^2 + cT + d \quad (2)$$

According to Eq.(1) and Eq.(2), it can be found that the influence of temperature on wear speed is cubic. Therefore, through the antifriction of texture, the heat generated by cutting can be reduced. In addition, according to Fig.9, when the texture is of appropriate size, it can also affect the chip morphology,

so that the heat can be taken away by the broken chip rather than transferred to the tool, so as to reduce the wear volume of the tool as Fig.10 shown.

Fig. 10: Wear and adhesion at the cutting edge

4.3 Analysis of chips morphology

As shown in Fig.9, different tool textures produce different chips. The change of chip morphology is caused by many factors, including (1)Secondary cutting phenomena may occur[20–22]. As shown in Fig.11, there is chip material adhesion covering the texture. (2)The friction state of the tool chip interface changes, resulting in the change of the tool chip contact length, which changes the chip shape. In addition, for some tools, the chip shape changes at the initial and final stages of cutting, because the chamfering of the tool will have a great impact on the chip morphology[23]. Due to the serious wear of the tool caused by the turning of GH4202, the tool is constantly worn during the cutting process, resulting in the formation of larger chamfering, chip breaking at the initial stage of cutting. After the tool is worn, banded chips appear.

5 Conclusions

In this paper, some MTTs with novel variable distribution density were prepared on the rake face. The MTs with variable distribution density were prepared on the inserts by femtosecond laser technology and applied to the turning process of nickel-based superalloy GH4202. The width and distribution density of texture will affect the rake wear, wear volume, adhesion volume and

Fig. 11: Chip materials cover the grooves of micro texture

chip morphology. However, the difference between texture and edge distance will lead to different effects on these three parameters.

- The rake wear increases with the increase of Part A (close to the cutting edge) texture width, but decreases with the increase of Part B (away from the cutting edge) texture width. For the distribution density, the distribution density of Part A has little effect on the rake face, while the distribution density of Part B is negatively correlated with the rake wear.
- The adhesion volume increases with the increase of the width density of Part B and the density of part a, and the width of part a is the smallest at 0.04mm. When the width of Part B increases, the wear volume decreases; When the width of part a and the density of Part B take the middle value, the wear volume is the smallest; When the density of part a takes the middle value, the wear volume is the largest.
- By changing the width and distribution density of texture at different positions, the curl degree and chip breaking can be controlled.

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Author contribution. The first author Xin Yu has been responsible for writing this paper, design the variable distribution density micro-texture and analysis the experimental results. Dejin Lv has been responsible for collecting experimental data and the examining. Zi Ye has been responsible for the technology support for the chip morphology analysis. Yuan Gao has been responsible for the technology support for the cutting experiment design. The corresponding author Yongguo Wang has been responsible for determining the overall logical structure of the paper and guiding the entire experiment.

Declarations

Ethical approval. The authors declare that there is no ethical issue applied to this article.

Consent to participate. The authors declare that all authors have read and approved to submit this manuscript to IJAMT.

Consent to publish. The authors declare that all authors agree to sign the transfer of copyright for the publisher to publish this article upon on acceptance.

Competing interests. The authors declare that there is no conflict of interest.

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