Taiho Kogyo Tribology Research Foundation

Main report

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Theme: Measurement and Identification of Variable Friction on Micro-Textured Tungsten Carbide Cutting Tool Surfaces in High Speed Machining

1. Progress and result of the research

There are several distinct advantages offered by micro-textures applied to cutting tool surfaces to reduce forces, friction, and wear. This project provides investigations on micro-grooves fabricated on the rake face of tungsten carbide inserts that were used in turning a titanium alloy under dry conditions. There are several distinct surface texture patterns applied for cutting tools including grooved (square-, round-, or V- shape), dimpled, and pitted patterns depending on the fabrication method utilized and the cutting application intended. These textured surfaces can be fabricated in micro- or nano- scales and applied on rake and/or flank faces of cutting tool inserts. This work is focused on investigating diagonal patterned micro-grooves on tungsten carbide (WC/Co) cutting tool inserts in turning of titanium alloy Ti-6Al-4V. For this purpose, diagonal patterned micro-grooves with 45° direction on the tool rake face of tungsten carbide inserts were fabricated via micro-EDM milling process using a SARIX SX100 machine (Fig.1). The groove width (w = 50 um, 100 um), spacing between grooves (s = 50 um, 15 um, 100 um), and groove depth (d = 10 um, 20 um, 30 um) were varied for three different inserts. All micro-grooved inserts have a pattern distance from the groove beginning to the cutting edge as t = 100 um and an orthogonal length of grooved region as l = 800 um.

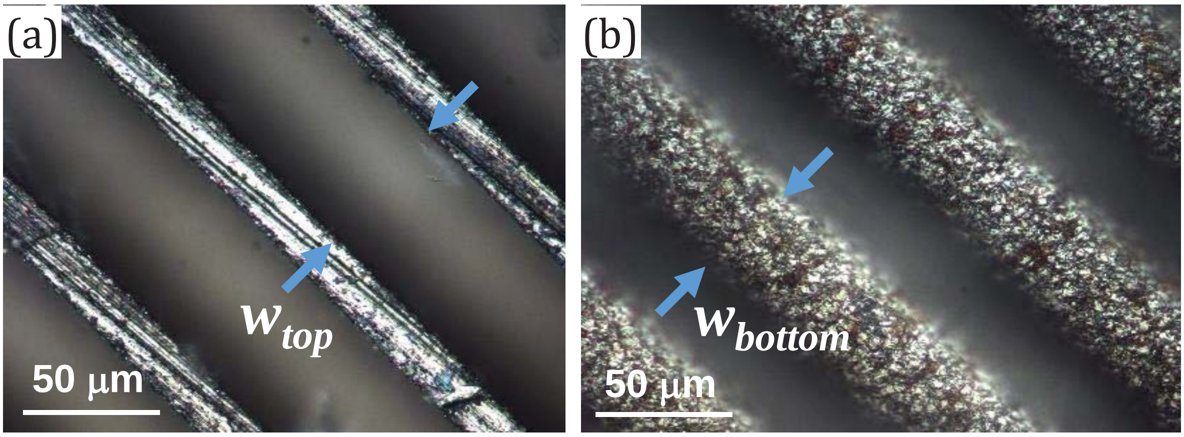

Fig. 1: Images of micro-grooves at the top (a) and the bottom (b) surfaces (micro-groove parameters; w = 50 μm, s = 15 μm, t = 100 μm, d = 30 μm).

Surface profile measurements were obtained from rake faces of micro-grooved tool inserts by using focus variation microscopy system (Alicona InFocus G4 XL200). The surfaces of non-textured areas on the carbide inserts have been characterized with the arithmetic mean deviation Ra and root-mean squared deviation Rq (standard filtering conditions). The average and standard deviation of nine sample measurements yielded Ra = 0.19 ± 0.02 μm and Rq = 0.25 ± 0.04 μm. The micro-groove depth profiles revealed some geometrical inconsistencies and inaccuracies due to micro-EDM milling (Fig.2).

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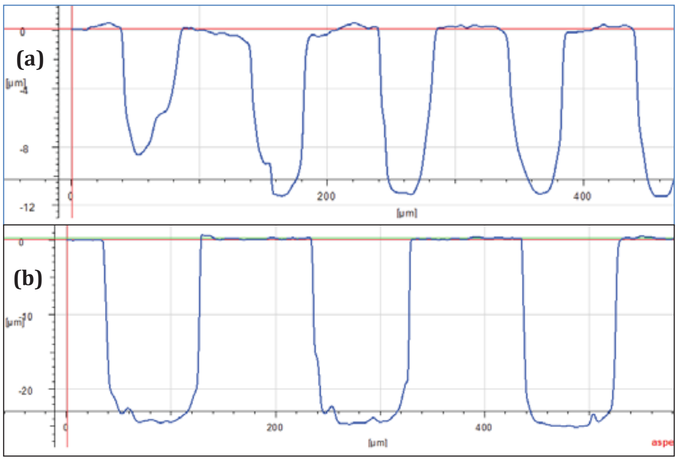

Fig. 2. Profile measurement of micro-grooves on the tool surface with micro-grooved pattern parameters; (a) *w* = 50 μm, *s* = 50 μm, *d* = 10 μm, and (b) *w* = 100 μm, *s* = 100 μm, *d* = 20 μm.

In the experiments, a constant depth of cut and a cutting speed were used. The effect of micro-grooved pattern parameters and feed rate on cutting forces and tool wear were studied. In cutting tests, a constant cutting speed (v_c = 90 m/min) and depth of cut (a_p = 2 mm) were selected while the feed per revolution varied between f = 0.1 mm/rev and f = 0.3 mm/rev. The axial distance of cut in the feed direction was kept constant as l_f = 10 mm under all cutting conditions. Three different micro-grooved tools were tested to investigate effect of micro-groove spacing, micro-groove depth, and micro-groove width.

The results of the turning experiments were utilized to investigate the effect of varying feed rate on the measured cutting forces. The measured mean cutting forces and their standard deviations against the feed rate under different micro-grooved tool designs revealed that the effects of feed rate on the cutting forces were the same, i.e. the cutting forces increased steadily with the increasing feed rate (Fig.3). Since a constant distance from the cutting edge (t = 100 um) is used for all micro-grooved tool inserts, there was no significant effect of the micro-groove design on the measured cutting forces (F_c). This is because; most of the chip load was received at the non-textured section along main and trailing cutting edges. However, measured thrust forces (F_t) were affected by micro-grooved tool designs. The feed force (F_f) was not much affected by increasing feed rate when the micro-grooved tool with the smallest spacing of s = 15 μm and the largest depth of d = 30 μm was used in micro-grooves. It was also noticed that the total micro-grooved area is more influential on measured cutting forces.

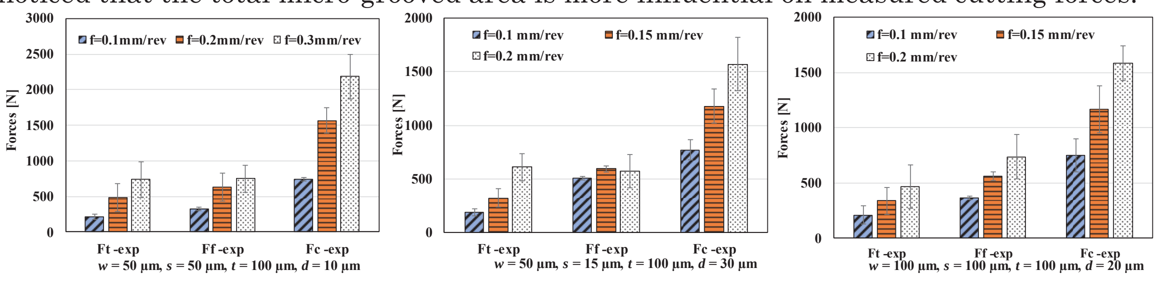

Fig. 3: Measured cutting forces using micro-grooved tool for varying feed rate, (v_c = 90 m/min, a_p = 2 mm).

The optical microscopy images of micro-grooved tool rake faces after the cutting process revealed that severe wear incurred on the tool rake face during all cutting conditions, and catastrophic tool fracture occurred at some conditions especially at high feed rates. Smearing of chips into micro-grooves was found on all insert rake faces. It is also seen that the degree of wear on the rake face is higher near to the main cutting edge and lowers toward the micro-grooved section, which meant that the tool wear rate varies along the tool-chip contact into the micro-grooved section. The widths of worn areas on the tool rake face were measured along main and trailing cutting edges. The tool wear was measured when same axial distance of cut was taken under all cutting conditions. The wear along rake face can represent the effect of feed rate.

The effect of feed rate on the tool rake face wear width with different micro-grooved tool designs is investigated. It is seen that the effect of feed rate on the tool rake face wear width is the same on all micro-grooved tool designs, i.e. the tool rake face wear increased overall with increasing feed rate. The increased feed rate will result in larger undeformed chip thickness on the tool rake face in the direction against the main cutting edge. Therefore, the tool rake face wear width will increase as well. In addition, the increased feed rate generated higher cutting forces, which also resulted in severe wear on the tool rake face and even tool fracture around the tool nose region.

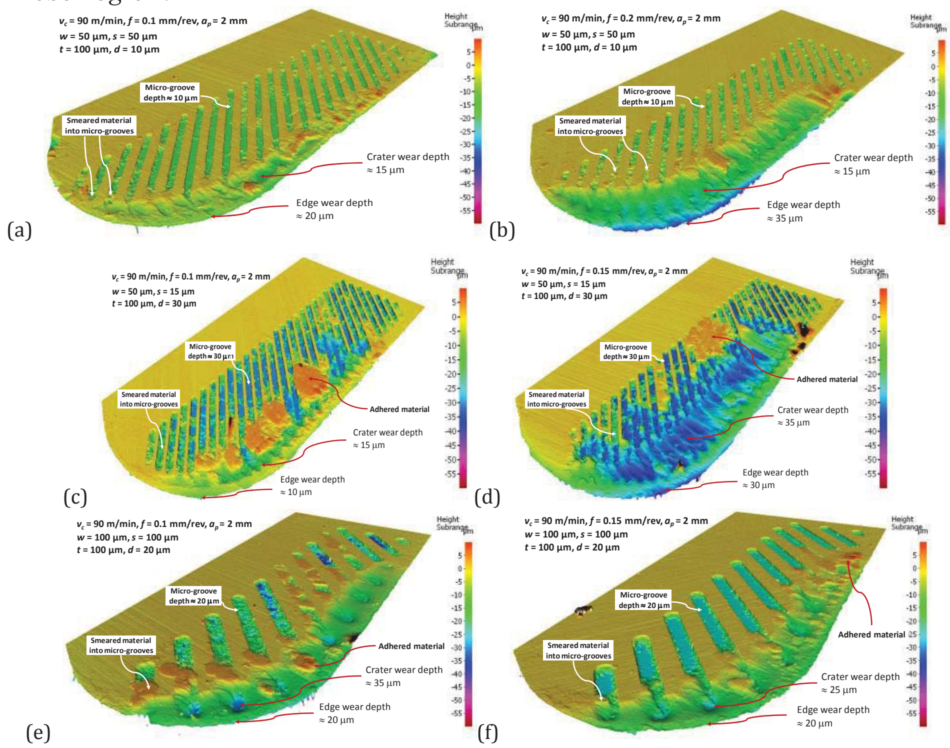

Fig. 4. The areal height maps obtained from micro-grooved tool rake faces.

Furthermore, areal surface height maps were obtained from rake faces of micro-grooved tool inserts by using focus variation microscopy (Alicona InFocus G4 XL200). These areal height maps provide further details about crater wear depth, edge wear depth, locations of chip smearing into micro-grooves and material adhesion, and tool edge chipping (Fig.4). The cutting conditions at high feed rate resulted in some chipping of the cutting edge but also chip smearing and material adhesion have been observed almost all cutting conditions and micro-grooved tool designs. Titanium material that is smearing into micro-grooves show evidence of chip flow following diagonal groove direction (45°) and a distribution of chip-tool contact over micro-grooved surfaces. Volume measurements above and below the surface give indications about the volume of chip material smeared to the surface and volume of tool material worn were obtained revealing certain advantages.
It was found that micro-texture parameters affect cutting forces and tool wear. Furthermore, micro-texture parameters, groove depth, width, and spacing, are found to be influential on the amount of material smearing into grooves and adhering on the tool surface while reducing thrust forces due to lower contact. Therefore, the micro-texture design on the tool surfaces can be optimized to obtain lowered cutting forces, improved tool wear, and minimal material adherence.

The effects of micro-texture geometry on the cutting forces, tool stresses, tool temperatures, tool wear rate and variable friction coefficient were studied with 3D finite element simulations. Finite element simulations of turning experiments were developed using

DEFORM-3D (Fig. 5) to investigate the effects of micro-grooved tool parameters on the machining performance during the machining of titanium alloy Ti-6Al-4V.

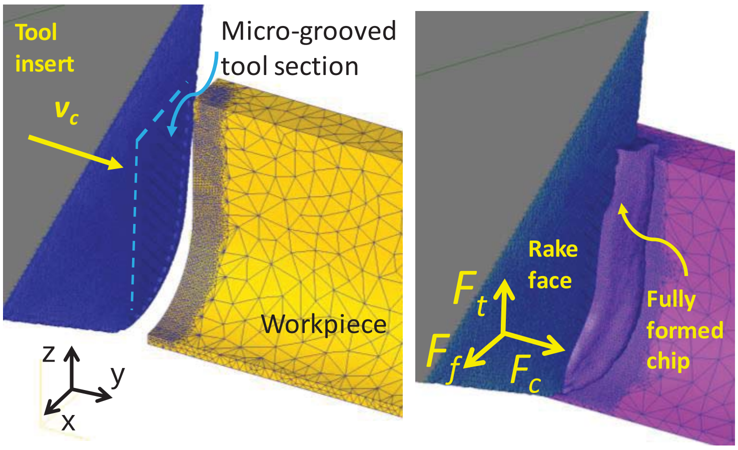

Fig. 5: Finite element model of turning using micro-grooved tool.

The micro-groove width and spacing could affect the cutting forces mainly by changing the actual tool-chip contact area and the degree of chip deformation. Usually, the reduced tool-chip contact area, which reduces friction forces, can result in more severely chip smearing into the grooves, and thus increase the additional micro-groove dependent forces. The deeper micro-grooves could reduce the interaction between the chip and the bottom of the micro-grooves. However, the increased micro-groove depth could lead deformed chips to reach a deeper area and thus increase the interaction between the chips and the side of the grooves. When the chip flows and passes the diagonal micro-grooves, the grooves with different width and spacing could affect the contact area and thus change the normal and frictional stresses. For some micro-grooved tool designs with particular width and spacing parameters, normal and frictional stresses did not reduce steadily. The deeper micro-grooves resulted in larger normal and frictional stresses overall (Fig. 6).

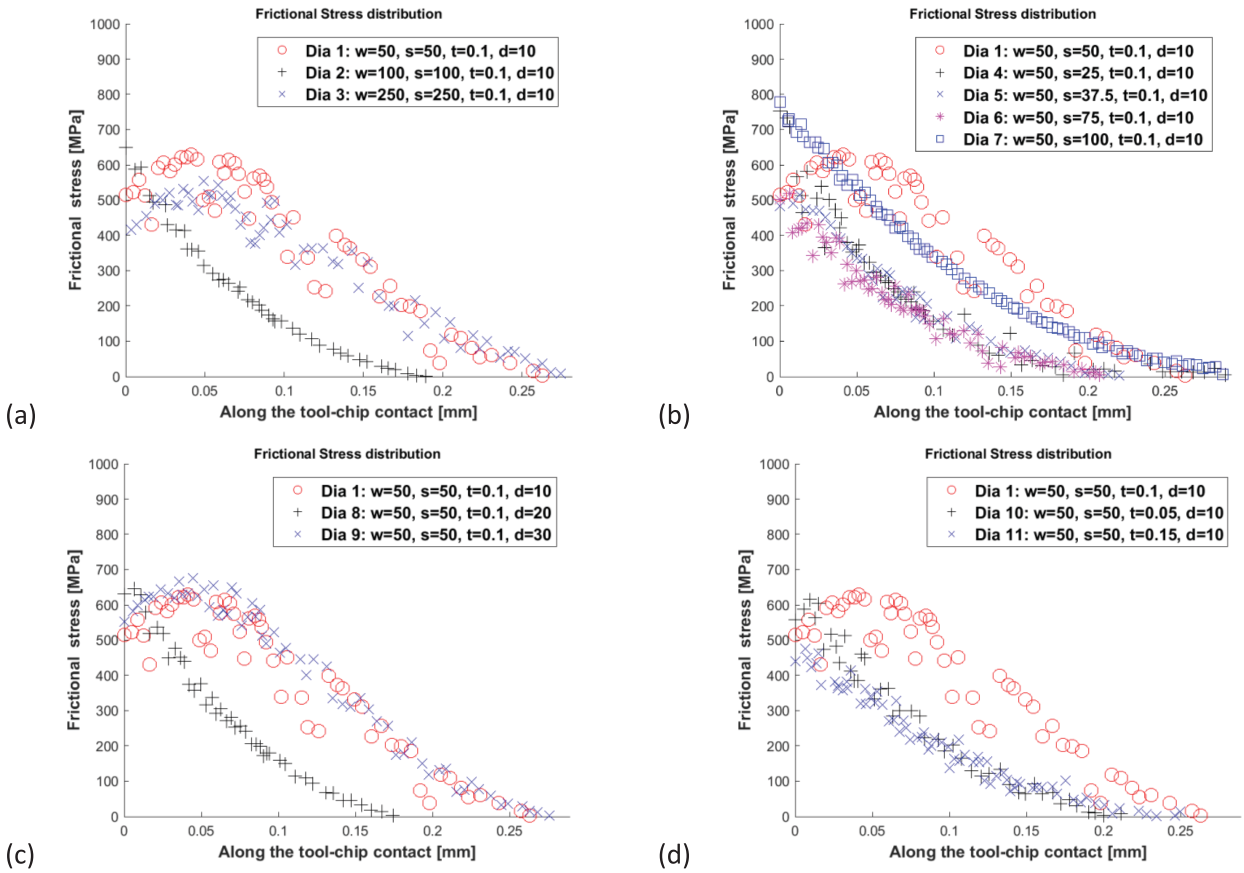

Fig. 6: Effects of micro-groove parameters on the frictional stress along tool-chip contact.

The effect of feed rate on the tool rake face wear length with different micro-grooved tool designs is investigated (Fig. 7). It can be seen that the effect of feed rate on the tool rake face wear length is the same on all micro-grooved tool designs, i.e. the tool rake face wear length increased overall with increasing feed rate. The tool wear rate was calculated by using predicted normal stresses and temperatures (Fig. 8). The micro-groove depth and distance to the cutting edge are the most significant factors. Both larger groove depth and distance to the cutting edge can result in higher tool wear rate overall. Comparing with the effects of micro-groove depth and distance to the cutting edge on tool normal stress and temperature distributions in previous sections, we can observe that tool wear rate follows temperature results in most cases, which proves that temperature influence in the adhesive wear mechanism is stronger than normal stresses.

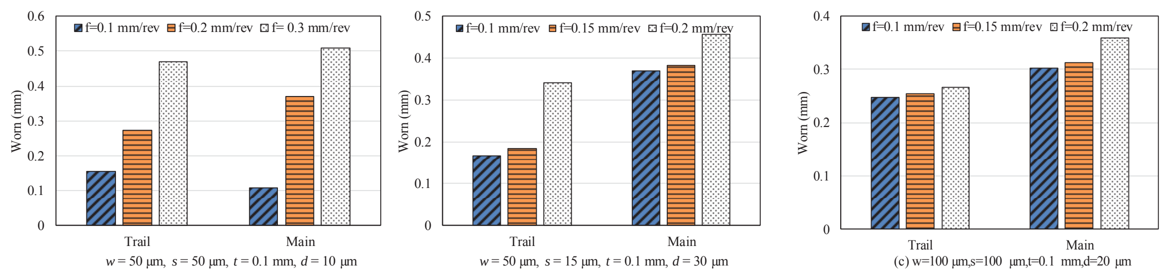

Fig. 7: Tool rake face wear against the feed rate.

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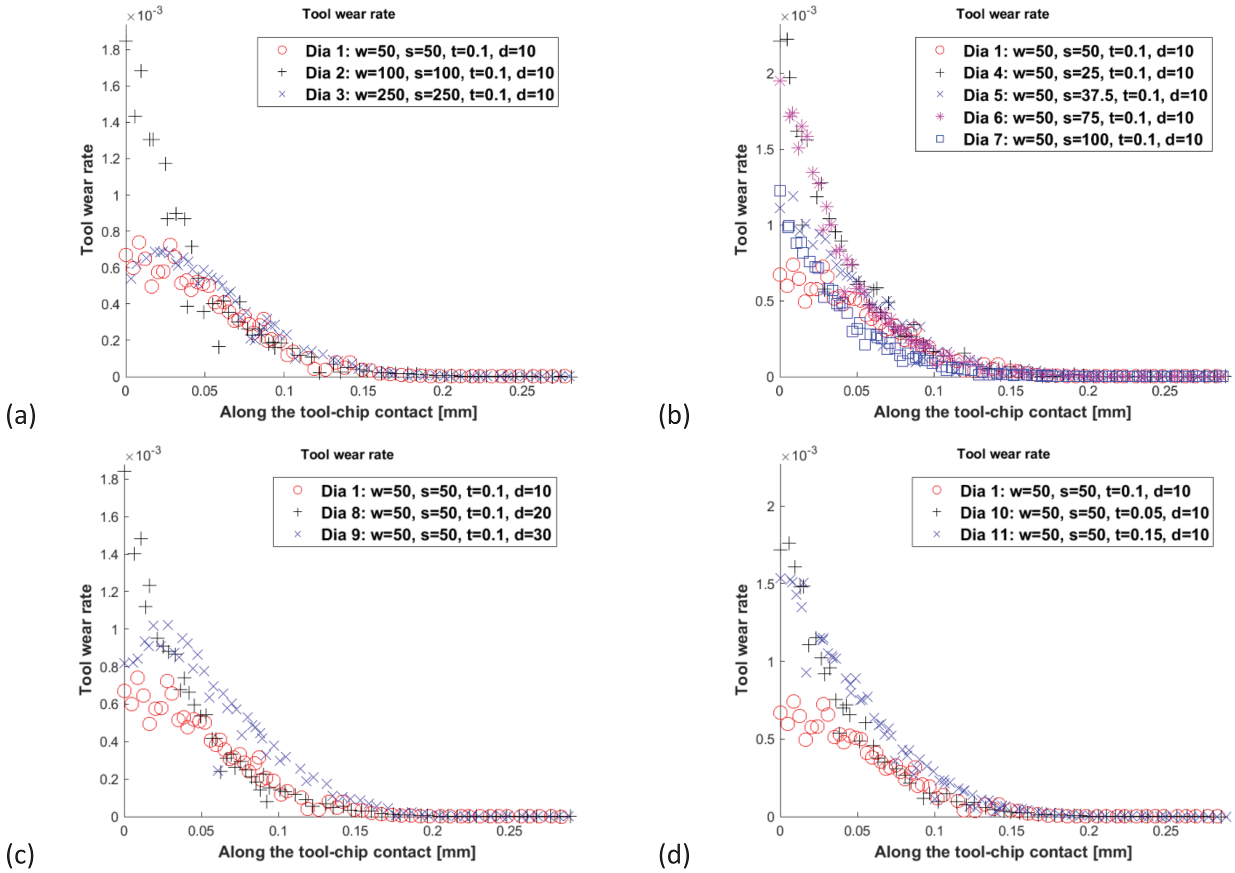

Fig. 8: Effects of micro-groove parameters on tool wear rate.

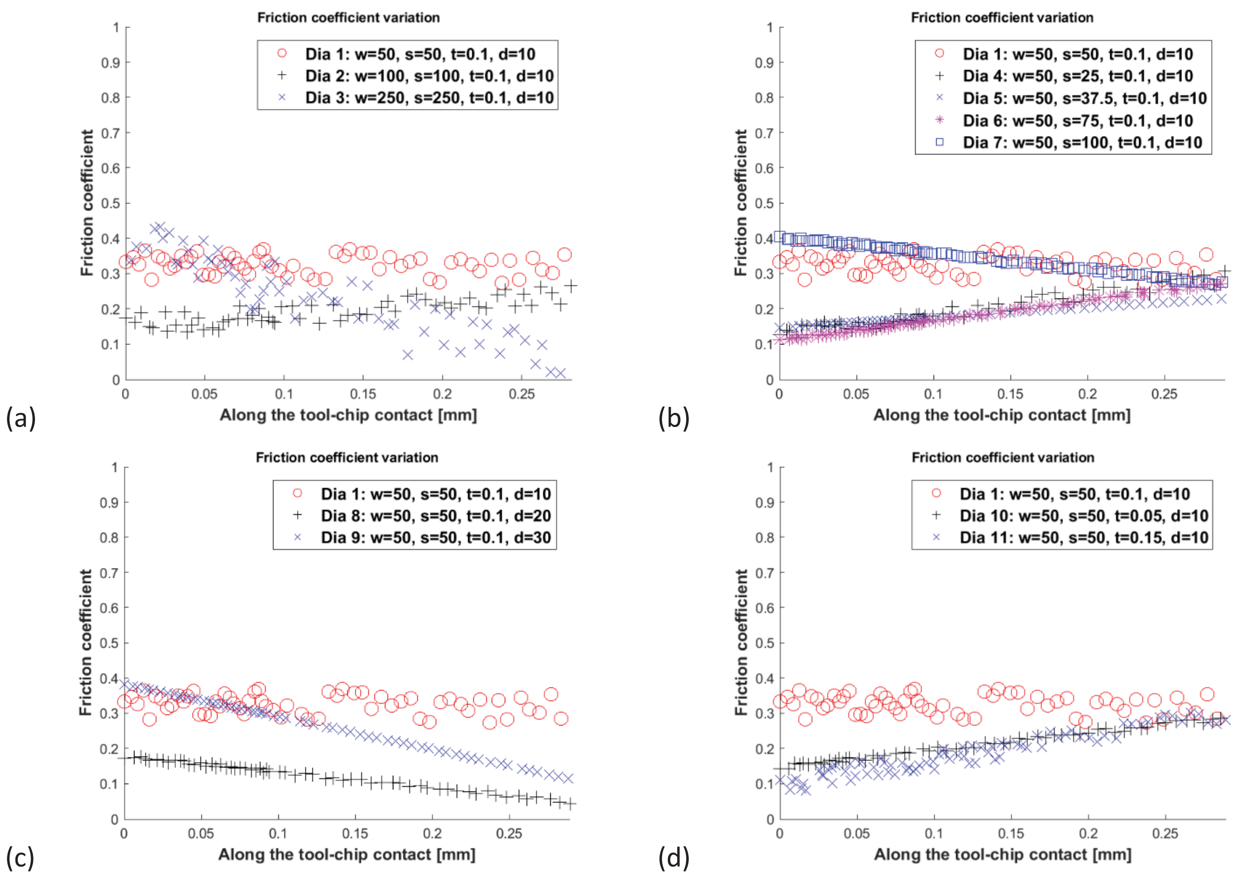

Fig. 9: Effects of micro-grooved tool design parameters on variable friction coefficient.

Furthermore, by utilizing the stress and temperature distributions computed along the tool rake face for various micro-grooved tool design, it is possible to obtain variable friction coefficient either stress or temperature dependent. Therefore, friction expressions for stress dependent variable friction coefficient.

$$\mu(\sigma) = k_1 + k_2 e^{\frac{-\sigma}{\sigma_{max}}} \quad (1)$$

$$\mu(T) = k_3 + k_4 e^{\frac{-T}{T_{max}}} \quad (2)$$

Table 1: Model constants for stress dependent and temperature dependent friction coefficient.

Tool design	Dia. 1	Dia. 2	Dia. 3	Dia. 4	Dia. 5	Dia. 6	Dia. 7	Dia. 8	Dia. 9	Dia. 10	Dia. 11
k_1	0.3414	0.0585	0.4909	-0.0295	0.1029	-0.0579	0.5485	0.2843	0.4980	-0.0051	-0.0213
k_2	-0.0287	0.1952	-0.4517	0.3495	0.1447	0.3621	-0.3059	-0.2388	-0.4179	0.3179	0.3594
k_3	0.3544	0.0541	0.6645	-0.0661	0.0555	-0.0823	0.5527	0.3154	0.6141	-0.0211	-0.1408
k_4	-0.0499	0.2505	-0.8000	0.4631	0.2282	0.4686	-0.3614	-0.3445	-0.6133	0.4016	0.5780

Similarly, a variable friction coefficient expression as a function of micro-groove design parameters (w, s, t, d) as well as nodal location on tool rake face (x, z) can be defined. The nodal location parameter z represents the direction along main cutting edge and x represents the direction along the feed.

$$\mu_1 = a_1 x + b_1 z + c_1 xz + d_1 w + e_1 s + f_1 t + g_1 d + h_1 ws + i_1 \quad (3)$$

Table 2: Model constants for location dependent variable friction coefficient.

a_1	b_1	c_1	d_1	e_1	f_1	g_1	h_1	i_1
-0.17966	-0.03985	0.0972	-0.00262	0.00164	-0.441	0.000683	0.00000359	0.347906

2. Subjects remain to be solved in future/Subjects required further investigation

This project presents micro-grooved texture design on the cutting tool rake face for application of turning titanium alloy Ti-6Al-4V. In cutting tests, cutting forces and tool wear were measured. 3D finite element modelling based investigations were conducted on the effects of micro-grooved tool design upon cutting forces, tool temperature, tool stress and tool wear rate distributions, and variable friction coefficients. The following specific subjects require further investigations:

(1) The effect of feed rate on the cutting forces and tool wear was found significant and not influenced much with micro-grooved tool designs. Other micro-texture patterns such as variable diagonal with curvilinear groove edges may be required to be investigated.

(2) The effect of micro-grooved tool design on cutting forces shows that the effect of micro-groove spacing is not significant. The effect of micro-groove distance from the cutting edge is that the forces are increasing with an increase in this distance. Micro-cutting tests where focusing near the cutting edge and micro-texture pattern may be interesting to investigate.

(3) The effect of increasing micro-groove width and depth shows that there exist optimum width and depth values that may minimize cutting forces. More accurate micro-groove fabrication methods are required to be investigated such as focused ion beam machining and ultra-fast pulsed laser micro/nano machining.

(4) The effects of micro-groove width, spacing between micro-grooves and the distance between the micro-groove beginning to the cutting edge on tool stresses were not evident. Deeper micro-grooves resulted in higher normal and shear stresses. Stress concentration around micro-groove corners and edges must be investigated for improving material adhesion on tool surfaces.

(5) Micro-groove depth and distance to the cutting edge are the most significant factors for tool temperatures. The higher the depth and the distance to the cutting edge the higher the tool

temperature on the tool rake face. The distance from cutting edge that a micro-texture pattern has should be optimized using Finite Element studies prior to finalizing the design on cutting tools.

(6) The groove depth and distance to the cutting edge can affect tool wear rate significantly. The influence of tool temperature on the calculated wear rate was found to be stronger than normal stresses. Better and more accurate wear rate prediction especially for chemical wear should be studied.

3. Plan and past presentation or publication of your research results

K. Patel, S. R. Shah, G. Liu, T. Özel, B. Kaftanoğlu (2019) Investigation on micro-textured cutting tool surfaces in dry turning of titanium alloy Ti-6Al-4V, CIRP Annals Manufacturing Technology, submitted, under review. Editor. E. Tekkaya

K. Patel, S. R. Shah, T. Özel (2019) Orthogonal cutting of alloy steel 4340 with micro-grooved cutting tools, 17th CIRP Conference on Modelling of Machining Operations, submitted, under review.Editor. E. Ozturk.

K. Patel, S. R. Shah, G. Liu, T. Özel (2019) Experimental and finite element simulation studies on the effect of micro-textured tool geometry on forces, friction and wear rate in titanium alloy machining, ASME Journal of Manufacturing Science and Engineering, to be submitted. Editor. L. Yao.

A. Olleak, T. Özel (2017) 3D Finite Element Modeling Based Investigations of Micro-Textured Tool Designs in Machining Titanium Alloy Ti-6Al-4V. Procedia Manufacturing, Volume 10, pp. 536-545.