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Experimental study of residual stress profiles evolution in face turning with flank wear progress

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Abstract

Face turning is a major process to generate a continuous profile such as a fillet geometry. Although face turning is a widely used process, lack of data on residual stress profiles evolution in face turning with tool flank wear progress motivated us to conduct this study. It is necessary to continuously perform three different turnings (longitudinal-fillet radius-face turnings) to produce a fillet radius in a helicopter rotor. Thus, the same cutting conditions used in longitudinal turning were applied to the face turning. Three levels of flank wears (new, VB150, VB300) were chosen to present a flank wear progress within an acceptable limit of VB in industry. X-ray diffraction method was also employed to analyze residual stress profiles on the face turned surfaces. Good repeatability among measured residual stress profiles was found. Significant penetration force increase with flank wear progress induced more compressive residual stress profiles, suggesting that penetration force plays an important role to generate residual stress profiles in face turning.

Keywords: Residual stress profile, face turning, flank wear, X-ray diffraction (XRD)

1. Introduction

Face turning is a major process to generate a continuous fillet profile effectively in helicopter rotors in three stages (longitudinal-fillet radius-face turnings) [1, 2]. Most of papers on face turning were dedicated to investigate residual stresses in some domains, such as tribology test and metallurgy. Jawahir et al. [3] created discs for ball grinding tests (the ball on disc tests) by face turning with new cubic boron nitride (CBN) inserts and evaluated wear resistance performance of the machined surface. In their study, only surface residual stress was used as a factor to affect wear resistance. Hua et al. [4] created some discs by face turning with new CBN tools. Corresponding residual stress profiles were measured to show effects of new tool geometries, such as different hone radius (0.02, 0.05, 0.1 mm) and chamfer angle (0°, 20°, 30°, 40°). Li et al. [5] and Choi [6] measured residual stress profiles in the face turned surfaces with new and worn tools. They made a simple comparison of residual stress profiles between new and worn tools. Recently, Mičietová et al. [7] performed face turning in downhill direction with different flank wears (VB = 0.05, 0.1, 0.2, 0.4, 0.6, 0.8 mm) and presented their residual stress profiles. The acronym, VB is a commonly used term to represent flank wear land [8]. Only one profile per each level of flank wear was demonstrated. After reviewing studies on residual stresses induced by face turning, it was found that following information is still lacking;

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- Residual stress profiles as a function of VB in face turning are still lacking.
- Replications of residual stress profiles have rarely been made.
- Most of face turning have been conducted in downhill direction, which produce a similar cut section and uncut chip thickness of longitudinal turning.

In industry application, uphill face turning is frequently performed to produce continuous and complex geometries. Thus, it is necessary to investigate residual stress profiles induced by uphill face turning, which has a very long contact between tool edge and workpiece surface with a very small uncut chip thickness (about 10 µm) [1] .

A flank wear, VB is advised to be used within 300 µm for its proper characterization and tool life [8]. Thus, in this study, three levels of tool flank wears (new, VB150, VB300) were chosen within the limit of VB 300 and generated to present flank wear progress. Three replications of uphill face turning tests were conducted with each level of VB in an optimized cutting condition. Detailed experimental procedures are described in the next section.

2. Material and methods

2.1. Face turning with flank wear progress

Dumas et al. [1] investigated residual stress profiles induced by a new tool in longitudinal and uphill face turnings. In this study, we continue to investigate residual stress profiles induced by a worn tool in uphill face turning with the same workpiece material, 15-5PH stainless steel employed in their study [1]. It has the chemical composition of 0.07% C, 1% Mn, 1% Si, 14-15.5% Cr, 3.5-5.5% Ni, 2.5-4.5% Cu, 0.15-0.45% Nb, 0.03% S, 0.04% P, Fe balance. After workpiece is prepared as a design, it was tempered at 400°C for 4 hours, yielding a hardness of 35 HRC. This tempering process was conducted to relieve the initial residual stress remaining in the specimen before face turning tests. The workpiece design is illustrated in Fig. 1(a). In this study, an uphill face turning is employed. The feed direction is indicated as a red arrow. Thus, a tool insert moves from the center (R = 0 mm) to the external edge (R = 40 mm) of the face surface. Its cut section [1] and projected cutting edge (Lp), uncut chip thickness (h) are also shown in Fig. 1(b).

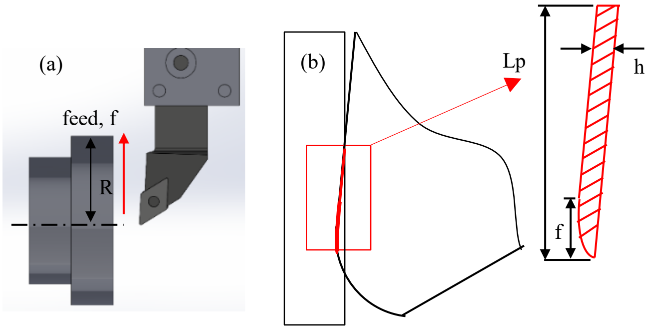

Fig. 1. (a) Workpiece design and (b) cut section of uphill face turning.

Tool flank wears (VB150, VB300) were prepared with an edge grinding process [9]. Considering a contact zone between the tool edge and the workpiece in face turning, flank wear was characterized with an optical microscope. The tool insert was put in the tool holder. The viewing direction is indicated in Fig. 2(a). The optical micrographs to show flank wears are given in Fig. 2 (b) and (c).

Considering a continuous tool path in the fillet radius turning (longitudinal – fillet radius – face turnings), the same equipment in the longitudinal turning [10] was employed in face turning. Thus, the same tool insert (DNMG 150608 PM 4425, Sandvik) and tool holder (PDJNL 2020K 15, Sandvik) in longitudinal turning were used for face turning. A dynamometer (Kistler 9255C) is installed to measure cutting forces during face turning. Its coordinate system is indicated. Thus, cutting force, F_c, feed force, F_f, and penetration force, F_p, can be measured (i.e., F_x=F_c, F_Y=F_f, F_z=F_p in Fig. 3).

The cutting conditions are summarized in Table 1. The optimized cutting parameters, such as a cutting speed, V_c, a feed, f, and a depth of cut, a_p, are fixed in this study. Level of flank wear, VB, is an only parameter to change. For each level of VB, three replications of face turning were performed. As a result, nine face turned surfaces to analyse residual stress profiles were obtained. All rough and finish cutting were performed in dry condition.

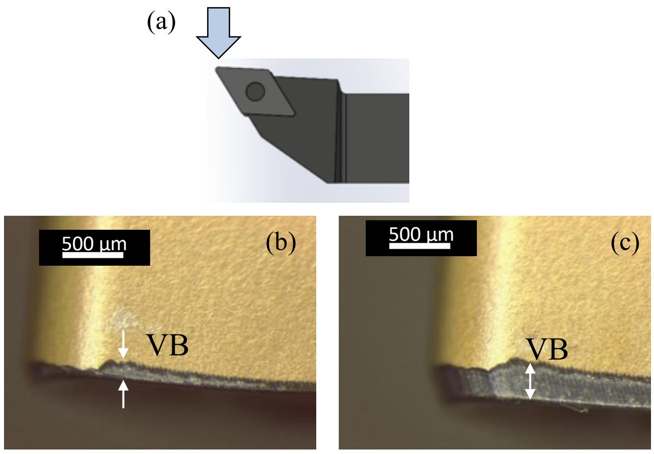

Fig. 2. (a) Viewing direction to characterize flank wear for face turning, corresponding flank wear, VB, on the cutting edge for face turning: (b) VB 150; (c) VB 300.

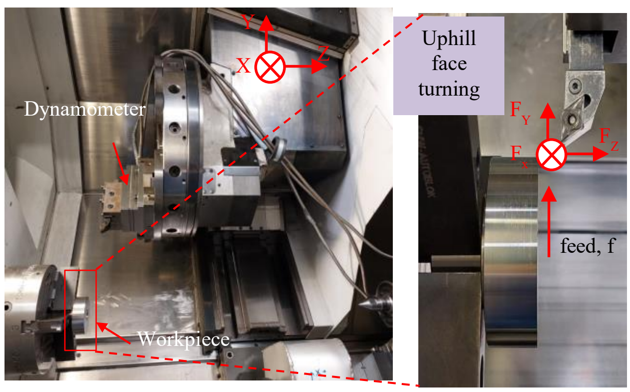

Fig. 3. Experimental set-up: workpiece mounted in the CNC machine (CMZ TC25Y) for uphill face turning.

Table 1. Cutting conditions for face turning.

Vc (m/min)	f (mm/rev)	a_p (mm)	VB (µm)
120	0.2	0.2	New, 150, 300

2.2. Residual stress profile measurement in uphill face turned surfaces

After finishing tests, all nine uphill face turned surfaces were obtained and analyzed by X-ray diffraction method. The same XRD measurement conditions to analyse 15-5PH longitudinal turned surfaces were used as given in Table 2 [10]. The uphill face turned specimen was mounted in the fixture to characterize residual stress profiles. In the coordinate system of X-ray diffraction machine (Proto®), feed and cutting directions are shown in Fig. 4(a). In the fillet radius turning, the uphill face turning was performed from a location (R = 30 mm) to the external surface (R = 40 mm) [1, 2]. Thus, the point (R = 33 mm), which is 7 mm apart from the external surface in Fig. 4(b), is chosen to analyze residual stress profile produced by uphill face turning.

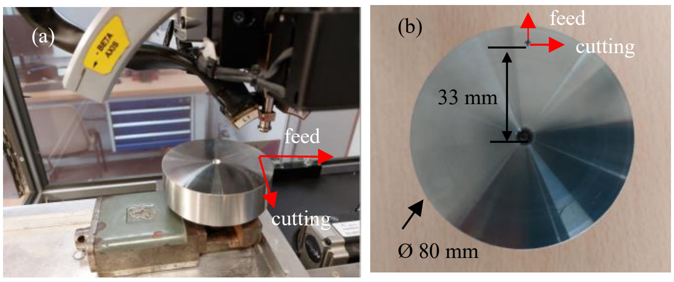

Fig. 4. (a) Face turned specimen mounted in X-ray diffraction machine, (b) a measured location in the coordinate system of X-ray diffraction machine.

Table 2. Residual stress measurement parameters of 15-5PH stainless steel [10].

Parameter	Value
Diffraction condition	Cr Kα radiation with 20 kV, 4 mA
Wavelength	λ= 0.229 nm
-S1 (v/E)	1.28×10^{-3} GPa^{-1}
S2/2 (1+v)/E	5.92×10^{-3} GPa^{-1}
Plan { h k l }	{ 2 1 1 }
Bragg's angle	$2\theta = 155°$
Beam size	ø2 mm
Polishing strategy	Electropolishing process

3. Results and discussion

3.1. Measured cutting forces during face turning

Three replications of measured cutting forces with different VB during uphill face turning are given in Fig. 5. They show a good repeatability. With VB increasing, distinct increase in F_p is observed. The flank wear progress was monitored with an optical microscopy after three replications. Especially, in VB300 tests, flank wear increase (about 60 µm) was observed after three replications, contributing to a significant increase in the penetration force, F_p.

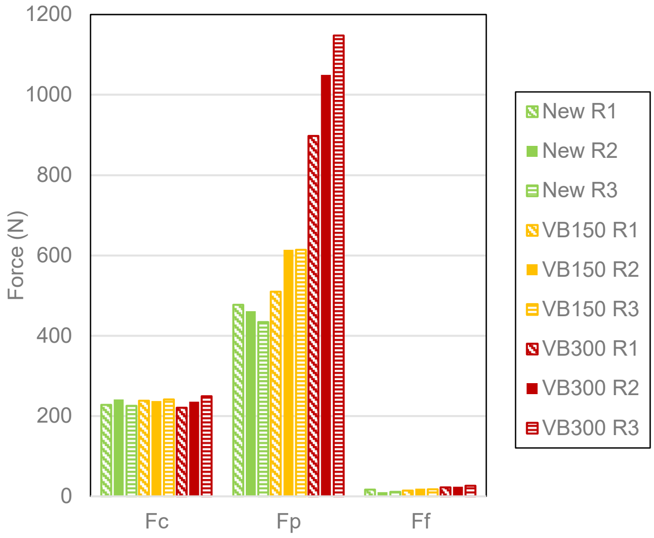

Fig. 5. Three replications of measured cutting forces with different VB during uphill face turning.

3.2. Measured residual stress profiles with flank wear progress

Three replications of residual stress profiles in two direction (feed and cutting) with different flank wears (new, VB150, VB300) in their face turned surfaces were shown in Fig. 6. In all six cases, they showed a typical hook shape profile with a good repeatability. Umbrello et al. [11] denoted four major quantities (surface residual stress, penetration depth, maximum compressive residual stress, affected depth) in this hook shape profile. These four major quantities are indispensable information to characterize the residual stress profile. Like the study of longitudinal turning, all three replications of residual stress profiles in each VB can be superposed in Fig. 7(a). After that, a cloud to include three replications in each VB can be constructed in Fig. 7(b). Three clouds to represent residual stress profiles with different flank wear (new, VB150, VB300) are compared. The overall residual stress profiles evolution seems to be similar to that in longitudinal turning [10];

- As VB increases, the clouds progressed toward compression and became broader. In other word, the cloud developed the higher maximum compressive residual stress and the greater affected depth.

However, having looked at the residual stress profiles evolution in this uphill face turning in detail, it shows different evolutions as compared to that in longitudinal turning.

First of all in uphill face turning, in both directions in Fig. 7, surface residual stress shows a nonlinear evolution (e.g., tensile → high tensile → compressive) as VB increases. As Liao et al. [12] justified, the residual stress is the result of a combination of thermal and mechanical effects. From their statement, in face turning with new and VB150 in this study, thermal effect plays a dominating role in tensile surface residual stress generation.

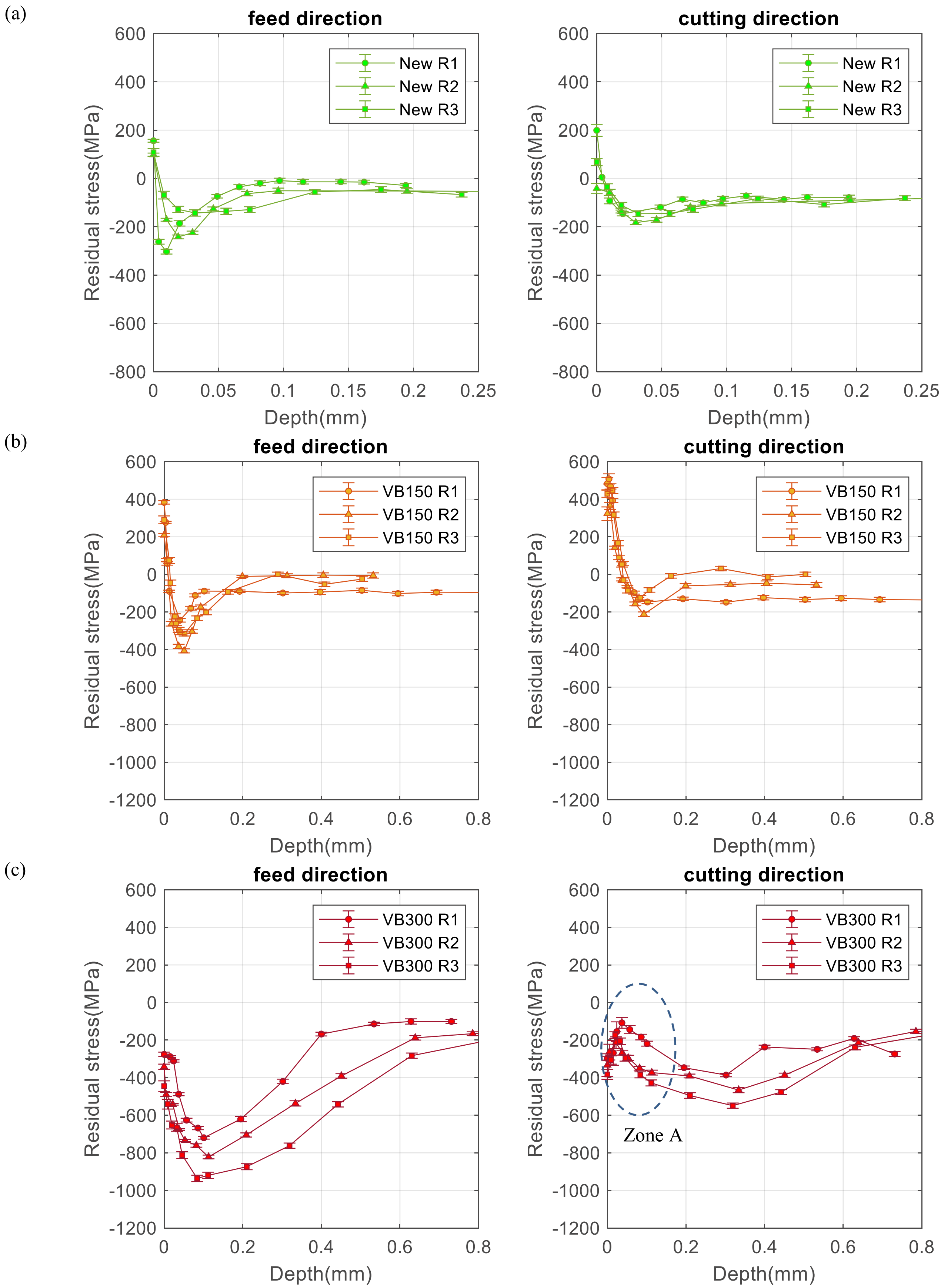

Fig. 6. Experimental residual stress profiles of face turned surfaces: (a) new tool, (b) VB150, and (c) VB300.

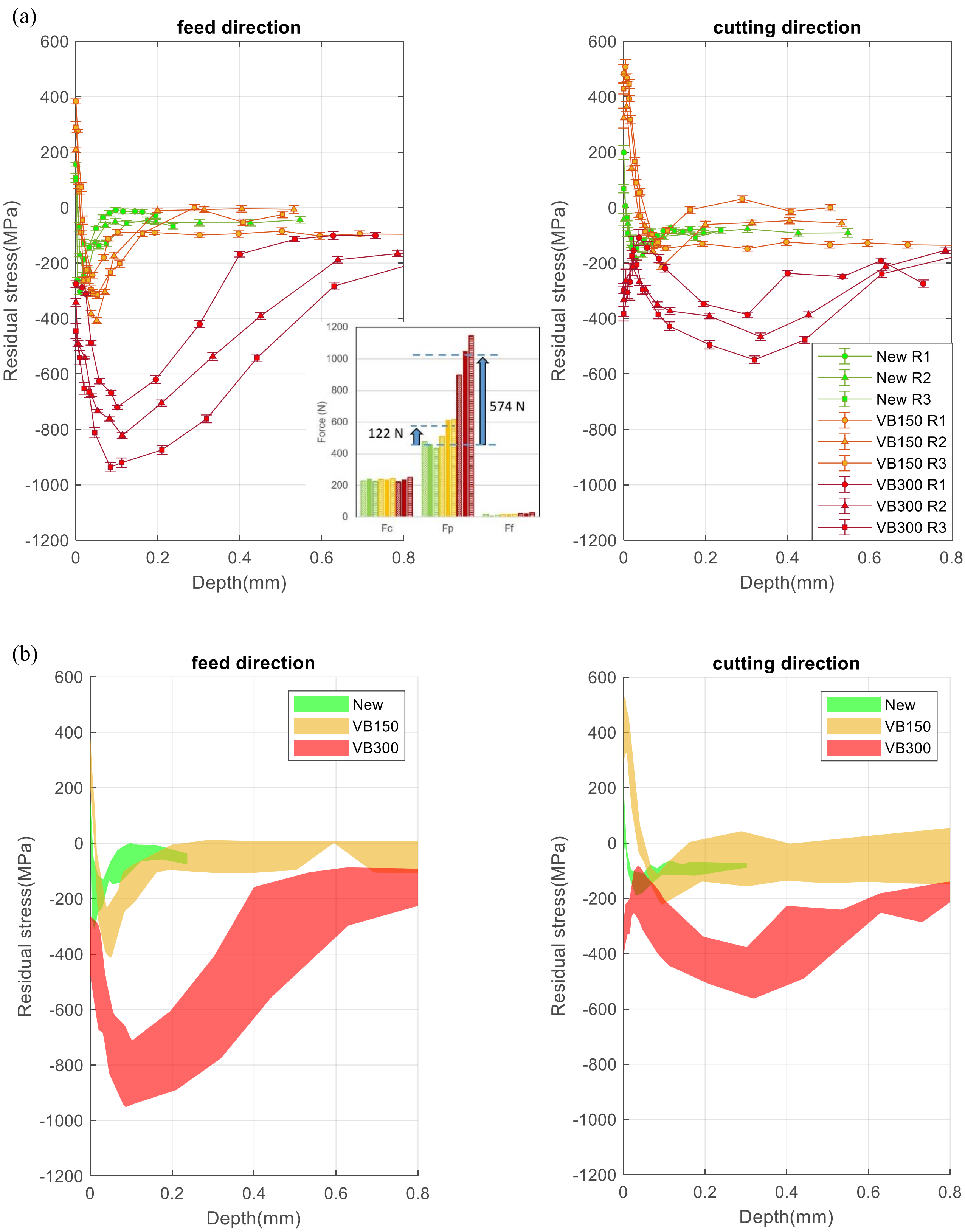

Fig. 7. (a) Superposed residual stress profiles and (b) their cloud groups in face turned surfaces.

After that face turning with VB300, mechanical effect became dominant in surface residual stress generation. Possible generation regime transition (thermally dominating → mechanically dominating) in surface residual stress creation may occur during flank wear progress. This phenomenon can be correlated to the cutting force evolution in Fig. 5. For that, the force data capture is overlapped in Fig. 7(a). The average penetration force, F_p (in three replications in each VB) is indicated as a dotted line in the captured Fig. 5. As compared to the penetration force in the new tool, the penetration force in VB150 increased from 457 to 579 N (F_p increase = 122 N). The penetration force in VB300 increased from 457 to 1032 N (F_p

increase = 574 N). A big jump in penetration force, F_p, in VB300 is very visible. In previous studies [13-15], increase in F_p together with VB was referred to the mechanical effect to generate more compressive residual stress. Therefore, this big increase in the penetration force, F_p in VB300 contributed to a dominating mechanical effect in residual stress generation, leading to the compressive surface residual stresses in VB300.

Secondly, this force evolution also reflects evolution of the compressive residual stress. The red cloud (VB300) forms far from the other green (new) and yellow (VB150) clouds in Fig. 7(b). This trend shows remarkable increase in the compressive residual stress together with such big increase in F_p in VB300.

At third, among three replications in VB300 in Fig. 7(a), gradual evolution toward compression is also observed. As stated in section 3.1, this observation can be associated with flank wear progress during replications in VB300.

Finally, some local change near surface (about 20 μm deep) in the profile in the cutting direction, which is denoted as "zone A" in Fig. 6(c), is noteworthy. Possible microstructure change in the near surface regions with a big flank wear (VB300) can cause this profile. Metallurgical effect on residual stress profile in the near surface can be investigated further.

4. Conclusion

This study presented residual stress profiles evolution induced by uphill face turning with different flank wears (new, VB150, VB300) of 15-5PH stainless steel. Its overall evolution looks comparable to that in longitudinal turning. The maximum compressive residual stress and the affected depth tend to increase in both face turning and longitudinal turning as VB increases. However, different residual stress profile evolution in detail was also seen;

- Different states of the surface residual stresses were observed as flank wear progresses.
- A big increase of the maximum compressive residual stresses and affected depth in face turned surface with VB300 as compared to others (new and VB150) was observed.

These observations can be linked to cutting forces evolution with VB increase in the uphill face turning. Thus, in turning of the complex geometries, such as the fillet turning, the uphill face turned and longitudinal turned regions can yield different residual stress profiles evolution as flank wear progress. Their underlying mechanisms of residual stress generation can be also different. Therefore, careful monitoring of overall turning conditions, such as tool flank wear progress can be required to ensure the best surface integrity of the parts.

This type of residual stress evolution mapping with respect to a tool flank wear progress can give a guideline to use a tool insert in turning. If the target surface residual stress or the target maximum compressive residual stress are given as a specification of the part, corresponding tool flank wear range to meet the target residual stresses can be predicted and decided in the residual stress evolution mapping.

Using the tool insert geometry including flank wear as well as experimentally measured cutting force, F_c and penetration force, F_p, the new developed software, MISULAB® allows us to calculate residual stress profiles induced by machining. This calculation works are currently underway.

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