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

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Abstract

This study presents residual stress profiles evolution in longitudinal turning. While tool wear progresses during machining. Especially, tool flank wear significantly affects residual stress profiles. Thus, in this study, three replications of longitudinal turnings with three levels of flank wears (new, VB150, VB300) were conducted. Cutting forces were measured during longitudinal turning. To verify repeatability of residual stress profiles, three replications of measurements of residual stress profiles in the longitudinal turned surfaces were done. Those three replications of residual stress profiles show good repeatability. Distinct trend of residual stress profiles evolution with tool flank wear progress was also observed.

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

1. Introduction

There have been a number of papers to report that residual stress profiles have a significant influence on fatigue performance of the machined parts. These papers are well summarized and addressed by extensive review works [1-3]. Thus, in order to ensure part's right performance, it is important to monitor residual stress profile of the produced part surface. In long-term machining process, tool wear always occurs. Especially, flank wear contacts the workpiece surface directly and it can significantly affect residual stress profiles on the surface region [4]. Therefore, residual stress profiles evolution with flank wear progress are important surface integrity information. On the other hand, from comprehensive review on studies on residual stress generated by worn tool, residual stress profiles data are still lacking because it requires a relatively longer time to obtain one full residual stress profile than one simple surface residual stress. Some studies [5-7] reported residual stress profiles induced by worn tools. However, they made a simple comparison between new tool and worn tool. Fernández-Valdivielso et al. [8] conducted turning of Inconel 718 with multiple flank wears (new, VB = 0.1, 0.2, 0.3 mm). However, only surface residual stress was presented. More recently, Clavier et al. [9] reported residual stress profiles induced by longitudinal turning with new and various ranges of flank wears (VB = 540, 567, 670, 682 µm).

From review on the past researches on residual stress profiles induced by longitudinal turning with new and worn tools, following issues can be addressed;

- Information on residual stress profiles with progressive increase of flank wear is still lacking.

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- Replications of residual stress profiles in one cutting condition were rarely attempted.

Therefore, this study presents residual stress profiles generated by longitudinal turning with three levels of flank wears (new, VB = 150 µm, VB = 300 µm). This range of flank wear is accepted level in industry. Three replications of turnings with each level of flank wear were performed. Three replications of residual stress profiles measurements were also conducted. Detailed experimental works are demonstrated and discussed in the next section.

2. Material and methods

2.1. Longitudinal turning with flank wear progress

15-5PH stainless steel is adopted in this study because it is frequently used in aerospace, automobile, and nuclear industries. Its chemical compositions are given in the previous studies [10]. A workpiece design for longitudinal turning is given in Fig. 1. It has a diameter of d = 80 mm and a cutting length of l = 25 mm. Its feed direction is indicated with a red arrow.

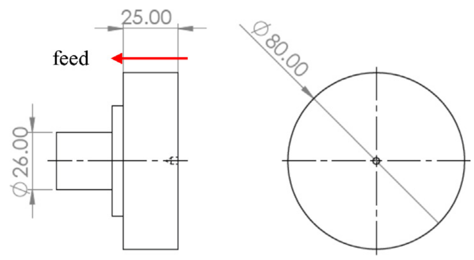

Fig. 1. Workpiece design for longitudinal turning.

As stated introduction, this study addresses residual stress profiles evolutions with three levels of flank wears (new, VB 150, VB 300). In fact, it requires very long time and lots of material removal to generate one flank wear. Moreover, it is complicated to produce repeatable flank wears. Thus, in this study, the flank wear was produced by an edge grinding process [9]. Optical micrographs of flank wear lands generated by edge grinding are illustrated in Fig. 2. They have a relatively uniform width.

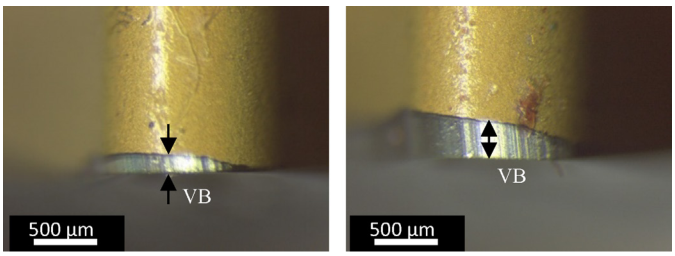

Fig. 2. Flank wear, VB, on the cutting edge for longitudinal turning: (a) VB 150; (b) VB 300.

Ten points of flank wears were measured along the cutting edge. For the medium and large levels of VB, they were measured to be 155 µm and 301 µm in average. In practice, the edge grinding process shows a tolerance of +20 µm. Thus, in this study, an amount of VB = 150+20 µm and 300+20 µm can be grouped as VB150 and VB300. After preparing workpiece materials and flank wears, longitudinal turning tests were conducted. Experimental set-up for turning tests are shown in Fig. 3. The workpiece is mounted in the chuck in the CNC turning machine (CMZ TC25Y). Tool insert (DNMG 150608 PM 4425, Sandvik) and tool holder (PDJNL 2020K 15, Sandvik) are employed. A dynamometer (Kistler 9255C) is installed to measure cutting forces ($F_X = F_c$, $F_Y = F_p$, and $F_Z = F_a$) as shown in Fig. 3.

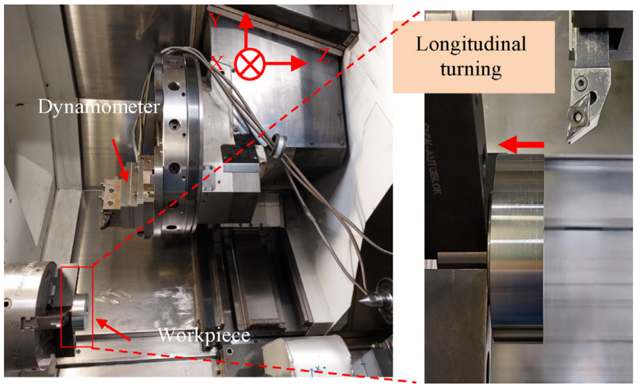

Fig. 3. Experimental set-up: workpiece mounted in the CNC machine for longitudinal turning.

The cutting condition is given in Table 1. The cutting speed, V_c, feed, f, and depth of cut, a_p, are the optimized cutting conditions. Flank wear, VB, is the only variable in these turning tests. Three replications of turnings (R1, R2, and R3) with each level of VB were conducted. Thus, total nine longitudinal turned surfaces were produced for measurement of corresponding residual stress profiles. In case of new tool, each cutting edge was used only one time. In case of worn tool, each cutting edge was used repeatedly. Thus, the tool insert-tool edge number was specified in Table 1. Rough cuttings were performed with the same cutting condition with a new tool. All rough and finish cuttings were performed in dry condition in this study.

Table 1. The test matrix and cutting conditions for longitudinal turning.

No.	Test name	V_c (m/min)	f (mm/rev)	a_p (mm)	VB (µm)	Tool insert-edge no.
1	New R1	120	0.2	0.2	New	1-1
2	New R2	120	0.2	0.2	New	1-2
3	New R3	120	0.2	0.2	New	1-3
4	VB150 R1	120	0.2	0.2	150	2-1
5	VB150 R2	120	0.2	0.2	150	2-1
6	VB150 R3	120	0.2	0.2	150	2-1
7	VB300 R1	120	0.2	0.2	300	3-1
8	VB300 R2	120	0.2	0.2	300	3-1
9	VB300 R3	120	0.2	0.2	300	3-1

2.2. Residual stress profiles measurement with X-ray diffraction

Residual stress profiles in the turned surface were measured with X-ray diffraction (XRD) method. The workpiece was mounted in the X-ray diffraction machine (Proto®) as shown in Fig. 4. The X-ray beam is focused on the middle point of the turned surface. Two directions (feed and cutting directions) of residual stresses are indicated in the turned surface in Fig. 4. Detailed XRD measurement parameters are given in Table 2. Electropolishing method was used to obtain one full residual stress profile below the machined surface.

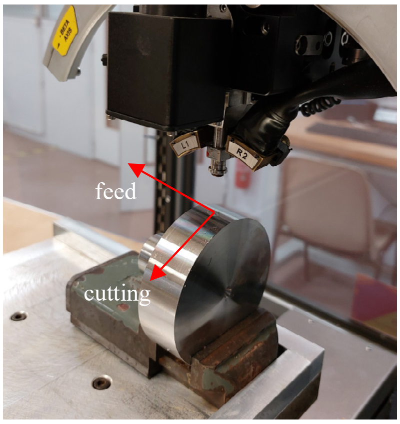

Fig. 4. Longitudinally turned specimens mounted in X-ray diffraction machine (Proto®).

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

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	2θ = 155°
Beam size	ø2 mm
Polishing strategy	Electropolishing process

3. Result and discussion

3.1. Cutting forces

As described in section 2.1, a dynamometer is used to measure cutting forces (F_c, F_p, F_a) during longitudinal turning. Their average force values of all nine tests in Table 1 are shown in Fig. 5. Three replications of cutting forces were measured. They showed a very good repeatability. Especially, with VB increasing, very big increase in penetration force, F_p, is noticeable. This observation is very consistent with previous researches on turning with flank wears [5-9].

Cutting forces are closely related to underlying thermomechanical effects on the workpiece surface during turning. Thus, cutting force data is indispensable information to explain residual stress profile generation. Residual stress evolution will be explained in the next section in conjunction with these cutting force data.

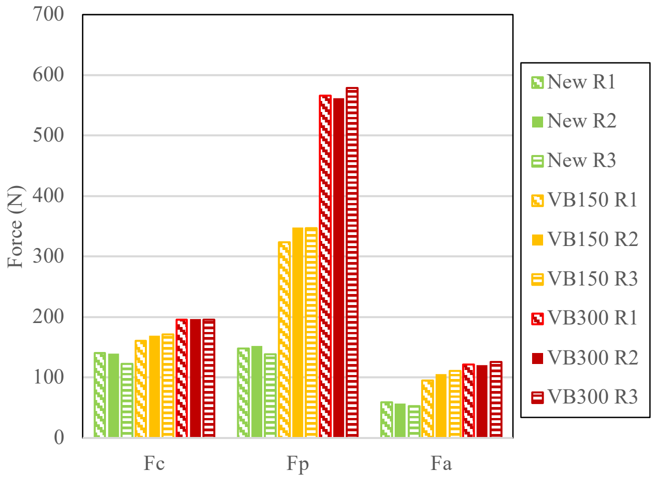

Fig. 5. Force data (Fc, Fp, and Fa) with different levels of VB (3 replications in longitudinal turning).

3.2. Residual stress profiles and their evolution with flank wear progress

Three replication of residual stress profiles with each level of VB (new, VB150, VB300) in two directions (feed and cutting) are shown in Fig. 6. The error bars represent uncertainty in the XRD measurement. In all six cases, residual stress profiles show a hooked shape curve. This hooked shape curve can be characterized by four major quantities (e.g., surface residual stress, maximum compressive residual stress, penetration depth, affected depth/beneficial depth) according to studies of Dumas et al. [10] and Umbrello et al. [11, 12]. In each case, residual stress profiles are gathered, exhibiting very good repeatability. There is a deviation of residual stress profiles in the cutting direction in the first replication with new tool (New R1 in the legend) in Fig. 6(a). This may be due to that the initial residual stress in the test specimen has not been completely relieved by tempering process.

To compare residual stress profiles with tool flank wear progress, nine profiles (3 replications × 3 levels of VB) are superposed in one graph in Fig. 7(a). Then, 3 replications of data with each level of VB are indicated as a group data like a cloud in Fig. 7(b). These group data are denoted as green, orange, and red clouds for new, VB150, VB300 in Fig. 7(b). Thanks to these cloud data, overall residual stress evolution can be clearly seen. Most of all, one significant evolution trend is seen;

- As VB increases, each cloud became more compressive and broader in both directions (feed and cutting).

This trend is very similar to those in previous studies to investigate residual stress profile in turning with worn tools [5-7, 9]:

- Substantial compressive residual stress profiles with a higher maximum compressive residual stress and a bigger affected depth are generated in turned surfaces with worn tools.

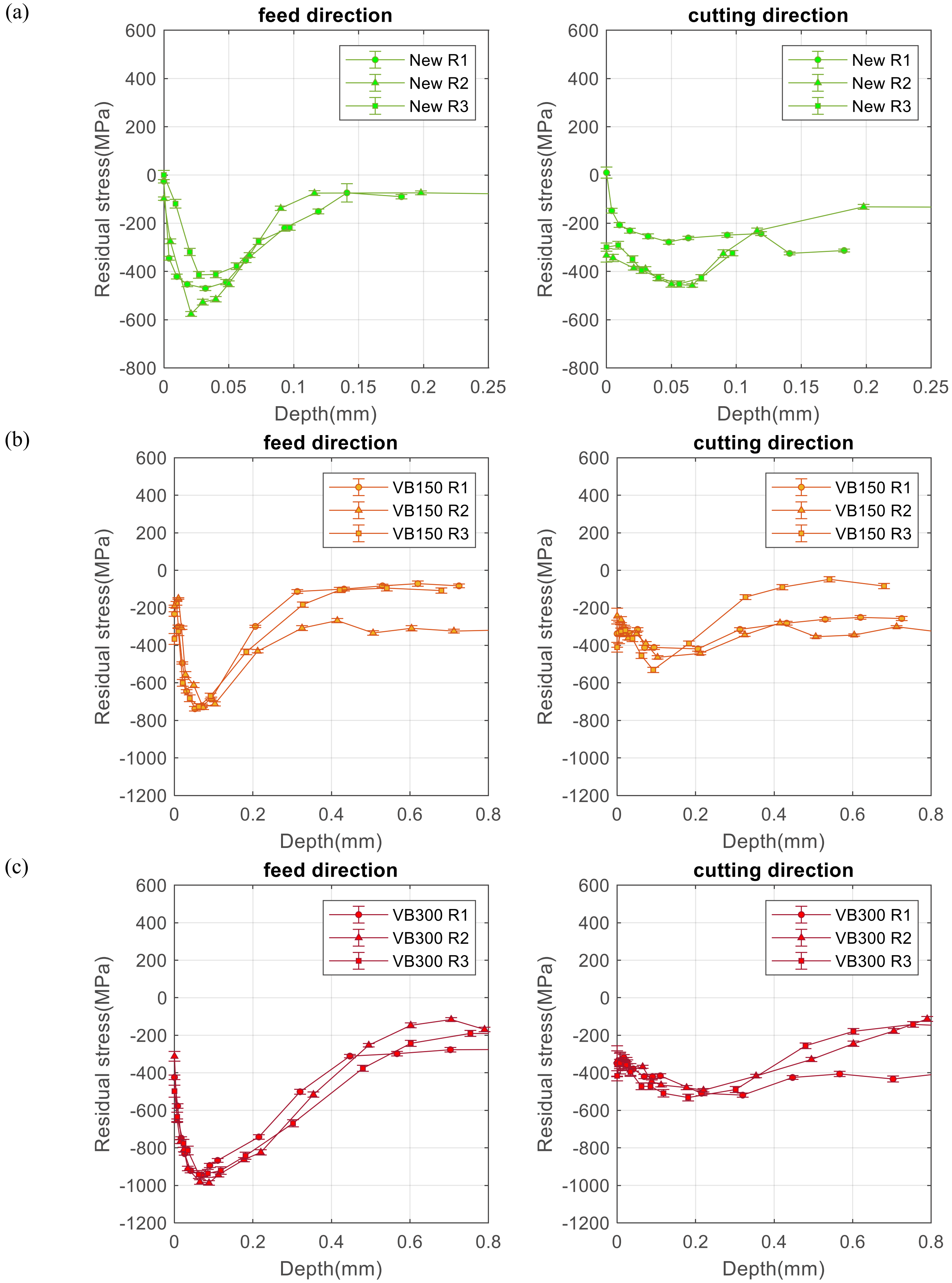

Fig. 6. Experimental residual stress profiles of longitudinal turned surfaces: (a) new tool, (b) VB150, and (c) VB300.

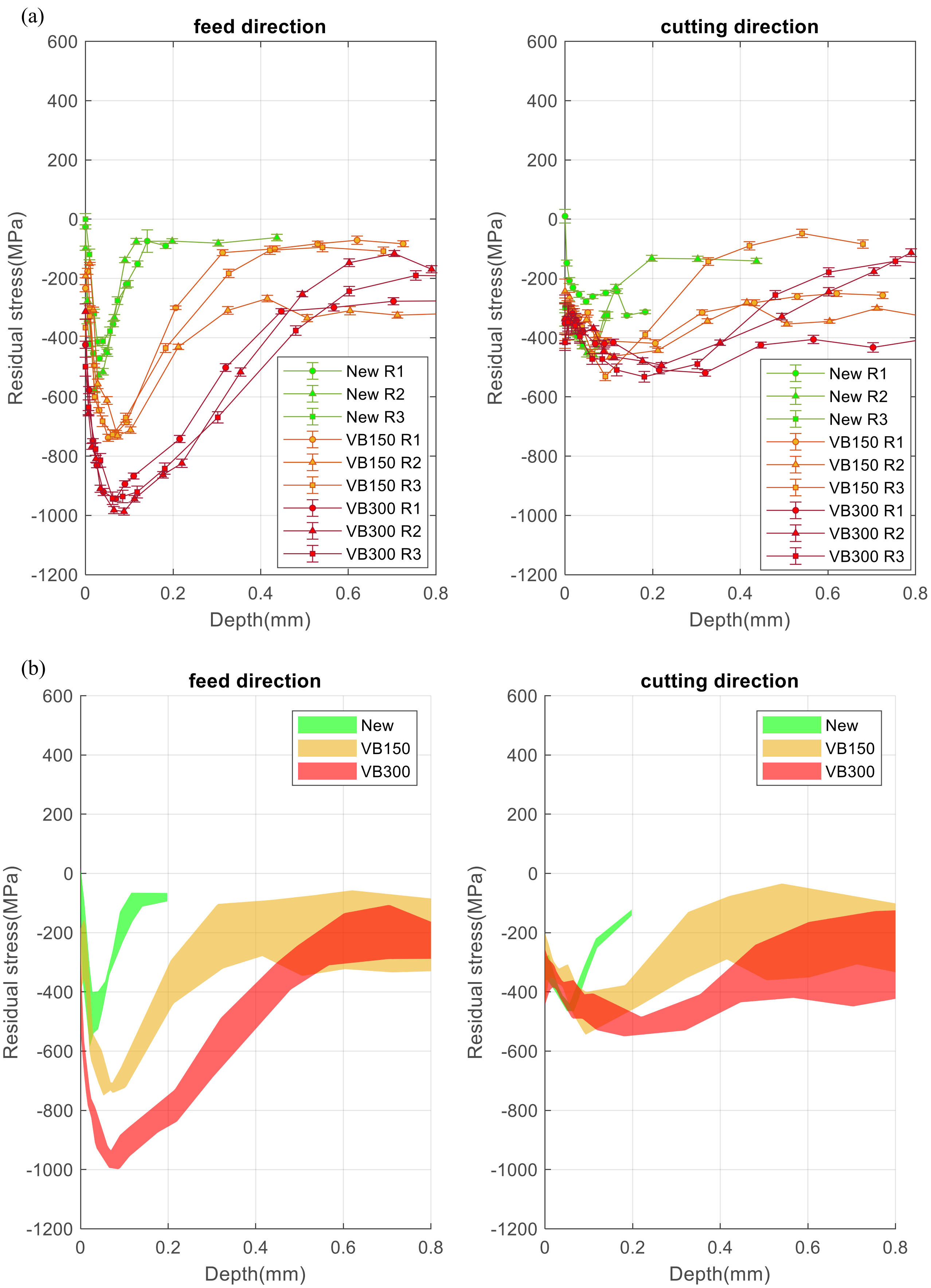

Fig. 7. (a) Superposed residual stress profiles and (b) their cloud groups in the longitudinal turned surfaces.

Especially, Liu et al. [5] stated that this significant increase in F_p can attribute to the mechanical effect in residual stress profile generation. As explained in force data in Fig. 5, significant increase in Fp was observed. In Fig. 7, comparing evolution of the maximum compressive residual stress, their evolution (-487 MPa → -732 MPa → -966 MPa in average value of three replications) in feed direction is much greater than that (-412 MPa → -471 MPa → -506 MPa) in cutting direction. Thus, this phenomenon indicates that mechanical effects play a more dominating role in generation of the maximum compressive residual stress in feed direction than in cutting direction.

Regarding evolution of the surface residual stress, it also became more compressive as VB increases as shown in Fig. 7. Residual stress is a result of competition of tensile residual stress caused by thermal effects and compressive residual stress caused by mechanical effects. This scheme to induce tensile and compressive residual stress is demonstrated in the review paper [13]. Thus, in the range of VB and optimized cutting parameters in this study, it can be said that mechanical effects are also dominating in generation of surface residual stress.

In actual worn tool generation process, flank face and rake face wears occur simultaneously. Thus, tool edge geometry became complicated, making it difficult to ensure repeatability in cutting forces and residual stress data in the machined surface. On the other hand, artificially generated flank wear shows its uniform flank wear land and simple geometry as shown in section 2.1. Good repeatability of cutting forces and residual stress profiles were observed thanks to the artificial flank wear in this study. Regarding possible effects on residual stress of both actual and artificial flank wear, Clavier et al. [4] found that the effect of the rake face wear on the residual stress in the machined surface is not significant. Thus, the residual stresses induced by the actual and artificial flank wears, which have the same VB, is expected to be similar.

4. Conclusion

This study shows evolution of the residual stress profiles as the tool flank wear progress gradually in longitudinal turning of 15-5PH stainless steel. Three levels of flank wears (new, VB150, VB300) were addressed. Three replications of cutting forces and residual stress profiles in each VB level were presented, showing a good repeatability. All force components tend to increase as VB increases. Especially, with VB increasing, F_p increase is very noticeable. Their residual stress profile evolution in feed and cutting directions shows clear trends;

- The overall residual stress profiles became more compressive with a greater maximum compressive residual stress and a bigger affected depth as VB increases.

Especially, in feed direction, its compressive trend is much more discernible than that in cutting direction. Possible dominating mechanical effects can be attributed to this trend. This experimental study can contribute to residual stress evolution monitoring due to possible tool wear progress.

Using these experimental tool geometry and cutting forces (F_c and F_p), recently developed 3D residual stress modelling software, MISULAB® enables us to predict residual stress profiles in the turned surface. This simulation works are currently on the way.

Acknowledgements

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