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6th CIRP Conference on Surface Integrity

Residual stress profiles induced by machining of two types of 27MnCr5 hardened steels

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Abstract

This paper investigates the influence of heat treatment on the surface integrity induced by a hard turning operation on a 27MnCr5 carburized steel. Two heat treatments have been investigated, leading to two residual stress profiles. After that, the steels with the two different case hardened conditions have been hard turned. Residual stress profiles induced by hard turning are analyzed for various cutting speeds and tool flank wear. As a result, it is shown that the final residual stress profiles generated after hard turning depends strongly on the original residual stress profiles.

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Keywords: Residual stress; heat treatment; hard machining

1. Introduction

In the automotive industry, gears and gear shafts are commonly made of case-hardened steels, such as 27MnCr5 steel. Parts are pre-machined and then heat treated to reach their mechanical properties. After the heat treatment, various finish cutting processes can be used. Hard turning with c-BN inserts becomes even more popular as this process is very flexible and easy to handle. It is well known that the fatigue resistance of a shaft is determined by its surface integrity (surface roughness / residual stress state / microstructure) [1, 2]. As a consequence, several papers have investigated the influence of hard turning on the surface integrity of case-hardened steels. [2-5]. They concluded that cutting inserts and cutting conditions have a key effect on the final surface integrity, and especially on the residual stress profiles. However, none of these works have investigated the influence of the original residual stress profile induced by various heat treatments on the final residual stress profile after hard turning. This paper aims to investigate the

influence of two case-hardening conditions on the final residual stress profiles after hard turning for various cutting conditions.

Nomenclature

V_c	cutting speed (m/min)
f	feed (mm/rev)
a_p	depth of cut (mm)
VB	flank wear width (μm)
σ_{xx}	residual stress in the axial direction (MPa)
σ_{yy}	residual stress in the circumferential direction (MPa)
d	depth of residual stress profile (μm)

2. Experimental methods

2.1. Workpiece preparation

Two types of 27MnCr5 annealed steels were obtained from two steel makers. However, they have the same chemical

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composition as given in Table 1. Both 27MnCr5 annealed steels were machined to have dimensions as shown in Fig. 1 and case hardened in two different heat treatment shops.

Table 1. Chemical composition of 27MnCr5 steel [3, 6].

C	Mn	Cr	Cu	Ti	Al	Si	S	P
0.23	1.1	1.0	<0.4	<0.01	0.015	0.1	0.025	<0.03

The type 1 steel was case-hardened by carburizing process. It was heated at 920 °C for 1h30 and cooled under a high nitrogen pressure (about 15 bars) very quickly. It was tempered at 150 °C in air for 2h. The type 2 steel was also case-hardened by carburizing process (internal heat treatment condition [6]). It was heated at 960 °C for 2h30 and quenched under a high nitrogen pressure (about 15 bars). It was tempered at 180 °C in air for 2h. As a result, two types of case-hardened steels exhibit some differences of hardness.

According to a diagram (carbon concentration vs. distance from the surface) shown by Goldstein and Moren [7], carbon concentration at a depth of 0.35 mm from the surface is about 1.0 % after carburization. Therefore, mechanical and thermophysical properties of case hardened 27MnCr5 steel can be referred to those of AISI 52100 steel [8].

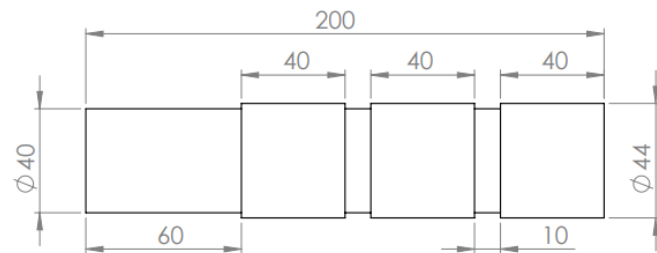


Fig. 1. Dimension of the rough bar. (unit: mm)

2.2. Hard machining of two types of 27MnCr5 hardened steels

Hard machining of these two 27MnCr5 hardened steels were conducted on a turning machine as shown in Fig. 2(a). A c-BN insert (Sandvik, DNGA 150408S01020) and a tool holder (Sandvik, DDJNL2020K1504) were employed in dry conditions. The geometry of the insert edge is given in Fig. 2(b). Hard turning tests were composed by two rough cuts (depth of cut $a_p \approx 0.1$ mm) and a single finish cut (depth of cut $a_p \approx 0.15$ mm). From hardness profiles of two steels, the case hardening depth (having desired hardness over 700 HV1 in this study) was found to be about 0.6 mm. Thus, to minimize its removal, it was decided to apply small depth of cut of $a_p \approx 0.1$ mm during rough cut. The two rough cuts aims to calibrate the geometry of surfaces as some differences may exist among samples due to the heat treatment. Only the surface integrity induced by finish hard turning was analyzed.

The total depth of material removal was 0.35 mm (= 0.1 + 0.1 + 0.15 mm). 8 surfaces have been hard turned (2 steels \times 4 hard turning conditions). It is noted that the flank wear was generated by hard machining with conditions of $V_c = 110$ m/min, $f = 0.1$ mm/rev, and $a_p = 0.15$ mm of a case-hardened bar for 12 minutes.

This work has investigated the influence of cutting speed (V_c) and flank wear (VB) on surface integrity. As shown in Table 2, Four different cutting conditions with three different levels of cutting speeds (e.g., 80, 110, 140 m/min) and two different levels of flank wear (e.g., 0, 70 μ m) were used in this study.

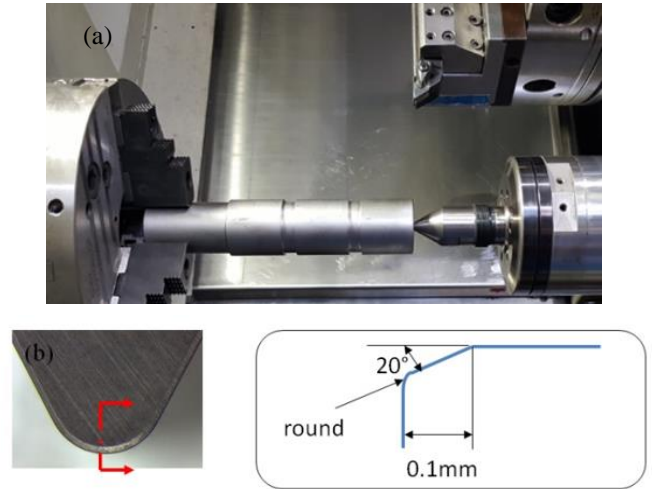


Fig. 2. (a) Experimental set-up for hard machining; (b) CBN insert and its cutting edge.

Table 2. Hard machining conditions: rough and finish cuts.

Process	Cutting speed, V_c (m/min)	Feed, f (mm/rev)	Depth of cut, a_p (mm)	Flank wear, VB (μ m)
Rough cut #1	80	0.1	0.1	0
Rough cut #2	80	0.1	0.1	0
Finish cut (1)	80	0.1	0.15	0
Finish cut (2)	110			0
Finish cut (3)	140			0
Finish cut (4)	110			70
Total removed depth (mm)			0.35	

2.3. Residual stress measurement of hard machined surfaces

Residual stress measurements of each hard turned surface were conducted with an X-ray diffraction (XRD) method. Residual stresses in the subsurface of the heat treated workpiece were also measured to look into the residual stress profiles induced by case-hardening. Experimental set up and conditions of the XRD measurement are shown in Fig. 3 and Table 3. Two components of residual stresses, such as circumferential and axial stresses, were measured. These components are denoted as σ_{xx} and σ_{yy} in Fig. 3(b).

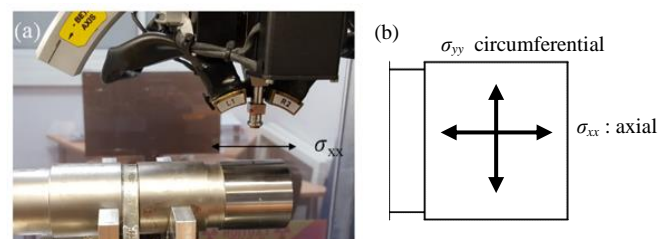


Fig. 3. XRD measurement set-up of the hard machined surface.

Table 3. XRD measurement conditions.

Diffraction condition	Cr K _α radiation with 18 kV, 4 mA
Wavelength	λ = 2.291 nm
-S1 (ν/E)	1.2 × 10 ⁻³ GPa ⁻¹
S2/2 (1+ν)/E	5.67 × 10 ⁻³ GPa ⁻¹
Plan { h k l }	{ -2 1 1 }
Bragg's angle	2θ = 155.1°
Beam size	ø2 mm
Polishing strategy	Electropolishing process

In this study, residual stress profiles can be characterized by some magnitudes, such as ‘Surface stress’ (MPa), ‘Compressive valley intensity’ (MPa), ‘Compressive valley position’ (μm), and ‘Affected depth’ (μm) in the profile as shown in Fig. 4.

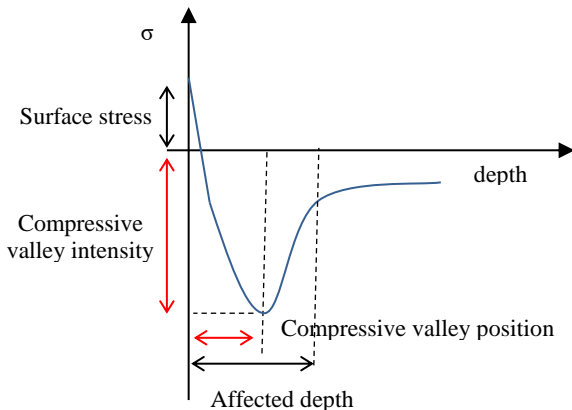


Fig. 4. Characterization of a residual stress profile [9].

3. Results and discussion

3.1. Residual stress and hardness profiles of two types of 27MnCr5 steels after case hardening

Residual stress and hardness profiles of two types of 27MnCr5 case hardened steels are shown in Fig. 5. The case-hardened layer exhibits a compressive residual stress state, which was expected. Indeed, the transformation of perlite-ferrite into martensite induces an increase of the volume, which leads to compressive stresses [10].

When comparing the two types, greater compressive residual stresses were induced in the type 1 hardened steel, as compared to the type 2 one. Higher compressive residual stress of type 1 steel can be attributed to its lower tempering temperature than that of type 2 one (150 °C vs. 180 °C). Réti [11] stated that, at higher tempering temperature, more retained austenite transforms into martensite, decreasing in volume. Consequently, decrease in compressive residual stress at higher tempering temperature was seen.

Total removed depth of 350 μm by machining (Table 2) is indicated in the residual stress profiles in Fig. 5. The final machined surface corresponds to the depth of 350 μm in the residual stress profile. Thus, the residual stress difference between two types of steels is indicated at the depth of 350 μm with a red arrow. The type 1 and type 2 hardened steels have different hardness (790 HV1 vs. 750 HV1) at the depth of 350 μm due to different heat treatment conditions.

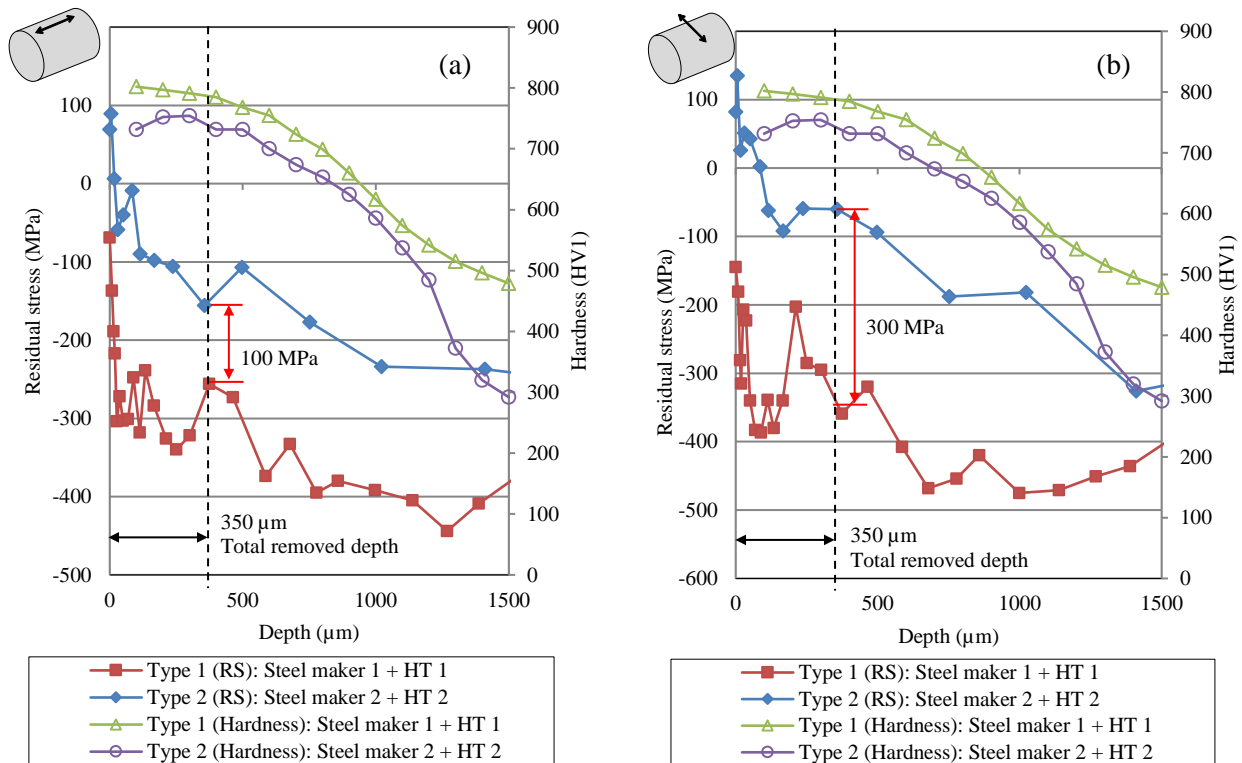


Fig. 5. Residual stress and hardness profiles of two types of 27MnCr5 case-hardened steels: (a) axial direction; (b) circumferential direction. (hardness in type 2 [6])

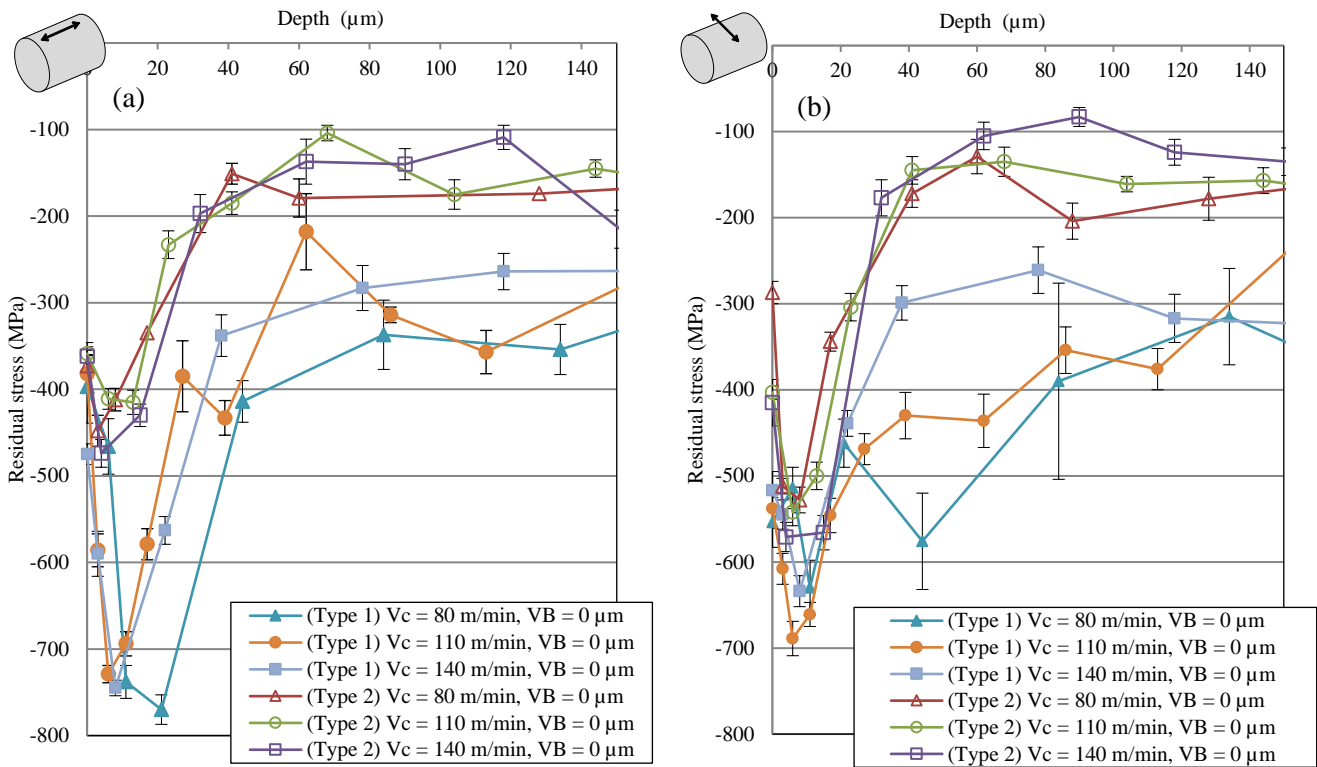


Fig. 6. Residual stress profiles after machining with different cutting speeds ($V_c = 80, 110, 140$ m/min) of case-hardened 27MnCr5 steel (type 1 vs. type 2): (a) axial direction; (b) circumferential direction.

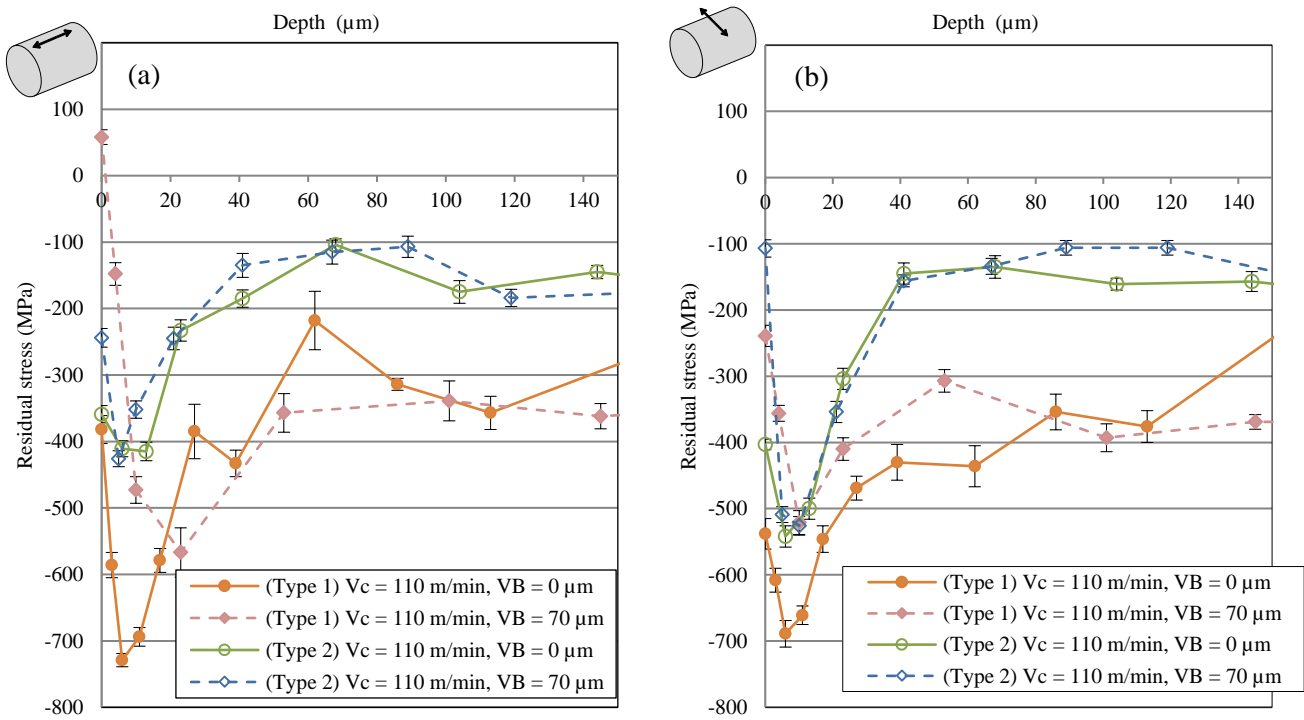


Fig. 7. Residual stress profiles after machining with different flank wear ($V_B = 0, 70$ μm) of case hardened 27MnCr5 steel (type 1 vs. type 2): (a) axial direction; (b) circumferential direction.

3.2. Residual stress profiles after machining of case-hardened 27MnCr5 steel

After hard machining, residual stress profiles (in axial and circumferential directions) induced by three cutting speeds ($V_c = 80, 110, 140$ m/min) with a new tool ($VB = 0$ μm) are shown in Fig. 6. Residual stress profiles have a hooked shape, which is in accordance with previous scientific works [2-5]. The surface residual stress and intensities of compressive valleys in all profiles are compressive. They are more compressive than that of the bulk. Mechanical effect such as plastic deformation can induce such high compressive residual stress after hard machining.

There is an offset between two groups of profiles (type 1 vs. type 2) through all depths – a heat affected depth ($0 < d < 40$ μm) and a bulk region ($40 < d < 140$ μm). Within the heat affected depth, overall compressive residual stresses, such as surface stresses (MPa) and compressive valley intensities (MPa) of type 1 is bigger than those of type 2. Recall that residual stress induced by heat treatment (HT) of type 1 was greater than those of type 2 (Fig. 5). The difference in the HT residual stresses seems to affect this offset between two profiles after machining.

As shown in Fig. 6, in all residual stress profiles with three cutting speeds ($V_c = 80, 110, 140$ m/min) in each type of steel, compressive valley positions were generated within 20 μm , and affected depth was created within 40 μm . Their overall residual profiles seem to be very similar in terms of compressive valley intensity (MPa), compressive valley position (μm), and affected depth (μm). For a given cutting speed range in this study, difference in residual stress profile is not significant.

Fig. 7 shows residual stress profiles (in axial and circumferential directions) induced by two different levels of flank wear ($VB = 0, 70$ μm) with the same cutting speed of $V_c = 110$ m/min. The surface stress and compressive valley intensity produced by a worn tool ($VB = 70$ μm) moved toward the tensile direction, as compared to those by a new tool ($VB = 0$ μm). The amount of shift of the surface residual stress toward tensile stress in type 1 are 440 MPa and 299 MPa in axial and circumferential directions. Those amounts in type 2 are 115 MPa and 296 MPa in axial and circumferential directions.

Additional heat flux generated by rubbing between flank wear and workpiece surface can be flowed into the workpiece surface. Gunnberg et al. [5] stated that this thermal effect can move residual stresses toward tensile stress in case hardened steel. For this reason, moderate level of flank wear of $VB = 70$ μm was employed to minimize the thermal effect in this study. However, the amounts of shift toward tensile stress in both type 1 and type 2 are still significant.

Compressive residual stress was induced after hard machining in gentle cutting conditions in this study. The higher compressive stress can be beneficial because it was shown to increase fatigue strength [12-14]. Higher initial compressive residual stress after heat treatment can induce higher compressive residual stress after hard machining. Thus, initial residual stress after heat treatment needs to be studied before hard machining. Considering factors, such as initial HT residual stresses and machining conditions, residual stresses after hard machining of different types of case hardened steels

can be predicted and analysed.

4. Conclusion

Hard machining of two types of 27MnCr5 case hardened steels was performed and their residual stresses were analysed and compared (type 1 vs. type 2) in this study. Following conclusions can be drawn:

- Heat treatment plays an important role in generating residual stress profiles before and after hard machining. The amount of initial compressive residual stress depends on heat treatment conditions.
- For a gentle cutting speed range ($V_c = 80, 110, 140$ m/min) in this study, cutting speed is not an influential parameter to change residual stress profiles.
- Hard machining with a moderate flank wear ($VB = 70$ μm) moved residual stress profiles toward tensile stress. In particular, the shift of surface residual stress toward tensile stress is significant.

Acknowledgements

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