Effects of grinding parameters on residual stress of 42CrMo steel surface layer in Grind-hardening

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***Abstract*—Grind-hardening is an integrated manufacturing technology of surface-quenching and grinding process. The residual stress is one of the main characteristic parameters of grinding-hardened surface quality. On the basis of the grinding-hardening test, influences of the grinding speed, the grinding depth and the feed speed on residual stress in grinding-hardened layer of 42CrMo steel were systematically studied. Basic regularities of above-mentioned grinding parameters on residual stress and its relationship with micro-hardness distribution of the hardened layer are generally revealed. The results show that compress residual stresses decrease with the grinding speed and grinding depth increasing or feed speed decreasing, whereas maximal compress residual stress and the action depth of stress rise accordingly. This study provides the theoretical and experimental foundation for actively controlling grinding-hardened surface quality.**

***Keywords*—grind-hardening; micro-hardness; residual stress; grinding parameters**

I. INTRODUCTION

As a modern manufacturing technology integrating surface quenching and grinding process, grind-hardening has the advantage of “green, energy-saving and high-efficiency”, whose application fields are expanding constantly. The coupling of thermal stress, mechanical stress and material transformation stress in grind-hardening process results in a large residual stress on the work-piece surface after hardening. Under constraints of boundary conditions, these stresses interact and balance, which eventually cause a great influence on the parts performance [1]. Z. H. Hu and Z. J. Yuan et al. [2] summarized and analyzed the mechanism of grinding residual stress. Afterwards, they studied effects of normal grinding force, grinding mode and material diffusion of grinding wheel on residual stress. Finally, they put forward a new viewpoint that constraint conditions affect residual stress. Based on thermal elastic-plastic theory, H. N. Hu and Z. H. Zhou et al. [3]quantitatively analyzed surface residual stresses under the condition of pre-stress and then pointed out that pre-stress is an effective method to control the surface residual stress. After simplifying the mechanical problem, X. L. Tian and Y. S. Xu et al. [4] established a stress model affected by moving concentrated force and heat source. The surface residual stress of ceramics eventually was calculated by the thermal elastic-plastic finite element method, which provided the theoretical basis for positively predicting and controlling residual stresses in ceramic grinding. Berg and Monahan et al. [5] studied the strength and residual stresses after ceramic grinding. Then influences of the system rigidity and the grinding wheel on residual stresses were explored respectively. By means of the finite element method, P. N. Moulik et al. [6] simulated the thermal stress in the grinding process and analyzed effects of the heat source distribution, feed rate and heat flux density on residual stresses. The result shows that heat source distribution has little effect on residual stresses. Along with feed rate rising, residual stress reduces and with the increase of heat flux, residual stress builds up accordingly. Using the corrosion stripping method, J. D. Liu and G. C. Wang et al. [7] measured surface residual stresses under four different conditions of down-grinding, reverse-grinding, dry-grinding and wet-grinding in the hardened layer of 40Cr steel by X-Ray Diffraction. Eventually, the distribution curves along the depth direction were obtained. According to the principle of energy distribution in ultra-high speed cutting, Y. M. Liu and Y. D. Gong et al. [9] transformed a super-high speed model into a single abrasive grinding model and gained the rule of the cutting speed on the surface residual stress.

So far, although above domestic and foreign scholars studied and simulated problems of residual stresses in grinding-hardened layer from different aspects, such as formation mechanism, grinding conditions and grinding wheel, how grinding parameters affect the residual stresses and its relationship with hardness distribution have not yet been studied, which influence and restrict the development of grind-hardening process theory and the expand of application fields. Therefore, this study took 42CrMo steel as the experimental material and systematically studies the formation and variation of residual stresses, in order to further enrich and develop the grind-hardening process technology.

II. EXPERIMENTAL CONDITIONS

A. *Experimental Material and Equipment*

This experiment selected the quenched-tempered 42CrMo steel and carried out the grind-hardening experiment by the flat CNC grinding machine MKL7132X6/12. The grinding wheel type was WA60L6V. The measuring apparatus were digital hardness-tester (HVS-1000), electrolytic polishing machine and X-Ray Diffraction residual stress tester. The experiment was carried out in materials science and engineering laboratory of Shanghai Jiaotong University. Fig. 1 and Fig. 2 are micro-hardness tester and residual stress measurement equipment respectively.

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Fig. 1. Digital hardness tester

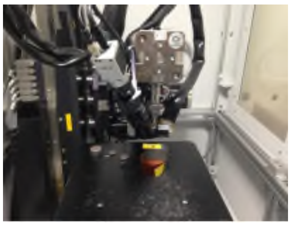


Fig. 2. Residual stress measurement

B. *Experimental Programme and Method*

The grinding test conditions are shown in Table I. Among them, three underlined data were reference and the single factor method was adopted in the experiment. The residual stress of the hardened layer was measured with the corrosion stripping method by a X-Ray Diffraction equipment (LXRD-CHI type). The measurement conditions are shown in Table II. Each experimental data was calculated through the arithmetic mean of three measurements and abnormal values measured in the test were excluded. In addition, corresponding experiments were carried out repeatedly.

TABLE I. THE GRINDING TEST CONDITIONS

Grinding parameters	**Values**
Grinding speed v_s(m/s)	25、30、35
Grinding depth a_p(mm)	0. 2、0. 3、0. 4
Feed speed v_w(m/min)	0. 2、0. 3、0. 4
Grinding mode	One-way cutting-in down-grinding
Cooling	Dry

TABLE II. THE RESIDUAL STRESS MEASUREMENT CONDITIONS

Measurement method	Tilted fixed psi	**Inter-planar spacing**	1. 17
Peak determination	Cross-correlation	**Bragg Angle**	156. 41°
Radiation	Crka	**wavelength**	2. 29
Diffraction crystal	(211)	**Counting time**	1s
Ψ(°)	-45°-45°	**Tube pressure**	35kV
Elastic constant S2 /2	5. 92×10-6	**Tube current**	30mA
Elastic constant S1	-1. 17×10-6	**Tube diameter**	3mm

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. *Experimental Results*

Fig. 3-Fig. 5 are distribution curves of the residual stress σ_x in the grinding-hardened layer under different grinding conditions. It can be seen from three figures that residual compress stresses exist on the surface of the hardened layer and the maximal residual compress stress is in the subsurface. With the increase of distances from the work-piece surface, the distribution of residual stresses along the depth direction appears three regions: the high-stress region, the stress-transition region and the tensile-stress region. In the high-stress region, the residual compress stress increases slowly and the maximum is about -732MPa. In the transition region, the residual stress decreases sharply and then convert into tensile stress. The depth of the transition region is relatively small, which is about 0. 3mm. In the tensile-stress region, the stress value is finally stable at around 520MPa.

B. *The Relationship between Grinding Speed and Residual Stresses*

Fig. 3 shows the experimental result of the influence of grinding speed v_s on the residual stress σ_x in the grinding-hardened layer. Based on Fig. 3, when v_s was 25m/s, the residual compress stress on the surface of the grinding-hardened layer and the maximum were -278MPa and -644MPa respectively. The stress depth was 1100μm; When v_s was 35m/s, two above-mentioned values were -368MPa and -608MPa individually. The stress depth was 1360μm; Both stress values were stable at 520MPa eventually. This is because, as the grinding speed increasing, the number of grinding grains involved in the cutting per unit time and the thermal effect increases, which causes the residual compress stress in the grinding-hardened layer decreasing. While the grinding temperature rises rapidly and the volume of martensitic transformation builds up correspondingly, the stress depth increasing accordingly. Therefore, with the increase of grinding speed v_s, the residual stress in grinding-hardened layer gradually reduces and the stress depth increases conversely.

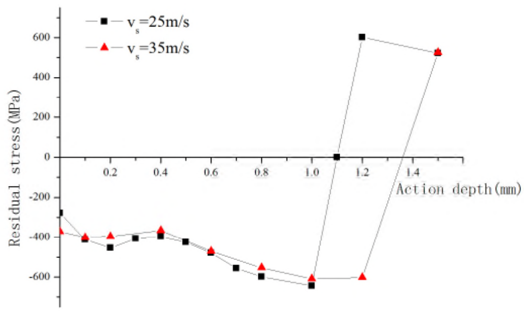


Fig. 3. The effect of grinding speed on residual stresses

C. The Relationship between Grinding Depth and Residual Stresses

Fig. 4 shows the experimental result of the influence of grinding depth a_p on the residual stress σ_x in the grinding-hardened layer. It can be seen from Fig. 4. that when a_p was 0. 4mm, the residual compress stress on the surface of the grinding-hardened layer and the maximal stress were -259MPa and -732MPa respectively. The stress depth was 1680 μ m. Compared with the standard parameter, the residual compress stress on the surface of the grinding-hardened layer decreased by 19MPa and the maximum increased by 89MPa. Meanwhile, the stress depth also went up by 580μm. Due to the increase of grinding depth a_p, the average undeformed chip thickness of single abrasive particle rise. The thermal stress and plastic deformation enhancing, the proportion of tensile stress built up, which contributes to the transformation of residual stress along the stretching direction. The increase of grinding depth a_p leads to a sharp rise in the normal grinding force and the squeezing effect of the work-piece surface material. The maximal residual stress and the stress depth also go up. Consequently, as the grinding depth a_p increasing, the residual compress stress reduces. However, the maximum residual stress and the stress depth increase.

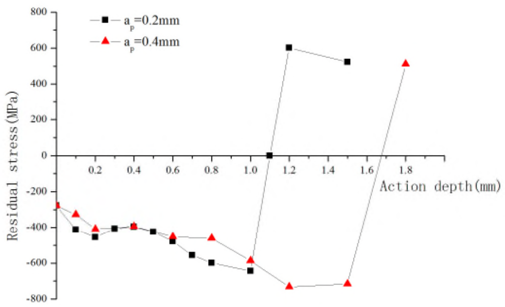


Fig. 4. The effect of grinding depth on residual stresses

D. The Relationship between Feed Speed and Residual Stresses

Fig. 5 shows the experimental result of the influence of feed speed v_w on the residual stress σ_x in the grinding-hardened layer. It is obvious from Fig. 5 that when v_w was 0. 4m/min, the residual compress stress on the surface of the grinding-hardened layer and the maximum residual stress were -278MPa and -644MPa respectively; When v_w was 0. 2m/min, these two values were -230MPa and -672MPa; The stress depth were 1100μm and 2145μm individually. With the increase of feed speed v_w, the maximum cutting depth of abrasive grain h_m and the heat flux density q increase, which result in the rise of heat generation. However, the moving speed of the heat source along the processed surface accelerated and the contact time between the grinding wheel and the work-piece reduced. Then the grinding heat cannot be transferred to the inner promptly, contributing to the decrease of the stress depth. The increase of work-piece feed speed reduces the influence of heat effect, which makes the residual stress build up in the grinding-hardened layer. In addition, the stress depth soars sharply as the feed speed reducing according to Fig. 5. It indicates that v_w has the most significant impact on the depth of residual stress in hardened layer. Therefore, in the process of grinding-hardening, it is necessary to select the lower feed speed v_w as far as possible to ensure the premise of processing efficiency, in order to obtain the optimum stress depth.

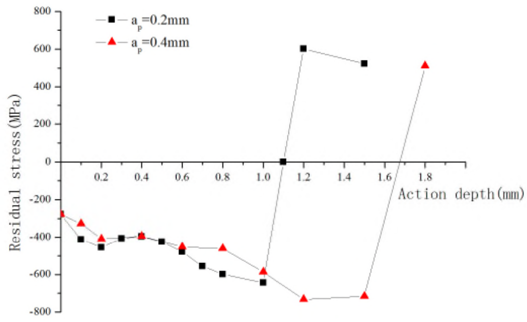
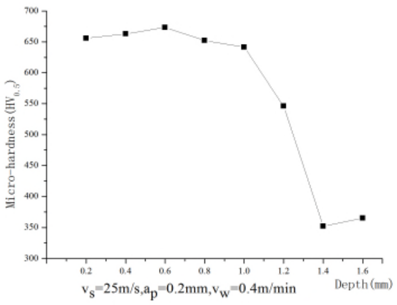


Fig. 5. The effect of feed speed on residual stresses

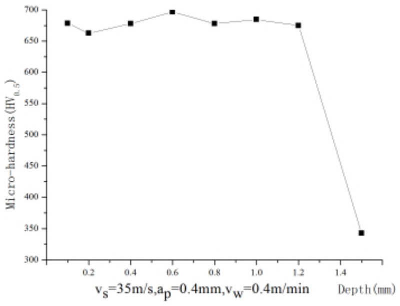
E. The Relationship between the Residual Stress and Hardness

Fig. 6 presents the experimental results of micro-hardness of grinding-hardened layer. As shown in Fig. 6, with distances from the work-piece surface increasing, the distribution of micro-hardness of the grinding-hardened layer appears regular and the layer can be divided into high-hardness region, drop-hardness region and low-hardness region in the depth direction. In the high-hardness region, the hardness value fluctuates around 650HV and tend to be stable eventually; In the drop-hardness region, the value reduces sharply and the depth of this region is smaller about 0. 4mm. In the low-hardness region, the value is stable at about 320HV, which is in the base of the work-piece. In addition, it can be found from Fig. 6 that when the grinding speed, grinding depth and feed speed change, the hardness of the high-hardness region in grinding-hardened layer basically change between 600HV and 700HV. The micro-hardness value of grinding-hardened layer is determined by the heating temperature and the cooling rate. In the process of grinding-hardening, due to the dry grinding, the heating temperature of the surface metal of the work-piece are all higher than A_{c3} under different grinding parameters and the austenization is realized. Because of the air cooling, the influence of cooling speed is not considered here. Accordingly, the micro-hardness of high-hardness region is mainly determined by the carbon content of the material itself, which is irrelevant to the change of grinding parameters.

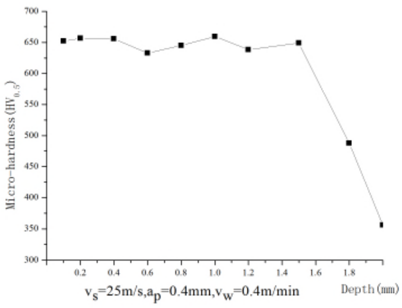
Combining Fig. 3-Fig. 5 with Fig. 6, it can be shown that along the depth direction, residual stress in the grinding-hardened layer can be divided into the high-stress area, transition area and tensile-stress area, which correspond to high-hardness area, drop-hardness area and low-hardness area respectively. There is a relatively stable residual compress stress in the high-hardness area; In the drop-hardness area, residual compress stress decreases drastically and then converts into the tensile stress. In the low-hardness area, it completely transforms into residual tensile stress. The depth of the grinding-hardened layer includes the depth of high-hardness region and the depth of drop-hardness region. Since the depth of the residual compress stress converting into the tensile stress is relatively narrow, it is considered that residual compress stress exists in the whole hardened layer.



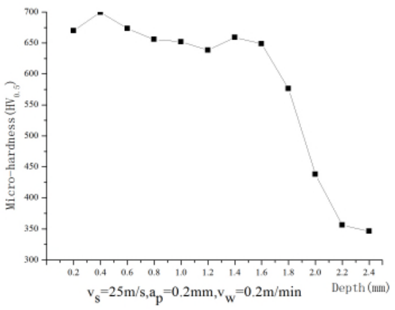
(a)



(b)



(c)



(d)

Fig. 6. The distribution micro-hardness of the grinding-hardened layer

IV. Conclusions

1) The residual stress forming on the surface of the 42CrMo steel grinding-hardened layer can be divided into three regions: the residual compress stress forming on the surface, the maximum residual compress stress in the subsurface and the tensile stress converted from the residual compress stress in the deeper inner layer.

2) As the grinding speed and grinding depth increasing, the work-piece feed rate decreasing, the surface residual stress value of the grinding-hardened layer decreases correspondingly, but the maximal residual stress and the action depth increase accordingly. Among them, the grinding depth has the greatest influence on the maximum residual compress stress value and the feed rate has the greatest influence on the stress depth.

3) Along the depth direction, the residual stress of the grinding-hardened layer can be divided into high-pressure stress region, transition region and tensile-stress region, which correspond to the high-hardness region, drop-hardness region and low-hardness region individually. Due to the small depth of transition, it can be considered that the residual compress stress exists in the entire grinding-hardened layer.

Acknowledgment

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