Effect of Grinding Parameters on the Hardness Penetration Depth of the Steel GCr15 in Internal Grind Hardening Process

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Abstract. This paper discusses the effects of the depth of cut ($a_p$), the workpiece speed ($v_w$) and the grinding wheel speed ($v_s$) on the structure and hardness of the grind hardening layer on the steel GCr15. It was found that the completely hardened zone of the internal grind-hardened layer on the steel GCr15 mainly contains needle-shaped martensite and a very low amount of carbides and retained austenite. The grinding parameters have no significant effect on the martensite microstructure and hardness of the high-hardness zone in the internal grind-hardening process. An increase of the depth of cut and the grinding wheel speed or a decrease of the workpiece speed, leads to a thicker grind-hardening layer. From the viewpoint of increasing the hardness penetration depth, a larger the depth of cut and the grinding wheel speed and a smaller the workpiece speed should be selected, under the internal grind-hardening experimental conditions.

1. Introduction
Grind hardening is a surface hardening and grinding process. The process relies on the heat generated in the grinding zone in order to heat the surface of the workpiece above austenitizing temperature, and subsequent the workpiece undergoes martensitic transformation to achieve high surface hardness of the workpiece[1].

At present, scholars have discussed the effect of the depth of cut on the hardness penetration depth (HPD), the distribution of the microstructure, the simulation of the grinding force and thermal effects [2-10].

The present paper on grind hardening process is mainly focused on the formation mechanism of surface grind hardening. However, in all works above, the forming mechanism of internal grind hardening of the steel GCr15 has not been discussed.

This paper is to understand the feasibility of obtaining a hardened layer of the internal surface of the steel GCr15. The assessment will be made through the experiment under various grinding parameters. The results obtained, including the macro-microstructure, micro-hardness distribution and HPD, will be analyzed by the heat transfer mechanism and the relationship between structure and hardness.

2. Experiment of Internal Grind Hardening
The workpiece material was the spheroidized annealed steel GCr15. The hardness of the as-received GCr15 is around 200 HV. The Matrix of Steel GCr15 is shown in Fig. 1. The chemical composition is...
shown in Table 1. The size of the workpiece (outer diameter × thickness × inner diameter) is 110 mm × 10 mm × 70 mm. The grinding-hardening experiments were conducted on a modified internal grinder, M2120. A vitrified chrome-corundum grinding wheel, PA46L6V, of 60 mm in diameter and 32 mm in width was selected.

The down-grinding mode was used, with the depth of cut of 0.1, 0.2, 0.3 mm, the feeding rate of 0.10, 0.15, 0.20 m / min, the grinding wheel speed of 24, 27, 30 m/s. The details of the grinding conditions are shown in Table 2. In order to ensure the reliability and reproducibility of the experimental results, each experiment was repeated three times. The equipment of the grinding experiment is shown in Fig. 2.

After the grinding process, all the workpieces were sliced to samples with a length of 10 mm, a width of 10 mm and a height of 9 mm every 90°. The sliced pieces were hot-mounted in a specimen using an XQ-2B mounting press. The mounted specimens were subsequently polished with successively finer emery papers and then cloth-polished on a PA-2 polisher until a mirror-like surface was obtained. The HX-1000TMC automatic turret micro-hardness tester was elected to measure the hardness value.

The fine polished samples were then etched with reagent (4 ml nitric acid in 96 ml ethanol) for about 45 s to reveal the microstructure of the HPD. Afterwards, macrographs of the HPD were examined in a VHX-700F digital microscope. Finally, detailed micrographs of the HPD were taken by means of a Phenom-XL scanning electron microscopy at the condition of 15 kV.

Table 1. Chemical composition of the steel GCr15 (mass fraction, %) [6]

| C  | Cr  | Fe  | Mn  | P   | S  | Si |
|----|-----|-----|-----|-----|----|----|
| 0.98–1.10 | 1.45 | 97  | 0.35 | 0.025 max | 0.025 max | 0.23 |

Table 2. Internal grind-hardening experiment

| No | a_p/(mm) | v_w/(m/min) | v_s/(m/s) |
|----|----------|-------------|-----------|
| 1  | 0.1      | 0.10        | 24        |
| 2  | 0.2      | 0.10        | 24        |
| 3  | 0.3      | 0.10        | 24        |
| 4  | 0.3      | 0.15        | 24        |
| 5  | 0.3      | 0.20        | 24        |
| 6  | 0.3      | 0.10        | 27        |
| 7  | 0.3      | 0.10        | 30        |

Figure 1. Matrix microstructure of the steel GCr15.

Figure 2. Experimental setup.
3. Experimental Results of Cylindrical Internal Grind Hardening

Fig. 3 is the macroscopic morphology of the grind hardening layer. As can be seen in the Fig. 3, the workpieces show different color characteristics with the increased subsurface depth. Furthermore, the grind hardening layer was divided into light yellow zone, light black zone, and gray zone from workpiece surface to the bottom. The heat generated by the grinding arc zone is transmitted to the surface of the workpiece. The heat diffuses subsequently to the matrix in the form of heat conduction, leading to the formed temperature field. According to the distribution law of the temperature field, the workpiece was divided into the completely hardened zone with the temperature exceeding $A_{C3}$, transition zone with the temperature between $A_{C1}$ and $A_{C3}$, and matrix with the temperature between ambient temperature ($20 ^\circ C$) and $A_{C1}$ in the internal grind hardening process. The macrostructure division of the hardening layer of the workpiece is the direct result of the temperature distribution in the grind hardening process.

![Figure 3. Macroscopic morphology of the grind hardening layer.](image)

Fig. 4 shows the microstructure of the completely hardened zone under the different grinding parameters. As can be seen in Fig. 4 (a), (b), (c) and (d), the microstructure of the completely hardened zone under the different grinding parameters mainly contains needle-shaped martensite and a very low amount of carbides and retained austenite.

Fig. 5 is the hardness distribution curve of sample 7. As shown in Fig. 5, the micro-hardness of the hardening layer has a regular distribution in the subsurface depth. The hardness distribution curve was divided into high-hardness zone, hardness decreased zone, and low hardness zone, corresponding to the completely hardened zone, transition zone and matrix of the macrostructure division. The hardness keeps steady in the high hardness zone with the value of between 700 and 780 HV, which is more than 3.5 times the matrix hardness (200 HV) of steel GCr15, higher than ordinary martensite (560 HV) in normal quenching process.

The hardness decreases slowly in the hardness decreased zone, and the hardness drop is close to 500 HV. The HPD is defined as the distance from the surface of the workpiece to 80% of the average hardness value in the high hardness zone (the average hardness value of the high hardness zone is 750 HV in the experiment)[9]. Furthermore, as shown in Fig. 5, the depth larger than 600 HV is defined as HPD.

Hardness distribution curves for samples of steel GCr15 under the different grinding parameters is shown in Fig. 6. The effect of grinding parameters on HPD (Fig. 7) is from Fig. 6 curves. As can be seen in Fig. 7 (a), the HPD significantly increases with the increasing of $a_p$. The maximum HPD that can be achieved is close to 0.92 mm with $a_p$ equaling to 300 μm. As can be seen in Fig. 7 (b), the HPD decreases with the increasing of $v_w$. The maximum HPD that can be achieved is close to 0.92 mm with $v_w$ equaling to 0.10 m/min. As can be seen in Fig. 7 (c), the HPD increases with the increasing of $v_c$. The maximum HPD that can be achieved is close to 1.08 mm with $v_c$ equaling to 0.30 m/s.
Figure 4. Microstructure of the completely hardened zone under the different grinding parameters (a) \( a_p=0.1 \) mm, \( v_w=0.10 \) m/min, \( v_s=24 \) m/s, (b) \( a_p=0.3 \) mm, \( v_w=0.10 \) m/min, \( v_s=24 \) m/s, (c) \( a_p=0.3 \) mm, \( v_w=0.20 \) m/min, \( v_s=24 \) m/s and (d) \( a_p=0.3 \) mm, \( v_w=0.10 \) m/min, \( v_s=30 \) m/s.

Figure 5. Hardness distribution curve for sample 7 of steel GCr15.

Figure 6. Hardness distribution curves for samples of steel GCr15 under the different grinding parameters.
Figure 7. Effect of grinding parameters on HPD (a) the depth of cut ($a_p$), the workpiece speed ($v_w$) and the grinding wheel speed ($v_s$)).

4. Analysis on the Experimental Results
The above experiment results show that HPD increases with the increasing of $a_p$ and $v_s$ or the decreasing of $v_w$.

The undeformed cutting thickness of the single grit increases with the increasing of $a_p$. The contact arc length subsequently lengthens, the number of the grit increases, and the thermal action time extends. Therefore, the grinding force and the grinding heat increases with the increasing of $a_p$, leading to the increasing of the grinding temperature and then the HPD increases.

When increasing $v_s$, the undeformed cutting thickness of the single grit decreases and then the chip deformation energy and the number of the grit involving in ploughing and sliding increases, leading to aggravated friction. Therefore, the grinding heat increases with the increasing of $v_s$, leading to the increasing of the grinding temperature and then the HPD increases.

The undeformed cutting thickness of the single grit decreases with the decreasing of $v_w$ and subsequently the number of the grits decreases, leading to the decreasing of the grinding force and heat flux density, the extending of the thermal action time and the increasing of the grinding heat and the grinding temperature. In addition, the heat of the surface has enough time to conduct to the inner layer of the workpiece, leading to expanding the zone above the $A_{c3}$ temperature. Therefore, the HPD increases with the increasing of $v_s$.

As shown in Fig. 4, 5 and 6, the effect of fine grain strengthening on the hardness of the high hardness zone is generally the same. Therefore, the grinding parameters have no significant effect on the hardness of the high hardness zone.

5. Conclusions
1. According to the distribution of the grinding temperature field, the internal grind hardening layer was divided into the completely hardened zone, transition zone and matrix of the workpiece. The completely hardened zone of the internal grind hardening layer on the steel GCr15 mainly contains needle-shaped martensite and a very low amount of carbides and retained austenite.

2. The grinding parameters have no significant effect on the hardness of the high hardness zone under the coupling of heat and force in internal grind hardening process.

3. An increase of the depth of cut and the grinding wheel speed and a decrease of the workpiece speed, leads to a thicker grind hardening layer. From the perspective of saliency analysis, the effect of the depth of cut on the HPD is the most significant.

4. From the viewpoint of increasing the HPD, a larger the depth of cut and the grinding wheel speed and a smaller the workpiece speed should be selected in the internal grind-hardening experimental conditions.

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7. References

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