Orthogonal Experimental Study on Two Side-direction Burrs of Grind-hardening Workpiece Based on Transverse Feed

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Abstract: Based on the orthogonal experiment, the influences of grinding depth \((a_p)\), the workpiece feeding rate \((v_w)\) and the transverse regrinding value \((C_r)\) on two side-direction burr of 40Cr steel large-plane grind-hardening workpiece were investigated. The results show that, under the coupling of heat and force in the grind-hardening process, the surface metal of the workpiece metal flows toward the unconstrained direction on both sides, resulting in the formation of the burr. The grinding depth and the workpiece feeding rate become leading factors affecting the size of the burr. Moreover, the significance of three factors to the size of the burrs is as follows: the grinding depth \((a_p)\) > the workpiece feeding rate \((v_w)\) > the transverse regrinding value \((C_r)\). The result showed that the maximum size of the first-pass and the second-pass burr would increase with the increasing of the grinding depth and the transverse regrinding value in grind-hardening processes, but it decreases with the workpiece feeding rate. The optimal process parameters are \(a_p=0.1\text{mm}, v_w=0.8\text{m/min}\), and \(C_r=1\text{mm}\) under the experiment conditions.

1. Introduction

Hardening layer with a certain thickness will be formed on the workpiece surface when the grinding depth reached to a certain value in the dry grinding process. This process could be called grind hardening. It realizes the integration of grinding and surface quenching, and has broad application prospects in the field of metal material grinding and surface modification [1]. At present, scholars mainly study on plunge grinding [2-11]. Nevertheless, the research of the burrs on both sides of the workpiece in the grind-hardening process based on the transverse feed is concerned less. When the width of the workpiece is wider than the width of the grinding wheel, the workpiece needs to be longitudinal reciprocating motion. At the same time, the grinding wheel needs to be transverse intermittent feed motion. Transverse feed grinding simplified schematic diagram is shown in Fig.1.
shown in the figure, a regrind zone is the overlapping portion of between the first grinding process and the second grinding process. Combined with the previous researches on the deep microstructure and hardness of the hardening layer and the depth of the hardened layer and its uniformity [8], this paper will analyze the effect of grinding depth, workpiece feeding rate and transverse regrinding value on the size of the burrs on both sides of the surface grind-hardening workpiece. Then the size of the burrs on both sides of the workpiece is optimized based on the orthogonal experiment.

2. Experiment of grind hardening

Experiment of grind-hardening process is based on 40Cr specimens. A two-pass and two-way reciprocating plunge grinding experiment is designed to analyze the effect of the transverse regrinding value on the size of the burrs on both sides of the surface grind-hardening workpiece. In addition, the grind-hardening process is shown in Fig. 1. The area of experimental workpiece materials is 50 × 10 × 20 mm. In the grind-hardening experiment, the first-pass width of grind-hardening is 5 mm and the second-pass width of grind-hardening are 5 mm, 6 mm, 7 mm, and 8 mm, respectively, which are corresponding to the transverse regrinding value of 0mm, 1mm, 2mm and 3mm. Then process conditions of the experiment are shown in Table 1. After grind-hardening process, the wire electric discharge machine is used to evenly divide the specimen into four equal parts along the longitudinal direction of the workpiece. Then the size of each part is 5×10×5mm. It is made into four metallographic specimens after being inlaid and polished. VK-X100K microscope is used in the size and the surface morphology of the burrs on both sides of the surface grind-hardening workpiece. The size of burrs is shown in Fig. 2, which is the burr height and is the burr root depth. The left of the part is first-pass burr zone and the right of the part is second-pass burr zone. Since the maximum burr size play a leading role in the burr removal, the maximum burr size is used as a crucial index.

Table 1. Process conditions of the experiment

| Machine tool       | Grinding wheel | \(v_s/(m/s)\) | \(a_p/(mm)\) | \(v_w/(m/min)\) | \(C_r/(mm)\) | Grinding mode                      |
|--------------------|----------------|--------------|--------------|-----------------|----------------|------------------------------------|
| M7130 surface grinder | P340×40×127    | 25.6         | 0.1, 0.2, 0.2, 0.4 | 0.1, 0.1, 0.2, 0.4, 0.6, 0.8, 2, 3 | first-pass down-grinding + second-pass up-grinding |

3. Experiment and analysis of grind hardening

The range of the grinding depth for the maximum height of the first-pass burr is 0.578, the range of the workpiece feeding rate for the maximum height of the first-pass burr is 0.218 and the range of the transverse regrinding value for the maximum height of the first-pass burr is 0.139. The results show that the influence of each factor on the maximum height of the first-pass burr is the grinding depth \((a_p)\) > the workpiece feeding rate \((v_w)\) > the transverse regrinding value \((C_r)\). The influence of the
grinding depth, the workpiece feeding rate and the transverse regrinding value on the maximum height of the first-pass burr is shown in Fig. 3. Moreover, the optimal process parameters for the maximum height size of the first-pass burr of the 40Cr steel are \( a_p = 0.1 \text{mm}, v_w = 0.8 \text{m/min}, \) and \( C_r = 0 \text{mm} \) under the experiment conditions.

The variance analysis of the maximum height of the first-pass burr is shown in Table 2. In the case of significant levels, \( \alpha = 0.1, \alpha = 0.05 \) and \( \alpha = 0.01 \), the \( F \)-values of the grinding depth, the workpiece feeding rate and the transverse regrinding value are larger than the critical value. Thus, the grinding depth and the workpiece feeding rate highly become leading factors affecting the maximum height of the first-pass burr, and the transverse regrinding value becomes a leading less factor in the grind-hardening process.

**Table 2.** Variance analysis of the maximum height of the first-pass burr

| Source of variance | Sum of squares, \( S \) | Freedom, \( f \) | \( MS \) | \( F \) | Criticality value | Significance |
|--------------------|--------------------------|-----------------|--------|-------|-----------------|--------------|
| \( a_p \)          | 0.772                    | 3               | 0.257  | 49.941| \( F_{0.00(3,6)}=3.29 \) | ** *** |
| \( v_w \)          | 0.107                    | 3               | 0.036  | 6.901 | \( F_{0.05(3,6)}=4.76 \) | ** |
| \( C_r \)          | 0.061                    | 3               | 0.020  | 3.940 | \( F_{0.00(3,6)}=9.78 \) | * |
| \( e \)            | 0.031                    | 6               | 0.005  |       |                 |              |
| sum                | 0.97                     | 15              |        |       |                 |              |

The range of the grinding depth for the maximum root depth of the first-pass burr is 0.521, the range of the workpiece feeding rate for the maximum root depth of the first-pass burr is 0.313 and the range of the transverse regrinding value for the maximum root depth of the first-pass burr is 0.041. The results show that the influence of each factor on the maximum root depth of the first-pass burr is
the grinding depth \((a_p)\) > the workpiece feeding rate \((v_w)\) > the transverse regrinding value \((C_r)\). The influence of the grinding depth, the workpiece feeding rate and the transverse regrinding value on the maximum root depth of the first-pass burr is shown in Fig. 4. Moreover, the optimal process parameters for the maximum root depth of the first-pass burr of the 40Cr steel are \(a_p=0.1\)mm, \(v_w=0.8\)m/min, and \(C_r=0\)mm under the experiment conditions.

The variance analysis of the maximum root depth of the first-pass burr is shown in Table 3. In the case of significant levels, \(\alpha=0.1\), \(\alpha=0.05\) and \(\alpha=0.01\), the \(F\)-values of the grinding depth, the workpiece feeding rate and the transverse regrinding value are larger than the critical value. Thus, the grinding depth and the workpiece feeding rate highly become leading factors affecting the maximum root depth of the first-pass burr, and the transverse regrinding value becomes no obvious in the grind-hardening process.

Table 3. Variance analysis of the maximum root depth of the first-pass burr

| Source of variance | Sum of squares, \(S\) | Freedom, \(f\) | MS | \(F\) | Criticality value | Significance |
|-------------------|----------------------|---------------|----|------|------------------|-------------|
| \(a_p\)           | 0.646                | 3             | 0.215 | 293.246 | \(F_{0.99}(3,6)=3.29\) | ***        |
| \(v_w\)           | 0.210                | 3             | 0.070 | 95.202 | \(F_{0.99}(3,6)=4.76\) | ***        |
| \(C_r\)           | 0.004                | 3             | 0.001 | 1.907 | \(F_{0.99}(3,6)=9.78\) |            |
| \(e\)             | 0.004                | 6             | 0.001 |        |                   |             |
| sum               | 0.865                | 15            |      |       |                   |             |

The range of the grinding depth for the maximum height of the second-pass burr is 0.577, the range of the workpiece feeding rate for the maximum height of the second-pass burr is 0.188 and the range of the transverse regrinding value for the maximum height of the second-pass burr is 0.112. The results show that the influence of each factor on the maximum height of the second-pass burr is the grinding depth \((a_p)\) > the workpiece feeding rate \((v_w)\) > the transverse regrinding value \((C_r)\). The influence of the grinding depth, the workpiece feeding rate and the transverse regrinding value on the maximum height of the second-pass burr is shown in Fig. 5. Moreover, the optimal process parameters for the maximum height of the second-pass burr of the 40Cr steel are \(a_p=0.1\)mm, \(v_w=0.8\)m/min, and \(C_r=0\)mm under the experiment conditions.

Figure 5. Effect of the grinding depth \((a_p)\), the workpiece feeding rate \((v_w)\) and the transverse regrinding value \((C_r)\) on the maximum height of the second-pass burr

The variance analysis of the maximum height of the second-pass burr is shown in Table 4. In the case of significant levels, \(\alpha=0.1\), \(\alpha=0.05\) and \(\alpha=0.01\), the \(F\)-values of the grinding depth, the workpiece feeding rate and the transverse regrinding value are larger than the critical value. Thus, the grinding depth and the workpiece feeding rate highly become leading factors affecting the maximum height of the second-pass burr, and the transverse regrinding value becomes a leading factor in the
Table 4. Variance analysis of the maximum height of the second-pass burr

| Source of variance | Sum of squares, S | Freedom, f | MS  | F      | Criticality value | Significance |
|--------------------|------------------|------------|-----|--------|------------------|--------------|
| $a_p$              | 0.753            | 3          | 0.251 | 91.141 | $F_{0.05(3,6)}=3.29$ | ***          |
| $v_w$              | 0.088            | 3          | 0.029 | 10.661 | $F_{0.05(3,6)}=4.76$ | ***          |
| $C_r$              | 0.040            | 3          | 0.013 | 4.842  | $F_{0.05(3,6)}=9.78$ | * *          |
| $e$                | 0.017            | 6          | 0.003 |        |                  |              |
| sum                | 0.898            | 15         |      |        |                  |              |

The range of the grinding depth for the maximum root depth of the second-pass burr is 0.588, the range of the workpiece feeding rate for the maximum root depth of the second-pass burr is 0.239 and the range of the transverse regrinding value for the maximum root depth of the second-pass burr is 0.072. The results show that the influence of each factor on the maximum root depth of the second-pass burr is the grinding depth ($a_p$) > the workpiece feeding rate ($v_w$) > the transverse regrinding value ($C_r$). The influence of the grinding depth, the workpiece feeding rate and the transverse regrinding value on the maximum root depth of the second-pass burr is shown in Fig. 6. Moreover, the optimal process parameters for the maximum root depth of the second-pass burr of the 40Cr steel are $a_p=0.1\text{mm}, v_w=0.8\text{m/min}$, and $C_r=1\text{mm}$ under the experiment conditions.

Figure 6. Effect of the grinding depth ($a_p$), the workpiece feeding rate ($v_w$) and the transverse regrinding value ($C_r$) on the maximum root depth of the second-pass burr

Table 5. Variance analysis of the maximum root depth of the second-pass burr

| Source of variance | Sum of squares, S | Freedom, f | MS  | F      | Criticality value | Significance |
|--------------------|------------------|------------|-----|--------|------------------|--------------|
| $a_p$              | 0.863            | 3          | 0.288 | 264.109 | $F_{0.05(3,6)}=3.29$ | ***          |
| $v_w$              | 0.148            | 3          | 0.049 | 45.365 | $F_{0.05(3,6)}=4.76$ | ***          |
| $C_r$              | 0.014            | 3          | 0.005 | 4.168  | $F_{0.05(3,6)}=9.78$ | *            |
| $e$                | 0.007            | 6          | 0.001 |        |                  |              |
| sum                | 1.031            | 15         |      |        |                  |              |

The variance analysis of the maximum root depth of the second-pass burr is shown in Table 5. In the case of significant levels, $\alpha=0.1$, $\alpha=0.05$ and $\alpha=0.01$, the F-values of the grinding depth, the workpiece feeding rate and the transverse regrinding value are larger than the critical value. Thus, the grinding depth and the workpiece feeding rate highly become leading factors affecting the maximum root depth of the second-pass burr, and the transverse regrinding value becomes a leading factor in the grind-hardening process.
4. Method of reducing the burr size

According to our previous research results, the softened band between first-pass grind-hardening process and second-pass grind-hardening process would increase with the increasing of the workpiece feeding rate or with the decreasing of the grinding depth, but it increases with the increasing of transverse regrinding value. When the transverse regrinding value \((C_r)\) is 1mm, the softened band between first-pass grind-hardening process and second-pass grind-hardening process is quite narrow, which means the grind-hardening quality is obvious highly [8]. Therefore, under the premise of reducing the burr size and improving uniformity of grind-hardened layer, the optimal process parameters are \(a_p=0.1\text{mm}, v_w=0.8\text{m/min},\) and \(C_r=1\text{mm}\) under the experiment conditions.

5. Conclusions

1. The surface metal of the grind-hardening workpiece flows to the unconstrained direction on both sides under the coupling of heating and force in the grind-hardening process. Therefore, the burrs on both sides formed. Then the size of the burrs on both sides of the surface grind-hardening workpiece gradually increases with the decreasing of workpiece feeding rate and with the increasing of the grinding depth and the transverse regrinding value in the grind-hardening process.

2. The grinding depth and the workpiece feeding rate become leading factors affecting the size of the burr, and the transverse regrinding value becomes not a leading factor in the grind-hardening process relatively. Moreover, the significant factors of the size of the burrs are as follows: the grinding depth \((a_p)\) > the workpiece feeding rate \((v_w)\) > the transverse regrinding value \((C_r)\).

3. Under the premise of ensuring the grind-hardening quality of the specimen, the optimal process parameters are \(a_p=0.1\text{mm}, v_w=0.8\text{m/min},\) and \(C_r=1\text{mm}\) under the experiment conditions.

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