Investigation on burrs in micro milling of stainless steel 310S

YUAN Meixia¹,²,³ LIU Shaonan¹,²,³ Xue Hongxin¹,²,³ Tang Boyan¹,²,³ Zhao Linlin¹

¹ School of Mechanical-electronic and Automobile Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044
² Beijing Key Laboratory of Performance Guarantee on Urban Rail Transit Vehicles, Beijing 100044
³ Beijing Engineering Research Center of Monitoring for Construction Safety, Beijing 100044
E-mail: yuanmeixia@bucea.edu.cn

Abstract. In the process of micro milling stainless steel 310S, the influence of milling parameters (cutting depth, \(a_p\), feed per tooth \(f_z\), cutting speed \(v\)) and down and up milling method were revealed, which provides reference for controlling burrs of stainless steel 310S, improving surface quality and optimizing cutting process. Based on the orthogonal test method, the coated carbide micro diameter cutter was used and milling experiments were carried out on stainless steel 310S. Top burr size data information was collected and analyzed. Up milling is better than down milling because the shape and size of burr are relatively small. With the increase of cutting depth, the shape of burrs appears long fibrous and tearing and wavy serrated, which means the burr getting large and worse. In order to minimize burrs, it is the good way to choose the sharp cutting tools and up milling, control the cutting depth and select feed rate.

1. Introduction
Burr is a serious defect affecting the surface quality of parts, especially for micro parts. If the burr in the cutting process cannot be effectively controlled, it is easy to cause the parts coordination failure or even dimensional error. Therefore, the formation mechanism and control process of burr are the hotspot and research focus of micro cutting. Many domestic and foreign scholars have done a lot of experiments on burrs [1-8]. Fu [9] considered that in the process of cutting, burr generally refer to tiny, prominent residues on the machined surface or the edges of the workpiece. Luo [10] thought that burr generation was due to the undesirable separation of chips and workpiece. Burr was divided into eight categories according to the location of the burr, the up milling edge burr and side burr were studied emphatically, and both of them have the greatest influence on the workpiece. It is considered that the friction angle of the tool rake face causes serious deformation in the cutting zone, resulting in greater burr, so the sharpness of cutting tools greatly affects the generation of burr. The separation of the chip at the workpiece boundary is not complete, or the boundary contour remaining after separation is not an ideal contour, tiny burr is formed. Gillespie [11] divided burr into three basic models: transverse deformation of workpiece, chip bending and chip breaking. The burr formation mechanism of micro cutting is different from that of conventional machining, due to the influence of the minimum cutting thickness, the negative shear zone results in the edge collapse of the workpiece and the plastic deformation resulting in micro burr. In the experiment of micro milling Ni-base superalloy, Lu [12] analyzed the cause of burr formation, and considered that the tool wear affected the chip breaking performance, and the uncut chip accumulation eventually formed strip burr.
Stainless steel 310S is austenitic chromium nickel stainless steel, with a relatively high percentage of chromium and nickel, so 310S has strong creep strength, good heat resistance, suitable for working continuously under high temperature, the material has good corrosion resistance, oxidation resistance, commonly used in steam turbine, aviation machine parts. Micro blade not only requires high profile accuracy, but also requires high surface accuracy. Micro milling cutting tool is generally used for micro milling. In this paper, the surface burrs of stainless steel 310S have been studied. The test results have reference significance for controlling the burrs of stainless steel 310S and improving its surface quality.

2. Formation mechanism of micro cutting burr
The formation mechanism of burrs in micro milling is considered as the scale effect of micro cutting, which results in the formation of negative shear zone\textsuperscript{[13]}, as shown in Figure 1, there are three deformation zones in the cutting process. In micro cutting process, due to the arc radius of cutting edge and cutting thickness are in an order of magnitude, compared with the conventional cutting process, the cutting deformation area will be changed, that is the negative shear IV area. In addition, the stiffness of the end support of the workpiece is relatively low, which will also affect the negative shear area\textsuperscript{[14]}. The $\beta$ is the negative shear angle, and its size determines the amount of deformation at the end of the workpiece. The angle formed by the negative shear plane OD and the machined plane is the negative shear angle, and its size also affects the shape and size of the final burrs formation. The end deformation increases with the increase of the negative shear angle, and the final thickness and height of the burrs increase accordingly.

![Figure 1. Diagram of generation of negative shear region.](image)

3. Experiment design
The machining center used in this experiment was Carver-45-400. Worktable size: 490×430mm. The cutter is made of Sumitomo carbide with micro diameter, the model is GLM2005SF, the diameter of cutter is $\Phi 0.5$mm, cutting edge length is 1.25mm, shank diameter is 3mm. The workpiece material is stainless steel 310S aluminum alloy.

The factors and levels of the orthogonal test are shown in Table 1.

| Factors and levels | A Spindle speed $n$(r/min) | B Milling depth $a_p$(mm) | C Feed per tooth $f_z$ (mm/2) |
|--------------------|-----------------|-----------------|-----------------|
| 1                  | 6000            | 0.01            | 0.001           |
| 2                  | 7000            | 0.03            | 0.002           |
| 3                  | 8000            | 0.05            | 0.003           |
| 4                  | 9000            | 0.07            | 0.004           |
KEYENCE microscope system was used to measure and observe the size and shape of the burr. The observed burr measurements are shown in Figure 2. The size and shape of burrs along each groove at different positions are not exactly the same, at the same time, in order to avoid measurement errors, the top burrs of each groove in the eight positions of the up and down milling side were selected respectively. By measuring its width, the average value was then obtained, calculated by equation 1[15].

$$W = \frac{\sum_{i=1}^{8} \Delta W_i}{8}$$  \hspace{1cm} (1)

Where $W$ represents the average width of the top burr; $\Delta W_i$ represents the width of the top burr at each position.

4. Results and analysis of burr test of stainless steel 310S
This experiment was carried out strictly according to orthogonal design of micro milling process. Through data arrangement, measurement and analysis, the results of orthogonal test of top burr size were obtained. The burr width of down and up milling are shown in Table 2. The burr width of up milling is smaller than that of down milling, and the quality of up milling workpiece is higher. Therefore, only the analysis of burr width of up milling is carried out in the subsequent data analysis.

| Test number | A Spindle speed $n$ (r/min) | B Milling depth $a_p$ (mm) | C Feed per tooth $f_z$ (mm/z) | Width of burr $\omega_w$ ($\mu$m) (up milling) | Width of burr $\omega_w$ ($\mu$m) (down milling) |
|-------------|-----------------------------|-----------------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1           | 6000                        | 0.01                        | 0.001                         | 83.9292                                       | 106.198                                       |
| 2           | 6000                        | 0.03                        | 0.002                         | 116.028                                       | 118.485                                       |
| 3           | 6000                        | 0.05                        | 0.002                         | 107.303                                       | 91.9902                                       |
| 4           | 6000                        | 0.07                        | 0.004                         | 90.3633                                       | 83.79475                                      |
| 5           | 7000                        | 0.01                        | 0.002                         | 237.341                                       | 165.826                                       |
| 6           | 7000                        | 0.03                        | 0.001                         | 155.222                                       | 134.522                                       |
| 7           | 7000                        | 0.05                        | 0.004                         | 76.393                                        | 149.151                                       |
| 8           | 7000                        | 0.07                        | 0.003                         | 77.536                                        | 204.433                                       |
| 9           | 8000                        | 0.01                        | 0.003                         | 136.029                                       | 70.655                                        |
| 10          | 8000                        | 0.03                        | 0.004                         | 116.736                                       | 140.360                                       |
| 11          | 8000                        | 0.05                        | 0.001                         | 99.532                                        | 198.509                                       |
| 12          | 8000                        | 0.07                        | 0.002                         | 77.038                                        | 163.639                                       |
| 13          | 9000                        | 0.01                        | 0.004                         | 138.050                                       | 78.363                                        |
| 14          | 9000                        | 0.03                        | 0.003                         | 70.236                                        | 86.806                                        |
| 15          | 9000                        | 0.05                        | 0.002                         | 114.982                                       | 119.652                                       |
| 16          | 9000                        | 0.07                        | 0.001                         | 137.450                                       | 93.292                                        |
4.1. Range analysis of measurement results based on orthogonal test method

Range analysis, abbreviation is R method, is also called visual analysis. Through the range analysis, the primary and secondary order of the influence of each factor on the experimental indexes was obtained. The optimal level of each experimental factor, the optimal combination of processing parameters and the experimental indexes vary with each experimental factor. \( K_j \) represents the sum of all test indexes value corresponding to the test factors of column \( j \) on the level of factor \( i \). \( \bar{K}_ji \) represents the average value of \( K_{ji} \). By comparing the size of the \( \bar{K}_ji \), the optimal level of the experimental factors in the group can be determined. The optimal combination of experimental factors was formed by combining the optimal levels of the experimental factors in each group.

\[
R_j = \max(\bar{K}_{j1}, \bar{K}_{j2}, ..., \bar{K}_{jn}) - \min(\bar{K}_{j1}, \bar{K}_{j2}, ..., \bar{K}_{jn})
\]

(2)

\( R_j \) reflects the influence of experimental factors on experimental indexes. The greater of the value of \( R_j \), the greater influence of the experimental factors on the experimental indexes, and the smaller of the value of \( R_j \), the opposite.

**Table 3.** Range analysis of orthogonal test (up milling).

| Serial number | A Spindle speed \( n(\text{r/min}) \) | B Milling depth \( a_p(\text{mm}) \) | C Feed per tooth \( f_z(\text{mm/z}) \) |
|---------------|----------------------------------|------------------------------------|----------------------------------|
| \( K_{j1} \)  | 397.624 (6000)                  | 595.349 (0.01)                    | 476.133 (0.012)                 |
| \( K_{j2} \)  | 546.492 (7000)                  | 458.222 (0.03)                    | 545.389 (0.028)                 |
| \( K_{j3} \)  | 429.335 (8000)                  | 398.21 (0.05)                     | 391.104 (0.048)                 |
| \( K_{j4} \)  | 460.718 (9000)                  | 382.387 (0.07)                    | 421.542 (0.072)                 |
| \( \bar{K}_{j1} \) | 99.406                          | 148.84                           | 119.033                         |
| \( \bar{K}_{j2} \) | 136.623                          | 114.556                           | 136.347                         |
| \( \bar{K}_{j3} \) | 107.334                          | 99.553                            | 97.776                          |
| \( \bar{K}_{j4} \) | 115.180                          | 95.597                            | 105.386                         |
| \( R_j \)     | 37.217                           | 53.243                            | 38.571                          |

Primary and secondary order: \( R_b > R_c > R_a \)

Better level: A_1 B_4 C_3

Optimal combination: A_1B_4C_3

Based on the results of orthogonal tests in Table 2, a range analysis of Table 3 can be obtained. It can be seen from the range analysis that the magnitude of the range \( R_j \) is \( R_b > R_c > R_a \). The results show that the main order of influence of each experimental factor on the burr size of micro milling groove is milling depth > feed rate > spindle speed. Therefore, within the range of the experimental level, the influence of cutting depth on the surface roughness of the test index is the biggest, followed by the feed rate, and the speed has the least influence on the burr size. By the \( \bar{K}_ji \) of each experimental factor, it can be seen that the optimum machining parameter combination is A1B4C3. It means that when the spindle speed is 9000r/min, the milling depth is 0.01 mm and the feed per tooth is 0.072mm/z, the up milling burr size of the micro milling can be better controlled.
In order to make a more intuitive analysis of the relationship between the experimental factors and the experimental indexes, according to Table 2 and Table 3, the influence trend of the cutting parameters on the burr size at the top of the groove is obtained. The abscissa in the figure is different values of each experimental factor. The ordinate is the top burr size of the workpiece $\omega$, and the smaller the $\omega$ value, the smaller the burr size; otherwise, the larger of the burr size.

4.2. Influence of spindle speed on burr size of micro groove

In the up milling process, with the increase of spindle speed, the top burr size of workpiece groove firstly increases, then decreases and then increases, and the overall trend is increasing. As shown in Figure 3, when the spindle speed reaches 7000r/min, the top burr size is the maximum. When the spindle speed continues to increase, the top burr size tends to decrease, and the size of top burr increases with the further increase of the speed. The reason is with the increase of spindle speed, the increase of vibration of up milling spindle leads to lower cutting stability, cutting is not uniform; at the same time, because the wear of cutting tool is aggravated after processing, the top burr size is increased as well.

![Figure 3. The influence of the spindle speed at the up milling side on the top burr size of the micro groove.](image)

4.3. Influence of spindle speed on burr size of micro groove

As shown in Figure 4, the top burr size of the micro groove in the up milling side decreases as a whole. When the milling depth reaches 0.01mm, the burr size will be the maximum. With the increase of cutting depth, the size effect decreases, forming continuous chips, and the top burr size of the micro groove decreases.

![Figure 4. The influence of the cutting depth at the up milling side on the top burr size of the micro groove.](image)
4.4. Influence of feed per tooth on burr size of micro groove

In the up milling side, when the feed rate of each tooth increases continuously, the top burr size of the micro groove first increases and then decreases. It can be seen from the Figure 5 that when the feed rate is small, the size of the top burr increases as the feed per tooth increases, when the feed per tooth is 0.028mm/z, the size of top burr reaches the maximum 136.347mm. With the further increase of feed per tooth, the top burr size decreased, and when the feed per tooth is 0.048mm/z, the top burr size is the lowest. With the further increase of feed per tooth, the cutting thickness increases, the machined surface residual area increases, and the cutter cutting resistance increases, which increases the plastic deformation of the workpiece and leads to the increase of burr size.

![Figure 5. The influence of the feed per tooth at the up milling side on the top burr size of the micro groove.](image)

5. Conclusion

Taking the top burr size of micro milling groove as the experimental index, the micro milling experiments of stainless steel 310S were carried out with the spindle speed, the milling depth and the feed amount as the experimental factors. Through range analysis, the following conclusions are drawn:

(1) Up milling is better than down milling because the shape and size of burr are relatively small.
(2) The main order of influence of cutting parameters on the burr size of micro milling groove is milling depth > feed rate > spindle speed. Within the range of the selected experimental level, the milling depth has the biggest influence on the top burr size of the micro milling groove, followed by the feed per tooth, and the spindle speed has the least influence on the burr size of the up milling side of the micro milling groove.
(3) The effect of cutting depth on the burr size of micro groove milling is very important. With the increase of cutting depth, shape and size of the burr change greatly, converted from a long strip to a wavy zigzag. So the range of cutting depth should be controlled as much as possible.

Fund: Suported by Beijing Municipal Organization Department (Item no. 2014000020124G056);Beijing Municipal Commission of Education (Item no. KM201510016008)

6. References

[1] T Zhang, Z Q Liu, C H Xu. Influence of Size Effect on Burr Formation in Micro Cutting[J]. Int JAdv Manuf Technol, 2013, 170:4801-08
[2] D. Biermann, M. Steiner. Analysis of Micro Burr Formation in Austenitic Stainless Steel X5CrNi18-10[J]. Procedia CIRP, 2012, 3:97-102
[3] ZHANG Haijun , HUANG Yanhua , YUAN Guanghui , TAO Yang , LIU Feng. Experimental Study on Burrs in Micro Milling ICF Micro Targets. Technology and test, 2012(07)
[4] Tao Zhang, Zhanqiang Liu, Chonghai Xu. Influence of Size Effect on Burr Formation in Micro Cutting[J]. The International Journal of Advanced Manufacturing Technology, 2013 (9-12)
[5] Seyed Ali Niknam, Victor Songmene. Simultaneous Optimization of Burrs Size and Surface Finish When Milling 6061-T6 Aluminium Alloy[J]. International Journal of Precision Engineering and Manufacturing, 2013 (8)
[6] L.Zhou, Y.Wang, Z.Y.Ma, X.L. Yu. Finite Element and Experimental Studies of the Formation Mechanism of Edge Defects During Machining of SiCp/Al Composites[J]. International Journal of Machine Tools and Manufacture, 2014, 84 (6): 9-16
[7] Wen Jun Deng, Zi Chun Xie, Ping Lin, Tong Kui Xu, Ming-Xing Zhang. Study on Burr Formation at the Top Edge in Rectangular Groove Cutting[J]. Advances in Materials Science and Engineering, 2012
[8] Seyed Ali Niknam, Victor Songmene. Analytical Modelling of Groove Milling Exit Burr Size[J]. The International Journal of Advanced Manufacturing Technology, 2014 (1-4)
[9] FU Tian-jiao. Research on Formation and Control Technology of Micro - milling Burr[D].Shan Dong University, 2014
[10] Luo Meng. Mechanism and Control Methods of Burr Formation in Metal Cutting Process[D]. Shang Hai: Shang Hai Jiao Tong University, 2007
[11] L.K.Gilespie, P.T.Blotter. The Formation and Properties of Machining Burrs[J]. ASME J.Eng Ind., 1976, 98(1):66-74
[12] LU Xiaohong, Wang Wenyi, Wang Wentao, et al. Experimental Study on Burrs in Micro-milling Nickel-base Superalloy Inconel718[J]. Modular Machine Tool & Automatic Manufacturing Technology, 2015(1):1-3
[13] YANG Kai, BAI Qingshun, Yu Fuli, Modelling and Experimental Analysis of the Mechanism of Micro-burr Formation and Micro-end-milling Process[J]. Nanotechnology and Precision Engineering, 2010, 8(1): 75-83
[14] Zhu Yunming, Wang Jingui, Wang Guicheng, et.al. Study on Simulation of Turning Burr Formation Based on Finite Element Method[J]. Journal of System Simulation, 2015, 27(5):1120-1126
[15] NI Hai-bo. Simulation and Experimental Study on the Forming Process of Micro-milling Burr[D]. Harbin:Harbin Institute of Technology, 2012