Process Analysis and Roller Optimization of Micro-Groove Multi-Pass Rolling

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Abstract

Micro-grooves with special structure can reduce the surface friction resistance. Rolling method can be used to form micro-grooves on metal surface efficiently. However, the micro grooves formed by this plastic forming method still had some defects, which had a serious negative impact on the drag reduction and mechanical properties of the micro grooves. Therefore, it is of great significance to optimize the multi pass rolling process to avoid the micro-groove defects. In this paper, a series of analysis on the microstructure, strain and material displacement of micro-grooves were carried out to explain the causes of micro groove defects. It was found that the overall extension of the plate has an adverse effect on the formation of micro-grooves and the hole types of the roller were optimized accordingly. The results of simulation and experiment showed that the optimized roller could produce the designed micro-groove, which perfectly avoided the generation of micro defects.

1. Introduction

The micro-groove structure with specific shape has the lower surface flow resistance[1–3]. Bechert et al. [4–7] conducted numerical calculations and fluid experiments on the surface of several bionic non-smooth grooves with different shapes, and concluded that the blade-shaped micro-riblets had the best drag reduction effect. Bhushan et al. [8–11] summarized the general principle of drag reduction of fluids on micro-groove surfaces: The micro-groove size is as small as possible, and the ratio of the height to the width of the micro-groove $h / s = 0.5$.

However, micro-grooves are difficult to manufacture due to their special shape and extremely small size. Among the typical forming methods that have been studied, the rolling process has many unique advantages, such as less material loss, high surface quality of the workpiece, high production efficiency and low processing costs[12]. And more importantly, the adverse effect of the micro-groove structure on the fatigue life is compensated, due to material hardening and residual compressive stress generated at the bottom of the micro-groove[13–15].

G. Hirt et al. [16–19] designed a semi-circular hole type work roller by winding a thin steel wire with a diameter of 100µm on the roll. This kind of roller can only form semicircular micro-grooves, and the structure formed is a short-distance straight line, due to the influence of the spiral winding of the steel wire.

Gao et al. [20, 21] designed the Roll to Plate(R2P) method to manufacture rectangular micro-grooves. That is, the workpiece was placed on a mold plate with micro-grooves, and the micro-groove structures were pressed on the workpiece by the pressure of two flat rollers. The deformation degree of the two sides of the micro groove formed by this method is different, as shown in Fig. 1(a). Similar forming defects were also found in the research of Klock et al.[22–24]. What they proposed was an incremental rolling process to produce U-shaped micro-grooves on the surface of a titanium alloy plate. Obvious deflection
was observed in the metal streamline, from the metallographic image of the U-shaped micro-groove shown in Fig. 1(b).

Based on the concept of incremental rolling, Yin et al. [25, 26] developed a multi-pass rolling process for manufacturing micro-grooves. The shape of the micro-groove was gradually formed into the designed shape, after being rolled by several different hole types in sequence. It was proved that multi-pass deformation was more conducive to the plastic flow of metal materials and can improve the quality of the micro-groove structure. In this paper, trapezoidal micro-grooves were successfully fabricated on the surface of the copper plate using self-developed multi-pass rollers. Defects such as metal folding and ridge skew were found on these micro-grooves, which were similar to those on micro-grooves fabricated by R2P method and incremental rolling method in previous studies. These defects are common in the roll forming of micro-grooves and have a serious negative impact on the application of the micro-grooves.

Therefore, the causes of defects and how to avoid them are important issues that need to be studied. A finite element model is established to simulate the multi-pass rolling process of micro grooves. Based on the simulating result of finite element model, the strain and displacement of micro grooves are analyzed to explain the causes of defects. In order to produce the defect-free micro groove, the hole types of multi-pass roller was optimized, and the effect of optimization was verified by experiment and simulation.

2. Multi-pass Rolling Process

2.1 Process principle of multi-pass rolling

In the multi-pass rolling experiment in this paper, the rolling process was determined to be six passes to achieve the desired forming effect and high efficiency. The roller designed for multi-pass rolling is shown in Fig. 2. Six different hole types were arranged on the work roller, and the width of each pass was the same size of 1000µm. The design height of the gap in the last pass was 500µm, due to the design principle that the height of the micro groove is half the size of the gap width. The profile of the teeth of each pass of the roller was designed as a smooth curve without sharp corners, which was beneficial to reduce the deformation resistance and promote the plastic flow of the metal. The shape of the roller pressed into the metal material gradually transitioned from a triangle to a trapezoid from the first to the fifth pass. In this multi-pass incremental forming process, the extruded metal continuously flowed into the gap of the pass, forming sufficiently high and sharp riblets and gradual trapezoidal grooves. The same geometric profile was selected as the hole type in the last two passes, so the sixth pass of rolling played a role in modifying the micro-grooves.

The processing principle of multi-pass rolling is shown in Fig. 1. The roller will return to the original position after rolling in the + X direction once, and then the roller will move in the -Y direction by a distance equal to the width of the micro-grooves (1000µm). The roller will continue to rolling in the + X direction after it reaches the new position. Multi-pass rolling is achieved by repeating the above process.

2.2 Multi-pass rolling experiment
The self-developed rolling device as shown in Fig. 3 (a) was used for the multi-pass rolling experiment on copper plate. A multi-pass roller (Fig. 3(b)) and a flat roller were respectively installed on the two arms of the rolling device. The 3D photo of the work roll’s pass is shown in the Fig. 3(c). The arm can move in parallel along the slide rail on the device, and the gap between the rollers can be adjusted.

After adjusting the gap between the two rolls to the calculated value before rolling, the three-axis machine tool drove the rolling device to move down at a uniform speed. The pure copper plate with a thickness of 2 mm was squeezed between the two rollers, forming a groove on one side of the work roll, as shown in Fig. 3(d) and 3(e).

2.3 Simulation of multi-pass rolling

A finite element model was established to simulate multi-pass rolling process. The model should be as close as possible to the real experimental situation to ensure the reliability of the simulation results. To realize the pure rolling of the roller, just set the horizontal movement speed \( v \) and the angular velocity \( \omega \) of the roller according to the relationship of \( v = \omega r \), where \( r \) is the diameter of the roller. One end of the model was set with full constraints, based on real rolling experiments. The shear friction model was adopted for the contact relationship between the roll and the workpiece, and the friction coefficient was set to 0.12.

Because of the elasticity of the material, it will be weakened that the deformation caused by the multi-pass roller on the surface of the workpiece. Therefore, it is necessary to select an elastoplastic model in the simulation. Pure copper with a thickness of 2 mm was selected as the workpiece material in both the rolling experiment and simulation. The mechanical properties of pure copper are shown in Table 1.

| Properties                        | Yield strength /MPa | Tensile strength /MPa | Elastic modulus /GPa | Thermal conductivity /(W-(m·K)^{-1}) | Density / (kg·m^3) | Elongation /% |
|-----------------------------------|---------------------|-----------------------|----------------------|-------------------------------------|---------------------|--------------|
| Value                             | 60                  | 220                   | 110                  | 397                                 | 8960                | 45           |

3. Results

3.1 General description

The SEM image of the formed micro-grooves is shown in Fig. 4(a). From the cross section, trapezoidal micro-grooves and leaf-shaped riblets can be clearly observed. The height of riblets reaches 400µm. The width of the micro-grooves, that is, the distance between the tops of two adjacent riblets, is about 1000µm. It can be seen that the shape of the micro-grooves formed by multi-pass rolling is basically the same as the expected structure. In the enlarged image Fig. 4(c), the folding defects of the micro-grooves were initially found.
The clear crystal grain structure can be observed in Fig. 5. The crystal grains in the deformed area were squashed and extended along a certain direction and then evolved into fibrous structure. The appearance of the fibrous structure indicated that the deformed area has been work hardened, as evidenced by the hardness data in Fig. 6. The original hardness of the copper plate was about 75HV. While after the deformation, the two sides of the bottom of the micro-groove obtained a higher hardness of about 90HV or even close to 100HV. The hardness of the center and top of the riblets is only maintained at 80HV, due to the weaker compression. The area with fibrous tissue distribution has higher hardness, and the hardness is positively correlated with the density of fibrous tissue.

The position and degree of deformation can be observed through the overall fiber structure distributed on the micro-groove section. Compared with other positions on the cross section of micro groove, the fibrous structure on both sides of the riblet was denser, indicating that it is the main area of plastic deformation. Defects mainly appeared on both sides of the riblet. The fibrous structure on one side of the riblet is smooth and clear, but there are additional small protrusions near the bottom as shown in Fig. 5(b). On the contrary, the defect of metal folding as shown in Fig. 5(c) appears on the right side. These folded metals are stacked as a whole and inserted into the root of the riblet like a wedge, which not only causes the loss of fine fibrous structure, but also causes the metal streamline of the riblet to be skewed to the right side.

It can be seen from Fig. 6 that the hardness of the folded position on the right side has not increased too much because the fibrous structure was destroyed by the severe deformation, which causes the hardness of the corresponding position on the left side to be significantly higher. In comparison, the position where there are streamline folds has poor mechanical properties. The stress concentration will inevitably appear on both sides of the bottom of the micro-groove [18, 23, 27]. Cracks are easily initiates prematurely at the metal streamline folding position on account of poor surface quality and weak mechanical properties. Therefore, metal streamline folding defects will significantly reduce the fatigue life of the metal plate with micro-grooves. Another problem that cannot be ignored is that the above-mentioned defects have caused irregularities in the cross-sectional geometry of the micro-grooves. Since the drag reduction characteristics of the micro-grooves depend on the geometry of the specific micro-grooves section, the above-mentioned defects will have a great adverse effect on the application of the micro-grooves. Therefore, it is necessary to study how to eliminate these defects.

### 3.2 Defect analysis

Finite element simulation was used for further analysis in order to explore the reasons of micro-groove defects. The strain of the micro-groove section is illustrated in Fig. 7. It intuitively reflects the degree of deformation of the workpiece through the strain distribution. The strain of the micro-grooves shows an upward trend with the increase of rolling passes. In Fig. 7(b), it can be seen that the strain value at point A has increased at a higher rate since the third pass, which far exceeds point B. After six times of rolling, the strain value of F reached 3.4, and the strain value of point B was only 2.1. There was a considerable difference in strain present in the micro-grooves, meaning that more severe deformation occured on the point A compared to the point B. A and B points are the places where folds and protrusions appear. It can be concluded that these abnormal deformations were the direct cause of defects on the micro-groove.
Figure 7(c) lists the strains of five points arranged along the thickness of the plate. The strain is mainly distributed on the upper surface where the micro-grooves are formed. On the contrary, the farther away from the micro-groove, the lower the strain level. The strain value of the lower part of the plate can be almost ignored in the early stage of rolling. As the number of rolling passes increases the strain values of points E, F, and G were increased to a certain extent, which means that different degrees of deformation have occurred at corresponding positions. Through the above analysis, it cannot be ignored in the process is the deformation of the material below the micro-grooves, which will caused the plate to be extended in the Y direction.

Figure 8 shows the displacement of the rolled metal in the +Y direction. As shown in Fig. 8(b), after each pass of rolling, the plate extended a certain distance in the +Y direction. An increasing trend of displacement from point A to point E can be observed. After rolling, the movement distance of point E in the Y direction was 100µm longer than that of point A. Based on the above phenomenon, it was inferred that the multi-pass roller acted as an obstacle to the movement of the material in the Y direction. It also means that the reaction force in -Y direction is produced on the micro groove by the hole types, which is the reason for the uneven deformation of the micro groove position.

After multiple passes of rolling, the obtained trapezoidal micro-grooves were offset by 200µm in the Y direction, and the width of the micro-grooves was increased to 1080µm. It will have a great impact on the formation of micro-grooves even if these changes are subtle, because the size of the micro-grooves itself is very small.

Based on the above series of analyses, the cause of the defect has been clear. The center of the micro-groove deviated from the original position in the case of the width increase of the micro-groove. During subsequent rolling, the gear hobbing and micro-grooves cannot be centered according to the designed offset. Figure 9 is a schematic diagram of the positional relationship between the roller and the micro-grooves during rolling. It was obvious from Fig. 9 that the hole type of the roller and the micro-grooves were not completely aligned. There was a small gap between the right side of the hole and the workpiece, so the roller cannot deform enough on the right side of the groove. The material was squeezed into the gap under the pressure of the roller, thus forming a protrusion at this position. On the contrary, the deformation on the left side of the micro-groove was more complicated and excessive. As the roller rolling, the material on the side of the riblet was cut off by the roller and pressed into the bottom of the micro-groove. The material was repeatedly cut and folded due to multiple rolling, so multiple folds of the material was formed at the bottom of the micro-grooves. The material flow was disrupted by the action of the folded material accumulating at the bottom of the micro-groove. Therefore, there was no obvious fiber structure at this position, and the metal streamline at the riblet was biased to one side, as shown in Fig. 5.

The experiments in this paper showed the same type of defects for the same reason in Gao [20, 21] and Klocke[22–24]. It was difficult to coordinate the two simultaneous behaviors of plate extension and
micro-groove formation. The extension of the plate negatively affected the formation of the micro-grooves, which ultimately manifested as defects in the micro-grooves.

### 3.3 Roller hole type optimization

It has been proved that the microgrooves are worse due to the extension of the plate in the Y direction. Under different rolling depth conditions, the degree of extension of the copper plate is different. A series of finite element simulations were completed to simulate the multi-pass rolling of 1mm thick copper plate, and the rolling depth $D$ gradually increased from 0.025mm to 0.3mm.

The micro-groove forming result is evaluated by a normalized form filling (FF) calculated by the obtained riblet height $h$ and the maximum achievable riblet height $H$ as follows:

$$\text{FF} = \frac{h}{H} \times 100\%$$

The distance that the point located at the middle thickness of the plate moved along the Y direction is the plate extension length $L$. Table 2 lists the data of FF and $L$.

| $D$/mm | FF/% | $L$/µm |
|--------|------|--------|
| 0.025  | 4.67 | 8.23   |
| 0.05   | 9.84 | 21.25  |
| 0.075  | 13.464 | 44.24   |
| 0.1    | 20.576 | 84.96   |
| 0.125  | 25.878 | 121.35  |
| 0.15   | 36.541 | 157.31  |
| 0.175  | 53.95 | 186.23  |
| 0.2    | 77.796 | 258.38  |
| 0.225  | 80.308 | 291.7   |
| 0.25   | 85.266 | 371.2   |
| 0.275  | 87.99 | 449.87  |
| 0.3    | 91.474 | 512.34  |

Corresponding formulas were obtained to express the relationship between $D$ and FF and the relationship between $D$ and $L$ by fitting these data, as follows:
\[ \begin{align*}
FF &= -12251D^2 + 5954.7D^3 - 432.94D + 14.87 \\
L &= 4219.4D^2 + 2492.7D^3 + 640.87D - 13.033
\end{align*} \]

Figure 10 shows the data points and the formula curve. It can be seen from Fig. 10 that as the depth D decreases, L shows a trend of uniform growth. The variation of FF can be divided into three stages. When D is lower than 0.125mm, FF increases at a lower rate. In the second stage, FF increased significantly to nearly 80% when D increased from 0.125mm to 0.2mm. In the third stage, when D continues to increase from 0.2mm, FF was almost unchanged.

Selecting a suitable rolling depth is the premise of producing high quality micro grooves. In order to avoid the damage caused by the elongation of the sheet, a small rolling depth can be selected, but the forming height of the microgrooves cannot meet the design requirements. If the rolling depth is close to 0.3 mm, the plate will become too thin and too long. The selection of the rolling depth should follow the following principles: first, ensure that a sufficient forming height is reached, and secondly, the length of the sheet should be as small as possible. Therefore, 0.2mm is suitable. In this case, The form filling can reached 77.796%. The problem of plate extension cannot be ignored, which can be solved by optimizing the hole type of the roller.

The defects on the micro-grooves originate from the inevitable extension of the plate during rolling. Therefore, an attempt was made to reduce its adverse effects by optimizing the hole type of the roller. The change of the distance between two adjacent riblets can be analyzed by measuring the geometric model of the micro-groove in the simulation. The width of a single micro-groove was 1080µm, which was an increase of nearly 8% compared with the hole type width of 1000µm.

The hole types of the roller were improved according to the acquired simulation data, only modify the width of each hole type while keeping the contour unchanged. As shown in Fig. 11(a), the width of the original hole types was 1000µm. In the new design, the hole type width increased with the rolling pass, from 920µm to 1000µm, as shown in Fig. 11(b). When using the newly designed roller for rolling, the only thing that needs to be changed is to change the incremental distance of the roller along the +Y direction to 920µm, and the other conditions remain the same. In view of the width of the micro-groove will increase with rolling, the new design method made the width of each pass no longer constant, so as to ensure that the micro-groove matches the corresponding hole type. The problems of riblet streamline skew and folding defects will be effectively solved by optimizing the width design of the roller pass.

The effectiveness of the new roller was initially verified by finite element simulation. Although the width of the micro-grooves created by the first hole type was only 920µm, the width of the micro-grooves reached 1000µm after six passes of rolling due to the extension of the plate. According to Fig. 12, symmetrical and uniform strain was distributed on the micro-grooves section, and there was no excessive strain on the side of the micro-groove. Uniform strain means that the micro groove will not cause defects due to excessive abnormal deformation, which proves that the optimized roller can produce defect-free micro-grooves.
The effectiveness of the new roller was further verified in the rolling experiment. A multi-pass roller with new hole types was fabricated to produce defect-free micro-grooves on the copper plate. It can be seen from Fig. 13 that the new micro-grooves have a regular trapezoidal cross-sectional shape. The crystal grains on both sides of the micro-grooves were elongated and formed a clear fiber structure instead of the previous defects. The riblets were perpendicular to the surface of the plate and were no longer skewed due to the symmetrical deformation on both sides of the micro-grooves. The simulation and experimental results showed that by using the optimized rollers, there were no more forming defects such as riblet tilt and metal streamline folding when forming micro grooves on the copper plate.

4. Summary And Outlook

In this paper, the defects existing in the formation of micro-grooves through multi-pass rolling were introduced in detail. The causes of defects were explained in terms of the coordination between the overall deformation of the plate and the forming of micro-grooves with the help of finite element simulation. These defects have a negative impact on the drag reduction performance and fatigue performance of the micro-grooves. The multi-pass roller is optimized by adjusting the hole type width of each pass. Finally, it was verified through experiments and simulations that the optimized roller can be used to effectively form defect-free micro-grooves.

Multi-pass rolling technology has shown great potential through the manufacture and analysis of 1000µm micro-grooves, so the follow-up research should further improve the multi-pass rolling technology on this basis. At present, there are two main challenges. The first is to achieve a multi-pass rolling process for manufacturing smaller micro-grooves ranging from hundreds of microns to less than 100 microns. Secondly, it is necessary to develop a multi-pass roller manufacturing method that is easy to operate and has high manufacturing accuracy, which provides a basis for forming smaller micro-grooves.

In the future, it is possible to manufacture micro-grooves of several hundred microns or even less than 100 microns on the surface of the workpiece efficiently and at low cost. These micro-grooves can be applied to aircraft surfaces or engine blades to achieve effective drag reduction.

5. Declarations

Ethical Approval: This chapter does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate: Not applicable.

Consent to Publish: All authors have read and agreed to the published version of the manuscript.

Authors Contributions:
Huihang Wang: Methodology; Software; Writing - Original Draft; Writing - Review & Editing

Xujie Gao: Software; Validation; Writing - Original Draft;

Guangming Zhu: Resources; Supervision;

Zheng Chang: Resources; Supervision;

Nana Guo: Investigation;

Zongshen Wang: Investigation;

Lihua Zhu: Investigation.

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**Availability of data and materials:** All data generated or analysed during this study are included in this article.

**Code availability (software application or custom code):** Not applicable.

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**Figures**

![Figure 1](image1)

**Figure 1**

(a) Micro-grooves manufactured by R2P rolling (b) Micro-grooves manufactured by incremental rolling

The cross-sectional shape of the micro-grooves

![Figure 2](image2)

**Figure 2**
Schematic diagram of multi-pass rolling

Figure 3

(a) Rolling device (b) Roller (c) Roller hole type (d) Workpiece (e) Micro-grooves formed by multi-pass rolling Multi-pass rolling experiment

Rolling speed: 5mm/s
Workpiece thickness: 2mm
Roller clearance: 1.2mm
Figure 4

(a) Micro-groove (b) Riblet (c) Folding defect SEM micrograph of micro-grooves

Figure 5

(a) Micro-groove (b) Protuberance (c) Folding defect Metallographic micrograph of micro-grooves

Figure 6

Hardness of micro-grooves
Figure 7

(a) Strain distribution map (b) Strain on both sides of the micro-groove (c) Strain in the thickness direction of the plate

Strain of micro-groove section
Figure 8

(a) Y displacement distribution map (b) Y displacement stacked bar graph Y-direction displacement on the micro-groove section

Figure 9

Comparison of the position of the roller hole type and the micro-groove
Figure 10

Results of micro groove rolling simulation
Figure 11
(a) Original hole types (b) Modified hole types Comparison of the original hole types and the improved hole types

Figure 12
Strain distribution diagram of micro-groove produced by optimized roller

Figure 13
Metallography image of micro-groove produced by optimized roller