Investigation on Electrically-Assisted Rolling Process of Surface Texture for Drag Reduction

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Abstract. Surface texture is employed for drag reduction in the aviation and aerospace, since it has a positive effect on boundary layers of flow. In this paper, the triangular surface texture was formed via the rolling process. The effects of the roll gap, sheet thickness, the space and size of the triangular shape on the forming quality of the surface texture were studied. The simulation indicates that a small roll gap is benefit for forming full profile. With the decrease of sheet thickness, the forming height is greater, but the sheet flatness is poorer. The size and space of riblet have significant effects on the stress and strain distribution and forming height. When the electric current is introduced into the rolling process, the formed surface texture shows greater forming profile and better flatness. It is concluded that the electrically-assisted rolling process is a promising way of forming surface texture on metal sheets.

1. Introduction
Surface texturing as a viscous drag reduction technology has become the research focus, since it is effective in reducing drag by changing the boundary layers of flow. Walsh [1, 2] indicated that the surface texture could produce significantly drag reduction and discussed the effect of the varying cross-sectional geometry. The results demonstrated that the V-groove was the optimal geometry for drag reduction, and when its dimensionless height $h^+$ and spacing $s^+$ were both 15, the effect was greatest. Yu et al. [3] investigated the turbulent drag reduction of the V-groove and spaced triangular geometry using a developed third-order flux-difference splitting technique. The results were consistent with that of Walsh [2]. The surface texture is mainly created by the micro-machining [4], the electrochemical method [5] and the laser machining technology [6]. However, these methods have lower production efficiency and higher cost. In contrast, the rolling process has higher efficiency and lower cost, and it is environment-friendly. Romans and Hirt [7] carried out the rolling process by a cold roll wound with a fine steel wire. They found the form filling increased linearly with the increase of the thickness reduction. Hu et al. [8] studied the rolling force and stress and strain distribution during rolling deformation process by simulations. Lu et al. [9] successfully rolled micro structures on the surfaces of Al and Cu.
The micro structures are extremely small, which are in similar order with the grain size, resulting in the obvious size effect and low forming quality. Some studies had found that the current can weaken the size effect [10]. Therefore, the electrically-assisted (EA) forming process could be a promising forming method of surface texturing. Wang et al. [11] found that the EA micro-embossed channel depth of the sharklet patterns increased with elevated current density. Cao et al. [12] developed a desktop surface texturing system, and conducted the rolling experiments and simulations. The results show that rolling force and rolling temperature can improve the channel depth. Wang et al. [13] investigated the EA corrugated surface microstructure, and indicated that there was a threshold of current density in the rolling process. The forming height remarkably increased when the threshold value was reached.

In this paper, the rolling process of the surface texture was studied by simulations experiments. The effects of the process parameters, including the roll gap, the sheet thickness, and the space and size of triangle on the forming quality were discussed. The forming quality was evaluated by the forming height, rolling force and sheet flatness. A large area of accurate surface texture was formed on the T2 copper sheet by EA rolling process, which was compared with that formed by a conventional rolling process.

2. Simulation and experimental methods

2.1. Simulation method

The finite element (FE) analysis was carried out using Abaqus/Explicit software. The model consists of three parts: a rigid top roll, a sheet and a rigid down roll, as shown in figure 1. The texture is on the top roll with a radius of 15mm. The dimensions of the microstructure are shown in table 1. The material parameters of T2 copper in Ref.13 are used in the FE model. Both rolls are modelled as discrete rigid and meshed using a 4-node 3-D bilinear rigid quadrilateral. A 8-node linear brick with reduced integration and hourglass control (C3D8R) are applied to model the sheet. To improve the accuracy of the model and calculation speed, the local grids are refined in the thickness direction of the sheet. The frictional behaviour is described by Coulomb’s model, and the friction coefficients at the sheet and two rolls are considered as 0.2. The rolling speed is 10rad/s.

![Figure 1. The FE model of rolling process.](image)

| Number | s/μm | S/μm | α/°  | R/μm |
|--------|------|------|------|------|
| #1     | 150  | 300  | 60   | 30   |
| #2     | 150  | 225  | 60   | 30   |
| #3     | 150  | 150  | 60   | 30   |
| #4     | 225  | 375  | 60   | 45   |
| #5     | 300  | 450  | 60   | 60   |
| #6     | 310  | 420  | 64   | 0    |

Table 1. Key dimensions of the surface texture.
2.2. Experimental
The commercial T2 copper sheets (rolled state) with a thickness of 1mm were used. The EA micro-rolling system consisting of a rolling device and a DC power is shown in figure 2.

![Figure 2. The EA rolling forming device.](image)

3. Results and discussions

3.1. The effect of roll gap
As shown in figure 3, the rolling force during the process could be divided into three phases. In the first phase, the force sharply increases with the increase of top roll reduction, as shown in figure 3(a). The force then keeps constant until the sheet leaves the roll, as shown in figure 3(b). In the last phase, the force dramatically decreases, as shown in figure 3(c). The texture is formed on the top surface of sheet after the rolling. Figure 5 shows the cross section of the rolled sheet. It is found that the deformation mainly occurs on the top part of the sheet, especially at the groove. The material flows from the groove to the riblet, like the mesh lines under deformation. And the distribution of the stress and strain is uneven. The maximum stress and strain appear on the side of riblet.

Figures 3 and 4 show the effect of roll gap on the rolling force and forming height, respectively. When the roll gap reduces, the rolling force increases, and the filling profile get closer to the design value. Figure 6 shows that the sheet thickness decreases, and the flatness becomes poor with the reduction of the roll gap. It is due to the contact stress on the top surface is larger than that on the bottom surface [14]. Therefore, the sheet becomes bend.

![Figure 3. The rolling force under different roll gap in (a) the first phase, (b) the second phase, and (c) the third phase.](image)

![Figure 4. The forming profile under different roll gaps.](image)
3.2. The effect of sheet thickness

Figures 7-9 show that the rolling force, forming height and the degree of bending increase when the sheet thickness decreases under the same reduction of the top roll. The top roll reductions are similar, but the roll gap is different because of various thicknesses of sheets. Due to the local deformation during the rolling process, it means that a greater proportion of the material is deformed for thin plate under the same reduction.

**Figure 6.** The plate profile under different roll gaps: (a) 500μm, (b) 450μm, (c) 400μm, (d) 350μm, and (e) 250μm.
3.3. The effect of width and space of riblet

Figure 10 shows the equivalent stress (left) and strain (right) distribution in the rolled sheet for different width sizes of the riblet. It is found that the forming height and rolling force increase when the riblet width increases. The material flow is restricted when the width is small. It is also known from figure 10 that the difference of equivalent stress and strain between upper part and lower part becomes greater when the width increases. Since the contact pressure is much larger at upper part than that at lower part, the deformation occurs on the top surface. In addition, the intensive local deformation results in the obvious bend, as shown in figure 11.

Figure 12 shows the equivalent stress (left) and strain (right) distribution in the rolled sheet for different spaces of riblet. It can be seen that the riblet space should not be as big as possible. The forming height reaches the maximum (74μm) when the space is 225 under same roll gap for three conditions in this study. The equivalent stress and strain on the groove of #2 are larger than those of #1 and #3. When the space is big, the local pressure is too low to lead to big local deformation. However, the small spacing results in the difficult material flow.

Figure 9. The plate profile under different sheet thicknesses (a) 0.5mm (b) 1mm (c) 1.5mm

Figure 10. Equivalent stress (left) and strain (right) distribution for riblets with different widths: (a) #1, (b) #4, and (c) #5.

Figure 11. The plate profile for riblets with different widths: (a) #1, (b) #4, and (c) #5.
Figure 12. Equivalent stress (left) and strain (right) distribution for riblets with different spaces: (a) #1, (b) #2, and (c) #3.

3.4. Experimental results

The simulation indicates that the forming height can be improved by adjusting the roll gap, plate thickness and riblet size and space. However, when the forming depth increases, the plate profile becomes poor. Cao et al. [14] introduced an asymmetric rolling process to improve the flatness. In this paper, the EA rolling process is introduced to improve the flatness and further increase the forming height. Figure 13 shows the forming profile by two types of rolling processes. The forming profile and forming height are significantly improved when the current is present, compared to the conventional rolling process. Figure 14 shows the flatness of the sheet is dramatically improved by EA rolling process.

Figure 13. The forming profile under different rolling styles: (a) conventional rolling process, and (b) EA rolling process.

Figure 14. The plate profile under different rolling styles: (a) conventional rolling process and (b) EA rolling process.
4. Conclusion
The rolling process of the surface texture on T2 copper sheets is studied. Based on the evolution of the rolling force, the forming process can be divided into three phases, and the force is maximum and keeps constant at the second phase. And the equivalent stress and strain reach the maximums at the groove part, which shows the local deformation style of the rolling. The roll gap plays an important role on improving the forming height. The forming height and bend extent increase with the reduction of the roll gap. Under the same reduction, the thin sheet is formed with the bigger forming height, but the bigger bend extent. The space and size of riblet also affect the forming quality. Large width and modest interval are benefit for the forming height. The degree of curvature is positively related to the degree of deformation of the upper surface. When the electric current is introduced to the rolling process, the forming profile and sheet flatness are both significantly improved, which demonstrates the feasibility to fabricate the surface texture by the EA rolling process.

5. References
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