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Fin formation model during pre-roll ploughing of copper 3D outside fin tube①

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[Abstract] The mechanism of pre-roll ploughing for 3D fins on the outside surface of copper tube was studied systematically, and especially the process and conditions of 3D fin formation were analyzed. The right mathematical model was also established. Based on the volume of fin ploughed out is equal to the volume of the metal extruded up by the extruding face of the tool, the relations between fin height, pre-roll ploughing feed and pre-roll ploughing depth have been achieved. With the increase of pre-roll ploughing depth which must be equal to groove depth, the fin height gradually becomes larger. There are different critical feeds with the various depths of pre-roll ploughing. The pre-roll ploughing feed is the critical one, the height of fin is largest. And when the feed is above the critical one, the fin height will reduce with the increase of feed. The theoretical analysis basically accords with experimental results.

[Key words] pre-roll ploughing; copper 3D outside fin tube; heat transfer
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1 INTRODUCTION

With the development of industrial technologies, people become stricter with the use of heat transfer tubes of heat exchangers. As the fins on the outside surface of tubes can greatly improve the heat transfer efficiency, the enhanced heat transfer technology on the machining outside fin tubes is being more and more important, and has made great progress[1~2]. The average heat transfer coefficients of a finned tube can be several times as large as those of a bare tube with the same diameter, and the fin tubes have been used in broad range of heat transfer applications, including boiling, condensation, and single-phase fluid heating/cooling. Without doubt it is a trend that the bare tubes will surely be replaced by all types of enhancement tubes, the surface on which is machined for fins[3~4]. Now reports on the characteristic and application of fin tubes are more than ones on the machining[5~9]. Enhancement techniques can be classified either as passive methods, which require no direct application of external power, or as active methods which require external power[10]. One of the passive methods with wide uses is finned surfaces, the advantage of which is that no material is wasted, but also there is no thermal contact resistance between the fins and the base tubes. In recent years the fins distributing on the outside surface of copper tube by ploughing have been developed from two-dimensions to three-dimensions, so a new kind of ploughing way, pre-roll ploughing, has been proposed by the author for copper 3D outside fin tube (Fig. 1). Firstly, rolling is done for grooves on the outside surface of copper tube, and then ploughing in the cross direction, so the distributing fins have been formed. As the fin structure directly influences the heat transfer behavior, controlling the fin shape and size on the outside surface of copper tube is very exigent during machining process. Therefore it is necessary to further study on the mechanism of fin formation by pre-roll ploughing on the outside surface of copper tube.

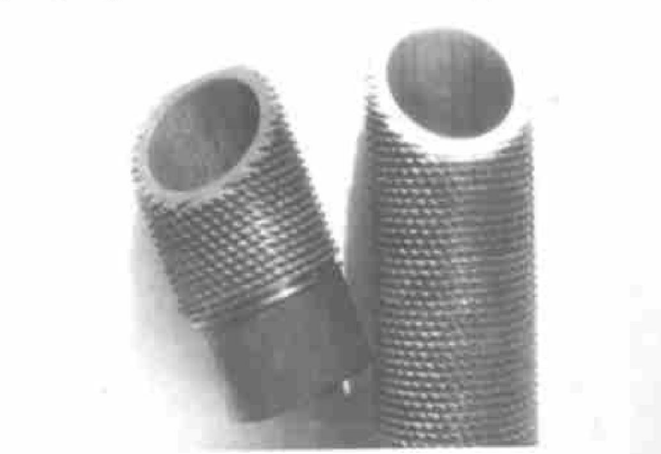

Fig. 1 3D outside fin copper tube machined by pre-roll ploughing

2 BASIC PRINCIPLES OF PRO-ROLL PLOUGHING

As the purpose of ploughing is different from the one of cutting, the tools used for ploughing are also

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different, which make them essentially different on the formation mechanism. Cutting process would make surplus chips[11], while ploughing on the outside surface of copper tube is working without chips and the fin are formed utilizing plastic deformation by ploughing, which makes the fin height much higher than the depth of ploughing.

As we have known, it is the tools that make the difference between ploughing and cutting. The latter uses traditional tools, while the former uses special tool (Fig. 2). The rake face of this special tool is made of two curved faces, so its cross section is like a wedging (to the section A-A in Fig. 2). This tool's wedging blade can plough into the out surface of tube (like a streamline prow of a ship splitting water) and split it in two, and meanwhile the curved faces in the different directions individually extrudes the metal material, so that fin and side ridge are formed plastically.

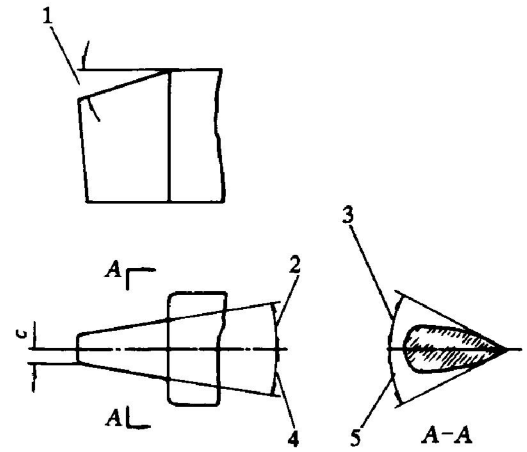

Fig. 2 Shape of ploughing tool
1 —Top inclination angle; 2 —Fin inclination angle;
3 —Fin forming angle; 4 —Extruding inclination angle;
5 —Extruding angle

3 ANALYSIS OF PRO-ROLL PLOUGHING PROCESS

As stated above, to form 3 D fins distributing, pre-roll ploughing includes pre-roll and ploughing process. Compared with traditional ploughing, pre-roll ploughing is only ploughing on metal surface, not on flat metal surface. In this way, pre-roll ploughing can turn out 3D fins (Fig. 3), but traditional ploughing turn out continuous fins. Among above two processes, the second process is important to fin formation, which has three stages.

3.1 Pre-roll process

Firstly, grooves on the outside surface of copper tube have formed by rolling, and the shape of the cross section of groove is like V (Fig. 4).

Meanwhile triangular ribs are forming, whose top should be sharp. If the top of rib is flat, 3D fin like wolf's fang can not form during the next process —ploughing process. The crossing angle (β) between the groove direction and the axial direction of tube should be larger than or equal to 45°. If less than 45°, continuous fins formed by ploughing would build up with groove. In other words, only the continuous fins shifted is achieved. The depth of grooves formed by pre-roll should be equal to the ploughing depth, and or else the bottom of fins would not be whole.

3.2 Ploughing process

During this process, the 3D fins is forming through being squeezed first and then being split (Fig. 4). Here why should we call it ploughing? That is because the process is just like a plough dividing soil into two sides, not like the traditional cutting that cuts the metal out and becomes chips. This process consists of three stages, extrusion-bulging, splitting and fin forming.

1) The first stage —the extrusion-bulging

Because of the tool feed movement, the extrusion face of tool squeezes the metal surface into a lump (named as side ridge), as shown in Fig. 5. The extrusion magnitude of the lump depends on the appearance of the extrusion face of the tool which has direct effect on the fin height.

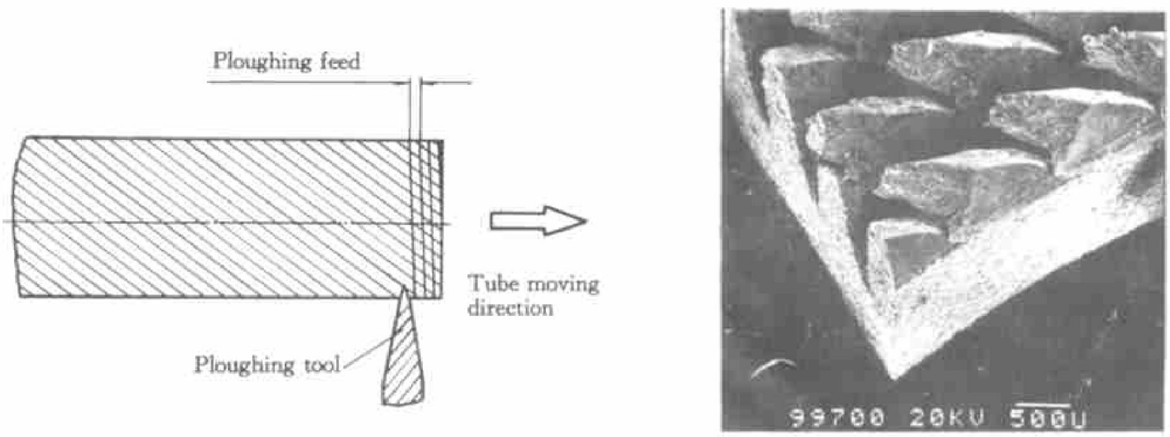

Fig. 3 Pre-roll ploughing

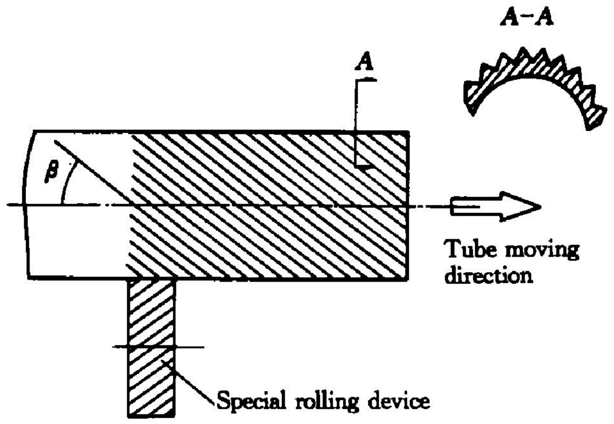

Fig. 4 Cross section of grooves

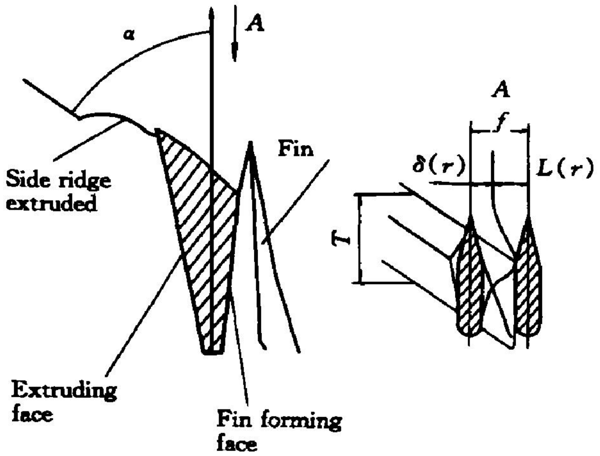

Fig. 5 Three stages of ploughing process

2) The second stage —the splitting stage

In this stage, owing to the tool feed movement, the tool top blade performed by the junction of the two curves cuts the lump into two pieces which was squeezed up in last time. So the thickness of fins and of extrusion faces depend on the feed of tool (Fig. 5). The relation between them is as follows:

$$\delta(r) = f - L(r)$$

where $\delta(r)$ —thickness of fin; $L(r)$ —thickness of the tool extrusion face; f —ploughing feed.

This stage decides on the height of fins formed.

3) The third stage —the fin formation stage

After the old lump is cut in two, the right-side face of the tool (the fin formation face) squeezes the right-side metal to become fins. At the same time, the tool's extrusion face extrudes out a new lump in other side. So the fin formation stage and the namely bulging stage are carried out simultaneously. The extrusion magnitude of the lump depends on the appearance of the extrusion face of the tool, which has direct effect on the fin height.

The deformed area was observed and verified, including both the metal slippage and plastic deformation. The fin size and shape mainly depend on tool geometry, tool moving track and pre-roll ploughing parameters.

4 MATHEMATICAL MODEL

For every triangular rib, if the volume of fin metal ploughed out is less than the enlarged volume of the lump extruded, the lump will become higher and higher and then turns up the overlap which will prevent the process from going on normally. So, in order to keep the stability of the process and the fin height, the conditions below must be satisfied: the volume of the fin ploughed by the top blade of the tool must be larger than or equal to the volume of the metal extruded up by the extrusion face of the tool (supposed the plastic deformation caused by extrusion has no effect on metal density). Thus we can get this formula below:

$$F = V_c - V_j = \frac{2}{3}\int_{R_0}^{R_0+h}\int_0^{2\pi}\delta(r)\,r\,\mathrm{d}r\,\mathrm{d}\theta - \frac{2}{3}\int_{R_0}^{R_0+a_p}\int_0^{2\pi}L(r)\,r\,\mathrm{d}r\,\mathrm{d}\theta \geqslant 0$$

Put $\delta(r) = f - L(r)$ into the formula above to get:

$$F = \frac{2}{3}\int_{R_0}^{R_0+h}\int_0^{2\pi}[f - L(r)]\,r\,\mathrm{d}r\,\mathrm{d}\theta - \frac{2}{3}\int_{R_0}^{R_0+a_p}\int_0^{2\pi}L(r)\,r\,\mathrm{d}r\,\mathrm{d}\theta \geqslant 0 \qquad (1)$$

where $L(r) = (r - R_0)\mathrm{tg}\beta + C$; a_p —depth of pre-roll ploughing; R_0 —fin root radius of outside fin tube; β —extruding inclination angle; c —width of front blade.

If the volume of fin ploughed out by the top blade is equal to the volume of the metal extruded up by the extruding face of the tool, the height of fin is the largest, for the top blade of the tool divides the lump from its top. Hence, when let Eqn. (1) be zero and simplified (leave the high-order value out), the fin height is

$$h = a_p + \sqrt{\left(\frac{f}{\mathrm{tg}\beta} - \frac{c}{\mathrm{tg}\beta}\right)^2 + 2a_p\left(\frac{2c}{\mathrm{tg}\beta} - \frac{f}{\mathrm{tg}\beta}\right) + 2a_p^2} - \left(\frac{f}{\mathrm{tg}\beta} - \frac{c}{\mathrm{tg}\beta}\right) \qquad (2)$$

The formula above should satisfy the condition, $a_p\mathrm{tg}\beta + c < f < a_p\mathrm{tg}\beta + 2c$, otherwise the process of fin formation can not carry out stably.

5 EXPERIMENTAL RESULTS

5.1 Critical feed

The critical condition under that overlap appears depends on feed, when the other parameters ($c = 0.35$ mm, $\beta = 250$) have been chosen. The theoretical critical feed can be gained by Eqn. (2) condition ($f > a_p\mathrm{tg}\beta + c$), and the theoretical and experimental results show in Fig. 6. But limited by the strength

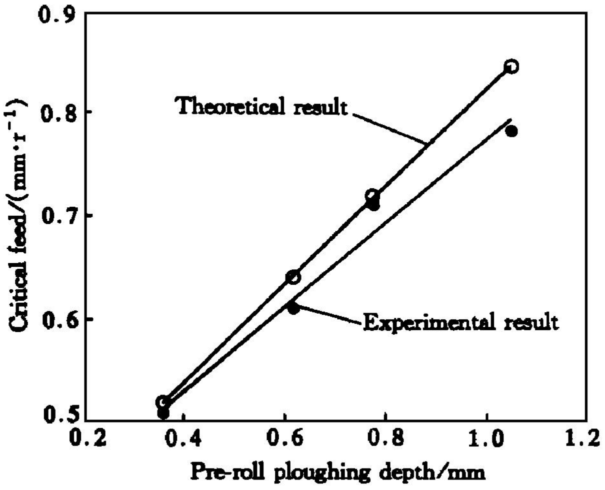

Fig. 6 Pre-roll ploughing depth's effect on critical feed

of tools and the stiffness of the system, the depth is always less than 1.2 mm.

For different pre-roll ploughing depths, the critical feeds increase with the increase of pre-roll ploughing depths. Experimental critical feeds are less than theoretical ones.

5.2 Fin formation scope

The regulation of the feed affecting the fin height can be concluded from the Eqn. (2). Postulate the pre-roll ploughing depth (a_p) is 0.80 mm and substitute the other parameters ($c = 0.35$ mm, $\beta = 25°$) into Eqn. (2), and we can get the theoretical result.

The theoretical and experimental results for a_p 0.80 mm (as shown in Fig. 7) indicate that the height of fin corresponding to the critical pre-roll ploughing feed is largest. And when the feed is above the critical one (the optimum scope), the fin height will reduce with the increase of the feed. Conversely, when the feed is below the critical one, the formation

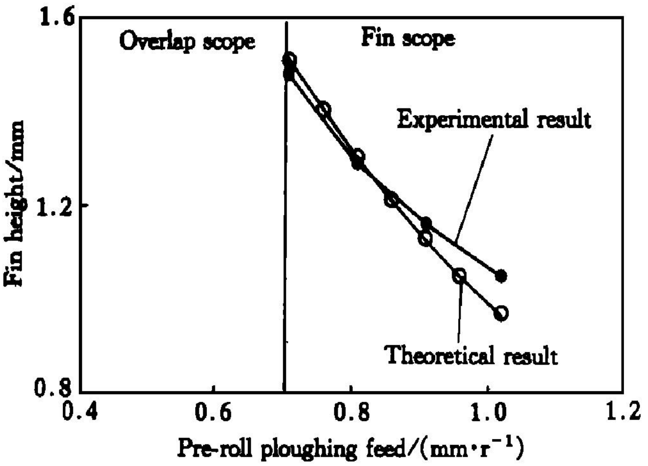

Fig. 7 Pre-roll ploughing feed's effect on fin height

of fins is difficult and the overlap will be made. So it is necessary for us to choose the feed from the optimum scope above the critical one.

5.3 Effect of pre-roll ploughing depth on fin height

Also the regulation of the pre-roll ploughing depth affecting the fin height is shown in the Fig. 8 ($f = 0.81$ mm/r, $c = 0.35$ mm, $\beta = 25°$). With the increase of pre-roll ploughing depth, which is equal to groove depth, the fin height gradually becomes larger. The fin height mainly depends on the pre-roll ploughing depth, but the pre-roll ploughing depth is limited by the strength of tools and the stiffness of the system.

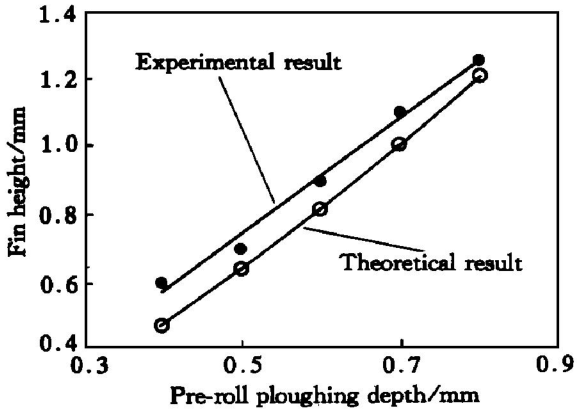

Fig. 8 Effect of pre-roll ploughing depth on fin height

6 CONCLUSIONS

1) The copper 3D outside fin tube could be achieved by pre-roll ploughing, which includes two processes, pre-roll process and ploughing process. In ploughing process, there are three stages, extrusion-bulging, splitting and fin forming. The ploughing depth must be equal to groove depth made by pre-roll.

2) Only if the volume of the fin ploughed out by the top blade of the tool must be larger than or equal to the volume of the metal extruded up by the extrusion face of the tool, the stability of ploughing process could be kept, which renders the fin to form continuously.

3) The fin height mainly depends on the ploughing feed and depth of pre-roll ploughing. With the increase of pre-roll ploughing depth, the fin height gradually becomes larger. There are different critical feeds with various depths of pre-roll ploughing. The pre-roll ploughing feed is the critical one, the height of fin is largest. And when the feed is above the critical one, the fin height will reduce with the increase of the feed. The theoretical analyses basically accords with experimental results.

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