Manufacturing of a 3D finned tube for enhanced boiling and condensation using rolling-cutting-extruding composite forming

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Abstract

3D finned tube is a highly efficient heat transfer enhanced element, and its manufacturing has always been the focus of research’s attention. It is a challenging job to manufacture a 3D finned tube that can enhance both boiling and condensation since the enhanced boiling structure is completely different from the enhanced condensation structure due to their different heat transfer enhancement mechanisms. An innovative rolling-cutting-extruding composite forming method is developed to realize the manufacture of a staggered-stepped lattice finned tube (SLFT) with helical fins, two layers of staggered-stepped lattice fins, and inner helical threads, which can enhance boiling as well as condensation heat transfer. The three specially designed skewed rolling-cutting tools are uniformly distributed around the base tube, and the kinematic of rolling-cutting-extruding process is analyzed. The relative plunge depth of a rolling blade cannot exceed a certain limit value, and the feeding angle has to be equal to the helix angle of outer helical fin. According to the kinematic analysis, the parameters of the rolling-cutting tool are selected, and processing experiments of the SLFT are conducted.

Keywords Rolling · 3D finned tube · Enhanced boiling/condensation · Rolling-cutting tool

1 Introduction

The heat exchange tube is the core component of a shell and tube heat exchanger, and the enhanced boiling and condensation heat exchange tubes can promote the performance of an evaporator and condenser greatly [1, 2]. In recent years, to meet the increasing demand of high-efficient, light-weight, and compact requirements, the new-generation heat exchanger, such as heat pump, has been developed towards integration of refrigerating and heating. It demands that heat exchange tubes not only have excellent boiling heat transfer performance, but also possess brilliant condensation heat transfer performance. Hence, it puts forward to the heat exchange tubes and their manufacturing a big challenge because the enhanced boiling structure is completely different from the enhanced condensation structure due to different heat transfer enhancement mechanisms. Encouragingly, a novel three-dimensional (3D) finned tube, staggered-stepped lattice finned tube (SLFT) with outer helical fins, two layers of staggered-stepped lattice fins, and inner helical threads, is presented and has been proven to be able to enhance both boiling and condensation heat transfer greatly [3]. However, a low-cost, efficient, and effective manufacturing method to produce the SLFT is still missing, although the manufacture of enhanced heat exchange tubes for boiling and condensation heat transfer has always caught researcher’s interest.

So far, many researchers have gravitated towards the manufacture of enhanced boiling and condensation tubes. The surface porous tube and finned tube are the typical representatives of enhanced boiling tubes [1]. The finned tube types are mainly of dimple tube, micro-fin tube, integral fin tube, and dimple-grooved tube [4]. The main manufacturing methods of these enhanced tubes are coating and sintering [5], flame spraying [6], machining [7], and electrochemical corrosion methods [8]. Among these methods, the most commonly used method is sintering, followed by flame spraying because the surface porous structures produced by sintering
and flame spraying have very excellent enhanced boiling properties. The third method used widely is machining, e.g., ploughing by which the finned structure with rough surface can be produced [7]. The electrochemical corrosion methods are mainly used to manufacture the enhanced boiling tube for some special applications [8]. In addition, the high-speed spinning is a machining method for internally grooved tube [9], aiming at boiling enhancement inside the tube. To promote productivity and reduce cost, Kuboki et al. [10] developed a special extruding method to manufacture the tube with helical inner fins.

Edge-shaped finned tube [11], micro-fin tube [12], turbo C tube, herringbone tube, V-type and W-type micro-finned tubes, dimple-grooved tube [13], and 3D finned tube [14] are the main types of enhanced condensation heat exchange tubes. The manufacturing methods of these enhanced condensation tubes mainly include extruding [15], casting [16], welding [17, 18], rolling [19, 20], extrusion-ploughing [21], chopping-extrusion [22], and rolling-wedging/extruding methods [23]. Among them, the extruding method is a conventional and common manufacturing method for condenser tube, but it is very difficult to produce complex fins [15]. The casing [16] and welding methods [17, 18] are used to manufacture non-integral finned tubes and complex special-shaped tubes. However, the enhanced tubes produced by casting and welding have a large contact thermal resistance though the laser welding can improve the quality of welded joints [18].

The rolling-wedging/extruding method is widely used to manufacturing enhanced condensation tube with three-dimensional integral fins. Recently, to promote fin efficiency, some novel fins, such as the circular plain fin, circular integrated pin fin, and serrated integrated pin fin, are fabricated by the selective laser melting [24]. The selective laser melting can fabricate complex fins, but its productivity and manufacturing cost cannot meet the requirements of producers.

Obviously, the above manufacturing methods cannot be applied to the SLFT production at low cost and high efficiency. Moreover, the enhanced boiling and condensation tubes manufactured by the above methods can only be applied to a single boiling or condensation condition. Namely, if an enhanced boiling tube is used to condensation condition, its heat transfer performance will drop dramatically, and vice versa. Therefore, how to manufacture this kind of heat exchange tube which can enhance boiling as well as condensation, e.g., SLFT, is a severe challenging job and has become an obstacle to the development of new heat exchanger which integrates refrigerating and heating.

This work proposes a novel manufacturing method—rolling-cutting-extruding composite forming based on the three-roll skewed rolling to manufacture the new 3D finned tube—SLFT. To achieve the efficient and collaborative manufacturing of outer and inner fins of the SLFT, the combined rolling-cutting tool is designed, and the kinematics of rolling-cutting-extruding process is investigated. The influence of processing parameters on the morphologies and geometric dimensions of the outer fin structure is revealed.

2 Development of rolling-cutting-extruding composite forming

2.1 Structure characteristics of the SLFT

The schematic diagram of the SLFT is shown in Fig. 1. The two-dimensional (2D) helical fin is the outer fin structure foundation. The pitch and size of the 2D helical fins are small, and the groove bottom is concave, which meets the requirements of enhancing boiling and condensation at the same time. Two layers of staggered lattice fins with a certain height difference are distributed on both side walls of the helical fins. Thus, the groove is divided into upper and lower parts by the two layers of staggered fins and two porous layers which form along the circumferential direction. Under the separation of the stepped fins, the lower part of the fin slot becomes a semi-closed chamber, and the holes formed between the two stepped fins connect the upper and lower slots. The chambers communicate with each other to form a helical channel. In addition, trapezoidal threaded fins are distributed on the inner surface of the SLFT. The geometric parameters of the SLFT can be characterized by the pitch $p$, height of 2D helical fin $h$, fin width $w$, and height difference of the two stepped fins $\Delta h$.

2.2 Manufacturing of 3D staggered-stepped lattice fins

(1) Multi-stage rolling of outer 2D helical fins

Since the outer fin structure foundation is the 2D helical fin, the manufacturing method of the SLFT should be based on the rolling process which is an efficient and stable method for producing outer helical fin. In order to obtain the 2D helical fins with a large aspect ratio and high integrity, a multi-stage rolling is adopted, as shown in Fig. 2. Thus, the 2D helical fins can be rolled out progressively.

(2) Rolling-cutting of staggered-stepped lattice fins

After the helical fins formed, the lower layer of stepped fins is machined on the side walls of the adjacent helical fins by a tooth cutter as shown in Fig. 3a. The teeth of the tooth cutter are intermittently distributed. Then, a flat cutter is used to machine the upper layer of stepped fins as shown in Fig. 3b. Thus, the two staggered layers of fins are machined out on the side wall of the 2D helical fins.
Based on the multi-stage rolling of 2D helical fins and the rolling-cutting of staggered-stepped lattice fins, the rolling-cutting forming tool of the 3D stepped lattice fins is designed as shown in Fig. 4. The forming tool is consisted of rolling blades, shims, tooth cutter, and flat cutter. To assure the 3D staggered-stepped lattice fins forming, the diameter of the rolling blades increases progressively.

2.3 Collaborative manufacturing of 3D outer fin and inner helical thread

From the above analysis, the forming process of 3D outer fins can be divided into two stages: One is the rolling of 2D helical fins, and the other is the rolling-cutting of the 3D stepped lattice fins. During the 3D outer fins forming, the base tube is subjected to a large rolling force. So, adding a threaded mandrel to the inside of the tube (as shown in Fig. 5a) can achieve the extruding forming of inner helical threads as well as bearing rolling force and preventing the rolled tube from collapsing. Fig. 5b presents the configuration of the threaded mandrel. A relative rotation between the threaded mandrel and the base tube is needed in the process of extruding forming of inner helical threads. In this work, the threaded mandrel remains fixed and the base tube rotates.

Therefore, the progressive forming of 2D outer helical fins can be characterized by three periodically repetitive processes: biting, finishing rolling, and shaping.

(1) Biting

The rotating rolling blades act on the tube surface and bite the tube, thus causing the tube rotating and moving forward axially. As the processing proceeds, the helical fins form gradually due to the progressive increase of the rolling blade diameter. At the same time, the inner wall of the tube shrinks and comes into contact with the threaded mandrel. In this stage, the height of helical fins increases progressively due to the restriction of material flowing in the axial direction.

(2) Finishing rolling

After the action of the first several rolling blades, the outer and inner helical fins have been initially formed. To achieve the finishing rolling, the outer diameter of the next two rolling blades remains unchanged at this stage. Under the action of the finishing rolling, the fins are basically formed, and the morphological qualities are improved due to the reduced elastic recovery of the material.

(3) Shaping

The helical fins are trimmed by the following shaping blades, and the morphological qualities of the fins are further improved. Thus, the forming of the outer helical fins completes. Moreover, the inner helical fins are created simultaneously under the combined extruding action of the rolling cutter and the threaded mandrel.
After the outer helical fins form fully, the tooth cutter and flat cutter act on the side walls of two adjacent helical fins successively as shown in Fig. 5a. Then two layers of staggered-stepped lattice fins are machined out under the cutting and extruding action of the tooth and the flat cutter. A groove is divided into upper and lower parts by the two layers of staggered-stepped fins and porous structure forms. The lower part of the fin slot forms an evaporation chamber under the sealing effect of the stepped fins, and there are lots of pores between the upper and lower parts of the fin slot.

### 3 Kinematic analysis of rolling-cutting-extruding process

As above-mentioned, to realize continuous manufacturing of the SLFT, the relative rotational and axial motions are needed between the rolling-cutting tool and the base tube. To achieve the goal, three skewed rolling-cutting tools are used and uniformly distributed around the base tube as shown in Fig. 6a.

There is a skewing angle called feeding angle $\alpha$ between the two axes of rolling-cutting tool and tube. Hence, the speed of a point A on a rolling blade can be resolved into axial speed $V_x$ and tangential speed $V_y$ as indicated in Fig. 6b. During the 3D outer fins forming, the base tube is rolled by the skewed rolling-cutting tools. In this case, the frictional force generated between the rolling-cutting tool and the base tube can be decomposed into tangential force and axial force. Consequently, the base tube rotates and moves axially driven by the tangential and axial forces, respectively. In the following kinematic analysis, it is assumed that no relative sliding between the rolling-cutting tool and the base tube occurs. In addition, the three rolling-cutting tools are staggered by one-third pitch along the axis.

#### 3.1 Rotational motion condition

To make the tube rotate and move forward axially at the same time, the conditions of rotation and axial movements must be met. The forces imposed on the tube during the rolling-cutting-extruding process are shown in Fig. 7. The condition of rotational motion is that the torque of friction force $F_a$ is greater than the torque of pressure $P_b$, named as:

$$Fa > Pb$$

where $a$ and $b$ are the force arms of the friction force and pressure against the axis of the tube.

The relationship between the friction force $F$ and the pressure $P$ is:

$$F = \mu P$$

where $\mu$ is the friction coefficient between tube and rolling-cutting tool. From the analysis of forces imposed on the tube shown in Fig. 7, the calculation of the force arms $a$ and $b$ is as follows:

$$a = \left[ r - \left( \frac{R}{\cos \varphi} - R \right) \right] \cos \varphi$$

where $r$ is the radius of the base tube, $R$ is the radius of the rolling blade, and $\varphi$ is the skewing angle.
\[ b = (R + r) \sin \frac{\varphi}{2} \]  

where \( R \) is the radius of a rolling blade, \( r \) is the external radius of the tube, and \( \varphi \) is the center angle corresponding to the arc length between the rolling-cutting tool and the tube. In addition, the following formula can be obtained from geometric relations:

\[ \cos \varphi = 1 - \frac{2(dZ + Z^2)}{D(D + d)} \]  

where \( Z \) is the plunge depth of a rolling blade of the rolling-cutting tool and \( D \) and \( d \) are the diameter of a rolling blade and the outer diameter of the tube, respectively. Therefore, the condition for stable rotation of the tube is as follows:

\[ \mu^2 \geq \left( 1 + \frac{d}{D} \right) \left( \frac{Z}{d} \right) \]  

It can be seen that the friction coefficient \( \mu \) has the greatest influence on the rotation conditions of skew-rolling. In cold rolling, the friction coefficient is a constant value. Hence, the relative plunge depth of a rolling blade \( \frac{Z}{d} \) has a maximum value as follows:

\[ \left( \frac{Z}{d} \right)_{\text{max}} = \frac{\mu^2}{1 + \frac{d}{D}} \]  

It can also be known that the smaller the ratio of the diameter of the tube to a rolling blade, the easier it is for the tube to rotate. Generally, the value of \( \frac{d}{D} \) is 1/2~1/6 in the skew-
rolling process. Hence, the relative plunge depth of a rolling blade of the rolling-cutting tool should not exceed the maximum permissible value.

3.2 Axial motion condition

Moreover, the tube also needs to follow the principle of axial movement. When the tube advances one pitch \( p \) in the axial direction, it exactly rotates one revolution. In this way, the axial velocity \( V_t \) of the tube is:

\[
V_t = \frac{p\omega_2}{2\pi} = \frac{pR_A}{2\pi r_A} \omega_1 \cos \alpha 
\]

(8)

When \( V_s \) is greater than or less than \( V_t \), the tube cannot pass through the rolling zone smoothly, which will cause damage to the tube and severe wear of the rolling-cutting tool. Only when \( V_s \) is equal to \( V_t \), the tube can be steadily rolled. The helical rise angle \( \theta \) of the finned tube is:

\[
\theta = \arctan \frac{p}{2\pi r_A} 
\]

(9)

Thus, it can be concluded that the axial movement condition of the tube is:

\[
\alpha = \theta 
\]

(10)

That is, the feeding angle of three-roller is equal to the helical rise angle of the finned tube.

4 Experimental results

4.1 Experimental setup and conditions

Experiments are conducted on the self-developed three-roll skewed rolling mill. The friction coefficient \( \mu \) obtained from experiments is 0.12. Thus, it can be calculated from Eq. (7) that the plunge depth of every rolling blade \( Z \) cannot exceed 0.21 mm. Hence, \( Z \) is set as 0.15 mm to achieve stable processing of helical fins. Accordingly, in the biting stage, seven rolling blades are needed, and the total plunge depth is 0.9 mm. In the finishing rolling stage, the outer diameter of the two rolling cutters keeps fixed and is equal to the diameter of the seventh rolling blade. In the shaping stage, the plunge depth is set as 0.1 mm, and two rolling blades are used. In the light of the actual processing situation, the diameter of the first rolling blade is chosen as 65.3 mm. An image of the finished rolling-cutting tool is given in Fig. 8. In addition, the thicknesses of shim and rolling blade depend on the pitch and the thickness of 2D helical fin. In this work, the thickness of shim is set to be 0.254 mm.

In the experiments, the workpiece is red copper tube with outer diameter of 19 mm, wall thickness of 1.15 mm, and length of 2000 mm. The material of rolling-cutting tool is T8MnA. According to the actual needs, the outer helical fin height and helix angle are determined as 1 mm and 42° respectively. Accordingly, in the rolling-cutting-extruding process, the feed angle is set as 42°.

4.2 Appearance and characteristics of a manufactured SLFT

Figure 9 presents the appearance and characteristics of the SLFT obtained at rolling speed of 173 r/min. From Fig. 9, the outer fins are consisted of 2D helical fins, along with
two layers of intermittent and staggered fins. The 2D helical fin is the foundation of outer 3D fin, and the two layers of staggered fin protrude on the side wall of 2D helical fins. The staggered-stepped lattice fins have sharp edges and a rough surface. The lower fins and grooves of helical fins contribute to lower semi-enclosed slots along the circumference. The upper fins, lower fins, and side walls of helical fins compose upper slots. As shown in Fig. 9(b–c), there are also many porous structures along the radial direction of the copper tube. Besides, the inner helical threads with trapezoidal cross sections are rolled out as shown in Fig. 9(d). Therefore, the SLFT can be manufactured perfectly by the rolling-cutting-extruding composite forming method.

4.3 Influence of technical parameters on forming of SLFT

4.3.1 Theoretical calculation of SLFT parameters

The definition of geometric parameters of the SLFT is shown in Fig. 1. The pitch \( P \) of 2D helical fin is the sum of the rolling blade and the shim thickness. So, the fin pitch \( p \) is calculated as:

\[
P = t + t_s
\]

The theoretical relationship between the lower stepped fin width \( w \), the tooth number, and the outer diameter of the tooth cutter is:

\[
w = \frac{\pi D_i}{2N} - h_t \tan \frac{\delta}{2}
\]

where \( h_t \) is the tooth height of the tooth cutter (0.5mm) and \( \delta \) is the included angle between the two side edges of a tooth. From the theoretical calculation formula, it can be known that the fin width is negatively correlated with the number of teeth and positively correlated with the outer diameter of tooth cutter. The difference in height \( \Delta h \) between the two stepped fins is equal to the half of the difference between the outer diameters of the tooth cutter and the flat cutter \( \Delta H \):

\[
\Delta h = \Delta H = \frac{1}{2}(D_r - D_f)
\]

where \( D_f \) is the diameter of the flat cutter.

4.3.2 Influence of rolling speed

Figure 10 shows the SEM images of the SLFT machined at the three different rolling speeds. When the rolling speed is 337 r/min, the 2D helical fins of the SLFT are well formed, but the stepped lattice fins have serious defects as shown in Fig. 10a–b. The reason is that the 337 r/min rolling speed makes the tube rotate at 1180 r/min. In this case, the fins formed by the previous tooth of the tooth cutter can be easily cut by the next tooth, leading to defects in the stepped fins. In addition, when the tube rotates at so high speed, a severe vibration occurs, resulting in deviations of the tooth cutter and flat cutter during the rolling-cutting process.

When the rolling speed drops to 235 r/min, the vibration level decreases greatly, which reduces the deviation between the tooth cutter and the flat cutter. Hence, the integrity of the two stepped lattice fins is improved as shown in Fig. 10c–d. But, it is not perfect yet. When the rolling speed is reduced to 173 r/min, the rolling process becomes very smooth. The
forming quality of helical fins and the two stepped lattice fins are further improved, and only a few defects can be found as shown in Fig. 10e–f. Therefore, to achieve the SLFT forming smoothly, a low rolling speed should be used.

### 4.3.3 Influence of tool parameters

When the speed of the rolling-cutting tool is 173 r/min, the changes of the pitch and height of the 2D helical fins with the thickness of the rolling blade are shown in Fig. 11. Obviously, the pitch of the helical fin increases with the increase of rolling blade thickness, and the experimental results agree well with the theoretical values. From Fig. 11b, the height of the helical fin increases with the increase of rolling blade thickness, while the rate of rise decreases gradually. As the height of the helical fin increases, the friction force between the metal material and the sidewall of the rolling blade increases due to the flow of the material in the radial direction. In the meantime, the axial elongation of the finned tube increases as the rolling blade thickness increases. Under the two effects, the increasing rate of the helical fin height gradually slows down.

Figure 12a shows the relationship between the width of the lower lattice fin and the teeth number of the tooth cutter when the outer diameter of the tooth cutter is 66.6 mm. The fin width decreases with the increase of the number of teeth. It is because the tooth width of a tooth cutter decreases as the number
of teeth increases. Besides, the experimental data are slightly greater than the theoretical values due to the lateral cutting deformation during the stepped lattice fin forming. Fig. 12b shows the variation of $\Delta h$ (the height difference of two layers of stepped fins) with $\Delta H$ (the height difference of the tooth cutter radius and the flat cutter radius). The height difference $\Delta h$ increases with the increase of the height difference $\Delta H$, and the experimental data and theoretical values are in good agreement.

5 Conclusion

(1) A new rolling-cutting-extruding composite forming method is developed to realize the efficient manufacturing of the three-dimensional SLFT, which removes the obstacle to the manufacturing of heat exchange tubes possessing excellent enhanced boiling heat transfer as well as condensation heat transfer.

(2) The forming process of the SLFT is divided into two of stages: 2D helical fins rolling forming and staggered-stepped fins cutting/extruding forming. The forming process of the 2D helical fins includes biting, finishing rolling, and shaping process, and the inner threaded fins are also formed at this stage. During the staggered lattice fins forming, the 2D helical fins are successively cut and extruded by the tooth cutter and flat cutter to form two layers of stepped fins with a height difference.

(3) To meet the rotational and axial movement requirements during the SLFT rolling-cutting-extruding forming, the plunge depth of any single rolling blade cannot exceed its maximum allowable value; moreover, the feeding angle needs to be equal to the helical angle of the 2D fin. Excessive rolling speed is unfavorable for manufacturing of the SLFT.
(4) The pitch and height of the 2D helical fin increase with the increase of the rolling blade thickness. The fin width decreases with the increase of the tooth number of the tooth cutter. Furthermore, the height difference of the two stepped fins is slightly smaller than the height difference between the tooth cutter and the flat cutter in radial direction.

Nomenclature  
- $p$: Pitch of helical fin (mm)  
- $h$: Height of helical fin (mm)  
- $w$: Lower stepped fin width (mm)  
- $\omega_1$: Angular speed of rolling cutter (rad/min)  
- $D$: Diameter of a rolling blade (mm)  
- $d$: Diameter of tube (mm)  
- $Z$: Plunge depth of a rolling blade (mm)  
- $t$: Thickness of a rolling blade (mm)  
- $N$: Number of teeth of rolling cutter  
- $\alpha$: Arm of tangential force (mm)  
- $V_c$: Axial speed of a point on a rolling blade  
- $R$: Radius of a rolling blade (mm)  
- $\Delta h$: Height difference of two stepped fins (mm)  
- $h_t$: Tooth height of the tooth cutter  
- $\Delta H$: Height difference in radius of tooth and flat cutter (mm)  
- $\delta$: The included angle between the two side edges of a tooth  
- $\theta$: Helix angle (°)  
- $\alpha_f$: Feeding angle (°)  
- $\mu$: Friction coefficient  
- $\omega_2$: Angular speed of tube (rad/min)  
- $D_t$: Diameter of a tooth cutter (mm)  
- $P$: Rolling force (N)  
- $F$: Tangential friction force (N)  
- $t_e$: Thickness of shim  
- $\varphi$: Center angle (°)  
- $b$: Arm of rolling force (mm)  
- $V_e$: Axial speed of tube  
- $r$: External radius of the tube  
- $n$: Rolling speed (r/min)

Author contribution  
Xiaofang Huang performed the data analyses and wrote the manuscript; Hanping Chen performed the experiment; Zhenping Wan contributed significantly to analysis and manuscript preparation; Longsheng Lu and Hongguan Zhu helped perform the analysis; Xintao Wu contributed to the conception of the study.

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Data availability  
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability  
Not applicable

Declarations

Ethics approval  
Not applicable

Consent to participate  
Not applicable

Consent for publication  
The manuscript is approved by all authors for publication; all the authors listed have approved the manuscript that is enclosed.

Conflict of interest  
The authors declare no competing interests.

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