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Multitool Deformation and Cutting in Applying Fins to Heat-Exchanger Pipe

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Abstract—High-speed systems for the production of external fins on heat-exchanger pipes by a hybrid technology based on deforming and cutting are developed. The factors that affect the precision of fin application are analyzed.

Keywords: deformation and cutting, fin application, heat-exchanger pipe, multitool machining
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Finned pipe is widely used in shell-and-tube heat exchangers. The weight of the nonferrous heat-exchanger pipe in such systems may amount to tens of tons [1]. The intensification of heat transfer by adding fins to the pipe significantly reduces the metal consumption and weight in heat exchangers. Widely spaced fins are effective for gases, but a spacing of less than 1.5 mm is required for heat exchangers based on phase transitions (condensers and evaporators).

With widely spaced fins, the heat-transfer area may be increased by a factor of 20 as a result of methods such as strip welding or soldering, the use of wire fins, and crosshelical rolling of the pipe. For closely spaced fins, attachment by methods such as soldering and welding is difficult, and rolling technic poses problems on account of the pipe material employed and the height of the resulting fins.

Analysis of manufacturers' catalogs indicates that the introduction of closely spaced fins increases the external surface area by factors of no more than 2.6 for titanium, 4.7 for copper, and 2.9 for steel (including stainless steel). In Russia, for copper pipe, the corresponding figure is no more than 3.5; crosshelical rolling is not used for titanium and steel pipe.

By a hybrid technology based on deformation and cutting (Fig. 1a), fins may be produced on pipe made from practically any alloy [2]. The surface area may be increased by a factor of 12 for copper pipe [3]. The efficiency of this approach is confirmed by industrial experience [4–6].

For the short pipe finning (up to 1 m) in small batches, we may expediently use a lathe with a work rest and a single support for the rotating pipe. More than 10000 finned pipes have been produced by the technology developed at Bauman Moscow State Technical University and supplied to ZAO Novomet-Perm' (Perm), OKB Zenit (Krasnoyarsk), OAO DoKon (Domodedovo), and elsewhere.

The pipe length in shell-and-tube heat exchangers is a few meters. The application of fins to long pipe on a conventional lathe is possible but not practical, on account of its low productivity and the need to machine the pipe in sections whose length is within the range of the lathe's longitudinal carriage motion. That entails the development of specialized equipment for applying fins by deformation and cutting.

Kinematic analysis suggests that the rotation of three deformation and cutting tools may be adopted as the primary cutting motion; the feed motion is linear motion of the pipe blank along axis. An important goal is to minimize manufacturing costs by using the housing and spindle of a widely used 16K20 screw-cutting lathe.

Finned must have smooth ends for attachment in the pipes of the heat exchanger. In other words, in machining, the tools must be inserted to the cutting

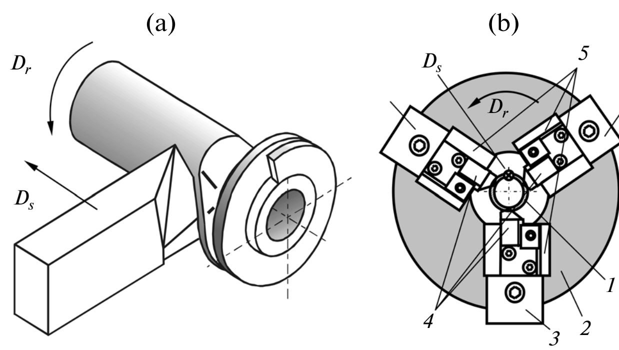

Fig. 1. Deformation and cutting process (a) and three-tool cutting assembly based on an automatic lathe chuck (b): (*1*) pipe blank; (*2*) automatic chuck; (*3*) jaws; (*4*) deformational and cutting inserts; (*5*) tool holder; D_r, primary cutting motion; D_s, feed motion.

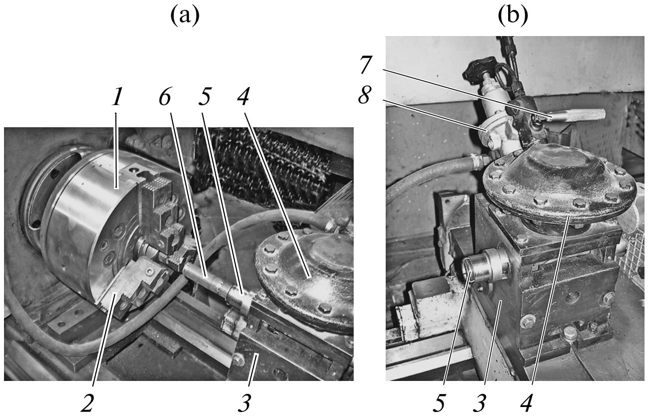

Fig. 2. Tool assembly (a) and device for the pipe blank feeding (b): (*1*) automatic chuck; (*2*) jaws with deformation and cutting tools; (*3*) housing of supply device; (*4*) pneumatic chamber; (*5*) clamping bush; (*6*) pipe blank; (*7*) valve supplying air to the pneumatic chamber; (*8*) pressure regulator.

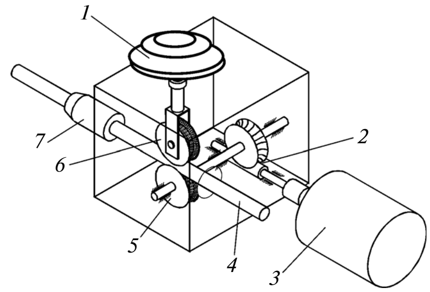

Fig. 3. Structure of the device for feed the pipe blank: (*1*) pneumatic chamber; (*2*) worm gear; (*3*) electric motor; (*4*) pipe blank; (*5*) driving roller; (*6*) hold-down roller; (*7*) centering clamping bush.

depth and then removed at the end of the process. This may be accomplished by mounting the hybrid deformation and cutting tools on the jaws of an automatic lathe chuck (Fig. 1b); the radial motion of the jaws is ensured by a hollow nonrotating pneumatic cylinder. Carbide cutting inserts *4* with the geometric parameters of a deformation and cutting tool are attached in holders *5* attached to the jaws *3* of automatic lathe chuck *2*. The force is transmitted from the nonrotating hollow shaft of the pneumatic cylinder to the rotating chuck through a bearing assembly with radial and thrust bearings.

The system (Fig. 2a) for fin application is based on a 16K20F3S5 lathe, with a BISON-BIAL 2409 automatic chuck (diameter 250 mm; jaw radial path 5 mm). A device for the pipe blank feeding and for compensation of the torque due to the deformation and cutting forces is mounted on the lathe's transverse support (Fig. 2b). The system also includes devices for supporting the pipe blank and the finned pipe at the right and left sides of the lathe.

The system for feeding the pipe blank (Fig. 2b) moves the pipe linearly along the spindle axis at specified speed toward the tool assembly and, at the same time, compensates the torque on the pipe due to the tools. Its basic structure is shown in Fig. 3. The shaft speed of the electric motor *3* in this system is controlled by a frequency regulator. Alignment of tube feed rate with tool assembly velocity of rotation ensures requared fins spacing.

The toroidal working surface of rollers *5* and *6* has pyramidal projections (height 1.2 mm) at 2.0-mm intervals. That prevents slipping of the pipe in compensation of the axial force and torque in hybrid deformation and cutting. The split-design roller consists of two halves. The presence of a washer between the two halves permits maximization of the contact arc between the driving roller and the pipe blank.

The pipe blank is centered on leaving the unit by means of clamping bush *7*, whose internal dimension is adjusted in accordance with the diameter of the pipe blank so as to ensure centering without free play.

In comparison with single-cutter machining, the use of three cutters, at higher speeds, permits several times greater productivity. Such productivity is difficult to attain for long pipe blanks on traditional lathe. The basic characteristics of the system for fin application are as follows:

Dimensions (length × width × height), mm	2150 × 1450 × 1200
Mass, kg	1260
Power of the spindle drive, kW	5.0
Power of the feed drive motor, kW	0.4
Voltage, V	380
Spindle speed, rpm	1600
Productivity, m/min	(*S*, mm, is the fin spacing) 4.8 × *S*
Pipe-blank diameter, mm	16–20
Fin spacing, mm	0.25–1.5
Fin height, mm	(for copper)up to 3 mm but no more than *w*
Wall thickness *w* of pipe blank	At least 1.5
Length of pipe blank, m	3–8
Tool life before regrinding, min	60

Fins may be applied to copper, brass, titanium, cupronickel, or steel pipe blank, at any point.

In single-pass fin application by hybrid deformation and cutting on a lathe, the fin height and spacing may be readily regulated by adjusting the cutting depth and the feed rate. On the proposed system, fin application requires three-start finning. Therefore, the mutual position of the tools significantly affects the

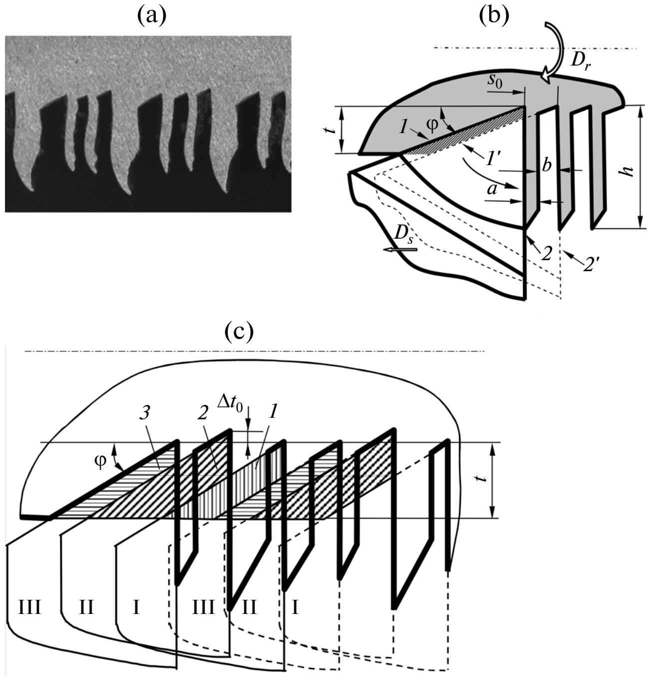

Fig. 4. Profile in three-start fin application when using tools with axial and radial positional errors, for a VT1-0 titanium pipe blank with an intended spacing of 0.36 mm between the fins in successive passes (a); single-cutter fin application by hybrid deformation and cutting on a lathe (b); and fin errors with positional errors of one of the tools (tool II) in terms of the cutting depth t (c): a, h, fin thickness and height; b, gap between fins; φ, cutting angle (the tool cutting edge angle); s_{ro}, feed per rotation; Δt_0, radial error in tool position; *1*, *2*, *3*, cross sections of layers cut by tools I, II, and III, respectively. The other notation is explained in the text.

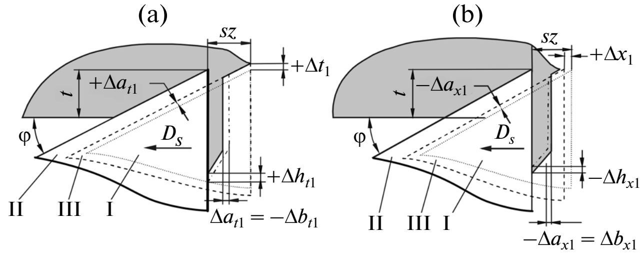

Fig. 5. Influence of the radial error Δt_1 (a) and axial error Δx_1 (b) in the cutter position on the geometric parameters of the fins in multitool machining: (I) calculated position of preceding cutter; (II) required position of the cutter considered; and (III) actual position of the cutter considered. The other notation is explained in the text.

precision of the outcome. Slight errors in tool position will lead to nonuniform spacing and height of the fins in the different starts (Fig. 4a). That calls for analysis of the factors determining the precision of multipass fin application.

We first consider single-start fin application by hybrid deformation and cutting (Fig. 4b). The tool position is indicated by a continuous line. The dashed line indicates the tool position in the previous rotation of the part, which differs from the current position by the feed per rotation s_{ro}. The layer between the adjacent positions *1* and *1'* of the cutting edge is the next to be cut (shaded in Fig. 4b). Without losing its connection to the blank, it is deformed by the rake face of the tool and becomes a fin. Its position is determined by the deformation edge *2*.

For vertical fins, the height h is determined with sufficient precision by the cutting depth t and the cutting angle φ (tool cutting edge angle)

$$h = t/\sin\varphi + 0.5 s_{ro}\cos\varphi.$$

The fin thickness is $a = s_{ro}\sin\varphi$. The gap between the fins is $b = s_{ro}(1 - \sin\varphi)$ [7].

In the proposed system, fin application is a three-start process. When the tools are positioned around the blank with equal angular spacing so as to obtain fins with equal height and spacing in successive starts, all the cutting tips must lie in a single plane perpendicular to the axis of the blank and have the same cutting depth. In practice, the position of the tool tips depends significantly on the precision of tool sharpening and their basing.

In Fig. 4c, only one of the tools (tool II) has a radial positional error Δt_0. This error changes the thickness of the layers removed by tools II and III. As a result, only tool I forms a fin of the required height and thickness. Those values will be too high for the fin formed by tool II; and too low for the fin formed by tool III.

As we see, a radial positional error of only one tool distorts all the geometric parameters of the fins produced. Both radial and axial errors of all the tools will also distort the fin profile (Fig. 4c). We see that the fin height and thickness and the fin spacing are significantly different for successive starts.

We now consider in more detail the case in which the tools are in the required positions (without radial or axial errors), except that one particular tool has a radial positional error Δt_1 (Fig. 5a) and an axial positional error Δx_1 (Fig. 5b). In Fig. 5, I is the initial position of the preceding tool; II is the required position of the tool considered; and III is its actual position, including an error.

The positional error of the tool—an increase in the cutting depth Δt_1 (Fig. 5a)—leads to increase in fin thickness Δa_{t1}, decrease in fin gap Δt_1, and increase in fin height Δh_{t1}.

These errors may be written in the form

$$\Delta a_{t1} = -\Delta t_1 \cos\varphi;\ \Delta b_{t1} = -\Delta a_{t1} = \Delta t_1 \cos\varphi;$$

$$\Delta h_{t1} = -\frac{\Delta t_1}{\sin\varphi} - \frac{\Delta a_{t1}}{2\tan\varphi} = -\Delta t_1\left(\frac{3}{2\sin\varphi} - \frac{\sin\varphi}{2}\right).$$

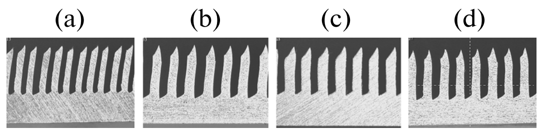

Fig. 6. Fin profiles for three-start processes: (a) M1 copper pipe, spacing 0.28 mm, height 1.13 mm; (b) MNZhMts 10-1-1 cupronickel pipe, spacing 0.41 mm, height 1.06 mm; (c) M1 copper pipe, spacing 0.42 mm, height 1.4 mm; (d) MNZhMts30-0.8-1 cupronickel pipe, spacing 0.4 mm, height 1.3 mm.

Plus and minus signs correspond to displacement of the tool, respectively, toward and away from the center of the blank.

The error Δx_1 (Fig. 5b)—displacement of the tool tip from the required plane perpendicular to the axis of the blank—also distorts the fin profile. When the tool has an axial positional error Δx_1, we may write the error Δa_{x1} in the fin thickness, the error in the gap width Δb_{x1}, and the error in the fin height Δh_{x1} in the following form

$$\Delta a_{x1} = -\Delta x_1 \sin\varphi; \ \Delta b_{x1} = -\Delta a_{x1} = \Delta x_1 \sin\varphi;$$
$$\Delta h_{x1} = -0.5\Delta x_1 \cos\varphi.$$

Plus and minus signs correspond to displacement of the tool, respectively, in the feed direction and in the opposite direction.

The total geometric errors of fin application with radial and axial errors of tool positioning take the form

$$\Delta a_1 = -(\Delta t_1 \cos\varphi + \Delta x_1 \sin\varphi);$$
$$\Delta b_1 = \Delta t_1 \cos\varphi + \Delta x_1 \sin\varphi;$$
$$\Delta h_1 = -\left[\Delta t_1\left(\frac{3}{2\sin\varphi} - \frac{\sin\varphi}{2}\right)\right] + \frac{\Delta x_1}{2}\cos\varphi.$$

Adopting an analogous approach, we may obtain expressions for the error of fin application as a function of the positional error of the preceding cutter. These deviations are identical in magnitude to those already given, but opposite in sign.

For the general case of multitool machining, the geometric errors of the resulting fin only depend on the positional errors of the cutter being considered and the preceding cutter. None of the other cutters have any influence. The general formulas for the geometric errors of fin i produced by cutter i are as follows

$$\Delta a_i = \cos\varphi(\Delta t_i - \Delta t_{i-1}) + \sin\varphi(\Delta x_i - \Delta x_{i-1});$$
$$\Delta b_i = \cos\varphi(\Delta t_{i-1} - \Delta t_i) + (1 - \sin\varphi)(\Delta x_{i-1} + \Delta x_i);$$
$$\Delta h_i = \left(\frac{3}{2\sin\varphi} - \frac{\sin\varphi}{2}\right)(\Delta t_1 - \Delta t_{i-1})$$
$$+ \frac{\cos\varphi}{2}(\Delta x_1 - \Delta x_{i-1}),$$

where subscript $i - 1$ denotes the positional error of the preceding tool.

Thus, if we know the radial and axial errors of each tool, we may determine all the geometric errors for each fin, with any number of simultaneously operating tools.

We now consider the influence of the tools' positional errors on the error in fin height and thickness and fin spacing for the example of fins with equal spacing. In this case, a tool with $\varphi = 30°$ is required [8].

The error in the cutting depth for successive tools has most influence on the fin thickness and spacing; for $\varphi = 30°$, its influence coefficient is 0.86. The corresponding figure for the axial positional error is 0.5.

Analogously, the radial error in the positions of successive cutters affects the fin height. Such radial displacement (the error in the cutting depth) increases the difference in fin height by a factor of 2.75. For example, 0.1-mm error in each successive cutter results in difference in the height of adjacent fins by 0.55 mm. Axial displacement of adjacent cutters has little influence on the fin height. (The influence coefficient is 0.43.)

The formulas obtained may also be used for the inverse problem: determination of the precision of the tool configuration from the required fin precision.

In some cases, it is expedient to produce fins with nonuniform height and spacing in different passes. For example, that applies to dual-purpose condensation and evaporation systems. In such systems, the optimal fin height and spacing are different for condensation and evaporation and may be obtained in different passes. The formulas here derived then permit the calculation of the required radial and/or axial tool displacement.

In Fig. 6, we show various results of three-start fin application. The difference in height and spacing for successive passes is no more than 5%. That is permissible for heat-exchanger pipe.

By the proposed approach, we may determine the maximum permissible tool-insertion speed for single-tool and multitool fin application. There are constraints on the tool-insertion speed in hybrid deformation and cutting, not only on account of impermissible decrease in the kinematic rear angles, as in ordinary cutting, but also on account of limits on the permissible cut-layer thickness, which are more significant in hybrid deformation and cutting.

In insertion, the cut-layer thickness may be equal to the tool's axial feed in some cases. The gap between the fins will then be zero, and the layer removed will not be guided by the previously formed gap. Instead, the cut layer will be forced against the machined surface, resulting in impermissible loads on the cutter, which consequently fractures.

It is important to determine the maximum permissible tool-insertion speed in hybrid deformation and cutting both in designing the mechanism for radial cutter feed per revolution for fin-application systems and when using ordinary numerically controlled lathes for hybrid deformation and cutting.

Consider multitool machining in which all the cutters are free of positional error and are characterized by the same axial feed s_{ro} per rotation. In radial supply, the cutter is displaced radially by $s_{rz} = s_{r.ro}/z$, where z is the number of tools. Assuming that the error Δt is numerically equal to s_{rz}, we may write a formula for the increase in cut-layer thickness, which is numerically equal to the decrease in the fin spacing: $\Delta a = -\Delta b = s_{rz}\cos\varphi$. In this case, the fin spacing is

$$b = s_z(1-\sin\varphi) - s_{rz}\cos\varphi.$$

Since the radial feed per revolution s_{rz} must be such that $b \geq 0$, we require that $s_{rz} \leq [s_z(1-\sin\varphi)]/\cos\varphi$. For example, when $\varphi = 30°$, to ensure that $s_{ro} = 0.6$ mm in three-tool machining, we require that s_{rz} be no more than 0.35 mm/turn. For single-tool machining, analogously, $s_r \leq [s_{ro}(1-\sin\varphi)]/\cos\varphi$.

Summarizing, in both single-tool and multitool machining, we require that the ratio of the radial and axial feed speeds $v_r/v_{ax} \leq (1-\sin\varphi)/\cos\varphi$.

CONCLUSIONS

(1) We have developed and tested a system for fin application to long pipe on the basis of hybrid deformation and cutting. The primary cutting motion is the rotation of three tools around the pipe blank; the auxiliary motion is feed of the pipe blank along its axis.

(2) We have developed a specialized system for three-pass fin application on heat-exchanger pipe, at a rate of 4 m/min (when fin spacing 0.82 mm).

(3) For multitool machining, we have formulated requirements on the positional errors of the cutters in hybrid deformation and cutting so as to ensure specified fin precision.

(4) We have established limits on the speed of tool insertion in hybrid deformation and cutting.

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