Production of helical heat exchanger tubes by roller spinning

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Abstract
Technologies are developed, and experimental production of helical heat exchanger tubes on screw-cutting lathe is conducted by several roller spinning schemes. The one-start helical tube was made by the following scheme: using profiled mandrel, using granular material instead of the mandrel, profiling without mandrel and granular material. The three-start helical tubes are produced using three-roll spinning-head. The several options of roller spinning of one- and three-start helical groove on the tube using a software package Deform 3D are modeled. The effect of various parameters (diameter of roller D_r, screw pitch of the mandrel k, groove depth h, frequency of mandrel and tube rotation n) on the formation of helical grooves is investigated. It was found that the ratio of grooves depth h to screw pitch of the mandrel k has the greatest influence on the stress-strain state in the process of production of such tubes.
Key words: ROLLER SPINNING, ONE- AND THREE-START HELICAL TUBE, STRESS-STRAIN STATE, THREE-ROLL SPINNING-HEAD

Introduction

The intensification of heat exchange in channels is an effective method of reduction of overall dimensions and metal intensity of heat-exchanging devices. As a rule, when developing of new heat-exchanging devices, the high intensity of heat transfer in case of the minimum costs of energy for heat-carrying medium pumping is tried to be reached [1]. The analysis of papers in this regard shows that helical tubes with equideveloped heat exchange surface [2] are the most effective. The mass production of such tubes is not available at present time.

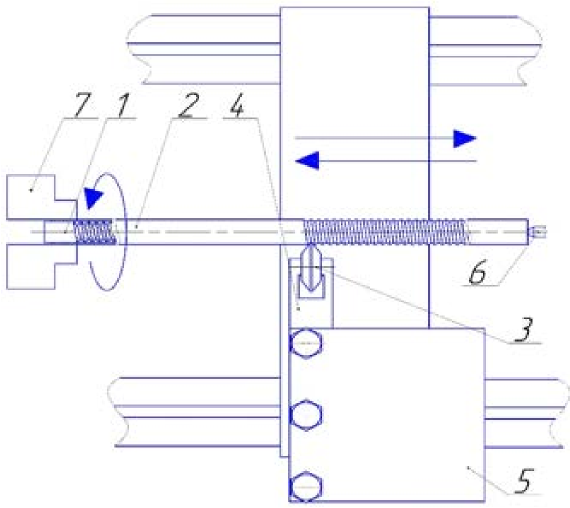
It is possible to increase flow transition of heat-carrying medium when using helical tubes, which are produced by method of roller spinning. A lot of the patented methods and devices of helical tubes production by roller spinning are known; the most of them are similar. They consist in profiling of tube rotating on a mandrel by roller, which forms helical grooves in a tube using helical profile of a mandrel [3].

The paper **objective** is development of mass production technology of one- and three-start helical tubes by roller spinning with use of mandrel as well as without it, and also research of influence of spinning parameters (diameter of roller D_r, screw pitch of the mandrel k, rotating rate of a mandrel n, quantity of helical grooves in the mandrel j). The possibility of obtaining the maximum depth h of helical groove without destruction has been investigated.

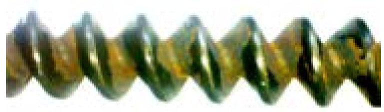
Helical tubes are produced using the following diagrams of this method implementation:

1. Production of helical tubes by roller spinning on screw-cutting lathe with use of mandrel and roller

The diagram of process is shown in Figure 1, and mandrel 1 is put on tube 2. During experimental investigation, the tube made of stainless steel AISI 304 with diameter (external) D_{tub}=38 mm and thickness of 1 mm was used. The roller 3 is fixed on body 4, which is set in cutter support 5 of the lathe. The mandrel 1 with the tube 2, which is put on it, was fixed on one side by center of screw-cutting tailstock 6, and on the other side, cams 7 of three-jaw chuck of the lathe, than provided impossibility of tube rotation about a mandrel.



a)



b)

c)

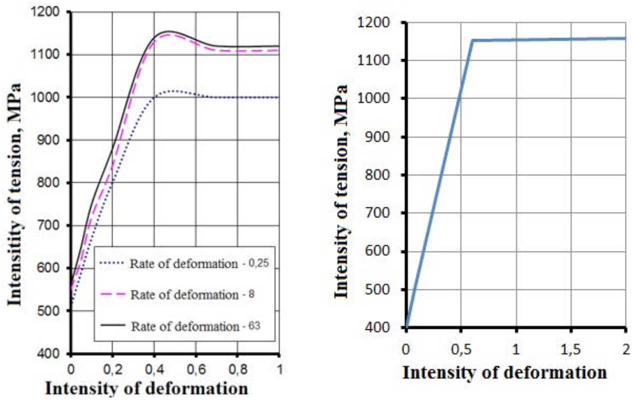
d)

Figure 1. The diagram of process of one-roller spinning of helical groove in the tube (a) and the photo: b) – mandrel, c) - tube with a screw pitch of 20 mm, d) tube with a screw pitch of 12 mm

According to this diagram, the experimental production of helical tubes is held in several stages before obtaining grooves of depth h=4.5 mm. At the beginning, when forming grooves of depth h=2mm, a roller with blunt angle of profile (100º) and edge rounding radius r=3mm. Finishing operations, when forming final grooves h=4,5mm depth, were conducted by roller with an acute angle of a profile (70º) and the same radius of rounding of an edge of r=3mm. Finishing operations, when forming final grooves of depth h=4.5mm, were executed by a roller with an acute angle of profile (70º) and the same radius of edge rounding r=3mm. At the same time, the deformation process was conducted several times with pass of roller to one side and to other one till formation of final helical profile in the tube. For creation of optimum technology of spinning, and also development of equipment, numerical simulation and comparing of rollers spinning of tube using single-start and multiple-start methods were carried out [4, 5]. The spinning of the following helical tubes with an identical width of all the grooves was modelled for this purpose: one-start with a step of 8 mm, three-start with a step of 24 mm. Simulation was conducted by software package Deform 3D, which was temporarily provided by the Tesis company Moscow. The tube was broken down by tetrahedral terminal elements. The tube with a diameter D_{tub}=38 mm with thickness of a wall S=1 mm was used in these models. The friction coefficient was 0.1. The curve of hardening of AISI 304 stainless steel, which is shown in Figure 2, was assigned to the program. In each case of simulation, the mandrel rotated with the speed of n=160 r/min in direction opposite to rollers rotation.

In the specified cases, process of numerical simulation took place in several stages [5].

At the first stage of simulation of helical tube spinning, the roller or rollers are pressed into a tube on depth of h=2 mm, then on depth of 3.5 mm, and at the last stages on depth of 4,3 mm. At that, formation of 3.5 mm grooves in a tube took place after obtaining 2 mm groove, and formation of a groove of 4,3 mm in depth took place after obtaining 3.5 mm groove. That is formation of helical tube took place by interchanging of stages of rollers pressing into a fixed tube and stages of its spinning. These two stages correspond to one pass of rollers. The stages of helical tubes simulation are described in more detail in the paper [5].



a) b)

Figure 2. Hardening curves: a) AISI 304 steel, b) – AISI 321 steel

The analysis of a primary stage of simulation (pressing of roller into a fixed tube) shows that in this case stress-strain state (SSS) takes place in a local cell of deformation. SSS consists of the following: two principal tensile stresses (σ_1, σ_2) and compression stress σ_3, which value is close to zero; two principal tensile deformations ε_1 and ε_2 (ε_2 is close to zero), and also compressive deformation ε_3. At this stage, the unfavorable diagram of SSS is formed that does not allow production of helical tubes with deep grooves $h/D_{tub} \geq 0.15$ ($h/k \geq 0.4$). At a stage of roller pressing into a pipe, distribution of intensity of stress σ_i and deformation ε_i, gives the chance to select two zones of an intensive metal current [4, 5]. The first zone is near the rounded mandrel edges, the second one is near the rounded roller edges. The stress in these two curvilinear zones of tube is close to biaxial tension as it has been mentioned. Tension, which emerges in these zones, depends on radii of these zones curvature depending on radii of roller and mandrel rounding. Thus, the less these radius of rounding are, the greater values of principal stresses will be.

Simulation of a secondary stage of spinning (in case of rotation of tube on its axial and movement of rollers along this axis, therefore the helical grooves are formed in a pipe) of one- and three-start helical tubes with an identical width of groove has shown that there is no significant difference in SSS in case of production of such products [4]. The quantity of the helical grooves *j* in a tube does not affect its SSS. For evaluation of possibility of tube destruction in the course of its spinning, the energetic failure criterion Brozzo, which is based on determination of specific work of form change, was used in the program:

$$\int_0^{\varepsilon_{ul}} \frac{\sigma_1}{\sigma_1 - \sigma} d\varepsilon_i = const = \psi \, , \qquad (1)$$

where σ_1 – maximum principal stress; ε_i – deformation intensity; σ – hydrostatic pressure; $\sigma = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$; ε_{ul} – ultimate deformation.

For evaluation of impact of spinning parameters, the numerical simulation of tube spinning by rollers of different diameters (D_r = 25; 30; 38; 40; 45; 100; 150 mm) with different rotating speed of tube (n = 50; 100; 160; 200; 250 r/min), and with different step of helical mandrel (k = 6; 8; 12; 20 mm) is carried out. On the basis of the obtained results, the influence of the specified parameters on the maximum values of intensity of tension σ_i, intensity of deformation ε_i and Brozzo criterion is found out. It is established that on the internal surface of tube, the values of intensity of tension, deformations and value of Brozzo criterion are 8 ... 10% higher than on external one. In the course of production of such tubes, the step of helical mandrel k has the greatest impact on SSS; and higher its value is, the deeper groove can be formed in a tube. It is preferable that the ratio between groove depth *h* and a step k (*h/k* - the relative depth of groove) to be no more than h/k≤0.4 (Figure 3). Frequency of mandrel rotation *n* slightly influences the process of a roller spinning of helical tube. It is established that the optimum ratio of roller diameter to diameter of tube is D_r/D_{tub}=3.

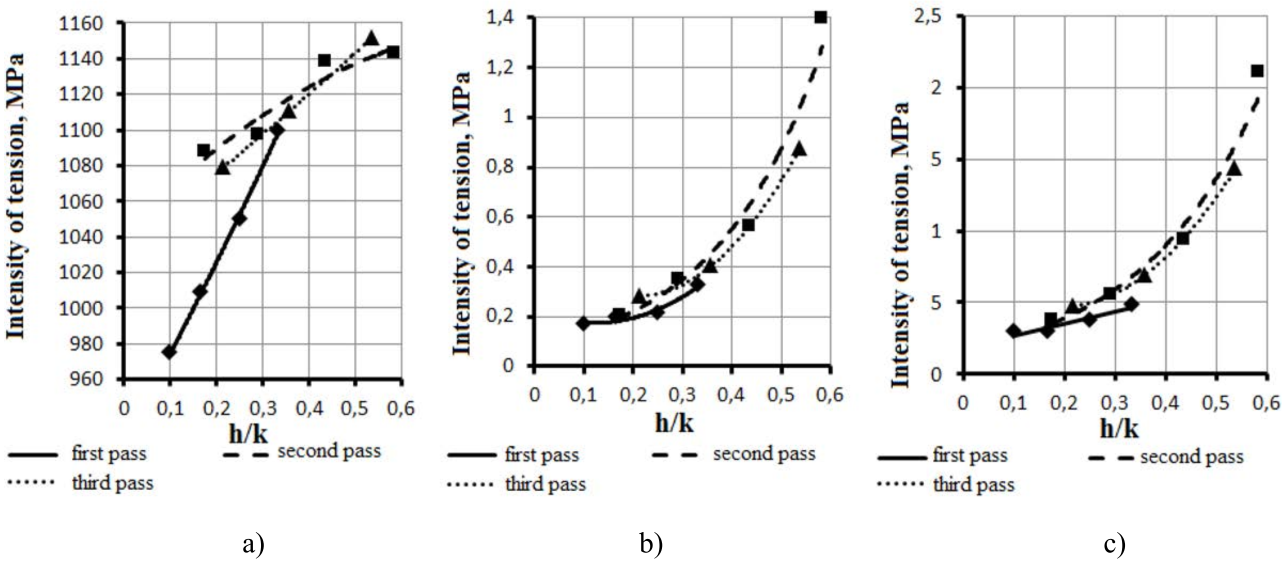
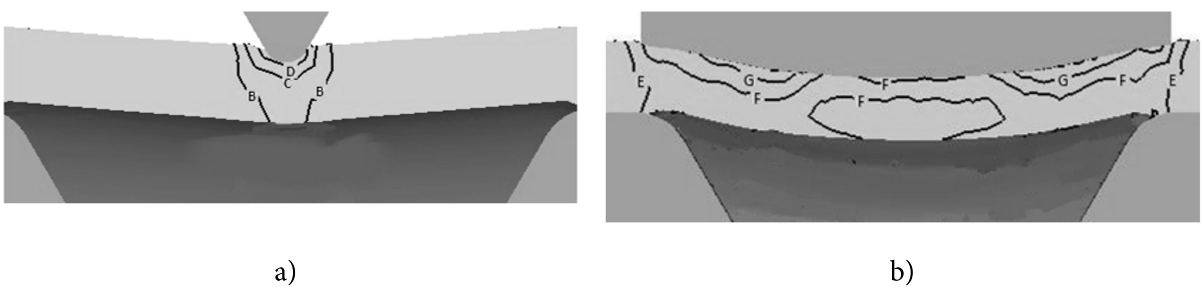
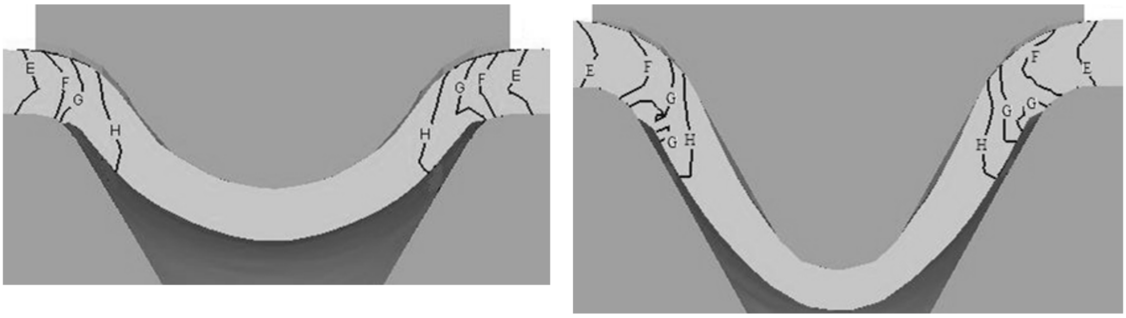


Figure 3. Influence (at the different number of rollers passes) of ratio of groove depth *h*, which is formed in a tube, to a step of a one- start helical mandrel *k* (relative depth of groove) on the maximum values: a – intensity of tension, b – intensity of deformations, c – values of Brozzo criterion

Distribution of isolines of tension intensity in a local zone of deformation is obtained by numerical simulation at spinning by a sharp roller (Figure 4, a) of annular groove in the tube consisting of the material AISI 321 (Figure 2, b). Distribution of isolines of tension intensity is obtained similarly at multiroller spinning of annular groove in the tube made of the same material (4 mm in depth) by rollers with different radii of rounding (Figure 4,b-d). At the same time, decrease in intensity of tension and deformations at multiroller spinning with use of rollers of different sharpness (Figure 5) is established. Due to the use of several rollers with different radii of rounding, each of which increased the groove depth made by the previous roller, more material of tube has been involved in deformation process.

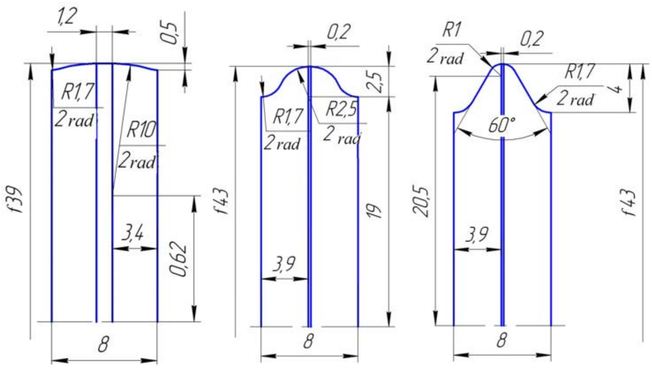




c) d)

Figure 4. Distribution of tension intensity in tube sections at spinning by sharp roller – a) at multiroller spinning (E–663 MPa, F–829 MPa, G–995 MPa, H–1160 MPa): b) – depth of groove is 0.5 mm, c) – depth is 2,5 mm, d) – depth is 4 mm

On the basis of experimental researches and results of numerical simulation with the use of Deform 3D program, it has been established that it is better to perform the process of helical tube spinning with the relative depth of groove h/k≥0.25 and ratio h/Dtr ≥0.05 in several stages (two or three passes of rollers), in each of which rollers of various geometry will be involved. At the beginning, when forming grooves with the relative depth h/k≤0.25 and ratio $h/D_{tub}\leq 0.05$, it is preferable to use a roller with an obtuse angle of profile (>90º) and the relative radius of edge rounding r/k≥0.25. When forming of final grooves with relative depth 0.4≥h/k≥0.25 and ratio h/Dtr ≥0.05, finishing operations must be performed by roller with an acute angle of profile (<90º) and the relative radius of edge rounding not less than r/k≥0.05 (depending on a mandrel groove profile angle).



a) b) c)

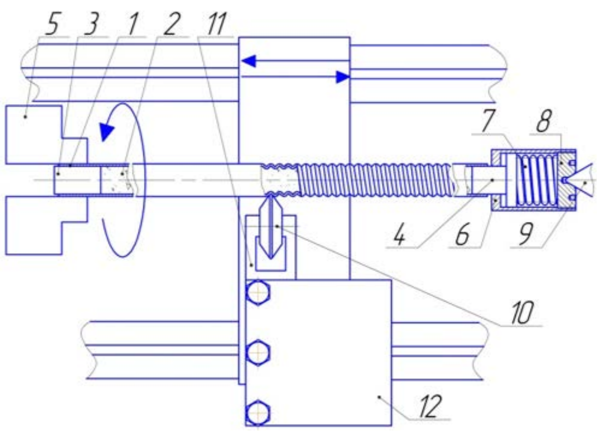
Figure 5. Diagrams of rollers, which were used at multiroller spinning: a) – for formation of 0.5 mm groove, b) – for increase in depth of groove up to 2.5 mm, c) – for increase in depth of droove up to 4 mm

In the course of spinning, there can emerge a helical crack at the bottom of helical groove of tube. The crack is formed due to exhaustion of material plasticity.

2. Production of helical tubes by roller spinning on the screw-cutting lathe with use of granular medium instead of mandrel

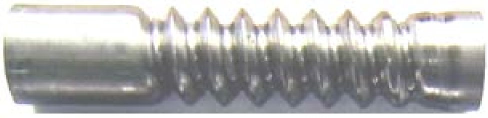
The mandrel is technologically complex detail. Also, after process of formation of helical profile, there emerge difficulties in removal of ready-made tube. Therefore, there is a need of development of the scheme of helical tubes obtaining without mandrel for simplification of manufacturing techniques.

The use of granular materials is alternative of a mandrel [6]; and also, it provides a possibility of backward pressure in the tube. The scheme of helical tubes production process by roller spinning with the use of granular medium instead of mandrel is presented in Figure 6 a. The granular material 2, which consists of sand and graphite, is filled up into the tube 1, and plugs 3, 4 are put into its ends. The left plug 3 together with tube 1 is fixed by cams 5 of three-jaw chuck of the lathe. The right plug 4 is put into the body 6 where the spring 7 puts pressure upon it. Pressure force of spring 7 is regulated by cover 8, on which there is an opening where the center 9 of screw-cutting tailstock is established. Spinning is performed by roller 10, which is established in spinning-head 11 that is fixed in cutter support 12 of the lathe.



a)

b)



c)

Figure 6. The scheme of obtaining helical tubes with use of granular material instead of mandrel (a) and the picture of the obtained tubes: b) – with a step of helical screw 8 mm, c) – with a step of helical screw 12 mm

In course of spinning with a roller, granular material is condensed at the beginning, and then begins to affect a plug, which squeezes the spring in the body. By means of this scheme, the samples of helical tubes with a different step of helical screw have been obtained. They are presented in Figure 6 b, c.

3. Production of three-start helical tubes

For obtaining of three-start helical tubes, the experimental version of three-roll spinning-head on the basis of three-jaw chuck, on which cams the rollers are fixed has been designed and developed [4]. The spinning-head is fixed on support of screw-cutting lathe. The production technique of three-start helical tubes is implemented as follows: the helical mandrel with tube, which is put on it, is fixed in the chuck of lathe on the one side, and on the another side is backed by the center of tailstock. Rollers are arranged by grooves of a three-star mandrel, and at the same time, press them into tube on depth 1.5 – 2.0 mm, after that begin to rotate a tube together with mandrel, and move a three-roll spinning-head along a pipe axis. The three-roll spinning-head is moved by means of kinematical connections of the lathe that allows controlling of movement step rigidly. After the first pass, the lathe is switched to the mode of reverse motion, and the spinning-head comes back to initial position. At the next stage, the rollers are pressed into tube on 1.0 – 1.5 mm and process of spinning is repeated. Then, several stages of deformation are performed before obtaining necessary depth of groove, then the mandrel and tube are removed from the lathe and the tube is rolled from a mandrel.

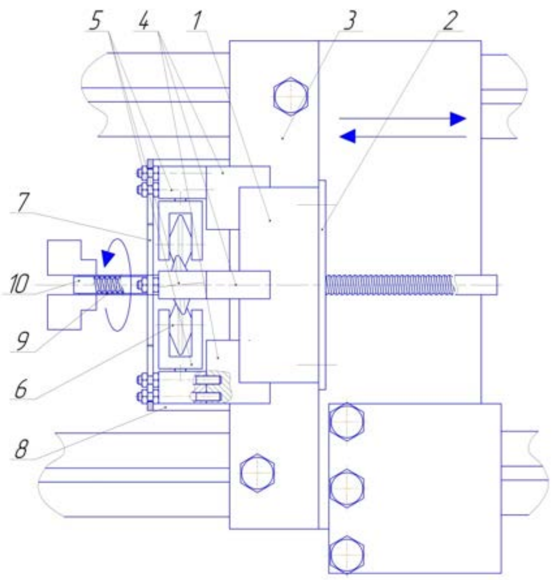
The scheme of spinning process with use of three-roll spinning-head is shown in Figure 7 a.

The three-roll spinning-head consists of three-jaw chuck 1, which is fixed to a plate 2 by means of screws, and the plate in turn is fixed to a support 3 that is arranged on lathe support. Spinning-heads 5 with rollers 6 are attached to cams 4 of three-jaw chuck 1. Rigidity of construction is increased by the guide plate 7 with grooves, by means of which spinning-heads 5 are further directed. The guide plate 7 is connected with support 3 by means of screws and plate 8. A tube 9 together with mandrel 10 is fixed in three-jaw chuck of the screw-cutting lathe.

The spinning of three-start helical tubes can also be carried out without mandrel, instead of which the granular material is used (50% of sand and 50% of graphite). The three-start helical tube, which is obtained with the use use of such materials, is shown in Figure 7 b.

4. Technology of profiling of helical tubes by two spinning-heads without mandrel

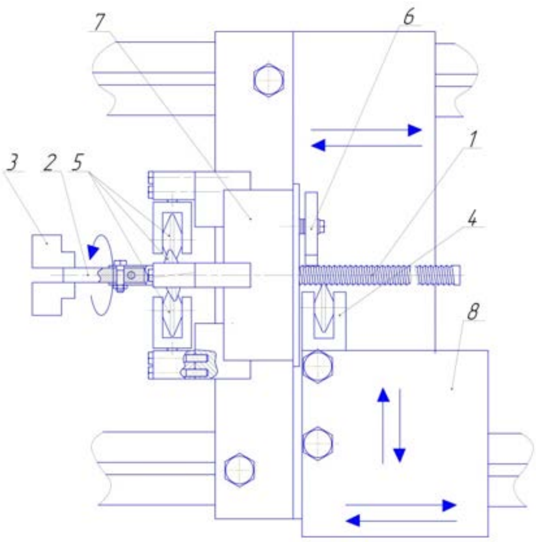
Relying on the previous researches and developed technologies, there was suggested the scheme of profiling of long helical brass tubes with an external diameter of 16 mm and thickness of 1 mm without use of mandrels or any fillers that will allow reducing of cost of such tubes production, and will simplify their production technique. As the deforming tools, three- and one-roll spinning-heads were used. This equipment is arranged on the screw-cutting lathe. The schematic diagram of this equipment operation is shown in Figure 8 a.



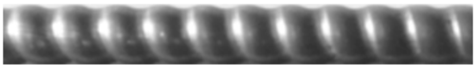
a)

b)

Figure 7. The schematic diagram of equipment operation with a three-roll spinning-head (a) and the picture of the three-start helical tube produced without mandrel



a)



b)

Figure 8. The schematic diagram of equipment operation with two spinning-heads (a) and the picture of obtained tube (b)

The equipment contains three-roll spinning-head 7, which is fixed on a support of screw-cutting lathe and one-roll spinning-head 4, which is fixed in cutter support 8 of this lathe. The tube 1 is arranged between rollers 5 of head 7 and fixed by core extender 2, which is fixed in the chuck of lathe cams 3. As the areas of deformation by three-roll spinning-head 7 and one-roll spinning-head 4 are at considerable distance, it is necessary to use a core extender 2, which allows minimizing of withdrawal and prevents twisting of tube. For prevention of tube deflection in the course of profiling the support 6 is used. The tube obtained by this technology is presented in Figure 8.

Conclusions

1. During production of helical tubes, a step of helical mandrel *k* had the greatest impact on SSS, and the higher it is (more than width of groove), the deeper groove can be formed. It is preferable that the ratio between groove depth *h* and a step *k* to be no more than $h/k \leq 0.4$, at that $h/D_{tub} \leq 0.15$. Distinctions between SSS when forming of one-start and multiple-start helical tubes with grooves of identical width are insignificant. Frequency of mandrel rotation *n* affects insignificantly the process of roller spinning of helical tube. It is established that the optimum ratio of roller diameter to tube diameter is $D_r/D_{tub} = 3$. It allows reducing of deformation of tube wall and reducing the possibility of helical crack in the course of production.

2. The possibility of production of high-quality helical profiles up to 1.5 mm in depth for one pass on tubes of brass heat exchangers with an external diameter of 16 mm and wall thickness of 1 mm has been established. This is sufficient for increase in heat transmission by 30….50 %.

3. The technology and equipment for profiling of tubes with use of a three-roll spinning-head has been developed.

4. It is established that formation of helical grooves in the tube is carried out due to local plastic deformation and improvement of its wall. The general increase in hardness in hollows of grooves layers can reach 50% (h/k=0.56). In case of plasticity exhaustion of material, there is helical crack in groove hollows.

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