Modeling and research of the deformation treatment process of 585 gold fineness alloys for obtaining wire for jewelry purpose

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Abstract
The results of studies of the process of obtaining wire for the manufacture of jewelry chains from new nickel-free 585 gold fineness alloys are presented. New 585 gold fineness alloys, alloyed with palladium, silver and other elements, and as modifiers – with rhodium and ruthenium in the stated quantities have been proposed. By modeling the process of section rolling of rods in octagonal calibers using the variation method of minimum total power, the broadening of the metal and the energy-power parameters of rolling rods from the investigated alloys have been determined. The regularities of their change have been found. Software has been developed for designing processes for the production of longish deformed semi-finished products and technological modes of rolling and drawing of new gold alloys. With the help of experimental studies, the adequacy of the results of calculations and modeling was checked, and new data were obtained on the mechanical properties of the metal and its structure. It has been found that the proposed alloys and the modes of their processing using the processes of section rolling and drawing make it possible in industrial conditions to obtain jewelry wire with a diameter of up to 0.25 mm with the level of mechanical and operational properties required for chain tying.

Keywords Jewelry production · Gold alloys · Wire · Mechanical properties · Metal structure · Drawing

1 Introduction

The gold market has been developing in recent years despite fluctuations and world events [1]. Single publications [2–7] are devoted to the issues of jewelry production, including the manufacture of deformed semi-finished products from precious metal alloys [4–7]. Research in this area is mainly the work of scientists from the Ural and Siberian Federal Universities and specialists from the Krasnoyarsk and Yekaterinburg plants of non-ferrous metals [8–11]. Therefore, the task of creating new hypoallergenic alloys with a given level of mechanical and operational properties, as well as technologies for their deformation processing, along with a decrease in anthropogenic load on the environment [12, 13] is urgent and requires modeling these processes and comprehensive theoretical and experimental studies.

On the basis of the analysis of scientific and technical literature and the results of patent search [14–22] for the manufacture of jewelry from 585 gold fineness alloys, new chemical compositions of such alloys were proposed [23–26]. The distinctive features of proposed alloys are the absence of nickel and the choice of modifying additives (Table 1) and the method of modification [27].

Analysis of the technological scheme for the production of rods and wires for the manufacture of jewelry chains, equipment, and gauge systems for section rolling of precious metals showed that to obtain longish deformed semi-finished products a cast rod made of precious metal alloys with a diameter of 8–10 mm is used. Cast rod is subjected to cold section rolling on continuous mills in three stages in 28...
The chemical composition of the alloy, the mass fraction of the component, %

| Alloy | Au  | Ag  | Pd  | Cu  | Zn  | In  | Ru  | Rh  | Sn  | Si  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| №1   | 58.5| 21.6| 10.0| 8.4 | 1.5 | -   | 0.01| -   | -   | -   |
| №2   | 58.5| 26.0| 8.0 | 5.5 | 1.5 | 0.5 | 0.01| -   | -   | -   |
| №3   | 58.5| 26.0| 8.0 | 5.5 | 1.5 | 0.5 | -   | 0.1 | -   | -   |
| №4   | 58.5| 26.0| 8.0 | 5.5 | 1.5 | 0.5 | 0.05| 0.05| -   | -   |

Passes with intermediate anneals. A square billet with a size of 1.1×1.1 mm is drawn to obtain a wire with a diameter of 0.25–0.35 mm.

The analysis of scientific, technical, and patent literature made it possible to draw the following conclusions:

1. One of the important trends in the production of long-deformed semi-finished products for the production of jewelry chains is the creation of new nickel-free gold alloys and technologies for their deformation processing to improve their mechanical, technological, and operational properties, reduce the cost of products made from them, and ensure compliance with existing safety standards.

2. Improving the technology for the production of rods from alloys of precious metals, obtained in industrial practice by cold section rolling using octagonal gauges, is an urgent task and requires new scientifically grounded solutions.

3. Existing methods for calculating the shape change and energy-power parameters of section rolling are developed mainly for other gauge systems and conditions for hot rolling of steels, or are based on the use of empirical formulas. Therefore, for new alloys of precious metals, a comprehensive study of the rolling process in octagonal gauges using methods of mathematical and physical modeling.

4. Development of software for designing technological processes of section rolling and calibration of rolls is advisable in the Delphi programming environment, based on the obtained mathematical model with a block of graphic support and using the capabilities of Microsoft Acces and Autodesk FeatureCAM software products, and computer modeling of section rolling for new alloys according to the proposed routes are recommended to be carried out in the DEFORM-3D software package, since there are numerous examples of its successful use for metal forming processes.

2 Materials and method of carrying out research

Based on the conclusions made, a mathematical and computer model of the process of section rolling in octagonal gauges has been developed.

The solution of the variational problem of determining the shape change of cold section rolling in octagonal calibers of precious metal alloys was carried out using the methodology of Professor V.K. Smirnov based on the use of the principle of minimum total power and the power balance method [28]:

\[
\delta(N_{int} + N_{sh} + N_{ss} + N_r) = 0,
\]

\[
N_{int} + N_{sh} + N_{ss} + N_r = 0
\]

where \(N_{int}\) is power of internal forces; \(N_{sh}\) power of the shear forces in the plane of metal entry into the rolls; \(N_{ss}\) power of friction forces at sliding speeds; and \(N_r\) power supplied by the rolls.

When solving the problem, the independent dimensionless parameters which uniquely describe the deformation zone during rolling in octagonal calibers (Fig. 1) varied at three levels for the ranges of their variation used in practice within the following limits: \(1/h = h_0/h_i = 1.0–1.5\); reduced roll diameter \(A = D_0/h_i = 10–80\); aspect ratio \(a = 0.92–1.08\); shape factor \(k_a = 1.23–1.37\) (square gauge, \(k_a = (1.85 \cdot b_i)/b'_i\); rhombic gauge, \(k_a = (0.8 \cdot h_i)/b'_i\)), where \(h_i\) caliber height; \(D_0\) roll diameter; \(b_i\) caliber width, \(b'_i\) caliber pad width. The friction coefficient is \(\mu = 0.1–0.5\).

The symmetry of the deformation zone allows considering the fourth part of it. The geometric zone of deformation consists of contact zones \(A\) and \(B\), lateral non-contact zone \(C\) and vertical zones in the planes of entry and exit of metal from the rolls at \(x = 0\) and \(x = l_{mk}\). To simplify the solution of the problem, it is assumed that the intermediate zone at \(l^* < x < l_{mk}\) and \(0 < y < b'_{ix}\) is small and negligible. In accordance with the methodology for solving the problem [28], the broadening coefficient \(\beta\) and the advance coefficient \(\nu\) were chosen as unknown variable parameters.

The surface equations have the form:

\[
h^A = h_{iy} + 0.5 \chi^2 R_y,
\]

\[
h^B = a_{ok}(b_{mx} - y).
\]

The unknown parameters were the broadening coefficient \(\beta\) and advance coefficient \(\nu\).
Here $a_{0k} = \frac{b_0}{b_0}$ – aspect ratio of the previous caliber, $b_{mx}$, width of the caliber, taking into account the area on the metal vertically.

The current cross-sectional area of the workpiece in the deformation zone:

$$w_x = \frac{1}{2} b_{mx} \left( b'_{Kx} + b_{mx} \right) + h'_{Kx} \cdot b_{mx},$$

(6)

where $b'_{Kx}$ and $h'_{Kx}$ are dimensions of pads in width and height of the caliber.

The metal flow velocity field was determined taking into account the hypothesis of flat sections, the hypothesis of straight verticals, the incompressibility condition, and the kinematic boundary condition. In this case, the longitudinal $V_x$, transverse $V_y$, and vertical $V_z$ speeds of metal movement are described as follows:

$$V_x = V_1 \cdot \frac{w_1}{w_x},$$

(7)

where $w_1$ and $V_1$, respectively, are the cross-sectional area of the roll and the longitudinal speed of the metal in the plane of the exit of the metal from the rolls (at $x = 0$) and $w_x$ is cross-sectional area of the roll flowing along the $x$-axis.

For zone $A$

$$V_y = -\frac{1}{h^2} \int_0^y \frac{\partial}{\partial x} (V \cdot h_x^3);$$

(8)

For zone $B$

$$V_z = -\frac{1}{h^2} \int_0^y \frac{\partial}{\partial x} (V_y \cdot h^3) - V_z \cdot h^3 |_{y = b_{mx}};$$

(9)

For zone $C$

$$V_z = V_x \cdot \frac{\partial h}{\partial x} - \frac{1}{h^3} \cdot z.$$

(10)

The rolling speed in the section of the exit from the rolls is equal to:

$$V_1 = \nu \cdot V^*_{r},$$

(11)

where $\nu$ is the advance coefficient and $V^*_{r}$, is the circumferential speed of the roll in the longitudinal-vertical section at $y = 0$.

Thus, the kinematically possible velocity field in the deformation zone is determined with an accuracy of two unknown quantities: the broadening coefficient $\beta$ and the advance coefficient $\nu$.

It is assumed that the metal slides relative to the rolls over the entire contact surface and the average friction stress are:

$$\bar{\tau}_{fr, ad} = \psi \cdot \tau_s,$$

(12)

where $\psi$ is the friction coefficient depending on the rolling temperature and the surface condition of the rolls and $\tau_s$ is the metal shear yield strength.

It is assumed that the average friction stress is distributed over the lagging and leading zones in proportion to the average sliding speeds in these zones. Taking this into account, the average friction stresses in the lagging and leading zones are calculated by the formulas:

$$\bar{\tau}_{fr, ad} = \bar{\tau}_{fr} \cdot \frac{\bar{V}_{sl, lag}}{\bar{V}_{sl}};$$

(13)

$$\bar{\tau}_{fr, ad} = \bar{\tau}_{fr} \cdot \frac{\bar{V}_{sl, ad}}{\bar{V}_{sl}}.$$  

(14)

Average sliding speeds are:

$$\bar{V}_{sl, lag} = \frac{1}{F_{lag}} \cdot \int_{F_{lag}} \bar{V}_{sl} dF;$$

(15)

$$\bar{V}_{sl, ad} = \frac{1}{F_{ad}} \cdot \int_{F_{ad}} \bar{V}_{sl} dF;$$

(16)

$$\bar{V}_{sl} = \frac{\bar{V}_{sl, lag} \cdot F_{lag} + \bar{V}_{sl, ad} \cdot F_{ad}}{F_{lag} + F_{ad}}.$$  

(17)
The boundary between the contact surface into the lead and lag zones is the neutral line, the equation of which is determined from the condition that the projection of the total sliding speed on the tangent to the roll circumference is equal to zero. Since the projection of the total sliding speed is zero, then:

$$V^*_{sl} = V_{sl,x} \cdot \cos \alpha_{xy} + V_{sl,z} \cdot \sin \alpha_{xy}, \quad (18)$$

To determine the power components, the following expressions are used:

For the power of internal forces:

$$N_m = \int \tau_s \cdot H \cdot dV, \quad (19)$$

where $H$ is the shear strain rate intensity and $\tau_s$ is metal yield strength.

For the power of the shear forces in the plane of metal entry into the rolls:

$$N_{sh} = \sum_n \int \tau_s |V^+ - V^-| dF, \quad (20)$$

where $V^+$ and $V^-$ are the projection of the metal flow velocity on the tangent plane to the cut surface $F_{sh,i}$ from the inner and outer sides of the surface.

For the power of frictional forces at sliding speeds:

$$N_{sl} = -\int_{F_{lag}} \tau_{fr,lag} U_{sl} dF - \int_{F_{ad}} \tau_{fr,ad} U_{sl} dF; \quad (21)$$

For the power supplied by the rolls:

$$N_r = \int_{F_{sig}} \tau_{sl,lag} U_r dF + \int_{F_{ad}} \tau_{fr,ad} U_r dF, \quad (22)$$

where

$$\tau_{fr,lag} = -\tau_{fr,lag}^* U_{sl} / U_{sl}, \quad (23)$$

$$\tau_{fr,ad} = -\tau_{fr,ad}^* U_{sl} / U_{sl}, \quad (24)$$

The power of the friction forces at sliding speeds and the power supplied by the rolls are determined taking into account the difference in the values of the friction stress in the lead and lag zones.

The basic system of Eqs. (1) and (2) was solved by a numerical method on a computer using the MATHCAD software package when changing independent parameters.

As a result, approximating formulas were obtained for calculating the coefficients $\beta$ and $\nu$:

$$\beta = 1 + 0.357 \cdot \left( \frac{1}{\eta} - 1 \right)^{0.023} \cdot A^{0.325} \cdot k_a^{-1.134} \cdot \psi^{-0.095}, \quad (25)$$

$$\nu = 1 + 0.087 \cdot \left( \frac{1}{\eta} - 1 \right)^{0.954} \cdot A^{0.084} \cdot k_a^{0.148} \cdot \psi^{-0.036}, \quad (26)$$

where $1/\eta$, reduction ratio, an increase in which during rolling in drawing grooves leads to an increase in the degree of filling the deformation zone with metal, which ensures a decrease in the proportion of transverse deformation; $A$, reduced roll diameter; $k_a$, coefficient taking into account the shape of the octagonal caliber; and $\psi$, friction coefficient.

Dimensionless independent quantities are:

reduction ratio $1/\eta = \frac{h_{i-1}}{h_1}; \quad (27)$

reduced roll diameter $A = \frac{D_0 - H_i}{H_i}; \quad (28)$

Coefficient taking into account the shape of the octagonal gauge:

square gauge $k_a = \frac{1.85 \cdot b_i^{x-1}}{b_i^{x-1}},$ rhombic gauge $k_a = \frac{0.8 \cdot b_i^{x-1}}{b_i^{x-1}}, \quad (29)$

where $h_i$, caliber height; $H_i$, geometrical height of the caliber; $D_0$, roll diameter; and $b_i^{x-1}$, caliber pad width.

When solving the problem, the independent dimensionless parameters and the friction coefficient were changed at three levels for the ranges of their variation used in practice within the following limits:

- Reduction ratio $1/\eta = 1.0 \div 1.5$
- Reduced roll diameter $A = 10 \div 80$
- Aspect ratio of the original roll $a = 0.92 \div 1.08$
- Aspect ratio $k_a = 1.23 \div 1.37$
- Friction coefficient $\psi = 0.1 \div 0.5$

Experimental data were used to verify the solution results. The accuracy of the approximating formulas was determined by the formula:

$$x = \frac{x_{cal} - x_{exp}}{x_{exp}}, \quad (30)$$

where $x_{cal}$ and $x_{exp}$, respectively, are the calculated and experimental values of the investigated parameter.
Fig. 3  Influence of dimensionless independent parameters on the coefficient of broadening during rolling in octagonal gauges: 

- **a** compression ratio (at \( A = 45, \psi = 0.4 \));
- **b** the reduced diameter of the rolls (at \( 1/\eta = 1.25, \psi = 0.4 \));
- **c** friction coefficient (at \( A = 45, 1/\eta = 1.5 \)).
3 Results and discussion

The results of solving the variational problem are shown in Figs. 2 and 3.

The error in determining the calculated values in comparison with the experimental ones did not exceed 1–3% (Fig. 4). This makes it possible to judge the adequacy of the obtained mathematical model. The calculation was carried out at fixed values of the friction coefficient and the reduced diameter of the rolls ($\psi = 0.4$, $A = 45$, the relationship of the sides of the original rolled product $a = 1.0$).

Using the obtained mathematical model an algorithm and method for calculating the shape change of metal and energy-power parameters of cold section rolling have been developed. On their basis the “PROVOL” program was created for designing a technology for manufacturing semi-finished products from precious metal alloys and calibrating rolls (Fig. 5).
The “PROVOL” program is implemented in the Delphi programming environment and includes modules for designing technological processes of rolling and drawing. It can be used independently or in combination for calculating deformation modes of longish deformed semi-finished products made of non-ferrous metals and their alloys, as well as for determining energy and power parameters and selection of equipment. With the use of the “PROVOL” program, rational routes for section rolling of longish deformed semi-finished products for jewelry chains from new precious metal alloys have been designed (Fig. 6). Their use makes it possible to reduce the number of passes, optimize the power load of the equipment, and ensure uniform deformation of the billet during rolling along the proposed routes.

Computer modeling of the section rolling process and the tool was carried out using the DEFORM-3D software package (Fig. 7a) and the FeatureCAM system (Fig. 7b) in order to form a 3D model of the rolls and their calibration.

**Fig. 6** Change in the rolling force along the existing (1) and proposed (2) routes for the investigated alloys: a alloy №1; b alloy №2; c alloy №3; d alloy №4.

![Graphs showing rolling force change](image)
as well as for their production on turning and milling equipment. Calculations based on the developed model confirmed the feasibility of the process of section rolling of rods from the investigated alloys along the developed routes without breaks and exceeding the permissible rolling force. Comparison of the rolling force according to the results of modeling $P_m$ and calculations $P_c$ with the data of experiments $P_e$ was carried out according to the formula (30), which showed that the calculation error does not exceed 5% (Table 2).

The change in the rolling force for alloy №4 in the fourth pass is shown in Fig. 8a. Analysis of the simulation data showed that the values of the rolling force reach the maximum value in the 4th pass and then (Table 2) gradually decrease in the course of the process and do not exceed the permissible values. Analysis of the stress state during modeling (Fig. 8b) made it possible to assert that the maximum tensile stresses reach 320 MPa in the 4th pass and are realized in the zone of maximum reduction, which corresponds to the 4th pass.

Table 2  Rolling force for gold alloy №4

| Caliber number | Side size, mm | Total elongation ratio $\lambda_{\text{single}}$ | $P_m$, kN | $P_c$, kN | $P_e$, kN | Error, % modeling | Error, % calculation |
|----------------|---------------|----------------------------------|-----------|----------|----------|-------------------|-------------------|
| 1              | 6.82          | 1.08                             | 45.1      | 44.3     | 45.2     | 0.1               | 1.9               |
| 2              | 6.40          | 1.23                             | 45.8      | 45.8     | 47.5     | 3.2               | 3.5               |
| 3              | 5.86          | 1.35                             | 54.4      | 55.8     | 56.4     | 3.7               | 1.1               |
| 4              | 5.29          | 1.23                             | 55.9      | 58.8     | 57.0     | -4.3              | -3.1              |
| 5              | 4.60          | 1.32                             | 52.6      | 57.2     | 56.3     | 1.5               | -1.5              |
| 6*             | 3.98          | 1.34                             | 47.6      | 53.2     | 55.7     | 2.7               | 4.4               |
| 7              | 3.38          | 1.39                             | 22.0      | 25.3     | 24.6     | 1.9               | -2.6              |
| 8              | 2.92          | 1.34                             | 25.7      | 29.9     | 28.8     | 2.4               | -4.0              |
| 9              | 2.49          | 1.38                             | 36.5      | 42.9     | 44.4     | 3.6               | 3.5               |
| 10             | 2.22          | 1.26                             | 22.7      | 26.7     | 27.1     | 3.5               | 1.6               |
| 11             | 2.03          | 1.20                             | 21.1      | 24.6     | 24.4     | 2.9               | -0.7              |
| 12             | 1.84          | 1.22                             | 19.0      | 21.9     | 22.1     | 3.5               | 0.8               |
| 13             | 1.62          | 1.29                             | 24.7      | 27.8     | 27.9     | 3.4               | 0.4               |
| 14             | 1.43          | 1.28                             | 14.3      | 15.5     | 15.6     | 3.8               | 1.1               |
| 15             | 1.27          | 1.27                             | 18.6      | 19.1     | 18.7     | 0.5               | -2.0              |
| 16             | 1.20          | 1.12                             | 17.4      | 17.3     | 16.9     | 2.4               | -2.5              |
| 17             | 1.09          | 1.21                             | 15.4      | 14.3     | 14.9     | 1.9               | 4.1               |
| 18             | 1.00          | 1.19                             | 9.2       | 7.9      | 8.0      | 3.5               | 1.6               |

*a* pass after which annealing was carried out
to the traditional concepts of rolling theory. Since these stresses do not exceed critical values (the ultimate tensile strength at these degrees of deformation in the 4th pass is 716 MPa, Table 3), it can be assumed that the rolling processes will proceed without the formation of scrap (destruction of the workpiece).

To assess the effect of the value of the accumulated degree of deformation ($\varepsilon_\Sigma$) during section rolling on the level of mechanical properties (yield stress $R_p$ and ultimate tensile strength $R_m$), a full factorial experiment was planned. A full factorial experiment made it possible to obtain regression dependences to determine the strength properties of new alloys:

\begin{align*}
\text{Alloy N\textsuperscript{2}1 :} & \quad R_p &= -0.0096 \varepsilon_\Sigma^2 + 2.60 \varepsilon_\Sigma + 150.96; \quad (31) \\
& \quad R_m &= -0.0023 \varepsilon_\Sigma^2 + 2.55 \varepsilon_\Sigma + 333.91. \quad (32)
\end{align*}

\begin{align*}
\text{Alloy N\textsuperscript{2}2 :} & \quad R_p &= -0.0041 \varepsilon_\Sigma^2 + 2.02 \varepsilon_\Sigma + 150.72; \quad (33) \\
& \quad R_m &= -0.0017 \varepsilon_\Sigma^2 + 3.11 \varepsilon_\Sigma + 220.18. \quad (34)
\end{align*}

### Table 3 Properties of cast and deformed samples from test alloys

| Rolling pass after which a sample was taken | Degree of deformation, % | Yield stress $R_p$, MPa | Ultimate tensile strength $R_m$, MPa | Elongation to failure A, % | Microhardness, kgf/mm$^2$ |
|-------------------------------------------|--------------------------|--------------------------|-------------------------------|--------------------------|-----------------------------|
| **Alloy N\textsuperscript{2}3** Cast sample |                          |                          |                               |                          |                             |
| 4                                         | 44.3                     | 266                      | 336                           | 33.8                     | 150                         |
| 12                                        | 78.8                     | 730                      | 794                           | 8.3                      | 204                         |
| 13                                        | 83.6                     | 802                      | 814                           | 4.9                      | 210                         |
| 14                                        | 87.2                     | 804                      | 816                           | 4.7                      | 212                         |
| 17                                        | 92.6                     | 809                      | 830                           | 4.1                      | 214                         |
| 18                                        | 93.8                     | 878                      | 891                           | 4.0                      | 217                         |
| **Alloy N\textsuperscript{2}4** Cast sample |                          |                          |                               |                          |                             |
| 4                                         | 44.3                     | 307                      | 384                           | 31.0                     | 158                         |
| 7                                         | 69.0                     | 667                      | 716                           | 11.9                     | 202                         |
| 17                                        | 92.6                     | 799                      | 882                           | 4.9                      | 207                         |
| 18                                        | 93.8                     | 883                      | 903                           | 4.8                      | 215                         |
In the course of experimental studies on a section rolling mill model AMBI FILO VELOCE ROSEN 180 \( \times \) \( \Omega \) 130 from Mario Di Maio with an octagonal gauge system, the designed compression modes for alloys No 3, No 4 were worked out. The metal broadening and contact area were measured, as well as using tensometric equipment and mesoscale recorded the rolling force. In the course of rolling the samples were taken. The mechanical properties (Table 3) were determined by the stretching method on a universal tensile testing machine LFM 400.

Studies have shown that the new alloys have a high level of mechanical properties, a fine-grained structure, good manufacturability during casting and metal forming, which ensures the production of wire for chain-knitting with high consumer characteristics.

Metallographic studies made it possible to reveal that the structure of alloy No 3 in the cast state (Fig. 9a) is characterized by the presence of dendritic segregation. However, it has finely branched dendrite branches with a small dendritic cell size. This ensures the production of dendritic crystals with a dendritic cell size of 4 \( \mu m \). By the last rolling passes, a fibrous structure uniform along the length and cross section of the semi-finished product was achieved (Fig. 9b). The increased strength and plastic properties of alloy No 3 made it possible to exclude intermediate annealing operations in the processing flow chart.

Dendritic segregation is observed inside equiaxed large grains (from 260 \( \mu m \)), while it is not observed in smaller grains, since they have time to undergo equalizing diffusion.

### Alloy No 3:

\[
R_p = -0.0045 \varepsilon_\Sigma^2 + 6.20 \varepsilon_\Sigma + 265.84; \quad (35)
\]

\[
R_m = -0.0434 \varepsilon_\Sigma^2 + 9.44 \varepsilon_\Sigma + 336.25. \quad (36)
\]

### Alloy No 4:

\[
R_p = -0.0036 \varepsilon_\Sigma^2 + 9.41 \varepsilon_\Sigma + 321.22; \quad (37)
\]

\[
R_m = -0.0074 \varepsilon_\Sigma^2 + 12.39 \varepsilon_\Sigma + 401.31. \quad (38)
\]
processes. The average grain size of the investigated cast billet was 216 μm, and the average size of the dendritic cell was 7 μm, which indicates a high degree of supercooling during crystallization.

Since the main task was the development of nickel-free alloys based on white 585 gold fineness alloys, with high corrosion resistance and products from it, having an increased level of consumer and mechanical properties, as well as obtaining their uniform distribution along the length of deformed semi-finished products, research was carried out on new alloys №1 and №2 based on gold with modifying additives. In the compositions of these alloys the gold content was in the range of 58.0–59.0%, due to which their fineness was ensured. The introduction of palladium was the main technical solution for replacing nickel, as a result of which an increase in corrosion resistance was achieved, prevention of embrittlement and provision of a color range of alloys. Copper was introduced to lower the melting temperature, provide the necessary ductility, and improve the manufacturability of the alloys during casting. Zinc lowered the melting point, while silver imparted softness, malleability, and a lower melting point to alloys. Indium addition in the range of 0.4–0.6 wt. % provides the required melting temperature range of the alloy.

Ruthenium was chosen as the main modifying additive, which in the range of 0.001–0.10 wt. % provided a fine-grained structure of alloys №1 and №2 and the required range of grain size variation within 5–10 μm and also contributed to an increase in plasticity and equalization of properties along the length and section of the cast billet. At the same time, in the known method of introducing ruthenium into the melt, its limited solubility in gold due to the high melting temperature led to the formation of large inclusions in the alloy structure (Fig. 10a). That was the reason for the appearance of defects during metal forming.

To increase the modifying ability of the alloy material, which is expressed in the refinement of the grain structure of gold alloy ingots, a new method of alloy modification was developed [27], according to which ruthenium was introduced into the melt in the form of an Ag-Ru alloy with a ruthenium content of 0.001 wt. % immediately before crystallization. This made it possible to improve its dissolution in gold, as a result of which a complete assimilation of the introduced modifier occurs in the alloy. In addition, this method provides an accurate determination of the amount of ruthenium added to the melt. Semi-finished products from a white 585 gold fineness alloys obtained using this technology have a uniform fine-grained structure along the entire length and section of the ingot (Fig. 10b), which confirms the high quality and efficiency of modification.

To check the results of theoretical studies and modeling, a pilot-industrial testing of the technology for producing wire for the production of jewelry chains from new white 585 gold fineness alloys (alloys №1 and №2) was carried out. As a result of its implementation, pilot batches of wire were obtained, from which the most sophisticated jewelry chains of the “Snake” type were made on a chain tying machine (Fig. 11).

| Operation        | Side size, mm | Deformed state | Annealed state |
|------------------|---------------|----------------|----------------|
|                  |               | Rm, MPa        | A, % Microhardness, kgf/mm² | Rm, MPa | A, % Microhardness, kgf/mm² |
| Alloy №1         |               |                |                |
| 1 stage of rolling | 3.7×3.7      | 940            | 4.0 307        | 533     | 35.0 242        |
| 2 stage of rolling | 2.1×2.1      | 881            | 2.4 292        | 464     | 27.2 185        |
| 3 stage of rolling | 1.1×1.1      | 820            | 1.5 294        | 489     | 31.0 160        |
| Drawing          | diameter 0.25 | 958            | 4.2 300        | 560     | 33.0 145        |
| Alloy №2         |               |                |                |
| 1 stage of rolling | 3.7×3.7      | 942            | 3.6 228        | 450     | 35.0 124        |
| 2 stage of rolling | 2.1×2.1      | 753            | 2.6 271        | 430     | 32.0 163        |
| 3 stage of rolling | 1.1×1.1      | 661            | 1.9 264        | 434     | 25.0 149        |
| Drawing          | diameter 0.25 | 879            | 3.6 273        | 503     | 39.2 139        |
Studies of the mechanical properties (Table 4) of the experimental alloys have shown that they have a sufficiently high level of plastic and strength properties, which ensures the production of wire with high consumer characteristics. The results of the research, as well as the receipt of pilot batches of jewelry chains of the “Snake” type, allow asserting that the wire for jewelry purposes from new nickel-free 585 gold fineness alloy has the required level of mechanical properties and is suitable for making jewelry chains in industrial conditions.

4 Summary

Thus as a result of the research the following main results were obtained:

1. A number of new nickel-free alloys based on white 585 gold fineness alloys have been developed, which provide improved mechanical and operational properties of deformed semi-finished products intended for the manufacture of jewelry chains.
2. Mathematical model of the process of cold section rolling of bars in octagonal gauges created.
3. With help of created mathematical model, the shape change of the metal and the force parameters of rolling of the investigated gold alloys were determined, and the regularities of their change were found.
4. Computer models of the roll tool for the process of cold section rolling in octagonal gauges have been created.
5. Using the results of computer modeling, the technological parameters of rolling were substantiated, and the power load of the equipment was determined.
6. Software has been developed for designing processes for the production of longish deformed semi-finished products from the investigated alloys, with the help of which the regimes of reduction in section rolling of new alloys have been calculated.
7. Experimental studies and regression analysis of experimental data were carried out, on the basis of which formulas were obtained to determine the strength properties of new alloys.
8. Experimental-industrial approbation of technical and technological solutions for the manufacture of wire from which batches of jewelry chains of the “Snake” type from new white 585 gold fineness alloys having the required performance characteristics were obtained.

Author contribution The authors declare that they are all participants in the work and none of them performed only administrative functions.

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Data availability Not applicable.

Declarations

Ethical approval The work contains no libellous or unlawful statements, does not infringe on the rights of others, or contain material or instructions that might cause harm or injury.

Consent to participate The authors consent to participate.

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Competing interests The authors declare no competing interests.

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