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Optimization of Procedures for Manufacture of Tubular Claddings and Pressure Tubes.

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ABSTRACT

Criteria were established and an algorithm was developed for optimizing the deformation procedures in manufacturing cladding and channel tubes and rolling tools. The criteria were based on the allowable intervals and uniformity in distribution of strain rate as well as of the tube treatment factor both in tube deformation zones and in the working area of rolling mills.

Criteria were defined for choosing the optimal tube billet rotation angle, the minimum allowable number of strokes and the maximum feed required for setting up uniform strain in a finished tube.

Based on these criteria and using special computer programs, tool calibrations for rolling mills were designed, manufactured and tested, followed by production of a tube batch. The old and new roll pass design and setting plug were selected, measured and compared. The new tool calibration affords a larger output of good industrial tubes with uniform metal structure and a longer service life of the tools.

KEY WORDS: fuel cladding, channel tube, texture, metallographic structure, tube rolling, deformation procedure, optimization, strain rate, tube treatment factor, tool calibration.

INTRODUCTION

Besides nuclear and physical properties of materials, design of reactor core components should take into account structural characteristics, such as metallographic and crystallographic texture, phase composition and grain size. A high quality of material calls for uniform distribution of initial structure with specified parameters throughout the volume of the whole product.

Development of deformation procedures is an important technological stage largely responsible for the economic efficiency and quality of manufacturing channel and cladding tubes.

Optimization of such manufacture with stringent requirements for geometry, surface condition, mechanical properties, texture and structural characteristics of the metal, has to deal with a whole number of complicated technological problems:

- Development of an optimal deformation procedure adapted to the capabilities of the manufacturer's rolling mills;
- Geometry design and manufacture of rolling mill tooling;
- Choice of tube rolling conditions;
- Choice of heat treatments for process stages and of final annealing to attain the required mechanical properties, texture and structural characteristics of the tube metal.

Modern high-duty processes of manufacturing channel and cladding tubes involve very great dimensional changes from the starting tube billet to a finished component, with the total tube strain, Wo, being many times in excess of the maximum allowable plastic strain of the metal, W_p, as well as of the rolling mill capabilities. Therefore, the total tube deformation is divided among a number, N, of process stages, with the strain reduced to below the limit allowable for the metal, $W_i < W_p$ and with the process stages adapted to the rolling mill capabilities. Intermediate annealing is introduced between the tube deformation stages to remove all the residual stresses from cold hardening. This gives rise to an important practical problem of optimizing the deformation procedure: with the least number of deformation stages, the greatest possible continuity in tube deformation and dimensional ratios (sequential tube diameters) should be ensured for a specific system of rolling mills with stable production of high-quality components.

MAXIMUM ALLOWABLE PLASTIC STRAIN OF METAL

The production rate and scope for manufacture of high-quality tubes depend to a significant degree on the maximum allowable plastic strain of metal. It is common knowledge that ductility is the ability of a metal to undergo irreversible change of form without visible damage. Ultimate ductility is commonly quantified by the value of plastic strain (Λ_p) at the time of stressed metal rupture [1]. Quantity Λ_p is the cumulative strain of the previous stress history, i.e. it is a measure of overall accumulation of metal flaws by the moment of rupture. With uniform strain, Λ_p coincides with the ultimate strain rate, $W_P \leq \Lambda_p$, at the pre-rupture instant [1]:

$$W_p = \sqrt{\frac{2}{3}}\ \sqrt{(e_S - e_D)^2 + (e_S - e_L)^2 + (e_D - e_L)^2}\ =\ 2\,|e_D|\,\sqrt{Q^2 + Q + 1} \qquad (1)$$

where e_S, e_D, e_L — basic logarithmic strains across the tube wall and diameter and along its length at the pre-rupture instant; Q – tube treatment factor ($Q = e_S / e_D$).

The value of W_P depends not only on the metal properties and strain temperature, but also on the type of stressed state in case of plastic strain [1], e.g. on the tube treatment factor, Q. Each kind of mechanical treatment (extrusion, rolling, drawing, etc.) is associated with its specific stress pattern, wherefore the limit of ductility may vary with different types of tests. We have analyzed the maximum allowable plastic strain, W_p, as a function of the tube deformation factor, Q, for Zr – 2.5%Nb alloy with cold tube rolling (Fig. 1), taking values ranging from Q = 1 to Q≈10 (with practically pure rolling).

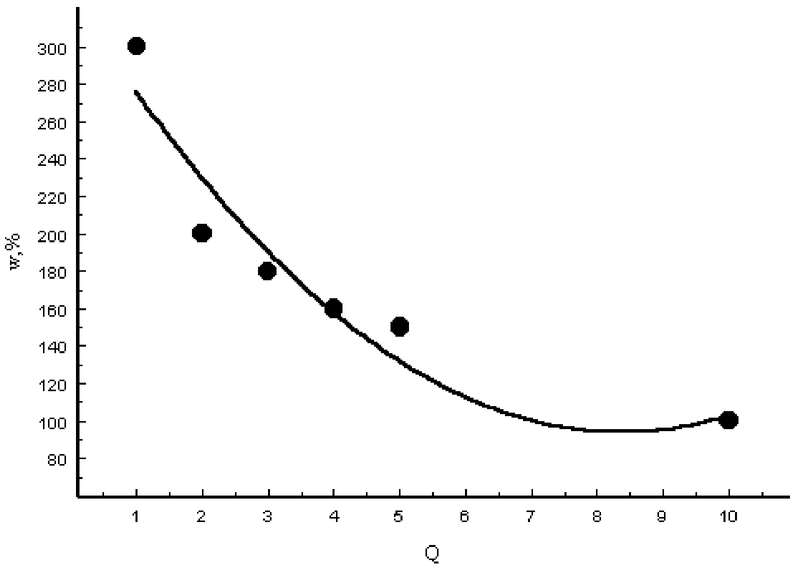

Fig. 1 Ultimate plastic strain W_p as a function of factor Q for alloy Zr – 2,5%Nb with cold tube rolling

Assessment of the relationship between the ultimate plastic strain W_p and the factor Q for alloy Zr – 2.5%Nb with cold tube rolling has placed an upper limit on the total tube strain for one deformation stage W_i, or for several stages, ΣW_i, if they have no intermediate annealing between them. Besides, the strain rate at each stage, W_i, should match the capabilities of a specific rolling mill and should meet the tube quality requirements pertaining to the process stage in question. Thus, higher-duty processes with smaller Q_i and higher W_i are admissible at the beginning of the deformation procedure, whereas at the end of the route with a specified factor Q, deformation has to be split into more stages with refining of geometry and final quality of the tube.

OPTIMISING THE DEFORMATION PROCEDURE IN COLD TUBE ROLLING

The procedure of tube reshaping from one standard size to another is fully defined by four parameters: the diameters of the starting tube billet (D_n, D_i) and finished tube (d_n,d_i). Moreover, if these four diameters are specified, the entire deformation procedure is predetermined, i.e. all its general parameters (W, Q, e_S, e_D , e_L) are known. If the finished tube diameters (d_n, d_i) alone are given, any other two among the remaining independent parameters of tube deformation (D_n, D_i, W, Q, e_S, e_D , e_L) will have to be specified to get a definite procedure. All the calculations, in this case, should only involve logarithmic strain values. Among the remaining variable parameters, strain rate for each (*i* – th) process stage, W_i, is directly related to the productivity rate of the deformation procedure. The total strain for the whole deformation procedure is equal to the sum of strains over all its N stages, $W_o = \Sigma W_i$, which is only true with logarithmic strain estimation. With the known total strain for the whole deformation procedure, W_o, the higher is the strain rate for each process stage, W_i, the smaller is the total number of stages, the more productive and economical is the deformation procedure of tube manufacture.

The second most important parameter of tube deformation is the tube treatment factor Q, which defines the strain type. For extrusion and pressing Q = 1, for sheet rolling, $Q \to \infty$. With tube rolling, the factor Q may vary within wide limits, but in actual practice it is found to range from 0.5 to 10. For cold pilgering mills, this factor should be kept at $Q \geq 1$ due to the existing side roll clearance and cross groove spreading, which will not provide the same strain across the tube diameter and wall. Even larger values of this factor ($Q > 3$) need to be maintained for roller mills.

With the finished tube diameters d_n, d_i specified, it is necessary to set additionally the value of the tube treatment factor, Q, and the total tube strain value, W, so as to match the splitting of the deformation process in stages and the capabilities of the particular rolling mill. Using these data, the inner and outer diameters, D_n, D_i of the tube billet may be calculated:

$$\begin{cases} D_n = ((d_n + d_i)\cdot e^{\left(\frac{W}{2\cdot\sqrt{Q^2+Q+1}}\right)} + (d_n - d_i)\cdot e^{\left(\frac{WQ}{2\cdot\sqrt{Q^2+Q+1}}\right)})/2; \\ D_i = ((d_n + d_i)\cdot e^{\left(\frac{W}{2\cdot\sqrt{Q^2+Q+1}}\right)} - (d_n - d_i)\cdot e^{\left(\frac{WQ}{2\cdot\sqrt{Q^2+Q+1}}\right)})/2; \end{cases} \quad (2)$$

Given the finished tube diameters - d_n, d_i, Eqs. (2), describe the smooth surfaces of possible changes in D_n, D_i, of the billet during deformation as a function of parameters W and Q (Fig. 2).

The design and optimization of the tube deformation procedure should apparently proceed in a reversed order – from the specified dimensions of the finished tube to determining the dimensions of the billet. The first step in developing the industrial deformation procedure is to assess the maximum outer diameter {max D_z} and wall thickness {max t_z} of the starting billet, which may be "handled" by the rolling mill of greatest capacity available at the manufacturing plant. Thereby all the basic parameters of the deformation procedure may be determined in the initial phase of its development.

If a specified texture is to be provided in manufacturing zirconium channel and cladding tubes, the total tube treatment factor, Q_o, should be adopted in agreement with the previously established functional relation [2,3]. The value of factor Q is closely linked to the standard requirement for fuel claddings, i.e. hydride orientation, F_N, which is one of the factors to control their quality. To have $F_N \leq 0.4$, Q should be > 2.5.

The second phase of the procedure development involves determining the section path on the surfaces of possible changes in the billet diameters D_n, D_i with the specified diameters of finished tubes (Fig. 2).

In a general case, the section path is defined by the relation Q = f (W), which itself is a surface perpendicular to surface (Q, W), Fig.2.

Construction of an optimal section path is subject to the following main requirements:

Section path should pass through the overlapping areas of rolling mills on the surfaces of possible variations in diameters D_n, D_i. This requirement is essential to practical implementation of the deformation procedure. Areas of allowable billet and finished tube diameters may be plotted on the corresponding surfaces of D_n, D_i for each rolling mill likely to be involved in the deformation procedure. These areas should partly overlap so that previous rolling mill may roll a tube to diameters acceptable for the next-in-the-line mill. The plotted section path should go through these partly overlapping areas.

The average tube treatment factor Q_{av} of the adopted section path should be equal to the total factor Q_o of the whole deformation procedure: $Q_{av} = Q_o$. If the section path is a continuous function, the above requirement will be automatically fulfilled, i.e. any continuous section path has the average factor $Q_{av} = Q_o$.

Among all the possible section paths on the surfaces of variations in diameters D_n, D_i, which meet the above requirements, those should be taken that have the least deviation from the section path with constant Q_o. This requirement dictates the degree of uniformity of metal texture and structure across the tube wall.

One of the simple and often fairly efficient solutions is to adopt a section with constant factor Q_o. All the deformation procedure consistency conditions will be met for the chosen section: the section profiles (variations of diameters) are basic to calibration of the whole rolling line at which tubes will be shaped to the same pattern – from the billet to the finished product – with uniform metal treatment throughout the tube volume. Once the section path has been chosen, it has to be divided into areas related to the deformation stages. In doing so it is important to take correct account of the deformation divisibility for each process stage. First of all, the strain rate W_i in each stage should not exceed the maximum allowable value of plastic strain rate ($W_i < W_p < \Lambda_p$) for the given alloy, Fig. 1.

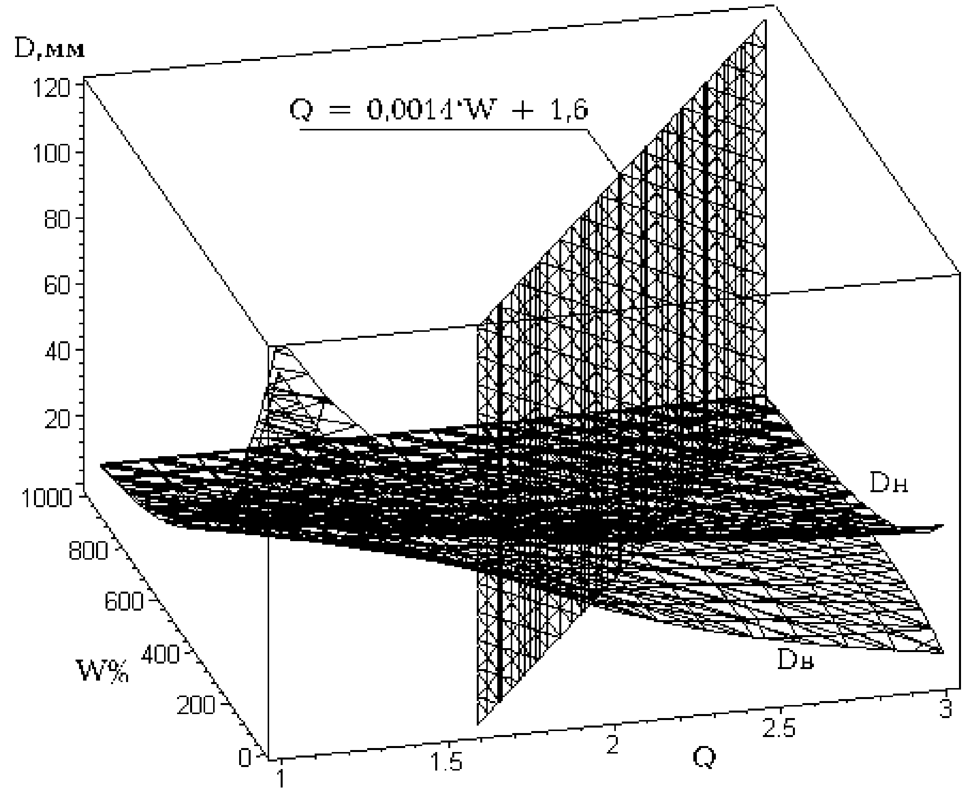

Fig. 2 Section of the surface of variations in billet diameters, D_n, D_i, by the section with variable factor Q as a function of strain rate, W.

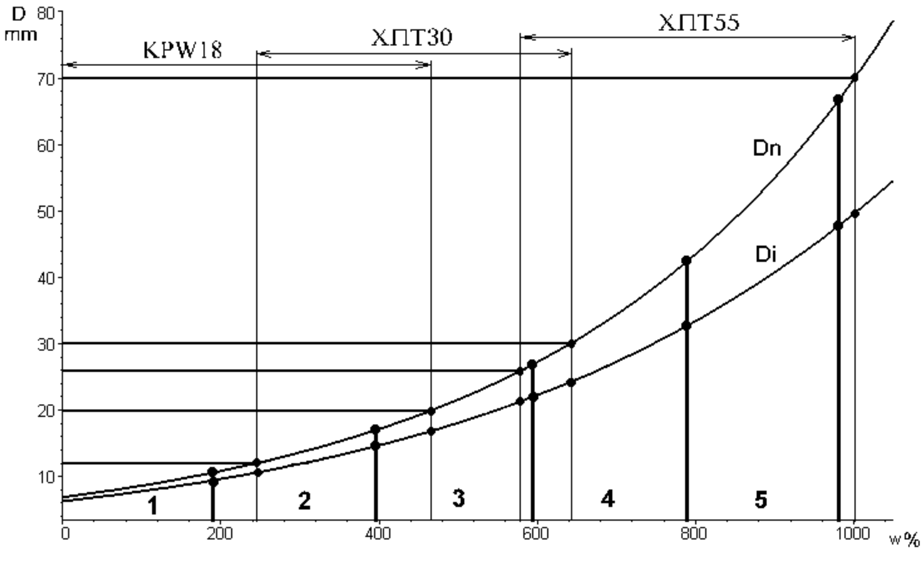

Fig. 3 Section splitting into five tube deformation stages with regard to rolling mill capabilities.

KEY STAGES IN DEVELOPING THE DEFORMATION PROCEDURE
IN TUBE MANUFACTURING

Assessing the maximum outer diameter {max D_z} and wall thickness {max t_z} of the starting billet.
Determining all the basic parameters:
D_n, D_i, Wo, Qo, e_S, e_D, e_L.

↓

Determining the section path on the surfaces of possible variations in diameters D_n, D_i.
Optimizing the section path.

↓

Splitting the section path into deformation stage areas with regard to the metal ductility limit Wp (Q), metal structure requirements and rolling mills' capabilities

On the other hand, this strain rate should not be smaller than the minimum allowable strain, W_{min}, to form a recrystallised metal structure in heat treatment, $W_{min} \leq W_i$. Besides, the total strain rate in each stage, W_i, should conform to the capabilities of the specific rolling mill (W_s) and the tube quality requirements for the given process stage: $W_i < W_s$, Fig.3. So, whereas higher-duty deformation processes with a smaller tube treatment factor ($Q_i < Q_O$) and higher strain rate ($W_i > W_O/N$) are admissible early in the deformation procedure, at the end of this route with $Q_i > Q_O$, the deformation should be divided among more stages ($W_i < W_O/N$) with adjustments made in regard to geometry, required metal structure and finished tube quality.

OPTIMIZATION OF BASIC ROLLING TOOL PROFILES

The tooling pair of cold pilgering mills – rolls and mandrel – have variable longitudinal and lateral profiles. Among the numerous parameters set in tool manufacturing and determining the process of cold tube rolling at these mills, the basic ones are the longitudinal profiles of the mandrel and the groove. The basic tool profiles dictate primarily the distribution of tube treatment factor Q_i and strain rate W_i throughout the working area of the tool for a given process stage.

The working area is conventionally divided into four zones: initial reduction of the billet; tube rolling; pre-calibration; and calibration. The short initial reduction zone is characterized by predominant bending strain. The main tube deformation takes place within the tube rolling, with the plastic deformation completed in the pre-calibration zone and geometry adjustment, in the calibration zone.

The key idea behind the logic of designing and optimizing the basic tool profiles lies in the invariant type of tube deformation (Q_i = const) and uniform distribution of strain rate density dW throughout the tool's working area. The requirement of constant Q_i provides for the same type of metal strain along the tube length, while uniform distribution of dW makes for "homogeneous" strain, which prevents formation of stress sites and concentrators in the working area.

The design and optimization of the basic profiles of the groove profile, the mandrel profile and eccentricity, essential to tool manufacture, follow an algorithm similar to the one described above for deformation procedure design – from the end of deformation backward, covering reference sections step by step and making allowance for current metal drawing by successive iterations. A design and optimization program was developed for calibrating tools for cold rolling mills. The program involves uniform strain rate distribution, $W_i = \int dw$, over the working zone with smooth decline by a sinusoidal function to the minimum value in the pre-calibration zone (Fig. 4).

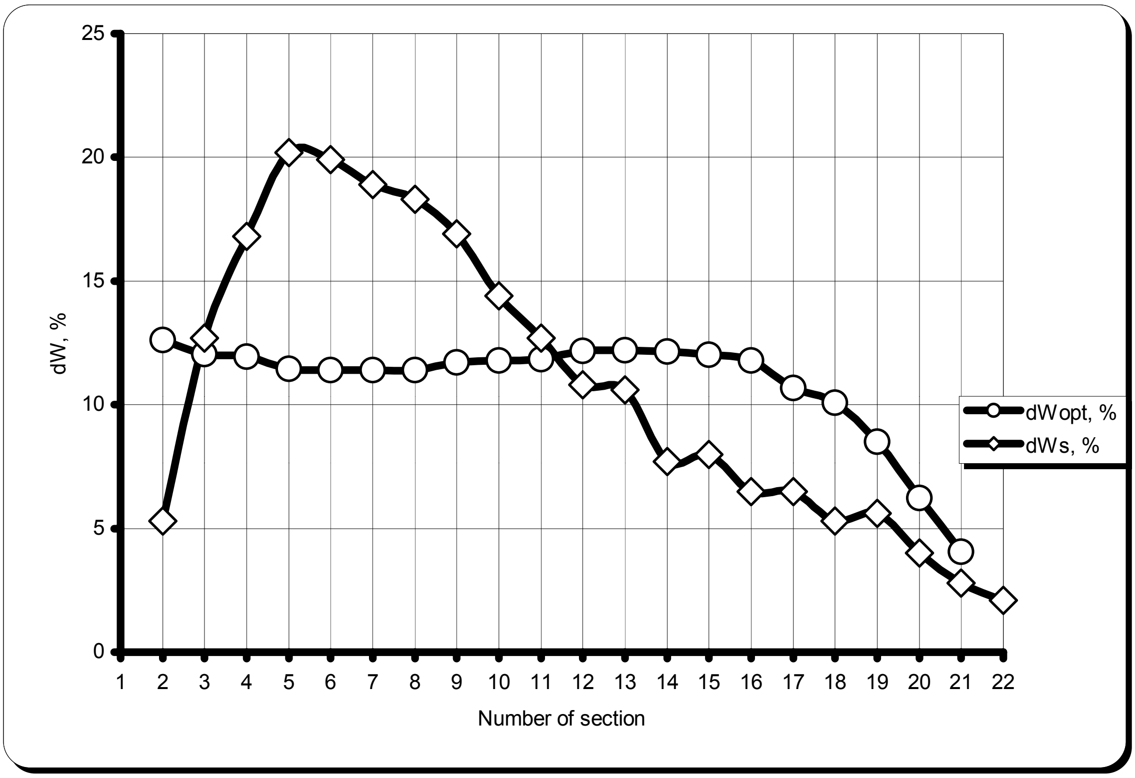

Fig. 4 Distribution of strain rate density, dW, over the working area at rolled and measured pilgering tools of regular, dWs, and optimized design, dWopt.

OPTIMIZED FEED AND ROTATION ANGLE OF BILLETS

The above procedures for designing tool calibration profiles are based on uniform strain throughout the tube circumference. The requirements indicated apply to extrusion, pressure molding and drawing, when it takes one pass to complete the tube deformation. Successive division of rolling is typical of cold pilgering mills, KPW, and roller mills, where a tube is cyclically rolled to a specified geometry by roller dies or rolls in a mandrel, with the billet fed and rotated for each stroke. Such a tube deformation procedure has inherent conditions for appearance of circumferential nonuniformity in strain distribution, which may be eliminated by successive adjustment to the required tube geometry.

The billet rotation angle is of particular importance among many other parameters governing the tube rolling conditions. During alternate motion of the sizing stand, the dies form deformation tracks on the tube, which will take more than one pass to cover the whole tube circumference due to the side roll clearance and groove camber. For a contact arrangement, the die is designed with regard to tangential and radial components. In any case, a strained state arises in the side sectors of the roll clearance, which is different from the strain in the working sectors of the die. Given an appropriate billet rotation angle at the back and front dead point of the die travel, the circumferential nonuniformity of tube strain may be reduced by superimposition or partial overlapping of the working sectors of the die. Hence comes the problem of optimizing the billet rotation angle.

We have developed an algorithm and a program for calculating the optimal rotation angle, F, billet feed, V, so as to minimize the tube strain nonuniformity.

The relative variance, dE, i.e. the maximum range divided by the average value over the tube circumference, was taken as a measure of nonuniformity in circumferential distribution of strain for tubes rolled at a KPW mill. The relative variance was calculated for the finished tube portion at the end of the working area with wide variations of the billet rotation angle $F \in (1 - 120°)$ for different sectors of the circumferential contact zone $dF \in (30°\text{-}130°)$ and varied number of stand passes $N \in (10\text{-}150)$.

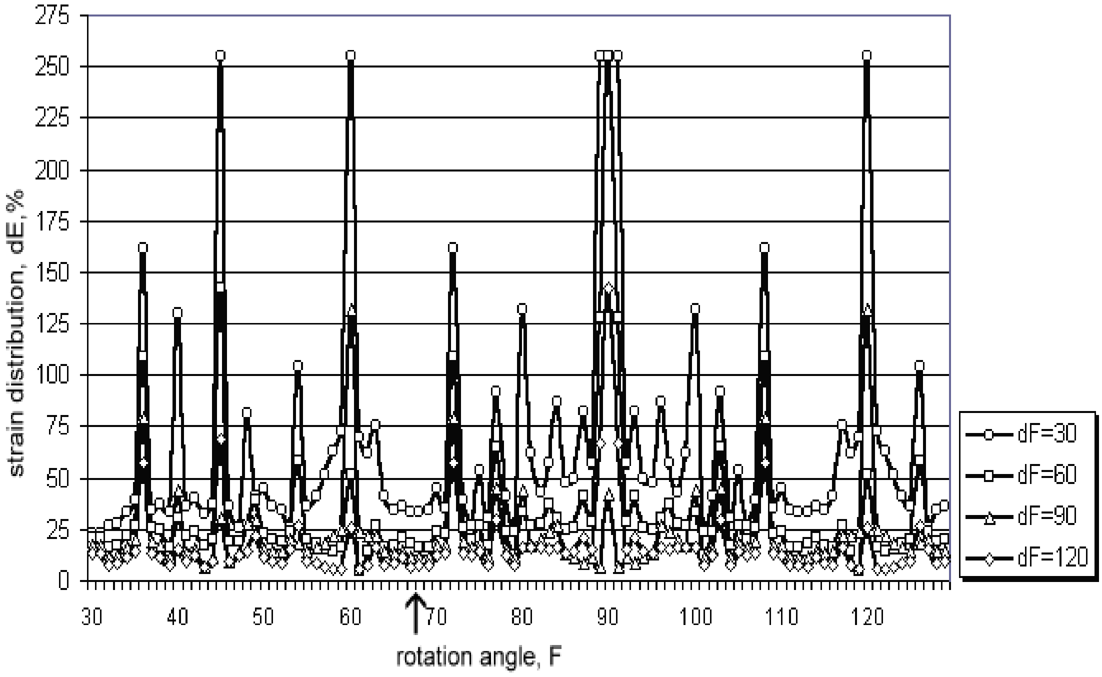

Figure 5. Strain distribution versus rotation angle.

Figure 5 shows the results of calculating the nonuniformity of circumferential strain distribution, dE, as a function of billet rotation angle F and circumferential contact zone width dF. Analysis of the results points to the existence of angle intervals with minimum variance, which are stable in a broad range of dF and N variations: $F \in (27°\pm2°)$; $F \in (33°\pm2°)$; $F \in (57°\pm2°)$; $F \in (67°\pm4°)$.

As the billet feed, V, increases, so does the metal portion, V_1, fed into the working draft zone in one pass (stroke), with a corresponding decrease in the number of double strokes, N_o, required for complete metal rolling throughout the working area of the tool. This obviously adds to the nonuniformity of strain distribution over the tube surface.

The number of strokes to have the metal go all the way though the rolling tube zone, N_o, is defined as the ratio of the pilgering head volume, V_o, to the volume of the billet metal fed in one stoke, $V_1=VS_o$, equal to the product of billet feed, V, by the billet cross-section area, S_o, i.e. $N_o = V_o/(VS_o)$. On the other hand, the number of strokes required for the metal to go through the entire calibration zone, $N_к$, is defined as the ratio of the calibration zone length, $L_к$, to the tube metal displacement in one pass, $N_к \approx L_к/(V\cdot\mu)$. Normally, $N_к << N_o$ for industrial tubes and $N_к \approx N_o$ for precision tubes. The critical – least allowable – number of double strokes was established, $N_P \approx 50$, which ensures uniform metal treatment throughout the tube volume. This estimate allows calculating the maximum allowable feed of the billet: $V_{max}=V_o/(N_P\ S_o)$.

The developed algorithms and programs were employed for designing, manufacturing and testing of the tool calibrations for a KPW-18 mill involved in the final stage of cold rolling of cladding tubes from the starting dimensions of Ø14x0.9 mm to the specified dimensions of the finished tube - Ø8x0.45 mm (with the total strain of tube deformation, W=220%, Q=1.3, and drawing μ = 3,5). In producing cladding tubes, the rolled pilgering heads were selected for the regular and optimized pass design, with subsequent measurements of their geometry and calculation of deformation parameters. As may be seen from Fig. 4, the measured strain rate dW with the regular pass design is nonuniformly distributed along the tool's working area: the tube strain falls largely within the first half of the draft zone. With the optimized pass design, dW shows uniform distribution throughout the tool's working area, which eliminates strain centers and affords a three-fold increase in the feed size and an accordingly augmented rate of cladding tube rolling. The choice of the optimal billet rotation angle resulted in uniform tube strain in high-duty rolling. The new rolling tools outperformed the regular tools in production rate, surface quality achieved, tolerances for the geometry, tube metal structure, and wear resistance.

CONCLUSION

Criteria were proposed for optimizing the design of deformation procedures and calibration of tools for cold tube rolling mills, based on equitype plastic strain, allowable intervals and uniform distribution of plastic strain rates throughout the working area of the tool. The valuation of plastic strain relies on integral estimates. The requirements concerning the allowable intervals, assuring the same type of strain and its uniform distribution aim ultimately at the continuity and general homogeneity of strain throughout the tube metal volume, while ruling out undesirable structural heredity of the starting billet. Moreover, they help enhance the wear resistance of tools. Based on the defined criteria, algorithms and programs were developed for optimizing the tube deformation procedures and the calibration of tools for cold rolling mills.

The optimal intervals of billet rotation angles were determined so as to reduce the asymmetry of transverse strain. The critical – least allowable – number of double strokes and the maximum billet feed were established for uniform metal treatment throughout the volume of the tool's working area with the highest production rate of the rolling mill.

Based on the identified criteria and using the developed program, gear for calibration of tools for rolling mills of the KPW type were designed, produced and tested, followed by manufacture of a batch of cladding tubes. Pilgering heads rolled with the use of old and new dies were selected, measured and compared. Use of the new tool calibration resulted in a higher tube rolling rate and lower spoilage levels, as well as in more uniform metal structure and longer service life of rolling tools.

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