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Formation of the Strips Surface Macro relief during Rolling with Lubrication

The mechanism and laws of the lubricating action of emulsions and suspensions during the strips rolling were considered. The regularities of the impact of the lubricant entering the deformation zone during rolling on the formation of the rolled metal micro relief were determined. The experimental results were analyzed. Recommendations on the application of theoretical solutions for the choice of process lubricant and rolling modes to ensure the specified requirements for the surface quality of the finished metal products were given. References – 17 sources.

Keywords: *metal, quality, surface, micro relief, rolling, lubrication, emulsion, suspension*

In recent years, the requirements for the quality of the surface of sheet steel, tin, pipes, wire, and other types of metal products have significantly increased. The regulation of micro relief characteristics of the rolled products has been tightened. Scientific research organizations and metallurgical enterprises are equipped with sophisticated equipment to control the surface roughness of the metal including the same in 3D. In general, the production technology of metal with a specified surface micro relief is brought to a new higher level of development. This is evidenced by a surge in research and publications on the subject. However, the analysis [1-3 and others] shows that along with the undoubted significance of new scientific results, many of the surface micro relief development patterns of the metal deformed during rolling remain not fully revealed. This is related primarily to the forming mechanism of the surface relief of the wrought metal in the conditions of application of the process lubricant in the form of emulsions. Hence,, the objectives of this article are as follows: to draw up scientific foundations and to discover the patterns of the strips surface micro relief formation in the deformation zone during rolling under the influence of a lubricating medium based on the materials of well-known theoretical and experimental studies and, first of all, the results of the own developments and, in addition, to give the recommendations on the industrial use of new technical solutions in this area.

Surface micro relief of a plastically deformed metal. There are various terms refer to the state of the surface of strips, pipes, and other metal products in the literature devoted to the metal forming. The most commonly used terms are roughness, micro relief, texture, topography, structure, microgeometry [4-5, etc.]. In a meaning of set of the microroughnesses, the term “roughness” is used in the most of the standards to evaluate the micro relief of a metal surface after various treatments including rolling. The surface roughness in accordance with the relevant standards is described by a set of parameters characterizing the average and maximum heights of roughnesses, the number (density) of microprotrusions per unit surface area, etc. The roughness values of sheet steel are regulated by standards depending on its purpose (for example, stamping products, coatings, painting, etc.).

The concept of surface “relief”, as well as “roughness”, imply a combination of roughnesses of convex or concave forms. The prefix “micro” in the words «micro relief» and «micro roughness» indicates a small amount of the irregularities or the relief. Accordingly, microroughnesses can be microprotrusions or microcavities on the surface.

The term “topography” is usually understood as a geographical and geometric study of the terrain. However, it does not quite fit to characterize the state and the properties of the surface of the wrought metal, as well as the term «texture». In metallurgy, the term «texture», as in general determines the preferential orientation of crystallites in polycrystalline metals.

Thus, the use of the terms micro relief and roughness will certainly be correct in assessment the state and surface structure of a plastically deformed metal. In the case when it is necessary to consider not only the microgeometry of the surface, but the whole range of characteristics of its state (for example, the presence of scale, smut, grease residues, etc. on the surface), then it is possible to call the collected information a topographic map of the surface.

In addition to the altitude parameters, the micro relief of the surface of the rolled strips is characterized by its anisotropy that is the dependence of the size and shape of microroughnesses relative to the direction of their control. It shall be noted that the standards that define the requirements for surface quality, for example, sheet steel, pipes, and other metal products do not regulate the anisotropy of the micro relief [3-4]. At the same time, it is known that, due to the anisotropy of the sheet steel surface roughness, the stamped parts of the car body after painting under the same conditions can have a different texture and different shades.

Another example shows that the results of jet etching of the inner surface of pipes made of high-quality steels and alloys substantially depend on the micro relief anisotropy. Microroughnesses on the inner surface of pipes oriented perpendicular to their centerline are well removed by jet etching. The longitudinal roughnesses are eliminated worse. Moreover, sometimes the microcavities are getting even deeper, which significantly degrades the quality of the pipes. Obviously, it is time to regulate the degree of permissible anisotropy of the surface micro relief in the standards that determine the quality of cold-rolled steel, as well as special-purpose pipes. Other cases are also possible, in particular, when the consumer needs metal with an anisotropic surface micro relief.

Let us consider, on the one hand, the effect of process lubricant used in rolling of strips, pipes, etc., on the micro relief of a wrought metal and, on the other hand, the influence of the surface roughness of the initial billet including the direction of microroughnesses of its surface on the amount of lubricant and friction conditions in the deformation zone.

The use of multiphase fluids as a process lubricant during rolling. In general, in metal forming processes, the process lubricants are multiphase fluids. The emulsions and suspensions come into greatest use in rolling. The emulsions are the dispersed systems consisting of small droplets of a liquid (dispersed phase) distributed in another liquid (dispersion medium). In the emulsions used in the cold rolling of the strips, in general, oil is the dispersed phase and water is the dispersion medium. In the general case, the dispersed phase can consist of many even solid particles of a material. For example, when drawing or cold rolling of pipes, the coarsely dispersed colloidal systems are used as the process lubricants, in which graphite, molybdenum sulphide, talc, zinc oxide and other fillers serve as the dispersed phase and oil is the dispersion medium. Such lubricants can be classified as suspensions and suspended matters, since they are coarse-dispersed systems with a solid dispersed phase and a liquid dispersion medium. Moreover, the solid particles are suspended in the liquid substance. The decisive influence on the mechanism of entry of the lubricating medium into the plastic deformation zone during the rolling of metals is exerted by the sizes of particles of the dispersed phase and their concentration in the dispersion medium (oil). If the particle sizes of the dispersed phase are larger than ~ 10 microns, then they can settle under the action of gravity. The size and concentration of particles of graphite, talc and other fillers in the lubricant should not lead to their sedimentation or separation of the lubricating medium. In general, the concentration of solid particles is selected experimentally. For example, when rolling stainless steel pipes in cold reducing mills, a lubricant consisting of 55-60% of vegetable oil and 45-40% of talc is fed to the mandrel. The outer surface of the pipes is lubricated with a mixture of 70% of oil (industrial I-20A or I-12A or castor oil) and 30% of talc or ammonium chloride [6, p.p. 211-212]. Hence, the conditions for lubricating the outer and inner surfaces of pipes are different.

It should be emphasized that if the mechanism and regularities of the action of oils and emulsions used as process lubricants during rolling have been studied relatively deeply [6-10 and others], then the scientific aspects of entering the multiphase lubricating media containing solid particles in the deformation zone have not been fully discovered. This explains the fact that the compositions of such lubricating media are selected for the temperature and deformation conditions of specific metal forming processes mainly by means of experiments.

Peculiarities of the mechanism of entering of grease lubricants containing solid particles into the deformation zone during rolling. It should be noted that the lubricating mechanisms for rolling the emulsions consisting of oil droplets suspended in a dispersion medium (water) and suspensions the composition of which consists of solid particles distributed in oil of some kind of powder, for example talc ($Mg_3C_4O_3$ mineral) or graphite are principally different. The main feature of the lubricating mechanism of emulsions during rolling is that the droplets of oil suspended in the dispersion medium collide with each other as they enter the deformation zone and this is followed by their coarsening and coagulation. As a result, immediately before the inlet section of the deformation zone, there is a sharp increase in the concentration of oil in the lubricating medium, which is hydrodynamically drawn into its plastic zone. In this case, a certain amount of oil is adsorbed on the surfaces of the rolls and the rolled metal and in this way enters the deformation zone. In real industrial conditions normally both of these mechanisms are involved in feeding to the deformation zone of the oil component from the emulsion. Which one of them prevails depends on the specific technological conditions such as the properties of the metal being rolled, emulsion concentration, viscosity and adhesiveness of dispersed oil, rolling modes (speed, degree of deformation, temperature and other factors).

The scientific basis of the emulsion flow in the inlet area of the deformation zone during rolling is discussed in publications [7-10]. It is shown that in a simplified approach, the concept of effective viscosity of multiphase lubricant fluids in relation to emulsions, the formulas for which are given in [6-7, 10, etc.] is allowed to be applied in theoretical analysis. And then the well-known solutions shall be followed to determine the thickness of ξ_{in} layer of lubricant at the inlet area to the deformation zone based on the hydrodynamics of the flow of a single-phase fluid with a previously calculated effective viscosity. This approach is acceptable when performing high-quality estimated calculations.

The solution for the case when the emulsion used in rolling is considered as a micropolar fluid has been proposed in our monograph [7, p.p. 159-160]. In the performed theoretical analysis, the lubricant flow was considered within the framework of a two-speed medium model including the equations of motion of the dispersive and dispersed phases. It is shown that as a result of the impact of the dispersion medium, the particles of the dispersed phase change the trajectory of their movement, are rotated and moved both towards the deformation zone and in the perpendicular direction with respect to the roll and strip surfaces. As a result, as already noted above, the oil droplets representing the dispersed phase are enlarged and they are coupling before entering the deformation zone generating an area of «pure» oil, which is hydrodynamically drawn into the plastic zone. However, due to the increase in pressure in the lubricant medium as it moves to the deformation zone, the oil also sticks to the surface of the rolls and the strip.

The problem statement, the equations used and the solutions obtained in [7] are not fundamentally changed if the dispersed phase consists of the solid particles. However, the following differences should be reflected in the physical model and in mathematical models describing the process of entrance of the lubricating medium containing the solid particles to the deformation zone.

In cases when water-oil emulsions and mixtures are used as a process lubricant, the limiting states of the lubricating fluid are as follows: water at zero concentration of the dispersed medium (in the absence of an oil phase); "pure" oil at 100% concentration. Both in the first and second limiting states, the lubricating medium remains a fluid, the flow of which is described by hydrodynamic equations.

When using micropolar liquids, in particular, suspensions, in which the dispersed phase is solid particles of talc powder, graphite or some other filler, the limiting states of the lubricant medium are radically different. In one extreme case, when there are no solid particles in the dispersion medium, the lubricant is a "pure" oil (liquid), for describing the flow of which the hydrodynamic equations are suitable. In the opposite case, the lubricating medium is not a liquid, but a powder of some substance consisting of small particles of various sizes, hardness, strength and plasticity. The mechanism of the entrance of such a powder lubricant in the deformation zone during rolling and the friction mode are do not have any liquid nature anymore. It is similar to the mechanism observed in powder rolling processes [11].

Obviously, in real conditions of rolling, pressing or drawing various metals using suspensions as a process lubricant, the mechanics of the lubricant medium consisting of powder-thickened oil fed into the deformation zone is a symbiosis of hydrodynamic and powder mechanisms. Which of them prevails depends primarily on the concentration of solid particles in the lubricant. At the same time, in the considered process, the functions of both dispersed and dispersion media are changed to a certain extent.

First, in general case, the solid particles are not spherical like droplets of oil in the emulsions. As the lubricating medium moves towards the deformation zone, the solid particles do not coagulate and do not coarsen. Under the influence of the pressure, they collide with each other and may be broken up into the small components. As a result, the number of particles in the lubricating medium may increase and their sizes may decrease. Solid particles in the lubricant while moving in the direction of the deformation zone prevent each other from falling into its plastic zone.

Second, the dispersion medium (now this is oil) hydrodynamically engage the solid particles into its flow and draws them into the plastic deformation zone. However, accumulating in front of the rolls, the solid particles of the dispersed phase prevent the generation of «pure» oil area directly in front of the inlet section of the plastic area of the deformation zone and thereby weaken the hydrodynamic effect of the flow of the lubricant medium. In this regard, the dependence of the amount of oil itself and the amount of solid filler particles entering the plastic area of the deformation zone shall be determined as a function of the viscosity of the dispersion phase (oil) in the lubricant medium and as the concentration, size and properties of the particles of the solid phase and rolling conditions. If the maximum possible amount of solid phase in the deformation zone shall be ensured, then you need to solve the problem of finding the extremum of this function. The optimization criterion is the layer thickness or the amount, the volume of the solid phase entering the plastic deformation zone with restrictions imposed by the technology of a particular production. Obviously, to find an analytical solution to this problem is extremely difficult.

Third, solids suspended in the lubricating medium are compacted as they approach the deformation zone (Fig. 1). The degree of compaction depends both on the friction of the particles in contact with each other (internal friction) and the friction of the particles against the surfaces of the rolls and the rolled metal (external friction). The mentioned internal and external friction forces depend on the lubricity of the oil component. The effective viscosity of the medium changes along and across the lubricating layer due to compaction of particles of the solid phase as it moves towards the center of plastic deformation of the rolled metal.

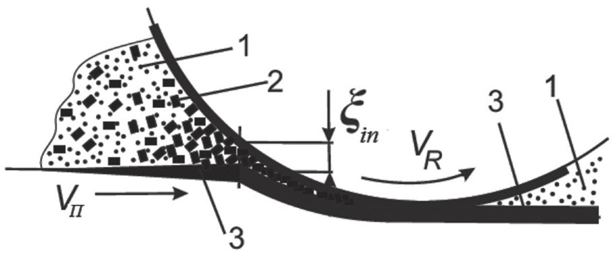

Figure. 1. The lubricating layer formation in the deformation zone during rolling with the process lubricant containing the solid particles: 1 - the liquid phase in the lubricant; 2 – the solid particles; 3 – the oil adhered on the surfaces of rolls and strip; ξ_{in} – the thickness of the lubricant layer in the inlet section of the deformation zone; V_R and $V_П$ – the speeds of the rolls and the rolled metal surfaces.

The degree of compaction (pressing together) of solid particles depends primarily on their size and pressure in the lubricant medium in the inlet area of the deformation zone. Since the process of increasing the density of solid particles arrangement in the lubricant volume as they approach the plastic deformation zone occurs in time, the degree of solidification of the solid phase in the lubricant medium and the area where it takes place depends on the rolling speed. With an increase in the rolling speed, the effect of compaction of solid particles before entering the deformation zone weakens, but at the same time the volume of oil involved in the deformation zone increases hydrodynamically. The main factor determining the degree of compaction of the solid phase particles when they enter the deformation zone is the pressure in its inlet section and, therefore, the yield strength of the rolled metal.

The role of the micro relief of the rolls and the strip surfaces during the rolling of strips with the use of suspensions as lubricant increases significantly. The solid particles of the powder in the lubricating medium glide relative to the rolls and the strip is the stronger, the smaller the roughness of their surfaces. In turn, microroughnesses capture solid particles adjacent to the surfaces in the lubricant and mechanically draw them into the plastic deformation zone. Oil in a lubricating environment reduces the influence of this factor. In addition, the oil itself provides a hydrodynamic flow of the lubricating medium, which again depends on the size and directionality of the surface roughness.

When a developed roughness of the surfaces of the rolls and the strip, the microroughnesses draw up and transport the adjacent solid particles to the deformation zone faster than the particles move in the rolling direction in the medium thickness zone of the lubricating medium. Moreover, in the contrary, with very smooth surfaces of the rolls and the strip, the particles of the solid phase adjacent to them slide and slip as a result of which their speed of motion to the deformation zone decreases. Due to the fact that the gap between the surfaces of the rolls and the strip as they approach the inlet section of the plastic deformation zone gradually decreases, the solid particles in the lubricant medium make the vertical and the rotational motions.

Fourth, the solid particles of the dispersed phase interacting with the surfaces of the cast rolls and the wrought metal hinder the adhesion of the oil phase on them. The presence of solid particles in the lubricant changes the magnitude of the tangential stresses on the surfaces of the rolls and the strip, which under fluid (hydrodynamic) friction can be described by the Newton friction law [7, p. 20-21].

Fifth, the solid phase entering the plastic area of the deformation zone plays the role of a shielding layer between the surfaces of the rolling tool (rolls, mandrel) and the rolled metal. The task of this separation layer is not only to reduce the contact friction forces in the deformation zone and thereby reduce the power parameters of the rolling process, but also to prevent the formation of scouring or any other defects on the surface of the wrought metal. At the same time, after leaving the deformation zone of the rolled metal, a relatively thick layer of the solid phase substance is observed on its surface (Fig. 1), which usually deteriorates the quality of metal products and, therefore, it is required to be removed during the subsequent process stages [12]. The above mentioned is greatly related to the processes of cold and warm rolling of pipes from high-strength steels and special alloys, the surface finish of which has particularly stringent requirements. For example, a graphite-based lubricant is unacceptable for use in the production of pipes from special steels for critical purposes, since it contributes to the carburization of the surface layers of steel during the annealing process.

The formation of the strip surfaces micro relief during rolling with the use of the process lubricant in the form of emulsions and suspensions. Fig. 2 shows the model of the micro relief formation of the strip surfaces during their rough rolls rolling applying the emulsion as a process lubricant. The figure presents that in the zone of input of the lubricating medium into the deformation zone, the oil phase is adsorbed in the microcavities of the rolls and the strip surfaces fully or partially filling them. Microdeepenings in a rough layer of the rolls and the rolled metal surfaces are one kind of microreservoirs in which lubrication is mechanically introduced into the deformation zone.

The influence of this factor is clearly come out as when used both as a process lubricant oils and as emulsions and suspensions. This conclusion is confirmed by the results of numerous experiments. For example, the publication [8, p.p. 152-153] shows the results of experiments which have testified that an increase in the initial surface roughness of the strips from Ra=0.06 micron to *Ra*=1.3 micron during rolling in smooth rolls with a lubricant viscosity of 0.086 Ps significantly increases the thickness of the lubricating film in the deformation zone from $\xi \approx 0.15$ micron to $\xi \approx 0.7$ micron (almost in ~ 5times) at rolling speed of $V_R = 0.2$ m/s. With an increase in the rolling speed to $V_R = 2$ m/s, a significant difference in the lubricant thickness is no longer observed $\xi = 1.5$-1.7 micron. Thus, at low rolling speeds, the involvement of lubricant into the deformation zone occurs mainly by its capture by the microroughnesses of the strip surface. With an increase in the rolling speed, the hydrodynamic effect has the prevailing influence on the lubricant flow into the deformation zone. At the same time, the degree of filling with the lubricant medium of the microvations of the working rolls surface relief and the thickness of the lubricant layer adhered on the surface are stable, since the rolls operate practically in a steady-state mode.

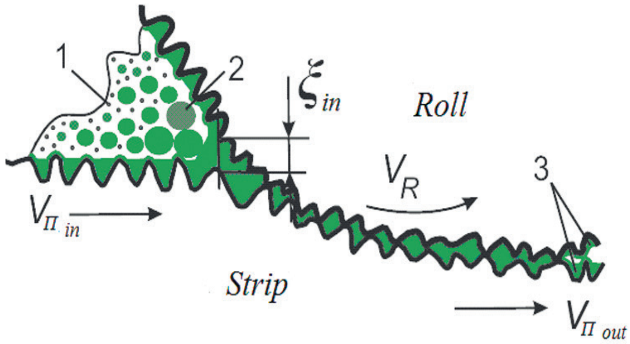

Figure. 2. Scheme of the deformation zone during the rolling of strips in rough rolls using emulsion as a process lubricant: 1 – the dispersion phase (water); 2 – the dispersed phase (oil); 3 – the oil adhered on the surfaces of the rolls and strips. The remaining designations are the same as in Figure.1.

Filling of the microdepressions in the bar surface while it moves to deformation site, increases little by little, when the oil phase is deposited from emulsion due to effect of the increasing pressure in it. In addition, thickness of adhered layer slowly increases on the surface, as in the case of roughened and smooth surface of the bar, regardless whether the lubricant is emulsion or suspension (Fig. 1). Almost 0.7-0.9 microdepressions volume are taken by stagnation zones of the lubricant and only its upper boundary layer is involved into hydrodynamic flow. During rolling such things as oil, particles of hard phase, which effect on rolled metal micro relief formation, get into microdepressions on the surfaces of the rolls and the fringes along with lubricant in form of suspensions.

In the process of fringes rolling with roughened surface by the plain rollers the lubricant, «locked» into micropits, complicates bearing strain of the surface microirregularities. Moreover, the light oil is partially squeezed by rolls from rolled fringes surface micropits. The solid particles remain in the microdepressions and, when they are impressed into the wrought metal, they enlarge undulation of the surface. The same situation is in cases, when they use the substances with high degree of viscosity as process lubricant. The highly viscous lubricant, which has no easy flow capacity, falls within the working zone in big volume, being impressed into the surface of the wrought metal, increasing its undulation.

The example which shows this objective law is the results outlined in the works[12-14] of surfaces micro relief research on the cold-rolled tubes made of rust-resisting steels 08X18H10T and 03X17H14M3, and also of the alloy Zr1Nb. Value of pipes surface roughness, intended for transportation of superfine gases in food and electronic industry to produce fuel elements of nuclear power plants, should not exceed Ra≤0.3-1.6 mcm. Application of technological lubricant during cold rolling based on high viscous polymers and chlorinated paraffin waxes cause increase of outer pipe surface roughness to Ra=2.9-4.8 mcm and inner one to Ra=5.9-6.3 mcm. Exclusion of the polymers from composition of the lubricant media provide outer surface micro relief in the pipes of first cold processing within Ra=0.9-1.8 mcm, inner - Ra=0.8-1.5 mcm. Roughness of the prepared pipes surface of size 9.13×0.7 mm from the alloy Zr1Nb, intended for manufacturing the fuel element jackets, was within Ra=0.4-0.6 mcm [12].

During rolling by rough rolls of comparatively smooth fringes to give the rolled metal surface its targeted micro relief, formation of which happens in a different way. Under such conditions during rolling with using the emulsion microirregularities surface rolls as emulsions lubricant exceeds thickness of the lubricant film, formed in the working zone. The large microirregularities of the rolls pierce the lubricant film and are implemented into the rolled metal surface. Depth of their implementation depends, in the first place, on how microdepressions of the work rolls surface roughness are filled and second – dimensions of the contact voltages in the working zone, more precisely, on voltage state coefficient, which represents relation of voltage state to the value of stimulated yield voltage wrought metal. So the bigger thickness of lubricant film in the working zone, the larger volume of lubricant goes into the rolls contact zone with the wrought metal, the weaker roughness of the rolls is transferred into the rolled fringes surface.

In cases when the initial roughness of the fringe is commensurable by value with roughness of the rolls, and the diagrams, considered above are grouping and are complemented with both microirregularities surfaces interaction mechanism.

Effect of the rolls surfaces' and rolled metal micro reliefs on conditions of friction in the working zone. The lubricant in the working zone carries out several functions at the same time. Besides filling of the rolls roughness microdepressions and creation of the separation layer between the rolls surfaces and the rolled metal the lubricant determines values of the friction coefficient and contact voltages in the working zone, which crucially effect the fringes micro relief formation. The rolls surfaces micro relief and the fringes along with lubricant film thickness determine length of boundary and liquid frictions areas, and also of the areas, on which the rolls surfaces microirregularities "plough through" the wrought metal surface. As a result, they determine mode of friction in the working zone during rolling.

Diagram, which shows effect of rolls surface micro relief, of the rolled metal and process lubricant on distribution of direct ρ and tangential τ voltages in the working zone is presented on Fig. 3. Direction of frictional forces on the rolls surfaces and the fringes on Fig. 3 where chosen in respect to backward slip zone in the working zone. The essence of approach to friction conditions analysis during rolling with the lubricant do not change, if we consider forward slip zone and point the arrows on the diagram to the opposite side. Relation of the sums of lengths $в_i$ of the boundary friction areas to the length $l_Д$ of the contact arc describes degree to which the liquid friction of boundary friction mode prevails in the working zone. On the boundary friction areas $в_i$ the roll and the wrought metal are separated by the lubricant layer, attached to their surfaces.

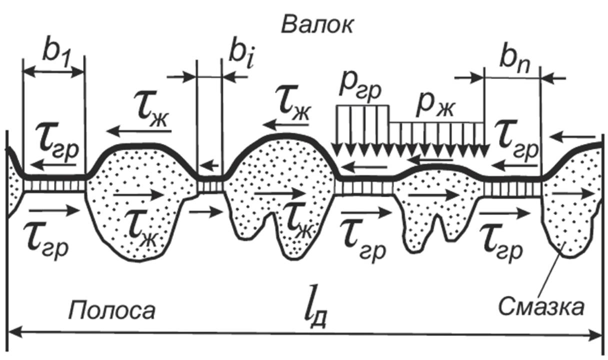

Figure. 3. Diagram of distribution of direct p and transient τ contact voltages on the areas of boundary and liquid friction in the working zone. Indicated as: b1,... bi ...bn - length of the separate boundary friction areas; i – number of the area; n – number of the areas; lД – length of the working zone. Indexes: гр - boundary; ж - liquid

The friction model in the working zone, presented on Fig. 3 is similar to the models, considered in the monographs [15, p. 117-126; 16, p. 138]. It should be noted that the author of the work [16] calls the friction ratio on the areas $в_i$ a microfriction ratio and marks it as $f_{микро(micro)}$. On the areas where the lubricant separates the surfaces of the rolls and the fringes, friction ratio is marked as $f_{гидро(hydro)}$. Computations of the value $f_{гидро(hydro)}$ for two typical examples of the cold rolling process (1 is initial thickness of the fringe $h_{вх(inc.)}$ =1.3 mm, after rolling $h_{вых(outc.)}$=1 mm, rolling rate V_R=10 m/s, pressure p=1000 H/mm², viscosity of the lubricant μ=10 mPas, the medium thickness of the lubricant layer in microdepressions on the liquid friction areas ξ_{cp}=0.5 mcm; 2-$h_{вх(inc.)}$=1.5 m; $h_{вых(out.)}$=1 mm; V_R=30 m/s; p=500 H/mm^2; μ=100 mPas; ξ_{cp}=0.2 mcm) showed [16, p. 140], that in the first example $f_{гидро(hydro)}$=0,00002, in the second $f_{гидро(hydro)}$=0,005. In other words the values $f_{гидро(hydro)}$ are ten or more times lesser than $f_{микро(hydro)}$. These results confirm again correctness of the conclusions made earlier [15, p. 123], saying that for the conditions of the steel sheet cold rolling it is allowable to accept $f \approx f_{гр(bound.)} \cdot l_{гр(bound)}/l_{Д(d)}$.

In the layers of the lubricant, which is in the rolls surfaces formed by the relief irregularities and in the microreservoirs fringes the value of the tangential voltages, according to Newtonian friction law, equals to $\tau_Ж = \mu \frac{du}{dx}$, where μ is dynamic viscosity of the lubricant, u is projection of speeds vectors of its motion to the axis x. The axes x and y are pointed along the rolling axis and perpendicularly to the contact rolls surfaces and the fringes (on Fig. 3 these axes are shown). On the roll surface

$$\tau_Ж = -\mu \cdot \frac{V_{R-}V_x}{\xi} - \frac{1}{2}\xi\frac{dp}{dx}.$$

On the fringe surface $\cdot \tau_Ж = \mu \cdot \frac{V_{R-}V_x}{\xi} - \frac{1}{2}\xi\frac{dp}{dx}$

Here ξ is a thickness of the lubricant film, V_R and V_x – are the rates of the rolls and the fringe surface.

Full frictional force T and full effort P of the singular width fringe rolling are equal correspondingly $T= \tau_{гр(bound.)} l_{гр(bound.)} + \tau_{Ж(L)} l_{Ж(L)}$, where $l_{гр(bound.)}$ is length of all the boundary friction areas $l_{гр(bound.)} = \sum_{i=1}^{i=n} b_i$; $l_{Ж(L)}$ – length of liquid friction areas $l_{Ж(L)}$=$l_{Д(D)}$ - $l_{гр(bound.)}$. Considering these expressions coefficient of external friction is $f = \frac{T}{P} = \frac{\tau_{гр} l_{гр} + \tau_Ж l_Ж}{p_{гр} l_{гр} + p_Ж l_Ж}$.

In the approach, proposed in the work [16, p. 207], the microscopic coefficient of friction (ion our interpretation – coefficient of external friction in the working zone) equals to $f = l_{гр(bound)} \cdot f_{микро(micro)} + [1-(l_{Д(D)} - l_{гр(bound.)})] f_{гидро(hydro)}]$. According to the last dependencies analysis, coefficient of friction f during rolling with the lubricant in the conditions when surfaces of the rolls and the fringe have a developed micro relief, is a function of actual surfaces contact area. First of all f depends on rolls and fringe surfaces contact actual area relation, where $\tau = \tau_{гр(bound.)}$, к nominal area of working zone, as $\tau_{гр(bound.)} >> \tau_{Ж(L)}$.

In the diagram on Fig. 3 we can also consider without especial difficulties the interaction, direct contact of the microirregularities, which are on the surfaces of the rolls and wrought metal. In this case depende3nce of the full frictional force must be complemented by and addendum, which takes into account the component of specific force, conditioned by resistance to shift of the fringe deformed microirregularities metal. Therefore, in general case during rolling with the lubricant in the rough rolls of the fringes with rough surface the full friction force T is determined by sum of components, which reflect contribution of the elements in boundary and liquid friction and forces, conditioned by mechanical contacting microirregularities of the rolls and wrought metal.

Engineering applications. Concerning the considered theme the biggest number of researches and publications were carried out in cold-rolled sheet steel production, including, in particular, autobody sheet [17], intended for manufacturing of autocar body parts by cold-forming method. Requirements to roughness of cold-rolled sheet steel, scientific fundamentals to rolling production technology with targeted roughness of the surface, means to provide requirements to micro relief, experience of industrial enterprises to solve this problem are considered to a great detail in the above mentioned [1-4, 15 and so on] articles and books. Questions of provision comparatively smooth surface of the metal products of ferrous and nonferrous metals are not highlighted enough in technical literature. So below we more focus on a problem of minimizing microirregularities of the metal surface, rolled with process lubricant.

It should be noted at once that in the conditions of the rolling process performed in the mode of liquid friction [18], when surfaces of the rolls and of the fringe are separated by self-standing lubricant layer, generation of the micro relief of the rolled metal is taking place by scheme of "free" deformation of its surface layers. Under such conditions, the lubricant does not restrict free movement of the surface metal layers grains and this is reflected on the micro relief of its surface. The resulting state of the surface is determined by size of the grains in the rolled metal structure, degree of deformation during rolling, number of the lubricant in the working zone and by some other factors [4, 7, 15]. The rolling with full separation of the rolls' and fringe' surfaces in industrial sheet rolling practice, where emulsion is used as process lubricant, we can rarely see it. But such conditions occur pretty often, as we noted above, during cold rolling of the pipes with usage highly viscous media as lubricants, including suspensions, in the zone where their inner surface contacts with internal tool. If condition of the metal surface micro relief is unsatisfactory, then solution lies in replacing the lubricant on the less viscous one, but which provides low values of the friction coefficient and contains anti-scuff supplements.

In production of sheet low carbon steel, intended for manufacturing of autocar body parts, the task for tooling engineers is to create roughnesses of size *Ra*=0.8-1.6 mcm on the surface of the rolls when the power process parameters of rolling are minimized and some processing limits are observed. And on the contrary during production of sheet stainless steel in most orders they require to provide mirrored fringes surface with possibly lesser roughness. In these conditions selection of the process lubricant is crucial because increase of lubricant film thickness in the working zone worsens smoothness of the surface and its shine. For example during rolling of the fringes of stainless steel, containing 17% Cr, with initial roughness of *Ra*=0.04 mcm in the rolls with mirrored surface *Ra*=0.025 mcm increase of the process lubricant viscosity worsened shine of the fringes to the same strength equal to rolling rate [8, p. 155-169]. The reason was increase of number of the lubricant, which was entering the working zone, and as a result – length of the areas with hydrodynamic regime of friction. Thus during production of the stainless steel of the rolling sheet with mirrored surface the selected viscosity of the process lubricant, rate of rolling and level of the fringe per pass must minimize amount of the lubricant which enters the working zone. Upon that the work rolls must have полированную поверхность with roughness *Ra*≈0,1 mcm.

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