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Preventing Surface Defects in the Uncoiling of Thin Steel Sheet

V. L. Mazur
Institute of Metals and Alloys, Ukrainian Academy of Sciences, Kiev, Ukraine
e-mail: prof.vlm@ukr.net

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Abstract—The formation of surface defects when annealed thin cold-rolled steel sheet is uncoiled for temper rolling is analyzed. The appearance of such defects is mainly due to adhesion and welding of the contacting surfaces of the turns in the coil. The influence of the strip thickness, surface roughness, temperature, properties of the metal, and other factors on the stress–state of the coil and the likelihood of surface defects is analyzed. Preventive measures are recommended.

Keywords: steel strip, coils, quality, technology, temper rolling, tension, defect prevention

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Several generations of researchers have developed the basic production technology for cold-rolled steel [1, 2]. Key considerations here are the maintenance of sheet quality and the prevention of surface defects on sheets, strips, and tinplate [2–4]. The continuous evolution of steel production constantly poses new problems in terms of maintaining defect-free sheet surfaces with specified microrelief. Kinking defects are common (State Standard GOST 21014–88): the sharp bends that appear when coiling or uncoiling thin cold-rolled steel strip are associated with light transverse bands of increased surface roughness. Such bands may also be observed with change in the flexure of sheet assemblies on lifting or transportation.

In the literature and plant standards, these are sometimes referred to as kinks or kinking defects. According to the dictionary definitions, a kink is a bend, while a defect is a flaw; this term is readily applicable to the quality assessment of thin cold-rolled steel sheet.

Considerable efforts have been made to find means of preventing kinks [3–11]. In the present work, we summarize the results of our research, with analysis of concepts found in the literature. While various terms are used in the literature, we will describe this defect as a kink.

The prevention of kinks is a priority at all metallurgical enterprises producing thin cold-rolled steel sheet. Aside from foreign plants, these are the Zaporozhstal' [3, 12], Karagandinsk [2, 3], Cherepovetsk [3], and Magnitogorsk [3, 5, 10, 11] steel works. Despite the successes that have been achieved, further efforts are necessary [13, 14]. Kinks may pose problems in the processing not only of thin strip but of thick sheet. In particular, the risk of kinking at the edges of relatively thick sheet (~6 mm) used in the production of welded oil pipe (diameter 530 mm) was noted in [14]. Accordingly, available experience must constantly be reassessed in the light of recent developments, the requirements on sheet quality, and promising measures to minimize kinking. In the present work, we consider the prospects for such measures at the cold-rolling, annealing, and temper-rolling stages in the production of rolled steel sheet.

DEFECT MORPHOLOGY

In kinking, we observe light bands (width ~2.0 mm) on the darker sheet surface; they are usually perpendicular to the direction of rolling [3, 12]. As a rule, the metal is thinner in the defect region. The defect is the result of local plastic deformation of the sheet steel on account of extension or combined extension and flexure of the cold-rolled strip.

The surface roughness in the kinking zone is somewhat different from that in the adjacent sections. Some changes in the microprojections are seen in the defect zone, according to microphotographs of the surface microrelief on 0.76 × 1250 and 0.76 × 1325 mm samples of 08пс steel strip, using $3D$ criteria [13]. The bulk characteristics of the roughness are practically the same in the defect and the adjacent regions. The microprojections within the defect are sharper than usual.

The role of thinning in the production and processing of steel sheet was not addressed in [13]. It is possible that the data in [13] are partial and do not apply to other steel-sheet samples.

We accept that the surface microrelief in the defect region must differ from that in adjacent sections of the sheet. In plastic deformation, the surface relief of the metal is formed either without direct surface contact

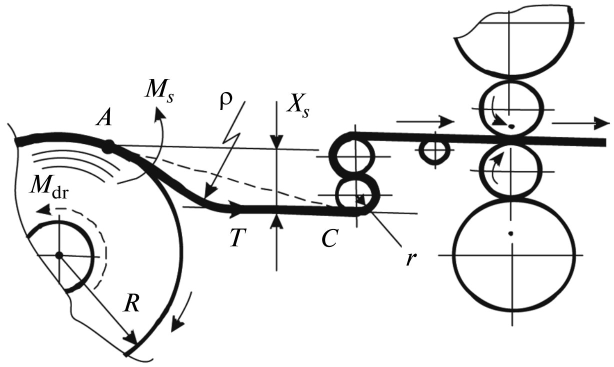

Fig. 1. Plastic flexure of strip in unwinding a coil with tension T created by the braking torque M_{dr} of the uncoiling drum.

of the tool and the sheet (free deformation) or with such contact (coupled deformation). If the defects on the sheet surface arise on account of the extension of local sections of strip in kinking—that is, in free deformation—the microstructure (the ferrite grain size) will be modified in the defect zone. If the size of the microprojections exceeds the grain size in the initial steel structure, the surface roughness in the defect will be somewhat reduced, as shown in [15]; otherwise, it will be increased. However, if the defects are formed as a result of flexure with extension—for example, when the strip bends around the tension rollers when the steel coil is unwound in the temper-rolling mill, the surface roughness in the defect zone will be formed in coupled deformation or semicoupled deformation (coupled in one direction). In such conditions, the deformation of the steel's microstructure will have less influence on the surface roughness of the defects. In all cases, kinking is clearly seen in the form of light bands on the dark surface.

The defects may appear at the edges or over the whole width of the strip. At the edges, the defects may extend over 250–300 mm. The appearance of the defects, their length and frequency, and their periodicity over the length of the strip depend on its thickness, the thickness of the tension rollers, the degree of welding of the turns, the tensile forces in the strip on uncoiling, the temperature, and the metal's yield point. These correlations have not been fully explored in the known studies [3–6, 12].

The kinking defects observed on thin cold-rolled steel sheet resemble, in their appearance and origins, another defect: slip bands and lines, which take the form of dark bands and branched lines that appear on the surface of cold-rolled sheet and strip on account of local stress exceeding the yield point of the metal. Slip lines are usually inclined at 45° to the rolling direction; in other words, they are in the direction of the primary tangential stress. These defects are known as Luders lines. As a rule, they appear in parallel groups. This is their main difference from kinks, which are always transverse to the longitudinal rolling axis. Kinks and Luders lines are often observed at the same time and are prevented by the same means [3].

DEFECT FORMATION

Despite extensive research on kinking defects, their formation is still poorly understood. We now consider their formation in detail. In unwinding, according to Fig. 1, the upper turn of the strip separates from the coil at point A in the ideal case—that is, without adhesion or welding of the surfaces of adjacent turns in the coil. In this case, the strip trajectory to the tension rollers (shown by the dashed line) does not depend on the tension T and the force required to straighten the unwound strip and is tangential to the surfaces of the coil at point A and the lower tension roller at point C. Since there is no welding of the adjacent turns, the separation of the upper turn from the coil at point A does not require any force perpendicular to the tangent at that point. Nevertheless, some bending torque M_s must be applied to straighten the upper turn of the strip and create the opposite curvature.

In unwinding the coil, when the strip is supplied to the rollers of the temper-rolling, its tension is created by the motor turning the unwinding drum, operating in generator mode. The torque due to the strip tension T is $M_{str} = TR$, where R is the radius of the upper turn on the coil. Steel strip (thickness h) is weakened after recrystallizing annealing. Straightening of the upper turn by plastic deformation calls for the creation of stress equal to or exceeding the metal's yield point on account of the tension T in the strip. We require that $T \geq \sigma_y bh$, where b is the strip width.

In industrial practice, the tension T on the uncoiling device is significantly less than $\sigma_y bh$. Production experience is usually employed in selecting the factor k by which the tension is reduced: $T \geq k\sigma_y bh$. According to publications of the Research Institute of Heavy Machinery, Ural Heavy-Machinery Plant, the range of k at different temper-rolling mills and finishing systems is fairly broad: 0.005–0.040. When the tension T is insufficient for equalization of the strip at point A (Fig. 1), the upper turn, as it separates from the coil, will be in the elastic state for some time and will retain curvature $1/R$. The bending torque M_s created by force T for flexure of the upper turn acts at a distance X_s (Fig. 1), which increases gradually as long as M_s is no less than the plastic-flexure torque of the strip $\sigma_y bh^2/4$. In other words, the upper turn of the coil is straightened when $M_s \geq \sigma_y bh^2/4$.

According to Fig. 1, $M_s = TX_s$. Equating these two expressions for M_s, we find that $TX_s = \sigma_y bh^2/4$. Hence, $X_s = (\sigma_y/T)bh^2/4$. Hence, the distance X_s determining the position of the region of strip straightening where the strip curvature falls to zero or is reversed is inversely proportional to the tensile stress of the strip. With increase in T, X_s declines, and hence the region of strip straightening beyond point A is reduced (Fig. 1). The distance between kinking defects will correspondingly be shorter. With increase in yield point of the metal, the reversal of curvature will be postponed.

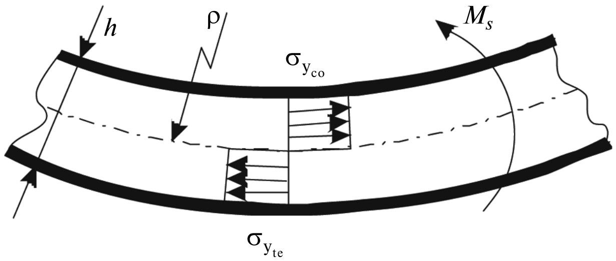

Fig. 2. Stress distribution in the upper turn of the strip in plastic flexure during the unwinding of a coil: $\sigma_{y_{co}}$, compressive yield point; $\sigma_{y_{te}}$, tensile yield point.

Thus, in order to the straighten the strip, the stress in its surface layer must be at least equal to the yield point of the metal. Note that kinking defects do not always appear in straightening and reversal of strip curvature. They only appear if the bending torque M_s converts the strip completely to the plastic state.

Plastic flexure of a strip offers a useful model here (Fig. 2). In the flexure of a smooth strip, we may assume that its neutral layers retain the same length; the outer layers are extended; and the inner layers are compressed. The strain of the outer layers is $\varepsilon = h/2\rho$, where ρ is the radius of curvature of the neutral cross section over the strip thickness. According to Hooke's law, $\varepsilon = \sigma/E$. In the limiting case, $h/2\rho = \sigma/E$ and $\rho = hE/2\sigma_y$.

This is the condition for transition of the metal to the plastic state over the whole strip thickness. However, this is insufficient for the formation of kinking defects. As a rule, local thinning of the strip occurs in the vicinity of the defect: a neck is formed. (This is the limit of sample failure in fracture tests.) Therefore, we may assume that kinking defects arise when the plastic strain of the metal on flexure exceeds the critical strain that corresponds to (is equal or close to) the uniform elongation in extension. Many researchers believe that the critical strain corresponding to kinking is twice the strain at the onset of plastic flow: $\varepsilon_{cr} = 2\sigma_y/E$.

According to Fig. 1, the tensile strain ε of the lower layers of the strip at the upper turn of the coil is the sum of the elastic strain σ/E of the strip, the plastic strain $h/2R$ in straightening of the upper turn, and the strain $h/2r$ created in the reversal of strip curvature as it passes around the lower tension roller (radius r). These components are of approximately the same order. Obviously, ε increases with decrease in R as the coil unwinds. Hence, the risk of kinking defects increases. Likewise, the probability of such defects declines with increase in radius r of the lower tension roller.

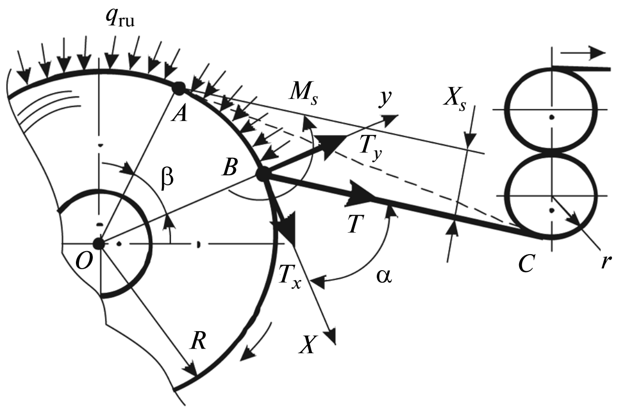

Fig. 3. Separation of a welded upper layer from the coil in unwinding: q_{ru} is the force required for separation of the welded surfaces of adjacent turns in the coil.

Analysis of the equation $\rho = hE/2\sigma_y$ indicates that kinking defects are more likely with increase in strip thickness h and decrease in σ_y, since the elastic strain in the metal becomes plastic strain at large flexure radius ρ in uncoiling. This is confirmed by production experience. Kinking defects are less common in relatively thin strip such as tinplate and strip of special hard-to-deform steel, for which σ_y is greater. With decrease in ρ, tensile outer layers of the strip will be obtained at higher plastic strain. Consequently, the risk of kinking defects is higher.

This description of the unwinding of steel coils does not include adhesion or welding of the surfaces of adjacent turns in the coil. Taking such behavior into account does not fundamentally change Fig. 1, but the analysis is more complex. In particular, we must take account of the force required to separate the upper turn from the one below. In Fig. 3, we show the separation of the upper turn of the strip welded to the lower layer; the two adjacent layers are separated at point B. The x axis runs along the tangent to the upper turn of the coil, while the y axis is perpendicular to the x axis at the origin (point B). As point B moves, the coordinate system xy changes its orientation relative to the coil and the tension rollers in the temper-rolling mill. The unit force required to separate the welded surfaces of the adjacent turns is q_{ru}. The total rupture force corresponding to the arc AB of the upper turn of the strip (width b) is $Q = q_{ru}bl_{AB}$, where $l_{AB} = R\beta$ is the length of arc AB; the angle β is measured in radians (Fig. 3).

In the first approximation, we may assume that the breakaway of the upper turn from the coil occurs over arc AB under the action of force T_y applied at point B along the y axis (perpendicular to the tangent to the coil surface). The component T_y of the tensile force T in the strip must be no less than Q. We see that T_y and Q depend on the interrelated angles α and β, which are determined by the position of point B (Fig. 3). Knowing the radius R of the coil's outer turn, the radius of

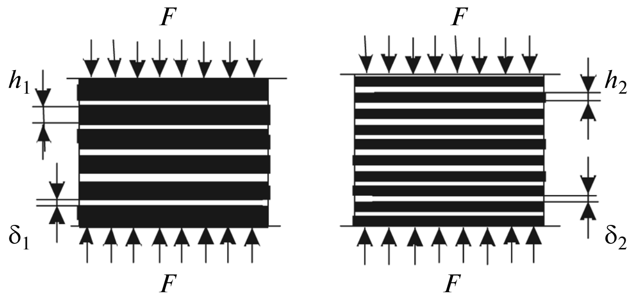

Fig. 4. Compressive tests of stacks of steel sheet of different thickness h ($h_1 \approx 2h_2$); δ_1 and δ_2 are the gaps between the plates ($\delta_1 \approx \delta_2$).

the tension rollers, and the distance between the vertical and horizontal axes of the coil and the lower tension roller—that is, the configuration of the mechanisms in the temper-rolling mill—we may determine the angle α (or $90° - \alpha$) determining the strip flexure in the region of the breakaway point B of the upper turn welded to the adjacent layer, for fixed q_{ru} and T.

In uncoiling sheet steel, both Figs. 1 and 3 apply. In the unwinding of a coil in which adjacent turns are welded together, we note partial or complete straightening of the strip on path BC under the action of tension T. Then the upper turn breaks away from the adjacent strip within an area corresponding to arc AB. In some cases, separation of the upper turn may only occur over part of the arc AB. The distance between defects will be less in those circumstances.

Analysis confirms that the appearance of kinking defects depends primarily on the adhesion or welding of the adjacent turns in the coil. With stronger welding of the adjacent turns on annealing, separation of the upper turn from the coil will be delayed. This is accompanied by increase in strip flexure and by higher risk of kinking defects. In turn, the degree of adhesion or welding of adjacent turns in the coil depends on the radial contact stress and the annealing conditions.

STRESS–STRAIN STATE OF COILS OF COLD-ROLLED STRIP

Determination of the radial and tangential stresses in coils of cold-rolled strip of finite width in subsequent processing is a very complex thermoelasticity problem. Research on this topic, conducted over a span of decades, has been published in the proceedings of the State Research Institute of Metallurgical Machinery and the Research Institute of Heavy Machinery, Ural Heavy-Machinery Plant, and also in the journals *Mekhanika Polimerov* and *Problemy Prochnosti*. A review may be found in [16].

At first, the calculation of the stress and strain in coils rested on relatively coarse assumptions. The multilayer coil was represented by a one-piece isotropic (or anisotropic) solid, whose elastic properties were assumed to be independent of the winding conditions. This approach omitted numerous significant factors: in particular, the influence of the turn thickness and temperature, the roughness of the contacting surfaces, the gap between the turns, the variation in strip tension in the course of winding, and the stress redistribution on coil heating and cooling in the course of annealing. Therefore, the results were unrealistic and could not be used to optimize the winding of cold-rolled strip.

A breakthrough came with a new approach to numerical solution of the direct and inverse problems, on the basis of additional information regarding the relative motion of the rough surfaces of adjacent turns in the coils with arbitrary variation in strip tension in the course of winding [19]. These results provided a fundamental new theoretical framework for such research [22]. Later, the thermoelasticity problem was solved in this formulation [7, 8, 21]. The temperature dependence of the strip's thermal expansion was also introduced in the mathematical model. Likewise, the change in the gap between the surfaces of adjacent turns on account of deformation of the surface microrelief under the action of compressive forces and temperature was taken into account. The resulting mathematical model and the corresponding algorithm were outlined in [16, 19, 21]. The successful application of this model in control systems for cold rolling and subsequent annealing of steel at Novolipetsk Metallurgical Works confirmed the utility of this approach.[1] The potential for taking account of the influence of factors such as the thickness and width of the strip, its surface roughness, and the temperature of the rolled metal on the stress–strain state of the coils, with gains in product quality, was discussed in [23]. We now present recommendations for preventing kinking defects on the basis of theoretical analysis of the influence of the stress–strain state of the coils on the adhesion and welding of adjacent turns in the coil.

INFLUENCE OF COMPRESSIVE FORCES AND TEMPERATURE ON THE DISTANCE BETWEEN CONTACTING SURFACES IN THE COIL

In determining the stress in a coil of cold-rolled strip as it is wound on a drum, after removal from the winding machine, on heating in annealing, and during subsequent cooling, we must establish the dependence of the interturn gap on the compressive forces and the temperature. For the compression of stacks of steel sheet of different thickness and roughness (Fig. 4), such results may be found in [15–17]. Their analysis permits the following conclusions.

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[1] This approach was introduced in practice by I.Yu. Prikhod'ko, P.P. Chernov, V.N. Skorokhodov, and their colleagues at Novolipetsk Metallurgical Works and the Institute of Ferrous Metals, Ukrainian Academy of Sciences.

For ideally smooth surfaces of the sheet in the coil, the distance between adjacent turns depends only on the pliability of the microrelief. In practice however, the strip wound into the coil is characterized by nonplanarity, on account of warping, undulation, and local distortion. In the compression of stacks of steel sheet, the contacting surfaces are pushed together on account of equalization of the plates and flattening of the microprojections. In stacks of thin sheets (thickness h^2), the number of gaps δ and their total volume will be less than for stacks of relatively thin sheets (thickness h_1), other conditions being equal (Fig. 4). However, on compression, the decrease $\Delta\delta$ of the gaps (absolute strain) is greater for the stacks of thicker sheets. In experiments at the Institute of Ferrouls Metals, Ukrainian Academy of Sciences and previously at the State Research Institute of Metallurgical Machinery, it was found that $\Delta\delta/h$ declines with increase in the sheet thickness h in the stack [15, 16]. The decrease in distance between the contacting surfaces is directly proportional to the compressive force on the stack, the sheet thickness, and the surface roughness and is inversely proportional to the yield point of the metal. That must be taken into account in assessing the change in stress–strain state of the coils on annealing.

The dependence of $\Delta\delta$ in the stack on the compressive force is significantly nonlinear, especially in the section where compression begins. The dependence on the surface roughness is close to linear. For the production of thin steel sheet, we may write

$$\Delta\delta_{Ra} = (0.91 + 0.09Ra)\Delta\delta.$$

Empirical formulas for $\Delta\delta/h$ were presented in [15, 16].

No significant difference in the deformation was noted in the compression of stacks with different numbers of sheets (disks) in [17, Fig. 14a]. The lack of information regarding the experimental conditions hinders the analysis of these results. The behavior of $\Delta\delta$ in stacks of steel sheet under load is basically the same in [15–17].

Extensive experimental and theoretical research on the interaction of rough surfaces (including elastoplastic deformation on compression) and the influence of the contact microgeometry and duration on the thermal conductivity—by Demkina, Kragel'skii, and others—has produced formulas in which the roughness of the contacting surfaces is characterized by parameters associated with considerable indeterminacy and complexity, with poor accuracy. Nevertheless, analysis of the theoretical literature permitted refined approaches to the thermal flux through the contact zone of adjacent turns in strip coils on heating and cooling [18]. The mathematical model of the stress–strain state of coils is enhanced by the findings in [18].

The actual heat-conducting contact area of the rough surfaces of adjacent turns in strip coils is formed predominantly by plastic deformation in one-time loading. With repeated analogous loads, the deformation of the microprojections is elastic. The thermal contact resistance falls with increase in the rated pressure in elastic and plastic contact of the microprojections of adjacent turns in the coil. The actual contact area increases with increase in the contact time under load, on account of creep of the metal, especially at relatively high temperatures. The corresponding decrease in distance between the surfaces increases the heat conduction.

Research shows that nonideal thermal contact of rough surfaces in the coil may be taken into account through the thermal resistivity, which depends on the microrelief, the surface contamination, and the compressive forces [7, 8]. The mathematical models of the stress–strain state of the coils on heating and cooling in the course of annealing employ an empirical formula presented in [7].

INFLUENCE OF THE TEMPERATURE AND COMPRESSIVE FORCE ON THE WELDING OF CONTACTING TURNS IN ANNEALING

The interturn welding in the coil determines the type of kinking defects, their position, and their frequency in the production of cold-rolled steel. The actual contact area of adjacent turns and their welding on annealing depend on the surface roughness of the strip, its temperature, and the interturn contact pressure. An inverse relation is observed. The temperature and compressive force on the turns and also the surface microrelief of the metal influence the contact area of adjacent turns and change the heating and cooling rate of the coils. Theoretical description of this behavior is very complex, and therefore experiments are conducted.

The results of research at various steel works were summarized in [3, 12, 15, 16]. The conclusions obtained are generally applicable. It is found that reduction in roughness and in the density of surface microprojections facilitates the welding of adjacent turns in the coil on annealing and the formation of kinking defects in subsequent temper rolling. Direct laboratory research regarding the influence of the compression, temperature, and residence time at high temperatures on the welding of contacting samples and the rupture force are of most value. It is found that the force required to separate welded contact surfaces increases sharply at annealing temperatures above 700°C [20]. The role of the strip's surface roughness increases with increase in contact pressure. The same conclusions may be drawn from similar experiments conducted by Pargamonov at Zaporozhstal' metallurgical works.

These findings are largely confirmed by later research [6]. The welding of adjacent turns in the coil mainly occurs on cooling. With increase in the residence time of the coil under load, more welding occurs, and the force required for their separation increases [6, 20]. (The increase is sharper at higher temperatures.) That confirms the significant role of creep of the surface microprojections in elastoplastic contact of the rough surfaces under load [18].

Summarizing all the research, we may say that the welding of adjacent turns in the coils depends greatly on the surface roughness of the metal. This dependence is greater at higher temperatures. With increase in the welding when the contact surfaces are less, greater force is required for the separation of the turns. Accordingly, the risk of kinking defects increases.

PREVENTIVE MEASURES

On the basis of Fig. 3, we may make certain conclusions even without mathematical analysis. Obviously, the position of point *B*, at which the upper turn separates from the coil, depends on many factors: the force q_{ru} required to separate the welded surfaces of the adjacent turns; the strip tension *T*; the radius of the upper turn, determined by the initial coil dimensions and the number of turns already unwound; and the relative position of the unwinding unit and the tension rollers in the temper-rolling mill. With constant tensile force *T*, its component T_y will increase as point *B* is moved away from point *A* and the angle β increases. If the upper turn separates from the coil at point *A*, we find that $T_y = 0$ and $\alpha = 0$ on account of the change in direction of coordinate axes *xy* and hence the forces (Fig. 3). With fixed q_{ru}, larger *T* results in earlier separation of the upper turn from the coil. In that case, point *B* moves close to point *A*. With stronger adhesion of the adjacent turns and higher q_{ru}, the force T_y required to separate the surfaces of the adjacent turns will be larger.

With increase in q_{ru} or decrease in *T*, point *B* descends, and the upper turn separates later from the coil. Correspondingly, with later separation of the upper turn from the coil, the strip's flexure angle will increase, the radius of curvature of the strip at point *B* will be smaller, and the probability of kinking defects will be greater. The degree of flexure and the radius of strip curvature at point *B* are determined by the angle α (Fig. 3). With increase in α, the risk of kinking defects increases. Hence, with increase in q_{ru} and decrease in *T*, the deviation α of the strip trajectory from the tangent to the coil surface at point *B* will increase. This means that, at smaller *T* and larger q_{ru}, the strip curvature at point *B* increases and the risk of kinking defects is higher.

In the unwinding of the coil, the radius of the upper turn declines; point *B* is shifted downward; and point *A* is shifted upward. On account of the decrease in external radius of the coil on unwinding, β will increase. Change in the position of point *B* affects the force T_y, which is a function of the radius of the upper turn in unwinding and q_{ru}. Note that our conclusions are not fundamentally changed if we consider the bending torque M_s rather than T_y (Fig. 3). The distance X_s at which M_s acts is equal to the distance between the line *BC* and the parallel line through point *A*.

The adhesion (welding) of the contacting surfaces varies over the thickness of the coil. That corresponds to the dependence of q_{ru} on the external coil radius on unwinding in the temper-rolling mill. The variation in the surface welding over the coil thickness depends on the strip tension selected on coiling in the cold-rolling mill; the cooling time before annealing; and the annealing conditions for the coil (the heating rate, the holding temperature, the holding time, and the cooling rate). At each enterprise, the production of thin cold-rolled steel sheet is different. Therefore, it is difficult to offer general recommendations. However, we may state a general conclusion: to prevent kinking defects, the strip tension $T(R)$ in unwinding the coils in the temper-rolling mill must be consistent with the winding conditions of the cold-rolled strip and the annealing conditions. In particular, since q_{ru} varies over the coil thickness, the tensile force $T(R)$ in unwinding must vary in direct proportion to $q_{\mathrm{ru}}(R)$. Examples of this approach in production conditions may be found in [7].

In the course of uncoiling, the point *C* at which strip contact with the tension rollers begins will also be shifted. However, this has no significant influence on the formation of kinking defects.

In industrial practice, kinking defects are often formed over only part of the strip width: for example, at the edges or at the center, on account of undulation or camber. In that case, their formation follows the same principles. Note, however, that the tensile force will be required to separate the upper turn from the coil not over the whole width of the strip but only over the area characterized by welding of the contacting surfaces. In that case, with constant total strip tension between the uncoiling unit and the tension rollers, the unit tension at point *B* will increase in proportion to the decrease in welding area of the contacting surfaces. Correspondingly, point *B* will move toward point *A*, and the spacing between the kinking defects—the distance between successive lines of strip flexure—will decrease. Camber, undulation, crescent distortion, thickness fluctuation, and other shape errors of the cold-rolled strip facilitate the formation of kinking defects.

Note that strip flexure at point *B*, where the upper turn separates from the coil, does not necessarily lead to kinking defects. Research by Kudin at the Institute of Ferrous Metals, Ukrainian Academy of Sciences, shows that the critical radius of curvature ρ_{cr} at which kinking defects appear (Figs. 1 and 2) depends on σ_y,

h, and T for the strip. In particular, to prevent kinking defects in the unwinding of steel-strip coils with $\sigma_y = 240$ N/mm^2, when the tension $\sigma_p = 70$ N/mm^2, the recommended value is $\rho_{cr} \geq 235h$ [2, 12]. The radius ρ of strip flexure must be no less than ρ_{cr}.

In the case of strip flexure (or straightening) with extension, the permissible radius of curvature declines with increase in yield point of the steel and decrease in unit tension in the strip. With increase in temperature, σ_y declines. Therefore, to prevent kinking defects, the coils of cold-rolled strip must be cooled to the lowest possible temperatures prior to unwinding.

In production conditions, the financial losses of steel works associated with inadequate quality of thin sheet on account of kinks over the life of the sheet rolling system—usually several decades—are often comparable with the cost of the temper-rolling mill. Therefore, in the design of the temper-rolling mill, the need to prevent kinks in the production of cold-rolled steel must be taken into account. It is clear from Figs. 1 and 3, which illustrate the unwinding of coils and the supply of strip to the tension rollers in the temper-rolling mill, that the direction of the tensile-force components and the radius of curvature in strip flexure at point B depend on the distance between the vertical axes of the coil and the tension rollers of the temper-rolling mill; on the alignment of the horizontal axes of the coil and the tension rollers with the rolling direction; and on the diameter (mass) of the coils. For the sake of clarity, the horizontal axes of the coil and the lower tension roller are shown separately in Figs. 1 and 3, although this is not necessary.

The formation of kinking defects depends on the diameter of the tension rollers (the ratio of the strip thickness to the roller diameter) and the direction in which the coils are unwound. In unwinding the coils from the top (Figs. 1 and 3), the deformation due to straightening of the strip is summed with the deformation of the same sign due to its flexure at the lower tension roller. That increases the risk of kinking defects; the risk is greater for thicker strip. In unwinding the coil from the bottom, when the coil turns in the opposite direction to that shown in Figs. 1 and 3, the internal layers of the strip extended in the course of equalization will be compressed as the strip passes around the lower tension roller, and so the total extension will be reduced. Correspondingly, the risk of kinking defects is reduced. The risk of kinking defects may also be reduced by supplying the strip to the temper-rolling mill without using tension rollers. However, in that case, the unwinding system must be relatively close to the temper-rolling mill. These considerations must be taken into account in the design of temper-rolling mills.

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