Influence of helical rolling and piercing on structure and mechanical properties of billets made of wheel steel of grade T

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Improvement of the technology for manufacture of billets of railroad wheels and hollow car axles, using intensive plastic deformation for effective rise of quality and functional properties of finished products, is the aim of this research. The paper presents the results of influence of deformation, which is realized via joint effect of rolling, reeling and consequent piercing, on mechanical properties of billets made of wheel steel of grade T. The rolling process in a three-roll mill is conducted via two passes with diameter reduction 20 % and elongation coefficient 1.56, while reeling in a two-roll mill is implemented with diameter reduction 12.5 % and elongation coefficient 1.31. Such deformation procedure creates the conditions allowing to increase strength and plastic properties of wheel steel and to form the structure in the central area of a deformed billet for consequent piercing. After piercing of preliminarily deformed billet, the properties of wheel steel stabilize significantly. When comparing the mechanical properties of wheel steel in the initial state and after deformation, the strength properties (σ_u, $\sigma_{0,2}$) increase by 1.6 times and plastic properties (δ, ψ) increase by 1.3 and 1.1 times respectively.
Key words: helical rolling, helical piercing, wheel steel, railroad wheels, radial-shear rolling, mechanical properties, impact strength, ingot microstructure.
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Actuality of the research

Intensive development of the railroad industry, increase of reliability and safety of passenger and freight deliveries requires revision of approaches to quality of the components and assemblies of railway vehicles equipment. The well-known manufacturing methods of billets can't provide meeting all requirements for mechanical properties, structure, geometric parameters, lowering of the effect of metallurgical processing defects etc. Improvement of the methods of quality management and rise of mechanical and operating properties of billets for railroad wheels and car axles is considered as a rather actual task.

It was established in the practice of manufacture of metal products and experimental investigations that improvement of billet structure increases with rise of accumulated deformation degree and has the effect on billet quality and the complex of physical and mechanical properties [1].

The helical rolling processes seem to be a prospective base for solving such problems in industrial scale [1–4]; they allow to implement control of metal flow, as a sequence of accumulated deformation degree, via varying deformation procedures [1, 5–8]. Helical metal flow according to the preset trajectories creates developed shear deformations; at the same time, accumulated deformation degree reaches principally larger values, e.g. in comparison with longitudinal rolling [3], compacted fine-dispersed metal structure is forming and its mechanical and operating properties improve substantially [1, 2–4]. After deformation in a helical rolling mill, quality improvement is usually noted, including improvement of mechanical properties of the following materials: steels [9–12], alloys [13, 14], aluminium alloys [15–17], titanium alloys [18] etc.

High shear deformations as the method for structure refining and complex improvement of metal properties are widely used in the processes united under the common title "the methods on intensive plastic deformation (IPD)" [19–23].

The billet deformation process in a helical rolling mill, accompanying with varying the preset parameters (feed angle, diameter reduction, elongation coefficient), allows creating the conditions providing "compaction" of cast structure in axial and peripheral billet areas (rolling in a three-roll mill, radial-shear rolling [1]), or "compaction" of the structure in peripheral billet area with forming of less compacted structure in the axial billet area (rolling in a two-roll mill). These processes are demonstrated by laboratorial testing, which was conducted with use of aluminium materials, which reflect metal flows in deformation area and macrostructure transformation [3, 5, 6]. **Fig. 1** presents macrostructure of the sample with 60 mm diameter in cast state and macrostructure transformation for the billet with 40 mm diameter after rolling in the three-roll mill with feed angle 12°, elongation coefficient 2.25 and after piercing in the two-roll mill with feed angle 12° [5, 6].

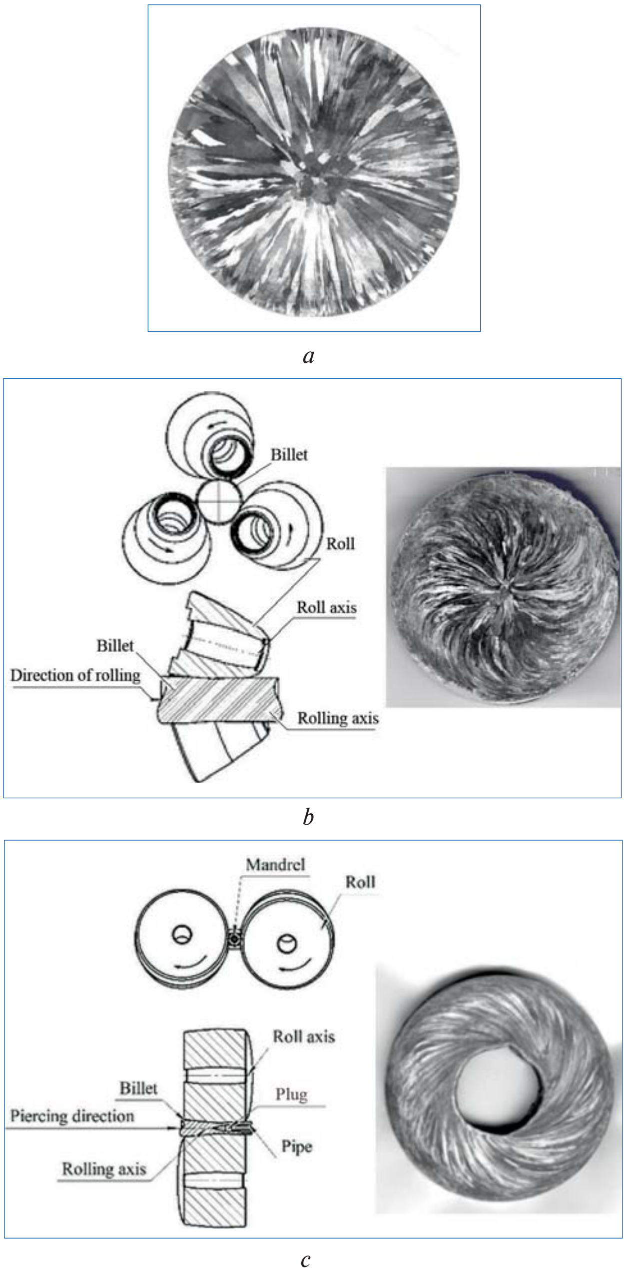

Fig. 1. Macrostructure transformation of the initial cast billet (*a*) after rolling in the three-roll mill (*b*) and piercing in the two-roll mill (*c*)

When manufacturing forgings used for consequent production of railroad wheels or hollow car axles [24, 25], use of extra thick-walled shells (D/S ≈ 3) as initial billets is rather interesting. Such shells can be obtained from cast billets via rolling and piercing in three-roll and two-roll helical rolling mills. It allows to achieve the above-mentioned advantages of intensive plastic deformation use in industrial conditions [26].

Despite essential volume of investigations [27–32], which were carried out in this direction, there are no experimental data received until present time about influence of deformation procedures with use or three-roll rolling, reeling and two-roll piercing on mechanical properties and structure. Taking this into account, the aim of this research is development of the technology for billet manufacture with consequent production of railroad wheels or hollow car axles using IPD methods (such as helical rolling) to improve quality and functional properties of finished products.

Technique of the research

The following semi-industrial equipment, allowing to conduct rolling process with a feed angle varying, was used in this research: the radial-shear rolling mill MISiS-130T with a feed angle varying β = 12–24° and the radial-shear rolling mill MISiS-130D with a feed angle varying β = 10–30°. This technological process includes heating od the billet with diameter 150 mm and length 350 mm made of wheel steel of grade T, according to the GOST 107-91.2011 and containing 0.67 % C, 0.79 % Mn and 0.38 % Si. The billets were cut from the ingot with diameter 472 mm (see the scheme in the **Fig. 2**).

The billets were heated up to 1180 °C before rolling and reeling in three-roll and two-roll mills. Then rolling in the three-roll mill MISiS-130T was carried out with reduction to the diameter 120 mm, via two passes with total elongation coefficient 1.56 and with feed angle 12°. Before reeling in the two-roll mill, the billets were held in the furnace at the temperature 1180 °C during 20 min. Reeling in the two-roll mill MISiS-130D was conducted via one pass with reduction to the diameter 105 mm, with elongation coefficient 1.31 and with feed angle 12°. Total elongation coefficient during rolling and reeling made 2.04.

Templates for metallographic examination and mechanical testing were cut from the billets with diameter 105 mm after rolling in the three-roll mill and reeling in the two-roll mill.

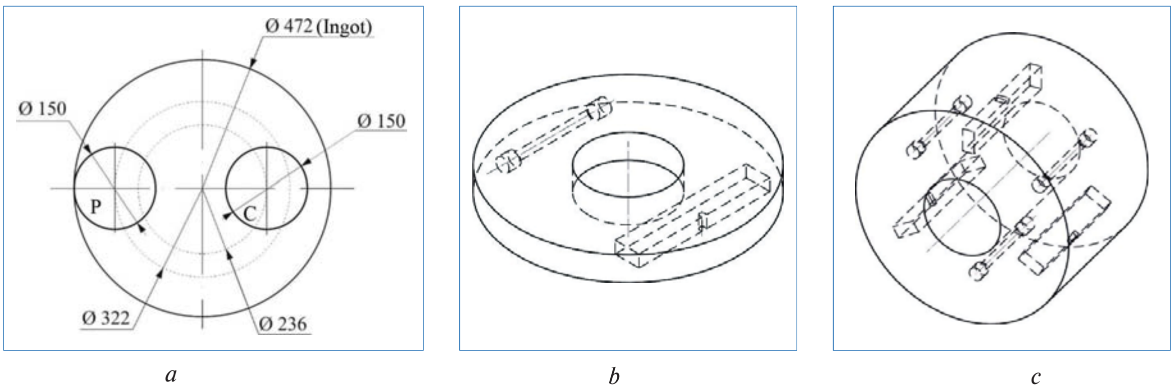

Fig. 2. The scheme of samples cutting from the ingot (*a*), samples cutting for mechanical testing in tangential (*b*) and axial (*c*) directions (C – central ingot part, P – peripheral ingot part)

The billets were heated up to 1180 °C before piercing, which was carried out in the rolling mill MISiS-130D, with producing the shell with external diameter 90 mm, internal diameter 38 mm and wall thickness 26 mm. Feed angle was 12° and elongation coefficient – 1.66. Total elongation coefficient of billets during rolling via two passes, reeling and piercing made 3.38.

Examination of mechanical properties of rolled billets was conducted in initial cast state, after rolling, reeling and piercing. Mechanical properties of wheel steel were measured during testing on stretching (GOST 1497-84) and impact bending (GOST 9454-78). The scheme of samples cutting for carrying out mechanical testing is presented in the Fig. 2. Impact strength testing of the samples was conducted using an impact pendulum-type testing machine RSV-30. The obtained values of mechanical properties, obtained during testing on stretching and impact bending were averaged on the base of the values for three samples.

Investigation of chemical heterogeneity and macrostructure of initial billets was carried out on templates with diameter 100 mm, which were made of initial billets with diameter 150 mm.

Results and discussion

Macrostructure of the billets in initial (cast) state is presented in the **Fig. 3 *a, b***. Central porosity was observed in the templates subjected to helical rolling. The template which was cut from the central ingot part is characterized by volumetric part of pores larger by 3 times in comparison with the template which was cut from the ingot periphery (**Fig. 3 *c, d***). Porosity in the axial part differs substantially, based on small deviations, conditional chemical homogeneity of initial billets and metal deformation in macro-volumes.

Smaller porosity in periphery is caused by initial increased metal density, which is inherited from this ingot area. Presence of pores in the central part of rolled material makes the consequent piercing process more easy.

No defects like cracks were revealed after piercing, including absence of any defects of macrostructure such as porosity in the samples subjected to various piercing procedures. Metal macrostructure is identified as compacted and homogenous (**Fig. 3 *e, f***).

Mechanical properties (extension and impact strength) are presented in the **Fig. 4**. Strength and plastic properties as well as impact strength of the cast billet increase from the ingot center to its periphery (see Fig. 4). For example, billet properties in tangential direction, which were taken from the ingot peripheral / central parts are as follows: σ_u = 935.0 / 880.0 MPa, $\sigma_{0.2}$ = 582.0 / 557.1 MPa, relative elongation δ = 10.3 % / 7.8 %, relative reduction of area ψ = 6.3 % / 5.6 %, impact strength KCU^{+20} = 16.7 / 12.0 J/cm^2.

When comparing the values of strength properties (σ_u, $\sigma_{0.2}$) of wheel steel in initial cast state, small differences are noted depending on directions of samples cutting (tangential and longitudinal); this difference does not exceed 1.05 times. Meaning plastic properties, wheel steel is also characterized

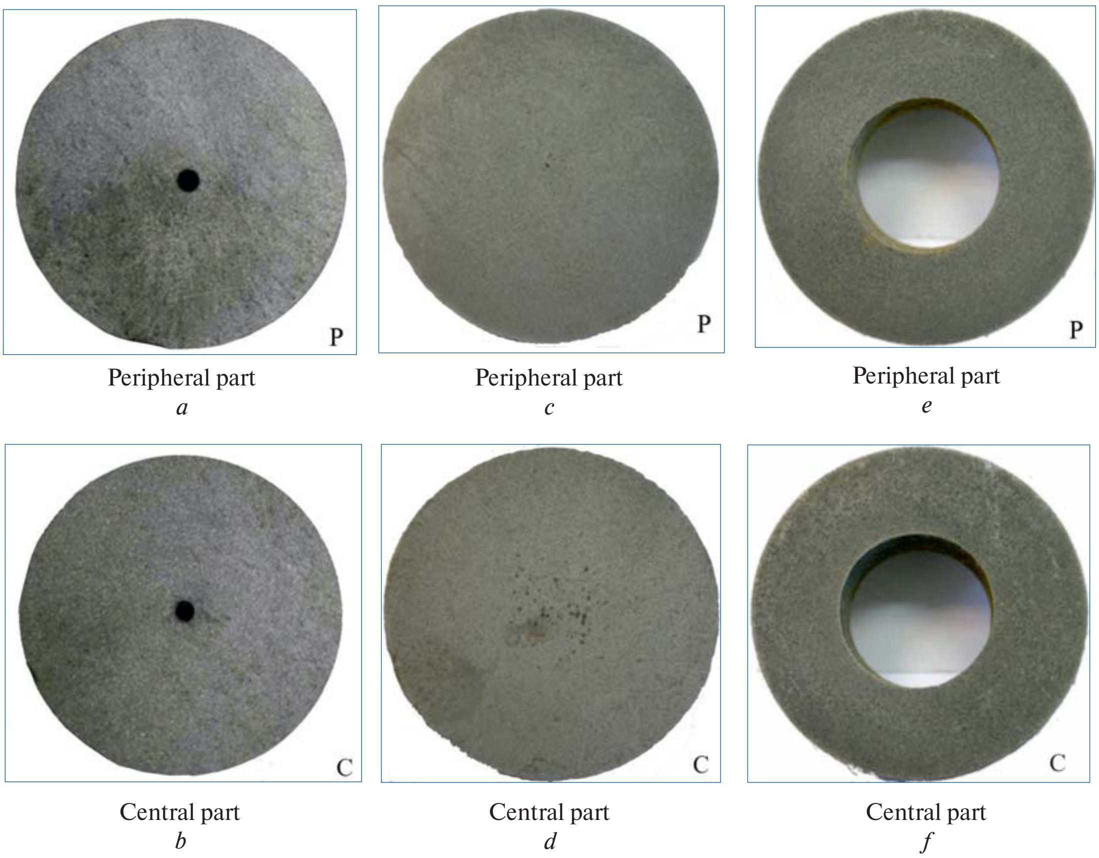

Fig. 3. Macrostructure of templates of wheel steel of grade T: *a, b* – in initial cast state; *c, d* – after rolling and reeling; *e, f* – after piercing (C – central ingot part, P – peripheral ingot part)

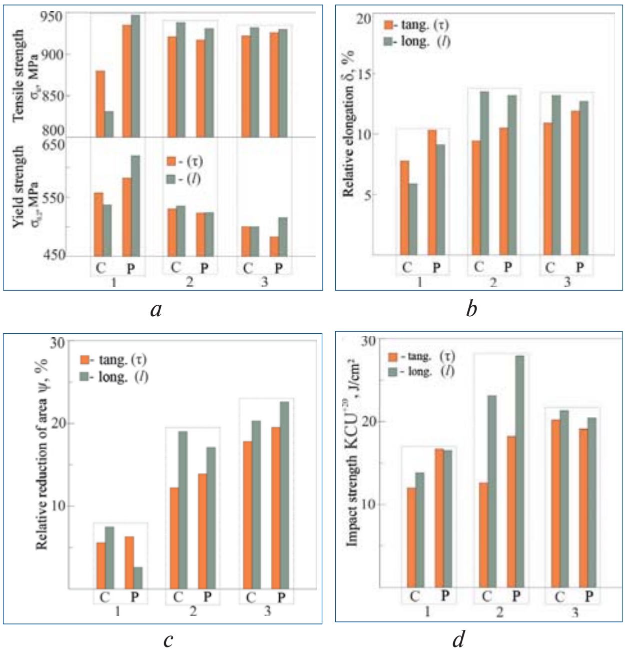

Fig. 4. Mechanical properties of wheel steel in initial cast state (*1*) and after deformation such as roll.ing and reeling (*2*) and piercing (*3*): *a* – Tensile strength σ_u, Yield strength $\sigma_{0.2}$; *b* – Relative elongation δ; *c* – Relative reduction of area ψ; *d* – Impact strength (C – central ingot part, P – peripheral ingot part)

by low values of relative elongation and relative reduction of area, while difference depending on directions of samples cutting makes (δ/ψ): 1.13 / 2.42 for the samples taken from the peripheral part and 1.32 / 1.33 for the samples taken from the central part (see Fig. 4).

Strength properties of the billets taken from the central ingot part increase after rolling and reeling, as well as plastic properties of the billets taken from both the central and peripheral ingot parts (see Fig. 4 a). The level of mechanical properties, such as tensile strength and yield strength of the billets taken from both the central and peripheral ingot parts (P/C), have comparable values: tensile strength in longitudinal directions (P/C) is σ_u = 938 / 931 MPa, yield strength (P/C) is $\sigma_{0.2}$ = 535 / 524 MPa. The level of yield strength of wheel steel after deformation is slightly lower than in initial cast state (see Fig. 4 a).

Relative elongation and relative reduction of area increase after rolling and reeling by 1.02 / 2.29 times and 2.18 / 6.58 times respectively (see Fig. 4 b, c). The value if impact strength of wheel steel taken from both the central and peripheral ingot parts (P/C) increases by 1.05 / 1/09 times in tangential direction and by 1.67 / 1.69 times in longitudinal direction (see Fig. 4 d).

After piercing in the two-roll mill, the level of tensile strength and yield strength is comparable with the properties after rolling and reeling. So, tensile strength in longitudinal direction (P/C) is σ_u = 932 / 930 MPa, yield strength (P/C) is $\sigma_{0.2}$ = 515 / 506 MPa. Tensile strength in tangential direction (P/C) is σ_u = 926 / 922 MPa, yield strength (P/C) is $\sigma_{0.2}$ = 483 / 502 MPa.

Increase of elongation coefficient (which characterizes accumulated deformation degree) leads to essential rise of the values of plastic properties. After piercing, the values of relative elongation for the billets taken from the peripheral ingot part increases by 1.15–1.39 times, and for the billets taken from the central ingot part increases by 1.39–2.23 times (in comparison with the properties in initial cast state).

More serious elevation of the properties is noted for the values of relative reduction of area: by 3.1–8.7 times for the billets taken from the peripheral ingot part and by 2.7–3.1 times for the billets taken from the central ingot part.

Deformation effect both during rolling and reeling, as well as during piercing, supports increase of the values of impact strength for the wheel steel of grade T. After rolling and reeling, impact strength for the billets taken from both the central and peripheral ingot parts (P/C), increases by 1.05 / 1.09 times in tangential direction and by 1.67 / 1.69 times in longitudinal direction. Increase of the same values of impact strength after piercing made 1.14 / 1.68 times in tangential direction and 1.23 / 1/54 times in longitudinal direction (see Fig. 4 d).

Comparison of mechanical properties of the wheel steel of grade T after rolling and reeling with total elongation coefficient 2.04 revealed difference between plastic properties (δ, ψ) and impact strength values depending on direction of the samples cutting for testing. The values δ and ψ in longitudinal direction are higher than in tangential direction. Maximal difference of impact strength values were noted for metal taken from the periphery by 1.5 times and for metal taken from the central ingot part by 1.83 times.

Typical increase of plastic properties (δ, ψ) and impact strength values in longitudinal direction in comparison with the properties in tangential direction was observed also for helical piercing of billets with small elongation coefficients (less than 2).

As soon as deformation degree increases due to piercing of preliminarily rolled and reeled billets with total elongation coefficients 3.38, the strength and plastic properties as well as impact strength values stabilize. Difference between plastic values and impact strength values of wheel steel becomes smaller. Difference of impact strength values of the wheel steel of grade T makes 1.06 for the billets taken from the periphery and 1.05 for the billets taken from the central part.

Conclusions

The influence of combined operations of rolling in the three-roll mill, reeling in the two-roll mill with consequent billet piercing in the two-roll mill on macrostructure and mechanical properties of the wheel steel of grade T was examined.

It is shown that the area with axial porosity is forming in a billet during rolling and reeling with total elongation coefficient 2.04; this area provides conduction of consequent piercing in the two-roll mill with smaller pressure applied on the plug. Plastic properties and impact strength values increase by 1.05–1.69 times. It is displayed that the billets after rolling and reeling are characterized by higher plastic properties, the same tendency is observed for impact strength values in longitudinal direction in comparison with those in tangential direction. For example, impact strength of the billets taken from periphery in longitudinal direction is higher comparing with impact strength values in tangential direction by 1.5 times, while for the central ingot area it is equal to 1.83 times.

Macrostructure improves substantially after piercing of preliminarily deformed billets and no scabs or discontinuity defects were found out inside shells. Metal macrostructure is compacted and homogenous, strength properties (tensile strength, yield strength) are stabilizing. Difference between plastic properties, impact strength values for the wheel steel of grade T are decreased in longitudinal / tangential directions. For example, impact strength of the billets taken from ingot periphery in longitudinal / tangential directions $KCU^{+20} = 22.6 / 19.5$ J/cm^2.

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