Study of macrostructure and mechanical properties changes during the upsetting of hollow billets produced by rotary piercing method

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The present paper sets forth the findings of a study undertaken to examine alterations in macrostructure during the combination of the rotary piercing and upsetting methods, as applied to aluminium samples of technical purity. The present study demonstrates that the spiral-shaped macrostructure, which is induced by the rotary piercing method, is maintained during subsequent deposition by plane-parallel plates on the press. The angle of inclination of the structural fibre in the proximity of the side surface of the forging is found to be $\gamma \approx 7$ degrees. A comparison of the mechanical properties of T-grade wheel steel forgings obtained from different types of billets (solid billet, hollow (drilling) and pierced billets at feed angles $\beta = 12°$ and $\beta = 14°$) has been undertaken. The results demonstrate that the preceding deformation (piercing in a helical rolling mill) is inherited and reflected in the mechanical properties of the forgings, particularly in the indices of relative contraction and impact toughness in the radial and tangential directions.

Key words: rotary piercing, helical rolling, feed angles, elongation ratio, extremely thick-walled shell, upsetting, hollow billet upsetting, disk-type forgings, metal flow, macrostructure, anisotropy, radially-oriented macrostructure, spiral-shaped macrostructure, wheel steel, railroad wheel.

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Introduction

The improvement of the cast metal structure according to the existing technological production schemes is achieved in the process of forming the billet on the press-rolling line. The most significant contribution to the formation of the mechanical properties of railroad wheels is attributable to the upsetting process. As demonstrated in [1], the application of further deformation during the process of press-rolling does not exert a substantial influence on the mechanical properties of railroad wheels.

It is important to note that the shape of disks is characterised by a distinct design, comprising various elements, including the disk, the hub, the rim, and the transition zones. These elements undergo deformation during the manufacturing process, with the magnitude of this deformation varying. It is noteworthy that the deformation levels of certain elements may not guarantee the complete elimination of the cast metal structure. In this regard, it is proposed that enhancement of the cast metal structure can be achieved through the implementation of a preliminary auxiliary operation.

It has been demonstrated through experimental data that it is possible to achieve a more intensive improvement in the cast macrostructure of the initial billet through deformation on a helical rolling mill. This is even possible at relatively low compression of the billet [2–7].

A distinctive attribute of the helical rolling process, particularly in the context of piercing billets, is the substantial structure refinement within the zones of interaction between the working tool (comprising rolls, rolls, and a mandrel) and the billet [2, 4, 6–14]. For instance, **Fig. 1** illustrates the macrostructure of the initial continuous-cast billet ∅125 mm, fabricated from stainless steel of 12X18H10T grade, and subsequent to deformation with a drawing coefficient $\mu = 2.2$. It has been demonstrated that, under such deformation conditions, the cast structure of the predominant portion of the cross-section area of the billet is enhanced.

The helical rolling method is advantageous in that it allows for the control of the plastic flow of metal by modifying the parameters of the deformation centre [2, 4, 6, 7, 15]. In the process of rolling billets with equal drawing coefficients, it is possible to obtain a structure with a different distribution of shear strains in the cross-section of the billet, provided that one factor is changed – the feed angle β [2, 4, 9].

The present study investigates the relevance of the rotary piercing method (a special case of helical rolling) as a preliminary operation for obtaining initial blanks for

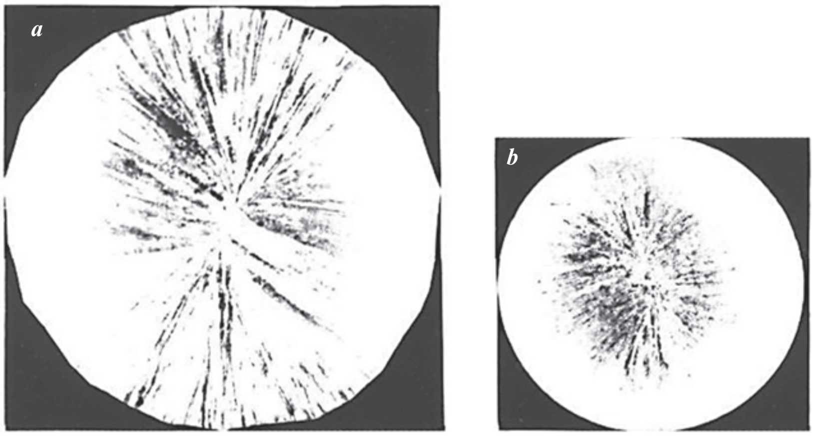


Fig. 1. Initial macrostructure of a continuous cast ∅125 mm billet made of 12X18H10T grade steel (*a*), and after deformation in a helical rolling mill with drawing coefficient $\mu = 2.2$ (*b*)

Table 1
Geometrical parameters of technically pure aluminium samples for upsetting

Billet type	*D*, mm	*H*, mm	*d*, mm	*H/D*	*d/D*	*S/H*	*D/S*
Solid (cast)	63.5	56.8	–	0.89	–	–	–
Hollow (pierced at β = 16°)	63.5	63.7	21.1	1.00	0.33	0.33	3.00

forgings, such as disks (railroad wheels). The rationale behind this method is that the upsetting of hollow blanks (obtained by shell cutout) requires less energy for deformation due to the two-way flow of metal [16, 17]. It is also possible to reduce the heating time of hollow billets in comparison with solid billets. Furthermore, when heating hollow billets in the furnace, the distribution of the temperature field in the volume of the billet is more uniform.

The utilisation of deformed billets within a helical rolling mill, accompanied by a pre-worked cast macrostructure, results in billets that exhibit superior strength, plastic properties and impact toughness when compared with cast billets [2, 6, 18–21]. Furthermore, products derived from billets that have been deformed by helical rolling exhibit elevated plastic properties and enhanced resistance to impact loads [2, 6, 15, 18, 22–24].

The process of deforming the billet in a helical rolling mill results in the formation of a spiral-type macrostructure in its cross-section. The preservation of this structure in the finished product has been shown to increase its resistance to both cyclic and impact loads when compared to its other orientation [6, 25].

In previous studies on the manufacturing of gears by rolling on a mill [24], it was demonstrated that the limit of fatigue spalling increases by approximately 1.32 times when the direction of metal fibres in relation to the applied load is altered.

The objective of the present study is to investigate the macrostructure changes during the upsetting of solid (type 1) and hollow billets (type 2) obtained by rotary piercing on a model material, and to determine the influence of the billet type on the mechanical properties of forgings made of wheel steel of *T*-grade.

Materials and methods

Billets of aluminium alloy of technical purity A85 (GOST 11069–2001) were used as the material for studying changes in macrostructure. The material has demonstrated its efficacy in conducting analogous studies during both deformation in helical rolling mills [6, 9, 26] and free upsetting by plane-parallel plates [27, 28]. The study utilised samples of equivalent volumes (V = constant), comprising both a cast radially oriented macrostructure (solid billet) and a spiral-shaped macrostructure induced by deformation by rotary piercing (hollow billet) [9].

Preliminary, ingots obtained in a graphite mould with a diameter of 63.5 mm and a height of 305 mm have a radially oriented dendritic structure, which is also characteristic of continuously cast billets (CCB) **(Fig. 1)**. During the process of piercing, the radially oriented structure undergoes a transformation into a spiral "long-fiber" macrostructure [6, 9]. It is evident that the structure, in both its initial and deformed states, is clearly visualised on longitudinal and transverse macro-section.

In order to induce a spiral macrostructure in the billet, the ingots were pierced on the MISIS-130D helical rolling mill in the cold state $T_{billet} = 25$°C at the feed angle $\beta = 16°$ with the drawing coefficient $\mu \approx 1.1$ [9]. The resultant piercing produced a shell with a diameter of 63.5 mm and a wall thickness of 21.2 mm (outer diameter to wall thickness ratio $D/S = 3.0$).

Deviations in volumes of research samples were found to be no greater than 3% **(Table 1)**.

The process of upsetting of solid and hollow blanks was carried out to a final height of approximately 30 mm in the cold state. The relative degree of deformation of the solid sample was found to be approximately 43%, whilst that of the hollow sample with a spiral-shaped macrostructure was approximately 53%.

In order to unveil the initial and macrostructure after deformation, the templates with prepared surfaces were subjected to etching in a "Marble" solution (hydrochloric acid HCl – 100 ml, copper sulfate $CuSO_4$ – 4 g, ethyl alcohol C_2H_5OH – 100 ml, distilled water – 100 ml).

The macrostructure was investigated in the initial cast state (in the transverse direction of the initial billets), after piercing in the helical rolling mill (transverse direction), and after upsetting on the press of solid and hollow billets (in the longitudinal and transverse directions).

The present study investigates the influence of billet type on the change of mechanical properties of forgings.

Table 2
Chemical composition of *T*-grade wheel steel

Mass fraction of chemical elements, %								
carbon	manganese	silicon	vanadium	sulfur	phosphorus	chromium	nickel	copper
0.62–0.70	0.50–1.00	0.22–0.65	≤0.15	0.005–0.025	≤0.030	≤0.40	≤0.30	≤0.30

Table 3
Geometrical parameters of *T*-grade wheel steel samples for upsetting

Billet type	*D*, mm	*H*, mm	*d*, mm	*H/D*	*d/D*	*S/H*	*D/S*
Solid (cast)	100.4	83.1	–	0.827	–	–	–
Hollow (pierced at $\beta = 12°$)	91.8	113.1	32.3	1.23	0.29	0.26	3.09
Hollow (pierced at $\beta = 14°$)	94.9	104.3	32.4	1.1	0.31	0.3	3.04

To this end, 100 mm diameter billets were cut from the central part **(Fig. 2)** of a 455 mm diameter continuous-cast billet of *T*-grade according to GOST 10791–2011 **(Table 2)**. This steel grade is used for the production of railway wheels.

The piercing of initial billets with a diameter of 100 mm was also carried out on the rotary piercing mill MISIS 130D. The piercing of cast blanks was conducted within two modes of the mill setting: at a feed angle $\beta = 12°$ and a drawing coefficient $\mu \approx 1.26$, and at a feed angle $\beta = 14°$ and a drawing coefficient $\mu \approx 1.36$. Upsetting experiments were conducted utilising solid specimens with cast structure and hollow specimens fabricated from shells obtained by piercing in a helical rolling mill at feed angles $\beta = 12°/\mu \approx 1.26$ and at feed angle $\beta = 14°/\mu \approx 1.36$ **(Table 3)**. The samples were composed of equal volumes, with a constant volume ratio being maintained ($V \approx$ const).

Prior to the processes of piercing and upsetting, the steel blanks of the wheel were subjected to a heating process in a furnace, to a temperature of 1180 °C.

The upsetting process was conducted on the press P-450 mm, with a deformation speed of approximately 1 mm/s. The solid and hollow billets were upstting without the use of lubrication, employing plane-parallel plates with approximately machined surfaces up to a final height of $H_f \approx 27$ mm. The relative degree of deformation of the solid billet $\varepsilon \approx 67.5\%$, while for the hollow specimen (piercing at $\beta = 12°$) $\varepsilon \approx 76.1\%$, and for the hollow specimen (piercing at $\beta = 14°$) $\varepsilon \approx 74.1\%$.

An investigation was conducted into the mechanical properties of wheel steel, encompassing tensile testing in accordance with GOST 1497–84 and impact bending testing in accordance with GOST 9454–78. Tensile testing was conducted on specimens with a diameter of 3 mm at the working part. Impact bending testing was conducted on specimens with dimensions of 5×10×55 mm, with a *U*-shaped notch depth of 2 mm. Tensile and impact bending tests were conducted at a temperature of +20 °C. Tensile tests were conducted utilising an Instron testing machine, with a strain rate of approximately 10^3 s^{-1}. Impact bending tests of the specimens were performed on a PCB-30 pendulum impact tester machine. The values of the mechanical properties obtained from the tensile and impact bending tests were subjected to averaging, with the calculation being performed over the values for three specimens.

Selection of templates from forgings was carried out in accordance with the proposed scheme of arrangement of samples in the volume of forgings **(Fig. 3)**.

As a result of upsetting of the solid (with a cast radially oriented structure) and hollow billets (with a pre-deformed spiral structure), forgings with close geometrical dimensions (solid sample/hollow) were obtained: diameter at the end face 80.2/81.3 mm, barrel diameter 91.2/91.5 mm, sample height 32.5/30.2 mm, relative degree of deformation (ε) 42.7/52.6 %.

It is evident from **Fig. 4** that, at comparable values of end face diameter, the barrel diameter of the billets after upsetting exhibits a significant difference depending on the type of billet selected.

Following the upsetting of a solid billet with a radially oriented macrostructure **(Fig. 4, *a*)**, the orientation of the macrostructure on the end surface and the surface in the plane of the cross-section (see **Fig. 4, *b*, *c*)** is maintained. In the longitudinal direction **(Fig. 4, *c*)**, the macrostructure of the metal is consistent with that of solid billets after upsetting [27], exhibiting regions of disparate strain distribution. The metal volumes in proximity to the contact surfaces exhibit minimal deformation [27, 28].

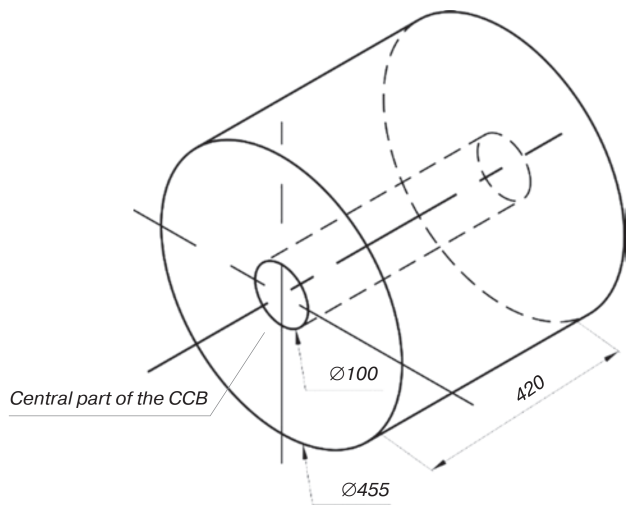
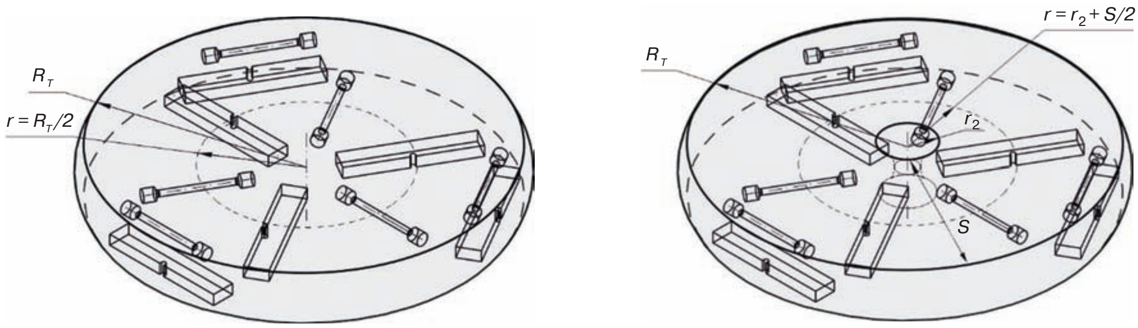


Fig. 2. Schematic of billet selection ∅100 mm from a continuous cast wheel billet ∅455 mm



a *b*

Fig. 3. Sampling scheme for the study of the mechanical properties of forgings:
a – Sampling from the solid billet after upsetting; *b* – Sampling from the hollow billet after upsetting (R_T – radius of the diameter on the end face of the forgings, *r* – radius of the location of the stress concentrator of the impact toughness samples)

The direction of metal flow distribution (deformations) within the billet volume is clearly reflected in the change of macrostructure. This is inextricably linked to the distribution of deformations and stresses [2, 4, 6, 27].

In the process of settling hollow billets with plane-parallel plates, the ratio $H/D \approx 1$, and $d/D \approx 0.33$. This results in metal flow occurring at the initial stage of deformation ($\varepsilon \approx 10–20\%$) with "undercutting" of the inner cavity (metal flow towards the periphery). As the degree of deformation increases, two distinct phenomena occur: firstly, metal flows both towards the periphery and towards the axis of the workpiece; secondly, when deformation increases to a level of ≈ 70-80%, the inner hole closes completely.

The macrostructure of a hollow sample obtained by piercing in a helical rolling mill (see **Fig. 4, *d, e***) serves as the initial billet for the upsetting process, which results in a disk-type forging. The macrostructure of the sample exhibits a spiral pattern, and it is possible to distinguish three zones that are characteristic of billets obtained by helical piercing [2, 3, 6, 9], namely:

– the zone of interaction between the mandrel and the workpiece is characterised by a macrostructure refinement, with the direction of fibre arrangement being implicitly expressed;

– the zone of interaction between the working rolls and the workpiece is characterised by a structure refinement, with the orientation of fibres opposite to the direction of "spiral rotation" [6, 9];

– the zone is characterised by a macrostructure that is expressed in a spiral pattern.

In **Fig. 4, *e***, the volume of the fine-structure zone (*t*) is 44816.5 mm^3 (outer diameter of the workpiece 63.5 mm, inner diameter of the selected area 56 mm, height 63.7 mm). The volume of metal in the zone *V(t)* relative to the total volume of the part is ≈25%.

In the cross-section, the macrostructure exhibits a spiral orientation, with a distinct region of more refined macrostructure located near the outer surface **(Fig. 4, *e*)**. The geometric location of the refined spiral-shaped macrostructure in the cross-section is consistent with the corresponding zone of refined macrostructure identified in the longitudinal section of the slice **(Fig. 4, *g*)**.

The depth of the layer with a refined spiral macrostructure is measured at 4 mm **(Fig. 4, *e*)**.

The volume of the selected zone *V(t)* **(Fig. 4, *g*)** is 47753.9 mm^3 (error in determining $\Delta V \approx 5\%$). The volume of the zone with crushed macrostructure is ≈26% in relation to the volume of the whole workpiece (V_z).

On the selected region with refined macrostructure **(Fig. 4, *e*)**, the angle of inclination (γ) of the structural fibre with respect to the line perpendicular to the radius (*R*), which is $\gamma \approx 7°$, is revealed at point *A*.

The paper [21] presents the results of mechanical properties of initial castings and after piercing in a helical rolling mill (for comparison and analysis the properties in the tangential direction are given, due to the lack of possibility of obtaining samples for mechanical tests in the radial direction of standard size).

The mechanical properties of the initial cast billet in the tangential direction are as follows: tensile strength (σ_B) = 636.2 N/mm^2, Offset yield strength ($\sigma_{0.2}$) = = 427.7 N/mm^2, relative elongation (δ) = 1.8%, contraction ratio (ψ) = 2.8%, and impact toughness (KCU^{+20}) = = 14.7 J/cm^2.

The mechanical properties of stitched blanks in the tangential direction (at feed angle $\beta = 12°$/ at feed angle $\beta = 14°$) are as follows: $\sigma_B = 870.6$ N/mm^2 / σ_B = = 833.5 N/mm^2, $\sigma_{0.2} = 479.7$ N/mm^2 / $\sigma_{0.2} = 506.1$ N/mm^2, $\delta = 5.5\%$ / $\delta = 3.9\%$, $\psi = 9.8\%$ / $\psi = 6.1\%$, KCU^{+20} = = 20 J/cm^2 / KCU^{+20} = 24.3 J/cm^2.

Following the process of upsetting, billets of *T*-grade wheel steel with the diameter of the end part ≈ 163 mm and height ≈ 27 mm were obtained.

In the process of hollow billet upsetting, which is obtained by piercing in a helical rolling mill, the inner bore is almost completely closed. The metal flow is occurring in both the peripheral and axial directions of the billet.

With the same arrangement of the investigated samples in radial and tangential direction in forgings after upsetting, the character of metal flow during upsetting and previous deformation is reflected in the distribution of mechanical properties of *T*-grade wheel steel **(Table 4)**.

The most significant disparities between the properties of forgings in the radial and tangential directions pertain to the values of contraction ratio and impact toughness of wheel steel after upsetting.

The highest values of relative contraction in the radial direction are seen in forgings made from solid billets, while the lowest values are seen in the tangential direction, in forgings made from hollow billets.

The impact toughness of the forging, obtained from the solid billet, shows that when the impact energy is distributed perpendicular to the radius (values in the radial direction), the values are higher compared to the values along the radius (values in the tangential direction). This is consistent with the macrostructure of the solid billet after upsetting **(Fig. 4, *b*)**. The impact toughness values are 1.17 times higher.

Changes in the nature of metal flow during the process of upsetting hollow billets (obtained by piercing in a helical rolling mill) are reflected in the mechanical properties of the billets. It has been demonstrated that, consequent to bilateral metal flow and prior deformation (piercing in a helical rolling mill), the values of contraction ratio and impact toughness are elevated in the tangential direction in comparison to the radial direction.

The distribution of metal flow streams resulting from both the initial deformation (piercing in a helical rolling mill) and subsequent deformation (on a press) enables the formation of a set of mechanical properties in forgings. When changing the piercing modes in a helical rolling mill by changing the feed angle β and the drawing coefficient μ, it is possible to obtain a billet with different distribution of properties (the most significant change in the feed angle affects the plastic properties and impact toughness [21]). During subsequent deformation on the press, the previous deformation is inherited and reflected in the mechanical properties of the forgings, which is noticeably reflected in the values of contraction ratio and impact toughness in the radial and tangential directions of the forgings obtained from pierced billets **(Table 4)**.

It is assumed that when the initial blank is pre-deformed by helical piercing method, thereby inducing a spiral structure and maintaining its orientation after upsetting near the working surface of the railway wheel, will acquire almost ring-shaped appearance. The arrangement of material fibres in the wheel

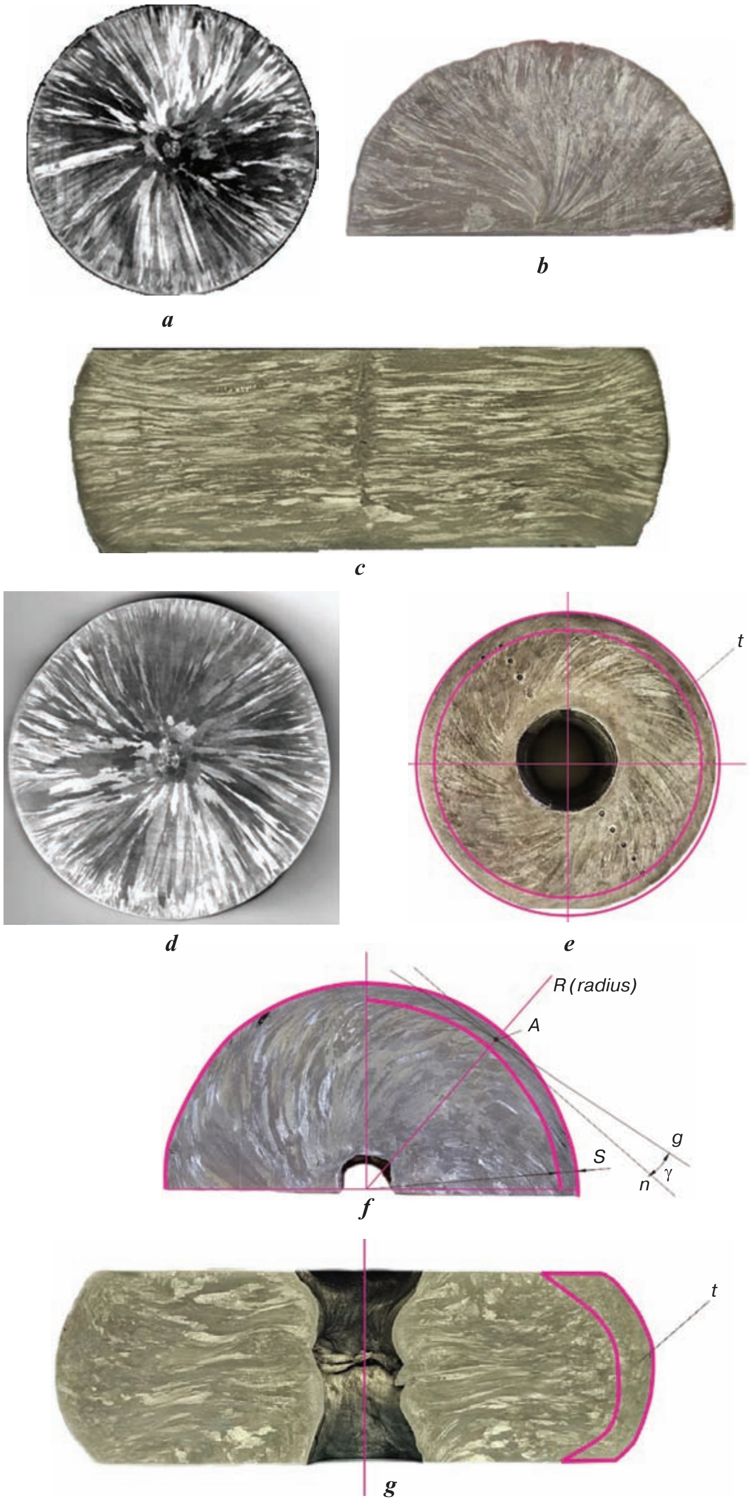


Fig. 4. Initial macrostructure of a solid billet ∅ 63.5 mm made of aluminum alloy of technical purity A85 (*a*), after upsetting of a solid specimen in cross section (*b*), after precipitation of a solid specimen in longitudinal section (*c*), initial macrostructure of a solid billet ∅ 63.5 mm (*d*) and after piercing in the helical rolling mill (*e*), macrostructure after upsetting of the pre-pierced hollow specimen in the cross section (*f*), macrostructure after upsetting of the pre-pierced hollow specimen in the longitudinal section (*g*)

Table 4
Mechanical properties of *T*-grade wheel steel after upsetting depending on the type of initial billets

Billet type		
Solid - cast (rad./tang.)	Hollow - pierced at β = 12° (rad./tang.)	Hollow - pierced at β = 14° (rad./tang.)
Tensile strength σ_B, H/mm^2		
913/993	925/940	918/946
Offset yield strength, $\sigma_{0.2}$, H/mm^2		
512/549	504/536	522/546
Relative elongation δ, %		
8.7/8.5	9.1/9.9	8.6/9.3
Contraction ratio ψ, %		
26.4/17	22.9/30.5	20.51/34.24
Impact toughness KCU^{+20}, J/cm^2		
27.3/23.3	19.6/26.1	27.7/28.3

rim (disc-type forgings) provides a higher level of endurance for the product when subjected to cyclic and impact loads, in comparison with their other orientation [6, 26]. Furthermore, additional deformation processing of the workpiece contributes to a more stable acquisition of a complex of mechanical properties in the railway wheel.

The application of the rotary piercing method is of relevance due to the possibility of controlling the plastic flow of metal by changing the mill setting parameters [2, 3, 6], which allows for the prediction and production of billets with spiral-shaped macrostructures of various types [9].

In previous studies on the impact of deformation caused by a combination of helical rolling, upsetting, and TMT (heat treatment and interrupted hardening of wheel rims), it has been demonstrated that the utilisation of pierced hollow billet enhances impact toughness by 1.5–2 times and increases the resistance to fatigue failure of wheel steel by approximately 1.5–1.7 times [18]. Characteristic increase of plastic properties (δ, ψ) and resistance to impact loads (KCU) without reduction of strength parameters (σ_B, σ_T), is typical for products obtained from billets deformed by helical rolling method [2, 5, 15, 18, 20, 22–24].

Conclusion

The study's findings demonstrate that the combination of helical rolling and upsetting techniques constitutes a viable approach for the control of axisymmetric forgings' properties, including disc-shaped components.

The present study demonstrates that after upsetting of hollow billet made of technically pure aluminium with an induced spiral structure by means of rotary piercing deformation, the spiral macrostructure is preserved in the billet's cross-section after upsetting. It has been demonstrated that the zone with a refined(spiral-shaped) macrostructure in the vicinity of the lateral surface is ≈25% of the volume of the original billet. The angle of inclination of the fibre forming the spiral-shaped macrostructure in the cross-section near the side surface of the billet deformed by rotary piercing and upsetting with plane-parallel plates is found to be $\gamma \approx 7$ degrees.

The nature of change in deformation modes of billets made of *T*-grade wheel steel in the helical rolling mill is reflected on the properties of the obtained forgings after upsetting on the press. The preceding deformation exerts a substantial influence on the values of relative contraction and impact toughness of wheel steel.

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