Investigation of metal flow during helical rolling at different feed angles

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The present paper sets forth the findings of an experimental study conducted to investigate the effects of altering the radially oriented macrostructure of initial castings, thereby transforming it into a spiral-type macrostructure. This transformation is achieved by the application of shear displacements of metal during the deformation process through the utilisation of helical rolling, utilising various combinations of feed angle β and drawing coefficient μ (β = 12°/μ = 2.2, β = 14°/μ = 2.5, β = 16°/μ = 2.3, β = 18°/μ = 2.3, β = 20°/μ = 2.3). For the first time in the world practice with the use of experimental-industrial equipment (radial shear rolling mill MISIS 100T) experimentally revealed the influence of feed angle β on the character of metal flow, reflecting the change of spiral structure in the cross section, shear line l_γ, shear angle γ: with increasing feed angle β the length of structural fibre l_γ decreases by ≈1.5 times (at β = 120 the length l_γ = = 28.48 mm, and at β = 200 the length l_γ = 19.01mm), the shear angle γ_c near the axis of the workpiece decreases by 9.8 times (at β = 120 γ_c = 26.40, and at β = 200 γ_c = 2.70). The studies undertaken demonstrate the efficacy of the radial shear rolling method in regulating metal flow within the deformation centre. The findings of the present study are instrumental in extending the theoretical framework of helical rolling and in the development of a methodological framework for analytical calculations in metal forming along specified trajectories, thereby facilitating the control of material properties that are sensitive to structure.

Key words: radial shear rolling (RSR), helical rolling, feed angle, aluminium, spiral-fibre macrostructure, shear deformation.

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1. Introduction

Helical rolling is a highly efficient method of metal forming. It is a process that contributes to the formation of the necessary complex of physical and mechanical properties of materials during deformation. [1–5]. The benefits of this method are manifold. Primarily, it enables the controlled flow of metal during the deform ation of the billet. This is achieved by altering a single parameter of the mill setting mode, namely the feed angle β [1, 4, 6–11]. The manner in which metal flows (streams) during the processes of metal pressure treatment contributes to the formation of a complex of physical, mechanical and functional properties of products [1, 2, 10, 12–15].

The inherent helicoidal flow of metal along predetermined trajectories engenders developed shear deformations, thereby promoting the deep elaboration of the metal structure at limited drawing ratios. [1, 2, 10, 16–18]. This processing method has been shown to significantly enhance the plastic properties of deformed billets [1, 14, 15, 19, 20]. These properties are also inherented in products manufactured by this method [21–23]. In the process of helical rolling, the deformation of billets gives rise to the formation of a spiral-type macrostructure within the billet's cross-section [10, 11, 24, 25].

In [10], the formation of a spiral macrostructure as a result of shear deformations developed in the plane of the cross-section during rolling with a feed angle less than β < 16° was described in detail.

A substantial corpus of theoretical and experimental work conducted within the framework of the OMD department at NITU MISIS [1, 4, 18, 19, 26, 27] has yielded findings that substantiate the hypothesis that the optimal conditions for the deformation of billets are achieved through the utilisation of helical rolling mills characterised by substantial feed angles (β = 16–30°). This assertion is predicated on the premise that such an approach engenders a substantial augmentation in the efficiency of the method, thereby ensuring the attainment of rolled products of a superlative quality from alloyed steels and alloys. It has been demonstrated that rolling at large feed angles (β > 16°) is accompanied by a significant compaction of the billet's central zone and an increase in its technological plasticity [1, 10].

It is challenging to ascertain the nature of metal flow and to determine the flow directions depending on the change of equipment setting modes at thermodynamic transformations of the billet structure and its estimation by indirect data (e.g. by change of mechanical properties, change of induced non-continuity defects, etc.).

At present, software packages (QForm, Deform, Abacus, ANSYS, etc.) are extensively utilised for the modelling of deformation processes, including helical rolling [28–34]. Nevertheless, these methodologies do not facilitate an objective evaluation of the shape change without experimental verification.

Despite the significant amount of research conducted in this domain, there is presently an absence of experimental data concerning metal flow during deformation in a helical rolling mill across a wide range of feed angle variation (β = 12°–20°, and beyond). In the present study, semi-industrial equipment is utilised, thereby enabling the execution of the rolling process over a broad spectrum of feed angle variations (mill RSP MISIS 130T – β = 12°–24°, mill RSP MISIS 100T – β = 12°–27°). In view of the aforementioned points, it is imperative to initiate a rigorous investigation into the dynamics of metal flow during the process of deformation in a helical rolling mill. This investigation is of paramount importance, as it will facilitate the development of innovative rolling modes that ensure the precise regulation of metal flow, thereby ensuring the consistent attainment of the desired quality in the rolled products.

The aim of the work is to investigate metal flow during billet deformation in a helical rolling mill at feed angles β = 12°, 14°, 16°, 18°, 20°. The obtained data are useful for extending the theory of helical rolling, as well as for creating a methodology for analytical calculation of metal forming along given trajectories and for controlling the formation of structurally sensitive material properties.

Methodology of the study

The study of metal flow during deformation is based on the analysis of changes in the macrostructure of billets, namely, the transformation of radially oriented macrostructure of the initial billet into a spiral-type m acrostructure after deformation in a helical rolling mill.

In the present study, aluminium alloy billets of technical purity A85 (GOST 11069–2001) were utilised as the material for the investigation of metal flow during deformation. The material has demonstrated its efficacy in the following studies [10, 11, 35–38] due to its distinctive texture and the capacity for precise visual assessment of its alterations following deformation. Billets (ingots) with a diameter of 63 mm and a length of 250 mm from this material were obtained by smelting in a graphite casting mold. This method of billet preparation has been shown to reveal the macrostructure with radially oriented fibre arrangement along the entire length of the cross-section **(Fig. 1)**.

The ingots were subjected to rolling in the MISIS-100 T radial shear rolling mill (see **Fig. 2**), utilising rolls with a barrel diameter of 207 mm and a length of 250 mm. The technical characteristics of the equipment of the RSR mill

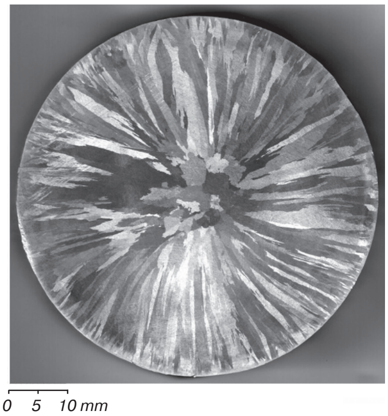

Fig. 1. Macrostructure of cast billet with diameter 63 mm and length 250 mm from aluminium of technical purity grade A85

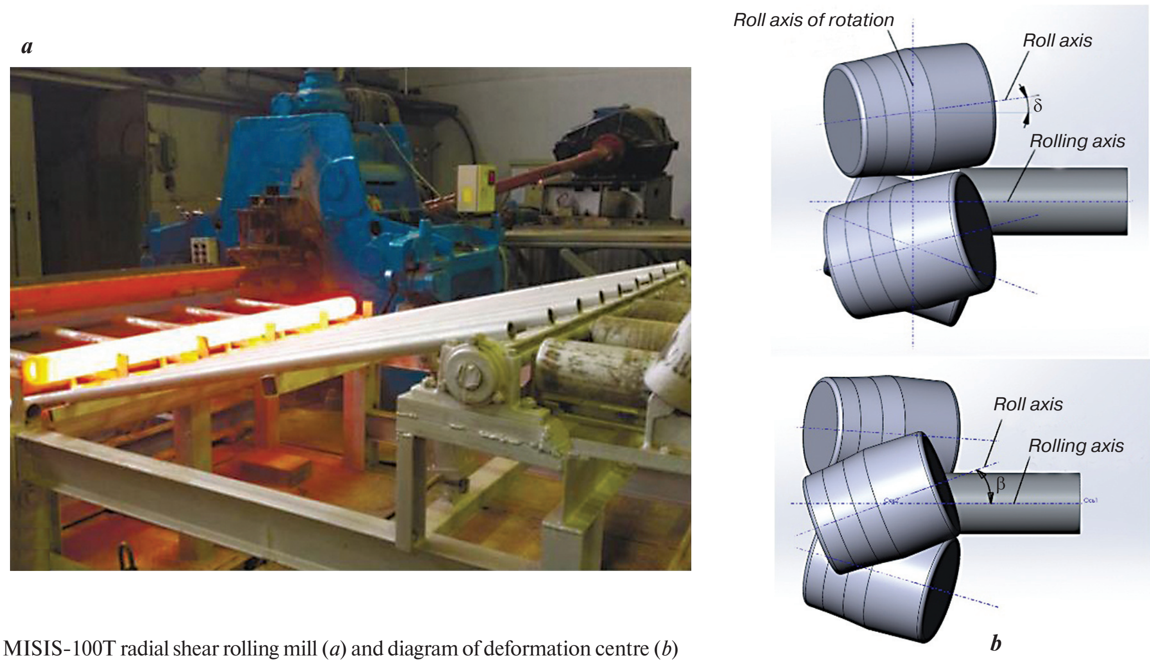

Fig. 2. MISIS-100T radial shear rolling mill (*a*) and diagram of deformation centre (*b*) (*photo by authors*)

Table 1
Technical characteristics of MISIS 100T radial shear rolling mill

Parameter	Value
Dimensions of the original workpiece: – diameter, mm – length, mm	 120–50 900–2000
Dimensions of the rolled billet: – diameter, mm – length, mm – accuracy, % – flexion, mm/m	 28–70 up to 6000 up to 1 up to 1
Lengthening coefficient, μ	1.1–4.0
Setting range of feed angle β, degree	12–27
Productivity, t/h	1.0–5.0
Drive power, kW	3×100
Stand weight, t	12.0

Table 2
Geometric dimensions of billets after rolling at different feed angles

Feed angle β, degree	Outer diameter of the workpiece D_w, mm	Lengthening coefficient, μ
12	42.1	2.2
14	40.2	2.5
16	41.1	2.3
18	41.1	2.3
20	41.2	2.3

are presented in **Table 1**. **Fig. 2, *b*** provides a visual representation of the deformation centre of a three-roll helical rolling mill.

The deformation of billets was conducted at feed angles of β = 12°, 14°, 16°, 18°, and 20°, with a constant rotational speed of the working rolls of $N = 76$ rpm, in a single pass from a diameter of ∅63 to a diameter of approximately ∅40 mm. Aluminium billets were deformed without preheating (i.e. at a temperature of +20 °C) in order to preserve the deformation texture. The initial temperature of the rolls used in the deformation process was approximately 150 °C. Subsequent to the rolling process, billets were obtained, and their diameter is presented in **Table 2**.

The selection of templates with initial cast structure was carried out at a distance of 30 mm from the bottom of the ingot. The rolling process was executed by positioning the billet with the ingot's lowermost section. Subsequent to the rolling process, the templates were sampled in the zone of steady rolling process (more than two diameters from the end of the billet ≈80 mm) from the side of the bottom part of the ingot.

Marble solution (20 g $CuSO_4$, 100 cm^3 HCl, 100 cm^3 C_2H_5OH) was used to reveal the macrostructure of the samples.

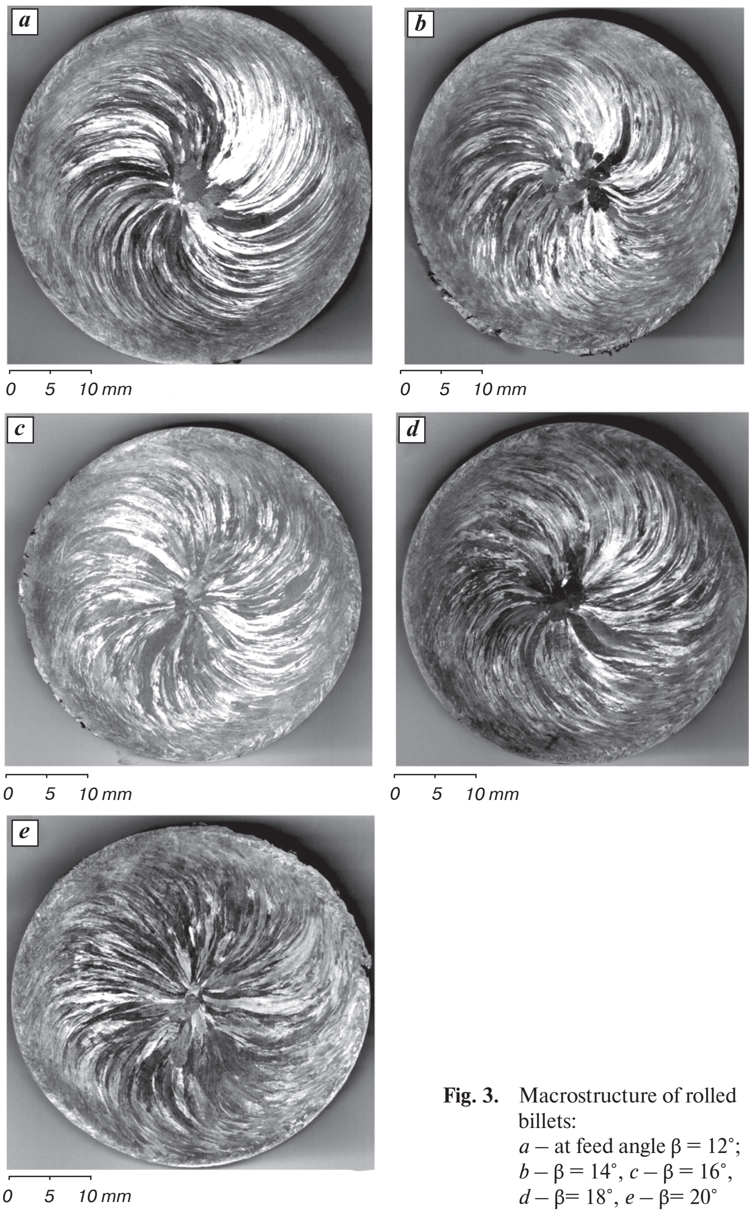

Fig. 3. Macrostructure of rolled billets:
a – at feed angle β = 12°;
b – β = 14°, *c* – β = 16°,
d – β= 18°, *e* – β= 20°

Results and discussion

The revealed spiral macrostructure of the billets rolled in the helical rolling mill at varying feed angle and drawing ratio: β = 12°/μ = 2.2, β = 14°/μ = 2.5, β = 16°/μ = 2.3, β = 18°/μ = 2.3, β = 20°/μ = 2.3, is shown in **Fig. 3**.

The study of metal flow during the rolling of aluminium billets was carried out by transforming the radial-oriented structure of the initial ingot **(Fig. 1)** into a spiral structure after deformation in a helical rolling mill **(Fig. 4)**.

The metal flow study was carried out in the area of:

– the central zone of the workpiece with radius $r_c = 3.5$mm (diameter $D_c = 7$ mm);

– the peripheral zone r_k = 18.5mm (diameter D_z = = 37 mm) **(Fig. 4, *d*)**.

The restriction of the area of study of shear lines in the peripheral part (zone III, **Fig. 4, *d***) of the billet is attributable to the fact that, in this region, during the process of rolling steel billets, nickel-based alloys, titanium alloys, hard-deformed steels and alloys, aluminium alloys and others, no mechanical texture of materials is formed during deformation, because the structure is finely dispersed [1, 16, 29]. Simultaneously, during the deformation of aluminium billets, the mechanical texture appears in the form of "reverse" flow [10, 11], oriented in the opposite direction to the formed spiral structure in zone II **(Fig. 4, *d*)**.

In the central area of the ingot, a zone with coarse grains was observed, which is crushed during the process of rolling **(Fig. 3)**. Due to the absence of clarity in visualising shear lines in the central region of the billet post-rolling, the radius of shear line investigation is constrained to r_c = 3.5 mm for all rolled billets.

In order to investigate the metal flow, the "averaged" shear line l_γ, obtained by "averaging" the lines identified on the macrostructure of the deformed specimen, was determined. This was achieved by delineating 6–8 lines that were clearly visualised and identified on the macrostructure (**Fig. 4**), lying at the intersection of the radius r_c and the horizontal axis X (**Fig. 5**).

The "averaged" shear line was determined by reducing the obtained contours of the shear lines of the 'spiral structure' to a single point by means of transformations.

In the process of transforming the contours of the shear lines, it was observed that the lines obtained cut off different parts of the arc at the point of intersection with the contour of radius r_k. To facilitate a comparative analysis of the data, the maximum (angle a_1) and minimum angle (a_2) of the arc lying on the radius r_k were measured (**Fig. 4, *d*, Table 3**). The discrepancy between these angles

Table 3
Maximum (a_1) and minimum (a_2) arc angle

Feed angle β, degree	Arc angle, degree	
	a_1	a_2
12	109.2	93.2
14	86.7	74.8
16	72.1	57.2
18	61.0	43.1
20	39.8	28.3

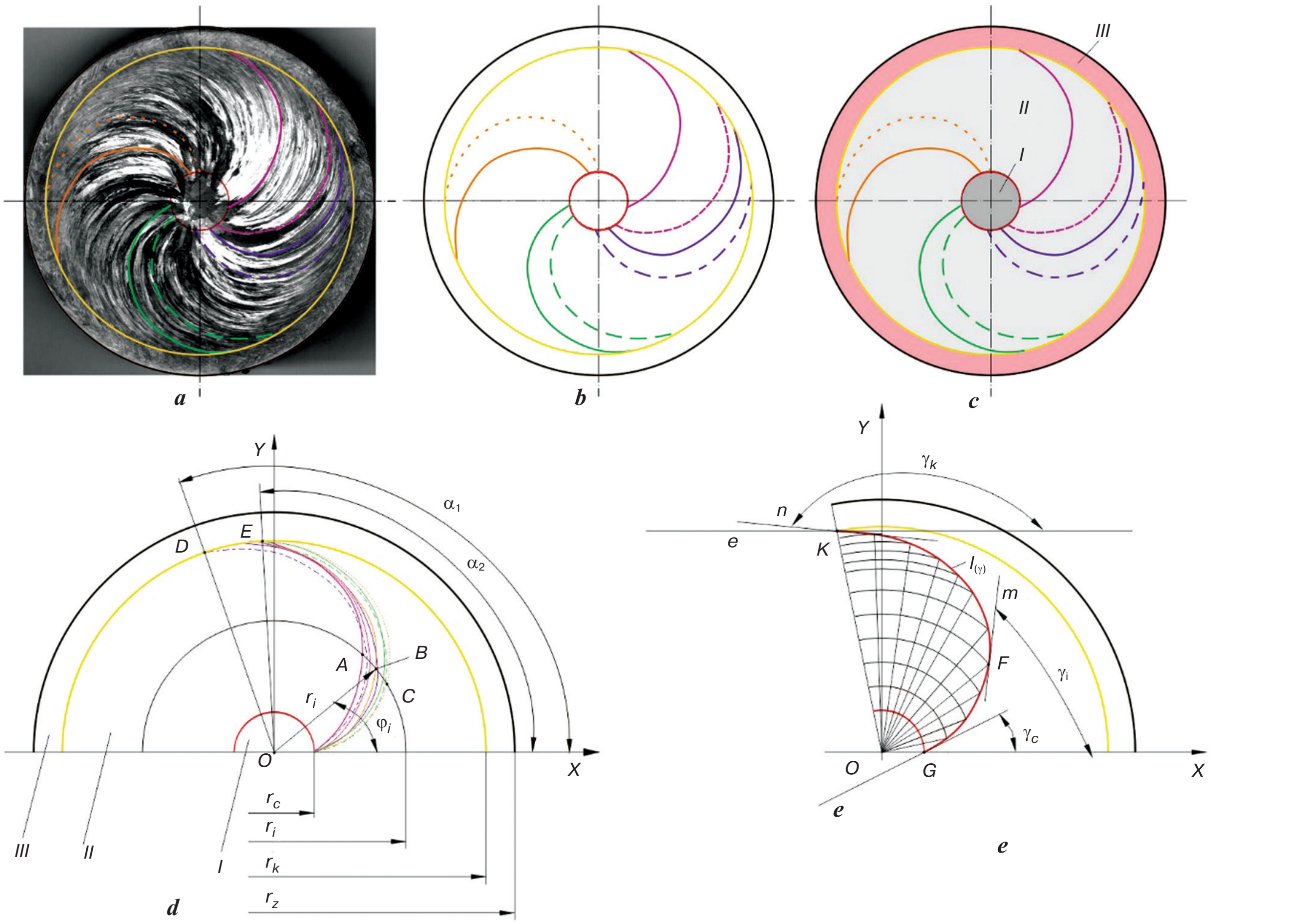

Fig. 4. Identification of the "average" shear line $l(\gamma)$:
a – macrostructure of the specimen deformed at feed angle β = 12° and outlined shear lines, *b* – outline of the identified shear lines, *c* – scheme of the shear line investigation area (*II*), *d* – scheme of determining the "average" shear line l_γ, *e* – scheme of determining the shear angle (γ)

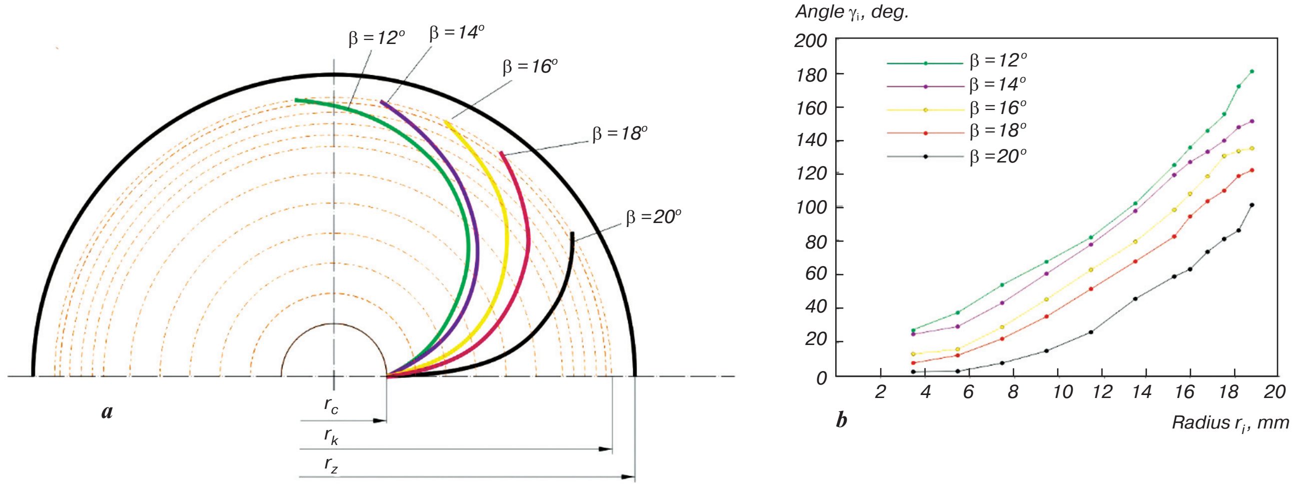

Fig. 5. "Average" shear lines after deformation in MISIS 100T radial shear rolling mill (*a*) and shear angle of structural fibre (γ_i) as a function of radius r_i at different feed angles β (*b*)

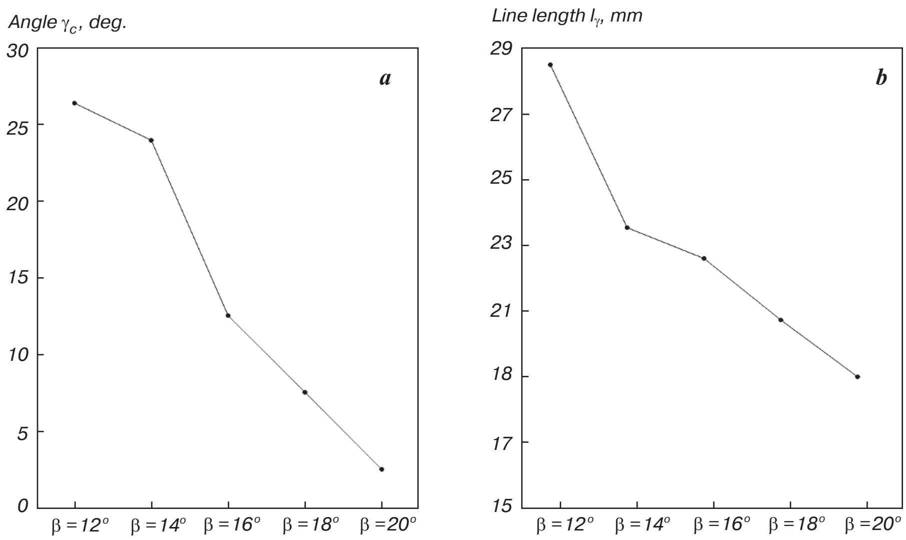

Fig. 6. Variation of shear angle (γ_c) near the centre of the workpiece (*a*) and shear line length l_γ (*b*) from feed angle β

(a_1 and a_2) is indicative of the precision achieved in the transformations performed.

The point *B* of the "averaged" line, lying on the radius r_i, was defined as the centre of the arc that is bounded by points *A* and *C* and belongs to the contours of the shift lines brought to one point **(Fig. 4, *d*)**.

The utilisation of the integrated functionality within the graphical editor facilitated the delineation of an "averaged" shear line (l_γ), thereby enabling the determination of the shear angle (γ_i) of the structural fibre, as illustrated in **Fig. 4, *e***.

The contours of "averaged" shear lines obtained by processing the graphic editor of the macrostructure of samples deformed with different feed angles are presented in **Fig. 5, *a***. The change of angle (γ_i) depending on the feed angle (β) is presented in **Fig. 5, *b***.

As is evident, with an increase in the feed angle β, there is a concomitant decrease in the shear angle γ_i of the structural fibre in the cross section. This phenomenon can be attributed to the distinct characteristics of metal flow.

When rolling is undertaken with equal drawing coefficients and the value of the feed angle β is increased, private compression increases and the number of deformation cycles decreases. This is advantageous to more intensive metal flow in the longitudinal direction [1, 2, 4, 5, 10, 39, 40].

In accordance with the findings of preceding studies [20, 40], it has been demonstrated that for the rolling process, a negligible alteration in the feed angle is reflected in the indices of mechanical properties. It has been established that screw rolling of a billet with a moulded structure, exhibiting insignificant drawing coefficients ($\mu < 1.5$), results in a substantial enhancement of mechanical properties [14, 20, 40]. Concurrently, the longitudinal direction demonstrates a more pronounced enhancement in mechanical properties when compared to the tangential direction [20, 40].

It is evident that the geometry of the spiral-shaped macrostructure is influenced by the feed angle, as illustrated in **Fig. 5.** This observation reflects the plastic flow in the centre of deformation in the cross-section of the billet. Consequently, it is possible to control the plastic flow of metal, thereby affecting its physical and mechanical properties. In this instance, the rolling process with large feed angles (β > 16°) creates the effect of volumetric macroshift, which contributes to the elaboration of the metal structure at all levels of metallographic structure.

The experimental data obtained has been analysed, and it is evident that as the feed angle increases, the shear angle γ_c decreases (see **Fig. 6, *a***). For instance, at a rolling feed angle of β = 120, the shear angle γ_c is measured at 26.4°, and at β = 200, it is recorded at 2.7° (a difference of approximately 9.8 times). A significant decrease in the shear angle γ_c is evident near the centre of the billet after rolling with a feed angle β > 16° (**Fig. 6, *a***).

The alteration in the feed angle during the process of rolling is also reflected in the length of the "averaged" structural fibre line l_γ (see **Fig. 6, *b***). Rolling of billets at a feed angle β = 12° results in an average shear line length of l_γ = 28.48 mm, whereas at β = 20°, the length is l_γ = = 19.01 mm (a difference of approximately 1.5 times).

Conclusions

This paper proposes a novel approach to experimental research, namely the comparative analysis of the change of a radial-oriented structure that transforms during deformation into a spiral shape. This method has the potential to control the plastic flow of metal, and it is realised by a method known as radial-shift rolling.

According to the developed method the influence of the feed angle (β) on the character of the spiral structure change was revealed:

– with the increase of the feed angle the shear angle near the central part of the workpiece changes significantly (at β = 12° the shear angle γ_c = 26.4°, and at β = 20° the shear angle γ_c = 2.7°. The difference is ≈ 9.8 times.

– with the increase of the feed angle the length of the spiral structure decreases in ≈ 1,5 times (at β = 12° the length l_γ = 28.48 mm, and at β = 20° the length l_γ = = 19.01 mm).

2. The identified trends indicate that the feed angle is the primary technological parameter that governs the trajectory shape change of metal in the deformation centre.

3. It has been demonstrated that increasing the feed angle to above 16 degrees has a beneficial effect on reducing the differences between the periphery and centre zone of the bar in terms of the intensification of deformation processes along the section.

4. The data obtained can prove advantageous in facilitating the advancement of the theory and the analytical calculations of the parameters of shape change during three-roll helical rolling. Furthermore, it can assist in enhancing the structure-dependent properties of metals and alloys.

5. In this study, the aluminium alloy A85 was selected as the model alloy. It is evident that this alloy undergoes a transformation of its radially oriented macrostructure into a spiral macrostructure during the process of helical rolling. However, it should be noted that this feature is not exclusive to the alloy A85 and is instead a characteristic that can be observed in all materials that exhibit a pronounced texture subsequent to deformation.

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