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STUDY OF THE FORMING MECHANISM OF THE CENTRAL DISCONTINUITY FLAW WITH DIFFERENT DIAMETERS AND DEFLECTED MODE OF CONTINUOUSLY CAST BILLETS IN CONDITIONS OF NONSTEADY ROLLING PROCESS

Finite element DEFORM™ 3D a commercial code based on the rigid-plastic finite-element method software is employed to examine the behavior of plastic flow in deformation zone during billet rolling out of square stock of spring steel 60C2 with size 150x150mm and central axial discontinuity flaw with size 3, 5 or 8mm under various rolling conditions. As a result of the study in non-stationary rolling process conditions have obtained data on the distribution of the effective stress, the effect of initial temperature of rolling on the behavior of discontinuity flaw with various diameters during rolling.
Keywords: *central discontinuity flaw, deflected mode, continuous cast billet, nonsteady rolling process, metal forming, finite element analysis.*
Fig. 5. Lit. 17.

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ВИВЧЕННЯ МЕХАНІЗМУ ФОРМОЗМІНЕННЯ ЦЕНТРАЛЬНОЇ НЕСПЛОШНОСТІ РІЗНИХ ДІАМЕТРІВ І НАПРУЖЕНО - ДЕФОРМОВАНОГО СТАНУ БЕЗПЕРЕРВНО-ЛИТОЇ ЗАГОТОВКИ В УМОВАХ НЕСТАЦІОНАРНОГО ПРОЦЕСУ ПРОКАТКИ

Програмний комплекс DEFORM - 3D, який використовує метод кінцевих елементів при розрахунках, був обраний в якості інструменту для аналізу поведінки пластичної течії в осередку деформації при деформуванні заготовки з ресорно - пружинної сталі 60С2 квадратного перетину 150х150мм і наявністю центральної осьової несплошності розмірами 3, 5 і 8мм за різних умов прокатки. В результаті проведених розрахунків в умовах нестаціонарного процесу прокатки отримані дані про характер розподілу ефективних напружень, вплив температури початку прокатки на поведінку несплошностей різних діаметрів при прокатці.
Ключові слова*: центральна несплошність, напружено - деформований стан, безперервнолита заготівка, нестаціонарний процес прокатки, деформація, метод кінцевих елементів.*

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ИЗУЧЕНИЕ МЕХАНИЗМА ФОРМОИЗМЕНЕНИЯ ЦЕНТРАЛЬНОЙ НЕСПЛОШНОСТИ РАЗЛИЧНЫХ ДИАМЕТРОВ И НАПРЯЖЕННО – ДЕФОРМИРОВАННОГО СОСТОЯНИЯ НЕПРЕРЫВНО-ЛИТОЙ ЗАГОТОВКИ В УСЛОВИЯХ НЕСТАЦИОНАРНОГО ПРОЦЕССА ПРОКАТКИ

Программный комплекс DEFORM – 3D, который использует метод конечных элементов при расчетах, был выбран в качестве инструмента для анализа поведения пластического течения в очаге деформации при деформировании заготовки из рессорно – пружинной стали 60С2 квадратного сечения 150х150мм и наличием центральной осевой несплошности размерами 3, 5 и 8мм при различных условиях прокатки. В результате проведенных расчетов в условиях нестационарного процесса прокатки получены данные о характере распределения эффективных напряжений, влиянии температуры начала прокатки на поведение несплошностей различных диаметров при прокатке.
Ключевые слова: *центральная несплошность, напряженно – деформированное состояние, непрерывно – литая заготовка, нестационарный процесс прокатки, деформация, метод конечных элементов.*

Statement of the problem. Occurred in recent years the transition from the ingot to the continuously cast billet steelmaking conversion outlined a number of priority areas related to further improve the quality of the final steel products. These include the stability of the chemical composition of the steel and macrostructure on section of continuously cast ingot, reduction of harmful dangerous nonmetallics as well as detrimental impurities and minimizing the workpiece surface defects [1, *354-378*]. However, from the point of rolling production view have been demanded a whole set of additional research related to the geometry features of the continuously cast billet.

Analysis of the literature has shown [2, *4*] that in the mathematical modeling in the most cases the following parameters are taken into account for describing metallurgical quality of the workpiece. The chemical composition of steel is taken into account by specifying heat-transfer properties. The shape of the workpiece surface defects is taken into account while creating a solid model of a billet and during consequent study of the defect behavior during rolling. At the same time, the least accounted to be considered are such metallurgical properties that relate to the macrostructure parameters of continuously cast billets (porosity, shrinkage cavity). This state of affairs is mainly determined by the peculiarities of the production technology continuously cast billets in each metallurgical company. It primarily relates to the set of available production tools for improving the quality of billets as such: electromagnetic stirrer, vacuum degasser, soft dynamic reduction equipment, etc. As in order to increase profitability of manufacturing the electric steelmaking complexes use a minimal set of technological tools to improve the quality continuously cast billet so this issue should be considered poorly known. To ensure the rapid implementation of changes in cost-effective manufactured production it is necessary to develop a mathematical model.

The analysis of recent research and publications. Voids are usually present in a slab or billet manufactured by casting due to the decreased gas solubility as well as the contraction of volume during cooling and solidification. Since these voids adversely influence the mechanical properties of the slab or billet, they need to be closed by subsequent processes such as forging or rolling. However, the closure of a void differs for locations since the stress distribution in a slab or billet is inhomogeneous [3, *2871-2876*].

Several studies have been performed to understand the phenomenon of void closure in an ingot or a slab occurred by plastic deformation during rolling processes. Wang et al. [4, *95-102*] investigated the closure and welding phenomena of cylindrical and round voids in a slab during hot rolling, and found that heavy reductions with large rolls were effective for the void closure, and that large magnitudes of hydrostatic stress for a sufficient time were effective for welding of closed voids. Ji et al. [5, *1591-1596*] investigated the void closure in rolling of a heavy slab, and found that a void at the middle layer was the most difficult to be closed since the hydrostatic stress as well as the effective strain at the location were the least in magnitude.

Because of its importance, void closure has been studied for more than 30 years. Various methods, such as upper bound analysis [6-8, *233–242; 133–143; 65–81*], finite element method [9 - 15, *65–75; 852–859; 238–244; 1035–1042; 195–200; 526–529; 95-102*] and experimental investigation [16-17; *633–645; 521–524*] are used to develop predictive measures for void closure during forging and rolling processes. For this study the finite element DEFORM™ 3D a commercial code has been chosen.

The gain of this paper is to study the forming mechanism of the central discontinuity flaw with different diameters and deflected mode of continuously cast billets in conditions of nonsteady rolling process in conditions of first section mill stand.

The mathematical modeling. This study has been conducted by mathematical modeling of continuously cast rolling billets made out of spring steel grades which are defective by axial discontinuity flaw at the conditions of a nonsteady rolling process. The preparatory phase of the study has been done in order to maximize the objectivity of the input data. The industrial experiment has performed to clarify causes of shrinkage phenomena under conditions of PJSC "Electrosteel" (Kurahovo city). The material for the study were billets out of steel 60C2 which were obtained by cutting an initial billet into four equal parts each is equal to 300 mm of length. The resulting samples have been cut by various ways: cutting by burn off (30 pieces), cutting by cold saws (20 pieces) and combined cutting method (12 pieces) where a one end of the billet cuts by cold saws and the second cuts by burnt off. After cutting each test material has been treated by rolling and estimation of crack tip billets have been done. The results of this full-scale experiment have established as a classification of mostly common axial flaw discontinuities (with diameters 3, 5 and 8 mm) (*Fig. 1*). The real rolling defects are classified in order to simulation help.

At the next stage of the research have been designed a solid model in the software package DEFORM™ 3D. The following assumptions were made to this aim: 1) all rollers are rigid bodies; 2) the investigated porous billets are fabricated out of plastic material; 3) the friction coefficient between the workpiece and the rolls remains constant during the rolling process.

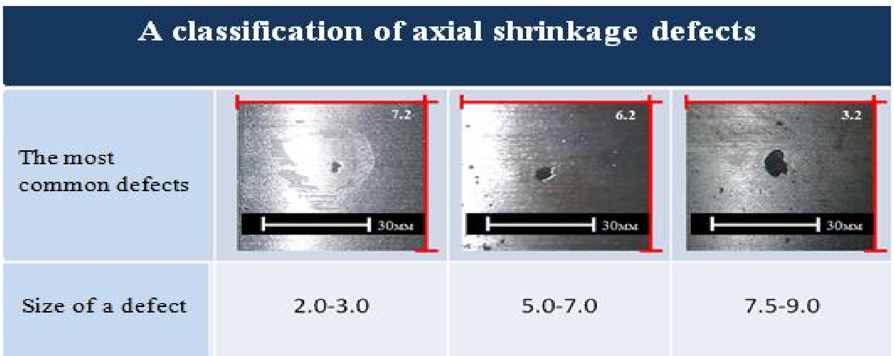

Fig. 1. **A classification of axial shrinkage defects. Authoring**

A solid three-dimensional model of working tool (rolls) and workpieces have been created in the AutoCAD ** in order to transfer they into DEFORM™ 3D* software. The assembly have been transported into DEFORM™ 3D after objects positioning (*Fig. 2*). Models of the pores have been designed in such way that they have a length equal to the diameter of the pores. As test piece materials

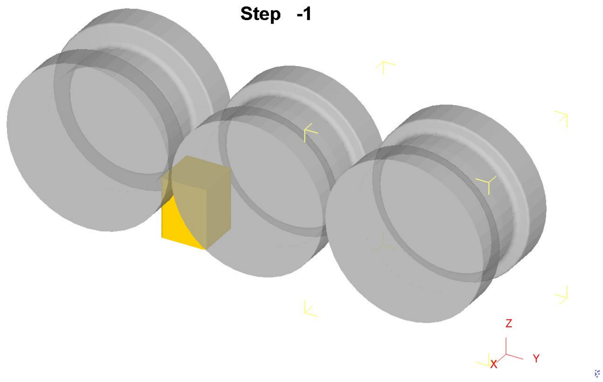

Fig. 2. **The three-dimensional model of rolling billets with a central discontinuity flaw at the first caliber. Authoring**

were chosen billets out of 60C2 (the analogue of steel AISI 9261 (900-1200°C)) with cross section 150x150mm and length 200mm. The initial temperatures of rolling are varied and have the following values in each series of experiments: 1200°C, 1150°C, 1100°C and 1050°C. For an objective description of thermal processes which are take place while rolling a battery of studies was execute aimed to determine the temperature of billets with different diameters of discontinuity flaw under initial temperatures of rolling 1200°C, 1150°C, 1100°C and 1050°C and different cooling time 20s, 40s, 60s. The obtained data of temperature change on the cross and longitudinal sections were used for establishing the workpiece boundary conditions during simulations. The each roll temperature is 200°C and assumed to be time-constant temperature.

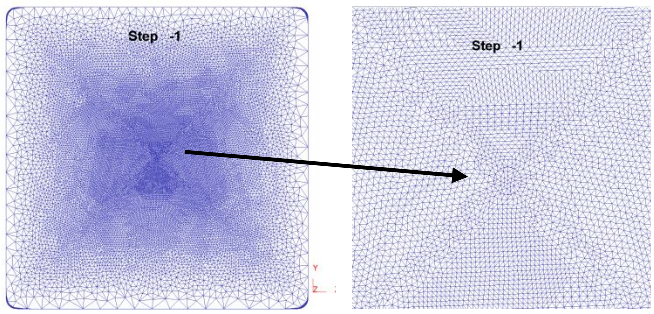

Fig. 3. **Finite - element mesh for a continuously cast billet with a diameter of central discontinuity flaw defect 3 mm. Authoring**

Finite element analysis is based on rigid - plastic rolls model so that temperature changes during the rolling process are quite small and can be neglected. The analytical model is used to examine the following system parameters: initial temperature of rolling, time of billet out of the furnace and temperature changes during the rolling process depending on the size of the pore in the condition of remain other process parameters (rolls velocity, billet reduction rate, etc.). However, the closure of the discontinuity flaw depends on the location of applied force since the distribution of stresses in the workpiece inhomogeneous. In this study simulated discontinuity flaw are considered as a cylindrical defect. The direction applied compressive strain is planar and situates at the width of billets.

Fig. 3 shows a finite - element mesh for a continuously cast billet with a diameter of central discontinuity flaw 3 mm before the rolling process. Note that the fine elements were distributed around the void in order to describe its geometric changes during rolling more precisely. Since strains are mainly dominate on the progress of the void closure, a series of the finite element analysis were performed to investigate the influence causes by billet deformation parameters.

Geometric changes in terms of the length of the major axis of the pores is determined as the ratio of the minimum voltages of the pore obtained by the finite element analysis of billet without pore under the same conditions. Although pore is an empty space, the term of deformation is used in this context for the purpose of convenience.

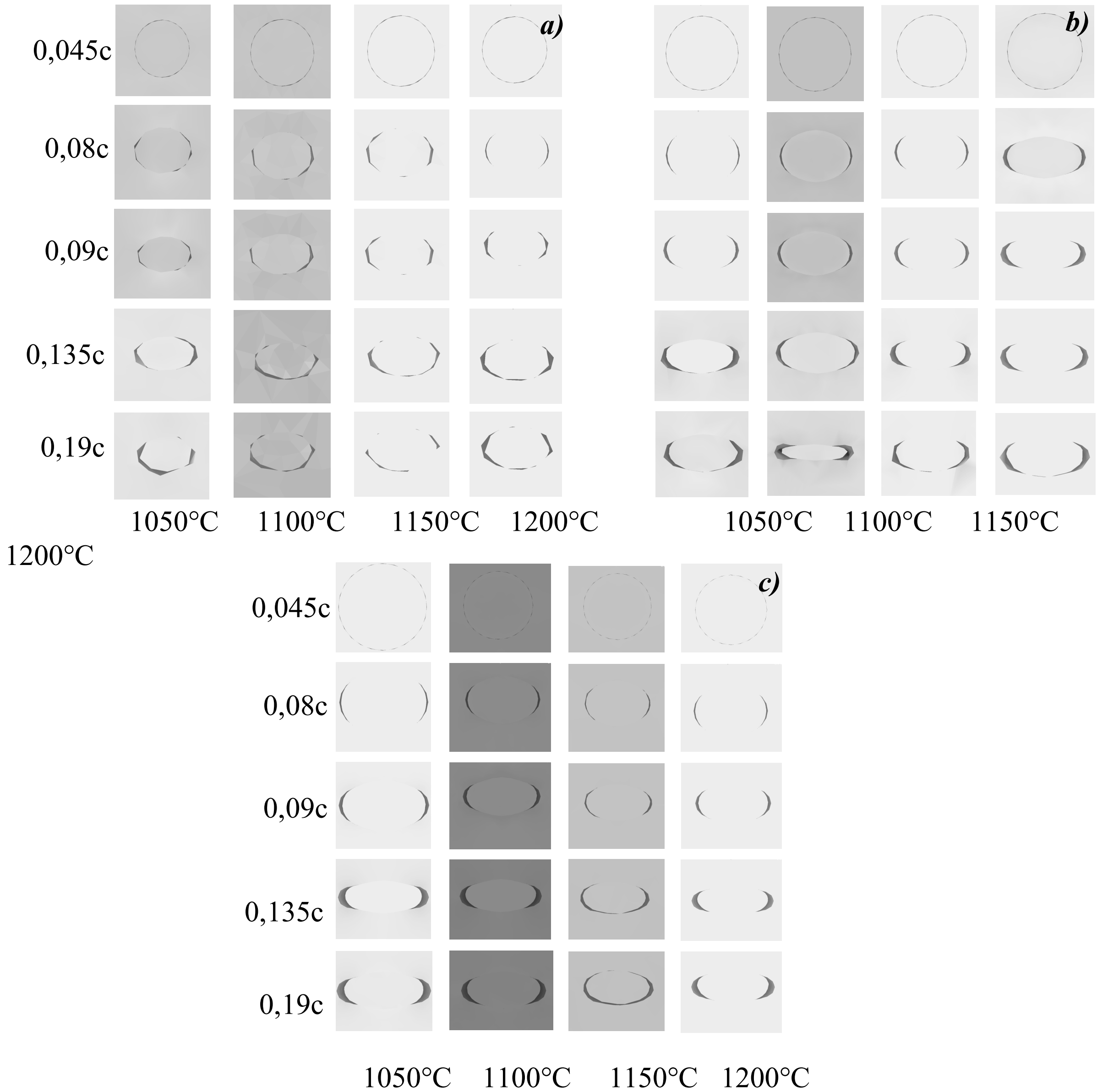

Fig. 4. **The central axis pore forming stages depending on time and the initial temperature of rolling:** *a)* **the central axis pore is equal to 3 mm;** *b)* **the central axis pore is equal to 5 mm,** *c)* **the central axis pore is equal to 8 mm. Authoring**.

Fig. 4 shows the behavior of a central axis discontinuity flaw deformation with various diameters obtained by the finite - element analysis. As seen from *Fig.4* a central axial discontinuity was deformed by several stages. At the first stage it was compressed by induced load and then metal started to failure. In the time point 0.09 seconds after rolling start the maximum dimensional changes are occurred. Has been found that the billet with a pore diameter 3mm in the time point 0.135 seconds and under initial temperature of rolling 1100°C has maximum forming changes of 0.3 mm which is on 10% above of the initial diameter of the discontinuity flaw. As shown by the simulation results, the annihilation of pore has the best effect when initial temperature of rolling is equal to1100°C. In *Fig. 4* these temperatures are colored by dark.

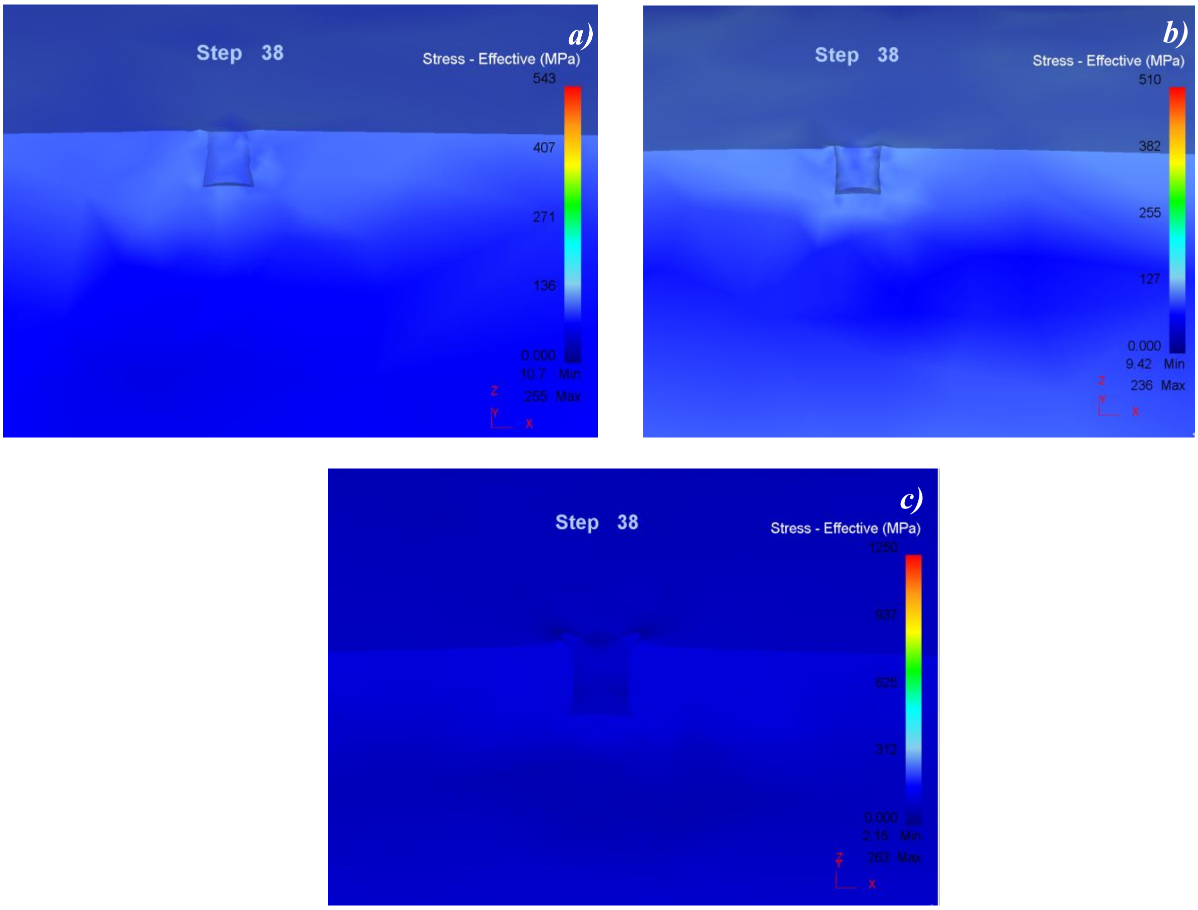

Fig. 5. **The central axis forming stages depends on different diameters in longitudinal section and time (T_{roll} = 1050°C):** *a)* **3 mm,** *b)* **5 mm,** *c)* **8 mm. Authoring**

The finite - element analysis of the billet with a discontinuity diameter 5mm has shown, that the maximum length of the pore is achieved in 1200°C and is 5.8 mm and the minimum length of the pore in 1100°C and is 5.00 mm. Also, like last time, the optimal temperature for defect closure is initial temperature of rolling of 1100°C.

Analysis of the discontinuity model forming with a discontinuity diameter 8 mm has shown the following results. To ensure a minimum length of the pore should be rolling under the temperature 1150°C while minimum length of the major axis of the ellipse has achieved 8.7 mm which is by 8.7% more than the original diameter. The choice of the temperature explained by the high expenditure of energy in order to ensure the sufficient flow rate for geometry changes of large pore. The least favorable porosity annihilation parameter is an initial temperature of rolling. The initial temperature of rolling 1200°C favors the development of a very large pore extent in the billet 9.44 mm which is almost impossible to eliminate.

As a criterion for characterizing the efficiency of pore closure process has chosen effective stress. The effective stress is used to describe the process of pore closure which is shown in *Fig. 5*. The discontinuity flaw closure which is takes place in the metal during rolling varies considerably because of the inhomogeneous stress deformation distribution that is depends on the location of the pore. The finite - element analysis has shown that inhomogeneous compression distributed not only but also on the longitudinal section of billets. *Fig.5, a* shows a longitudinal billet section with a central axial discontinuities diameter 3mm. According to the analysis, the height of this pore at the time point 0,19 seconds reaches value 3.13...3.23 mm. A diameter of this cross section changes from 2.24mm to 3.03mm under an average effective stress 115 MPa. The height of the billet with a central axial discontinuities diameter 5mm at the same time point reaches 5.85...5.93 mm and the diameter of the cross section changes from 5.41mm to 5.57mm under an average effective stress 117 MPa (*Fig. 5,b*). The billet with the largest central axial discontinuities diameter 8mm under an average effective stress 109 MPa is characterized by the following parameters: the height of the pore changes from 8.6mm to 9.4 mm, the diameter of the cross section fluctuates from 6.1mm to 9.8 mm (*Fig. 5,c*).

The smallest central axial discontinuities diameter 3mm of billet the minimal diameter reaches at the bottom of it. In contrary, the billet with the largest central axial discontinuities diameter 8mm reaches its minimum diameter at the top. The pore with a diameter 8mm have formed its outline as a funnel which is comes out by its maximal diameter under applied rolling forces while the small pore has been carried by flow of metal due to its small size. The billet with the medium central axial discontinuities diameter 5mm has almost the same height and cross-sectional diameter which helps obtaining in further homogeneously filled geometry.

The main results of the study. The closure phenomenon of a cylindrical void with a circular cross section in a continuously cast billet under plane – strain compression was investigated by the rigid-plastic finite element method, assuming voids are negligibly small compared to the billet in size. The industrial experiment was performed to define the most common defects of discontinuity flaw. The behavior of the forming mechanism of a central discontinuity flaw with different diameters has been studied as well as deflected mode of continuously cast billets in conditions of nonsteady rolling process.

Further research in this area. Received simulations results at this stage of the study analyze allow to go to the next stage of research. Future laboratory tests based on the finite - element analysis will provide the output experimental data and make comparative analysis. Clearly, these analytical results can provide useful knowledge for designing the pass-schedule of flat-and-edge rolling processes for eliminating or maximum closing internal voids.

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