DOI: 10.17580/cisisr.2019.01.06

USAGE OF PHYSICAL AND MATHEMATICAL SIMULATION FOR IMPROVEMENT OF THE PROCESSES OF METAL SHEAR CUTTING

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Key words:

shear cutting, flat punch, steel rolled coils, strip billets, stress-strain state, mathematical simulation, multi-disc shears

ABSTRACT

Possibilities of usage of imitating simulation for improvement of efficiency of wasteless shear cutting in the dies and the shears are examined. These processes are applied in blanking production facilities at metal processing companies that use section and sheet rolled metal. The relevance of this study is stipulated by increase of rolled metal cost and necessity to put into practice the resource-saving technologies. Conventional approaches to development of technologies on the basis of physical simulation are analyzed and it is offered to use computer simulation for essential reduction of time for preparation of production. The processes of the cantilever and two-bearing segments of the section billet are investigated.
The results of simulation of the process shear cutting of rolled section metal on the crank press and in the computer, using the finite element medium are presented. Based on the experimental results, mathematical models in the form of regression equations to determine geometric parameters of the process are developed. The analysis of the stress-strain state during cutting of rolled steel coils in strip billets using multi-disc shears incorporated in longitudinal cutting lines is performed. Mathematical models of geometrical parameters as quality indicators are developed on the basis of passive production experiment and processing of its results by the methods of statistics. The stress-strain state in the process of cutting of rolled steel coils into strip billets is determined. These results made it possible to optimize the process depending on the mechanical properties of the rolled products and their thickness, as well as to improve the quality of separation surface of the billets.

Introduction

The method of billet fabrication from rolled metal mainly determines production efficiency and product cost. There are several dozens of the methods of billet fabrication from sheet and section rolled metal as well as from tubes in metallurgy and machine-building. These methods differ essentially by their technical and economical parameters. The methods of separation using machine tools and saws were used in the end of the XX century, and they were accompanied by forming of large amount of wastes presented by chips. As soon as the cost of metal products increases by tens and hundreds times during several last decades, wasteless heavy-duty methods of rolled material separation in billets by shearing using dies and shears are considered as the most efficient; these processes are realized by advancing motion of moving blade relating to fixed one.

Rise of geometric accuracy and improvement of billet quality after their shear cutting from rolled material is the aim of this study, using laboratorial and passive production experiment with consequent processing of its results via the methods of regression analysis, mathematical statistics and finite element simulation.

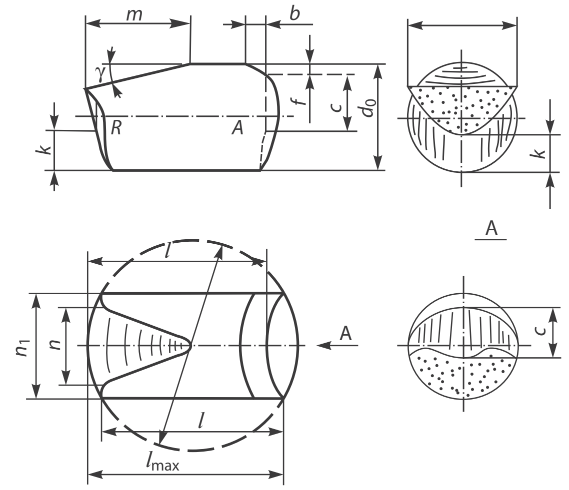
Theoretical aspects of separation processes have been examined in the works of many national and foreign researchers, such as E. A. Popov, V. T. Meshcherin, V. A. Timoshenko, G. Zemann (Germany), A. G. Lisin, F. P. Mikhalenko etc.

The main researching methods used in this study were the following ones: slip-line method, experimental-analytical method (including joint solution of differential equilibrium equations and ductility conditions) and upper-bound method (energy method).

The studies devoting to improvement of shear cutting processes have been initiated more than half-century ago in Mosstankin institute (at present time Moscow State Technical University "Stankin") under leadership of prof. S. S. Solovtsov [1] and they were based on physical simulation. Dimensions of a billet were calculated, experimental equipment was designed and manufactured, laboratorial investigations were conducted, pilot-industrial dies were designed based on the technical drawing. Putting into practice of the results of these experiments continued for 5-10 years, while experimental equipment weighted from hundreds kg to several tons. At present time it is possible to cut essentially labour intensity of experimental studies and preparation of production owing to appearance of large number of computer systems and graphic programs realizing engineering and technological production preparation using CAD methods on the market of intellectual property.

Technique of investigation of the shear cutting process for section rolled metal

Usage of the results of physical experiments together with the methods of mathematical simulation is considered as one of the tendencies of development of studying the metal forming processes. The method of experiment planning [2] was used in this work. Fractional factorial experiment (FFE) including conduction of 11 experiments without duplication has been conducted for simu-



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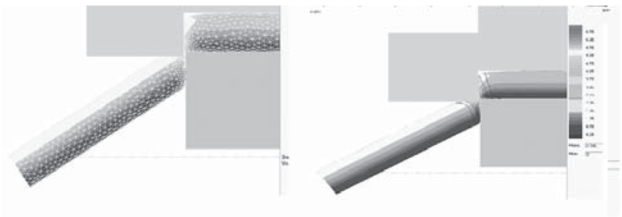

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Fig. 1. Scheme of measurement of billet parameters (*a*), cut from section rolled metal by a flat punch and finite element simulation of the cutting process (*b*)

lation of shear cutting processes of section rolled metal. The scheme of measurements of geometric parameters of physical simulation is presented on the **Fig. 1, *a*** [3].

The values of geometric parameters of the form inaccuracy (responses) obtained as a result of simulation based on FFE-2[3-1]-based simulation and processing of its results via the method of regression analysis and mathematical statistics are presented in the **Table**.

The following variable factors were examined: $\bar{l}_0, \bar{z}_n, \bar{z}_0$, (where $\bar{l}_0, \bar{z}_n, \bar{z}_0$ are relative length, transversal and axial gaps in relation to the length of rolled metal d_0, $\bar{l} = l/d_0$). Parameters presented at the Fig. 1, *a* were examined as responses (experimental results). The process models were built as regression equations based on processing of the experimental data [4]. So, the polynom for the model of edge chamfer angle γ characterizing geometric inaccuracy (deviation from the ideal cylinder shape) in the better way was presented by the following expression:

$$\gamma, [\text{degree}] = 15{,}1 + 0{,}57x_2 + 1{,}15x_3 - 0{,}4x_1x_2 - 0{,}07x_1x_3 - $$
$$- 0{,}25x_2x_3 - 0{,}167x_1^2 + 0{,}499x_2^2 + 0{,}166x_3^2 ,$$

where x_1, x_2 and x_3 are the coded values of the factors of relative length, transversal and axial gaps.

The finite element method was used to confirm the results of physical simulation. It was possible to simulate the above-mentioned experiment in the finite element programs *Q-FORM* (**Fig. 1, *b***) [5] and *DEFORM* [6] with usage of up-to-date computer systems. The features of forming during cantilever and two-bearing open cutting were established and their analogues with physical simulation were revealed. Forming of the areas with shrinkage holes, crumbling (as a result of plastic deformation) and deviation of the free billet part to a definite angle (edge chamfer angle) were mentioned among these analogues.

Discussion of the results

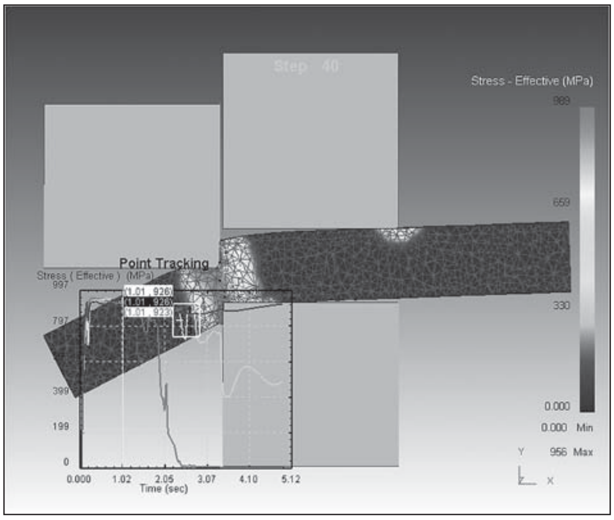
The conclusion about expedience of usage of two-bearing cutting was confirmed on the base of the results of imitating simulation in the finite element media (**Fig. 2, *b***) instead of cantilever cutting (**Fig. 2, *a***), owing to the more favourite scheme of the stress-strain state. In the case of two-bearing cutting the area of plastic deformation is localized in more narrow zone along the line of action of the maximal stresses. It leads to lowering of metal plastic deformation near separation area and, respectively, to reduction of distortions of geometric shape and dimensions of the billet subjected to cutting. The obtained results are characterized by good correlation with the data of physical experiment on metal samples that were cut from rolled metal via cantilever (**Fig. 2, *c***) and two-bearing (**Fig. 2, *d***) cutting.

It is expedient to apply two-bearing (multi-bearing, multi-positional) process for one-step cutting of several billets from a bar simultaneously. Multi-bearing cutting can elevate by several times cutting productivity of bars into billets using a punch, as well as to cut the billets of different length at the same time.

The first and consequent billets are characterized by different stress-strain states during cutting, ant it id the feature of multi-bearing cutting. The first billet is separated along one separation surface from cantilever bar part, while all consequent billets are separated just along two separation surfaces with two-bearing symmetric location of the cutting part. Thereby the first billet differs from the consequent ones in quality parameters and distortion of geometric shape; it is usually deleted.

Operating experimental matrix and results of investigation of cutting of round rolled metal from steel 10 with diameter 10 mm by flat cylindrical punch

No. of experiment	Operating matrix				Values of the responses						
	$\bar{l}_0$	$\bar{z}_0$	$\bar{z}_n$	γ, °	$\bar{m}$	$\bar{n}$	$\bar{c}$	$\bar{k}$	$\bar{n}_1$	$\bar{f}$	$\bar{b}$
1	2.37	0.0055	0.044	15	0.77	0.83	0.3	0.6	0.83	0.13	0.4
2	1.15	0.0055	0.012	14	0.83	0.77	0.3	0.6	0.78	0.09	0.2
3	2.37	0.0019	0.012	14	0.8	0.8	0.9	0.9	0.91	0.06	0.11
4	1.15	0.0019	0.044	16	0.7	0.9	0.6	0.9	0.89	0.13	0.3
5	2.82	0.0037	0.028	15	0.8	0.8	0.75	0.7	0.87	0.09	0.1
6	0.71	0.0037	0.028	15	0.7	0.92	0.8	0.7	0.87	0.13	0.3
7	1.76	0.0068	0.028	16	0.85	0.75	0.2	0.6	0.8	0.11	0.27
8	1.76	0.0006	0.028	16	0.8	0.8	0.8	0.8	0.97	0.1	0.26
9	1.76	0.0037	0.072	18	0.7	0.9	0.7	0.7	0.87	0.19	0.8
10	1.76	0.0037	0.000	14	1.2	0.4	1.0	0.7	0.85	0.03	0.1
11	1.76	0.0037	0.028	15	0.8	0.8	0.75	0.7	0.87	0.1	0.14



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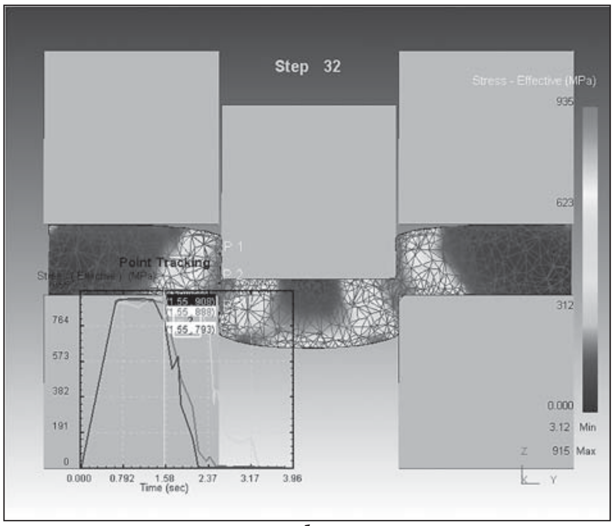

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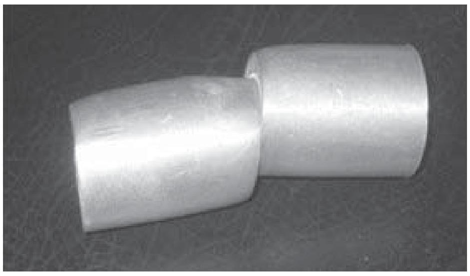

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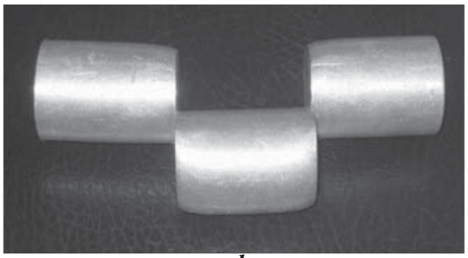
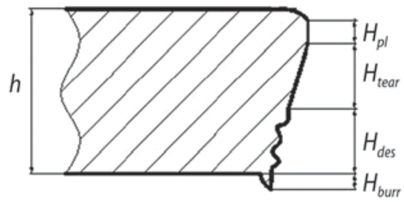


d

Fig. 2. Fields of stresses distribution during cantilever (*a*) and two-bearing (*b*) shear cutting on the base of calculation results in DEFORM-2D and kind of billets after cutting from rolled metal via cantilever (*c*) and two-bearing (*d*) cutting



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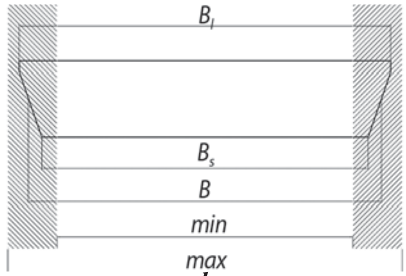

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Fig. 3. Defects of shape and deviations of cross section dimensions for a strip billet:
h — thickness (cross section height), mm; H_{pl} — plastic belt, mm; H_{tear} — tear-off surface, mm; H_{des} — destruction surface, mm; H_{bur} — burr height, mm; B_l — width of strip larger part; B_s — width of strip smaller part; *B* — nominal strip width; *min* — minimal allowable strip dimension according to EN 10219 and GOST 30245; *max* — maximal allowable strip dimension according to EN 10219 and GOST 30245

Symmetric loading eliminates bending of cutting billets, provides billet pressing to a blade and promotes rise of their geometric accuracy [7].

Cantilever cutting is characterized by increase of billet deformation during the whole process, the values of this deformation reach appr. 8% for steel 10 and 10% for steel 45.

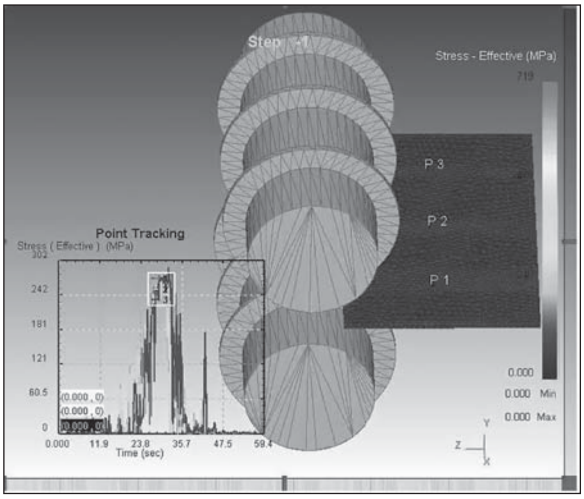
Stresses exceed the values of tensile strength for steels in the beginning of this process, meaning initiation of chipping cracks.

Maximal stresses reach 671 MPa for steel 10 and 949 MPa for steel 45. In the end of cutting process stresses reduce practically by two times. Analysis of stresses occurring during cutting shows that they can be compared with resistance to shearing cut, and therefore it is possible to determine the moment of initiation of chipping cracks.

To improve workability of billets made of hard-deforming high-alloyed steels and nonferrous alloys as well as to rise their technological ductility, heating up to the temperatures of semi-hot and hot deformation in the zone of structural transformation and above it is used [8].

Shear separation of rolled strips

The shears of different construction and with various drives are considered as the most efficient equipment for separation of rolled strip metal. There are no problems in cutting of rolled thin sheets, however, increase of strip thickness leads to appearance of more complicated stress-



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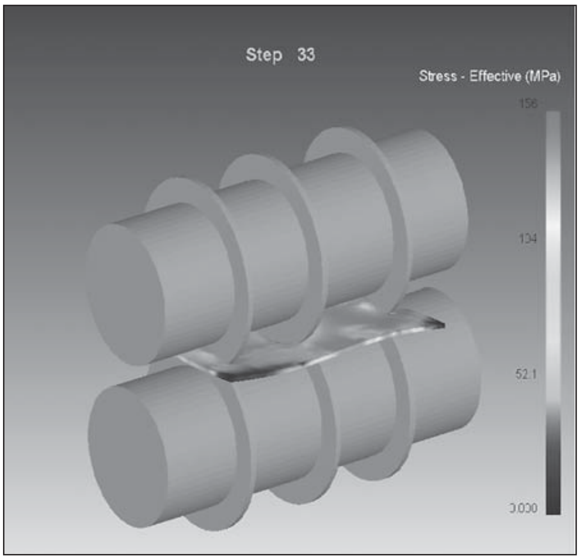

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Fig. 4. Solid body model for adjusting of multi-disc shears for strip cutting: start of the process (*a*) and distribution of stresses in the stationary process (*b*)

strain state in the cutting area. It finalizes to behaviour of separation process via several routes: elastic deformation, plastic deformation, tough and brittle destruction, forming of destruction surface consisting of several areas (plastic belt, chip and tear-off [9] (**Fig. 3**).

Only main normal stresses, effected by force action transferred from the blade to rolled material, are presented in the beginning of separation process in the cutting area. As soon as the blade penetrates in rolled material, billet is bending and the axes of main stresses are turning to any definite angle, what leads to arising of tangential stresses. The separation surface practically presents the path of maximal complicated S-formed tangential stresses with alternation of areas with tough-plastic and brittle destructions. Reduction of rolled coiled steel ductility can help to obtain more uniform destruction surface with higher geometric accuracy.

High-efficient equipment, such as multi-disc shears incorporated in the slitting lines are used for separation of rolled sheet metal to strip billets [9, 10]. These lines realize the route of multi-bearing shear cutting by rotation disc tools. Strip billets are used in manufacture of welded tubes.

The technique of examinations of rolled strip cutting

As soon as multi-bearing shears are rather expensive and heavy used equipment, the matrix for experiment planning, oriented for generation of production program was developed as well as the massif of factors having the effect on geometric accuracy and quality was formed.

The passive production experiment was conducted at the slitting line with the steels with different mechanical properties and thickness from 8 to 16 mm; it allowed to build mathematical models for cutting of rolled coiled steel as regression equations [10]. Relative trapezium B_{tr}/h (where B_{tr} is difference between widths of top and bottom parts of a strip billet and $B_{tr} = (B_t - B_s)/2$, similar to the chamfer angle during cutting of rolled sections (**Fig. 4,** *b*)), h is thickness of rolled steel толщина рулонной стали), having the effect on accuracy of joint of edges during tube billet forming. The regression equation for a relative trapezium is as follows:

$$B_{tr}/h = -0{,}088283 + 0{,}000497\,\sigma_m + 0{,}020982\,\delta + \\ + 4{,}307877\ s/h + 0{,}633264\,n/h - 0{,}017598\,V - \\ - 0{,}004253\,p - 0{,}000001\,\sigma_m^2 - 0{,}000341\,\delta^2 - \\ - 10{,}1437\,(s/h)^2 - 1{,}69302\,(n/h)^2 + 0{,}000115\,V^2 + \\ + 0{,}000526\,p,$$

where σ_m — flow stress, MPa; δ — relative elongation, %; s — gap between shears, mm ; n — coinciding of blades, mm; V — speed of strip motion, m/min; p — specific tension on uncoiler, MPa.

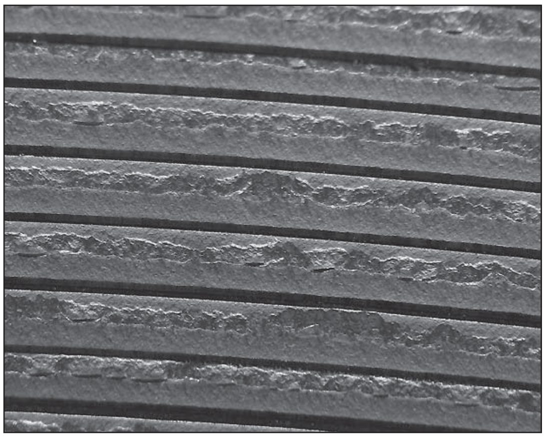
Simulation of cutting process in the finite element media displayed its high efficiency owing to absence of large stress gradient in the separation area [11].

The process of separation of one strip part from another one (chipping and tear-off) can’t be simulated by the finite element method because this technique is oriented on solving of plastic tasks. However, we can evaluate if destruction has just occurred based on the values of stresses and distribution of strains.

Discussion of the results

The results of cutting simulation at multi-disk shears in *Deform-3D* computer system allow to determine power and force parameters as well as to reveal stress-strained state.

Several solid state models of equipment with different combination of tool geometric parameters (see Fig. 4, *a* and *b*) were created during investigations in the graphic computer system *Solidworks* [12]. The files with solid body models were exported in the preprocessor *BC Deform-3D,* boundary conditions of motion were preset and the parameters of stress-strain state were calculated.



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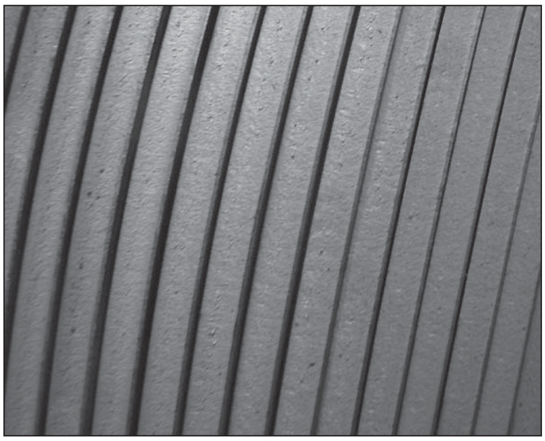

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Fig. 5. The image of separation surface of coiled steel before simulation (*a*) and after putting into practice the study results (*b*)

Screenshots of the parameters were made at the typical process stages. The values of these parameters were transformed in *Microsoft Excel,* where their relations were built.

Obtained relationships between stresses and deformations (from one side) and above-mentioned technological parameters σ_m, δ, s, n, V, p (from the other side) during cutting of coiled steel at multi-disk shears allow to minimize relative trapezium B_{tr}/h of a strip billet and to improve the quality of separation surface (**Fig. 5**).

The figure shows that tears-off (areas of tough-plastic destruction) are eliminated from separation surface as a result of conducted works, and the image of separation surface (brittle destruction) varies as well. It is connected with the fact that material ductility has the effect on the image of separation surface. Usage of less ductile steel with higher relation $\sigma_m/\sigma_в$ has positive effect on the quality [10].

The results of simulation can be used for improvement of the parameters of shear cutting of rolled metal in dies and shears in order to manufacture the billets of required quality.

Conclusions

Technological parameters of shear cutting are the most important characteristics of these processes, because they determine efficiency of these processes and possibility of manufacturing billets with required quality. It is expedient to optimize the parameters based on combination of the conventional methods of physical experiment and computer simulation, in particular – finite element calculations using up-to-date computer systems. Putting into practice the results of investigations displayed essential decrease of labour intensity of production preparation and equipment adjustment in order to rise geometric accuracy and quality of billets.

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