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# ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

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# SIMULATION OF COMBINED PROCESS OF ROD EXTROLLING IN THREE-ROLL MILL USING Deform-3D

**Abstract.** In the article, using the Deform 3D program, a computer simulation of the combined screw rolling process and pressing of the billet in the continuous pressing device was performed and the calculated values of the stress-strain state of the metal ponds are presented. An analysis of the stress-strain state of a metal during deformation in a continuous-pressing device with different drawing coefficients has been made. It is noted that in the first stage of deformation in the continuous pressing device, the stress and deformation intensities are localized on the surface of the workpiece, and in the subsequent stages of pressing these values are concentrated in the central zones of the workpiece.

It is shown that when compressing in a new device, due to the reversal of zones with the maximum stress and deformation intensities along the section of the workpiece, the macro-shear deformations are developed intensively, and as result they cause deep changes in the structure of the metal, due to transgender sliding.

**Key words:** computer simulation, combined process, equipment for continuous compaction, stress-strain state, shear deformation, fine-grain structure.

**Introduction.** The demand for technology of pressure treatment enabling the arrangement of cost-effective production of small- and medium-batch items has grown up in recent times. Herewith the essential requirements are accuracy of forms, cross-sectional dimensions and establishment of regulated structure in raw materials.

The production of round long half-finished product in metallurgic and metal-processing plants by screw rolling serves as an example of such technology.

It should be noted that the combined processes of pressure metal treatment (PMT) are used widely in aforesaid producing operations in current times [1]. The significant engineering of material structure and manufacture of items with high mechanical and performance properties is peculiar to combined processes of pressure metal treatment.

It is known that the designing of combined processes of pressure metal treatment is related to solution of such technical and process tasks as selection of temperature-speed rates of deformation and power processing parameters, assessment of the impact of strain distribution on structure and properties of resulting product as well as design engineering of instrument [2]. Despite the engineers aiming to process engineering with uniform distribution of stress-strain state (SSS) throughout deformable raw part, the uniform distribution of SSS fails to be achieved in real PMT processes. This leads to non-uniform work up of material structure, its uneven-grained structure and mechanical anisotropy.

According to the authors of works [3,4], the deformations during rolling in cross-rolling mills has a complicated nature, so much the more it is hard to anticipate the nature of SSS ofraw part during concatenation of screw rolling and compaction processes. For this reason, the study of severe plastic deformation (SPD) impact on metal structure of rollable product and determination of SSS nature and its impact on quality of resulting rods in rolling mills of “cross rolling and compaction” combined process is a relevant object.

In reference with the above, the current studies in the area of combined processes of PMT should be performed towards development of process enabling the management of structure and properties of metal in resulting items at various processing stages of combined processes [5].

According to the authors of work [6] the employment of mathematic simulation tools is the most advanced line of research for PMT processes. In their view, it allows, firstly, conducting the detailed and multi-factor analysis of impact of SSS and temperature-speed rates of deformation on product properties and, secondly, substantially reduced expenses and time for pursuance of research.

At the present time the CAE-systems based on finite element method (FEM) are widely used as the tools of mathematic simulation of operating procedures [7]. This method allows studying of SSS in any point of ductile sample with pin-point accuracy with account of rheological peculiarities of its materials. The application of FEM allows without considerable amount of assumptions and limitations to build the improved mathematical models including three-dimensional (3D). Therefore, using FEM the obtained results are more objective. FEM is a universal method having simple basic physics and mathematical form, which is implemented using flexible algorithm well-adapted for solution on computing machine.

With application of CAE-system the PMT processes have been actively studied within the last 15 – 20 years. The powerful software packages such as ANSYS, LS-DYNA, NASTRAN, COSMOS, DeForm and QForm enabling to simulate such PMT processes as rolling, compaction, bulk forming, upsetting, etc. have appeared within this period [7]. Currently the researches have gained a vast experience in development of geometric models of instruments and raw parts, determination of components of stress and deformation tensors, strain rates, temperature fields at each point of deformable raw part, calculation of equipment power parameters. The gained experience in application of mathematic simulation tools has allowed taking the designing of PMT operating procedures to new scientific level, particularly, the critical task has appeared–having changed the parameters of SSS, temperature and speed to forecast and manage the properties in resulting product.

The following objective was set in this work: to design the combined process of high quality rods manufacture by calculation and uniform distribution of shear strain degree. The basis of the method consists in quantitative measurement of grain size depending on value and distribution of shearing strain degree in raw part during combined process of PMT.

It is important to note that for implementation of this method it is necessary to have functional relationship connecting the variables of heating and SSS processes with metal structure and properties. The obtaining of similar relationship requires the carrying out of large volume of experimental investigations. Therewith, the obtained dependencies will be fair for each individual group of materials under examination only.

Not withstanding the foregoing, the CAE-systems (DEFORM-3D program) having programming units enabling to perform the detailed analysis of [9] as well as functional relations [7] have been appeared in current time and regardless of the fact that averaged characteristics are used as initial parameters for employed material and the state of its initial structure is disregarded, this program and functional relations have produced the consistent results. The certainty of calculations and efficiency of DEFORM-3D application for computer simulation of process of rolling, black smithing and pressing confirms the experience of the leading industrial companies of Japan, USA and EU.

**Materials and experimental technique.** The new equipment of cross rolling, where the rods manufacture is performed continuously by concatenation of rolling and compaction processes is suggested in the work [10].

The equipment for continuous compaction of rods contains the main drive gear, reduction mill, rolls rotating in all directions and press die body. The rolls have the smooth and corrugated-conic sections of biting and drafting, accordingly and gauging cylindrical sections. At that the cusps and scallops of rolls having equal width and thus height and depth are made along helical curve with the angle between a line tangent to helical curve and line going through tangency point along forming perpendicular to roll foundation equal 45 to 60$^{o}$.

The compaction of rods is performed as follows. The raw part is delivered to the roll opening and deformed with cusps and scallops of corrugated-conic sections of rolls during rotation of rolls in the same direction. The rolls having rotated by own rotating motion move the wrought metal translationally and press out the press die bodies through its holes.

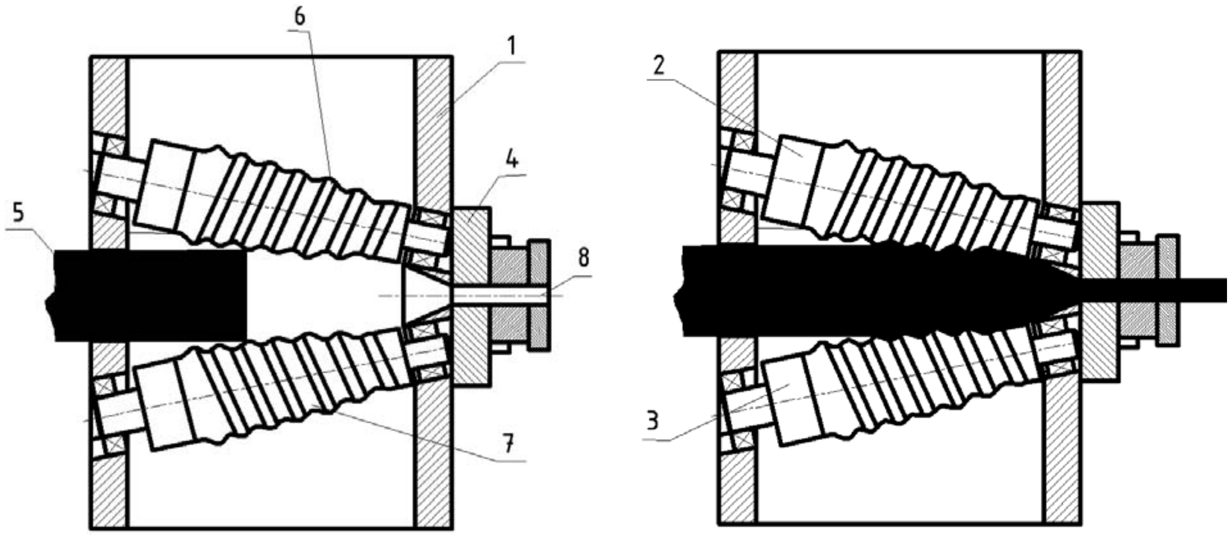


Figure 1 – Equipment for continuous compaction of rods:
1 – reductionmill, 2 and 3 – rolls; 4 – die body; 5 – raw part; 6 and 7 – cusps and scallops of rolls; 8 – hole for press die body

The rolling of raw part in corrugated-conic sections of rolls during rotation of rolls in one direction ensure the translation and rotational motion of raw part in the direction of rolling, effective structure refinement throughout the cross-section of raw part by means of development of shearing strain and decrease of roll force. Effective structure refinement ensures the recovery of quality product.

The finite element method using which the concerned process has been simulated was used for the analysis of SSS of metal. The DEFORM-3D [9] software package was applied as problem solver system. 3D geometrical model of raw part and instruments was constructed in the Compass CAD program and imported to the DEFORM-3D CAE program.

In such a manner, the elements of system in considered process is a 3D installation consisting of rolls, raw part, press die body, liners created in Compass. The file exported from CAD Compass 3D of *stl format was downloaded to the Pre-processor DEFORM-3D. The combined process was simulated in 3D environment with breakdown of raw part in 4 nodal elements (CTETRA). 2439 elements and 3096 nodes were required for the raw part model. Diameter of raw part – 30 mm, length of raw part – 200 mm, diameter of rolls in slots is 65 mm, and stud – 70 mm. The length of roll body is 85mm, feed angle – 6$^{o}$, toe angle – 20$^{o}$, diameter of discharge point of die body – 24 mm.

The work material – titanium alloy BT6 was set after download of geometrical arrangement to the Pre-processor DEFORM-3D. The rheological properties have been set from the data base of "MSC.SuperForge" software package. At that the work material was accepted as isotropic visco-plastic with non-linear age-hardening (BISO). The instruments were treated as perfectly rigid bodies. The friction was described according to Siebel law for the "roll-raw part" pair – 0.2; for "raw part–guide conduit" pair – 0.3; for the "raw part-die body" pair - 0.2; for the "pusher mechanism-raw part" pair – 0.3. The temperature of raw part was assigned as equal to 960 °C, temperature of rolls - 20 °C. The rolls rotational velocity was equal to 72 rpm. The calculation was performed with account of heat exchange between the raw part and rolls. During compaction, the elongation ratio was varied in the range of 1.2 – 1.6 with interval 0.2.

The "DEFORM-3D" program was activated. The displacement, conditions of compatibility of strain components, tensor components, rate of strain, components of stress, strain intensity, stress intensity, temperature distribution by volume of raw part have been calculated by step-by-step method.

**Results and discussion.** The pattern of strain intensity distribution in the raw part during rods compaction in the equipment for continuous compaction is shown on Figure 2. The temperature of raw part heating is 960 °C.

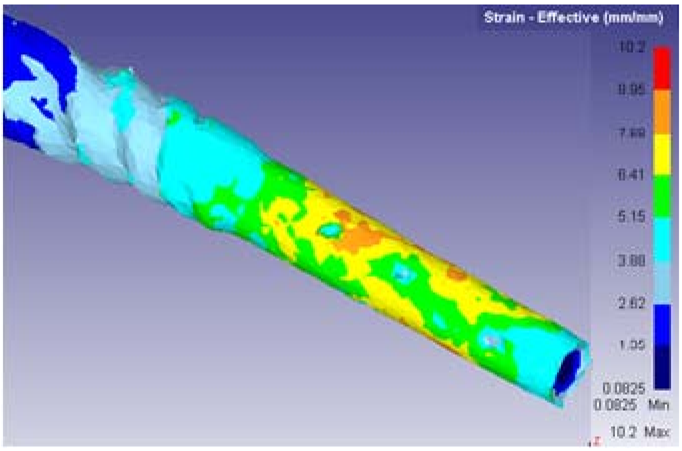


Figure 2 – The pattern of severe deformation distribution along
the cross section of raw part during continuous compaction of rods in new equipment of cross rolling with elongation ratio 1.2

On the basis of obtained results ofnumerical simulation it was established that:

- stress and strain intensity during deformation of round raw part in the equipment for continuous compaction is focused in the initial stage of processing in surface areas of raw part, and with the increase of drafting due to occurrence of friction force the focus of stress and strain intensity is transferred to central areas of a raw part;
- in the process of deformation the stress and strain in tensity along the cross section of raw part equalizes, i.e. during rotational and translational movement of raw part the transfer of sections with localization of stress and strain intensity from the surface to the center leads to equilibrium distribution of summarized rate of shearing strain along the cross section of raw part;
- gradual transfer of areas with localization of stress and strain from the surface area to central area of a raw part leads to elevation of heat evolution in these areas;
- rotational and translation movement of a raw part leads to the turn of sections with maximum stress and strain along the cross section of a raw part;
- during compaction of round raw part in equipment for continuous compaction, due to turn of areas with maximum stress and strain along the cross section of raw part, the macro-shearing deformations causing pervasive changes of metal structure by deformation zone by means of refinement of initial metal structure develop extensively;
- maximum possible shear is implemented with ratio of stud width to the slot width equal to 0.8…0.9;
- pattern of stress components distribution is testimony to the fact that tensile stress small in size appear in the core zone of pressed raw part. The effect of these stresses on raw part metal under certain condition may lead to appearance of defects in the central area of raw part. However, during subsequent uniform compression of raw part metal in the die body of equipment will lead to welding-up of these defects;
- during the compaction process in new equipment the temperature in areas of deformation localization increases, at that the area with elevated temperature also shifts along the deformation zone;
- in the areas of instrument contact with the raw part, the metal temperature drops to 900...920 $^{o}$C;
- increase of level and homogeneity of metal mechanical properties as well as lowering of its anisotropy of properties is a consequence of refinement of initial metal structure.

In such a manner, according to simulation results the obtained patterns of distribution for strain and stress intensity have shown that during compaction of round raw part in combined screw-shaped rolls and cylindrical die the value and nature of shearing strains varies significantly. The application of new continuous compaction equipment makes it possible to provide the additional macro shears in deformable material.

It is known that application of macro-shearing strains of cast products affords an opportunity with compressions only by 8 – 10 % to ensure the high quality gross structure of metal out of steel and alloy [11-13]. The effectiveness of macro-shearing strains impact on metal structure is related to actions taking place along the planes (surfaces) of macro-shear in micro-level [11-13]. The slide curves residing within the macro-shear bands penetrate through the entire grain. It is found [11-13], that during the process of plastic straining with additional macro shears the trans grain sliding taking place on the surface of macro shears of displacement appears. At that, the microsliding takes place in all grains being on these surfaces, in one direction regardless of orientation of sliding planes in metal grains and grain junction lines.

Thus, the macro-shearing strains cause pervasive changes in metal structure by means of trans-grain sliding, independent on crystal orientation of grains; result of these changes is increase of level and uniform quality of metal mechanical properties as well as lowering of its anisotropy.

The analysis of diagrams of strain intensity variation $\Gamma$ along the section of deformable raw part during compaction in combined equipment suggests that during compaction with elongation ratio 1.2 the strain intensity has the largest values in the surface area of pressed raw part (Figure 3, where $D_i$ – distance to the studied point by diameter of raw part; $D_0$ – diameter of raw part, $\varphi_i$ – rotation angle to studies point along cross section of raw part; $\varphi_0$ = 360° – angle of full circle of raw part). Thein crease of elongation ratio up to 1.6 leads to aligning of strain intensity along cross section of deformable raw part (Figure 4).

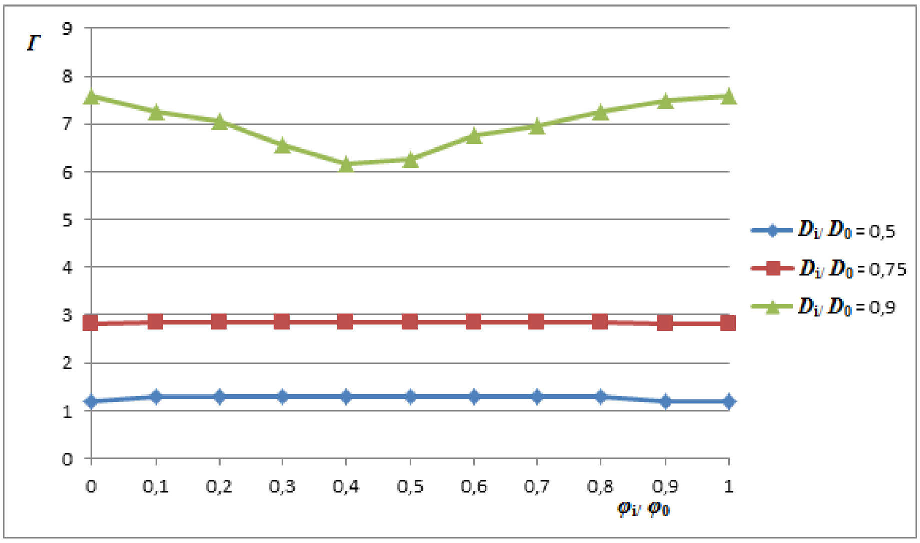


Figure 3 – Distribution of $\Gamma$ along cross section of raw part during compaction in combined equipment with elongation ratio 1.2

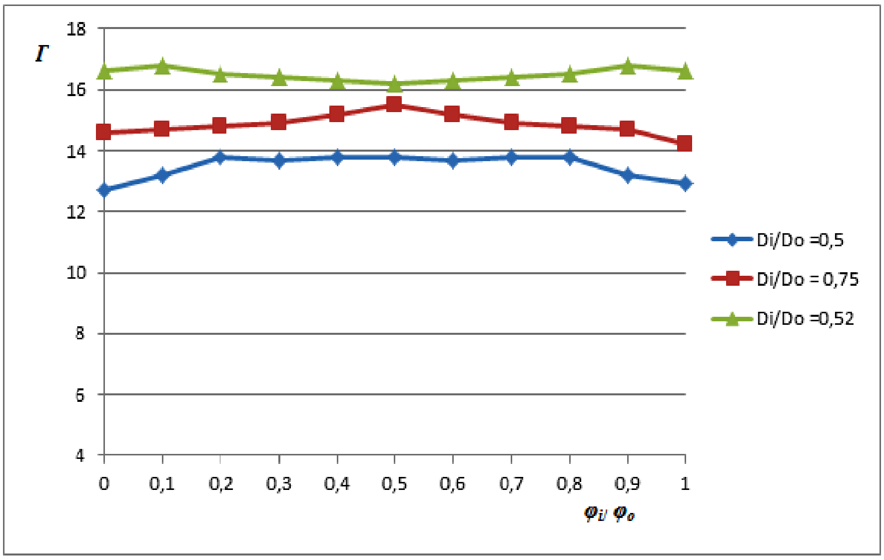


Figure 4 – Distribution of $\Gamma$ along cross section of a raw part during compaction in combined equipment with elongation ratio 1.6

The model of globularization for BT6 titanium alloy under Johnson-Male-Avraami-Kolmogorov, obtained in the work [14], was used for study of microstructural evolution. The calculation of volume ratio and mean size of equiaxial grain structure of BT6 titanium alloy have been performed according to these model.

During calculation the initial grain size was set as equal to 15 micron according to GOST 26492-85. The initial structure of raw parts was taken as lamellate.

The critical strain required for formation of globular grains was determined according to formula: $\varepsilon_c = a_1\varepsilon_p$, where $a_1 = 1$ – constant rate [14]; $\varepsilon_p = 0.5$ – strain intensity where in the formation of globular grains starts.

The volume ratio of globular grains of α-phase was calculated using Avraami equation [14]:

$$X_{rex} = 1 - \exp\left[-\beta_d\left(\frac{\Lambda}{\Lambda_{0,5}}\right)^k\right],$$

where $\beta_d$ and $k$ – constants of materials (values of materials constants are given in Table [14]); $\Lambda_{0,5} = a_2\dot{\varepsilon}^{m_1}$ - degree of strain wherein 50 % recrystallization takes place in the metal structure; $a_2$ and $m_1$ – empirical parameters enabling to determine the impact of strain rate on formation of globular grains [14]; $\dot{\varepsilon}$ - strain rate, $c^{-1}$.

Parameters of microstructural model for BT6 alloy

| t, °C | $a_2$ | $m_1$ | $\beta_d$ | k | $a_3$ | $n_1$ | $m_2$ |
|---|---|---|---|---|---|---|---|
| 1250 | 1,1 | 0,01 | 0,734 | 5,034 | 1,168 | –0,325 | –0,127 |
| 1000 | 1,1 | 0,01 | 0,734 | 5,034 | 1,168 | –0,325 | –0,127 |
| 980 | 1,1 | 0,01 | 0,734 | 5,034 | 1,168 | –0,325 | –0,127 |
| 850 | 1,16 | 0,01 | 0,734 | 5,034 | 1,997 | –0,595 | –0,058 |
| 780 | 1,321 | 0,01 | 0,734 | 5,034 | 2,294 | –0,424 | –0,101 |

The mean size of globular grain was calculated using the formula [14]:

$$d_{rex} = a_3\Lambda^{n_1}\dot{\varepsilon}^{m_2}, \text{ if } d_{rex} > d_o, \text{ then } d_{rex} = d_o,$$

where $a_3$, $n_1$, $m_2$ – empirical parameters considering the impact of strain rate and degree [153].

The following equation was used for determination of average grain size for α-phase [14]:

$$d_{cp} = X_{rex} \cdot d_{rex} + (1 - X_{rex})d_o.$$

The start of globularization takes place with strain degree $\varepsilon_c = 0.5$.

The change of globular grains share in the structure after compaction in new equipment with various elongation is shown in the Figure 5. From the picture it is apparent that after compressions in proposed equipment with elongation ratio 1.2 under temperature 960 °C the share of globular grains along the cross section of raw part amounts to 0.431...0.867. At that, because of large value of shearing strain rate in surface areas and areas adjacent to surface areas of raw part the grain globularization passes almost completely. However, because of small value of shearing strain rate in central areas of raw part, the grain globularization in these areas passes incompletely.

Following the compaction in new equipment under temperature 960 °C with elongation ratio 1.4 the share of globular grains along the cross section of raw part amount to 0.614...0.948, i.e. due to accumulation of shearing strain rate along the cross section of raw part the grain globularization passes almost completely.

During the process of deformation in the continuous compaction equipment with elongation ratio 1.6 and more, the areas of deformation zones obtain the sufficient deformation to the end that the structure was fully converted from lamellate to globular (Figure 5).

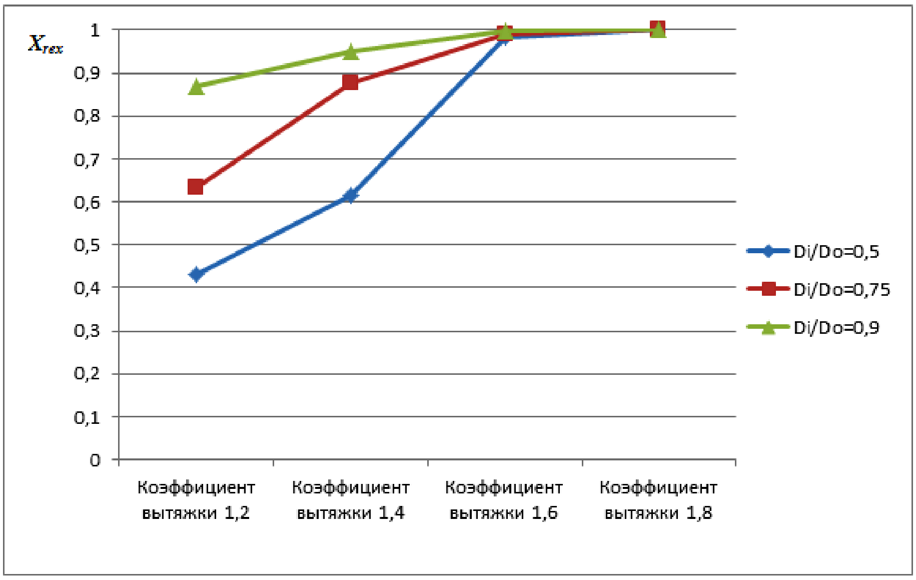


Figure 5 – Graph of variance of volume ratio in globular structure during production of rods by extrolling combined process

The variance of medium size of globular grain by transitions is presented in the Figure 6. In the process of compaction in new equipment with elongation ratio 1.2 and 1.4 the mean size of globular grain equals, accordingly: 6.954...9.247 micron and 4.861...5.243 micron. After processing in equipment for continuous compaction with elongation ratio 1.6 the finely grained uniform structure with medium size of globular grain 0.563...1.237 micron is formed.

In such a manner, the globularization of grains in the course of processing according to proposed operating procedure takes place almost throughout the rollable rod. Herewith, the finely grained homogenous micro pattern, which allows for improvement of titanium alloys quality, is resulted from in new equipment after pressing.

Hence, it appears that for production of rods with fine-grained structure out of BT6 alloy, it is possible to recommend its compaction in new equipment for continuous compaction out of pretreated primary raw part. The preliminary compaction in new equipment with elongation ratio 1.2 – 1.6 makes possible to redistribute and spread evenly the rate of shear deformation along the cross section of raw part. This, on one hand increases the value of shearing strain causing the refinement of initial structure, and on the other – reduces the risk of formation of coarse grained structure peculiar to compaction of rods according to existing technology.

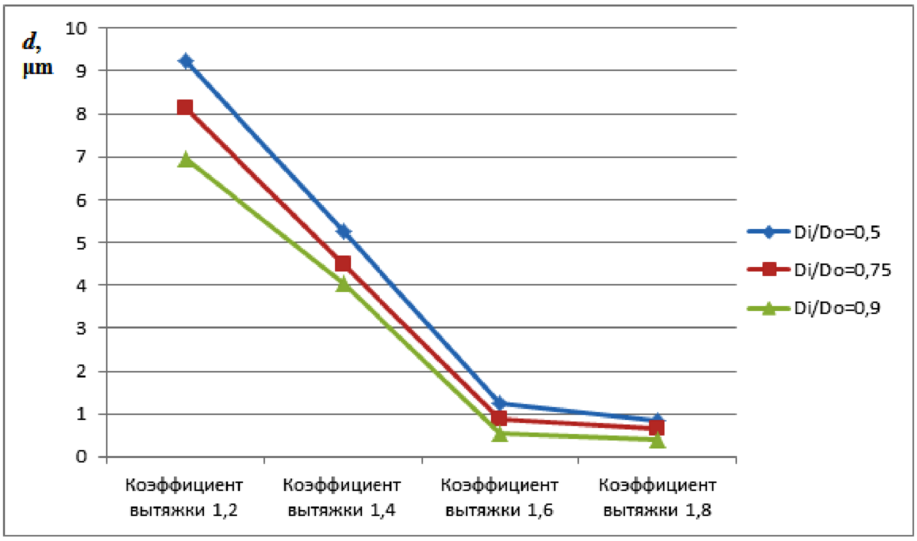


Figure 6 – Graph of variance of medium size globular grain during production of rods by the extrolling combined process

**Conclusion.** On the basis of the foregoing, it can be noted that

- at first stage of deformation in the continuous compaction equipment the stress and strain intensity are focused at the surface of raw part, and at the following stages of compaction these values concentrate in central areas of raw part;
- during compaction in new equipment due to turn of areas with maximum intensive stress and strain along the cross section of raw part the macro-shearing deformations causing pervasive changes in the metal structure by means of trans-grain sliding build up extensively;
- intensive grinding of metal structure and there by increase of level and homogeneity of metal-mechanical properties as well as decrease of its properties anisotropy is a consequence of macro-shearing strain development;
- application of new equipment for continuous compaction of rods in production will ensure there covery of fire-grain and homogenous structure, with volume ratio of globular structure equal to 1.0 and thus high mechanical properties.

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## Deform-3D КӨМЕГІМЕН ҮШБІЛІКТІ ОРНАҚТА ШЫБЫҚТЫ ЖАЙМАЛАП-БАСПАҚТАЙТЫН СЫЙСТЫРЫЛҒАН ПРОЦЕСТІ МОДЕЛДЕУ


**Аннотация.** Мақалада Deform 3D бағдарламасы көмегімен үздіксіз баспақтайтын қондырғыда дайындаманы бұрап илемдейтін және баспақтайтынсыйстырылған процесс компьютерлі модельденіп, шыбық металында пайда болатын кернеулі-деформациялы күйдің есептеліп алынған мәні келтірілген. Үздіксіз баспақтайтын қондырғыда дайындаманы әртүрлі кермеулеумен деформациялағанда металда пайда болатын кернеулі-деформациялы күй талданған. Үздіксіз баспақтайтын қондырғыда дайындаманы баспақтаудың бірінші сатысында кернеу мен деформацияның қарқындылығы дайындаманың беткі жағында, ал баспақтаудың келесі сатыларында айтылған мөлшерлер дайындаманың орталық аймақтарында шоғырланатын жұмыста анықталған. Жаңа қондырғыда баспақтаған кезде кернеу мен деформацияның максимальды қарқындылығы орналасқан аймақтар бұрылатын болғандықтан, дайындаманың қимасы бойынша макроығысу деформациясы қарқынды дамитындығы мақалада көрсетілген. Бұндай деформация транстүйіршікті сырғу есебінен металл құрылымын қатты өзгертетіндігі жұмыста табылған.

**Түйін сөздер:** компьютерлі модельдеу, сыйстырылған процесс, үздіксіз баспақтайтын процесс, кернеулі-деформациялы күй, ығысу деформациясы, ұсақтүйіршікті құрылым.

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## МОДЕЛИРОВАНИЕ СОВМЕЩЕННОГО ПРОЦЕССА ПРОКАТКИ-ПРЕССОВАНИЯ ПРУТКА В ТРЕХВАЛКОВОМ СТАНЕ С ПОМОЩЬЮ Deform-3D

**Аннотация.** В статье, с использованием программы Deform 3D, произведено компьютерное моделирование совмещенного процесса винтовой прокатки и прессования заготовки в устройстве для непрерывного прессования, и представлены рассчитанные значения напряженно-деформируемого состояния металла прутков. Произведен анализ напряженно-деформированного состояния металла при деформировании в устройстве непрерывного прессовании с различным коэффициентом вытяжки. Отмечено, что на первом этапе деформирования в устройстве непрерывного прессования интенсивности напряжений и деформации локализуются на поверхности заготовки, а в последующих этапах прессования данные величины сосредотачиваются в центральных зонах заготовки. Показано, что при прессовании в новом устройстве из-за разворота зон с максимальным интенсивным напряжением и деформацией по сечению заготовки интенсивно развиваются макросдвиговые деформации, вызывающие глубокие изменения в структуре металла за счет трансзеренного скольжения.

**Ключевые слова:** компьютерное моделирование, совмещенный процесс, устройство для непрерывного прессования, напряженно-деформированное состояние, сдвиговая деформация, мелкозернистая структура.

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