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# ISSUES ABOUT LIMIT PLASTIC DEFORMATIONS OF DEFORMING BROACHING OF CAST IRON PARTS

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***Summary.*** *Scientific and technical issues about the possibility of deforming broaching of bores in cast iron parts were investigated in the article. New methods to deform cast iron parts under conditions of all-round compression were developed. The diagram of plasticity was built according to results of mechanical tests of cast iron samples. The conditions of plastic deformation of half-brittle cast iron were determined. The dependence of the resource of cast iron plasticity from structural components and form of graphite inclusions was indicated. Necessary conditions for effective deforming broaching of bores in cast iron parts were determined. The measure of plastic deforming broaching of cast iron parts was chosen. The influence of tool geometry, thick walls of a part and element strain on plasticity during deforming broaching were investigated. The dependence to define limit deformations during deforming broaching of cast iron parts was suggested.*

***Key words:*** *deforming broaching, cast iron, plastic deformation.*

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**Problem setting.** Graphite cast iron is widely used as a constructive material in modern mechanical engineering. Traditional methods of deforming broaching of cast iron parts require considerable time consumption, however more than 80% is for total factory labour hours.

Deforming broaching is a highly productive operation on plastic materials and it is widely used. The use of this method during deforming broaching of bores in cast iron parts is restrained by low resource of plasticity of processed material.

The resource of used plasticity is one of important parameter of quality of parts machined by plastic deforming and characterizes the deficiency of finished surface. In works [1, 2] it was stated that the plasticity during cold plastic deforming depends on characteristics of machined material and the history of its deforming.

Consequently, the investigation of this quality parameter during plastic deforming of cast iron, which is half-brittle and composite material, should be certainly done.

**Research objective.** To study the possibilities of bores deforming broaching investigating its resource of plasticity and choice of optimal conditions of deformation.

**Review of recent investigations and papers.**

The issues of plasticity during deforming broaching were investigated in works [1, 2, 3], where tense state of machined material on the surface of the contact with the tool corresponds to volumetric pressure allowing to do considerable plastic deformations. At the same time, tense state corresponds to double-axis tension. While index of tense state $\eta = \frac{3 \cdot \sigma}{\sigma_0}$ (where $\sigma$ – hydrostatical pressure, $\sigma_0$ – stress intensity) changes owing to negative meanings (–7.16) in contact area up to positive meanings (+2) on external surface. It helps to forecast the beginning of failure during distribution of parts with different thickness of wall near external surface of a part.

Therefore, authors [1] suggest to use the directed deformation $e'$ to external surface depending on relative deformation of tension $a/d_0$ and thick walls of a part $t_0/r_0$ as determinative factor according to their investigations. This suggestion is caused by the following reasons. Conducted investigations regard to deforming broaching of plastic parts while at their distributions big tensions on considerable total plastic deformations of a bore are used. Using such big strains, transparent plastic deformation of bore is found that is either internal or external diameter of a part increases. The degree of used resource of plasticity $\psi$, caused, correspondingly by suggestions [1] made by V. Kolmohorov, is maximum near external surface where the failure of a part takes place.

Cast iron is known to be half-brittle composite material consisting of ferrite-pearlitic structure including free graphite of different form presenting brittle component of this material [4]. Methods and results shown in works [5, 6, 7, 8] are used for investigations of plastic deforming of cast iron parts.

**Research results.** Peculiarities of plastic deforming of cast ironware should be considered. Grey cast iron *СЧ20* (hardness HB 1.7 GPa) and high-test cast iron *ВЧ50* (HB 2.1 GPa) are widely used in modern mechanical engineering.

Diagram of plasticity (Fig. 1) was constructed to determine possibilities of plastic deforming of cast ironware that is mechanical characteristic of deformation of cast iron

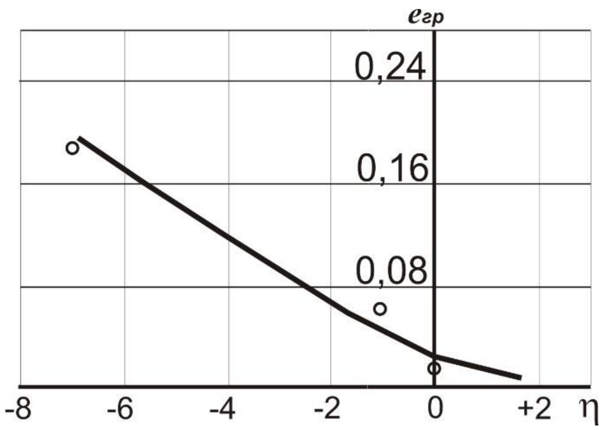



**Figure 1.** Diagram of plasticity of grey cast iron СЧ20

According to suggestions [5], to make such diagram, mechanical tests of cast iron under conditions of simple load and deformation when stresses change proportionally to one parameter were done. Such tests are of the following types: tension, torsion and compression. Besides, original methods of testing cast iron under conditions of deformation close to all-round compression have been developed in the given research.

Tests on tension of cast iron patterns *СЧ20* and *ВЧ50* were done on special tension testing machine.

For tests on compression, there were made samples, geometrical sizes of which were defined according to correlation $h/d$ = 1.5, where $h$ = 15 mm – height of a part; $d$ = 10 – its diameter. On patterns' ends, according to suggestions [6], cylindrical grooves about 0.4 mm in depth and 9.2 mm in diameter were made. Grooves were filled with hard oiling on the base of varnish Ф-9-К with MoS2 that should support deformations that are more homogeneous. Tests were made on press ПММ-200 using special instrument providing parallelism of supports. Compression of samples was made until their failure took place. After failure of samples on compression and tension, there were made sections on which toughness according to Vickers' scale was measured at the load $P$ = 49 N.

The following methods were used at deformation of cast iron under conditions close to all-round compression. Research data [7] used at deformation of plastic production were taken into consideration for the development of the first method. Samples made of investigated materials of cylindrical form about 35 mm in diameter and $h$ = 15 mm in height were prepared for using this method. Being previously machined by turning, samples' ends were polished on planogrinding machine tool of mod. 3Б71М. Micro-hardness of samples in starting position and strained state was measured by Vickers' method using micro-hardness tester «Shimadzu» (Japan). Load on indenter (diamond pyramid) at measuring micro-hardness of ferrite composite was 25 gr. and for pearlitic one – 100 gr. Microscope МИМ-7, optical microscope «Altamy», raster electronic microscope РЕМ-106И and instrumental microscope БМИ-1 were used to investigate microstructure of samples and state of machined surface.

Investigations were done according to recommendations [7] in the following way. Hard-alloyed ball about 10 mm in diameter with effort 30 kN was filled in previously polished surface. This operation was being processed on hardness tester ТШ-2М during 30 sec. After removing load, received bore and micro-hardness were measured and external strained area was observed for magnification. In case of failure on the surface of contact, deforming of sample was stopped. Surface of samples, where failure was not found out, was polished until initial diameter of bore was decreased in two times. After this, the sample was put on hardness tester and repeated cycles of load were done.

After each load, hardness of investigated area of a sample (according to Vickers) in the range of points situated radially starting from the centre of bore and ending with transition area was measured. Then, strained samples were cut in the middle of bore in cross-section, filled with epoxy resin to protect strained area and then they were polished and grinded.

Micro-hardness measuring of strained area was done in three areas (Fig. 2) in the direction from strained surface to the depth of a sample until hardness of material reached its initial value.

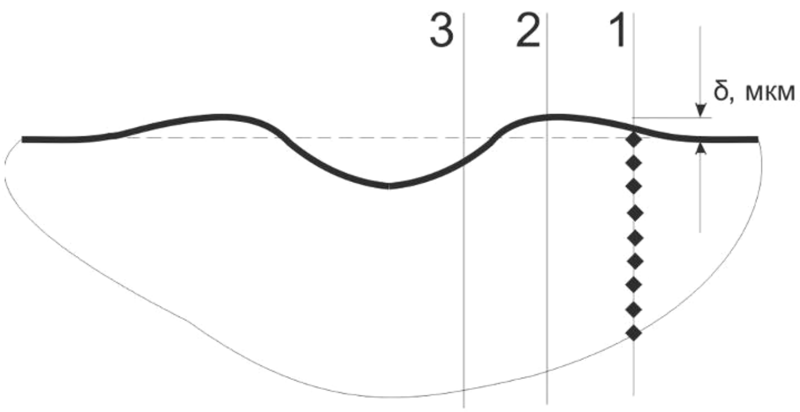



**Figure 2.** Dimension scheme of micro-hardness on samples

Dimension step was $\delta$ = 40 mkm. Areas were chosen on these samples, they were pickled by 5% solution of hydrogen nitrate in ethyl alcohol and then change of areas of ferrite and pearlite in initial and strained states was investigated.

We have developed one more method of modeling conditions close to all-round compression reproducing deformation of micro-ends on internal surface of bore deforming broaching. Model tests were made on samples of conic form made from stated above cast iron brands with angle $\beta = 90°$ according to the scheme (Fig. 3)

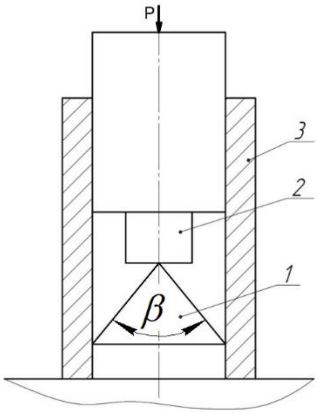



**Figure 3**. Test materials gain rate device: 1 – conic sample of test material; 2 – high-alloy head; 3 – guide pin bushing

Axial load, which is sufficient for plastic deformation of its top with the next unloading and measuring of contact area was applied to the top of a sample 1, which was fixed in the iron band 2, through high-alloy plunger. Besides, axial load was fixed using tensometric dynamometer of the known design [1].

Sections were made of fractured tested samples. Hardness measurements showed that in all test points the value of hardness is almost identical and is correspondent to initial hardness of samples. It shows the absence of strengthening and, thus the absence of plastic deformation at one-axial tension (that is at $\eta = +1$).

S. Lopatenko received similar results [8] at defining the limit deformation during torsion. His experiments showed the absence of visible plastic deformation at torsion (that is $\eta = 0$).

The results for deformation of samples of stated above cast iron brands at one-axial compression should be considered. Experiments, conducted according to method presented above, supported relatively more homogenous plastic deformations (for high-test cast iron *ВЧ50* up to 50% and for grey cast iron *СЧ20* up to 9%). Then sections were made of fractured samples, which were tested on hardness according to Vickers when load was 49N. Test results showed that test cast iron samples are essentially strengthened at compression. Thus, hardness of cast iron *ВЧ50* was changed from initial 2 up to 2.95 GPa and cast iron *СЧ20* was changed from 1.7 up to 2.25 GPa, in this case the degree of strengthening was 48 and 30% correspondingly. Such degree of strengthening shows the availability of considerable plastic deformations at deforming of cast iron at one-axial compression (that is $\eta = -1$).

As test results show, the diagram of limit plasticity for cast iron unlike similar diagram for plastic materials is developed from meanings of deformations which are correspond to $\eta = -1$, that is one-axial compression of samples.

The process of deformation of cast iron samples at conditions close to all-round compression should be considered. The meaning of tense state index is equal to $\eta \approx -7$ and is corresponding to this condition.

In Fig. 4 the change of hardness of deformed material on test area after some cycles of loading is shown, in addition the distance from the centre of bore is put on axis of abscissas and the hardness according to Vickers is put on axis of ordinates.

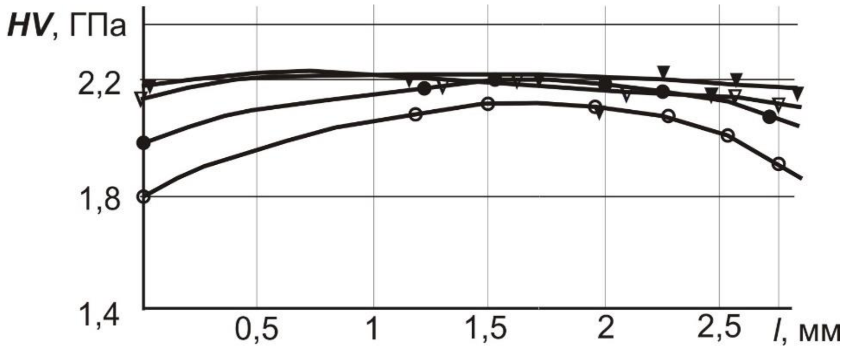



**Figure 4.** Change of hardness of cast iron СЧ20, HB1.7 GPa at deformation of a ball in ∅ 10 mm at load P = 30 kN. Deformation cycles ◦ – 1; • – 2; ∇ – 3; ▼– 4

As it is shown in Fig. 4 at such method of deformation, grey cast iron is under essential plastic deformations (to 20%), which explains the increase of hardness to HV 2.2 GPa, while maximum increase of hardness is observed near edge limiting bore. Identical picture is observed at deformation of high-test cast iron *ВЧ50* changing to maximum hardness HV 3.0 GPa.

Tests on modeling conditions close to all-round compression owing to compression of tops of cast iron cones *СЧ20* and high-test cast iron *ВЧ50* (Fig. 5) according to stated above method showed that the dependence of hardness from cycles of additional load is of extreme nature.

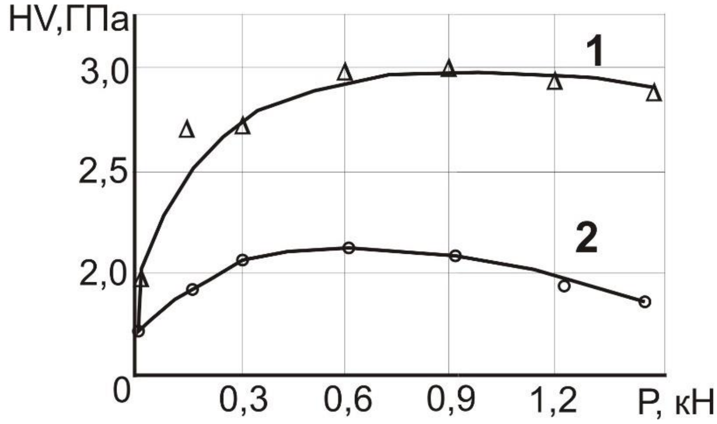
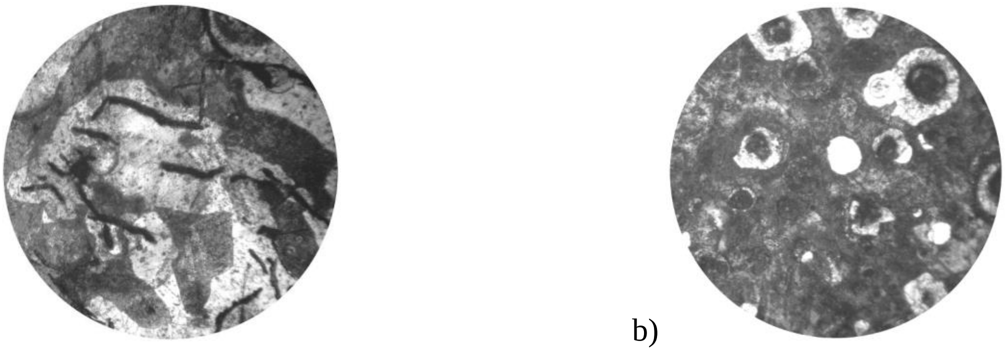



**Figure 5.** Dependence of hardness of strengthened layer from axial load on the top of cone: 1 – cast iron ВЧ50, 2 – cast iron СЧ20

Initial cone material hardness and hardness after each cycle of deformation were shown on axis of ordinates. Firstly, at first cycles of deformation, hardness increases and achieves its maximum while its maximum meaning is correspondent to hardness of identical materials received at pressing of a ball. Thus, for cast iron *СЧ20* maximum meaning of hardness is HV 2.25 GPa, and for high-test *ВЧ50* – HV 3.0 GPa.

Decrease of hardness of cast iron after peak achievement, especially for grey cast iron *СЧ20* was caused by relatively small resource of plasticity of the material leading to micro-failures on fractured surface of a cone. Limit contraction degree of cones is up to 18% before failure tracks appear on a fractured surface.

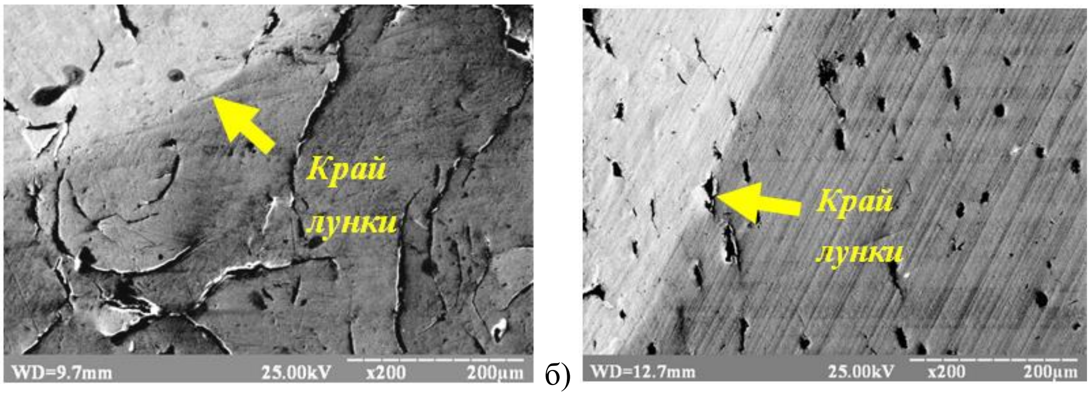
Changes of microstructure of test samples after deformation should be considered. Microstructure of test samples in initial state is shown in Fig. 6.



a) b)

**Figure 6.** Microstructure of samples (x380): a) СЧ20; b) ВЧ50

Surface patterns after some cycles of deformation of cast iron samples by a ball is shown in the pictures made by microscope (Fig. 7)



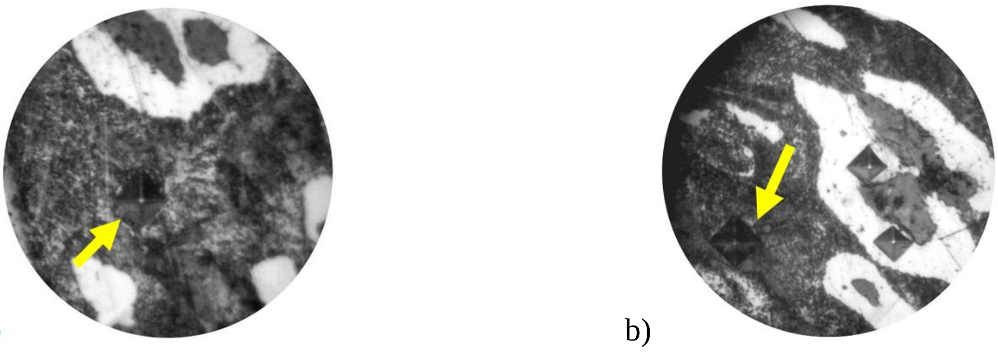

a) б)

**Figure 7.** Failure pattern of samples surface (x200): a) СЧ20, b) ВЧ50

Experiments showed that the process of fracture of grey cast iron started to fail after the fifth cycle of load (Fig. 7a). Appearance of small fractures alongside graphite inclusions are signs of failure. Moreover, there are areas where small fractures are merged into more main ones causing separation of some iron parts from a sample.

Availability of brittle graphite in the form of plates essentially makes weaker iron composite of cast iron structure and causes failure even at such favorable indication of tense state that is during pressing a ball, which can be seen in Fig. 7a.

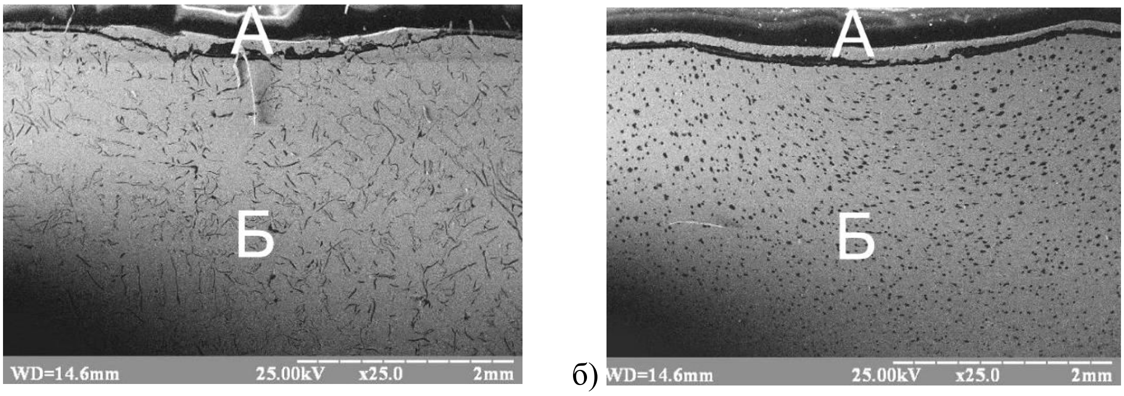
Slightly another pattern can be observed at deformation of samples of high-test cast iron *ВЧ50*. Even after the sixth cycle of load, failure of machined surface is not observed (Fig. 7b). To explain this fact, structure of a sample after deformation should be investigated (Fig. 7b). Deformation of surface layer in depth to 1 – 1.5 mm influences the form of ferrite composite and graphite inclusions. These spherical form composites in initial state (Fig. 8a) became of an oval form after deformation and in a considerable deformation they became of an elongate form (Fig. 8b). Pearlite composite of structure practically does not change its form (Fig. 8), that is plastically does not change in form what is confirmed by insignificant change of its micro-hardness.



a) b)

**Figure 8.** Cast iron structure ВЧ50 (x380): a) in initial state; b) after deformation

If cross-section of bore in area of maximum deformation of material is investigated, then for cast iron СЧ20, there can be observed areas, where strained grains of graphite forming micro-fractures are present, which are merged into main fractures (Fig. 9a). Strained graphite inclusions of spherical and oval form are observed on samples of high-test cast iron (Fig. 9b), fracture porosity of which is considerably less.




a) б)

**Figure 9.** Strained area of samples in cross-section of bore (x25), where A – compound (epoxy resin), Б – body of a sample. a) СЧ20; b) ВЧ50

It explains additionally higher resource of plasticity of high-test cast iron *ВЧ50*.

Consequently, conducted investigations showed that cast iron is deformed plastically under conditions of deformation close to all-round compression. Resource of plasticity of cast iron depends on its structural composites and form of free graphite.

As it was sated above, limit deformation for plastic materials is considered to be the deformation led to external surface of samples. Investigations conducted at developing a diagram of cast iron plasticity (Fig. 1) showed that its plastic deformation is possible only at negative meanings of index of tense state. Thus, at deforming broaching of cast iron samples it is necessary to avoid cross-section plastic deformation of a sample that is its external surface would not be plastically strained. That is why, plastic area should cover only internal part of a wall of a part. To make theoretical definition of a radius of limit of plastic area is a complex task. So, to determine limit deformation of cast iron samples, experimental methods were used to define limit deformation analyzing experimental results on a phenomenological level.

Total intensity of deformation of a part before failure should be taken into consideration according to suggestions [9] to evaluate quantitatively the meaning of plastic deformation before the failure appears during deforming broaching.

As a result, small plastic deformations appear on cast iron parts and deforming broaching is done by consecutive single deforming elements with identical nominal tensions, it can be suggested that in radial direction on some removing from contact area, deformation is monotonous and close to the scheme of distribution of pipe by internal pressure [1]. In this case, intensity of deformation can be shown in the following form:

$$e_i = \frac{2}{\sqrt{3}} \cdot \sqrt{\left(e_r - e_\varphi\right)^2 + \left(e_\varphi - e_z\right)^2 + \left(e_z - e_r\right)^2}, \tag{1}$$

where $e_r$, $e_\varphi$, $e_z$ – linear deformations in cylindrical coordinates: $e_r = t_i / t_0$; $e_\varphi = r_i / r_0$; $e_z = l_i / l_0$.

Using the condition of incompressibility for $e_z$ definition the equation (1) can be shown in the next form:

$$e_i = 2 \cdot \sqrt{2} \cdot \sqrt{e_r^2 - e_r \cdot e_\varphi + e_\varphi^2} = 2 \cdot \sqrt{2} \cdot \sqrt{\left(\frac{t_i}{t_0}\right)^2 - \frac{t_i}{t_0} \cdot \frac{r_i}{r_0} + \left(\frac{r_i}{r_0}\right)^2} \tag{2}$$

Dependence (2) was used for definition of limit plastic deformation $e_{np}$ of cast iron bushes СЧ20 at their machining by deforming elements of different angles $\alpha$. In Fig. 10 dependence $e_i = f\left(\frac{\Sigma a}{d_0}\right)$ is shown, from which comes $e_i$, which increases proportionally to total tension.

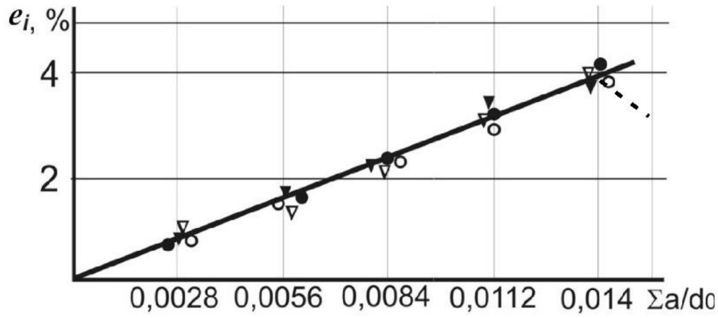



**Figure 10.** Intensiveness dependency of plastic deformations on total tension at deforming broaching of cast iron parts СЧ20, HCI1.7 GPa with thick wall $t_0 / r_0 = 0{,}56$, tension on element $a / d_0 = 0{,}0028$, angles of operating cone: • – $\alpha = 2°$; ° – $\alpha = 4°$; ▼ – $\alpha = 8°$; ∇ – $\alpha = 12°$

In such a case, limit plastic deformation reaches 4%. From Fig. 10 it can be observed that angle of operating cone of deforming element at using small tensions on element practically does not influence the value of limit deformation.

In technological practice, it is convenient to use relative total tension $\frac{\Sigma a}{d_0}$, as a measure of deformation of parts. Thickness of wall of a part influences the meaning of limit total tension $e_{гр} = \frac{\Sigma a}{d_0} = \Sigma \overline{a}$. The more is thickness of a wall, the higher is the contact pressure as well as hydrostatic pressure on plastic area, which increases the value of limit deformation $\Sigma \overline{a}$. It is proved by results of experiments (Fig. 11).

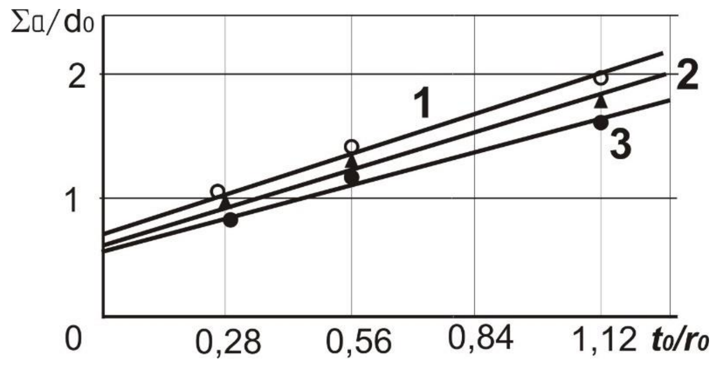



**Figure 11.** Dependency $\frac{\Sigma a}{d_0}$ on $t_0 / r_0$ at deforming broaching of cast iron bushes СЧ20 by deforming elements with angle $\alpha = 4°$ and tensions on element $a / d_0$: 1 – 0.0042; 2 – 0.0028; 3 – 0.0014

As can be seen in Fig. 11, the increase of thickness of a wall of a part causes the increase of limit meaning $\Sigma \overline{a}$. Tension on each deforming element influences the value of limit deformation too. The minimum tension is the most favorable for increase of resource of plasticity on element ($a / d_0 = 0,0014$, straight line 1). The value of limit deformation decreases while relative tension of value of limit deformation increases. Extrapolation of straight lines 1,2,3 on axis of ordinates, that is $t_0 / r_0 = 0$ shows the meaning of cast iron deformation at single-axle tension. For straight line 1 – *e*=0.7%; for 2 – 0.6%; 3 – 0.5%, which approximately corresponds to limit of elasticity of this material.

Statistical data processing, shown in Fig. 11, allowed receiving the equation:

$$e_{гр} = \left(0,008 - 0,71 \cdot \frac{a}{d_0}\right) + \left(0,014 - 0,71 \cdot \frac{a}{d_0}\right) \cdot \frac{t_0}{r_0} \qquad (3)$$

**Conclusions.** Having investigated the stated above issues, we can make the following conclusions:

1) Half-brittle cast iron was determined to be plastically strained at negative meanings of tense state index.

2) It was shown that the resource of plasticity depends on structural composites and the form of graphite inclusions at deforming cast iron. However, cast iron has maximum resource of plasticity, where ferrite structure and spherical form of free graphite are prevailing.

3) It was investigated that the main condition for deforming broaching of cast iron parts is the absence of plastic deformation on external surface of a part and plastic deformations should be expand only on internal part of thickness of a wall of a part.

4) It was suggested to evaluate plasticity of cast iron parts at deforming broaching using the value of total tension $\frac{\Sigma a}{d_0}$ before the failure, which does not depend on angle of operating cone of deforming element and increases while thickness of a wall of a part increases and tension on each deforming element decreases.

5) The dependence to define limit deformations at distribution of cast iron parts determining necessary quantity of deforming elements and distribution of tensions has been suggested.

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# ДО ПИТАННЯ ПРО ГРАНИЧНІ ПЛАСТИЧНІ ДЕФОРМАЦІЇ ЗАГОТОВОК ІЗ ЧАВУНУ, ОБРОБЛЕНИХ ДЕФОРМУВАЛЬНИМ ПРОТЯГУВАННЯМ

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***Резюме.*** *Розглянуто науково-технічні питання можливості обробки отворів у деталях із чавуну деформувальним протягуванням. Розроблено нові методики деформування зразків з чавуну в умовах всебічного стиску. За результатами механічних випробувань зразків із чавуну побудовано діаграму пластичності. Установлено умови пластичного деформування напівкрихкого чавуну. Показано залежність ресурсу пластичності чавуну від структурних складових та форми графітових включень. Установлено необхідні умови для ефективної обробки отворів у заготовках із чавуну деформувальним протягуванням. Вибрано міру пластичності при деформувальному протягуванні чавунних заготовок. Вивчено вплив геометрії інструмента, товстостінності заготовки та натягу на елемент на пластичність при деформувальному протягуванні. Запропоновано залежність для визначення граничних деформацій при деформуванні заготовок із чавуну.*

***Ключові слова:*** *деформувальне протягування, чавун, пластична деформація.*

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