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PECULIAR PROPERTIES OF TECHNOLOGICAL IMPROVEMENT AND OPTIMIZATION OF PRODUCTION COSTS OF 3D-CONFIGURATION PIPES

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The analyzes of the requirements to 3D-configuration pipelines production at the rocket and space industry enterprises is done. A review of different approaches to pipe bending technology (with heat treatment and without heat treatment) is carried out. The object of the study is the bending process and a universal bending machine for pipelines' production of complex configuration. The article is divided into four sections, which consider the key factors, causing directly the effectiveness of the technological operation of pipeline bending of a complex 3D-trajectory. An overview of no-temperature shaping of the pipeline is given in the first section. The requirements to the technology, excluding: corrugation, flattening, stretching and thinning of pipeline walls during their bending, are considered. The actual regulatory documents and industry aerospace standards, regulating production of pneumatic and hydraulic pipelines are given. An example of calculating the minimal allowable bend radius of the pipe, depending on the diameter and thickness of the pipe wall, is given. The requirements to unification of the pipe size production and gaps are listed. The dependence of the maximal allowable internal pressure in the pipeline is shown. The requirements to equipment, used in pipeline bending and to the design of the pipe bending machine are considered. In the second section, the possibilities of temperature influence on the pipe bending process are viewed. The analysis of patent and technical literature and six possible methods of effective thermal effects are presented: heating of the whole pipeline length, narrow zone heating of the bend pipe place, water cooling with nitrogen in the pipe, laser-cooling of atoms of the pipes, application of the petroleum products on the place of heating of the pipe and using of modern fillers inside the pipe to change its temperature. In the third section the tasks of the development of a universal bending machine are set; the system of the algorithm of the universal bending machine operation is considered; the system of algorithm of the bending machine operating with CNC is shown. The General functional scheme of the bending machine and the sequence diagram of the equipment operation is given.

Keywords: pipe bending, requirements to 3D-configuration pipe bending, universal bending machine, technology of pipe bending, influence of temperature on the process of pipe bending.

ОСОБЕННОСТИ ТЕХНОЛОГИЧЕСКОГО СОВЕРШЕНСТВОВАНИЯ И ОПТИМИЗАЦИИ ЗАТРАТ ПРОИЗВОДСТВА 3D-КОНФИГУРАЦИИ ТРУБ

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В работе сделан анализ требований, предъявляемых к изготовлению трубопроводов 3D-конфигурации на предприятии в ракетно-космической отрасли. Проведён обзор разных подходов к технологии гибки труб – с термообработкой и без термообработки. Объектом исследования является процесс гибки и универсальный гибочный агрегат изготовления трубопроводов сложной конфигурации. Статья разделена на четыре раздела, в которых рассмотрены ключевые факторы, непосредственно влияющие на успешность проведения технологической операции гибки трубопровода сложной 3D-траектории. Приведён обзор безтемпературного формо-

образования трубопровода. Рассматриваются требования к технологии, исключающей гофрообразование, сплющивание, растяжение и утонение стенок трубопроводов при их гибе. Указаны действующие нормативные документы и отраслевые аэрокосмические стандарты, регламентирующие изготовление пневмогидравлических трубопроводов. Приведён пример расчёта минимально допускаемого радиуса гиба трубы, зависящего от диаметра и толщины стенки трубы. Перечислены требования унификации размеров изготовления труб и требования к зазорам. Получена зависимость максимально допустимого внутреннего давления в трубопроводе. Рассмотрены требования к оснастке, применяемой в гибе трубопроводов. Перечислены требования к проектированию агрегата гибки труб. Во втором разделе рассмотрены возможности температурного воздействия на процесс гибки трубы. Представлен анализ патентной и технической литературы и описаны шесть возможных методов эффективного температурного воздействия: нагрев всего трубопровода, узкозональный нагрев места гиба на трубе, охлаждение азотом воды в трубе, лазерное охлаждение атомов трубы, нанесение смазок из нефтепродуктов на место нагрева на трубе и использование современных наполнителей внутри трубы изменяющих её температуру. В третьем разделе определены задачи, поставленные для разработки универсального гибочного аппарата, сформулированы требования к управляющей программе и устройству шкафа автоматики универсального гибочного аппарата, рассмотрена система алгоритма работы гибочного станка с ЧПУ. Показана общая функциональная схема работы агрегата гиба и циклограмма очерёдности работы оборудования.

Ключевые слова: гибка трубы, требования к гибке труб 3D-конфигурации, универсальный гибочный аппарат, технология гибки труб, влияние температуры на процесс гибки труб.

Introduction. The effectiveness of the process of technological development of production: large-size bench and frame structures, on which units are attached; elements of reinforcing structures – stiffeners and auxiliary fastening elements; pipes, intended for the transfer of any material resource (water, air, gas, fuel), and the production of electronic automation, high-tech mechanical aggregate elements and General Assembly depend on the created structure and model of functioning, as well as on the presence of a mechanism for self-regulating technological development.

New technological capabilities expand the space for implementing design innovations (in particular, manufacturing pipelines of a new, more complex configuration, etc.) and allow to solve economic problems – the production of more modern components of products with the required quality, reliability, service life and competitive cost.

Overview of the no-temperature pipeline forming method. The process of bending the pipeline can lead to corrugation on the part of the inner diameter of the bend, as well as to flattening, stretching and thinning of the outer wall of the pipe bend [1–5]. This factor is especially important if thin-walled pipelines with a thickness of 1–2 mm are subjected to bending. In this case determination of the minimal required wall thickness, which ensures transfer of the energy medium in the desired aggregate state and with the specified pressure, comes to the foreground during the pipe bending process.

In each industry, depending on the degree of significance and operating conditions of pipelines, the requirements for the minimal allowable bending radius are set, in case of violation of which critical deformation and rupture of the pipe wall may occur [6].

In the rocket and space industry, the production of pneumatic-hydraulic pipelines and assemblies is regulated by industry standards: OST 92-1600–84 ÷ OST 92-1604–84 [7–13].

OST 92-8536 should be followed when designing and manufacturing pipelines for stand equipment. The production of a particularly important product can be accompanied by a specially developed normative document of technical requirements (TR).

The design documentation (DD) for both pipelines and bending unit must be developed in accordance with the requirements for ensuring manufacturability of the product design, taking into consideration the following factors:

1. Availability of the materials given in the specification.
2. Maximum possible application of standardized parts.
3. To minimize the number (to standardize) the bend radius of the pipe.
4. Make the most of all-stamped pipe fittings instead of welded ones.
5. Make the most of use of drop-off ends on the ends of pipelines instead of turned ones made of bar.
6. Maximum use of compensators according to OST 92-4903, bellows or other compensating elements in pipeline systems, which take into account the effect of temperature fluctuations on the product.
7. Availability of x-ray inspection of the bending area, welded and soldered joints.
8. It is recommended to set bends in the CD with a single radius and without double curvature within a single bend.
9. All dimensions, defining spatial configuration, geometric cross-section dimensions, bending radius, length of straight sections, bending and turning angles must be specified in the pipeline CD or in the drawing TT it is required to indicate manufacturing of the pipeline according to the reference sample (OST 92-0191 and OST 92-1600).
10. Location of pipelines on the products should allow access to them for installation and dismantling works.
11. Straight part of the pipe length (for drop – off ending- shaping of the tip) from the end of the pipeline to bending is not to be less than 60 mm (except the weld or solder lugs, for which a straight length is regulated by ability to install the weld head on OST 92-1602 or soldering device according to OST 92-1603).

12. Straight part of the pipe length (no winglets on the ends) from the end of the pipeline to bending: for pipes with nominal diameters up to 20mm – not less than 10mm; for tube with internal diameter more than 20 mm up to 50 mm – not less 50 mm; for pipes with internal diameter more than 50 mm – not less than 100 mm (paragraph 3.3.2 OST 92-8751–80).

13. Between the curves there should be straight runs not less than 2 x of the external diameter of the pipe, in this case there may be a straight section between bends in the pipe less than 2D, if it is ensured by the technical capabilities of pipe bending equipment at the plant (OST 92-1600–84).

14. Thinning of the walls in places, where pipes bend (fig. 1) and transitions of curved sections to straight sections should not exceed the initial wall thickness: for steel pipes – 20 %; for titanium and copper alloy pipes – 20%; for aluminum alloy pipes – 25 % (point 6.1.7 OST 92-1600–84).

For sections of pipes subjected to maximum load during frequent exploitation, this refinement index for all materials should not exceed 10 % (paragraph 3.3.3 of OST 92-8751–80).

15. The ovality of pipes in the places of bend is the amount, defined as the difference between the greatest and the least diameters divided in half, which is to be: for pipes of nominal sizes up to 10 mm – not more than 0.5 mm; for pipes with internal diameters from 10mm up to 30 mm – not more than 1 mm; for pipes with internal diameters from 30mm to 90 mm – not more than 2 mm; for pipes with internal diameters of more than 90 mm not more than 3mm.

16. During the development of Assembly drawings and layout, it is necessary to provide gaps of at least 5 mm between adjacent pipelines, as well as between pipelines and other structural elements. In places where, because of structural or technological need, it is necessary to reduce the gap between pipelines and structural elements, its minimal allowable value must be specified in the CD, TT or TU.

17. Minimal bending radius for pipes of different diameters and with different wall thicknesses along the middle line (fig. 1), both for cold bending and for bending with heating must be not less the values shown in fig. 2. At the request of operational decision-making of minimal bending radius, without calculation, it is allowed to use paragraph 3.3.1 OST 92-8751–80, according to which the minimum bending radius (at the average diameter of the pipe) for pipes with internal diameters of up to 20mm should be at least 2.5 Dy, and for pipes with internal diameters more than 20 mm – not less than 3.5 Dy, it is allowed to use pipe bends with a bending radius in the single internal diameter, if the radius is obtained by stamping, pulling, or by specially tested bending.

In fig. 1 and 2 the following notations are accepted: Rcp is the bend radius along the middle line; S – is wall thickness of the pipe; D – is the outside diameter of the pipeline.

The sequence of calculating the minimal allowable radius of cold bending along the middle line of three pipelines: Ø8 × 1; Ø34 × 1 and Ø75 × 1.5.

First, the S/D value on the vertical axis of the diagram in fig. 1 is defined.

For the first pipeline: $S/D = 1/8 = 0.125$.

For the second pipeline: $S/D = 1/34 = 0.029$.

For the third pipeline: $S/D = 1.5/75 = 0.020$.

Then, using the values obtained on the vertical axis of the diagram in fig. 1, through the line “a”, the value “x” is determined on the horizontal axis of the diagram, followed by calculating the minimal allowable radius of cold bending along the middle line:

for the first pipeline: $x = 2.5$;

$$x = R_m/D \Rightarrow R_m = x \cdot D = 2{,}5 \cdot 8 \text{ mm} = 20 \text{ mm};$$

for the second pipeline: $x = 3.5$;

$$x = R_m/D \Rightarrow R_m = x \cdot D = 3{,}5 \cdot 34 \text{ mm} = 119 \text{ mm};$$

for the first pipeline: $x = 4.7$;

$$x = R_m/D \Rightarrow R_m = x \cdot D = 4{,}7 \cdot 75 \text{ mm} = 352 \text{ mm}.$$

After bending a pipeline with a wall thickness of at least 1.5 mm, when burrs are formed inside the pipeline, their electrochemical removal is allowed with a simultaneous increase in the internal diameter of the pipe of not more than 0.2 mm above the maximal error of the internal diameter and at a length of not more than 4 mm in the cleaning zone, ensuring the required roughness value.

18. The height of the corrugations at the bend of the pipe (see fig. 1) must not exceed the values: for pipes with a conditional passage up to 30 mm – no more than 0.3 mm; for pipes with a conditional passage over 30 to 50 mm – not more than 0.5 mm; for pipes with a conditional passage over 50 mm – not more than 1mm. At the same time, corrugations and dents should have smooth transitions without breaks and tears, and the dimensions of the outer diameter in the places of corrugations should not exceed the permissible ovality (paragraph 6.1.10 OST 92-1600–84).

19. Pipe bending should be carried out from preformed pipes that have sufficient technological allowance along the length. The value of technological allowances, depending on the bending methods, must comply with the standards of OST 92–9346.

20. For steel pipe the gap between the flexible mandrel and the inner diameter of the pipe should be selected: for pipe with external diameter up to 20–0.2 to 0.4 mm; for pipes with outer diameter from 23 to 35 mm from 0.3 to 0.5 mm; for pipes with outer diameter from 36 mm to 40mm from 0.4 to 0.6 mm; for pipes with outer diameter from 41 to 100 mm from 0.6 to 1.0 mm. For aluminum pipes and pipes made of aluminum alloys: for pipes with an outer diameter of up to 40 from 0.5 mm to 0.6 mm; for pipes with an outer diameter of 40 to 100 mm – from 0.6 to 1.0 mm.

21. The radius of the pipe bending equipment (rollers, clamps, bending mandrel) must be less than the radius of the pipe bending by the amount of spring of the pipe material.

22. Flexible mandrels should be made of materials that can withstand high pressure, with a small friction

coefficient for the pipe material with high resistance to abrasion, eliminating the possibility of contamination of flexible pipe, preventing formation of scratches and «nadirov» on the inner surface of the pipe, eliminating the thinning of pipe wall (e. g. steel, fiberglass plastics, textolite, nylon, etc.). There is an example of chrome plating and polishing of steel flexible mandrels with a surface layer hardness of 52÷58 HRCэ.

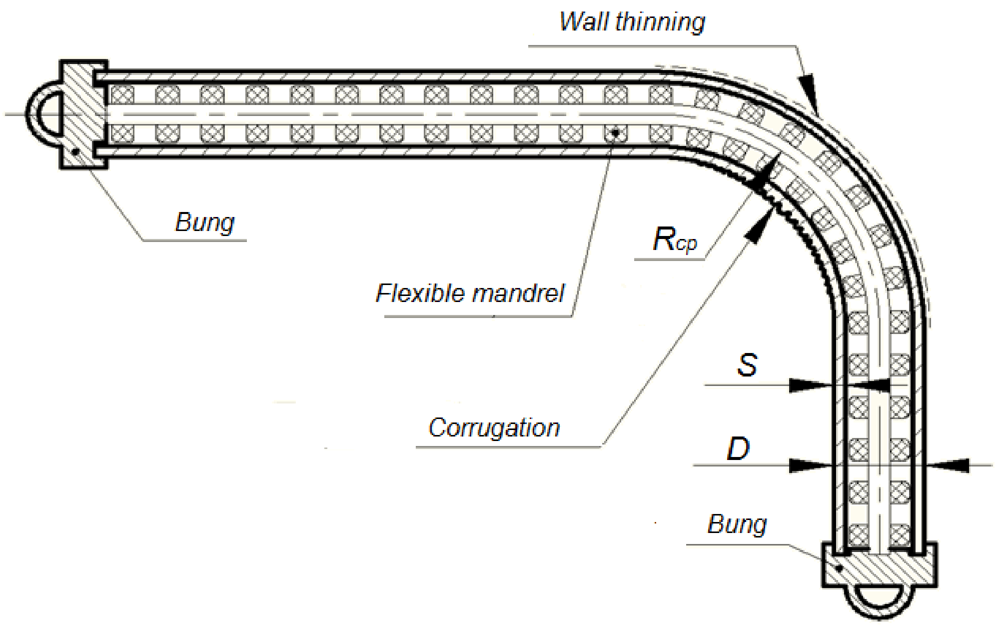

Fig. 1. Section of the projection of the bending in the mandrel

Рис. 1. Сечение проекции гиба трубопровода в дорне

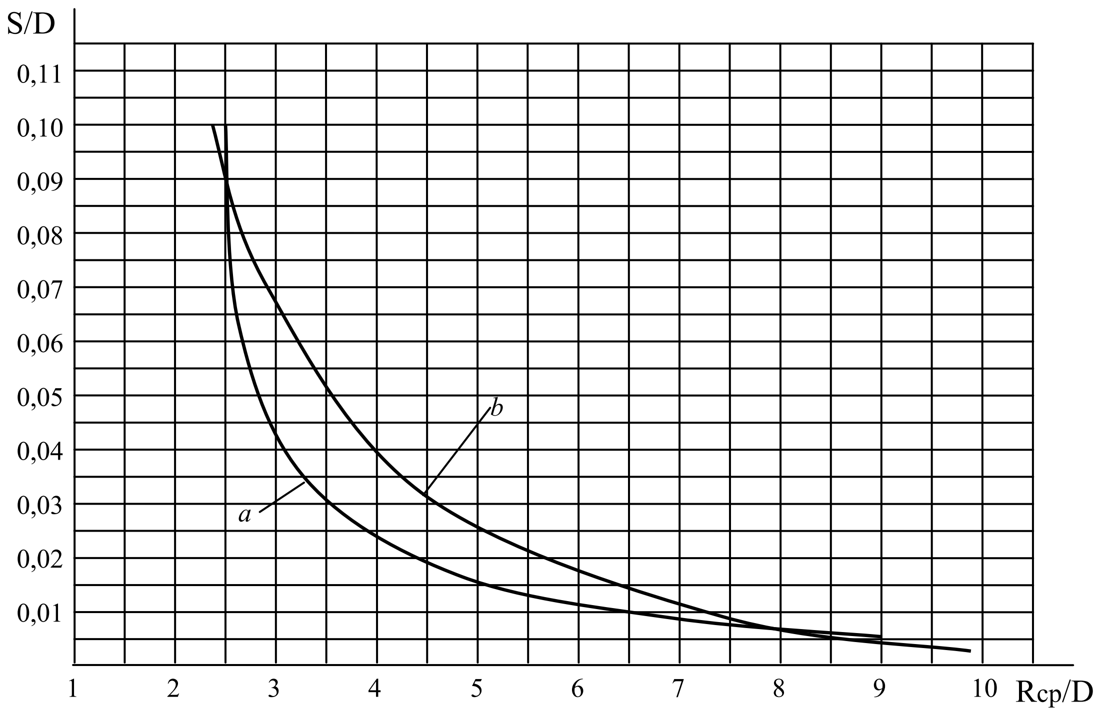

Fig. 2. Diagram of the minimal radiuses of a bend of pipelines:
a – for cold bending; *b* – for bending with heating

Рис. 2. Диаграмма минимальных радиусов изгиба трубопроводов:
a – для холодной гибки; *b* – для гибки с нагревом

Working pressure of the substance in steel pipe

Dy, mm	Pipe size, mm	Working pressure, MPa	Allowable internal pressure, MPa	Dy, mm	Pipe size, mm	Allowable internal pressure, MPa	Allowable internal pressure, MPa
4	6×1	0…39.2	47	50	56×3	0…9.8	13.5
6	9×1.5				60×5	9.8…19.6	22.3
10	14×2	0…39.2	39.6		65×8,5	19.6…39.2	39.2
20	24×2	0…19.6	19.8	80	85×3	0…2.5	8.8
	28×4	19.6…39.2	40.5		89×4.5	2.5…9.8	13.3
32	36×2	0…9.8	14		95×7.5	9.8…19.6	21.8
	38×3	9.8…19.6	20.5	100	110×5	2.5…9.8	11.8
	42×6	19.6…39.2	40.8		120×10	9.8…19.6	23

23. The allowable internal pressure in the pipe is determined by the formula:

$$P = \frac{2(\sigma_u / 2,6)\delta}{(D_O - \delta)} K,$$

where σ_u – is the ultimate tensile strength, N/m^2; δ – is the (average) wall thickness of the pipe, m; D_O – is the outer diameter of the pipe, m; K – is a dimensionless correction factor:

$$K = \frac{\dfrac{5\delta_{\min}^2 + h^2}{\delta} + 2\sqrt{D_P \delta}}{\dfrac{5\delta_{\min}(D_O - \delta)}{(D_O - \delta)} + (D_O - \delta) + 2 * \sqrt{D_P(\sigma_u / 2,6)}},$$

where $\delta_{\min}$ – is the minimal thickness of the pipe along the entire length of the pipeline, m; h – is the maximal pipe thickness over the entire length of the pipeline, m.

24. The working pressure of the medium, used in the steel pipeline, is determined according to OST 92-8751–80. Table shows some parameters that are allowed for the main sizes of steel pipelines/

25. In drawings, containing a complex configuration of 3D pipes, as well as in those, where there are bending forms of pipes, it is required to specify in the technical requirements, necessity to conduct hydraulic or pneumatic strength tests with a pressure exceeding the working pressure of the medium by 1.25÷1.5 times in accordance with paragraph 3.5.1 of OST 92-8751–80. This test must confirm absence of cracks, gas pores, and other non-metallic inclusions in the pipe wall and unacceptable wall thickness defects. In this case, the test equipment, technology for preparing and conducting tests must exclude contamination, grease, oil, gasoline and other liquids and their vapors from entering the internal cavities of the pipe. During the test, it is obligatory to perform pressure loading smoothly without sudden jumps to the set value for at least 30 seconds (deviation from the set pressure value by not more than ±5 % according to paragraph 3.5.11 of OST 82-8751–80). Measuring the pressure is to be held with pressure gauges of accuracy class not less than 2.5 in accordance with GOST 2405–88.

26. Requirements to the design of the bending unit are set out in section 2 of OST 92-8751–80. In particular, the following requirements are highlighted for the pipe bending unit: the unit must be protected from direct exposure to precipitation and the sun; the recoil and actuation forces must be firmly and reliably fixed in the unit (for example: it is necessary to specify the amount of tightening of threaded parts in the CD, provide locking – as a means of protection against disconnection of parts during vibration); the diameter of the trunk is to be chosen, according to the desired pressure drop and allowable pressure drop; parameters of composite components of the bending unit and pipes (working environment, working pressure, nominal diameter, order of operation, etc.) should correspond to each other; releasable connection of the unit is to be placed in locations convenient for maintenance and repair; the height of the pipe bending table on the unit should also be convenient for the operator (not more than 1.5 m); protection of parts and the pneumatic hydraulic system from corrosion must be provided; the safety system of the device must be followed for the service personnel. The symbol and image of pipeline elements are regulated in GOST 2.784-96 and in OST 92-0039–74.

Opportunities of temperature influence on the pipe bending process. When defining method and technology of pipe bending, the first place is given to implementation of the specified parameters of pipe bending, optimizing the costs of the technological process simultaneously. If to use an unprepared pipe for bending (according to technical characteristics) and perform bending on a non-specialized (economical) manual pipe-bending apparatus, it is very difficult to provide a bending radius of less than 4D.

When determining whether a material is ready for the bending process, the following technical parameters are considered. The phenomena of elasticity and plasticity are well illustrated using the material tension diagram (fig. 3).

Diagrams of stretch and mechanical characteristics of materials depend on many factors. The most significant influence on them exert the rate of deformation, temperature, and technological factors.

Increasing the rate of deformation of the material v leads to a decrease in the plastic properties and strengthening of the fragile ones, reducing the relative deformation at break δ. Simultaneously, σt and σb increase. In this case, the elastic characteristics of the material - modulus of elasticity E and the coefficient of transverse deformation μ remain unchanged.

The influence of higher and lower temperatures on metals is more significant. When temperature E increases, σ_s, σ_u, in their turn, decrease, and the coefficient of transverse deformation μ and δ increase.

Calculations of structures, which operate beyond the elastic limits of the materia, are based on experimentally obtained tensile diagrams. To perform calculations, the equation of the stretch diagram is given in the form: $\sigma = f(\varepsilon)$.

For an isotropic body within elastic deformations, when calculating the deformation process of a material, it is possible to write six equations, which link the stress components with components of deformation:

$$\begin{cases} \varepsilon_x = \dfrac{1}{E}(\sigma_x - \mu(\sigma_y + \sigma_x)) + \alpha T & \gamma_{xy} = \dfrac{\tau_{xy}}{G} \\ \varepsilon_y = \dfrac{1}{E}(\sigma_y - \mu(\sigma_x + \sigma_z)) + \alpha T & \gamma_{xz} = \dfrac{\tau_{xz}}{G}; \\ \varepsilon_z = \dfrac{1}{E}(\sigma_z - \mu(\sigma_x + \sigma_y)) + \alpha T & \gamma_{yz} = \dfrac{\tau_{yz}}{G} \end{cases}$$

Beyond the elastic limit, taking into account temperature deformations, Hooke's law has the following form:

$$\varepsilon_x = \frac{\varepsilon_i}{\sigma_i}\left[\sigma_x - \frac{1}{2}(\sigma_y + \sigma_z)\right] + \alpha T$$
$$\varepsilon_y = \frac{\varepsilon_i}{\sigma_i}\left[\sigma_y - \frac{1}{2}(\sigma_x + \sigma_z)\right] + \alpha T .$$
$$\varepsilon_z = \frac{\varepsilon_i}{\sigma_i}\left[\sigma_z - \frac{1}{2}(\sigma_y + \sigma_x)\right] + \alpha T$$

The modulus of elasticity is replaced by the ratio of the deformation intensity ε_i to the stress intensity σ_i:

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{\begin{aligned}&(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + \\ &+ (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\end{aligned}},$$

$$\varepsilon_i = \frac{\sqrt{2}}{3}\sqrt{\begin{aligned}&(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + \\ &+ \frac{3}{2}\left(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2\right)\end{aligned}}.$$

For an isotropic body, the main directions of deformation coincide with the main directions of displacement.

For aluminum, E = 0.7·105 MPa; for copper, E = 1.2·105 MPa; for steel, E = 2·105 MPa.

It is also necessary to take into consideration such indicators as: the elastic limit, which is the maximum value of mechanical stress at which the deformation of this material remains elastic, and the limit of proportionality is the maximum amount of stress for a particular material, at which Hooke's law is still applied, namely, deformation of the body depends directly on the applied load.

A study of patent documentation and technical literature was conducted, in which the issues of force and temperature effects on the pipe bending process [14–16] were considered. On the basis of analysis and generalization of the information obtained, the following main parameters and regularities of technological processes are identified:

1. Performing bending of a heated pipeline: when heated to 800÷1000 °C, the values of $\sigma_в$ and $\sigma_о$ are reduced up to three times, what lowers index of the bending force and makes it possible to obtain complex curved trajectories of the pipe. However, this process is extremely energy-intensive and economic profitability of this method of blending is very uncompetitive. This method is used only if there is no other way to manufacture a complex 3D pipeline.

2. Narrow-zone local heating of the place of bending on the pipe up to 1100 °C reduces the possibility of corrugation, and also the index of the impact force on the pipe by 6÷7 times. When using modern energy-intensive technologies for narrow-zone heating of the place of bending on the pipe, good indicators of the diameter and radius dimensions of the pipe bend can be achieved through the heating elements of the flexible mandrel. Additional energy costs for heating the mandrel elements in this case can be compensated by means of reduced energy costs on the force of impact on the pipe during bending.

3. The pipeline (usually an aluminum alloy pipe) is cooled with nitrogen before being bend to the temperature of –200 °C, and water is used as a filler in the pipe (according to OST 92-1511). It is necessary to take into consideration possible structural changes in the pipe material, so if reliability and strength indicators are lowered, what results in prohibiting further application of the pipe, subsequent heat treatment of this pipe, according to OST 92-1311, will be required to restore the strength properties of it, what will reduce the financial profitability of this method.

Therefore, in order to make a decision about using this method, it is necessary to conduct testing of experiments (different temperature conditions, different bending forces used, different materials and pipe alloys used, etc.) and choose the optimal bending technology with cooling without su4.

4. Laser cooling of atoms of the tube material (because of resonant light pressure) is laser irradiation of the tube material, and the average energy of the emitted photons must exceed the energy of the absorbed photons (in other words, when anti-Stokes emission occurs, at frequencies higher than the laser frequency, the Stokes emission dominates, frequencies of which have lower values, under a condition, that the speeds of non-radiative transitions from excited States are negligible in relation to the speeds of optical transitions), in this case, the internal degrees of freedom of the atoms of the pipe material, which are connected by heat exchange with the environment, are cooled. Cooling of atoms under resonant light pressure continues until the fluctuations of the atom's momentum, which are inevitable in the process of stochastic re-emission of a large number of atoms, enter the process. Types of laser cooling are as follows: anti-Stokes laser cooling (photoluminescence method); Doppler cooling (the method is based on the Doppler effect and spontaneous Raman scattering); fluorescent cooling (the frequency of laser radiation exceeds the frequency of ordinary light, absorbed by the tube material).

5. Application of greasing from petroleum products on the outer surface of the pipe material, such as mineral oils, fuel oil, paraffin, petrolatum, vegetable oils (castor), soap suspensions in oil (for example, an emulsion greasing for bending aluminum – a mixture of alkyl esters and an ox ethylated aliphatic mixture of surfactants), talc powders, graphite powders, molybdenum disulfide powders.

In the operation of cold bending of the pipe when applying one of the mixtures on the pipe in the material, near the surface in the stretch zone, stresses are reduced and plastic properties are improved. Slight heating of the bend area with this coating dramatically increases the coefficient of plasticity.

6. Application of modern fillers inside the bent pipe, which change its temperature and contain: over cooled ice, quartz sand, liquid mixtures, emulsions, oils, surface lubricants of the pipe and other fusible and loose fillers. It is necessary to conduct production experiments with different materials and temperature conditions: with registration of results; analysis of the results obtained and working out the most effective technology.

Mechatronic system of the CNC bending machine operation algorithm. The task of the 3D pipeline bending process is to create a universal bending machine (UBM), which has the following functions:

1. It is possible to use three types of bending technology: bending without heating and without cooling (including a flexible mandrel and without a flexible mandrel); bending only with narrow-zone heating; bending only with cooling.

2. It can operate in three operating modes: manual; automatic (with numerical control); universal variable mode (automatic reproduction of individual mechanical bending operations, using actuators or temperature control operations, which are started manually by the operator through control display).

3. The UBM is maintainable, has cheap, periodically replaced bending elements (bending rollers, gripping and rotating devices, oils, etc.) and does not have expensive imported parts and assemblies.

4. The UBM is designed as a constructor, allowing regulation and improvement of the machine, the possibility of using several bending technologies, and the possibility of experimenting with a bending head (consisting of lobes with bearings with an induction function), as well as allowing experiments with technologies.

5. The UBM allows the operator to produce a 3D pipeline according to the drawing without creating a special information program, that is, using only the interface and basic programs, recorded on the programmed logic microcontroller of the automation Cabinet.

The General functional schema of the UBM is shown in fig. 4.

A stand for entering a 3D pipeline bending task provides UBM with information for step-by-step operations [17; 18]. The device of the stand must be made in a universal mixed form: a touch-button panel [19].

The touch panel should perform the function of detailed input of bending information and allow further improvement of the UBM control software, and the keypad should reliably fulfill the function of performing a one-time mechanical bending operation. The pipe bending trajectory is set by pressing the keys on the sensor provided with designation of logical elements and numeric values for specifying the pipe size and the bending path. Also, the information input stand must have a USB socket for a Flash drive.

From the stand, information is sent to the programmable controller of the automation Cabinet (in which microelectronic integrated circuits can be used as an element base). When developing the automation Cabinet of the UBM control system, it is necessary to take into account that in comparison with the controller, having relay-contact equipment, the microcontroller has contactless electronic blocks, which in turn have high reliability in operation and small size. A serious drawback of the microcontroller is the limited number of programmable operations, so the final choice of using the controller or microcontroller will depend on this parameter. The control program of the controller (a set of commands, written on the programming language, coinciding specified algorithm for the operation of bending machine) must contain both geometric and technological information, which should be able to be adjusted by the profile specialists.

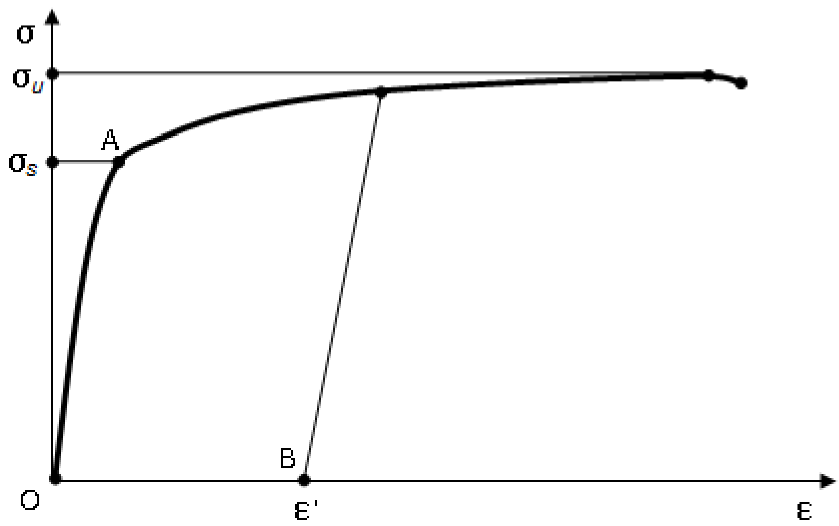

Fig. 3. The diagram of deformation of material under tension

Рис. 3. Диаграмма деформации материала при растяжении

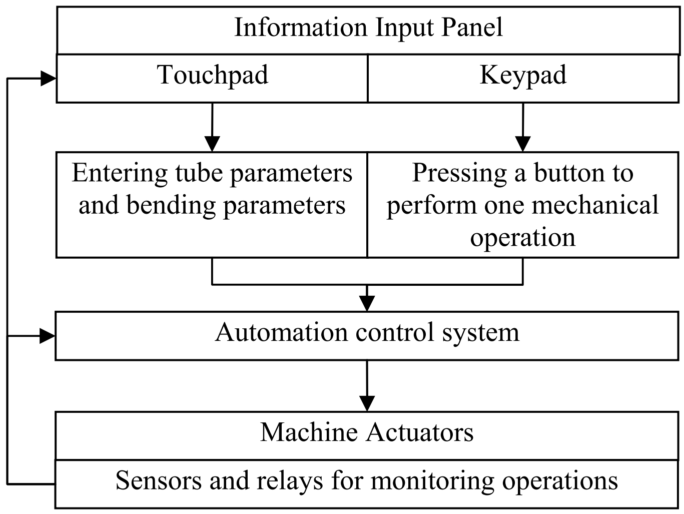

Fig. 4. Functional schema of the universal bending machine

Рис. 4. Функциональная схема работы универсального гибочного станка

The control program is to meet requirements of GOST 20999–83 (CMEA ST 3585–82), which will be clear to most systems, regardless of the manufacturer and operator.

Control of the UBM mechanisms' operation must be provided by sensors, located on the UBM bending table (light, magnetic, ray optical, etc.) and relays (pressure, time, etc.), the signal from which is sent to the controller of the automatic control system Cabinet. Connecting of the controller panel of automation system to the local network of the enterprise will allow to transmit information of the machine (presence of oil, air, pressure level in the system, etc.) and to perform maintenance in case of breakage or jamming of the operating mechanisms of the UBM. Operation of the actuators of the bending machine is determined by the drives (devices that convert electrical energy into mechanical energy through the electric motor and the actuators of the machine that control the parameters of the bending).

In the bending machine, it is possible to use the following types of drives: electric, electromechanical, pneumatic, hydraulic, and electro-hydraulic.

The movement parameters of the mechanism are controlled with the help of a control parameter Converter, a feedback sensor, a setting device, and a protection device. It is also necessary to use auxiliary drives, which implement movements, which have an auxiliary character: in clamping devices, loading devices, pumps, etc. With the help of an electric drive Converter, it is possible to smoothly adjust changes in current parameters – for example, with electric pitch splitting (which can allow changing the parameters of speed of bending rollers, as well as power of the roller pressure on the pipe, etc.) or voltage (for example, converting AC to DC).

Simultaneously, a mechanical transmission between the output link of the source of motion (the motor shaft) and the link consumption of mechanical energy (e. g. rod hydraulic cylinder) is to be used; in this process, a kinematic transformation of the change in the direction of force and speed of linear movement, or a transformation of the change in the plane of rotation during rotational movement takes place.

In the UBM mechanism it is necessary to determine the main motion drives, which are involved in the direct bending process and from which accuracy and quality of bending of pipelines depends. For this purpose, in these drives: increase of the range of regulation by the Converter, using zero position sensors (GOST 20523–80), ensuring shock-free start and braking (using a pulse sensor) are additionally used.

The cyclorama of the UBM executive mechanisms sequence is as follows:

1. Input pipe parameters on the touch panel (external diameter, wall thickness, total length of the pipe).
2. Installing the pipe in the UBM feed mechanism (in the delivery state).
3. Pipe capture by the "capture and movement Mechanism" of the UBM.
4. Input 3D bending path parameters sequentially on the touch panel:

LENGTH of straight section of pipe (mm)
↓
BENDING TECHNOLOGY
– application of prepared pipe for bending (chilled);
– application of a spray grease on the surface of the pipe;
– application of a mandrel for bending (yes/no);
↓
BEFORE BENDING WITH MANDREL
– application of a heating element of the mandrel (yes/no);
– input of the heating temperature of the heating elements;
↓
Horizontal turning RADIUS (mm)
↓
The ANGLE at which the radius is turned (up to 360)
↓

↓
LENGTH of straight section of pipe (mm)
↓
UGA STOP for checking obtained pipe dimensions (taking into consideration the spring back of the material)
↓
MODIFICATION of the pipe on the UGA using the keypad (if necessary)
↓
CHECKING the modified dimensions on the pipe
↓
THE LAUNCH OF THE UGA
↓
ANGEL of axial rotation of the pipe
↓
... (iteration).

5. Execution of the UBM of the straight part of pipe, using capture and movement mechanism.

6. Location change of the bending rollers of the machine from the starting position to the position, taking into different bending radius of the pipe (see fig. 5, *b*, *c*, *g*).

7. Execution of bend of the pipe on the UBM in accordance with a predetermined trajectory of 3D model.

Several key factors, which affect the bending process and increase the efficiency of the UBM, should be taken into consideration:

– the possibility of general or local zone heating (for example, by high-frequency currents, etc.) application in case of some difficulties in the process of bending (thick pipe walls, pipe breaks, unacceptable pipe sinking, etc.);

– the possibility of using greasing oils of the pipe walls;

– the possibility of using a prepared cold billet (inside the pipe, water ice obtained with cooled nitrogen);

– the possibility to reduce goffer formation by installing an additional roller from the center of the bend;

– the ability to control the UBM manually, when modifying the pipe bend, if the material spring coefficient is not taken into consideration.

Conclusion. In the review of this article an attempt to consider all the factors, which affect the efficiency of the pipe bending process, is made. An overview of the normative documentation of industry aerospace standards, regulating pipeline bending, is presented, as well as requirements for a universal bending machine, which allow application a temperature-free and non-temperature technological process of bending pipelines of complex configuration. A cyclorama of the sequence of functioning of the UBM executive mechanisms is given and a schematic drawing of the process of bending by a universal machine is presented.

The main advantage of the technology, being developed, and universal bending equipment is the possibility of application of different bending technologies on this equipment, a large range of sizes of pipes being bended, simplicity of operation of the equipment, comparative cheapness of technologies and opportunity of improving them, low cost of repairing, simplicity of maintenance of the UBM. Additional advantage of the UBM is the possibility of working out and finding the most effective bending technology and the possibility of making improvements to the design of the UBM.

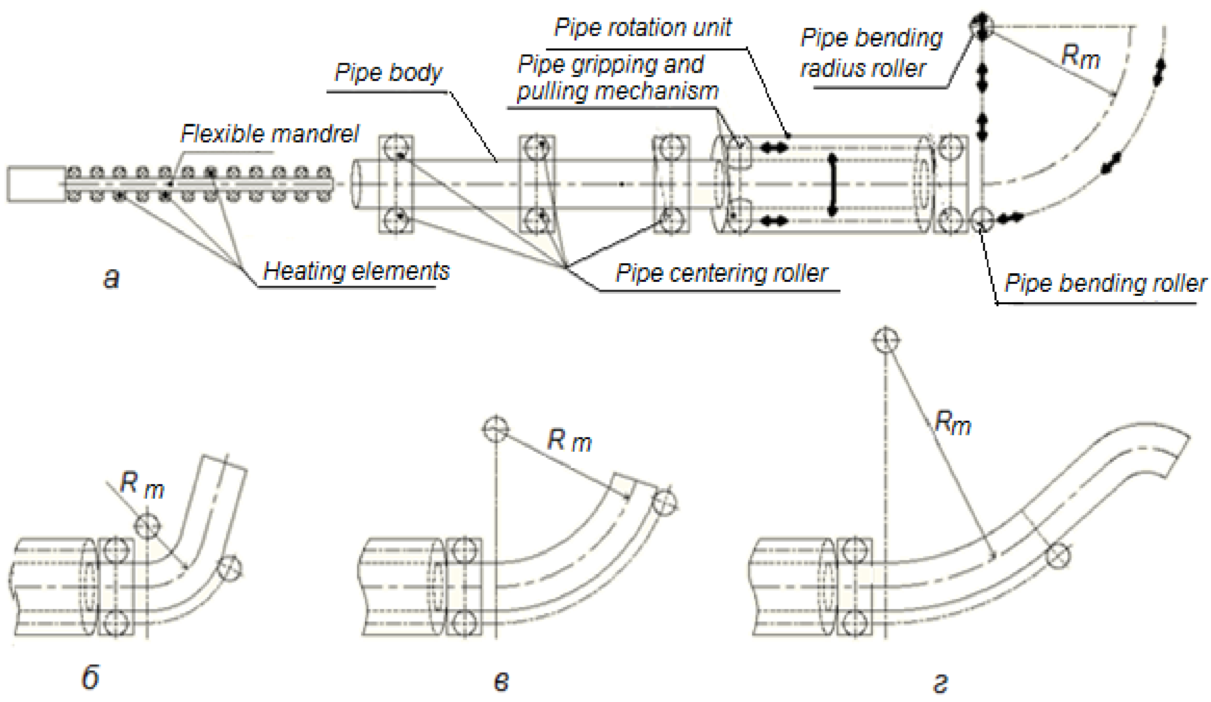

Fig. 5. Schematic drawing of the universal bending machine

Рис. 5. Схематический рисунок универсального гибочного агрегата

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