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Proceedings of the VI International Youth Scientific and Technical Conference

Edited by A.G. Korchunov

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These scientific publications constitute the proceedings of the VI International Youth Scientific and Technical Conference «Magnitogorsk Rolling Practice 2022» devoted to metal and alloy forming**.**

Subjects of the reports delivered by young researchers show a considerable interest in research areas related to development of finite element models of metal and alloy forming processes using special software, innovative cold and hot plastic working processes, new materials with a higher level of performance, methods used to determine true resistance of metals and alloys to deformation, and physical simulation of metal and alloy forming processes.

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PREFACE

This volume contains proceedings of the 6th International Youth Conference ***Magnitogorsk Rolling Practice 2022***, which took place on May 31st through June 4th 2022 at Nosov Magnitogorsk State Technical University.

Magnitogorsk is a city of heroic labourers, one of the world's major centres of ferrous metallurgy that boasts great scientific and industrial potentials. It has become a good tradition to hold this youth conference dedicated to the fundamental and applied problems of metals and alloys forming at NMSTU. The primary aim is to provide a platform for young researchers to discuss new trends, prospects and innovations that are entering their professional area.

The Conference participants included young researchers from 19 universities, 5 R&D institutions and 10 production companies. This volume contains 75 research papers by more than 160 authors from five countries of the world.

After the participants had presented their reports, nominees and prize winners were determined.

Iliyas Tuvalev (Bashkir State University, Ufa, Russia) and Anna Baryshnikova (Nosov Magnitogorsk State Technical University, Magnitogorsk, Russia) were recognized in the *Novice Researcher* category. Denis Akhmerov (Russian Research Institute of the Tube & Pipe Industries, Chelyabinsk, Russia) and Igor Snegirev (Kamensk Uralsky Metallurgical Works OJSC, Kamensk Uralsky, Russia) were recognized for *Best Implementation*. Vladislav Pishchikov (Rudny Industrial Institute, Rudny, Kazakhstan) was recognized for *Best Modelling of Metal Forming Processes*. Elizaveta Belolipetskaya (Lipetsk State Technical University, Lipetsk, Russia) was recognized for *Best Theoretical Study*. Maria Vetluzhskikh (Bauman Moscow State Technical University, Moscow, Russia) was recognized for *Best Cross-Disciplinary Solution*. Elvira Fakhretdinova (Ufa State Aviation Technical University, Ufa, Russia) was recognized for *Best Innovation*. Viktoria Gorbunova (South Ural State University, Chelyabinsk, Russia) was recognized for *Implementation of Priority Projects*.

Aleksey Sverchkov (Magnitogorsk Iron & Steel Works, Magnitogorsk, Russia) was awarded a 3rd degree certificate. Elvira Khafizova (Ufa State Aviation Technical University, Ufa, Russia) was awarded a 2nd degree certificate.

Ksenia Yakovleva (Russian Research Institute of the Tube & Pipe Industries, Chelyabinsk, Russia) was recognized the winner and was awarded a 1st degree certificate.

We kindly thank all participants for their contribution to the course of the Conference. We are looking forward to welcoming you again, at the 7th International Youth Conference ***Magnitogorsk Rolling Practice***, in this hospitable city of Magnitogorsk!

June 2022 Alexey Korchunov

SESSION 1 – Innovative Technology and Materials in Metal Forming

APPLYING COLD ISOSTATIC PRESSING FOR PROCESSING METALLIC POWDERS AND NON-METALLIC MATERIALS

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A method of uniaxial compression is mostly used for compacting powder materials. However, this method does not always contribute to achieving a good compaction in the middle part of the sample due to a strong influence of friction forces of particles on the container walls. The isostatic pressing method prevents such problems.

Cold-isostatic pressing (CIP), or hydrostatic pressing, is a method of barometric processing of products using high-pressure fluid in special units, requiring no additional heating. CIP is applied for compacting powder materials into a uniform solid sample for sintering or mechanical processing. Moreover, it is possible to compact materials into simple shapes, such as pellets, and in various complex shapes with internal cavities, which is impossible by ordinary pressing. CIP is used to manufacture high-strength workpieces, showing a uniform structure in volume. This method is also applicable for improving uniformity of products with a defective structure (pin holes, cracks) [1, 2].

The Institute of Physics of Metals, Ural Branch of the Russian Academy of Sciences, has developed a high-pressure unit for CIP, namely the isostatic press. Maximum operating pressure reaches 280 MPa and machine oil is used as a pressure fluid. Before processing a powder material is put in a sealed elastic shell, which transfers fluid pressure and helps to achieve a uniform reduction over the entire sample. The paper presents potential applications of such unit for compaction and high pressure treatment of metal pellets, non-metallic powders and other bulk materials at room temperature.

We ran the experiments on compacting the samples from AK4 and AK4-1 aluminum alloy pellets to produce rods of 85 mm in diameter. Maximum achieved density of the samples reaches 89% (Fig. 1). Cylindrical samples of a higher density were produced from a mixture of tungsten carbide and cobalt powders.

Test tubes were produced from nanodispersed powders of lithium oxide and lanthanum oxide with zirconium oxide additives, a prototype of lithium-ion batteries of a new generation. In spite of high hardness and strength of nanosized oxide powders, the test tubes maintain their given shape after processing in the isostatic press before annealing. Transparent ceramic samples based on yttrium and zirconium oxides were manufactured for solid-state lasers. Graphite electrical contacts underwent hydrostatic pressing. It was found that such processing contributed to improving uniformity of the samples and increasing the operational life of products by 5 times and over. It was shown that it was possible to obtain “iron wood”: hydrostatic treatment of a birch resulted in increasing density of the wooden sample by 2 times: from 0.6 g/cm3 to 1.2 g/cm3. It should be noted that definite optimum pressure was fixed for all materials. In case of higher pressure, the density of the products remained unchanged.

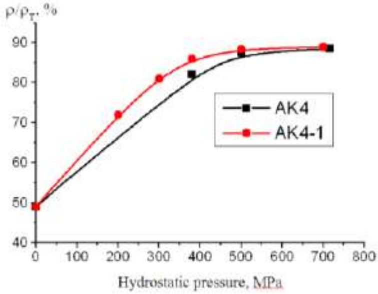

Fig. 1. Relative density-pressure curve, when compacting rods from aluminum pellets in the isostatic press (ρT is theoretical density)

Thus, the CIP method applied in the isostatic press has a wide range of applications for processing various materials: from metallic and ceramic powders to solid specimens of various origins to increase their uniformity, expand a range of application and achieve high functional characteristics.

The research was carried out as part of the state order on the subject "Pressure" (No. AAAAA18-118020190104-3).

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MEASURES FOR ELIMINATION OF LARGE CRYSTAL RIM IN THE WALL OF THE PIPE OBTAINED BY CONTINUOUS EXTRUSION

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During continuous extrusion of AD0 aluminum alloy tubes with the diameters of 8-20 mm by the Conform method, abnormally coarse grains are formed on the inner wall of the hollow section, which affects the performance.

The presence of this effect determines the level of energy received in the pressed metal, and is expressed as the Zener-Hollomon parameter. According to this, an increase in temperature and a decrease in the deformation rate reduce the tendency to form coarse-crystalline zones along the section of the part. In addition, the greater the degree of plastic deformation in a certain area of the section of the pressed part is, the higher the level of energy is that is stored in this zone. When using a combination die, the metal is first cut into strips and then welded. It is obvious that the zone near the inner wall of the tube is deformed to a greater extent and with a higher metal flow rate than that of the outer one. This mainly explains the formation of coarse grains inside the tube, but the process is quite complex and depends on multiple process factors and the composition of the alloy.

Analysis of the microstructure on longitudinal thin sections of the tube showed that recrystallization occurs mainly near the inner surface of the tube wall. Moreover, this process begins after the part has been released from the die, since the grains are not elongated in the direction of extrusion, which would indicate their growth during deformation and welding.

Apparently, the temperature-rate factors of the process have a greater influence on the grain size, which, in a certain combination, can give the desired effect, as noted by most researchers in the technical literature.

To reduce the energy consumption of the extrusion process and improve the quality of the tube wall in the areas where the metal strips are welded after the splitter, it has been experimentally established that the extrusion temperature should be within 550-580°C. In industrial conditions, this can be achieved when the wheel speed of the Conform installation is 0.2 m/s.

As a result of the studies carried out by the authors, it was established that:

– recrystallization and grain growth occur after the pressed tube has been released from the die;

– the extrusion temperature (all other things being equal such as speed, unevenness and degree of deformation, intensity of tube cooling, calibration by drawing, etc.) does not have a noticeable effect on the structure of the finished tube;

– to reduce the load on the drive of the installation and improve the quality of welding of metal strips after the splitter, it is advisable to maintain the extrusion temperature within 550-580°C;

– due to the fact that the formation of coarse grains on the inner surface of the tube is a rather complicated process that depends on multiple process factors and the alloy composition, in order to better understand this effect, it is advisable to conduct a series of experiments using the method of statistical processing of results.

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DEVELOPING AND STUDYING A NEW TECHNOLOGY OF PRESSING FORGINGS AND ROUND BARS

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One of the most advanced metal treatment methods, showing a significant decrease in a metal consumption coefficient, when manufacturing various products from ferrous and non-ferrous metals and alloys, and quality improvement subject to compliance with the treatment technology, is metal forming. Main metal forming methods include pressing. It has long been known that improvement in the metal quality during pressing, namely deformation of billets and bars, mainly depends on the preferred process of pressing and applied relevant tools. Research [1] proved that the most promising method of improving the quality of forgings and bars is evolving additional shear or alternating deformations, when pressing metals in various forging tools. For example, significant additional alternating deformations during pressing are achieved by using a new forging tool for pressing round bars and forgings (Fig. 1).

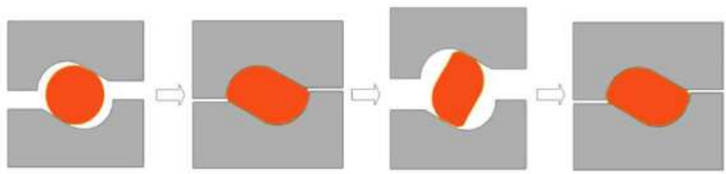

Fig. 1. A forging tool and a round bar pressing process

The research is aimed at carrying out a comprehensive study of a new technology of pressing round bars and forgings in the forging tool, developing alternating deformations in a total volume of the pressed metal.

Thus, DEFORM software was applied to carry out a finite-element modeling of a process of deformation of bars in dies of a new design, using alternating deformation, and determine reasonable parameters of forging in such dies, ensuring the best stress and strain state, and effect of process and geometry parameters of forging in new dies on the evolution of a microstructure of the bar material. The computer modeling showed that the most optimum option was dies with a radial joint of side planes and an angle of inclination of flat faces of 30°. The analysis of effect of such process parameters of forging in new dies, such as tool movement speed and bar heating temperature, on the evolution of the microstructure showed that both parameters under analysis influenced the rate of structure refinement; however, heating temperature produced a more significant effect. The most optimal bar heating temperature in terms of the grain size and force is 1000°C.

The computer modeling results were used for experimental forging of bars from two sparingly alloyed steel grades 7KhG2VM and 5KhV2S in the dies of the proposed design.

The analysis of the metallographic studies shows that the development of considerable alternating deformations in a total deformed body, when deforming the bars of 7KhG2VM and 5KhV2S steel grades in the proposed forging tool, contributes to a better processing of the cast steel structure and forming a fine equiaxed grain throughout the deformed bar without a significant change in its original dimensions compared to forging of similar bars in flat dies by the existing technology. The analysis of changes in mechanical properties of 7KhG2VM steel grade after deformation according to the proposed technology in the dies of a new design and in flat dies showed that by deforming the steel grade according to a new technology the strength characteristics was by 6-7% on average higher as compared to the existing technology. When deforming bars from 7KhG2VM steel grade according to the proposed technology, ductile properties decrease less as compared to deformation in flat dies, positively influencing the quality of the produced bars.

The study on the microstructure and mechanical properties carried out in the experimental forging of the bars concludes that the development of significant alternating deformations in the total deformed body, when deforming the bars in the proposed forging tool, provides for better processing of the cast steel structure to form a fine equiaxed grain throughout the deformed bar without considerable changes in its original dimensions compared to forging in flat dies, positively influencing the change in mechanical properties of the produced round bars.

The research was funded by the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09259236).

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COMPARATIVE ANALYSIS OF MODERN COMPACT STRIP PRODUCTION UNITS AND HOT STRIP MILLS

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Current trends in reducing hazardous emissions and increasing energy efficiency make metallurgists seek for solutions to minimize power consumption. One of such solutions is using a continuous casting machine in compact casting-rolling plants, eliminating a stage of heating billets.

Now, to produce strips, either continuous host strip mills, or casting-rolling plants are used. Every technology has its advantages and disadvantages; however, it occupies a niche in metallurgy. This review paper compares continuous host strip mills and modern complexes of continuous and quasi-continuous rolling, analyzes a product range, performance, quality and energy efficiency.

We analyzed open publications [1-5] and made conclusions: ISP, ESP, CSP and QSP were designed to adapt quickly to a new range of steel grades and limited production of high value-added materials, and hot strip rolling mills showed maximum efficiency in case of the large output of products of the same type. It was found that hot strip mills required higher capital expenditures and more areas, but offered a broader range of sizes, as there were no limitations on the melting stage. Energy efficiency of the two technologies is comparable, but the gas/electricity balance is shifted to electricity, contributing to lower air emissions of hazardous gases.

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FEM-STUDY OF BIMETALLIC WIRE DEFORMATION DURING COMBINED ECAP-DRAWING

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A set of strength and ductility properties of bimetallic wire and rods is one of the most important parameters, Properties of metals, included in bimetallic wire, are sensitive to the structure. Changes in the structure by metal forming contribute to improving structural properties of the material.

To carry out additional metal forming of bimetallic wire, we proposed combined ECAP-drawing (Fig. 1), which was used on the drawbench at Rudny Industrial Institute.

Success and efficiency of the combined process mainly depend on many geometrical and process parameters, including the joint angle of the channels of the ECA-matrix.

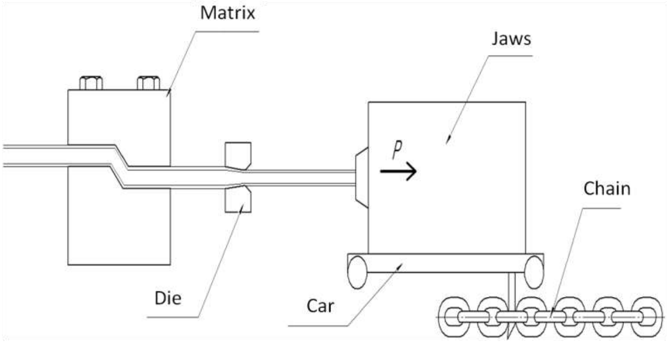

Fig. 1. Deformation process flow

To identify the effect of the joint angle of the channels of the ECA-matrix on the stress and strain state of metal in various layers of bimetallic wire, we used a computer simulation of the steel-copper wire deformation process according to a combined deformation process flow in DEFORM software suite. The analysis of the computer simulation showed that the most reasonable joint angle of the channels of the ECA-matrix was 135°. Shear stresses prevail over normal stresses at such angle and a sufficient strain rate is achieved without any bimetallic steel-copper wire fracture.

The research was funded by the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP08052852).

EFFECT OF ASYMMETRIC ROLLING ON FLATNESS OF SHEET PRODUCTS

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Manufacturing sheet products and introducing them into various sectors of industry, such as defense, automotive, domestic and conventional power engineering, nuclear and wind power, show a level of development of metallurgy of the respective state [1]. Sheet products shall meet strict requirements for the shape and thickness variation of the strip. The production process may include process faults or equipment failures, resulting in unrecoverable defects, such as thickness variation, camber and ridges/corrugation. Strip geometry can be set by relevant rolling process control systems of the hydraulic roll screwdown, hydraulic bending of work rolls, their axial shifting and thermal cambering, and asymmetric rolling.

Asymmetric rolling is a process, when deformation of steel differs on the top and bottom sides of the strip. This process uses the differentiation of kinematic or geometric conditions on the surfaces of steel contact with the rolls, resulting in different lengths of forward and backward slip zones on every surface. On the side of every roll the areas with oppositely directed tangential stresses are formed in the deformation zone. Length of such zones depends on the value of asymmetry, and in the boundary case, they may cover a total length of the deformation zone [2]. The zones, where friction forces on top and bottom rolls are oppositely directed, contribute to both lower pressure of steel on rolls and decrease in their elastic deflection [2]. Non-uniformity in the deformation zone results in a heterogeneous structure of rolled products. The fine-grained structure contributes to achieving a high level of mechanical properties and ductility of steel. An additional advantage of introducing asymmetric rolling is a reduction of wear of work rolls. In addition to the positive characteristics, asymmetric rolling can have disadvantages, such as overload of rolling mill drives and potential slippage in the deformation zone. This can be eliminated by alternating asymmetry from a stand to another stand. Another negative feature of asymmetric rolling is strip bending at the exit of the deformation zone, which may prevent an accident-free rolling process [3]. Thus, the asymmetric rolling technology applied in industrial conditions requires additional studies to determine acceptable ranges of changes in asymmetry coefficient values to prevent emergency situations or strips with unacceptable curve. Industrial development and constantly increasing requirements for the quality force using more complicated models to describe the phenomena in steel during hot metal forming and after it. A way to develop an efficient metal forming technology is computer simulation (Fig. 1). To run an efficient computer simulation, it shall use reliable simulations of physical processes that reflect the actual rolling conditions correctly.

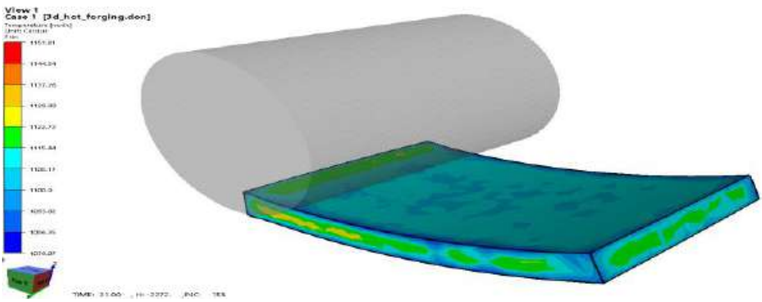

Fig. 1. Simulation of bending of the strip front end during asymmetric rolling

The paper presents and describes studies on the effect of asymmetric rolling on strip flatness (Fig. 2). Asymmetric rolling was used to react against an uncontrolled strip bending and improve strip flatness.

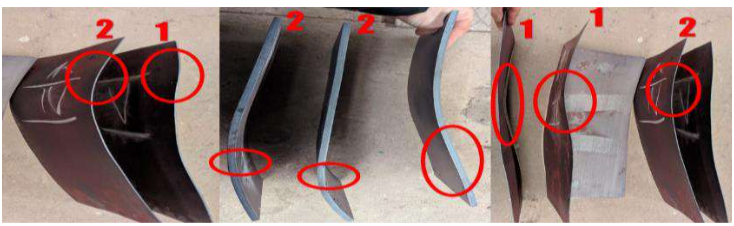

Fig. 2. Effect of asymmetry on strip flatness
(1 is symmetric rolling; 2 is asymmetric rolling)

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STRUCTURE AND MECHANICAL PROPERTIES OF HOT ROLLED SHEETS OF THE ALLOY SYSTEM: AL–2%CU–2%MN–0.4%SI–0.2%ZR SUBJECTED TO DOUBLE-SIDE FRICTION STIR WELDING

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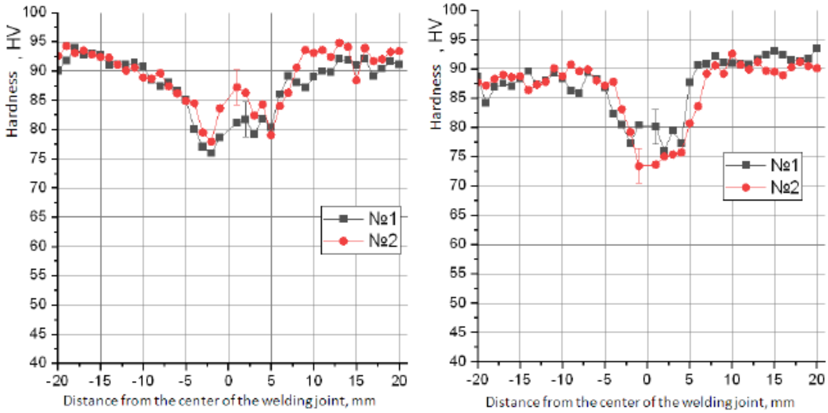
The studies on hot rolled sheets of Al-2Cu-2Mn-0.4Si-0.2Zr (wt %) aluminum alloy describe welding of joints, ensuring high mechanical properties and thermal stability, by friction stir welding (FSW). A non-homogenized billet (40 mm thick) of the said alloy was rolled on a laboratory rolling mill at 350 ^{0}C to produce a sheet, 4 mm thick (a reduction degree of 90%). After rolling, the sheet was cut in cards, joined by double-side FSW in 2 schedules with different longitudinal speeds of the tool. The tool rotation speed for both schedules was the same, 800 rpm. The structure and properties of the joints were studied before annealing at 400 ^{0}C for 3 hours and after it. It was found that the experimental alloy had high thermal stability. After FSW in the weld and heat-affected zones hardness did not decrease by over 15% and remained almost unchanged after annealing (Fig. 1). It is shown that the FSW method is used to achieve a high quality of welding joints, maintaining almost the original strength ($\sigma_в$ = 280-290 MPa) at a considerable increase in elongation (from ~3% to 12-16%). The increase in ductility is due to the formation of the ultrafine grain structure (a grain size is less than 5 μm) in the joint zone. This can be explained by dynamic recrystallization during FSW. According to the accumulated results, it is promising to apply the FSW method to produce full-strength and thermally stable joints of rolled sheets of the experimental alloys of the Al-Cu-Mn (Si, Zr) system, whose structure differs from the grade alloys of the 2xx series by a considerably higher content of Mn-bearing dispersoids.



a b

Fig. 1. Changes in hardness along welding joints produced by schedules 1 and 2:
a) without heat treatment; b) after 3 hours of annealing at 400°C

METHOD FOR CALCULATING THE PIPE SWAGING BY DIAMETER ALONG THE DEFORMATION CONE OF CPR MILLS

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A method is described for calculating the amount of swaging by diameter along the deformation cone for a double stroke of the CPR mill stand (Fig. 1). The method makes it possible to take into account the influence of most parameters of the CPT process on this value. The calculation method is based on a number of dependencies derived by different authors to determine the geometric parameters of the working tool and calculate the deformation parameters of the CPR process [1-4]. It also uses its own, specially derived dependence [4-5].

The proposed method allows leveling the inaccuracy of the previously used formulas. Optimized distribution of the reduction value along the diameter along the deformation cone makes it possible to reduce the likelihood of such defect as scratches on the inner surface of the cold-rolled pipe.

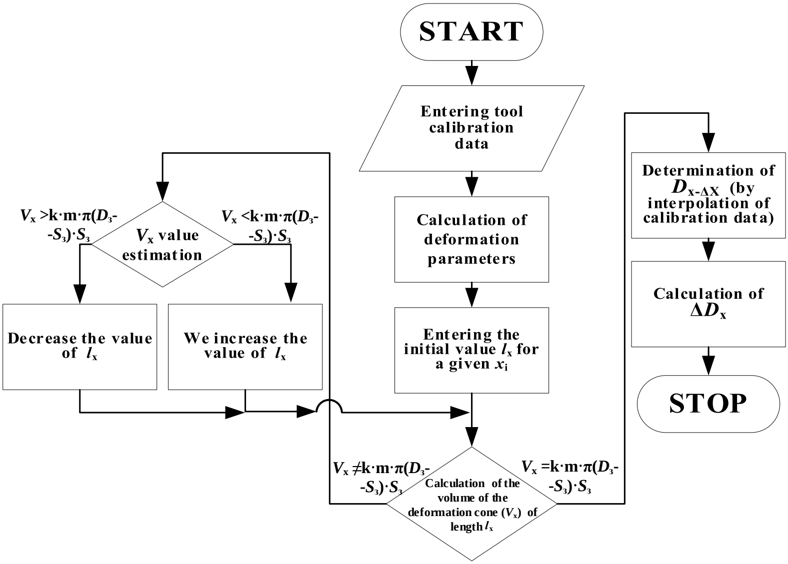

Fig. 1. Algorithm for determining the amount of reduction by diameter along the deformation cone of the cold rolling mill

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ANALYSIS OF THE EFFECT OF BEARING SECTION LENGTH ON FORMING RESIDUAL STRESSES IN ROUND WIRE FOR VARIOUS DIE SHAPES IN AN ISOTHERMAL PROCESS

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Now, development of an optimum draw plate shape is a relevant objective to produce wire of a higher quality.

Wire, having passed through the draw plate, shows residual stresses, whose distribution has a clear influence on the quality of the product and its lifetime. Die geometry (such as a geometrical type of the tool, entry section length and bearing section length) influences the distribution of residual stresses, including their decrease without additional process operations.

This paper describes the effect of bearing section length on the distribution of residual stresses in wire after drawing for various types of channels of draw plates.

Abaqus CAE software suite was used to design finite-element models of wire and relevant draw plates. Wire was made from steel grade 90, whose mechanical properties were described in papers [1] and [2]. Parameters did not include the effect of temperature due to an isothermal process.

The study was carried out for the following types of channels of draw plates: conical, radial convex, sigmoid, twin elliptic and twin parabolic ones.

The simulation of drawing processes showed a range of distributions of residual stresses along sections of wire under study. Fig. 1 shows the distribution of residual stress tensor components and Fig. 2 – rate of residual stresses for radial convex, sigmoid and twin parabolic shapes of dies at various bearing section lengths.

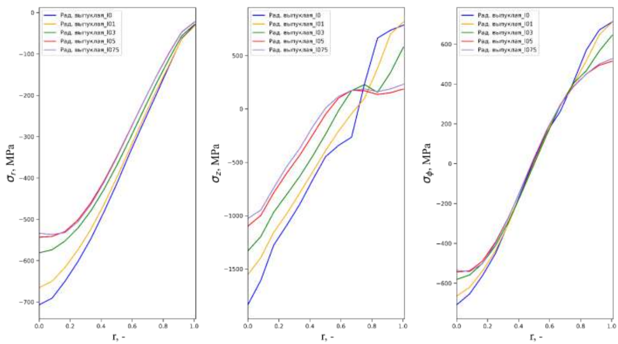

Fig.1. Average residual stress tensor values. Various bearing section lengths for a radial convex type of the draw plate, reduction to 2.45 mm, channel length without bearing section length is 1.8855, friction coefficient is 0.05

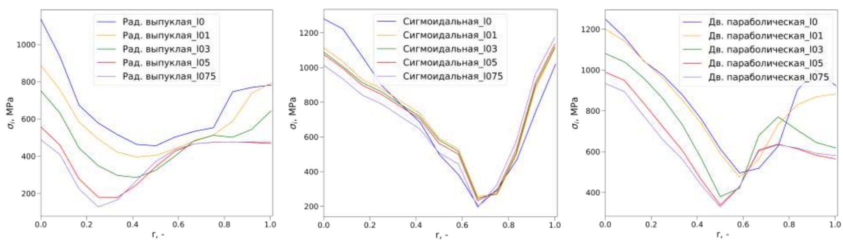

Fig.2. Average rates of residual stresses. Various bearing section lengths for radial convex, sigmoid and twin parabolic types of draw plates (from left to right), reduction to 2.45 mm, channel length without bearing section length is 1.8855 mm, friction coefficient is 0.05

Fig. 1 and Fig. 2 show that the draw plate without bearing section length results in the highest residual stresses in absolute value for all components of the stress tensor all over the radius of the sample, resulting in various potential defects of wire. The least difference in rates of residual stresses between central and contact areas of wire is achieved, when bearing section length is 0.75 of an initial diameter of the workpiece, which is true for the majority of the types of draw plates under study.

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COMPUTER SIMULATION OF A NEW TECHNOLOGY OF PRESSING RECTANGULAR CROSS-SECTION FORGINGS

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Producing billets is inevitably associated with casting defects, reducing the quality of steel. To remedy casting defects, forging ingots are pressed to treat the structure of the cast steel in addition to closing internal defects, and, consequently, to improve mechanical properties.

The currently used pressing technologies in many cases do not provide the required quality of the produced forgings. The quality of steel may be improved by using forging tools during upsetting and drawing for shear or alternating deformation in a total volume of deformed steel. One of such tools for forging (drawing) are step wedge dies (in two different designs) [1-2].

To study the effect of the proposed technology of pressing forging in step wedge dies on the stress and strain state and power parameters, we carried out the computer simulation. The analysis of the process of workpiece deformation in step wedge dies of two designs showed that the most reasonable design was the design, where the upper die was a wedge, and the lower die had a wedge-type hole. An optimum angle of joining the wedge and hole planes is 160°. The most optimum process schedules of deformation in the forging tool are a friction coefficient at the contact between the workpiece and the tool of 0.7; speed of the upper die movement is 1 mm/s; and heating temperature of the workpiece before forging is 1000 ^{0}C.

The research was funded by the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09057965).

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STUDY ON THE EFFECT OF THE INITIAL SHIFTING OF DRAW PLATES ON THE STRESS AND STRAIN STATE OF ROUND WIRE

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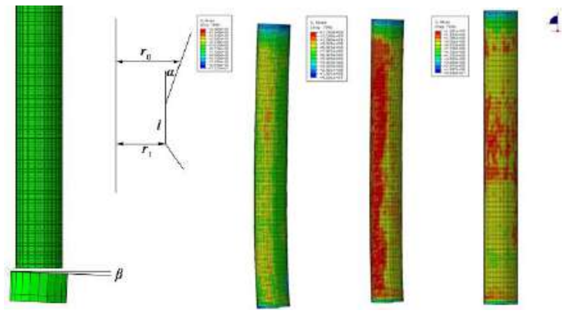
A simulation of drawing processes is based, as a rule, on the hypothesis of axial symmetry of the process. As a result, accumulated strains and residual stresses are also distributed symmetrically relative to the central line of the wire. In a general case, strains and stresses are distributed asymmetrically both during drawing processes and after their completion. Asymmetry can be developed as a result of minor deviations of tools relative to the central axis of the wire, as well as a non-uniform supply of lubricating materials and wear of tool channels [1].

This paper describes the simulation of the drawing process in a three-dimensional assembly at various angles of slope relative to the central line β =0,..,2° with a step of 0.25°. Angle of slope of the deformation zone of the draw plate channel α was 4°, initial and final radii $r_0 = 0.420$ mm and $r_1 = 0.412$ mm, bearing section length $l = 0.5r_1$ (Fig. 1a). Wire was made from steel grade 90 [2, 3].



a) b)

Fig. 1. a) The assembly and the draw plate channel;
b) Deformed wire after drawing at various values β

The numerical experiments showed the distributions of residual stress and strains along wire diameter. Fig. 1b and Fig. 2 showed that at $\beta \geq 0.75^\circ$ the deviation from the non-displaced case begins to make a considerable contribution to a non-uniform distribution of residual stresses. Besides, at $\beta \geq 0.75^\circ$ there is a bending of the central line and all layers of the wire, resulting in misalignment of the produced wires.

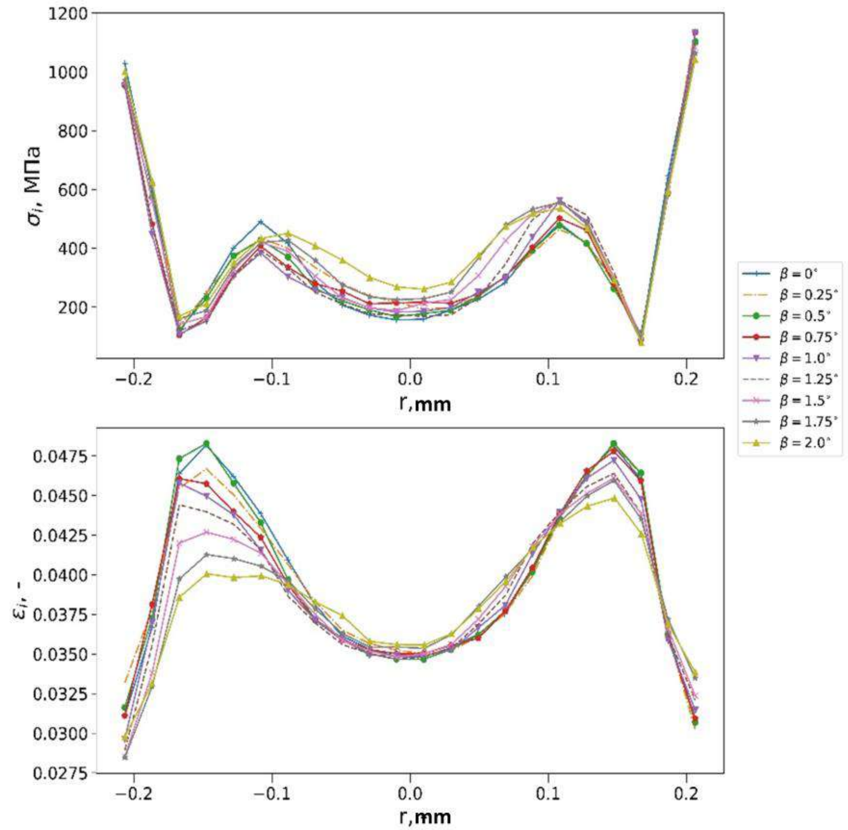


Fig. 2. Distribution of residual stresses and strains along the wire section at various values β

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SIMULATION OF THE RAIL WORKPIECE DEFORMATION IN A UNIVERSAL STAND APPLYING QFORM 3D

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An important requirement for the quality of finished products, when producing rails, is accuracy of a finished profile. This parameter includes a uniform deformation along the cross section area. It is difficult to ensure geometrical accuracy, when producing parts of a composite shape, such as railway rails. The difficulty lies in the cross section, consisting of three elements (the head, the web and the base), varying in sizes.

Achieving the uniform deformation over the cross section area of the rail requires factoring into kinematics of the process (steel forward slip during rolling) and deformation of steel (reduction and pulling-down of the head and base flanges). An unsatisfactory shape of these elements and the cross section in general can be attributed to an incomplete filling of the roll pass or its overfilling [1].

Besides, the calibration calculation in case of continuous groups shall factor into the interaction between neighboring stands, where rolling takes place in two or three stands at the same time. Continuous rolling entails tension or upthrust in the workpiece. Tension or upthrust in the workpiece produce effect on tightening and distortion of the profile of the finished element. Tension influences the stress state, which, in its turn, should be factored into in the roll pass design.

Complicated and extensive calculations shall be made in special software. One of such software is QForm 3D. The research is aimed at developing a roll pass design, factoring into the effect of interstand tension, with QForm.

The mill used to conduct the study was a rail and structural steel mill, including a continuous reverse group of universal stands (a tandem group), installed at the Rail and Beam Shop of OJSC EVRAZ-NKMK in Novokuznetsk [2].

The first stage of the mathematical simulation is creating roll passes in Autodesk Inventor for a subsequent simulation of the rolling process in one universal stand on the rail and structural steel mill, using QForm 3D. The roll pass of the universal stand consists of two horizontal and two vertical rolls with grooves installed in one plane. The roll pass of the first stand is given in Fig. 1.

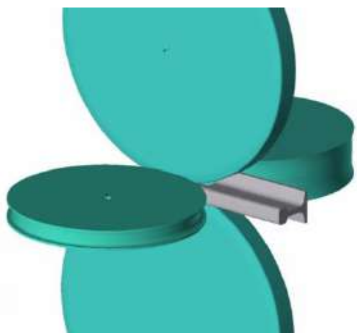

Fig. 1. Roll pass of the first universal stand

The rolling process was simulated in QForm 3D software. Initial data are as follows: workpiece temperature is 1000℃, steel grade of the strip is 4Kh13, and steel grade of the rolls is Kh12MF.

During rolling the workpiece is reduced by four rolls at the same time. Filling of the roll pass during rolling is given in Fig. 2. To simplify the calculations, we preferred to solve the problem as symmetric.

Fig. 2. Filling of the roll pass during the simulation

The result shows that in spite of the good base, there are “teeth” on the surface of the head. This is due to the inaccurate selection of the surface partitioning grid. The main difficulty of modeling the rail rolling lies in the correct selection of a ratio between the grid size and the calculation time of the problem, which can be several days of real time, when using a fine grid.

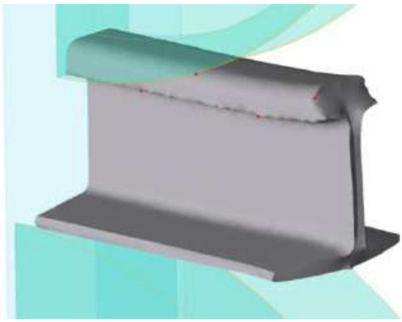

Fig 3. Defects of the grid on the surface of the rail head and base

Thus, it is possible to apply QForm 3D software to calculate reduction of composite workpieces in a universal stand. The next stage of the simulation is forming a group of two stands and tension rolling of the worpiece.

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EFFECT OF ANNEALING, WHEN DRAWING Al-Mg-Sc LONG BILLETS PRODUCED BY CASTING IN THE ELECTROMAGNETIC MOLD

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Casting long billets, 8-12 mm in diameter, in the electromagnetic mold at cooling speeds of quickly solidified, pelletized aluminum alloys ($10^3 \ldots 10^4$ K/s) in the long term may considerably reduce costs for input materials, such as wire for additive technologies.

Tension test specimens were cut from cast bars and tested for ultimate tensile strength $\sigma_в$ and yield strength $\sigma_т$, elongation δ and contraction Ψ.

Mechanical properties were determined, using Walter+Bai AG LFM 400 kN and LFM 20 kN (Walter + Bai AG, Switzerland) as per GOST 1497-84 for rods and GOST 10446-80 for wire.

Based on the data obtained, it was concluded that the Al-Mg-Sc alloy maintains its ductile properties at a rather high level even at the total strain rate of up to 60% (percentage elongation δ is 14 %). The alloy ductile properties decrease, when the strain rate reaches a level of 80 % (δ = 4.5 %). Therefore, when this value is reached, it is recommended to anneal this alloy to restore the ductile properties of wire.

The produced rods, 9 mm in diameter, underwent cold section rolling (on section rolling mill AMBIFILO VELOCE ROSEN 180+200×Ø130) and cold drawing to 1.2 mm in diameter. Such wire diameter is optimum for using in additive technologies. Drawing was on a single-chain drawbench.

In general, it should be noted that ultimate tensile strength of wire, 1.2 mm in diameter, being 422-485 MPa, is rather high. As the billets cast in the electromagnetic mold have no oxide spots, solid non-metallic inclusions and porosity due to a unique influence of the melt in a high-frequency electromagnetic field, wire has no casting defects. The billets do not undergo pressing or rolling, therefore, they do not inherit the defects that are found in products during metal forming processes.

A microstructure of wire, 1.2 mm in diameter, from the Al-Mg-Sc alloy showed that it had a rather uniform structure with dispersed precipitation of intermetallic phases (Fig. 1). No primary intermetallides were found across the wire section.

Wire, 1.2 mm in diameter, from the experimental alloy was annealed at 350˚C and 400°C within 2, 5 and 8 hours to study the effect of annealing on mechanical properties, and, using the obtained results of the indicative analysis of the processes in the structure during casting, drawing and annealing of billets.

The tests on mechanical properties of hard-drawn wire (1.2 mm in diameter) after annealing show that ultimate tensile strength decreases and ductility increases, when temperature increases from 350℃ to 400℃, and soaking time increases from 2 to 8 hours. The alloy with a higher content of transition metals has higher strength properties compared to the alloy with a lower content of transition metals.

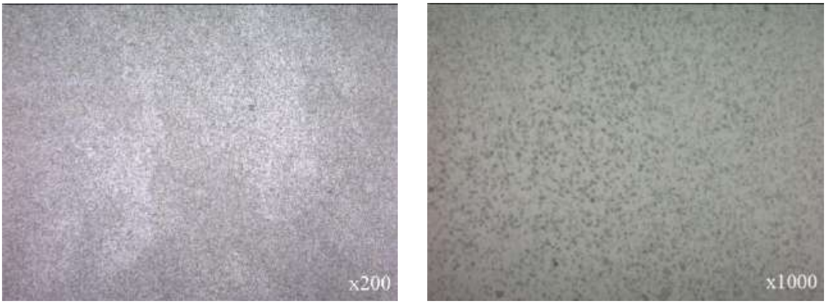

Fig. 1. Microstructure of Al-Mg-Sc wire, 1.2 mm in diameter, produced by drawing the billet, 9 mm in diameter, cast in the electromagnetic mold

The data obtained show that during annealing the aluminum solid solution supersaturated during billet crystallization is decomposed. As the wire strength properties decrease during annealing, it can be assumed that during wire cladding with additive technology and a high cooling rate, strength properties in the product can be expected to be the same as in hard-drawn wire, i.e. ~420-485 MPa.

The research was carried out as part of the state order of the Ministry of Science and Higher Education of the Russian Federation (research subject FSRZ-2020-0013).

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STUDY ON SAMPLES FROM TOOL STEEL R6M5 PROCESSED BY ASYMMETRIC ROLLING

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The most universal high-speed steel, widely used in the global metal processing industry, is deemed to be steel grade R6M5, containing 6% of tungsten and 5% of molybdenum. It has higher decarburization tendency, higher ductility, good wear resistance, and good grindability. Due to its properties, steel grade R6M5 is still relevant and widely used for manufacturing metal cutting tools. The required performance characteristics are achieved by special, multi-level heat treatment, deeply studied and thoroughly learnt within a long period [1]. The achieved properties are deemed to be reference ones for this type of tool steels and correspond to a modern state of their production technologies.

The paper is aimed at describing an experimental study on increasing hardness of steel R6M5 by an asymmetric rolling method.

Based on the research results, we manufactured 10 experimental samples of semi-finished rolled products from steel grade R6M5, 1.0 mm in thickness, and prepared a description of asymmetric rolling schedules. We determined microhardness and tensile properties of the experimental samples. Asymmetric rolling of sample sheets, 3.15×25×100 mm in size, from steel grade R6M5 at room temperature and at heating temperatures of 400°C, 500°C, 600°C, 700°C, 800°C resulted in strong fracture of the experimental samples in all ranges of varying parameters (a total reduction of 47.6…68.3%, a number of passes of 1…5, a coefficient of mismatching work roll speeds of 1.25…3.33) [2, 3]. The highest microhardness HV was achieved in pilot samples after asymmetric rolling at 1100℃ (by multi-pass rolling with a total reduction of 68.3% in 3…5 passes and a coefficient of mismatching work roll speeds of 1.25…2.00). Microhardness HV in central layers increased by 3.4 times (from 248 to 848) as compared to an original (non-rolled) state.

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COMPUTER VISION FOR STEEL SHEET SURFACE DEFECT DETECTION

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The role of machine learning – and computer vision, in particular – in the production process is currently seeing a drastic rise. Thanks to machine learning models, machines can replace humans in such functions as monitoring, data acquisition and analysis, as well as control over the production process.

For instance, in steel industry, computer vision can be used for surface defect detection, to determine the length of a casting, adjust the strip speed or the temperature regime, etc.

Neural networks would be of particular interest among machine learning techniques. They are a combination of hardware and software representing a mathematical model organized similarly to neural networks within living organisms. Neural networks are designed to perform multiple tasks and the latter dictate both the network architecture, characteristics and learning parameters to be selected. This choice is always an experiment and is based on the laws of statistics or linear algebra and mathematical analysis.

This paper tackles the problem of steel surface defect localization and classification. A neural network has been developed that is designed to learn from images showing various defects. The network was analyzed for accuracy with the help of different metrics. Figure 1 gives an example of images that are used for network learning.

Fig. 1. Roll (a defect taken from the set of data used for network learning)

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STRUCTURE OF COPPER AND NICKEL JOINTS BY ULTRASONIC WELDING

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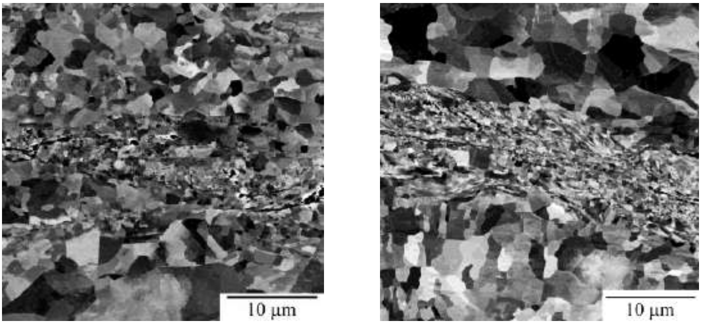
Ultrasonic welding (USW) is one of the methods of solid-state joining of metals and alloys applied in electrical, automotive and other sectors of industry to weld thin plates, tapes and foils [1, 2]. USW of metals is carried out by applying high-frequency shear vibrations to the joined workpieces and simultaneous compressive force. Metals are joined by forming and expanding bonding zones, promoted by the friction of the contacting surfaces, destroying oxide layers, and severe deformation of the surface layers. High-rate alternating shear deformation and heating in the contact zone result in considerable structural changes in the materials. The study on the microstructure in the welding zone is in focus, since the structure influences strength of joints, and its features are related to the mechanisms of joint formation. Despite extensive research, the principles of choosing welding modes, as well as the mechanisms of joint forming between metals and alloys during ultrasonic welding still remain open [2,3].

This paper describes the study on a microstructure of Cu-Cu and Ni-Ni joints by USW carried out by modern methods of a structural analysis.

Copper and nickel sheets, 0.8 and 0.5 mm thick, correspondingly, underwent USW at a vibration frequency of 20 kHz, an amplitude of 9-15 μm; a compressive load of ~4 kN; and an ultrasonic action time of 2 s.

The structure of initial sheets consisted of grains, about 15-20 μm in size, with annealing twins, typical of annealed metals with FCC lattice with average and low stacking fault energy.

The microstructure of the sheets in the welding spot after USW considerably differs from the initial one. The welding zones of copper and nickel sheets contain a layer with an ultrafine-grained structure about 10 μm wide (Fig. 1). The microstructure of the sheets is extremely non-uniform above and below this layer at a distance of 50-100 μm from the contact surfaces and consists of misoriented crystallites both less than 1 μm and considerably larger than 10 μm. The structure of the initial sheet remains unchanged outside the contact area between the sheets and the welding tip.



a) b)

Fig. 1. Microstructure in the welding zone: Cu-Cu (a), Ni-Ni (b)

The ultrafine-grained layer formed in the welding zone of the materials under study is accompanied by an increase in their microhardness by a factor of 1.5 or more joints carried out according to the recommendations of GOST 6996-66 have shown that fracture strain of joints of copper and nickel sheets was 700 ± 68 N and 1800 ± 153 N, respectively, that was close to the values given in [4, 5].

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IMPROVEMENT OF ASYMMETRIC ACCUMULATIVE ROLL BONDING PROCESS FOR PRODUCING LAMINATED ALUMINIUM COMPOSITES

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Today, the interest to the use of laminated composites in various industries is increasing. Unlike single-layer materials, laminated materials are more durable, corrosion-resistant and technologically advanced materials that can be used for the production of parts for various purposes. A laminated composite can have two layers of metal, which can be dissimilar (for example, aluminium-steel) or have a single metal as the base (for example, aluminium alloy 1070-aluminium alloy 5083). This paper considers laminated composites made of aluminium alloys. These are light materials and of particular interest are those alloys that have high strength. Products made of sheet laminated aluminium composites can be used in space, aviation, automotive, shipbuilding and other industries [1-3].

This research is aimed at developing the theory and technology of obtaining laminated aluminium composites 5083/1070 and 5083/2024 [4, 5]. The process was tested by means of asymmetric accumulative roll bonding in laboratory conditions. The principal equipment used includes Rolling Mill 400 owned by NMSTU’s Mechanics of Gradient Nanomaterials Laboratory.

Preliminary numerical research was carried out with the help of DEFORM 2D/3D and QFORM 2D/3D systems. The asymmetry factor was analyzed in a wide range of work roll speed ratios ($V_1/V_2 = 1…5$). It helped determine the necessary boundaries of the area that ensure a simultaneous increase in strength and technological plasticity. To achieve this area, it is necessary to carry out at least 2 cycles of asymmetric accumulative roll bonding.

A range of work roll speed ratios ($V_1/V_2 = 2{,}5…4$) was established in laboratory conditions that provides the maximum relative elongation δ (12%) and ratio of the tensile strength σv to the yield strength σt (1,55), as well as the rectilinear movement of metal at the exit from the deformation zone. The results of an experimental study show a significant increase in the technological plasticity and a decrease in the rolling force in the case of asymmetric accumulative roll bonding (in comparison with the rolling regime when the work rolls have the same speed).

The process of warm asymmetric accumulative roll bonding (heating temperature 380˚C) of laminated aluminium composite 5083/2024 showed that as the work roll speed ratio increases from 1 to 4 (with the roll gap unchanged):

- the relative reduction increases from 37 to 67 %;
- the rolling force drops from 1,330 kN to 600 kN.

The process of warm asymmetric accumulative roll bonding (heating temperature 380˚C) of laminated aluminium composite 5083/170 showed that as the work roll speed ratio increases from 1.4 to 3.3 (with the roll gap unchanged):

- the relative reduction increases from 40 to 60 %;
- the rolling force drops from 860 kN to 300 kN.

The process of cold asymmetric accumulative roll bonding of laminated aluminium composite 5083/5083 (with an increase in the work roll speed ratio to 1.9) made it possible:

- to increase the total relative reduction to 77.5 % avoiding fracture (compared with the symmetric rolling process when the workpiece fractured at 42 % reduction);

- to reduce the rolling force from 912 kN to 490 kN.

At the roll speed ratio of $V_1/V_2 = 5$, all samples melted.

The above findings describe unique processing schemes for asymmetric accumulative roll bonding of long products. The required level of mechanical properties has been reached.

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FEM SIMULATION OF THE EFFECT OF FRICTION CONDITIONS ON BEHAVIOR OF THE PLUG DURING LONGITUDINAL TUBE ROLLING

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The paper describes the FEM simulation studies on the effect of the friction coefficient on axial force on the plug. It contains the diagram showing dependence between force, acting on the plug, and a friction coefficient during tube deformation.

Now, the hollow billet delivery into the longitudinal rolling mill is accompanied by feeding lubrication, sodium tripolyphosphate. The method includes air-pressure fed of the lubricant into the hollow billet. Friction ψ between the plug and the billet during stable rolling is within a range of ψ=0.25…0.3 [1].

The disadvantage of this method is a rather non-uniform distribution of the lubricant on the inner surface of plugged hollow billets, which leads to rapid wear of the plugs (30-50 passes) and an unsatisfactory quality of the inner surface of tubes caused by grooves and scratches.

The study was run using a computer modeling in QForm. A 3D model of the plug rolling mill is given in Fig. 1. Shell diameter and wall thickness were $D_г$ =166 mm and $S_г$ = 10 mm, correspondingly; rough tube diameter and wall thickness were $D_ч$ =160 mm and $S_ч$=7 mm, correspondingly, in all computational experiments. Following the recommendation of the software developers and subject to practical data on tube rolling on longitudinal rolling mill No. 1 [2–5], tube temperate was set at T = 1200 °C, roll and plug temperature T = 150 °C, air temperature T = 20 °C. The Siebel friction law τ = ψ τs. Friction ψ between the roll and the billet was ψ = 0.7, and between the plug and the billet ψ = 0.1; 0.2; 0.3; 0.4. Frequency of roll rotation on longitudinal rolling mill No. 1 is 125 rpm.

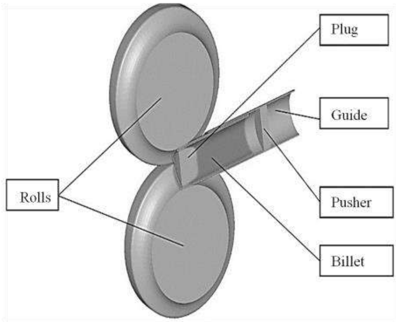

Fig. 1. 3D model of the plug rolling mill

Using the data obtained, we compiled the diagram (Fig. 2) characterizing dependence between force, acting on the plug, and a friction coefficient during tube deformation on the longitudinal rolling mill. In the diagram friction coefficient ψ(ksi) is represented in points and lines of the trend; a red vertical line is a point of time, characterizing the start of the stable rolling.

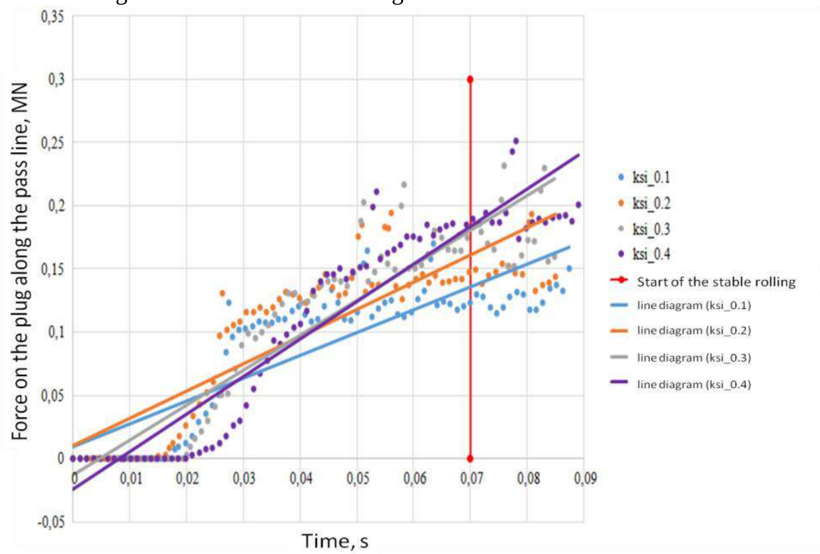

Fig. 2. Diagram characterizing dependence between force, acting on the plug, and a friction coefficient during tube deformation on the longitudinal rolling mill

Fig. 2 shows that when friction ψ decreases, force on the plug along the pass line decreases. Thus, it should be expected that when rolling friction ψ decreases, wear resistance of the plug increases, resulting in improving the quality of an inner surface.

The studies showed that the existing method of lubricant feeding before plugging hollow billets did not ensure a good and uniform distribution of the lubricant on the inner surface of hollow billets; friction ψ during the stable rolling is high and in the range ψ=0.25...0.3, which negatively influences the plug lifetime. As a result, short lifetime of plugs leads to an unsatisfactory quality of the tube inner surface caused by grooves and scratches. Thus, we can make a conclusion that by improving uniformity of the lubricant distribution on the inner surface of the hollow billet we reduce force on the plug along the pass line, improving plug wear resistance and, consequently, increasing the quality of the tube inner surface.

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GRADIENT STRUCTURE OBTAINED IN STEEL ‘08Ю’ AS A RESULT OF ASYMMETRIC SHEET ROLLING

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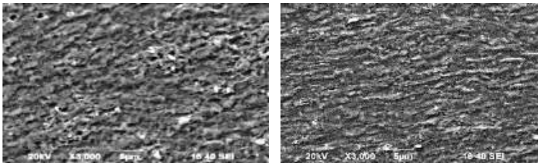
The Zhilyaev Mechanics of Gradient Nanomaterials Laboratory at NMSTU have designed a pilot two-high mill with a separate drive for the work rolls in order to implement asymmetric rolling processes with a maximum allowable rolling force of 2,500 kN (250 ton-force) and torques of 2×70 kNm. This asymmetric cold rolling mill was built in South Korea and is unique in Europe and one of the three of the kind in the world.

A structural study of steel ‘08Ю’ showed that asymmetric rolling with a 5 times roll speed difference resulted in a gradient structure (see Fig. 1), all other conditions being equal. The gradient structure became the result of dynamic recrystallization as the metal strip had heated up to 250-300 °C. A homogenous structure can be observed at the top of the strip section on the side of the lower rolling speed that consists of ultrafine, almost equiaxed grains smaller than 1,000 nm. At the same time, the bottom section on the side of the higher rolling speed has a clear fibrillar structure, with separate fibers containing smaller fragments, up to 200 nm. The fragmented regions account for 40 % of the total volume. At the same time, the hardness tended to rise from the top section of the strip to the bottom one and, compared with symmetric rolling, increased by approximately 44 %.



a) b)

Fig. 1. Optical photography – Strip microstructure after asymmetric rolling: a) top of the strip section; b) bottom of the strip section

It was established that the above asymmetric rolling conditions led to a rise in the reduction from 50 to 80 % whereas the rolling force dropped almost 3 times in one pass compared with symmetric rolling. This can be attributed to the structure refinement. At the same time, the hardness increased from 172 HV to 247 HV.

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HIGH-TEMPERATURE DEFORMATION OF METASTABLE AUSTENITIC STEEL 03Kh14N11K5M2YuT

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The technological cycle for obtaining high-strength corrosion-resistant materials begins with the production of a hot-rolled billet (wire rod). Depending on the steel grade, hot working by pressure is carried out in the temperature range of 1,200 to 800 °C. It is known [1] that in industrial chromium-nickel steels of the austenitic class 18-10, precipitation of excess carbide phases can occur under certain temperature-time conditions (with delayed cooling or exposure to the temperatures of 450 to 900°C), which can make these steels susceptible to intergranular corrosion.

Therefore, in order to determine the optimal temperature range for hot deformation of workpieces, the authors looked at the behavior of the austenitic steel 03Kh14N11K5M2YuT when it was heated to elevated temperatures, and analyzed the course of possible phase and structural transformations at those temperatures.

In previous studies [2, 3], it was shown that in the hardened state, the microstructure of 03Kh14N11K5M2YuT steel consists of polyhedral austenite grains with thin boundaries and annealing twins (Fig. 1, a). When the hardened steel is heated to 700-750 °C, the structure practically does not change, and only a slight increase in the etchability of the austenite phase at these temperatures can be noted (Fig. 1, b).

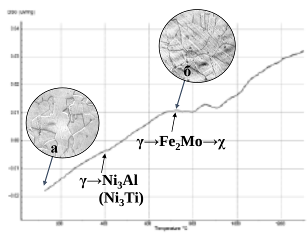

Fig. 1. DSC curve of hardened steel 03Kh14N11K5M2YUT

The study of the processes occurring during continuous heating and cooling was carried out on samples hardened from 1,000 °C.

The complex and multi-stage decomposition of a supersaturated γ-solid solution is reflected in the durometric data, as well as the data that show changes in the resistivity and the period of the austenite crystal lattice. Thus, it was shown that in the quenched metastable steel 03Kh14N11K5M2YuT, minor structural and phase transformations can occur upon heating.

It is known [4] that the temperature rises, the strength of metal and its resistance to deformation drastically decrease. Thus, as the results of tests conducted at room temperature indicate, the hardened metastable austenitic steel 03Kh14N11K5M2YuT has low strength and high plasticity, which makes it possible to apply high total plastic deformations and achieve a significant increase in the strength in the course of cold plastic deformation (by approximately 4 times compared with the hardened state). The hardening of the steel under study is due to the simultaneous action of several factors:

an increase in the defectiveness of the structure of the γ-solid solution and the developing martensitic transformation during tension. An increase in the degree of compression and a decrease in the deformation temperature contribute to the completeness of the transformation. With an increase in the test temperature to 400 °C (above M_d), it is not possible to induce martensitic transformation by plastic deformation of austenite up to failure. Under static loading conditions at temperatures of 400 and 500 °C, the structure forming process affects the hardening. At the above temperatures, nonequilibrium point defects are eliminated, the dislocation structure is rearranged, which is formed during deformation. Thus, the density of dislocations decreases, stable configurations are formed in the form of grids, which are low-angle boundaries. It should be noted that the higher the heating temperature is during tensile testing, the higher the hot deformability of the steel under study is. The temperature intervals of high hot deformability of the studied steel have been determined: the billet should be heated to 1,200 °C in the furnace, the temperature of the end of the billet should not be lower than 850 °C.

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ASYMMETRIC ROLLING WITH HIGH WORK ROLL SPEED DISCREPANCIES: EXTRAORDINARY EFFECTS, METAL PROPERTIES AND NEW PROCESSING SCHEMES

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In March 2021, the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory at NMSTU saw the commissioning of a new asymmetric rolling mill 400. In 2022, the mill was recognized as a unique research unit. The mill is designed for a work roll speed ratio starting from 1:10, whereas the maximum roll speed ratio enabled by any other mill in the world today is 5. Therefore, the Laboratory has capabilities to conduct studies in a broad range of work roll speed discrepancies.

Even the first studies carried out with the help of the mill indicated as follows:

1) The rolling forces can be 6 times lower than in the case of symmetric rolling.

2) The material gets very hot. Even at the entry to the deformation zone, the material can be as hot as 900 ^{o}C. At the exit from the deformation zone (air quenching) and for 1-2 minutes, the material cools down to room temperature (normalization). This way, a good structure is obtained without preheating or posterior heat treatment. At the roll speed ratio of 10:1.3, aluminium D16 melted.

3) A significant discrepancy of the work roll speeds is associated with dynamic recrystallization. Thus, a 3 mm sheet made of steel ‘08Ю’ reduced by 80% to the thickness of 0.6 mm had a gradient structure and the grain sizes were 70-80 nm on one surface and up to 5 µm on the other.

4) A significant rise in the in-process plasticity can be observed during the rolling of aluminium D16. The metal fractures at 42% reduction in a symmetric rolling mode. After the rolling operation at 89% reduction (6 to 0.65 mm thickness), the metal not only retains its plasticity, but its elongation increases twice compared with as-annealed condition.

5) When rolling steel ‘P6M5’ at the temperature of 1,100 ^{o}C from the initial thickness of 3 mm and with the total reduction of 67%, its hardness grew by 3.4 times reaching 870 Brinell units.

6) The study demonstrates the efficiency of cold and warm asymmetric accumulative rolling in application to laminar materials 1xxx/5xxx and 2xxx/5xxx.

The conducted study helped elaborate a proposal on rolling process optimization for the high-strength steel grades of 50, 65 G and 70. Using Mill 400, the researchers proved that the number of annealing cycles could be reduced by one or two, just as the number of passes through the 5-stand mill.

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UNEVEN STRAIN STATE DURING PIPE FLATTENING

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Today, the recycling technology is of particular relevance in steel industry. This paper looks at developing a recycling technology that would be applicable to stainless steel pipe shorts generated after the cold rolling stage.

The purpose of the technology is to obtain a commodity by reusing pipe production waste. This involves the following stages:

- Pipe shorts are flattened to produce flat sections;
- The sections are then rolled with smooth rolls to produce a double strip;
- The double strip is divided into single strips by splitting off edges.

More details about this technique and the sequence can be found in the sources [1, 2].

The authors simulated the first stage of the recycling technology by using steel [12X18H10T] pipe shorts. The pipe flattening operation was simulated with the help of the finite element method and the DEFORM-3D system. A 10x1.5 mm pipe was used for the initial workpiece. The pipe material is AISI 321 steel, which is a plastic material. Below is shown the strain distribution across the surface of the flattened pipe (Fig. 1).

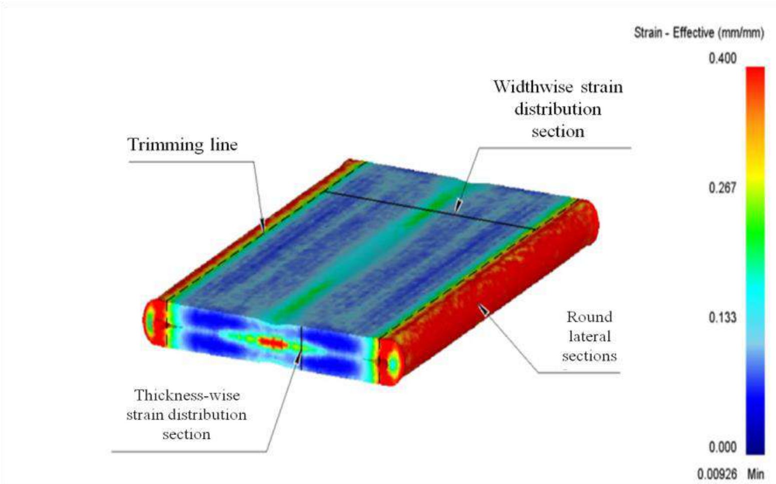
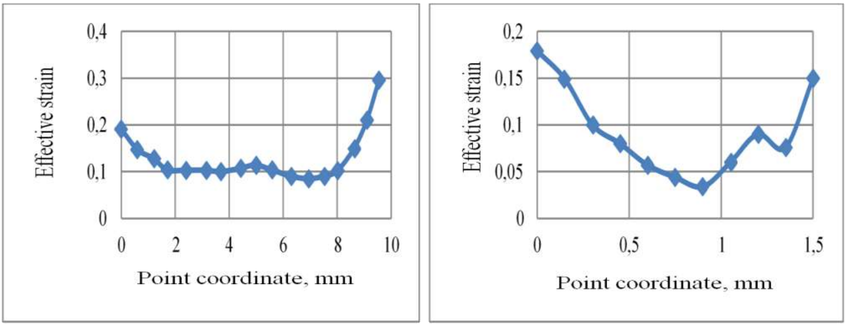


Fig. 1. Strain distribution across the pipe surface after flattening

The model shows a well-established sink mark in the centre of the strip, which can be attributed to the distribution of friction forces on the dies, as well as to widthwise stress state variations.

The distribution of accumulated strain along the strip width and thickness is not even (Fig. 2, a). The strain at the bend line reaches 0.45. From the recycling perspective, such areas should be cut off after flattening. The strain in the working part of the strip is from 0.2 to 0.009.

An uneven strain state can be observed along the strip thickness (Fig.2, b). The accumulated strain at the strip top and bottom reaches 0.179, while in the strip centre it is 0.043.



a) b)

Fig. 2. Widthwise (a) and thickness-wise (b) distribution of accumulated strain

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DEVELOPING A PROCESS FOR MAKING MEDICAL RINGS FROM RADIOPAQUE ALLOYS

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In order to increase the share of domestically produced medical components, EZOCM is currently working on developing a process for making special radiopaque (marker) rings used in endovascular surgery. The material used is platinum-iridium alloy 'ПлИ90-10' with the chemical composition per GOST 13498. The product assortment is quite broad. Manufacturers of medical appliances use rings with the outer diameters of 0.6 to 6.0 mm, the wall thicknesses of 0.025 to 0.100 mm and the heights of 0.5 to 5.0 mm.

The production process is comprised of the following main stages: smelting of a billet, planing, forging, rolling, bending, welding, drawing, cutting and polishing.

The small size (Fig. 1) of the rings and their specific application define the high quality requirements provided for in the standards. Precision of the ring inner diameter is critical. Besides, the rings cannot have slivers, dents or cracks, which may affect their performance.

Fig. 1. Rings compared with other items

The above properties are mainly achieved and controlled in the course of drawing. The tube shells used fall into the category of thin-walled and superthin-walled workpieces. Following a series of preliminary pilot tests, a concept of mandrel drawing was selected that would help minimize the sliding of metal over the mandrel [1]. Compared with other techniques, this process helped reduce the drawing force and thus prevent tubes from in-process breaking.

Tubes were drawn in a chain drawing bench SchumacherTech ZB100/2500. The tooling used included hard-alloy dies with the angle α equal to 10^o and steel rods with the minimum hardness of 55 HRC. Several tube batches were produced in the wall thickness range from 0.035 to 0.050 mm.

However, when, during the final passes, the drawing force dropped to values close to the ones associated with idle operation, it caused transverse tears and circular folds, which led to a higher breakage rate resulting in poorer cost-effectiveness. Also, because of the lack of tension, the chain would start swinging causing dents on the outer surface of the tubes.

Additionally, an optimum grain size needs to be established to enhance the ring quality as it can contribute to wall thickness variation in the case of thin-walled tubes [2, 3].

The authors consider a number of tube draw bench design options that would offer high rigidity and smooth operation. This is important for achieving production stability and a wider product assortment. The above conditions can be satisfied by hydraulic drives and draw benches driven by ball screws instead of chains.

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IMPROVING DEFORMATION REGULARITY ACROSS ROUND WIRE CROSS-SECTION USING SHAPED DRAWING DIES

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The primary method used today in round wire production is drawing in one-piece drawing dies. This method is widely used in practice and well-studied theoretically. However, to ensure consistent deformation across the wire cross-section is difficult or even impossible. The minimal accumulated deformation in the wire can be found along the axis, and the maximum one is in near-surface layers. There is also high irregularity around the wire perimeter.

Drawing in double roller dies improves the accumulated deformation both in the core and on the surface of the wire, while the irregularity gradient of the accumulated deformation on the wire surface falls down as the number of rollers increases. It has been found that, unlike double-roller grooves, multi-roller grooves show minimal accumulated deformation in the pass center and the minimal one in the gaps between the grooves [1-3].

Therefore, it would be helpful to find new methods of drawing and their combination.

This paper describes such methods as:

- drawing in oval one-piece drawing dies [4, 5];
- drawing of a round wire in a roller die into a flat oval followed by drawing in round one-piece drawing dies;
- drawing of a round wire in a roller die into an incomplete square followed by drawing in round one-piece drawing dies [6].

These methods are intended to select the shape and length ratios of the main oval axes. This shape of the cross-section at the start of drawing can efficiently work out central layers of the wire and then even out the accumulated deformation with the near-surface layers using round one-piece dies. This reduces the cross-sectional deformation irregularity.

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APPLICATION OF COMPUTER AND PHYSICAL MODELLING FOR PUNCH PIERCING OPTIMIZATION

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A variety of auxiliary processes makes an integral part of the hot-pressed tube production. One of the most critical operations includes expanding (in the case of hollow billets) or piercing (in the case of solid billets) implemented with the help of vertical hydraulic presses. Expanding and piercing, which can basically be subsumed under the process of backward extrusion, are associated with considerable plastic deformation of the material aimed at changing its dimensions to given parameters. Like any other metal forming process, punch piercing may lead to surface defects, which may occur on the shell that is to go to a horizontal extrusion press. The causes and the nature of such surface defects may vary as they may be caused by the actual process or be attributed to the initial properties of the material. In any case, piercing defects are inherited by the resultant hot-pressed tube. Consequently, the risk of obtaining a hot-pressed tube with defects can be minimized by eliminating piercing defects.

Using modern computer and physical modelling capabilities, this paper describes a number of examples of solving particular tube production problems related to the above processes. Thus, the paper examines the outcomes of research work that aimed to achieve the desired geometry of the billet head end after piercing. The results of pilot tests are also described here.

The paper also looks at minimizing piercing defects in continuous castings by identifying critical factors, defining their optimum values and conducting consequent pilot tests.

TITANIUM NICKELIDE: A COMPREHENSIVE STUDY OF PROPERTIES TODAY, STREAMLINED PRODUCTION OF STEEL PRODUCTS TOMORROW

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Because titanium nickelide cannot be easily melted and it is not easily processable or workable, it took years before this alloy found its practical application as a shape-memory effect material. Today, of all the known materials manifesting thermoelastic martensitic transformations, titanium nickelide has the broadest application.

Due to the specific plasticity properties of the NiTiNOL alloy, mainly hot and warm forming processes are used to process it, such as hot pressing, hot rolling, hot and warm drawing.

This paper describes the results of a study that looked at the properties of the NiTiNOL alloy during cold rolling and hot upsetting. It also describes the results of a study that examined the effect of heat treatment on the properties of the alloy.

Using the obtained data, this paper describes some deformation routes used for the production of wire and capillary tubes, and a process flow diagram of a wire and capillary tube production site. The calculated volume and weight parameters of commercial wire and tube production from the NiTINOL alloy helped elaborate specifications, as well as a list of main and auxiliary equipment to implement the above process.

COMPARATIVE QUALITY ANALYSIS OF SEMI-FINISHED PRODUCTS USED FOR THE PRODUCTION OF STAINLESS STEEL COLD-DEFORMED TUBES

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Cold-deformed tubes are made from hot-deformed tubes and the quality of the latter defines the efficiency of the production process. Kiberstal LLC, a producer of stainless steel cold-deformed tubes, uses the semi-finished products made by Pervouralsk New Pipe Plant JSC and Kazan Pipe Plant LLC.

The stainless steel tube production process employed by Pervouralsk New Pipe Plant involves piercing, rolling and sizing in a line that comprises an automatic pipe mill. At the same time, Kazan Pipe Plant only uses the piercing process performed in a roll mill. The production site houses a layout area, a centering machine, a reheating furnace, a piercing mill, and a cooling section [2].

The comparative analysis of the semi-finished products used was based on the following parameters: chemical composition, mechanical properties, dimensional precision, surface quality.

The chemical composition of the semi-finished products only differed when tube shells were supplied by different steel makers. Because the both producers rely on the same supplier (e.g. Krasny Oktyabr Corporation JSC), the researchers failed to establish a relationship between the chemical composition of the semi-finished product and its cold workability.

Table 1 below shows average values of the mechanical properties of the semi-finished products.

Table 1. Average values of the mechanical properties of the semi-finished products

Producer	$\sigma_в$, MPa	$\sigma_т$, MPa	δ_5,%
Kazan Pipe Plant	534.8	227.2	55.4
Pervouralsk New Pipe Plant	652.6	334.0	43.1

The performance of hot-deformed tubes produced by the piercing process only, which will ensure better cold workability.

Two parameters were used to analyze the dimensional accuracy: out-of-roundness of hot-rolled tubes ($\Delta D/D_{nom}$, %) and wall thickness variation ($\Delta S/S_{av}$, %). The results are presented in Table 2 below.

Table 2. Average values of the dimensional accuracy of the semi-finished products

Producer	$\Delta D/D_{nom}$, %	$\Delta S/S_{av}$, %
Kazan Pipe Plant	1.66	9.17
Pervouralsk New Pipe Plant	1.82	7.93

The wall thickness variation in hot-deformed tube shells that come out of piercing mills is normally 10÷20 % [1].

The surface quality comparison was based on rejection rate. The share of tubes that were rejected for continuous outer surface defects and required machining was 11% for Pervouralsk New Pipe Plant and 13% for Kazan Pipe Plant. The share of tubes with sporadic defects that required local repairs was 66% for Pervouralsk New Pipe Plant and 28% for Kazan Pipe Plant. Pervouralsk New Pipe Plant accounted for 6.06% of tubes rejected for inner defects, while Kazan Pipe Plant accounted for 4.0% of such tubes.

The hot-deformed tubes made by Kazan Pipe Plant are comparable – in terms of quality – to conventionally produced hot-deformed tubes and in certain aspects the former appear to outperform the latter.

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ELECTROPLASTIC EFFECT SIMULATED IN A MONOCRYSTAL BY MOLECULAR DYNAMICS METHOD

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Using the molecular dynamics method, this paper examines how a dislocational electroplastic effect may change the plasticity of a model monocrystal [1,2]. The Morse potential was used to describe the interatomic interactions [3, 4].

Using the molecular dynamics method, a model was built of a two-dimensional monocrystal with the interatomic spacing of a=0.995 and the atomic weight equal to 1. The model has the size of 256×256 atoms and was built in the C++ Builder 6 programme. An atomic chain was then removed from the cell centre to create a prismatic dislocation loop. After relaxation, two dislocations formed in the structure (Fig. 1).

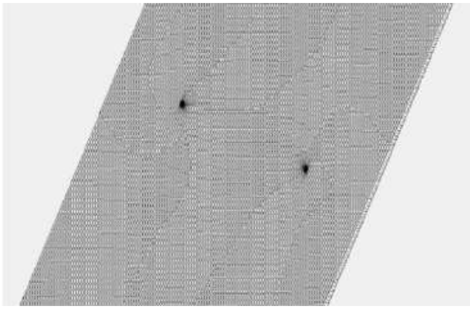

Fig. 1 Model monocrystal with two dislocations introduced in it

After that, the system was subjected to a monotonously rising shear strain and temperature effect. The temperature effect was achieved by introducing random initial atomic displacements within a given range. The larger the range is, the higher the temperature is. All calculations were done in dimensionless units. The depth of the Morse potential serves as a unit of bond energy between two atoms. The unit of spacing is an equilibrium spacing between two atoms. The unit of time was selected in such a way so that the atomic mass was equal to one.

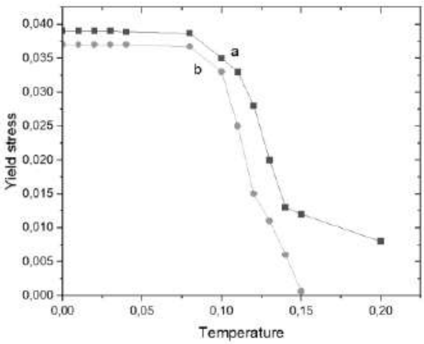

Fig. 2. Yield stress-temperature relationship: a) 256×256 atom model, no pulse current applied; b) 256×256 atom model, with electroplastic effect.

Graphs were built that show the relationship between yield stress and temperature with no current applied and with pulse current applied (Fig. 2). Analysis of the results shows that electroplastic effect helps the dislocations to move much easier only when the temperature is high. This can be attributed to the presence of the Peierls-Nabarro potential, which dislocations surmount easier at higher temperatures.

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UNDERSTANDING THE EFFECT OF WELDING PARAMETERS ON THE HARDNESS OF RESULTING LAMINAR MATERIAL DURING ASYMMETRIC ROLLING

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In March 2021, the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory at NMSTU saw the commissioning of a two-high asymmetric rolling mill 400, which has no counterparts in the world in terms of such an important parameter as work roll speed ratio (10:1). The mill is designed for the maximum rolling force of 2,500 kN, the maximum power of 200 kW, the maximum roll torques of 2×65 kNm, and the roll diameter of 340 mm.

This research is aimed at understanding the process of welding together different steel sheets during asymmetric rolling.

The following input parameters were used: materials – steel ‘08Ю’/copper, Al 6061/5083, copper/titanium; initial thicknesses of the workpieces – 3 mm (‘08Ю’), 2 mm (Al 6061, 5083, copper and titanium); initial temperatures of the workpieces – 20-450 °C; work roll speed ratios – (1:1, 2:4, 3:9, 2:8). The roll gap in all cases was 0.9 mm.

The output parameters that were registered included rolling forces, reduction, and hardnesses of the laminate composites.

In all cases, an increase in the roll speed ratio was associated with a significant decrease in the rolling force. Thus, when the workpiece was heated to 400 °C and the roll speed ratio increased from 1 to 3, the rolling force would go down from 750 to 490 kN (steel ‘08Ю’/copper), from 610 to 350 kN (Al 6061, 5083), and from 1,100 to 400 kN (copper and titanium). At the same time, the reduction rate would rise from 70 to 78 % (steel ‘08Ю’/copper), from 65 to 80 % (Al 6061, 5083) and from 68 to 78 % (copper and titanium) in one pass.

Of interest would be the relationships between the hardness of the final laminar materials and the roll speed ratio that were obtained. Thus, when the workpieces were heated to 400 °C and the roll speed ratio increased from 1 to 3, the hardness of the harder component '08Ю' dropped from 178 to 164 HB, while the hardness of the softer component increased from 66 to 78 HB (steel '08Ю'/copper). It was similar for Al 6061/5083 – the hardness of the harder component dropped from 114 to 90 HB, while the hardness of the softer component remained almost unchanged (85 HB). When the workpieces were heated to 300 °C and the roll speed ratio increased from 1 to 3, the hardness of copper dropped from 106 to 99 HB, and that of titanium increased from 199 to 215 HB (copper/titanium).

The conducted experiments demonstrated a strong effect of asymmetric speed on the rolling force, reduction and hardness, suggesting broad adjustment possibilities for the above parameters.

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EQUIPMENT DESIGNED FOR SHAPING HEXAGONAL TUBES WITH WIDTH ACROSS FLATS OF OVER 120 MM

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Hexagonal tubes are most widely used in nuclear industry where they serve as components of different equipment used in nuclear reactors, such as cooling pond racks, fuel assembly racks, canisters, fuel assembly ducts, etc. It takes seamless cold-deformed hexagonal tubes to build a reactor core, to which extremely high dimensional precision requirements are applied. The assortment of hexagonal tubes that are in demand for the nuclear industry today include tubes with the width across flats of up to 257 mm and with the wall thickness of up to 6 mm.

Cold-deformed hexagonal seamless tubes are conventionally produced in cold pilgering mills, and high quality can usually be achieved. However, this process is successfully used for tubes with the width across flats of up to 120 mm, as there are no bigger cold pilgering mills that exist in the world today. That is why it would be reasonable to use a shaping stand with a set of drive rolls and/or idlers to produce large-size shaped tubes with extremely thin walls. Today, Chelyabinsk Tube Rolling Plant (ChTPZ) is the only producer of large-size hexagonal seamless tubes. However, the shaping stand that is in use for this purpose has no fine roll adjustment capability. Neither can mandrel be used. This is the reason why the ChTPZ process fails to ensure the dimensional precision that is required from hexagonal tubes for them to be used in the reactor core.

The author has developed two solutions to enable the production of high-precision large-size hexagonal seamless tubes with extremely thin walls:

I – A round tube can be drawn through a 3-high shaping stand equipped with idlers;

II – A round tube can be reverse rolled in a 4-high combination stand.

It is proposed to use several passes (at least 3) for both the drawing and rolling processes, with the tube turned after each pass. Such process will help achieve the required radius and will make the mandrel removal easier due to a weakened collaring effect.

Draft designs of the shaping stand have also been prepared for both options. The required dimensional precision can be achieved by using a mandrel but also due to the roll adjustment capability. Both options are designed to have axial and radial roll adjustment systems. For the 4-high rolling stand, the radial adjustment of the horizontal drive rolls follows the conventional “screw-nut” pattern. An original solution is offered for vertical roll adjustment: roll chocks should be tight against the stand beams and the rolls get adjusted by moving the beams both axially and vertically. Original design solutions are also offered for the 3-high stand: each roll is adjusted separately; both the axial and radial adjustment systems are based on a wedge-type mechanism, which enables fine-tuning and ensures the required rigidity.

Design options for each component (rolls and a single-piece and split-type mandrel) have been elaborated for each type of the shaping stand. An original design is offered for a split-type hexagonal mandrel, which can easily be removed without affecting the tube geometry.

The proposed solutions have been tested on a prototype 4-high stand. It was built from a 4-high module of an experimental rolling mill that is currently functioning at RusNITI. A set of tools was inbuilt in the stand, and the stand and the tool set together make a large-scale prototype tube shaping stand. For physical modelling of the tube shaping process, large-scale specimens were used with the width across flats of 45.2 mm and the wall thickness of 0.87 mm (D/S=60, scale 4:1, for a hexagonal tube with the original width across flats of 181.0 mm and the wall thickness of 3.5 mm). Having analyzed the physical modelling results, the author came to the following findings: 1 – The proposed process and shaping regimes proved effective: the forming process was consistent, with proper grab and exit conditions; 2 – The possibility to use a hexagonal mandrel was confirmed: it can be easily introduced and removed; 3 – The lubricant used proved effective and the related operations were successful. The dimensions of the large-scale tube specimens achieved by means of physical modelling are characterized with a smaller tolerance range for maximum deviations versus the specification applicable to hexagonal tubes designed for nuclear reactor core applications.

So, the principal conclusion that can be drawn from this research is that it proves the effectiveness of the designed equipment and its capability to make products of the required quality. Due to the flexibility of the proposed processes and equipment, they can be redesigned (if necessary) for any other type of steel products – e.g. square tubes.

The above described design solutions were prepared as design assignments and were sent out to potential producers. The final dimensions of the large-scale hexagonal tube specimens were taken as references for updating the applicable specifications.

EXAMINING THE ROUGHNESS AND MICROHARDNESS OF ULTRAFINE-GRAINED TITANIUM GRADE 4 SUBJECTED TO NONABRASIVE ULTRASONIC MACHINING

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This paper aims to understand how different modes of nonabrasive ultrasonic machining affect the microhardness and roughness of a cylinder-shaped specimen made of commercially pure titanium Grade 4 in an ultrafine-grained (UFG) state. Alloys in a high-strength state are known to be highly sensitive to stress raisers and the surface roughness parameter, which, in turn, have a considerable effect on the fatigue resistance of items made of such alloys [1,2]. Consequently, in order to achieve the desired surface parameters and enhance the performance of the final products, additional surface polishing is required. For example, by nonabrasive ultrasonic machining [3].

The initial state is an UFG state achieved by the equal channel angular pressing (ECAP)-Conform method at the temperature of 300±10 °C followed by drawing at 300±10 °C. The microstructural analysis of the produced specimens showed that 6 ECAP-Conform cycles (Bc route, 90° angle) followed by a drawing operation (e=0.15) resulted in the average crosswise size of structure fragments of 180±26 nm. The initial state microhardness was 2,590±60 MPa and the roughness was Ra = 8.59 μm.

Different modes of nonabrasive ultrasonic machining were applied, with the following parameters varied: rate of rotation of the specimen (500, 1,000 and 1,600 RPM), static pressing force (25, 50 and 100 N), ultrasonic generator power (1, 1.5 and 2 kW).

The findings show a considerable increase in surface microhardness (2 to 3.5 times) and a decrease in the roughness parameter Ra in all studied modes.

A study of the effect produced by ultrasonic power showed that a rising power leads to a linear increase in microhardness, while the roughness parameter Ra tends to grow. As the rate of rotation of the specimen rises, the roughness parameter Ra tends to decrease. Thus, when the rate of rotation was increased from 500 to 1,600 RPM, with other things being equal, the roughness parameter Ra dropped from 0.42 to 0.36 μm, while the microhardness rose.

Using scanning electron microscopy, the authors examined the surface layer structure in the specimens with maximum microhardness. A longitudinal section study of the specimens indicates the presence of a deformed surface layer, which has the thickness of 40-50 μm.

When the surface was examined by means of scanning electron microscopy, it was found that the studied modes of machining produce a surface that consists of 3 to 5 μm fragments. It should be noted that such fragments tend to be more elongated in the state of maximum microhardness (at 1,600 RPM). This can probably be attributed to higher RPM.

The findings show that nonabrasive ultrasonic machining of commercially pure titanium Grade 4 in UFG state leads to a 2 to 3.5 times rise in surface microhardness and a considerable decrease in surface roughness (from Ra ~ 8.6 μm to Ra ~ 0.3-0.4 μm). In the selected modes of machining, as the rate of rotation of the specimen goes up, the roughness parameter is observed to decrease, while the microhardness tends to rise. A higher ultrasonic power applied leads to a linear rise in microhardness. At the same time, the roughness parameter grows in the selected modes. Between the considered options, the following mode of machining appears to be most efficient: the rate of rotation of the specimen – 1,600 RPM; static pressing force – 50 N; ultrasound power – 2 kW. The above parameters are associated with the maximum microhardness (i.e. 8,930±70 MPa) and the roughness of Ra = 0.36 μm.

Acknowledgements

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EFFECT OF THE MELTING PROCESS ON THE QUALITY OF FLATS MADE OF LOW-CARBON STEEL WITH HIGH COLD RESISTANCE

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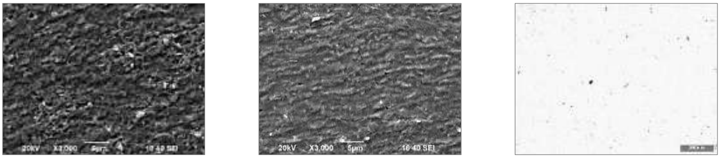
The steel designed for northern applications has to meet strict requirements in terms of strength, low-temperature ductility, cold resistance, weldability and purity. It cannot have cracks, slivers, tears, laps or other surface defects [1-2]. Such condition can be mostly achieved by vacuum remelting of steel.

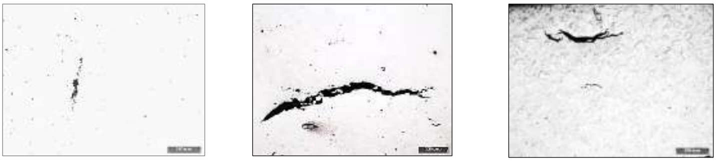
This paper looks at how the melting process (with or without vacuum) for highly cold resistant steel correlates with the presence of non-metallic impurities and its resistance to hydrogen-induced cracking.

A vacuum induction furnace ZG-0.06L was used for melting ingots with a specified chemical composition. The hot roughing mill process was simulated with the help of a hydraulic press P6334 designed for 250 tons. The finishing mill process was performed in a two-high reversing hot mill 500 combined with a controlled cooling line [3].

Non-metallic impurities were found in the microstructure of unetched specimens melted without vacuum. They are mostly round inclusions more or less evenly distributed throughout the specimen. Following GOST 1778-70, they can be identified as spot oxides (Fig. 1, a), stitched oxides (Fig. 1, b), non-deforming silicates (Fig. 1, c), and brittle silicates (Fig. 1, d). No sulphides, plastic silicates, nitrides or carbonitrides were found. The stringer inclusions have the maximum of 3 points, which could lead to the development and spread of cracks in axial and surface layers when the specimen was tested for its resistance to hydrogen-induced cracking (Fig. 1, e-f).



a) b) c)

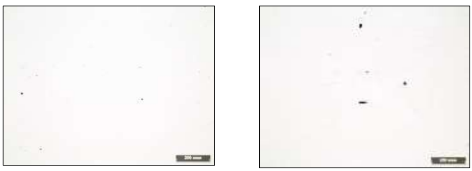


d) e) f)

Fig. 1. Surface photomicrography of an unetched microsection of specimens melted without vacuum: a) spot oxides; b) stitched oxides; c) non-deforming silicates; d) brittle silicates; e) axial cracks; f) surface cracks, x 100

To identify the types of non-metallic impurities, a separate study was conducted that relied on X-ray microanalysis. It was found that, apart from iron and carbon, the impurities contained oxygen, calcium, sulphur, manganese, silicon and aluminium. Hence, they can be referred to metallurgical silicate, oxysilicate and oxysulphide non-metallic inclusions, aluminium-magnesium spinel.

It was found that vacuum melting helps produce steel of high purity (in terms of non-metallic impurities), contributes to crack resistance and reduces the amount of non-metallic impurities in high-strength and highly cold resistant steel (Fig. 2).



a) b)

Fig. 2. Surface photomicrography of an unetched microsection of vacuum melted specimens: a) spot oxides; b) brittle silicates, x100

One can thus conclude that high purity (in terms of non-metallic impurities) and high cold resistance in steel can be achieved by vacuum melting.

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UNDERSTANDING THE ELECTRIC DRIVE PARAMETERS OF ENERGY AND FORCES DURING ASYMMETRIC ROLLING

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The problem of mathematical modelling of the main electric drives of sheet rolling mills has been thoroughly studied and models are successfully used for tackling various theoretical and applied problems. All such models are built for symmetric rolling conditions, which implies equal speeds and diameters of the rolls.

Asymmetric rolling, which is gaining more and more popularity today, takes lower rolling forces and helps achieve a certain deformation texture at the exit [1, 2]. At the same time, unequal speeds make the deformation zone shift, which makes the calculation of the required rolling energy and forces more challenging.

To build the model of an electric drive system, one needs to know its mechanical characteristic, i.e. the speed-torque relationship $M_c=f(\omega)$. In the case of asymmetric speeds, the rolling torques will be unequal, and the torques of the drive (1) and driven (2) rolls will be governed not only by their own speeds but also by the speed of the other roll. This can be expressed by the following dependencies: $M_1=f(\omega_1, \omega_2)$ and $M_2=f(\omega_2, \omega_1)$ [3, 4].

Possible solutions of the above problem would be:

a) to determine the rolling torques experimentally using laboratory equipment [1];

b) to build a model of the deformation zone and thus define the rolling forces and torques.

The drawback of the first solution is the limited range of process parameters that can be examined, which is due to the limited capabilities of the laboratory mill. Besides, the simplest case is examined this way as the steel goes through a single stand with no head or tail tension.

For an accurate description of stable and transient states of multi-stand mill drives during asymmetric rolling, one has to examine the deformation zone by using simulation models. This will help integrate the obtained results into the known models of the closed-loop mill drive systems and, by inputting the process parameters (steel grade, reduction rate, friction coefficient, etc.), obtain the required energy and forces from the system. Fig. 1 shows one possible implementation of this approach when the work roll drives follow the thyristor transducer-DC motor arrangement and have speed and armature current control loops.

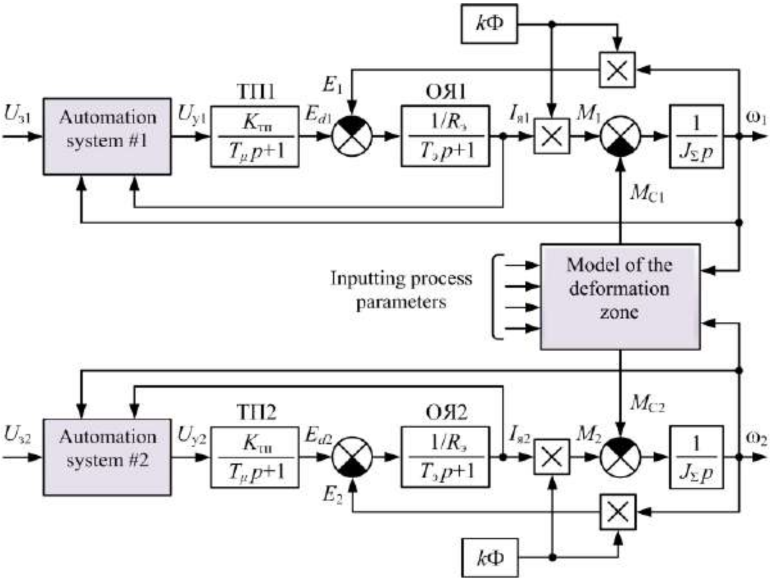

Fig. 1. A generic block diagram of a rolling mill drive during asymmetric rolling

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BUILDING A SPACE OF REDUCTION MODES FOR STAGE TWO OPTIMIZATION OF ROLL CALIBRATION IN STEEL CHANNEL PRODUCTION

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To obtain this or that rolled section, there is a huge number of various roll pass designs that are used even on a functioning rolling mill [1]. Hence, the problem of finding an optimal roll pass design for a specific steel section produced on a specific rolling mill is of relevance.

The papers [1, 2] propose a method for searching an optimal roll pass design for channel rolling based on a two-stage optimization concept developed by the Department of Metal Forming at the Ural Federal University. The essence of the Concept is to consider calibration as a functional system consisting of individual elements (grooves) and controls between them (reduction mode). Thus, a roll pass design can be called optimal if it has two components of optimality – the optimal scheme of roll pass design and the optimal reduction mode. To simplify the optimization procedure, the search for the optimal components of roll pass design is carried out in two successive stages (Fig. 1).

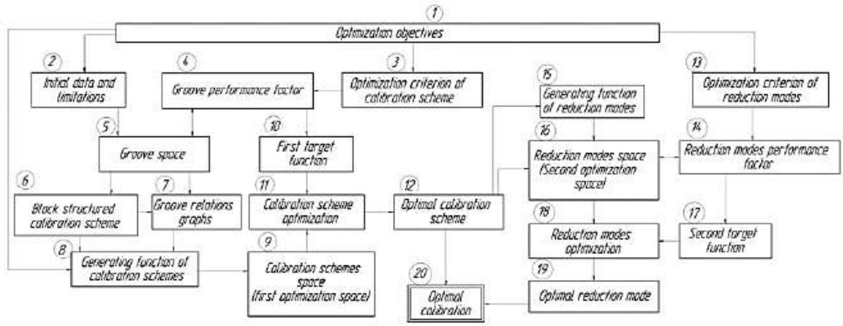

Fig. 1. Structural flowchart of two-stage optimization of roll pass design

First optimization stage – The subsequence of searching for the optimal scheme of roll pass design for rolling channels is considered in [1]. Formation of the space of reduction modes is a starting point for searching an optimal reduction mode (Stage 2).

The space of reduction modes for channel roll pass design is a continuous space which contains all possible variations of reduction modes for rolling a certain number and type of channels in a particular rolling mill for the selected optimal scheme of roll pass design.

The space of reduction modes is an n-dimensional space. Every point of this space corresponds to a separate reduction mode. Reduction ratios of the channel neck are the coordinates of the space of reduction modes $1/\eta_i$. The number of coordinates is determined by the number of passes in the calibration: n = N–1, where N is the number of passes. As one knows from the technical literature, it takes at least 5 passes through a rolling mill to produce channels [3]. Therefore, the smallest space will be a 4-dimensional space. However, a 4-dimensional space is quite difficult to represent, so for clarity Fig. 2 shows a 3-dimensional space of reduction modes (for the first four passes), which contains 1,296 different reduction modes for channel rolling.

The coordinates of the space or the reduction ratios for the channel neck are in the range of values from 1 to $1/\eta_\Sigma$, $1/\eta_\Sigma$ – total reduction factors.

Conditions for the distribution of reduction factors along the passes:

$$1/\eta_1 \le 1/\eta_2 \le 1/\eta_3 \le \ldots \le 1/\eta_n \text{ и } 1/\eta_\Sigma = 1/\eta_1\ 1\ 1/\eta_2\ 1\ 1/\eta_3\ 1\ \ldots\ 1\ 1/\eta_n.$$

The initial data and limitations for building a full-fledged space of reduction modes have been established.

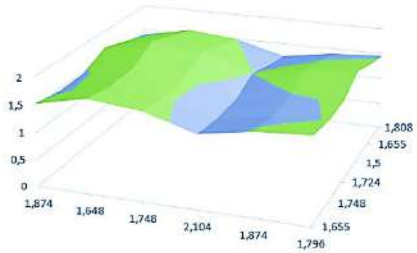

Fig. 2. Three-dimensional space of reduction modes

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AN INTEGRATED APPROACH TO IMPROVING PERFORMANCE PROPERTIES OF FERRITE-MARTENSITE STEELS

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Cold rolling within the temperature range below 30% of T_{melt} entails an increase in strength properties of steel, such as yield strength, tensile strength and hardness, but an increase in the rate of strain results in a sharp decrease in ductility [1, 2]. It was shown recently that subsequent heat treatment, such as heating above the ferrite/austenite phase transition temperature (subsequent quenching), can increase performance properties of steel [3].

To study an original structure of steel, we carried out standard heat treatment. As a result of tempering, a lath martensite structure was formed. Quenching contributes to a more equilibrium state. Coarser particles elongated along their axis are $M_{23}C_6$ carbides, smaller inclusions are MX particles.

Rolling results in considerable structural changes. An increased reduction rate results in forming a band structure. When deformation is 70%, texture is formed along the rolling direction. Coarse carbides are redistributed and formed in chains along grain boundaries. After rolling and subsequent quenching the steel structure is equiaxed.

It has been established that rolling and subsequent quenching result in an increase in microhardness of the samples to 4280 MPa, by 34% higher than the samples after standard heat treatment.

Rolling and additional quenching from temperature higher than the ferrite/austenite phase transition temperature contribute to an increase in ultimate tensile strength by 53% to 1380 MPa, maintaining ductility at 17%.

Rolling and subsequent quenching of steel grade EI-961Sh contribute to increasing fatigue strength by 59 %, from 472 MPa after standard treatment to 750 MPa. Finer particles of secondary phases and their uniform distribution along grain boundaries and body after rolling prevent crack propagation by increasing fatigue limit. An additional hardening factor was forming the structure, containing twin boundaries.

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STRUCTURAL CHANGES OF THE ALUMINUM COMPOSITE MANUFACTURED BY ARB

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Applying high-strength materials in various sectors contributed to a growing demand for forming a fine-grain structure in aluminum alloys of various series. A main method used to form such structure is severe plastic deformation. Accumulative roll bonding (ARB), developed by Saito, has its advantages among other SPD methods [1-2]. Sophisticated equipment is not required for this process; production output may be high, and produced materials are not limited by volume [3]. Aluminum alloys are the best material for the ARB process. Aluminum alloys are light materials, having high specific strength and ductility.

For years, alloy D16 has been the most widely used construction material. It is perfectly deformed in a hot or cold state to manufacture various types of semi-finished products, such as tubes, rods, plates, sheets, etc. [4]. The disadvantage of the alloy of this system is considered to be low corrosion resistance; therefore, it needs special anti-corrosion agents. In most cases, the alloy is clad or anodized to considerably increase its corrosion resistance. Aluminum cladding is applicable for sheets only, as a thin layer of aluminum (4% of product thickness or less) is to be applied on both sides of the workpiece. Thus, duralumin sheets are coated with layers of pure aluminum and then rolled. This results in semi-finished sheets, resistant to corrosion, scratches and other mechanical damages [5].

This paper describes the studies on the Al/D16 composite manufactured by accumulative roll bonding. Changes in a grain size of alloy Al and D16 and the effect of the deformation on corrosion resistant of the composite were studied in detail. Mechanical properties were also under study.

The material used in this study was pure Al and alloy D16 of a standard chemical composition (Al-4.4Cu-1.4Mg-0.7Mn, wt.%). Original thicknesses of the aluminum and D16 alloy plates were 1 and 6 mm, correspondingly. Thickness of the Al/D16 double-layer plate after rolling was 3.1 mm. Corrosion resistance of the Al/D16 composite was studied as per GOST 9.913-90, using a 3% solution of NaCl, at T = 20℃.

Structural changes in D16 in an initial state and after ARB were studied using SEM. There are fine particles of secondary phases. An average size did not change after rolling: 5±3 μm. Aluminum layer thickness is 450 μm.

Microhardness of D16 after ARB increases to 1560±50 MPa, Al - to 360±30 MPa.

Corrosion studies on D16 showed pitting corrosion. An aluminum layer of the composite is resistant to corrosion and may be an efficient protection for D16 against corrosion in sodium chloride. The size of pitting after rolling is higher by 45% as compared to an original sample and amounts to 8.25 μm on average, but there are less points of origin. D16 after rolling showed corrosion cracking. This was possibly due to residual stress on grain boundaries.

Thus, the ARB process applied for Al and D16 plates contributed to manufacturing the composite, showing a maximum strength of 1560±50 MPa and an aluminum surface layer, resistant to corrosion in a 3% solution of NaCl.

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DEVELOPING THE TECHNOLOGY OF APPLYING A ZINC-ALUMINUM COATING (GALFAN) ON WIRE OF VARIOUS APPLICATIONS AT OJSC MMK-METIZ

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The issue of producing metalware with efficient protective coatings has always been and remains relevant for current plants. In addition to a required level of protection properties, there are often special requirements for ductility (formability). According to global practice, zinc-aluminum coating Galfan satisfies all the mentioned requirements [1, 2].

OJSC MMK-METIZ intends to put into operation a wire hot dip galvanizing line [3] for products of various applications coated with Galfan: low-carbon wire for gabion structures [4], galvanized rope wire, etc. It is critical to produce the coating with a level of ductility at various load patterns (alternating bending, joint plastic strain with a metal substrate), providing its required performance characteristics.

This research is mainly aimed at analyzing key properties of a promising type of the coating, Galfan, and developing the technology of its application at OJSC MMK-METIZ.

The paper describes studies on main preferential differences of Galfan from zinc coatings [1-3]; a metallographic analysis of the samples of wire coated with Galfan, including an analysis of the location of intermetallic layers of a ZnAl coating (Fig. 1) carried out at laboratories of OJSC MMK-METIZ and Nosov Magnitogorsk State Technical University; the procedure of applying Galfan on wire, equipment used and its technical specifications; requirements for finished products coated with Galfan, and main issues regarding Galfan: how to select a supplier of the alloy, prepare for operations with the alloy and conduct incoming control of Galfan; and the analysis of a molten alloy in the bath and density of a coating on wire.

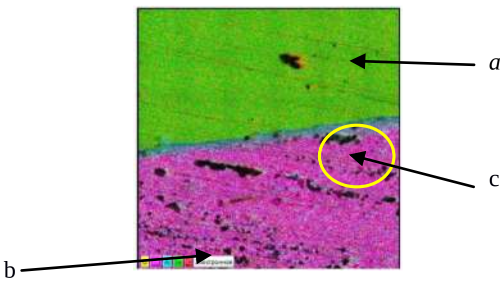

Fig. 1. A multilayer image of energy-dispersive spectrometry of the section: a is steel; b is a Zn-Al coating; c is an intermetallic layer (a layer with dominant Al)

The research outcomes:

- mischmetals and other elements in the composition of the metal bath ensure high corrosion resistance of the coating and considerably increase its formability. Therefore, this type of the coating can be used during its joint plastic strain with a metal substrate,
- the coating structure consists of several layers (the layer with dominant Al inhibits the rate of corrosion),
- the technology of applying Galfan on wire has been developed to be used at OJSC MMK-METIZ.

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EXPERIMENTAL STUDY ON APPLYING ASYMMETRIC COLD ROLLING AT ROLLING SHOP No. 8 OF PJSC MMK

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The research focuses on experimental modeling and potential application of asymmetric rolling at Rolling Shop No. 8 of PJSC MMK to reduce a number of process cycles "rolling-annealing", when producing narrow strips from high-strength steel grades. To apply the asymmetric rolling technology in practice, an independent drive for work rolls should be installed. PJSC MMK has relevant equipment on rolling mills at Rolling Shop No. 8.

At Rolling Shop No. 8 of PJSC MMK the current flow chart of rolling narrow strips, 0.8 mm in thickness, from 65G steel grade includes 2 stages of intermediate annealing:

2.8 mm → 2.0 mm → annealing → 1.3 mm → annealing → 0.8 mm

The experiments at the NMSTU laboratory showed that it was feasible to provide for asymmetric rolling of narrow strips, 0.8 mm in thickness, from 65G steel grade (or similar steel grades) <u>with 1 stage of intermediate annealing</u> according to the below schedule (Fig. 1.):

2.8 mm → 1.3 mm → annealing → 0.8 mm

Regarding a decrease in force, efficiency of asymmetric rolling considerably increases at higher reduction. When reduction is 10-15%, asymmetric rolling is not very efficient to decrease rolling force. When reduction is over 30-40%, efficiency shows a considerable increase. In particular, force during asymmetric rolling at 30-40% reductions correspond to force during symmetric rolling at 10-15% reductions.

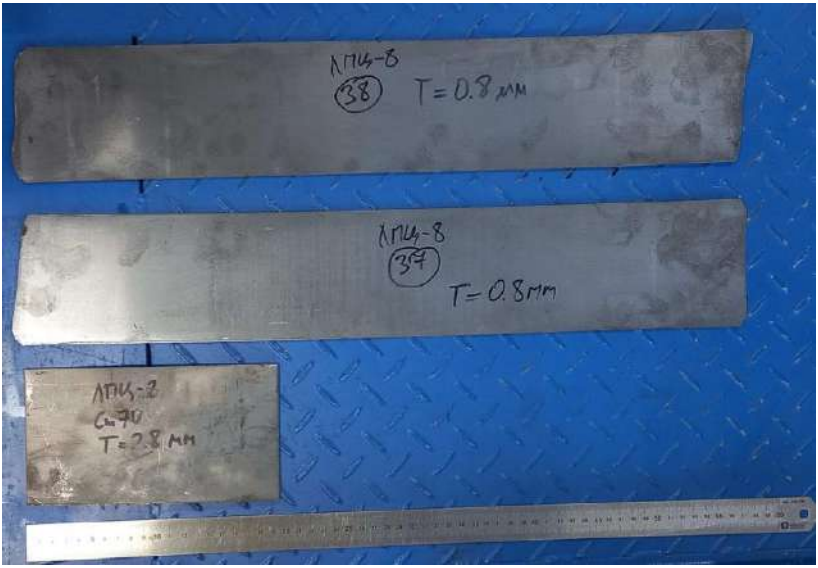

Fig. 1. General view of the samples of the 65G steel narrow strips 0.8 mm thick produced by asymmetric rolling (with lubrication) 2.8 mm → 0.8 mm (in 5 passes, no intermediate annealing)

Asymmetric rolling according to the schedule: 2.8 mm → 0.8 mm without stages of intermediate annealing in 5 passes shows an increase in hardness of the samples from 65G steel grade from original 141…146 HB to 271…287 HB.

Due to work roll speed difference, asymmetric rolling contributes to a considerable decrease in rolling force and increase in reduction in the stand. The experiments showed that asymmetric rolling (asymmetry degree of 40%) could be added in the 2nd pass (stand No. 2) with a percentage reduction of 36% (2.5 mm → 1.6 mm) at rolling force ≈370 tf for narrow strips from 65G steel grade.

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CLUSTER STRUCTURE FORMATION IN LONG PRODUCTS

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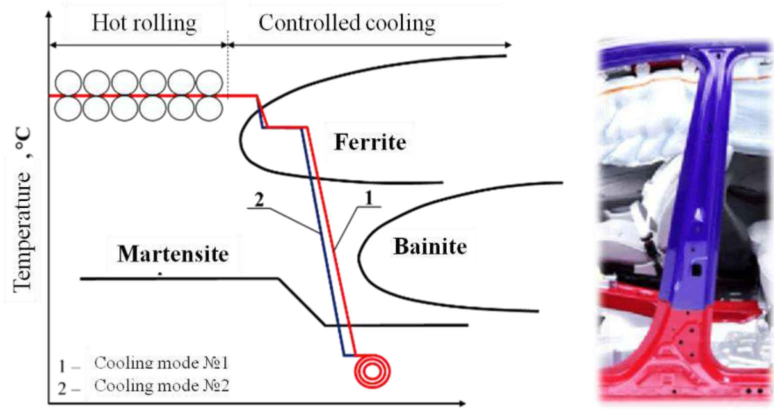
Reducing the cost, weight and fuel consumption, while increasing reliability, durability and safety of a modern car, makes automakers find alternative solutions, when choosing materials that meet modern environmental requirements and the safety policy. One of the most efficient methods of settling this issue is to choose rational materials and use optimal methods of hardening parts [1].

Now, multiphase steels, combining sufficient ductility, high strength, lightness, become particularly popular, entailing, in turn, the efficient use of cold forging methods for manufacturing individual parts [2]. However, it should be noted that to manufacture a modern car body, it is necessary to manufacture over a hundred separate parts, then connect them into a single structure, using several grades of metallic materials [3]. Therefore, the use of the combined assembly method implies multiple welds often located in places, which are the most exposed to breakage. Then, this may affect strength of the entire structure and, consequently, safety of passengers.

A metal segment hardening method during sheet stamping ("press hardening steel") [4] instead of welding is used to produce a part from the same grade composition, but with a different set of properties, avoiding multiple welds, and to reduce the number of manufactured individual parts. However, the use of this technology requires some time to produce the required body structure elements, which is not feasible for mass production. In this regard, the prospect of the automotive industry development in the Russian Federation requires learning how to produce automotive sheet steels at metallurgical enterprises with a high production potential, including the development and learning of the manufacturing technology for hot-rolled long products with a cluster of high strength and ductile properties, which are difficult to combine, for subsequent stamping, excluding the further use of welds of several metallic materials. This technology implies the production of large structural elements from hot-rolled coils with a cluster distribution of properties in steel across width.

Strips are produced on a hot rolling mill with controlled accelerated cooling (Fig. 1a).

When activating a set number of cooling semi-sections, heat exchange is achieved by removing heat to water jets from top and bottom headers to a water layer from the top surface of the strip. Thus, by controlling the process with strip cascade cooling on the discharge roller table, we achieve the required strength properties of high-strength steel (Fig. 1b).



a) b)

Fig. 1. Controlled cooling of the strip after hot rolling (a) and an example of a cluster location of properties in the finished product (b)

This method is efficient in terms of economics and power as compared to a steel hardening method by stamping due to a reduced process cycle.

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ANALYSIS AND QFORM MODELING OF THE ROLL FORMING PROCESS FOR FORMWORK SECTIONS

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In the monolithic construction of buildings, which has become very popular in recent years, reusable formwork is used when pouring concrete [1]. The main element of the shields is the supporting frame, the design of which uses a closed hollow section. Ultimately, the reliability of the entire building structure depends on the quality of this element. Therefore, special requirements are set for the quality of formwork sections. Formwork companies use a bent section as a frame (Fig. 1), which is obtained by roll forming of a welded pipe or forming of a steel strip which is welded after being formed.

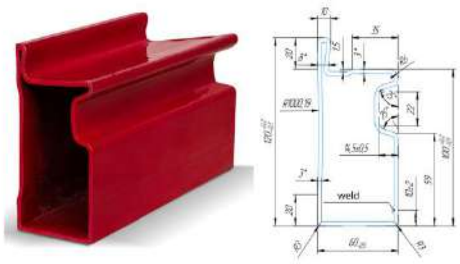
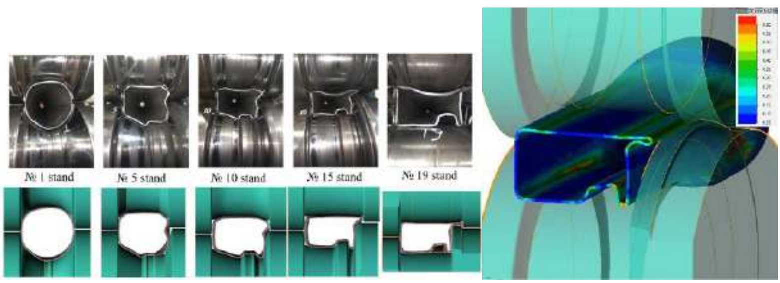


Fig. 1. Section

In this research study, a computer model has been developed in the QForm program, which makes it possible to simulate the process of shaping pipes from round ones in order to find resource-saving solutions for the manufacturing of the required steel frames from rolled products that would combine increased strength with reduced wall thicknesses.

QForm version 9.0.10 was used for the simulation. In the first case (Fig. 2a), the following parameters were set during the simulation [2]:

- workpiece length: 400 mm (deformable part: 300 mm);
- diameter: 120 mm;
- wall thickness: 3.0 mm;
- steel grade: St3 (1.0038),
- repartition of the workpiece: every 100 steps;
- constant step of deformation: 10 ms.



a) b)

Fig. 2. Section modeling results: a) comparison of the cross section of a real section and the one obtained in the process of computer modeling; b) results of modeling a section with the wall thickness of 2.2 mm made of steel 09G2S

Analysis of the obtained images showed that the convergence is sufficient for computer simulation in order to identify the features of shaping when using a pipe of increased strength with a reduced wall thickness as a workpiece.

In the second case (Fig. 2b), the following parameters were set during the simulation:

- workpiece length: 400 mm (deformable part: 300 mm);
- diameter: 120 mm;
- wall thickness: 2.2 mm;
- steel grade: 09G2S (13Mn6).

The developed computer model of the roll forming process that helps produce a complex shaped section from a welded pipe showed high convergence with the real forming processes performed in a 24-stand bending and rolling machine. The study of the forming processes that help produce sections from a Ø120 mm electric-welded longitudinal steel grade 09G2S pipe with the wall thickness of 2.2 mm demonstrated the possibility to produce steel sections with enhanced mechanical properties and reduced metal consumption using the existing equipment. Defects in the section obtained by modeling completely match those found in the real section. Computer simulation of the roll forming process in the QForm package can later be used to change the roll calibration in order to improve the quality of the finished product by improving the geometry of the section.

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DEVELOPING A COMPUTER PROGRAM APPLIED TO DETERMINE GEOMETRY PARAMETERS OF THE DEFORMATION ZONE, WHEN PIERCING ROUND BILLETS ON PIERCING MILLS

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When producing hot rolled seamless pipes, a main operation is piercing preheated round billets. The setting parameters of the piercing mill directly influence the quality and geometry of the rolled pipes. Unsatisfactory setting parameters of the mill may result in defects, such as inner and outer flaws, which is a main problem in pipe rolling. In order to prevent inner and outer flaws, the settings of the piercing mill should be accurate and optimum.

To settle the problem, a computer program with simplified interface was developed to determine the settings of the piercing mill and calculate optimum setting parameters promptly at the shop.

Eisen v2.0 (Fig. 1) computer program is used to calculate the deformation zone parameters, when piercing on two-high piercing mills with barrel-type, cup-shaped and cone-type rolls and has the following functions:

– original data input in the dialog box (mill settings),

– parameter range input, if necessary (distance between rolls, guides, plug advance, roll rotation angle),

– storing parameters of authorized tools (rolls, internal tools and guides),

– calculating deformation zone parameters (geometrical parameters of produced shells, reduction, contact conditions),

– outlining a diagram of the deformation zone,

– result output in the dialog box and in the table.

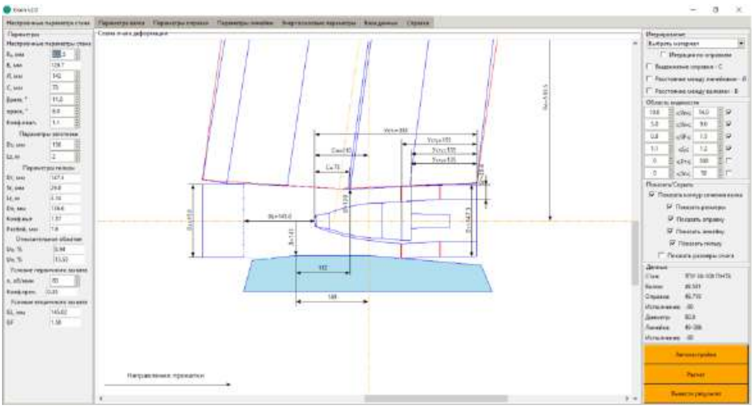

Fig. 1. Eisen v2.0 interface

The developed program is unique, as it is universal, flexible and highly accurate. Similar programs are developed according to a specific type of piercing mill rolls. This program may be used for piercing mills with barrel-type, cup-shaped and cone-type rolls.

A comparative analysis was carried out using KOMPAS 3D. The developed program showed a 100% convergence in the results of the comparative analysis. Consequently, the program calculates accurate geometrical parameters of the deformation zone, when piercing round billets on piercing mills with barrel-type, cup-shaped and cone-type rolls.

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ADVANTAGES OF ACCELERATED ROLLING OF RAILS

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The railway network of Russia consists mainly of rails R65. Rails 12.5 m and 25.0 m long are produced on linear rolling mills [1]. To produce longer rails, we need heavier workpieces. Rolling time increases, therefore, the required rolling temperature is not provided on linear mills.

Rails 100 m long and over are rolled on mills with a continuous group of stands to decrease heat losses of the workpiece during rolling and ensure the required finishing temperature of rolling. The mill consists of 6 stands: a roughing reduction stand; a reduction stand; a continuous reverse group of 3 stands and a sizing stand [2].

A temperature range of continuous reverse rolling is 850-1000ºC, and 820- 880 ºC in a universal non-reverse sizing stand. Then the rail head and base undergo accelerated cooling from 720-870℃ to 450-600℃. As a result, rails show higher wear resistance and contact fatigue resistance [3].

High-speed railways are built from rails with high accuracy of geometry. Vertical deviations of welded joints of rails from straightness on the rolling contact surface of the head shall not exceed 0.2 mm [4]. Thus, finishing rolling is effected in a separate universal non-reverse sizing stand to ensure the required geometry of the rail profile along its total length within the set range of tolerances.

However, sizes of finished rails are influenced not only by a shape and accuracy of grooves, but also rolling temperature.

During rolling steel of the rolled stock is cooled down. A great length of the workpiece results in “a temperature wedge”, namely a decrease in temperature along rail length during rolling in the sizing stand [5]. Rail web temperature difference along the length of rolled products may be 75 ºC (ΔT). Consequently, in the sizing stand the rail size is the same, but temperatures are different. Cooling the front and back ends of the rolled stock may result in different heights of finished rails.

Let us calculate a difference in rail height along length by the web temperature difference, as a main share of rail height is attributed to the rail web. Coefficient of thermal expansion α for steel grade 76KhF is $14.8 \cdot 10^{6}$ 1/ºC [6]. Height (H) of rail R65 is 180 mm [7]. Height difference along rail length is:

$$\Delta H = H \cdot \alpha \cdot \Delta T, = 180 \cdot 14.8 \cdot 10^{6} \cdot 75 = 0.1998 \text{ mm}.$$

The difference in height of the front and back ends of rails is close to a maximum allowable value, 0.2 mm. To eliminate the difference in height along rail length, we should eliminate the difference in rail temperature along length. Therefore, accelerated rolling should be applied on a core part of the rail.

Based on the experience with rolling thin strips on HSM [8], an assumed acceleration value will be 0.005-0.010 m/s^2. A reverse temperature wedge should ensure the same temperature of the web along rail length in the sizing stand to achieve the same height along the rail.

The temperature difference along rail length at the beginning of accelerated cooling may result in different mechanical and performance properties along the rail. In this case, rolling should also include the acceleration, ensuring the same temperature of the head along rail length at the beginning of accelerated cooling.

If applicable in terms of equipment, accelerated rolling can be in the sizing stand. This will reduce cooling time of the back end of the rolled stock before the stand and decrease the acceleration value in the last pass in the finishing continuous reverse group of stands.

Thus, accelerated rolling of a core part of the rolled stock in the continuous reverse group of stands contributes to ensuring the same height and the same mechanical and performance properties along the rail.

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ANALYSIS OF THE EFFECT OF FRICTION ON DEVELOPING RESIDUAL STRESSES IN ROUND WIRE, WHEN USING VARIOUS SHAPES OF DRAW PLATE CHANNELS

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Drawing processes are actively used to produce fine wire used in steel wire cords, ropes and other products. It is a relevant objective to select geometrical parameters of tools and process parameters to produce wire, which is the most resistant to loads. Full-scale experiments aimed at determining process parameters and the stress and strain state for the process consume time and money. Therefore, it is feasible to carry out preliminary numerical experiments, whose results, as stated in paper [1], do not differ greatly from full-scale one.

The paper [2] describes the study on the effect of the friction coefficient on the drawing process. It was revealed that changes in such coefficient entailed changes in the distribution of residual stresses and strains.

This paper analyzes how residual stresses are distributed in wire depending on the friction coefficient for various types of dies: conical, radial convex, sigmoid, twin elliptical and parabolic dies.

Fig. 1 shows that the friction coefficient has less influence on the distribution of average rates of residual stresses than the channel shape.

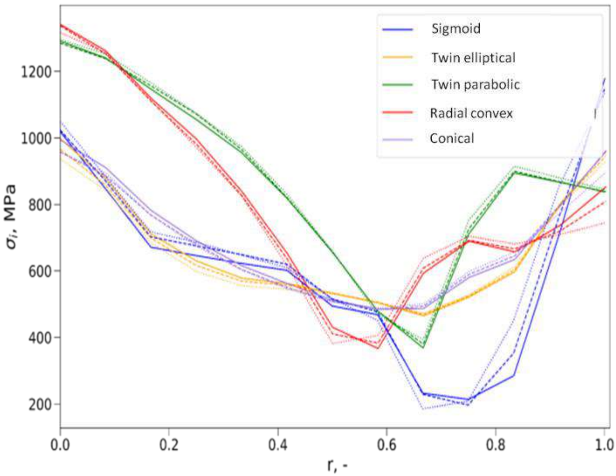

Fig. 1. Distribution of rates of residual stresses depending on the friction coefficient and the die type. Die parameters: initial radius is 2.45 mm, friction coefficient of the solid line is 0.01, dashed line is 0.025, dotted line is 0.05, and bearing section line is 1.115 mm

The greatest difference between the distributions of average rates of residual stress at various friction coefficients is shown, when using a sigmoid type of the die. When the friction coefficient is 0.01 for this type, the distribution of average rates of residual stress is comparable to similar distributions for conical and twin elliptical dies, but only in an area of up to 0.59r. The majority of the types of dies under study show an increase in stresses near the boundary.

The least difference between inner and boundary areas of wire corresponds to conical and twin elliptical types of dies. When using the conical die, the highest average residual stresses to central layers of wire are identified at a coefficient of 0.01. The least average rates of residual stresses are identified at a friction coefficient of 0.05 at a distance of up to 0.55r. When approaching the surface, the differences between the coefficients under study are not significant.

There is a sharp change in the behavior of average residual stresses for twin parabolic and radial dies at distances of 0.59r and 0.63r, correspondingly, similar to the situation with the sigmoid type of the die. However, changes for twin parabolic and radial dies at all the friction coefficients under study are not sharp as compared to the sigmoid die.

Thus, friction has the greatest influence on diagrams of average residual stresses for radial and sigmoid types of dies. Friction does not have a significant influence for other types of dies under study. When an entry radius is 2.45 mm, the most favorable average residual stresses may be achieved for all the friction coefficients under study for conical and twin elliptical types of dies.

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EFFECT OF TEMPERATURE AND SPEED ON THE STRESS AND STRAIN STATE OF WORKPIECES FROM ALLOY ZN-4AG-CU DURING ECAP

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There is current active development of innovative medical methods used to restore patients' lost functions. A special focus is given to biosoluble (bioresorbable) materials. Such materials include alloys based on Mg [1], Fe [2], and Zn [3-4]. They contribute to a considerable reduction of costs for surgical operations and treatment periods. But these metals have disadvantages, such as inadequate strength and embrittlement, preventing their use in medical implants. Therefore, improvement of mechanical properties of bioresorbable alloys is currently relevant.

Severe plastic deformation (SPD) is one of modern tools applied to improve properties of metallic materials by a severe refinement of an original structure to a nano- and ultrafine-grain structure [5-7]. One of efficient SPD methods is equal channel angular pressing (ECAP) [8].

This paper describes the study on the effect of deformation speeds (0.4 and 7.8 mm/s) and temperatures (150, 200℃) on the distribution of the accumulated strain degree, strain rate, average stresses and temperature and force conditions for zinc alloy Zn-4Ag-Cu, processed by ECAP. The computer simulation showed recommended ECAP at 150, 200℃ and 0.4 mm/s. As a result of the experiments, we have samples after 4 cycles of ECAP, showing improved mechanical properties, which are attractive for medical applications. A zinc alloy of higher strength contributes to minimizing sizes of implants, ensuring less injury during their installation and faster solubility in physiological environment of a body.

The research was funded by the Ministry of Science and Higher Education of the Russian Federation as part of the state assignment of USATU (Agreement No. 075-03-2022-318/1), the youth research laboratory of the research and education center "Metals and alloys in extreme conditions".

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DEFORMATION OF PRECIOUS METAL ALLOYS TO OBTAIN JEWELRY WIRE: PROCESS SIMULATION AND INVESTIGATION

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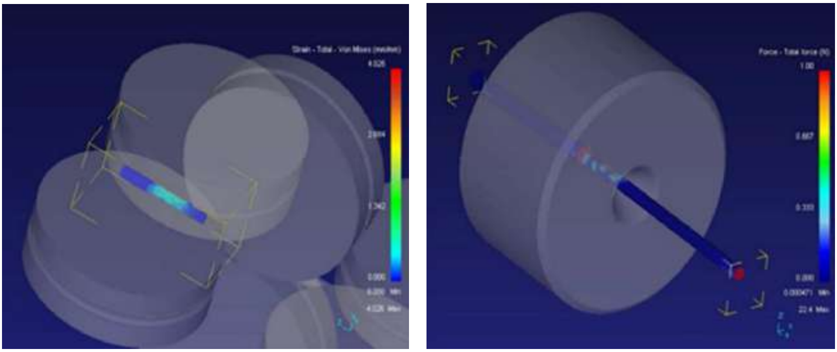
Modern jewelry production involves the use of a combination of machining and metallurgical processes, where chains and bracelets made of precious metal alloys [1 – 3] constitute a significant part of the products. Researchers from the Siberian Federal University, together with the Krasnoyarsk Non-Ferrous Metals Plant, have created and patented new gold, silver and palladium alloys and developed relevant processing regimes. The proposed alloys of multicomponent precious metals systems allow to manufacture products of better quality, with enhanced mechanical properties and performance.

Processes for manufacturing deformed semi-finished products for jewelry chains from new precious metal alloys were designed with the help of computer-aided design. The adequacy of the algorithms and automatic calculations was confirmed by computer simulation of the rolling and drawing processes. Using data on the mechanical properties of the new gold, palladium and silver alloys patented by the authors, the loads of power equipment were calculated taking into account the limitations with regard to rolling forces and torques (Fig. 1).

Using the variational method of minimum total power, the authors solved the problem of determining how the shape would change during cold rolling of bars in octahedral gauges [4].



a) b)

Fig. 1. Models of bar rolling *(a)* and drawing *(b)* in the DEFORM 3D package

The adequacy of the developed computer models was confirmed by physical modeling and the study of semi-finished products selected during the processes carried out in the Laboratory of Physical Chemistry of Metallurgical Processes and Materials.

The study was carried out as part of an assignment given by the Ministry of Science and Higher Education of the Russian Federation (Subject: FSRZ-2020-0013).

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STATISTICAL MODEL OF THERMAL EFFECT ON HYPOEUTECTOID STEELS

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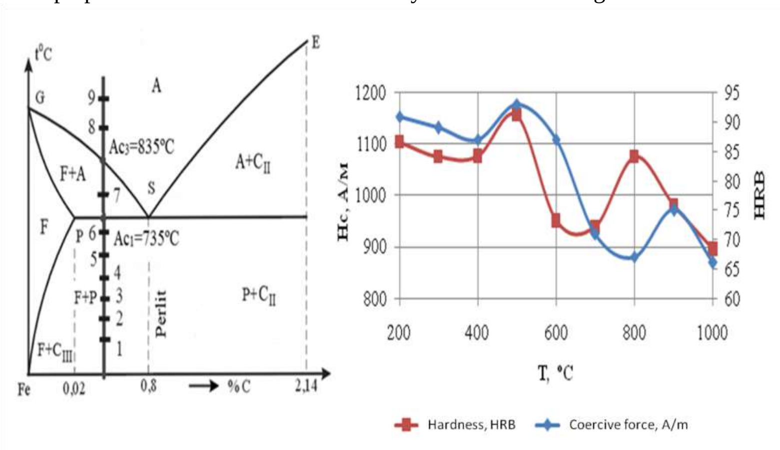
Nowadays, the degree of uncontrolled thermal effect on steel structures designed for various applications can be determined by the colours of thin oxide layers that occur on the surface of metals. They are referred to as heat tints [1]. The process of oxidation results in the formation of the following iron oxides: FeO (wustite), Fe_3O_4 (magnetite), Fe_2O_3 (hematite). The oxides are arranged in layers as the concentration of oxygen drops from the outer layer to the inner one. The method of assessing the thermal effect based on heat tints has certain drawbacks. The visual analysis can be quite subjective and there is a certain temperature limit. Thus, above the threshold of 500 ºC the relationship between the temperature and the surface colour effect that can be visually determined disappears. However, when steels are heated and then cooled down, two processes take place in them with a synergetic effect on each other: the structure and properties of the base metal change and oxide films tend to form on the metal surface with varying composition and properties. This research aimed at understanding how heat affects the hardness and magnetic properties of hypoeutectoid steel, which are governed by both the processes that take place in the base metal and the properties of the surface oxide films. The authors also tried to establish a relationship that would help determine the thermal effect (e.g. in case of fire) based on the changing hardness and coercive force of steel structures combined. An experiment was conducted in the following way: the specimens were placed in a pre-heated furnace, soaked for 15 minutes and cooled down in still air. The temperature was varied from 200 to 1,000 ºC (Fig. 1, a). The hardness and coercive force of each specimen were measured a few times along the length of the specimen before heating and after cooling down and the obtained values were averaged out. For all specimens before heating, the average Rockwell B hardness was 89 units, with the average coercive force being 1,023 A/m. The curves showing the relationships between the hardness and coercive force after heating are given in Fig. 1, b.

The findings show that the correlation between hardness and coercive force (which is the most structure sensitive characteristic of ferromagnetic materials) is not true for all the temperature intervals. At the same time, only one combination of hardness and coercive force values corresponds to each temperature applied. With the help of Brandon method, a model was developed following the conducted experiments that helps determine the temperature in Celsius based on the changing hardness and coercive force

$$C = (1341 \cdot \Delta_1^2 - 1376 \cdot \Delta_1 + 491{,}9) \cdot (8{,}5 \cdot \Delta_2^2 + 1{,}3 \cdot \Delta_2 + 0{,}9),$$

where $\Delta_1 = \dfrac{H_{c2} - H_{c1}}{H_{c1}}$ - a relative variation of the coercive force after heating, $\Delta_1 = \dfrac{HRB_2 - HRB_1}{HRB_1}$ - a relative variation of the Rockwell B hardness, H_{c1}, HRB_1 – parameters before heating, H_{c2}, HRB_2 - parameters after heating and cooling down.

The proposed model was tested in laboratory conditions showing a relative error of 7%.



a) b)

Fig. 1. a) Steel angle of Fe-Fe3C graph with points 1-9 corresponding to the experimental temperatures; b) Hardness and coercive force changing depending on the thermal effect

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ANALYZING FRACTURE RISKS DURING BACKWARD EXTRUSION OF A MAGNESIUM CUP

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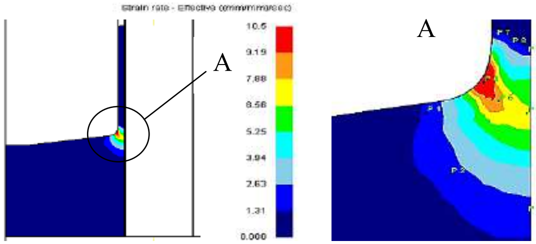
Magnesium as a hexagonal lattice material has a limited number of slip planes leading to low plasticity [1].

As the application of magnesium as a structural material has been continuously expanding, it appears to be of relevance to design cold forming processes that would involve compression stress states and thus help raise plasticity. Backward extrusion offers one of such processes [2-3].

The backward extrusion process was simulated with the help of the DEFORM-2D software. The specimen is made of magnesium grade Mg90 per GOST 804-93. The specimen is a cylinder with D = 6 mm and H = 4 mm. The punch diameter is 5.6 mm. The punch travel along Z-axis is equal to 1 mm. The friction parameter is 0.2.

The σ/T parameter was analyzed based on the solution of the backward extrusion problem. The structure of the deformation zone during backward extrusion helps understand the distribution of the strain rates (Fig. 1).

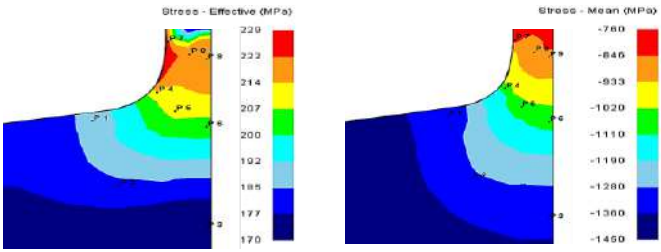


a) b)

Fig. 1. Strain rate distribution (a) and high strain rate region A (b)

Control points (P1,…, P9) had to be assigned for additional calculations in the deformation zone.

Stress intensity (Fig. 2, a) and mean stress (Fig. 2, b) were analyzed in the control points.



a) b)

Fig. 2. Distribution in the deformation zone: a) of stress intensity; b) of mean stress

Table 1 shows stress state calculations for P1 – P9 control points.

Table 1. Stress state indicators in P1 – P9 control points

Parameter	Point Number								
	1	2	3	4	5	6	7	8	9
σ/T	-12.3	-12.3	-13.2	-8.6	-8.7	-8.9	-6.5	-6.9	-6.7

One can see from Table 1 that the σ/T parameter in the deformation zone can vary from -6.5 to -13.2. Since the metal plasticity drops as the σ/T parameter rises, the above table suggests that the risky area borders points P7...P9. Hence, the cup wall is the most risky area in terms of cracking.

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ULTIMATE STRENGTH OF ALUMINIUM ALLOY AMG6 FLAT PRODUCTS: STATISTICAL ANALYSIS

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Semi-finished products made of aluminium alloy AMg6 are in demand in Russia even though it finds no counterparts in international standards. This aluminium alloy contains 5.8 to 6.8 % of magnesium as the main alloying element. Some of such semi-finished products are represented by hot-pressed items [1], whereas some of them are flat products. Statistical analysis of the mechanical properties of pressed items revealed a relationship between the performance of the final products and the dimensions of the semi-finished products, which was later replaced with a relationship between the strength and the extrusion ratio [2]. The latter had the nature of an extreme dependence, with the maximum strength of about 360 MPa reached at the extrusion ratio of 15.

This research included a statistical analysis of data reflecting the mechanical performance of flat products with a sample of 791 measurements. The analysis was performed for the thicknesses from 10 to 210 mm. On the basis of the total sample, a frequency distribution histogram was built that is shown in Fig. 1.

One can see that the frequency dependence corresponds to the normal distribution law. The entire range of thicknesses was divided into four groups with the average thicknesses of 25, 60, 110 and 160 mm, and average ultimate strength values were determined for them (Fig. 2).

One can see that maximum strength values are achieved at minimum thicknesses. At the same time, the ultimate strength values appear to be lower than the ones obtained for hot-pressed items. The most probable explanation is that a structural strengthening effect may occur during hot pressing, which is surely achieved in aluminium alloys when are hot pressed as the rate of deformation is not high. On the other hand, the hot rolling process is associated with high rates of deformation as it is essential that the metal stayed hot.

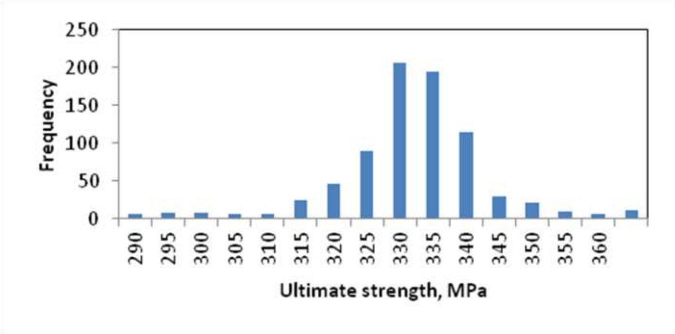

Fig. 1. Frequency distribution histogram for the ultimate strength of AMg6 alloy flat products

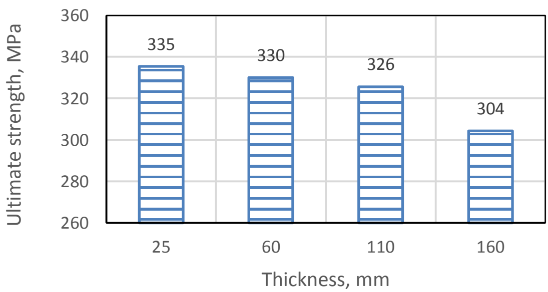

Fig. 2. Relationship between the ultimate strength of AMg6 alloy and the thickness of the flat product

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MODELLING THE INTERACTION OF DISLOCATIONS WITH OBSTACLES IN TUNGSTEN BCC LATTICE

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This paper looks at the mechanism of plastic deformation that is at work when an edge dislocation interacts with pores caused by radiation in nuclear reactors. By means of molecular dynamics, the authors simulated how a dislocation passes a pore. The paper examines the effect produced by the temperature, the pore diameter, as well as the interpore spacing.

The simulation was carried out with the help of the LAMMPS programme and the multi-particle interatomic potential for tungsten [1]. A similar problem was set for the BCC lattice of iron [2].

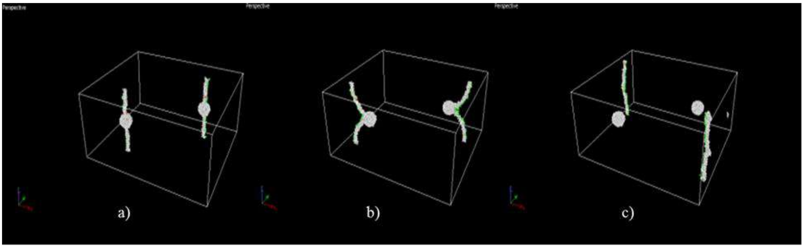

Fig. 1. Stages of the dislocation's passing of periodic pores. Only atoms with the coordination number different from the one of the BCC lattice are shown (8)

Fig. 1 shows how a dislocation passes a 2 nm pore at the temperature of 600 K. The dislocation is moving in a shear stress field, the size of which is controlled by the monotonously rising shear strain γ. View (a) shows how the dislocation is interacting with periodic particles (γ=0.03); View (b) shows the bowing of the dislocation segment between the two particles; in View (c) the dislocation is free from the particles.

These findings can be useful for the development of techniques to enhance the performance of materials used in nuclear reactors.

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ELASTIC EFFECT WHEN FORGING HIGH-STRENGTH STEEL 42H2GSNMA (VKS-1) WHILE TAKING INTO ACCOUNT THE ANISOTROPY OF PROPERTIES

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The anisotropy of the mechanical properties of rolled sheets obtained during rolling has a significant effect on the drawing process [1]. Its influence manifests itself in the form of uneven deformation of the workpiece, the formation of scallops, changes in the geometry of the part after removing the load, which requires additional annealing and calibration, as well as a significant allowance for edge machining.

Localization of deformation leading to local thinning is not allowed when manufacturing a number of products for critical applications from sheet steel. Therefore, the degree of shape change at which neck formation begins can be considered limiting in this case [2].

The ratio of stresses and strains can be estimated by analysing the digital model obtained by modelling the drawing process. The QFORM 10 software package designed by KvantorForm allows us to simulate the process of sheet stamping taking into account the anisotropy of the material, as well as to set various models for the depletion of the plasticity resource [1].

This paper describes some results of modelling the existing drawing process for the high-strength steel 42H2GSNMA (VKS-1) with respect to anisotropy (Fig. 1).

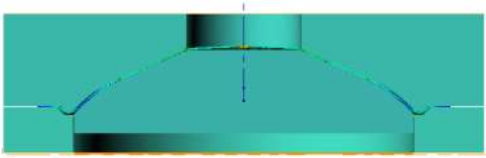
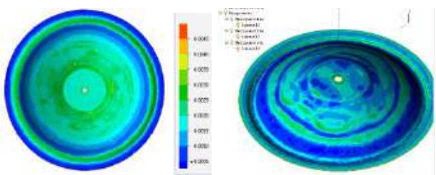


Fig. 1. Implementation of the drawing process

Initial data for the calculation: diameter of the workpiece 560 mm, diameter of the central hole 12 mm, drawing depth 155 mm, curvature constriction rib radius 10 mm; the tool material was set as absolutely rigid with 0.3 friction coefficient according to the Levanov law, 10 mm/s tool movement speed and single-pass drawing. The finished part is a truncated hemisphere of double curvature. Fig. 2 shows the deformation unevenness created during the stamping process.



a) b)

Fig. 2. Distribution of plastic deformation: a) at the end of drawing; b) after unloading

It is obvious that the plastic deformation in the flat area of the upper hemisphere part and the matrix constriction rib is insufficient to maintain the shape of the part, and after the load is removed elastic springback occurs (Fig. 3).

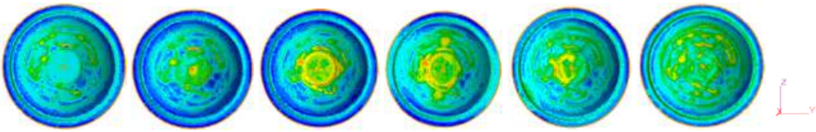


Fig. 3. Distribution of elastic deformation in the process of unloading

The elastic deformation during unloading first increases in the upper part of the part, then spreads to the flange and is oriented in the direction of the x-axis, practically without affecting the metal in the direction of the y-axis. Along the x-axis (along the direction of rolling), the part changes its shape more after the load is removed, which leads to the ovality of the finished part and the need for additional calibration.

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DEVELOPING A NEW INNOVATIVE TECHNIQUE FOR PISTON RING STRENGTHENING AND EXAMINING IT

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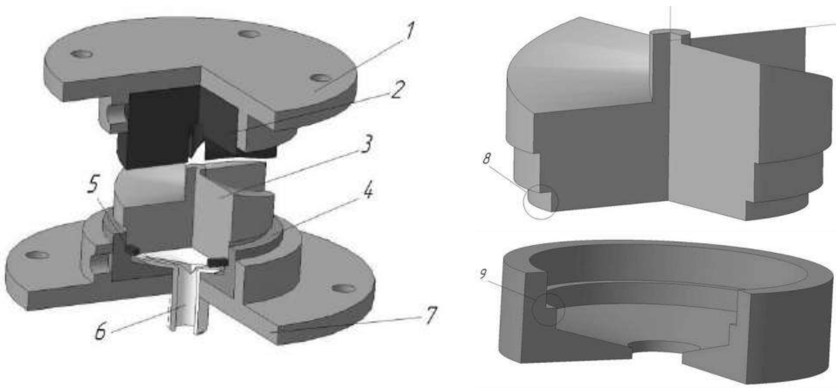
As one knows, today a variety of severe plastic deformation (SPD) techniques is applied to considerably change the structure, phase composition, as well as physical and mechanical properties of metallic materials. High-pressure torsion would be the most studied among such SPD techniques. It is worth mentioning that recent years have seen a rising interest to cryogenic cooling as part of severe deformation process. This can be justified by the fact that cryogenic cooling excludes dynamic recovery or recrystallization, which makes the grain refinement process more effective.

In view of the above, the Department of Metallurgy and Mining at the Rudny Industrial Institute has developed a new technique to improve the quality of piston rings [1] by achieving an ultrafine-grained microstructure in only a few deformation cycles. An appropriate tool has also been developed.

The developed technique implies high-pressure torsion performed in a tool that consists of a die (a cup with a recess), an upper anvil and a punch with a circular groove. As the punch enters the die, the groove creates a hollow ring-shaped space housing a ring-shaped workpiece. The punch is driven by the upper anvil due to spiral grooves present on both surfaces. Liquid nitrogen is sprayed inside the die with the help of a nozzle (Fig. 1).

This is how the strengthening effect is achieved: a ring-shaped workpiece is placed on the die recess, the width of which is equal to the ring width. The circular groove punch presses the workpiece from the top creating a confined space around the workpiece. The punch is connected to the upper anvil, which moves forward. Due to the spiral grooves present on the punch and the upper anvil, the punch moves forward while rotating thus realizing high-pressure torsion. Liquid nitrogen is sprayed inside the die through a nozzle at the bottom to enable cryogenic cooling of the workpiece. Forming is performed until both spiral surfaces have fully engaged, which corresponds to a 90° turn. After that the upper anvil rises. Then the spiral surfaces reengage and the operation is repeated. Four consecutive 90° turns constitute one work cycle.



1 – upper holder; 2 – upper anvil; 3 – punch; 4 – die; 5 – ring-shaped workpiece; 6 – liquid nitrogen nozzle; 7 – lower holder; 8 – circular groove on the punch; 9 – die recess

Fig. 1. Tool designed for strengthening of piston rings

To assess the efficiency of the proposed technique, a finite element model was built to understand the microstructural evolution under high-pressure torsion. The model was built for the developed tool for two temperature regimes: 20°C and -196°C. Four work cycles were performed for each case. The modelling results show that after four work cycles at 20°C, the initial 12 μm grain was refined to 0.8 μm. At -196°C, the same grain size was achieved after two work cycles, while the total four cycles resulted in 0.6 μm grains.

The conducted study indicates that the proposed strengthening technique enables to produce piston rings with given dimensions and ultrafine-grained structure using less work cycles than when applying the conventional strengthening techniques, which do not involve the use of liquid nitrogen temperatures or close temperatures.

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APPLICATION OF COLD ROLLING PROCESSES FOR FURTHERING WIRE PRODUCTION

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Wire and related items are the main types of steel products (in terms of both the assortment and the output) that are widely used in different industries. Wire is produced from almost all industrial metals and their alloys. The key metal forming process applied includes solid-die drawing. However, the way energy is introduced in the deformation zone, as well as the unfavourable stress state pattern typical of this process, may affect the product quality and the process efficiency. Besides, the principal strain pattern characterizing solid-die drawing does not allow to obtain a fine-dispersed equiaxed microstructure.

Cold rolling helps eliminate the above drawbacks. The current industrial practice involves the processes of flattening resulting in the production of rectangular wire with rounded edges and of cold rolling resulting in the production of round, shaped and corrugated wire. Significant contribution to furthering the above processes belongs to NMSTU's researchers [1, 2].

The South Ural State Technical University in Chelyabinsk [3,4] has developed some combined processes allowing to produce round wire from flat cold-rolled billets.

The studies into flat asymmetric rolling, which have been conducted for many years, resulted in the construction of an original asymmetric rolling mill designed for hot and cold rolling, which so far has no counterparts in Europe. The mill is the property of the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory at the Nosov Magnitogorsk State Technical University [5].

The experimental studies into the processes of flat asymmetric rolling conducted for flat and cylindrical billets, as well as analysis of the wire cold rolling and wire drawing practices, helped define a potential application of round wire with ultrafine-dispersed and nanostructures produced from asymmetrically rolled flat and flattened billets [6,7].

The current scope of work includes developing mathematical models of new production processes and conducting an experimental study that looks at obtaining asymmetrically rolled flat billets to be converted into round wire.

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EXAMINING DIFFERENT SCENARIOS OF MODULATION INSTABILITY OF DELOCALIZED MODES IN COPPER FCC LATTICE

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One of the essential chapters of crystal physics includes studies of crystal lattice vibrations as they dictate such important physical properties of crystals as heat conductivity, heat capacity, thermal expansion and others. Interatomic forces are non-linear and their linearization is only possible if atoms only slightly deviate from their equilibrium positions – i.e. by less than 1% of the interatomic spacing. Rising temperature or intensity of external effects on crystals lead to increased atomic vibration amplitudes, which makes it necessary to account for interatomic anharmonicity. Our approach implies analyzing the symmetry of the studied dynamic system and defining vibration modes dictated by the symmetry that exists independently of vibration amplitudes or the type of interaction between the system elements. For translational symmetry crystals, these are delocalized and periodic modes in three-dimensional coordinates. The stability and attenuation scenarios of delocalized vibration modes are governed by two factors: mode amplitude and frequency. Mode disintegration may take place during transition to thermodynamic equilibrium when the energy gets evenly distributed between all vibration frequencies. However, if the delocalized mode vibration frequency lies outside the phonon spectrum, one may observe energy localization as the result of modulation instability [1]. This phenomenon is associated with considerable localization of the vibrational energy, and it was first described in the paper [2]. Modulation instability may lead to excitation of long-lived discreet breathers, which, in turn, may affect the macroscopic characteristics of the crystal in view [3]. An important feature of delocalized nonlinear modes is their ability to change their mechanical characteristics [4].

This research is based on the FCC lattice of copper. Atomic displacement amplitudes varied from 0.01 to 0.1 Å. Stabilized amplitude was determined by averaging the atomic vibration swings of delocalized nonlinear vibrational modes in the moment of time equal to 1 picosecond. Periodic boundary conditions were applied along all three directions.

Copper atoms form a three-dimensional FCC lattice with a 10×10×10 primitive translational cell containing one Cu atom. The atomic weight of copper is equal to: m (Cu) = 63.55 amu. The equilibrium lattice constant a = 1.8075 Å. The modelling was performed in LAMMPS using the multi-body interatomic potential Mendelev for copper.

It was established that the time of modulation instability decreases as the amplitude increases while the localization parameter rises. We found that a crystal can have anisotropic planes leading to uneven stress distribution. We also found that the delocalized nonlinear vibrational modes may lead to the occurrence of discrete breathers, which localize a considerable portion of energy and may affect the macroproperties of metals (for example, their heat conductivity).

Acknowledgements: this research was funded by the Ministry of Science and Higher Education of the Russian Federation as part of the governmental assignment allocated to the Ufa State Aviation Technical University (Agreement No.075-03-2022-318/1): the youth R&D laboratory Metals and Alloys under Extreme Conditions for M.A.Yu. (simulation); Grant [НШ-4320.2022.1.2] for E.A.K. (analysis and discussion); Grant 21-12-00229 by the Russian Science Foundation for S.V.D. (problem statement, elaboration of key ideas).

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UNDERSTANDING THE APPLICABILITY OF FREQUENCY-BASED NDT TECHNIQUES FOR CRACK DETECTION IN FORGINGS

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Forgings may see defects occur during the forging process, with cracks being the most critical ones. This research aims to define a basic analytical and experimental technique for detecting cracks in forgings. The first step involved comparison of analytically and numerically calculated frequencies of an experimental beam. The study looked at a 100x50x5 mm cantilever beam made of St3 steel. The following formula applies for analytical calculation of the first mode frequency of natural vibrations: $f = \left(\frac{0.56}{L^2}\right) \cdot (E \cdot I/m)^{0.5}$, where L – beam length (m), E – elasticity modulus (Pa), $I = b \cdot h^3/12$ – second moment of area (m^4), $m = P \cdot b \cdot h$ – mass per unit length (kg/m), P – weight of 1 cubic meter of the beam material [1]. The analytical calculation showed that the first mode vibration frequency for the given beam parameters was 418 Hz.

The numerical calculation was carried out with the help of SolidWorks [2]. Vibrations of 5 different modes were calculated (see the top line of the table). The *f1* frequency was 426 Hz. The discrepancy between the analytical and numerical calculations is 2%, which can be attributed to the way the finite element mesh is broken down in the programme. Such low discrepancy suggests that numerical calculation of frequencies gives an adequate result.

Then, a 3 mm deep through crack was added to the same experimental model, with a varying position along the beam length. All calculation results are presented in the table below. Fig. 1 shows one of the calculation options.

Table. Numerical Calculation Results

#	Defect location	$f1$	$f2$	$f3$	$f4$	$f5$
1	No defect	426	1784	2633	3598	5747
2	Central crack	400	1745	21423	3480	5558
3	5 mm from the filled crack	301	1671	2271	3154	5535
4	95 mm from the filled crack	428	1782	2635	3603	5674

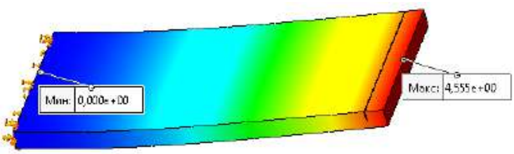

Fig. 1. Experimental model with the defect located 95 mm from the filled crack (*f1* frequency)

For the possibility to apply the calculated data to beams of different dimensions, the data were reorganized into dimensionless coordinates (Fig. 2).

Having determined the natural vibration frequency in a controlled part without and with defects by using instruments and through calculations, one can detect cracks and determine their parameters with a high degree of accuracy.

This is a test problem. The following was revealed: the frequency techniques are sensitive to discontinuities; consequently, they can be reliably applied for crack detection. The further aim of this research is to design automatic measurement software for in-process crack detection in forgings.

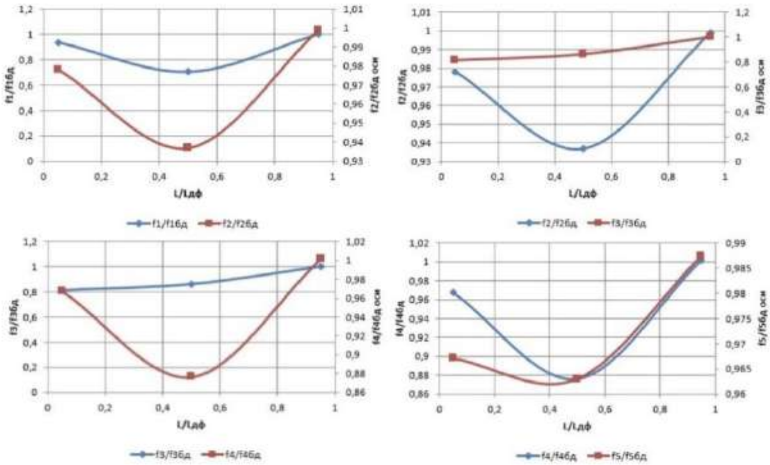

Fig.2. Graphs showing how the relative frequencies change depending on the defect location

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COMPUTER SIMULATION OF LASER CLADDING OF A CCM ROLLER IN THE SYSWELD SOFTWARE PACKAGE

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The roller of a continuous casting machine is intended for forming the surface of the ingot. Its working surface is subjected to high temperatures and abrasive wear. The maximum surface temperature can reach 650-750 °C. The rollers are made from centrifugally cast billets of steel grades 25Cr1Mo1V, 40CrMnNiMo and 30CrMo [1].

If defects are found on the working surface of the roller, it is replaced with a new one, and the worn one is restored by electric arc cladding. Today, to improve the performance and to restore parts to their original dimensions, laser cladding is increasingly used [2]. In contrast to electric arc cladding, laser cladding has a lower thermal effect on the product.

To extend the service life and improve the performance of parts restored by cladding, it is advisable to use more resistant materials that can withstand the effects of temperature and corrosion for a long time. Modified stainless hardfacing materials with a chromium content of 11-14% doped with carbon, nickel, molybdenum, vanadium, niobium and tungsten significantly improve the operational performance and the life of CCM rollers compared with low-alloyed hardfacing materials. Depending on their chemical composition, materials can behave differently in the process of surfacing. To improve the quality of a cladding, it is necessary to correctly and reasonably apply surfacing modes depending on the chemical composition of the material used and taking into account the characteristics of the restored product.

Currently, there exists a large number of software systems enabling computer simulation of the welding and cladding processes. One of the most common and well-established is the SYSWELD software package [3].

The aim of this research study is to simulate the process of laser cladding of a CCM roller alloyed with heat-resistant steel.

The following cladding process parameters were selected for the modeling purposes: radiation energy 10 kJ/cm, surfacing speed 5 mm/s, height of the deposited bead 2 mm. Combinations of cladding and roller materials are presented in Table 1.

The simulation results (Fig. 1) show that in the process of laser cladding using the indicated modes, concentrated local stresses of up to 1,000 MPa can arise at the boundary between the base material and the first deposited layer. Consequently, cracks and delamination of the deposited material may occur in those areas. To eliminate the risk of defect formation, it is necessary to adjust the surfacing modes and repeat the modeling process.

Table 1. Materials used for laser cladding simulation

Steel grade	Roller material	1st deposited layer	2nd deposited layer	3rd deposited layer
SYSWELD	16MnCr5	S355	X20Cr13	X20Cr13
Russian grade	18CrMn	17MnSi	20Cr13	20Cr13

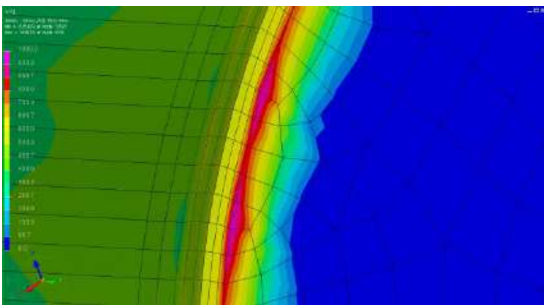

Fig. 1. Concentrated local tention

Thus, with the help of the SYSWELD software package, one can predict the quality of the deposited coating and reduce the number of unsuccessful laboratory experiments to determine the optimal parameters of the deposit.

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THE ROLE OF INTERATOMIC POTENTIAL IN THE DYNAMICS OF NONLINEAR DELOCALIZED VIBRATIONAL MODES IN TUNGSTEN

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One of the essential chapters of crystal physics includes studies of crystal lattice vibrations as they dictate such important physical properties of crystals as heat conductivity, heat capacity, thermal expansion and others. To study the nonlinear crystal lattice dynamics, together with experimental methods, researchers extensively use such methods as first-principles simulation and molecular dynamics method. The latter was used in this research.

It has recently been established that delocalized nonlinear vibrational modes (DNVM) are accurate solutions of atomic motion equations. The geometry of atoms is governed by the lattice symmetry and they are tightly bound to spatially localized nonlinear vibrational modes [1] known as discrete breathers (DB). Thus, the paper demonstrates that DBs can be generated by imposing the localizing function on DNVMs.

The authors used the molecular dynamics package LAMMPS [1] to study the DNVMs in the BCC lattice of tungsten. The study looked at two-dimensional vibrations in one of densely packed planes and at three-dimensional vibrations (i.e. when the atomic motion has three spatial components). Computer simulation helped build amplitude-frequency curves of these modes calculated for different interatomic potentials.

Out of all considered potentials, four were selected for which acceptable coincidence rate was reached. These potentials were later used to study the effect of delocalized vibrational modes on the macroscopic properties of tungsten crystals – i.e. pressure, kinetic energy and heat capacity (as a vibration stress parameter).

Amplitude-frequency curves were built as the result of numerical experiment. They show a rising frequency as a function of amplitude, which corresponds to hard nonlinearity. The authors also built curves showing the dependence of pressure and energy on the vibration amplitude. The former tend to rise as the vibration amplitude increases. Heat capacities were also calculated, which may deviate depending on the DNVM type.

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OPTIMIZED NUMBER OF SHEET METAL FORMING OPERATIONS IN AUTOMOBILE COMPONENTS MANUFACTURING

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Amid constantly changing market conditions, the problem of substituting imported components of different systems with domestically produced ones is gaining relevance. This is important for minimizing the risks of disrupting supplies and thus the production.

The sealing system designed for the ball joints used in chassis and steering systems is a critical component responsible for the quality and durability of the final product. Guided by this understanding, BelMag experts have designed an innovative sealing system that includes a stainless steel separator ring pressed on the ball joint and protecting the top flange of the seal [1]. Fig. 1 shows a ball joint with such separator.

This poses a problem of setting up a production of the above component at BelMag to ensure timely supplies and proper quality of the final product.

For designing a production process, one can utilize the well-known techniques that are used for designing sheet-metal forming processes [2]. To minimize the risk of defects, authors of the classical technique recommend using several operations to form a flange.

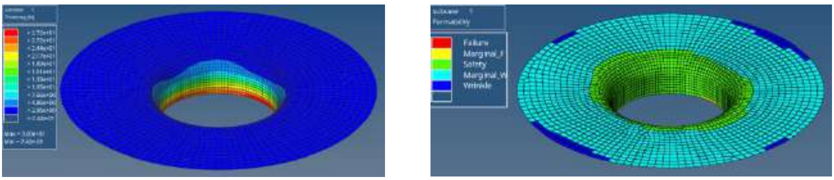
a) b)

Fig. 1. Ball joint with an optimized sealing system: a) General view; b) Separator ring

To minimize the tool related costs, the authors of this paper suggest optimizing the number of flanging operations by using the finite element method.

The rheological properties of the stainless steel used (including the plastic anisotropy ratio) were taken from paper [3].

Fig. 2 shows the results of simulating the first flanging operation and namely – thickness distribution over a cross-section and formability as illustrated by an automatically built FLD curve.



a) b)

Fig. 2. Modelling of the first flanging operation as part of separator forming:
a) % thinning; b) formability

The obtained formability values do not exceed the experimental values for the given stainless steel [4].

The above suggests that two flanging operations can be sufficient to obtain a quality component of the innovative sealing system. Compared with the process that involves several flanging operations, this approach offers better cost-efficiency.

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NORMAL INCIDENCE DEPOSITION AND SPUTTERING OF ATOMS ACCORDING TO THE FRENKEL-KONTOROVA MODEL

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The impact of a molecule from atoms K at speed V_0 on the free end of the Frenkel-Kontorova chain is numerically simulated. Depending on K and V_0, there are different scenarios of the molecule-chain interaction. Molecules, having low speed, stick to the chain. At slightly higher speeds, molecules rebound from the chain. A further increase in V_0 causes a molecule larger than the falling one to rebound. At even higher speeds, the molecule rebounds from the chain with the formation of a supersonic antikink (or crowdion), propagating along the chain. A very high collision rate leads to the atom precipitation from the chain and the formation of single and multiple supersonic crowdions. It is interesting that sputtering yield Y as a function of V_0 shows a non-monotonic dependence. This is due to the fact that supersonic crowdions may have a discrete set of propagation speeds. When V_0 is that supersonic crowdions are efficiently excited, they transfer energy deep into the chain, and sputtering is minimal. For some ranges of V_0, the formation of supersonic crowdions is suppressed. In these cases, energy transferred from the impact of the molecule to the chain is spent mainly on sputtering atoms. The results obtained qualitatively explain physics of bombarding the crystal surface with atomic clusters with applications for physical vapor deposition, ion implantation, ion-beam sputtering, and similar experimental methods.

Point defects play a very important role in the relaxation of the structure of materials during irradiation or ion-beam treatment [1]. Interstitial atoms, as compared to vacancies, have higher energy of formation, but lower energy of migration. Interstices in the form of crowdions have very low energy of migration and, consequently, high migration capacity, which makes their experimental analysis difficult. That is why the structure and movement of crowdions are often analyzed, using computer simulation methods, such as molecular dynamics [2], the Monte-Carlo procedure, multiscale simulation and ab initio simulation.

Crowdions may move along dense atomic rows at subsonic and even supersonic speeds. Supersonic crowdions (or antikinks) were studied, using the Klein-Gordon one-dimensional lattices [3], two-dimensional Morse lattices and FCC lattices. Moving crowdions transfer mass and energy, playing an important role in structural transitions of materials at high-energy attacks. It is shown that supersonic N-crowdions (multiple antikinks) transfer energy more efficiently, as they may be excited at less energy and transferred to a longer distance than supersonic 1-crowdions (single antikinks). Supersonic 2-crowdions may be excited by bombarding the crystal surface with molecules [4].

The Frenkel-Kontorova chain [5] was applied to study mass transfer by crowdions initiated by impact of the molecule on the end of the chain. It was shown that the molecule needed far less energy for initiating crowdions in the chain as compared to a single atom.

In this research the same model is used to analyze a modification of the crystal surface in case of impact of the molecule at various values of impact speed V_0 and number of atoms in molecule K. We will focus on analyzing a number of deposited or sputtered atoms. It will be shown that forming supersonic single and/or multiple crowdions plays a very important role in these processes.

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EFFECT OF LARGE DEFORMATIONS ON A MICROSTRUCTURE AND MECHANICAL PROPERTIES OF PURE ZINC AND ALLOY ZN-4AG-1CU

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Now, a great interest in materials science is taken in biodegradable metallic materials for medicine [1-3]. When manufacturing implants from biodegradable materials, there is no need for a second surgical operation and anesthesia, which are indicated in case of using conventional metal pins and screws. The implants are in due course degraded and safely assimilated by the body without any pain.

Zinc alloys are promising materials for developing biodegradable implants. Zinc, which is fragile in its pure form, needs further improvement to comply with clinical requirements. It is known that to increase mechanical properties of metallic materials, researchers often apply various scientific and technical approaches [4, 5] based on the principles of solid solution, precipitation and grain boundary strengthening [6, 7].

A particular interest is aroused to the grain structure refinement by severe plastic deformation (SPD) methods [8] based on applying large deformations at higher pressure and lower temperature of a phase transition.

The present paper describes the studies on pure zinc and the zinc alloy produced by SPD by torsion at various temperatures and various reduction degrees (with various numbers of rotation), and the effect of such deformation on the structure and mechanical properties.

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FEATURES OF THE WIRE DRAWING TECHNOLOGY FOR ADDITIVE MANUFACTURING

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Recently, additive technologies that do not rely on powder but on metal wire have been gaining popularity [1]. Depending on the alloy brand, the cost of welding wire can be 2 to 10 times lower than that of powder. A wide range of wire materials is available, and these are hundreds of items presented at the markets of Europe, the USA, China and Russia. For example, it won't be difficult to find high-quality wire made of titanium and titanium alloys, heat-resistant alloys, tantalum, tungsten, niobium, molybdenum, stainless or low-carbon steel, tool invar, aluminum alloys, zirconium, bronze, copper, copper-nickel, magnesium alloys, etc. The most common welding wire diameters for semi-automatic welding are 0.8, 1.0, 1.2, 1.4, 1.6 and 2.0 mm. With regard to the special industrial wire, things can get somewhat more complicated. The fact is that it is more expensive than welding wire, but can be made to customer requirements. Commercially available blanks or a specially smelted alloy can be used to obtain the desired wire diameter. In this case, it is necessary to understand how a particular alloy can be strengthened and what total degree of deformation can be used for drawing.

This paper describes a methodology for developing wire drawing technologies for the additive wire drawing production.

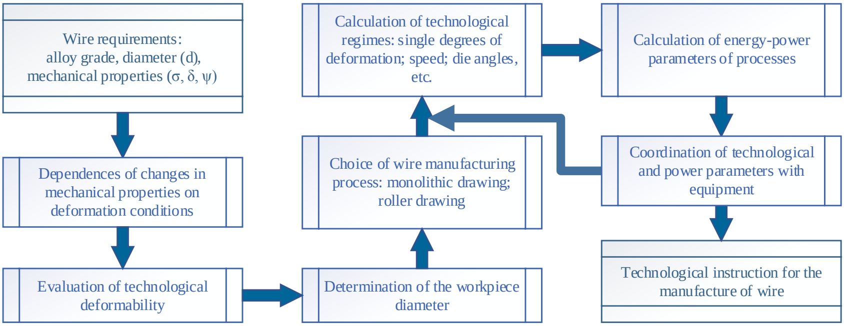

Fig. 1. Methodological scheme for the manufacture of wire by drawing

For any wire, including that used for additive manufacturing, there are certain requirements set for diameter and mechanical properties. The properties of the wire are governed by the chemical composition of the alloy, the heat treatment regime applied and the hardening reached by cold working. In the process of cold plastic deformation, the steel gets hardened and loses its plastic properties. The way the strength and plastic properties change is dictated by the chemical composition of the alloy and the initial microstructure, which is obtained during preliminary heat treatment. Therefore, one needs to know these dependencies to predict the properties of the finished wire. Depending on the chemical composition, alloys can have different degrees of technological deformability. There are alloys that can be easily drawn, and there are others, such as titanium alloy, that are very difficult to draw. Depending on the above two factors, the total degree of deformation is selected, and, consequently, the diameter of the workpiece. Once the diameter of the workpiece has been determined, it is necessary to set parameters of the drawing process. In order to do this, we have previously developed mathematical models and programs that greatly simplify this calculation [2]. A single degree of deformation, die angle, drawing speed, lubrication all have a significant impact not only on the stability of the drawing process, but also on the energy and forces of the drawing process and the quality of the finished wire [3]. Once the drawing process parameters and the required energy and forces have been determined, they should be coordinated with the available drawing equipment. If the available equipment is not designed for the calculated modes, they should be adjusted. The developed drawing technology should be able to deliver the required diameter of the finished wire, the mechanical properties that would meet the customer's requirements. It should be energy-efficient enabling trouble-free operation of the equipment. If all these parameters have been achieved, the wire drawing technology in the form of guidelines can be transferred to the production site.

The availability of software based on the method described above allows to quickly and efficiently develop technologies for manufacturing wire from various alloy grades for additive manufacturing.

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EXPERIMENTAL ASSESSMENT OF IMPROVED PERFORMANCE OF THE CONTINUOUS HOT STRIP ROLLING MILL, WHEN ROLLING STRIPS 2.5 MM THICK WITH A REVERSE TEMPERATURE WEDGE

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Wide strips are rolled on continuous hot strip mills. Mill performance is limited by a mill design, product mix and rolling schedules [1]. The paper describes an increase in mill performance by changing the rolling schedule, requiring no additional capital expenditures.

Now, strips are rolled with the acceleration in the finishing stands, ensuring constant temperature of the end of rolling along strip length. It is proposed to increase the acceleration, ensuring higher temperature of the end of rolling along strip length – with “an reverse temperature wedge” [2]. Rolling strips with the reverse temperature wedge reduces rolling time in the finishing stands of HSM and increases mill performance in general.

The experimental assessment of reducing rolling time was conducted by pilot rolling of strips on HSM 2000. 7 slabs of steel grade 08Yu 2.5 mm thick and 1250 mm wide were rolled.

Some specimens were rolled at constant temperature along strip length. Temperature range of the end of rolling (Ter) was 855 ±20 ºC and coiling temperature (Tcoil), 670 ±20 °C (Schedule TI3).

The other specimens were rolled with the reverse temperature wedge. Temperature of the end of rolling was gradually increased within a range from 835 to 925 °C (855 - 20+70 °C) at constant coiling temperature of 670 ±20 °C for the experimental schedule (Schedule LGTU3).

To get a fair assessment of the schedules, slabs from steel of the same heat were rolled under other equal conditions. The slabs were heated and rolled in the roughing stands of mill 2000 in compliance with the existing procedure. Thickness of the rolled stock was 32 mm; there were no delays on the intermediate roller table, the rolled stock was on the intermediate roller table for 49-52 s. There was a shield on the intermediate roller table. The AGC system and axial shifting were used during rolling.

The reverse temperature wedge along strip length is achieved on the hot strip mill by using a higher acceleration of the finishing stands compared to the acceleration used to ensure constant temperature of the end of rolling. The first two strips were rolled according to schedule TI, the second two strips were rolled with a gradual acceleration and the fifth strip was rolled according to the schedule, when temperature of the end of rolling increased from the beginning of the strip to the end from 850 to 920℃. The residual two strips were rolled in a similar way.

An increase in temperature of the end of rolling is achieved by increasing the acceleration of the strip in the finishing stands by 4 times.

Changes in temperature and speed along length were fixed with the metal monitoring system at the hot rolling shop. Using the data of the metal monitoring system, we designed the curves of changes in temperature of the end of rolling, coiling temperature and rolling speed along strip length (trend lines). The trend lines showed actual rolling schedules.

A decrease in rolling time due to rolling with the reverse temperature wedge was assessed by conditional performance calculated as the ratio between coil weights to rolling time. A potential decrease in rolling time was proposed to be assessed for coils of the same weight. However, weight of the coils rolled according to schedules TI3 and LGTU3 is different; therefore, we could not assess the rolling time reduction by a side-by-side comparison.

The increase in conditional performance, when rolling coils to a strip 2.5 mm thick, was 21 %. Factoring into that weight of coils rolled by different schedules differs by 22 %, the assumed reduction of rolling time of the product mix for color coating lines will be about 5-6 %. More accurate information on the reduction of rolling time will be obtained on a more representative sampling.

It should be noted that sprayer performance is sufficient for maintain constant coiling temperature along a total length of the strip within a range of 670 ±20 ℃.

The quality control system showed no critical defects influencing the surface quality of rolled products.

Conclusions:

1. The experimental industrial rolling showed that the proposed schedules with the reverse temperature wedge LGTU3 was feasible, when rolling strips 2.5 mm thick on HSM 2000.

2. Rolling with the reverse temperature wedge contributes to reducing rolling time in finishing stands by 5-6 %, when rolling strips 2.5 mm thick.

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DEVELOPING ASYMMETRIC ROLLING PROCESS PROCEDURES FOR ALUMINUM NARROW STRIPS, SHOWING HIGHER STRENGTH AND DUCTILITY

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Following the research previously done by the team of the Laboratory of Mechanics of Gradient Nanomaterials as part of project No. 15-19-10030 of the Russian Science Foundation, two-high rolling mill 400 with individually driven work rolls, unique in Russia, was designed and manufactured for asymmetric rolling with maximum allowable rolling force 2500 kN (250 tf) and torque 2×65 kN·m, ensuring production and tests of full-scale pilot specimens from various metals and alloys. In 2022 two-high rolling mill 400 was granted a status of unique research facilities.

All regulating and control units of the rolling mill are located on the same control pulpit with a sensor panel at a safe distance from the mill. The rolling mill control system ensures real-time monitoring with a digital (quantitative) indication of the process parameters. A general view of two-high rolling mill 400 with individually driven work rolls is given in Fig. 1.

Fig. 1. General view of two-high rolling mill 400 with individually driven work rolls for asymmetric and accumulative rolling

This research is aimed at analyzing dependences of asymmetric rolling of aluminum alloys to identify rational parameters, ensuring the required gradient structure.

The analysis was carried out by the asymmetric rolling process simulation in Deform 2D/3D, Qform 2D/3D software suite. The paper describe the study on asymmetric rolling of aluminum alloy D16, whose chemical composition was proved by an energy-dispersive analysis: Si – 0.26 %; Fe – 0.39 %; Cu – 4.00 %; Mn – 0.55 %; Mg – 1.48 %; Cr – 0.018 %; Zn – 0.16 %; Ti – 0.043 %; Ni – 0.030 %; B – 0.0018 %; Al – 93.09 %.

It is shown that at optimum parameters of the asymmetric rolling process (ε = 60%; ΔV = 57%; μ = 0.4) true strain per pass is 3.8…4.8 along sheet thickness. It is found that force parameters of the asymmetric rolling process is characterized by a significant decrease (by 2.4…3.2 times) in rolling force as compared to conventional rolling at other similar conditions. The results of the computer simulation in QForm 2D/3D software suite were compared to the experimental results. We compared the following data about alloy D16: deformation force (rolling force) and view of narrow strips after rolling.

Following the studies conducted, we developed the asymmetric rolling process procedures for aluminum narrow strips with a gradient structure, showing higher strength and ductility, on unique equipment, namely two-high asymmetric rolling mill 400, at the Zhilyaev Laboratory of Mechanics of Gradient Nanomaterials. It is shown that by adjusting the ratio between work roll speeds and percentage reduction, we may influence hardness and process ductility of metallic narrow strips. The developed process procedures may be used as the guidance for a correct operation, when rolling metallic narrow strips of various applications.

The study was carried out as part of the Resolution of the Government of the Russian Federation dated April 9, 2010, No. 220 (Contract No. 075-15-2021-627 dated June 08, 2021), funded by a grant of the Russian Science Foundation (project No. 20-69-46042 dated May 20, 2020) and by the Russian Foundation for Basic Research (research project number 20-38-90097 dated September 03, 2020).

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DEFINING PROCESS PARAMETERS FOR PRODUCING ALUMINIUM ALLOY 5083 PLATES AND SHEETS IN AS-RECEIVED STATES H116 & H321

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5xxx series aluminium alloys with magnesium added as the main alloying component is a good alternative to steel due to high strength and good weldability. Thus, they are widely used in automobile and shipbuilding industries. One of the factors limiting the application of the 5xxx series alloys includes their proneness to layer and intergranular corrosion (IGC) if the magnesium concentration exceeds 3% [1,2]. To make the corrosion resistance specification stricter, the following as-received states were introduced: H116 and H321.

KUMZ has conducted a study and a series of pilot tests with the purpose to streamline the production of sheets made of 5083 H116 and H321 alloys. The findings are described in this paper.

This research aimed at understanding how cold rolling and heat treatment regimes affect the mechanical and corrosion properties of aluminium alloy 5083 in production. It also aimed at streamlining the production of sheets using 5083 H116 and H321 alloys.

At the initial testing stage, sheets were rolled in a Siemag mill at different deformation degrees to determine the required degree of work hardening. Using the obtained data, an optimum deformation degree was determined that would translate into the required mechanical properties of the as-received state H116/H321.

Homogenizing annealing of the specimens was combined with heating of ingots to be followed by hot rolling. The metal temperature before hot rolling was 480^0C. After that, the material was fed into the roughing and finishing stands of a Danieli hot mill and a 7 mm thick coil was produced. The subsequent cold rolling process included a few passes with two intermediate annealing stages. Before intermediate annealing, the material was subjected to different degrees of cold rolling deformation, while the same regime of intermediate annealing was applied. Fig. 1 shows how the mechanical properties would change at different processing stages: 1 – after the hot rolling to the thickness of 7 mm; 2 – after cold forming (high degree of deformation); 3 – after intermediate annealing; 4 – after cold forming (medium degree of deformation); 5 – after intermediate annealing; 6 – after cold forming (low degree of deformation). It is obvious that the conventional yield strength is more sensitive to the process applied.

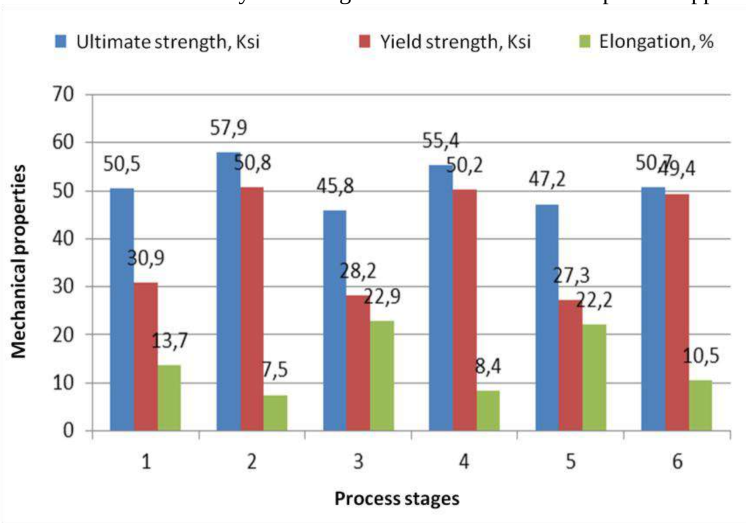

Fig. 1. Mechanical properties changing at different process stages

It can be noted that the mechanical performance resulting from stage 6 processing fully complies with the standard [2].

The authors measured the IGC rate and it was found that the rate may vary in the range of 4 to 15 mg/cm^2, with the standard specifying the limit of 15 mg/cm^2. The material approaches the above limit in an as-hot-rolled state and after the first cold rolling pass. The IGC indicator was observed to rise as the degree of cold deformation increased. It means that, in order to achieve the desired IGC level, lower deformation degrees should be maintained after intermediate annealing. A 3.2 mm thick sheet after final cold deformation meets the standard [2] in terms of corrosion performance.

This research helped define a reliable process for producing aluminium alloy 5083 plates and sheets in the as-received states H321 and H116 with the thicknesses of 3 to 8 mm and the required mechanical and corrosion performance.

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PIPE WALL THINNING IN A MULTI-STAND PIPE MILL AND AN OPTIMIZATION PLAN

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The pipe rolling process implemented on Pipe Mill 159-426 involves a pipe sizing operation, which is performed in a extracting and sizing mill. The latter is responsible for the final forming stage, but also for taking the pipe off the mandrel. When the pipe is taken off the mandrel, longitudinal tension arises, which can affect the pipe precision and in particular the longitudinal and transverse wall thickness [1,2]. It can especially impact the thickness of the stalk tail. As the stalk comes out of the seventh stand, it remains in contact with the mandrel for some time, while the extracting and sizing mill produces a tensile force leading to local thinning. This defect accounts for 8 % of the total pipe output that gets rejected. That is why looking for new solutions for minimizing the local thinning length is currently a relevant problem.

It takes specially calibrated rolls of the first stand of the extracting and sizing mill, as well as certain speed regimes of the mills to create the necessary pulling force. As the calibration parameters are non-adjustable, it is only by adjusting the roll RPM or changing the dimensions of the multi-stand pipe mill (MPM) mandrel that one can quickly control the joint operation of the MPM and extracting and sizing mill. Therefore, the optimization of the current pipe rolling process on Pipe Mill 159-426 is linked to finding the optimum roll RPM for the last stands of the MPM and for the first stands of the extracting and sizing mill. Besides, the geometry of the mandrel is also important for changing the take-off conditions.

The authors used computer modelling and data analysis to determine the optimum shape of the MPM mandrel.

The second stage of research involved physical modelling of the pipe rolling process. For conducting the experiment, a scheme was developed and tools prepared that enabled continuous stretch rolling of pipes [3].

Based on the conducted study, an optimum length of the mandrel groove and an optimum roll RPM were defined. Four pipe rolling regimes were selected for pilot production of pipes.

This research resulted in a positive outcome. No steel was wasted in connection with this research. The conducted pipe thickness measurements prove the efficiency of the above process and its optimization potential.

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THE PROBLEM OF DEVELOPING DIGITAL TWINS IN METALLURGY

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The relevance of this research subject is supported by the fact that the steel industry is in need of a new approach to real-time process monitoring and control for the possibility to adjust the process in a timely manner and produce high-quality products. Such need is drawing attention at the potential offered by digital twins, which will enable to not only monitor the processes at different levels but to also build predictive models with the help of acquired data and machine learning.

Experts estimate that the global digital twin market is likely to grow by 40 % on average in the nearest future and that this technology is no. 2 among technologies ensuring economic development and leadership.

Digital twins will enable to: carry out research work in order to find optimum process parameters ensuring product quality optimization and rejection rate minimization; predict the outcomes of the selected production process; perform real-time monitoring and streamline personnel training.

A few types of digital twins are distinguished. In this report, we shall give the following classification: Digital Twin Prototype (DTP) contains specification of the product and the relevant production process and demonstrates various scenarios of how the real object can function; Digital Twin Instance (DTI) represents *twins* of real objects, which remain connected to them throughout their life cycle; they usually contain instrument data, history data, predicted states, etc.; Digital Twin Aggregate (DTA) stands for a few DTIs combined, with a single control centre.

In terms of infoware as a part of the digital twin problem, scientific research and the search for practical solutions are carried out in at least three different areas: 1) developing new visualization forms and tools; 2) designing models and developing process status monitoring techniques by means of digital twins on the basis of BigData and predictive analytics; 3) developing methods for building different types of digital twins for the steel industry.

Recently, we have developed a DTP twin of a wire-rod mill. By further expanding the functionality of the digital twin, we will be able to implement a DTI twin, which will receive data from the instruments in real time.

UNDERSTANDING THE PLASTICITY OF MATERIALS AT NEGATIVE STRESS STATE VALUES: TECHNIQUE AND EQUIPMENT

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The processes of piercing, rolling, reducing, drawing and pressing involved in the pipe production may lead to metal fractures in the form of surface cracks and through tears. Pipes that have such defects are normally rejected. That is why it is important to assess the fracture probability when developing pipe production processes.

The phenomenological theory of metal and alloy fracture under forming conditions proposed by V.L. Kolmogorov [1] can be used to analyze the fracture probability. In order to use this theory, one should build an experimental plasticity graph - i.e. determine the ultimate strain Λ_p accumulated by the metal by the moment it fractured – based on the thermomechanical parameters of the deformation process.

Today, researchers have good tools at their disposal to build cold plasticity graphs [2]. In any case, as the practice shows, the plasticity of metal Λ_p only depends on the stress state. Plasticity graphs can be built with the help of a testing machine that is capable of creating tension combined with torsion in high-pressure fluid [3]. However, such machine fails to help with metal and alloy plasticity studies in the case of hot forming.

One may assume that the nature of the plasticity-stress state relationship that is true for cold testing conditions is also applicable to hot forming. In this case, one needs to determine two empirical factors for different loading conditions in order to build the plasticity-stress state relationship. For example, this can be done with the help of the multifunctional testing machine Gleeble 3800 [4], which enables to carry out tension, compression and torsion tests at high temperatures. However, no fracture was reached in the course of experiments during upsetting at hot metal forming temperatures (i.e. 900ºC to 1,250 ºC). Hence, Gleeble 3800 only helps determine the plasticity of metals and alloys when the stress state parameter changes in the positive region.

To expand the region of stress state measurements, the authors suggest introducing compression-torsion tests, which is quite feasible [5]. For this purpose, a testing machine was designed that is capable of creating compression combined with torsion at hot metal forming temperatures.

As this technique enables to determine the plasticity of metals and alloys at hot metal forming temperatures in the negative region of the plasticity graph, it will help optimize the utilization of hot metal forming equipment.

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DEFORMATION BEHAVIOUR OF CORROSION-RESISTANT NITROGEN-CONTAINING STEEL UNDER HOT DEFORMATION CONDITIONS

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In the context of the rapidly changing situation in the Russian metallurgical industry, the development of technologies for smelting, casting, forming and heat treatment of steel aimed at import substitution is of relevance. One of such steel grades, which are widely used in various industries, and in particular in the underwater extraction of hydrocarbons, is the STABALLOY AG17 steel [1], the chemical composition of which is presented in Table 1.

Table 1. Chemical composition of STABALLOY AG17 steel, wt. % (max.)

C	Mn	Si	P	S	Cr	Mo	Ni	N
0.05	20.0-21.5	0.60	0.025	0.010	17.0-18.5	1.5-2.5	3.0-4.5	0.40-0.55

Due to its physical and mechanical properties (such as tensile strength, corrosion resistance, magnetic permeability) that allow structures to resist a combination of external negative effects (hydrogen sulfide corrosion, marine corrosion, abrasive effects, low temperatures) [2-4], this steel grade has found its application in the manufacture of heavy drill pipes for underwater hydrocarbon production systems.

In order to assess how susceptible the material is to fracture during hot rolling or stamping, a series of tests was carried out for deformation induced cracking. The tests were carried out on a simulator of thermomechanical processes Gleeble-3800, in the temperature range of 850-1,250 °C with 50 °C increments. The deformation rate applied was 10 s^{-1}. At each test temperature, the deformation degree of the sample would increase discretely in 0.1 increments. A critical deformation degree was recorded at which the first cracks appeared, as well as a deformation degree corresponding to the formation of multiple cracks.

The data obtained were processed and systematized and the results obtained are presented in Fig. 1.

In the temperature range of 850 to 1,000 °C, the material is characterized by relatively low plasticity. The first cracks appear when the deformation rate has reached 0.2-0.25, and the growth of the deformation rate to 0.33-0.37 leads to the appearance of numerous cracks.

In the test temperature range of 1,050 to 1,100 °C, the plasticity of the material slightly increases. The first cracks form once the deformation rate has reached 0.45-0.48. In the temperature range of 1,150 to 1,250 °C, no cracks were observed up to a maximum deformation rate of 0.6. Additional tests are required to clarify the magnitude of critical deformation in this high-temperature range, which is probably the optimal *window* of possible hot deformation modes applicable to the material in view.

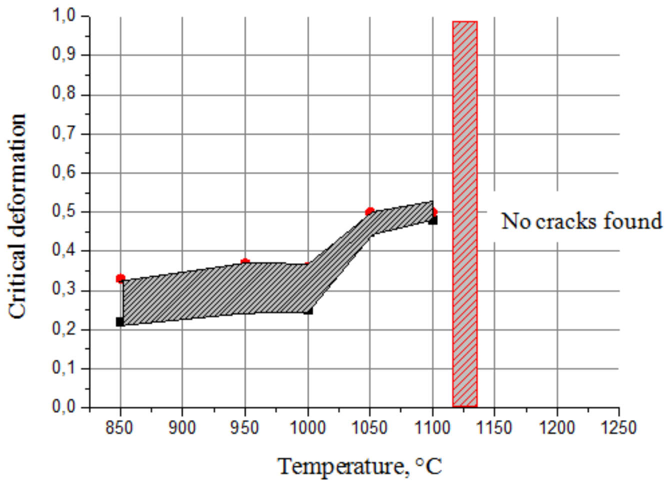

Fig. 1. Critical deformation before fracture

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DISCRETE BREATHERS IN METALS AND THEIR EFFECT ON THE PHYSICAL AND MECHANICAL PROPERTIES

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In the works of theorists, it was shown that nonlinear lattices can support spatially localized vibrational modes called discrete breathers (DBs) or intrinsic localized modes. DB is a spatially localized nonlinear vibrational mode of large amplitude in a defect-free lattice. DBs have been extensively studied over the past three decades, which is reflected in several review articles. The existence of DBs in crystal lattices have been confirmed experimentally and in a number of molecular dynamics as well as in some first-principles simulations. It is interesting how DBs affect the macroscopic properties of crystals. Probably the first systematic discussion of this issue was by Manley based on experimental results available at that time. Simulation results obtained for nonlinear chains also confirmed that DBs reduce thermal conductivity by scattering phonons, affect heat capacity, thermal expansion and elastic constants. In this talk the effect of DBs on macroscopic properties of metals is discussed.

STUDY OF INTERLAYER BOUNDARY FORMATION

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Modern metallurgical industry is looking at creating new clad metal composites (CMC), including functional composites, and enhancing their performance. Due to the ability of combining different properties in one part, CMCs are used in automotive, aircraft, space, chemical, energy, shipbuilding, oil industries and in many other industries. This advantage saves expensive materials and helps improve the reliability and performance of structures and equipment.

In this research work, the role of surface roughness in the interlayer boundary formation during manufacturing of clad metal composites was analyzed. One of the key aspects in the formation of strong bonds is to ensure a bigger contact area between materials, which will subsequently improve adhesion [1]. As the result of mathematical and computer simulations, which were described in [2], the dependence of the actual contact length l/L between dissimilar materials on R_z/S ratio and semi-angle of the ridge vertex was obtained (Fig. 1). It is important to take into account not only the arithmetical mean roughness R_a or ten-point mean roughness R_z, but also the R_z/S ratio (or semi-angle of the ridge vertex γ), because this relationship can affect the actual contact length of the materials. As can be seen in Fig. 1, the relative contact length increases as the semi-angle of the ridge vertex γ increases and the R_z/S ratio decreases. The resulting curve is well described by the following logarithmic dependence: $l/L=0{,}1946\cdot\ln(\gamma)-0{,}1674$.

To verify the proposed mathematical model of interlayer boundary formation, the process of joint plastic deformation of dissimilar materials was simulated using the finite element method in the Deform-2D program. For comparison, three problems with different semi-angles of the ridge vertex of the harder material γ were set: 30°, 45°, and 60°. A perfectly plastic medium was taken as a model for the softer material. As can be seen from Fig. 1, the error of the actual contact length calculated *via* FEM and mathematical simulation does not exceed 5 %, which indicates that the obtained results can be considered adequate.

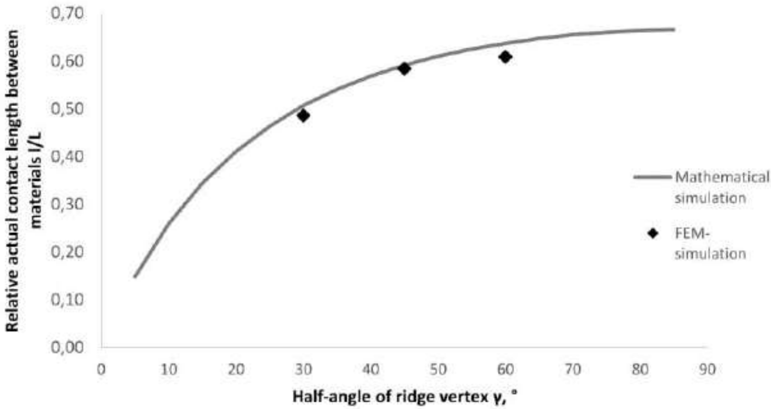

Fig. 1. Relationship between the actual contact between dissimilar materials and the semi-angle of the ridge vertex γ

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STATISTICAL MODELS FOR EVALUATING THE QUALITY OF THE COLD-DRAWN STEEL SURFACE DURING DRAWING

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Cold-drawn steel with controlled surface roughness parameters is in a high demand on the mechanical engineering market thanks to its high performance characteristics [1]. A main process, determining the cold-drawn steel surface quality, is single-pass drawing with small reductions (sizing) of hot rolled products after scale removal by chemical or mechanical methods [2, 3].

Achieving the set values of cold-drawn steel surface roughness parameters is a comprehensive task, including preparation of the bar surface and finishing of a tool, setting of deformation schedules and selection of lubricants [4-6].

A rather grounded approach to a qualitative evaluation of the steel surface quality during drawing is provided by statistical methods.

To carry out statistical analysis and evaluate changes in the surface roughness parameters during steel sizing, we selected the following factors (Table 1): diameter of hot rolled products d_0 and diameter of cold-drawn steel after drawing d_1; surface roughness of hot rolled products Ra_0; ultimate tensile strength of hot rolled products σ_{B0} and cold-drawn steel after drawing σ_B; working hole angle α and bearing length of die $l_{кп}$.

Table 1. Range of the process factors

Factor	Values
Diameter of hot rolled products d_0, mm	8-32
Diameter of cold-drawn steel d_1, mm	7-30
Surface roughness of hot rolled products Ra_0, μm	4-8
Ultimate tensile strength of hot rolled products σ_{B0}, MPa	412-930
Ultimate tensile strength of cold-drawn steel σ_B, MPa	540-990
Working die hole angle α,°	12-26
Bearing length of die $l_{кп}$, mm	2-6

A response function was a height parameter of surface roughness after drawing Ra, measured in longitudinal and cross directions.

Mathcad Professional was used to get multiple regression equations, describing the behavior of cold-drawn steel surface roughness.

The statistical model, developed as a result of data processing, describes changes in the height parameter of roughness *Ra* of cold-drawn steel in a longitudinal direction depending on the sizing process factors and parameters of original hot rolled bars:

$$\frac{Ra_{np}}{Ra_{0np}} = 1.63 - 1.27\frac{d_0}{d_1} + 0.28\frac{\sigma_B}{\sigma_{B0}} - 0.01\alpha - 0.23\frac{l_{кп}}{d_1} \quad (1)$$

The analysis of the regression coefficients showed that the biggest influence on the change in surface roughness Ra of cold-drawn steel after drawing in a longitudinal direction was attributed to criteria α and d_0/d_1, and the next ones, according to the significance level, criteria σ_B/σ_{B0} and $l_{кп}/d_1$.

The same method was used to develop a statistical model, describing changes in roughness *Ra* of cold-drawn steel after drawing in a cross direction:

$$\frac{Ra_{non}}{Ra_{0non}} = 4.11 - 2.41\frac{d_0}{d_1} + 0.23\frac{\sigma_B}{\sigma_{B0}} - 0.058\alpha - 0.98\frac{l_{кп}}{d_1} \quad (2)$$

To evaluate the quality of the models, we analyzed a system of indicators, characterizing their adequacy and accuracy. Adequacy was tested by analyzing a residual component. According to the Durbin-Watson criterion, the residuals are not autocorrelated. Using a histogram of residuals with overlaid normal density and a graph of residuals on normal probability paper, it was found that the distribution of the residual component corresponds to normal law with zero mathematical expectation. Model accuracy was estimated by the value of the error of prediction. Mean Absolute Percentage Error (MAPE) showed that the error of prediction did not exceed $|\delta|=18.83$ % ($|\delta|\leq 25.00$ %), indicating good accuracy of the models.

The analysis of the dependences (1-2) showed that during sizing surface roughness *Ra* in a cross section changes less as compared to a longitudinal one. Die angle and the deformation degree produce a higher effect on the cross microprofile of the surface than on a longitudinal one. Criterion σ_B/σ_{B0}, characterizing steel hardening during sizing, has the same effect on changes in the surface roughness parameters in both longitudinal and cross sections.

The above statistical models are used to determine efficient schedules of the sizing process, contributing to achievement of the required level of the surface quality finished products.

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STRUCTURE FORMATION BY THERMOMECHANICAL TREATMENT OF PIPE PRODUCTS OF K60 STRENGTH GRADE

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An increasing skelp production volume causes a need for forecasting consumer properties of products, factoring into a selected production schedule. As part of developing a set of solutions on this issue, LLC RTC Ausferr, Ural Federal University and Nosov Magnitogorsk State Technical University studied a microstructure and crystallographic texture of the samples manufactured in several experimental schedules of controlled rolling with accelerated cooling. The difference between the schedules lay in finishing temperature of rolling (Tfinish, 740-910 ºC) and the rate of accelerated cooling (AC), achieved by different speeds of movement of the workpieces in the accelerated cooling unit (1-1.9 m/s). Materials were samples of steel grade 06G2MB (strength grade K60), taken from one heat. The samples were studied using optical metallography and orientation imaging microscopy (EBSD).

The study showed that all the samples contained mainly bainite with added tempered martensite at a depth of $< \sim 3$ mm. At Tfinish ≥ 890 ºC there seems to be partial recrystallization in a section between the end of rolling and entry of the workpieces into the accelerated cooling unit. Decreasing accelerated cooling speed from 1.9 m/s to 1 m/s results in an increasing degree of dispersion by 5 % or so. After the schedule with Tfinish ≤ 760 ºC, the samples included long areas with a texture of rolling FCC metals.

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ACTIVITIES OF THE LABORATORY OF THE EURASIAN RESEARCH AND EDUCATION CENTER "METALS AND ALLOYS IN EXTREME CONDITIONS"

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The report discusses the core fields of activities of the youth laboratory of the Eurasian Research and Education Center (REC) "Metals and Alloys in Extreme Conditions" to find potential prospects for joint research and development. The laboratory was established in 2021 and became one of six laboratories established as part of the Eurasian Research and Education Center and one of a hundred ones established as part of all 15 Research and Education Centers of the Russian Federation. The studies carried out at the laboratory are aimed at experimental and theoretical studies on the effect of various high-intensity treatments on the structure and properties of metallic materials to find ways to prolong their lifetime, or intentionally improve their mechanical and performance properties. The activities are undertaken in three areas, namely, experimental studies on the structure and properties of metals and alloys underwent severe deformation, development of methods of application and architecture of functional coatings designed to be exposed to extreme conditions, and simulation of the behavior of crystal lattices of metals and alloys under conditions far from equilibrium.

More specific challenges solved at the laboratory include such areas as optimization of a set of performance properties of copper and aluminum conductors, while maintaining high electrical conductivity properties; study on the effect of grain boundary segregations on mechanical and performance properties of nanometals. The area of studies on functional coatings includes such challenges as developing new approaches and science of the duplex modification of the surface of tool materials; identifying the regularities of formation of performance layers with improved mechanical properties in the surface of tool materials and improving the existing technology of the duplex modification of the surface of metal cutting tools to improve their lifetime. Study on nonlinear dynamics of the crystal lattice of metals and alloys under severe external influences by methods of atomistic and mesoscopic simulation and adaptation of methods of machine learning to analyze dynamic, spatially-localized states in crystal lattices of metals are the main fields in the cluster of challenges solved by the simulation methods.

The report will contain main outcomes, research potential and core fields of potential collaboration.

The research was funded by the Ministry of Science and Higher Education of the Russian Federation as part of the state assignment of Ufa State Aviation Technical University (Agreement No. 075-03-2022-318/1-the youth research laboratory of the research and education center "Metals and Alloys in Extreme Conditions").

INNOVATIVE APPROACHES TO USING ALUMINUM WASTE

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A wide use of aluminum alloys in various sectors of industry in the Republic of Belarus entails generation of their waste, such as cutting waste and slags. Growing prices for utilities make conventional aluminum slag smelting unattractive due to low economic efficiency. Therefore, to ensure competitiveness of secondary alloys produced from aluminum scrap and waste, there is a need for comprehensive aluminum waste processing, applying modern and high-end technologies, while complying with all environmental requirements.

As a rule, the existing technologies of smelting aluminum scrap and slags involve the use of a significant amount of covering fluxes during melting, leading to an increase in the metallurgical yield of the metal melt and the formation of secondary slags, requiring further processing or disposal. Processing of low-grade aluminum slags, containing 10% of aluminum or less, is unprofitable. Such slags should be disposed as waste of hazard class 4, including payment of an environmental tax of 71.91 RUB/t. Over the past decade the environmental tax rate has increased by 5 times.

The staff of the BNTU Department of Metallurgy of Ferrous and Non-Ferrous Alloys and the staff of LLC Research and Production Firm Metallon have developed and introduced a waste-free technology of processing aluminum waste, slag and waste of grade 4 class G in a short-flame rotary furnace (SFRF), including production of reducing agents in ingots, pyramids and “dry” pellets, as well as the deoxidizing mixture (ARS) and thinning agents of refinery slags for steel ladle treatment. Balance heats showed that weight of used melting products (melt + slag + dust) was over 95% of charge weight. Thus, this technology is attributed to the waste-free category. Within a decade, the deoxidizing mixture produced by LLC RPF Metallon is supplied to metallurgical plants and iron and steel works in Belarus, Moldova and Russia. ARS is characterized by almost complete absence of chloride salts in its composition. Such composition is provided by flux-free melting of aluminum waste in SFRF. This decision was taken subject to the fact that initial aluminum slag still contained residual fluxes, which were enough to damage the oxide film on aluminum globules, including by furnace rotation. Such melting contributes to removing almost all chloride salts from final slag. It should be noted that in this type of melting dust from a cyclone mainly consists of aluminum oxides of various forms with the total concentration of about 75%, spinels containing aluminum oxides (about 12%) and 12% of pure aluminum, and only 1.4% of chlorine-containing compounds, which is 2.5 times lower as compared to melting with covering fluxes.

The analysis of the generated slag chemical composition showed that residual content of aluminum globules were 9–11 %, and a main component was Al_2O_3, whose share varied within 69–74 %. Oxides of magnesium, silicon, iron and alkali metals are found to a lesser extent.

The most suitable raw material for producing thinning agents of refinery slags is dump aluminum slags after long-term outdoor storage. Such storage contributes to partial oxidation of residual aluminum to Al_2O_3 and washing out of salt components of the flux.

To carry out studies, we took waste of processing secondary aluminum stored outdoors at LLC RPF Metallon. The samples taken from various levels were analyzed and showed that Al_2O_3 average content was 80.4% in the fraction size of 3 mm or less. To conduct industrial tests, an experimental lot of thinning agents were produced as pellets based on waste of processing secondary aluminum and added 40% of CaO and a binding agent. The pellets were pressed with rolls. Adding 250 kg of the pellets on the surface of refinery slag in a 100 ton steel ladle ensured a considerable dilution of slag and a higher sulfur distribution coefficient, showing better desulfurizing ability of slag. The studies showed that fluorspar (CaF_2) was to be excluded from the composition of refinery slag, as it negatively influenced the lining in the slag zone and a gas concentration in the operating area of the ladle furnace.

Thus, secondary slag and dust formed during flux-free melting of aluminum waste in SFRF are suitable components for the deoxidizing mixture (ARS) or thinning agents of refinery slags. This technology promotes economic, environmental and social effects. In this case, when wastes from a production division are raw materials for another one, an idea of Academician I.P. Bardin is totally implemented.

FORMING A SET OF PROPERTIES OF HIGHER STRENGTH FASTENERS FOR THE AUTOMOTIVE INDUSTRY

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In 2021 a group of the MMK companies and Bardin Central Research and Development Institute of Ferrous Metallurgy started research on high strength fasteners for needs of the automotive industry. One of the objectives of the research is producing fasteners of higher strength grades: 10.9, 12.9, and 14.9. To manufacture and test bolts, contacts have been established with manufacturing plants, such as PJSC KAMAZ and OJSC MAZ.

As the automotive industry is characterized by setting higher requirements for the quality, reliability and long lifetime of all the components used, new steel grades with additional alloying elements, 32CrB4, 36MnB4, 42CrMo4, and 40KhN2MA, were developed and melted to produce bolts. These materials should ensure strength and ductile properties of finished products, and be suitable for a deformation process, as bolts are manufactured on multi-position heading machines [1].

As part of the research, we manufactured wheel bolts M22x85 for PJSC KAMAZ. Bolts were manufactured according to the following technology:

- annealing of hot rolled products,
- preparing the surface of the rolled products,
- manufacturing gauged bars,
- stamping bolt blanks and rolling a thread on them,
- heat treatment of finished products,
- applying a coating.

All operations were supported with process design calculations, analyses of operations, studying of Russian and foreign theoretical information to prepare recommendations for further improvement in manufacturing fasteners for needs of the automotive industry.

When holding discussions with PJSC KAMAZ, it became clear that one of the most critical parameters for fasteners used in the automotive industry was fatigue limit of the fastener determined during cyclic tests. Having analyzed foreign papers [2, 3], we proposed to manufacture bolts with thread rolling after heat treatment (quenching and tempering) to increase the parameter. As part of a preliminary study on the issue, we conducted a computer simulation of the thread rolling process in QForm software suite. The analysis of the simulation results showed that there were compressive stresses formed in bottoms of the thread, and during the deformation stresses were changed in cycles, positively influencing the nature of the stress and strain state of the bolt. When using common practice of thread rolling before heat treatment, stresses along the bolt section are relieved as a result of tempering.

Besides, during thread rolling grains are extended in the thread base. A combination of factors does not favor a mechanism of crack formation and increases fatigue limit.

Thus, as a result of the research, the following measures have been taken:

- producing wheel bolts M22x85 for PJSC KAMAZ from new steel grade 42CrMo4 characterized by higher strength characteristics and maintained ductility properties,

- mastering heat treatment schedules for bolts to achieve a set of mechanical properties,

- simulating a thread rolling process, and analyzing the stress and strain state,

- making a conclusion regarding a need for forming properties of bolts not only by heat treatment, but also by plastic deformation (thread rolling after heat treatment).

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DEVELOPING TECHNOLOGIES OF STAMPING WHEEL BOLTS FROM ALLOYED STEELS FOR KAMAZ AND MAZ TRUCKS

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An annual production growth of motor vehicles of various applications entails a growing need for fasteners for the automotive industry both at original assembly plants (PJSC KAMAZ, MAZ, AVTOVAZ and others) and on automotive aftermarkets.

Automotive, machine building and other sectors of the industry widely use bolt joints of strength grade 8.8 and higher as high strength fasteners. Advantages of using high strength fasteners:

– they withstand load by 2-3 times higher as compared to strength grade 4.8,

– it is convenient to use fasteners of a smaller size at the same loads,

– metal consumption for fasteners is lower and, consequently, the price decreases to 15-25% [1].

As part of import substitution, in 2021 OJSC MMK-METIZ supported by the Ministry of Industry and Trade of the Russian Federation started to put into production higher strength fasteners for the automotive industry.

To gain this share of the metalware market, we have developed a program, including:

- studying a market of fasteners for KAMAZ trucks (namely, wheel fasteners),

- conducting research on some types of fasteners to determine final properties, steel grade, type and quality of the coating,

- developing the manufacturing technology at OJSC MMK-METIZ to produce pilot batches of finished products.

This paper describes a process of learning how to produce fasteners for the automotive industry, beginning from the development of the technology and ending with manufacturing of finished products.

Development of the production technology for wheel bolts M22x1.5x85 and special bolts M16x1.5x135 was supported with 3D models of blanks for bolts and tools for operations in Kompas 3D software to carry out the computer simulation in QFORM 3D software suite. Manufacturing technologies for bolts (Fig. 1), (Fig. 2) were developed subject to the simulation performed.

Having analyzed the research paper [2], we selected new steel grades alloyed with additional elements: 42CrMo4, 40KhN2MA to achieve the required properties of finished products. These steel grades improve manufacturability of fasteners of strength grade 10, 10.9, 12 and 12.9.

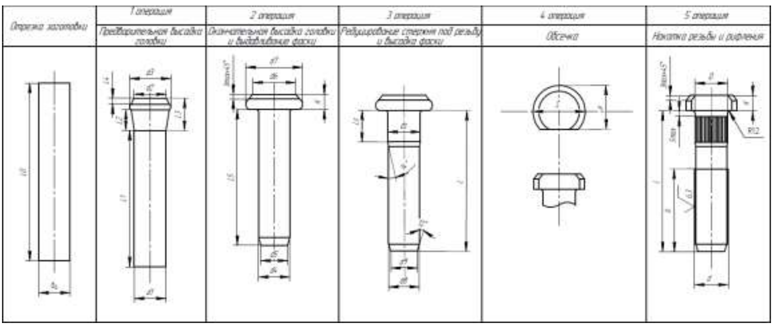

Fig. 1. Operations of stamping threaded wheel bolt M22

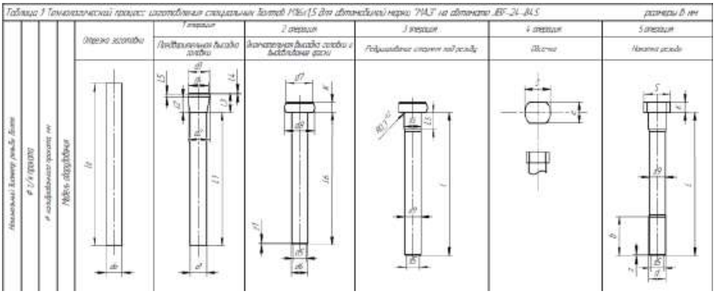

Fig. 2. Operations of stamping special bolt M16

Based on the research outcomes, the plant manufactured threaded wheel bolts M22x1.5x85 of strength class 12.9 for KAMAZ trucks (Fig. 3), and special bolts M16x1.5x135 of strength class 10.9 for MAZ trucks (Fig. 4).

Fig. 3. Wheel bolt M22x1.5x85 for KAMAZ trucks

Fig. 4. Special bolt M16x1.5x135 for MAZ trucks

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Content

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