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# MAGNITOGORSK ROLLING PRACTICE 2023

Proceedings of the VII International Youth Scientific
and Technical Conference

Edited by A.G. Korchunov

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# OUTCOMES OF THE «MAGNITOGORSK ROLLING PRACTICE 2023»

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This volume contains proceedings of the VII International Youth Scientific and Technical Conference ***Magnitogorsk Rolling Practice 2023***, which took place on May 30$^{st}$ through June 3$^{th}$ 2023 at Nosov Magnitogorsk State Technical University.

This year's Youth Conference devoted to the problems of metal and alloy forming gathered participants representing universities, research institutes, production companies and innovation firms from Russia, Belarus and Kazakhstan. The Conference programme encompassed reports by famous researchers, subject sections, a seminar on QForm, a presentation of the asymmetric rolling and incremental forging complex owned by the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory, a tour around the Magnitogorsk Iron & Steel Works and MMK-METIZ, a visit to the Magnetism Park and to the Metallurg-Magnitogorsk Ski Centre.

After the participants had presented their reports, nominees and prize winners were determined. Thus, Elmira Abdrakhmanova (Ufa University of Science and Technology, Ufa), Egor Melikhov (Nosov Magnitogorsk State Technical University, Magnitogorsk) and Nikolay Utkin (Rudny Industrial Institute, Rudny, Kazakhstan) were recognized in the Novice Researcher category.

Yulia Zamaraeva from Kamensk-Uralsky Metallurgical Works was recognized for Best Modelling.

Elena Korzunova (Mikheev Institute of Metal Physics, Ural Branch of the Russian Academy of Sciences, Yekaterinburg) and Arseny Kazakov (Ufa University of Science and Technology, Ufa) were recognized for Best Theoretical Study.

Kirill Tsydenov (University of Science and Technology MISIS, Moscow) was recognized for Best Innovation.

Fedor Stolyarov (Nosov Magnitogorsk State Technical University, Magnitogorsk) was recognized for Best Implementation.

Denis Brayko (Bauman Moscow State Technical University, Moscow) was recognized for Best Cross-Disciplinary Solution.

Vadim Bespalov (Siberian Federal University, Krasnoyarsk) was recognized for Implementation of Priority Projects.

Mahmoud Alhaj Ali Abdulla from the University of Science and Technology MISIS in Moscow and Sergey Zakharov from TMK R&D Centre LLC in Chelyabinsk were awarded 3rd degree certificates. Dmitry Demin from HSE University in Moscow and Olesya Biryukova from Nosov Magnitogorsk State Technical University in Magnitogorsk were awarded 2nd degree certificates.

Anna Levykina from Lipetsk State Technical University in Lipetsk was recognized the winner and was awarded a 1st degree certificate.

We are looking forward to welcoming you again, at the VIII International Youth Scientific and Technical Conference «Magnitogorsk Rolling Practice»!

# SECTION 1 – Fundamental problems of metal forming in the context of current global industrial needs

UDC 669.017

## METHODS OF STUDYING THE DEFORMATION BEHAVIOR OF METAL ALLOYS DURING HOT FORMING

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Objectives of identifying the deformation behavior of materials during hot forming arise when designing metal forming processes. Recommendations on the technological processes are prepared based on forecasts of material forming produced with the computer simulation, representing a finite element solution to boundary problems of continuum mechanics. Validity of such simulation results is determined by adequacy of setting boundary conditions and a description of mechanical properties of deformable materials [1, 2].

Mechanical properties of materials subjected to plastic deformation determine their deformation behavior described by equations relating yield stress and strain rate and degree. This relation is experimentally determined by mechanical tests, when a specimen is subjected to the set strain, taking measurements of forces, acting on a deforming tool [3, 4]. A type of tests is chosen subject to special features of a production process, whose analysis will be based on the obtained data.

The paper discusses methods for interpreting the mechanical tests contributing to improved reliability of obtained information about the deformation behavior of materials. The difficulty of a conventional approach to interpreting the tests lies in lack of direct measurement of stresses. Strain and stresses are calculated by measured values of movement of deforming tools and forces, using simple ratios based on the hypothesis on a uniform deformation of the overall workpiece. When conducting actual tests, the specimen showed a non-uniform deformation mainly due to boundary effects on the contact line between the specimen and the deforming tool [5, 6]. Errors in assessing stresses resulting from neglecting such effects may achieve tens of percent. [7, 8]

Non-uniform deformation of the specimen during the test may be factored into by video recording and identifying strain by digital image processing [9]. However, if tests are conducted at higher temperatures in inert atmosphere, as during tests of superplastic materials, it is challenging to install video equipment in a testing chamber [10]. Another method is to design a computer model of the specimen deformation during the tests and apply an iteration procedure of correcting the model of the deformation behavior [7].

The paper describes methods of designing models of the deformation behavior of materials during plane strain, uniaxial and biaxial tension. The proposed iteration procedure specifies a model of deformation behavior to factor into non-uniform deformation of the specimen during tests. The proposed approach may be used to increase validity of models of mechanical properties of materials subjected to plastic deformation, applying no additional equipment.

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# DESIGNING A MODEL OF CONTROLLING THE BENDING OF THE FRONT END OF HOT ROLLED SLABS IN DEFORM

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When rolling slabs in a roughing group of stands on the continuous hot strip mill, we often see the excessive vertical bending up or down of the front end of the slabs (Fig.1), a so-called “ski” of slabs. The direction and value of such bending are determined by various rolling parameters, such as the ratio of diameters and velocities of the top and bottom rolls, the slab temperature distribution along height, etc.

At plants, such situations are likely when there is an unpredictable excessive bending of the front end of the slab. This negative experience forces operators to adjust the velocity of the work rolls so that the slab is bent mainly down to have the possibility of compensating a rare unpredictable upbending of the slab. This leads to a force contact between the slab and the bed rollers and rollers of rolling tables and, eventually, to emergency breakdowns of the rollers [1-3].

The research is aimed at designing a computer model of controlling the bending of the front end of slabs in the roughing group of stands.

Fig.1 – Excessive upbending of the front end of the slab after stand 1 on mill 2000 of PJSC NLMK (for reference)

We applied DEFORM to design a model of the rolling stand with roll diameters of 1200 mm and body length of 1000 mm. Asymmetry was set by different angular velocities of rolls. Metal elongation was higher on the bottom surface of the slab and bending in the direction of the top roll. Angular velocity of the bottom roll is higher in comparison with the top one. When metal starts elongating upwards, we change velocity of the rolls asymmetrically to the opposite direction to correct “the ski”. At the final stage of the simulation, we set similar velocity for the top and bottom rolls and run symmetric rolling (Fig. 2)

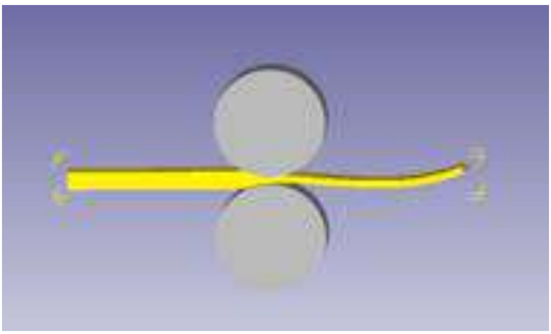

Fig. 2 – The model of asymmetric rolling in DEFORM

Thus, the designed computer model of the bending of the front end of the slab in reversing stand 1 ensured the simulated correction of "the ski" and exclusion of the emergency and strip wobbling against the rolling table.

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# HOT ROLLING OF FERROUS METALS VERSUS ALUMINIUM ALLOYS: PROCESS DIFFERENCES

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The mechanics of flat rolling of ferrous and non-ferrous metals can be described with a common set of formulas [1]. However, when it comes to real processes, one starts to notice differences between the metals in terms of their behavior and interaction with the rolls. The paper [2] describes some differences concerning the forces and power involved in the rolling of aluminium alloys. At the same time, one can distinguish other features. One of them includes sticking of metal to the rolls. In contrast to various grades of steel, this feature is typical of quite a few non-ferrous and noble metals, with copper, aluminium, gold, platinum etc. being among them.

Some papers examined the sticking process and it was established that if a rolling mill has rolls that have been reground, the friction factor appears to be minimal. When the rolls keep turning with the metal in them, the metal starts to stick up and the friction factor increases as a time function, which looks like a saturation curve. At a certain RPM value, the situation stabilizes, which would mean that the stuck metal covers the entire roll surface. When rolling aluminium, one can observe a whitish surface layer, while in the case of copper rolling it is reddish-and-yellowish. Rolling experiments carried out with lead [3] and platinum [4] show that such layer cannot be distinguished as it matches the material of the rolls. But if one measures the forward slip and correlates it with the friction coefficient, one can determine that the thickness of the stuck layer rises as the length of the rolled material increases.

The above described phenomenon results in particles stuck up to the roll surface, which eventually leave imprints on the rolled strip leading to high rejection rates. Besides, at high reduction degrees, the metal tends to slip in the forward slip zone, which results not simply in point defects but in grooves caused by stuck particles. Normally, such grooves have a certain length determined by the length of the forward slip zone [5].

When we compare the two processes, we can distinguish another differentiating factor. In ferrous metallurgy, they use water for cooling rolls during hot rolling, as there is no risk of metal sticking. At the same time, emulsion is used in hot rolling of aluminium alloys in order to prevent high adhesion. Use of emulsion increases the cost of the rolling process but makes it more steady thus ensuring the required product quality level.

In 2017, the Kamensk-Uralsky Metallurgical Works witnessed a launch of the $2^{nd}$ phase of the new rolling facility, which comprises a 2-stand hot mill by Danieli. After sanctions had been imposed on the Russian Federation, the site could not use the Quaker Houghton rolling oil any more. Alternatives were searched for, and Chinalco Lubricants from China was selected with its ZLR-115 and ZLR-230 rolling oils.

The Danieli hot mill uses the same lubricoolant system in the roughing and finishing stands. It comprises the following components:

- a 10 $m^3$ clean oil tank with heaters;
- a 30 $m^3$ mixing tank for preparing an oil water (10%) emulsion;
- a 30 $m^3$ demineralized water tank;
- a 160 $m^3$ or 130 $m^3$ clean lubricoolant tank with two pairs of belt skimmers for removing surface contamination;
- two vacuum filters and a self-cleaning flow-through filter;
- a 240 $m^3$ or 190 $m^3$ dirty lubricoolant tank with two pairs of belt skimmers.

Fresh oil is pumped into the mixing tank where it gets mixed up with hot demineralized water forming an oil water (10%) emulsion. To make up for the loss of oil and evaporated water during rolling, a certain amount of the prepared emulsion is fed into the clean oil tanks. Samples are taken on a daily basis to monitor the condition of the lubricoolant. The samples are then analyzed for concentration, ether content, ash content, acidity, conductivity, etc.

The lubricoolant system of the roughing and finishing stands also comprises a 700 $m^3$ caisson for collecting used lubricoolant. When a certain amount of used lubricoolant has accumulated in the caisson, it is pumped out for further disposal.

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## COLD SHEET STAMPING OF AUTOMOTIVE PARTS: ANALYZING THE NEED FOR PROCESS DESIGN UPGRADE

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Amid quickly changing market conditions, of acute importance is the problem of the timeframes and flexibility of designing production processes to make sure the domestic market did not experience any shortage of parts that were previously supplied from abroad.

Front suspension arms for vehicles (e.g. for LADA LARGUS) are made by cold sheet stamping. This is a suitable process in terms of cost effectiveness and performance. However, when looking at the design of cold stamping processes, one is facing a high risk of selecting the wrong changeovers or designing the wrong stamp geometry.

A few methods are distinguished today in production process design: direct design, synthesis and analysis [1].

This paper describes the direct design method, which implies developing a process chart by selecting standard design solutions from a pre-compiled well-organized database [2]. For designing cold sheet stamping processes for making automotive parts, there is no such database that would be available in open sources or would be complete. That’s why it is proposed to add data to the database to minimize production process design risks.

Fig. 1 shows a process flow chart of cold sheet stamping for making suspension arms.


Fig. 1 – Process flow chart: Cold sheet stamping of front suspension arms for LADA LARGUS vehicles

Design of changeovers and tooling is a labour-intensive process associated with risks and great financial losses in case of error. That’s why new standard solution database blocks should be developed.

One of the tools used in metal forming process design includes a finite element method. When using this method, it is very important to be accurate when presetting boundary conditions. The authors of this paper propose to introduce a boundary conditions block for the finite element modelling of cold sheet stamping processes. Such block would add to the openly available database of blocks for direct process design.

Fig. 2 shows a block diagram of boundary conditions to be preset when modelling cold sheet stamping processes [3].

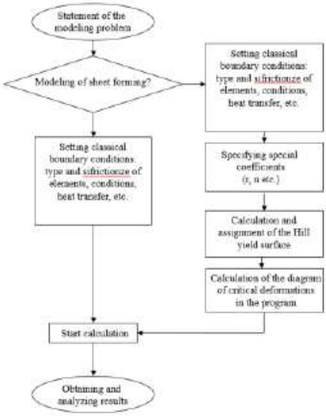


Fig. 2 – Boundary conditions block diagram

The proposed block diagram will help raise the accuracy of sheet stamping changeover modelling, which will reduce the risk of defects occurring in finished parts and, consequently, bring down the stamp upgrade cost.

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# POINT DEFECT DYNAMICS IN TUNGSTEN BCC LATTICE

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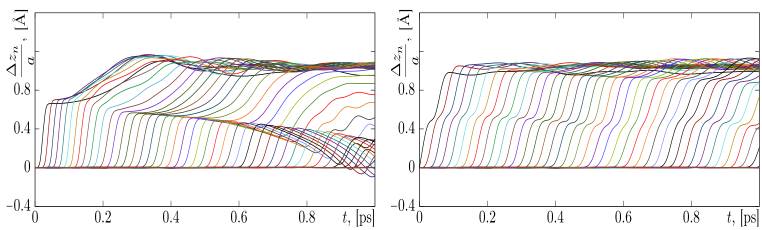
Extreme impacts, such as laser radiation, severe plastic deformation, ultrafast loading, X-ray radiation, plasma treatment, etc., cause irreversible changes in the crystal structure pushing the lattice into a non-equilibrium state. In these processes, atoms severely deviate from their equilibrium places on the lattice, and the non-linear nature of interatomic bonds start to play a significant role. Such extreme impacts lead to an abnormally high concentration of point defects referred to as Frenkel pairs (i.e. a vacancy and an interstitial).

An interstitial atom can exist in many configurations, including that of crowdion [1, 2], when it is situated in the nearest packed atomic row. Crowdions have a much higher migration capability than vacancies. Thus, the former are more efficient for mass transfer in materials. The high migration capability of crowdions leads to their quick annihilation, which makes it more difficult to analyze their structure and motion through experiments. That’s why it is a common practice to rely on computer modelling techniques. This paper relies on molecular dynamics method to examine the effect of vacancies on the crowdion dynamics in a close-packed row of the BCC lattice of tungsten. This problem is of importance in a sense that lattice defects create a stress field around them and thus impact the atomic motion in that field. The vacancy and the bivacancy realized in this case at the distance of 1 to 3 interatomic spaces from the close-packed row passed by the crowdion may also impact such parameters as run distance and speed. These problems were looked at in this study, with the simulation conducted in LAMMPS [3] and based on the multiparticle interatomic EAM potential for tungsten [4].




(a) (b)

Fig. 1 – Relative atomic displacements of atoms along which the following is spreading (a) 1-crowdion and (b) 2-crowdion, pulse excited with the starting energy of 137 eV in a perfect BCC lattice of tungsten in the <111> direction

The obtained data indicate that the dynamics of supersonic crowdions is mostly influenced by vacancies situated in the row that is nearest to the crowdion row. The energy transfer process can be slowed down due to the presence of defects near the supersonic crowdions. On the whole, one can conclude that point defects do not produce any significant effect on the defect dynamics as they fail to create long-range stresses.

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## UNDERSTANDING THE EFFECT OF PROCESS AND DIMENSIONAL PARAMETERS OF FORGING IN NEW DESIGN STEPPED V-SHAPED ANVILS ON MICROSTRUCTURE EVOLUTION

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Recently, many software products designed for metal forming process simulation have been paying a great deal of attention to the modelling capabilities related to microstructural evolution. With the help of this functionality, one can predict how a given initial grain size will change as a function of loading pattern and various process parameters. The Deform software offers two methods for microstructure simulation. The first one is the conventional Johnson-Mehl-Avrami-Kolmogorov (or, JMAK) method, while the second one is a discrete grid method realized with the help of the Cellular Automata [1] algorithm. The JMAK method is less preferred as it fails to account for the changing shape of the grain, but simply determines its average size.

It was decided to use different values of the angle formed by the wedge and the slot as varying dimensions, as one knows from the papers [2-3] that it is that factor that has a significant effect in V-shaped anvil blocks without a step. For process parameters, it was decided to use different values of the workpiece-tool friction coefficient, the speed of the upper anvil and the workpiece temperature.

It was decided that the following models should be considered:

1) With the angles of 170° and 150° (In the base model the angle is equal to 160°).

2) With the workpiece-tool friction coefficient of 0.3 (regular smooth surface) and 0.1 (polished and lubricated surface). In the base model the friction coefficient was equal to 0.7, which corresponds to an interrupted-type rough surface.

3) With the upper anvil speeds of 0.1 mm/sec and 10 mm/sec (In the base model the upper anvil speed was equal to 1 mm/sec).

4) With the workpiece heat-up temperatures of 1,000°C, 1,200°C, 900°C (In the base model the heat-up temperature was equal to 1,100°C).

The value of 60 µm was taken to be the initial grain size.

When analyzing models with different angles between the wedge and the slot, it was found that this parameter has a significant effect on the intensity of initial grain refinement. Thus, the refinement intensity rises as the angle gets smaller. For example, after two forming cycles in 170° anvils the initial 60 µm grain was reduced to the average size of 52 µm; in 160° anvils – to 46 µm; in 150° anvils – to 40 µm. The grain size level was identical crosswise and longitudinally. However, when examining the grain shape, certain grains were found to have grown longitudinally. Crosswise, the grain shape after two stages of drawing with a 90 degree turn between them remained relatively equiaxial.

When analyzing models with different friction coefficients at the workpiece/tool interface, it was found that that parameter has no effect on the grain refinement intensity. A grain refinement to the average value of 45-46 µm was registered in all the models. It was noted that a lower friction coefficient affects the stability of the workpiece in the anvils during the 2nd forming cycle after turning over, when the workpiece is reduced on the convex surface obtained after the first cycle. To make sure the workpiece is straight and level, it is recommended that the forming was carried out at high friction. That's why 0.7 appears to be the optimum friction coefficient.

Having analyzed the models with different speeds of the upper anvil, the authors found that a decrease of the base strain rate (1 mm/sec) to 0.1 mm/sec is associated with a slightly more intense grain refinement (to the level of 42-43 µm). At the same time, an increase of the strain rate up to 10 mm/sec has almost no impact on the grain size change. Having analyzed the models with different heat-up temperatures, the authors found that that parameter has no significant effect on the grain refinement intensity.

As a result, the authors determined that the following dimensions and process parameters were optimal: the angle between the wedge and the slot – 160°; workpiece/tool friction coefficient – 0.7; the upper anvil speed – 1 mm/sec; the workpiece heat-up temperature – 1,000°C.

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# DUAL-PHASE STEELS PRODUCED IN A HOT MILL USING INNOVATIVE ACCELERATED COOLING METHODS

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Every year, the use of dual-phase steels for car making is gaining more relevance because they satisfy the formability, high tensile strength, fatigue resistance and good weldability requirements. DP grades offer a unique combination of high strength and plasticity, which, in its turn, ensures a good strength-to-weight ratio. Besides, dual-phase steels are capable of absorbing 50% more energy than common steel grades, which is an important safety factor in case of accidents [1].

In order to obtain a DP steel with different concentrations of martensite (which influences the strength of the finished product), the metal should be cooled down in a controlled manner after hot rolling. An innovative approach would be a combined use of an ultrafast cooling (UFC) and laminar cooling (LC) units. The UFC unit has a wide range of cooling rates, which ensures that the solidified austenite remains in the high-temperature region at different dynamic transformation temperatures. The combined use of UFC and LC provides a flexible cooling control ensuring that the hot-rolled strip had the required properties. This process has a high potential of being adopted on a commercial scale. Such cooling section is situated between the finishing mill and the coiler (Fig.1), which helps obtain the required metal structure.

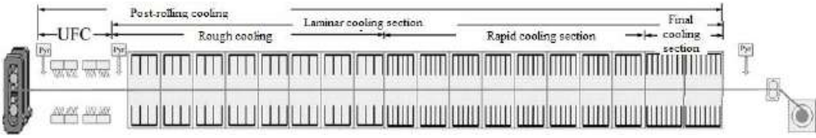


Fig. 1 – Arrangement of the cooling section after the rolling mill [2]

When producing DP steel, after rolling the strip undergoes staged cooling in the UFC+LC section and is then coiled. This process results in a moderate concentration of ferrite (approx. 70-85%), helps curb perlite and bainite, while the residual austenite is turned into martensite [3].

One can conclude that the use of UFC+LC unit enables a flexible control over cooling after rolling, which ensures the required structure and mechanical properties. The UFC+LC process is especially relevant for the production of dual-phase steels, which combine high strength and plasticity and are capable of absorbing more energy during accidents ensuring better safety. On the whole, this process has a high potential of being adopted on a commercial scale, especially by the car making industry, which needs high-strength and lightweight materials.

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## EXAMINING THE DURABILITY OF PRESS TOOLING MADE OF NOVEL MATERIALS

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Durability is a critical characteristic of press tooling determining the overall productivity and cost-effectiveness of the production process. The environment of pressing non-ferrous metals – and especially steels – is extremely harsh both in terms of temperatures and stresses created in the material. Different environments in which press tooling is used dictate different requirements to the press material, design, as well as the heat treatment regime. Drastically changing operating temperatures, regular heating to high temperatures and simultaneous loading followed by rapid cooling and impact unloading – these are the conditions that the press material should be suitable for.

This paper describes the results of a comprehensive study that looks at the standard tool material and compares it with the proposed one, examines the properties of specimens during hot upsetting with the aim to confirm the yield strength, gives an overview of known solutions and develops new ones, carries out theoretical and experimental studies of such solutions and subsequent trials. The paper also describes the results of a study that looked at the effect of heat treatment on the properties of the material.

At the same time, the authors describe an alternative technique for enhancing the durability of press tooling with the help of additive manufacturing.

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UDC 621.771.01

# DECREASED CRACK FORMATION ON SHEET PRODUCTS FROM ALLOY B-1441

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Aluminum is the most common metal in nature, its content in the Earth's crust is 7.5%, while iron is half as much [1]. Aluminum alloys are widely used in the industry. Lithium doping reduces specific gravity from 2.71 to 2.47 g/cm$^3$, while maintaining strength properties. So, when the lithium content is up to 2%, strength of aluminum alloys increases without a significant decrease in ductility; if the lithium content is higher, ductility shows a sharp decrease [2]. Such alloys are less apt to corrosion than alloy D16 and its similar alloys, whose specific gravity is 2.80 g/cm$^3$ at the same strength properties.

Alloy D16 is widely used in the aircraft industry, while alloy B-1441 is more preferable in its physical and mechanical properties. However, during hot rolling alloy B-1441 experiences the same problems with the crack formation on side edges as in D16. Therefore, there is a need to develop special modes of workpiece heating and hot rolling (HR).

Lithium alloys are deformed by hot rolling. During HR special attention is given to decreasing the crack formation of the strip edge. It is of high importance to select edging modes for hard-to-deform aluminum alloys, as rolling in edging rolls installed in a hot rolling mill complex is an efficient measure against cracking of the side edges of hot rolled strips, occurring as a result of a non-uniform metal flow and significant tensile stresses [3].

In addition to the edging of the side edges, we apply cladding of the workpiece from alloy B-1441, contributing to less crack formation during HR.

When producing coils on four-high hot rolling mill 4200 by DANIELI included in a new rolling complex of OJSC KUMZ, we tested a HR technology aimed at decreasing the edge cracking. The conditions applied for decreasing the crack formation of HR strips from alloy B-1441:

Increasing ingot discharge temperature to the top value of maximum permissible temperature in the mode; the equipment can maintain the temperature range within ±3 °C, reducing the ingot cooling.

To reduce rolling time and the rate of the metal temperature reduction during hot rolling, the number of passes is reduced. Rolled products are manufactured by maximum reduction per pass. Maximum permissible rolling force on the HR mill is 80MN. An additional increase in the edging force to 3500 kN improved the strip edge structure, having a positive effect on the quality of the side edge.

Regarding the two-pass rolling mode, the crack formation along the edge reached 15 cm along strip width on the finishing stand. An increase in the number of passes on the finishing stand is required to reduce the deformation in the passes, resulting in less crack formation of the strip edge.

Fig. 1 presents photos of HR coils from alloy B-1441 produced by the serial technology (Fig. 1, a) and after testing of the technology according to determined conditions of a less crack formation on the edges (Fig. 1, b).

a b

Fig. 1 – HR coils from alloy B-1441 produced by the serial technology (Fig. 1, a) and after testing of the technology according to determined conditions of a less crack formation on the edges (Fig. 1, b)

A set of the above factors: increased rolling temperature, increased applied forces during HR and, as a result, a decreased number of passes on the HR mill, increased reduction during edging, contributes to manufacturing products that meet the consumers' requirements with a higher yield and better performance qualities.

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UDC 538.9

# EFFECT OF SEGREGATIONS ON THE DEFORMATION OF HIGH-ENTROPY ALLOY CoCrCuFeNi

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Current technological progress sets high standards to the characteristics and properties that novel materials are expected to offer. In this sense, advanced alloys outperform conventional metals in a number of characteristics. This brings high-entropy alloys (HEAs), which are formed by mixing four or more elements, in the focus of today's research. Due to their unique characteristics, such as high specific entropy, slow diffusion and high lattice distortion [1], HEAs demonstrate better mechanical and physical properties [2] compared with conventional metals, which is in line with the demand of modern production. This paper relies on molecular dynamics method to examine the mechanism of forming a high-entropy bicrystal alloy CoCrCuFeNi at the temperatures of 100 and 300 K.

The modelling was based on the LAMMPS programme [3] and a multiparticle interatomic EAM potential [4]. The OVITO programme [5] was used for modelling results visualization.

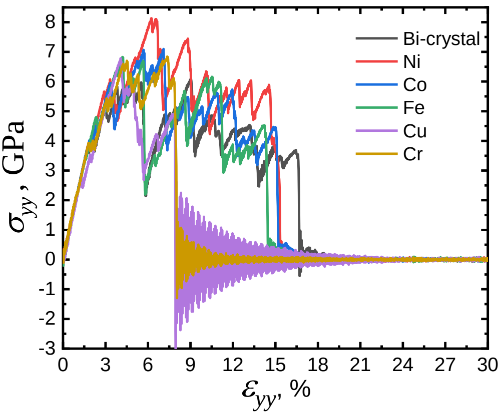


Fig. 1 – Stress-strain curves obtained as a result of tensile deformation of bicrystals. The legend specifies appropriate types of segregated elements, whereas the case with the bicrystal without segregations is indicated as *Bi-crystal*. The stress dropping to zero means fracture. The simulation temperature is equal to 300 K

As one can see from Fig. 1, the bicrystal without segregations has the highest plasticity as it does not fracture until the strain has reached 16%. Segregation of nickel, cobalt and iron brings the bicrystal plasticity down by 3-5%. Bicrystals with copper and chromium segregations demonstrate the biggest drop in plasticity as they tend to fracture once the strain has reached 8%.

The obtained results provide an important insight into the relationship between the structure and properties of HEAs while showing a potential to control the mechanical performance of HEAs by changing the thickness and type of segregations.

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## PREDICTION OF RESIDUAL STRESSES IN ROUND BARS AFTER DRAWING

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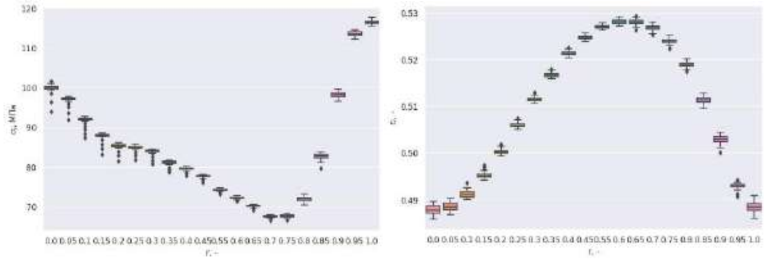
To determine the amount and nature of distributions of residual stresses, occurring in rods and wire as a result of drawing operations, researchers use both full-scale experiments [1, 2], and simulation modeling [3, 4].

To carry out a predictive analysis, preference is given to simulation modeling and analytical methods. However, recently, the methods based on neural network approaches are under active development and application for this kind of research [5, 6].

As a rule, learning of such type of algorithms requires a preliminary preparation of data sets. In view of this, this study included preliminary simulation modeling of a single-pass drawing process for steel grade AC 12 at reductions $Q = 1.5, 2.5, 5, 10, 15, 20, 25, 30$ and coefficient of proportionality of the bearing section $k = 0, 0.1, 0.3, 0.5, 0.75, 1$ and changes in angle of the deformation zone $\alpha$ within a range of 4°-20° with a step of 4°, and friction coefficients $\mu = 0.025, 0.05, 0.1$ [2,7].

To avoid problems with insufficiency of data in the learning sample, it was proposed to prepare a generator based on a statistical description of the results for the region of the sample, where the deformation process was considered to be established.

Fig.1 presents the performance results of the generator for distributions of intensity of stresses and intensity of strain.




a) b)

Fig. 1 – Distribution of values obtained as a result of operation of the generator for a) intensity of residual stresses; b) intensity of accumulated strain

The data sets generated in this way will be used for neural network learning.

The selected parameters used on the input layer are initial radius ($r_0$), nondimensionalized radius ($r$), reduction ($Q$), inclination of the deformation zone ($\alpha$), length of a bearing section ($l_k$), friction ($\mu$), parameters, describing ductile properties of the material according to the Ludwik's law [8] ($A, B, n$). The output layer contains a pair of values of intensity of residual stresses ($\sigma_i$) and accumulated strain ($\varepsilon_i$).

The neural network designed according to this scheme is tested on various test samples, including data that was not completely included in the learning sample.

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## EXPERIMENTAL STUDY ON DRAWING OF SEAMLESS PIPES WITH POWDER FILLERS

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Until recently, to weld high-strength low-alloyed steel grades, in Russia a wide use was gained by seamless welding wire, produced mainly abroad [1]. No longitudinal joint excludes the possibility of its opening and losing the filler, and also prevents the filler from watering during storage and use of wire. Now, there is a search for alternative solutions and various powder welding materials produced by Russian manufacturers are tested [2]. They are mainly represented by rolled wires with a longitudinal joint.

This research is aimed at studying the effect of compacting of powder fillers on changes in thickness of a seamless pipe wall, drawing degree, and power and force parameters of the process.

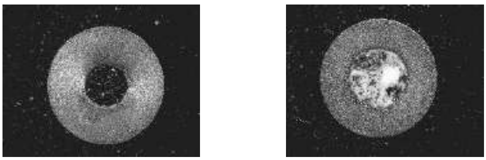
**Materials.** Cold-worked seamless pipe 6x1 mm as per GOST 8734-75 made of steel 20, subjected to recrystallization annealing at 670±10℃ and descaled. Ultimate tensile strength $\sigma_в$ is 402.0±17.1 MPa, yield strength $\sigma_{0.2}$ is 275.0±5.0 MPa, percentage elongation $\delta$ is 24.2±3.0 %. The filler of a general composition: titanium dioxide, fine-dispersed chalk, belite grade B-1, magnesium oxide, ferrochrome, metallic manganese (flakes), iron powder grade PZhRV 2.200.28, nickel (powder), aluminum (powder). The filler components were ground and dried at 350±10℃ for 3 hours, screened through a sieve with a mesh size of 200 μm and mixed in a drum mixer for 3 hours. Bulk density of the finished filler is 838 kg/m$^3$, theoretical density is 4430 kg/m$^3$. The pipes were filled manually. Initial density of the filler in the pipe was 1349±134 kg/m$^3$.

**Experiment.** Drawing in compliance with recommendations [3] was carried out in 7 passes to an outer diameter of 3 mm on the laboratory mill at 0.03 m/s. Semiangle of one-piece dies at transfers is 6°. During the experiment we measured the outer diameter of wire, drawing force and calculated the drawing rate (based on 100 mm). After every pass, we cut an end section, 20 mm long, from the samples with the filler and the test one (without the filler) for subsequent measurement of wall thickness.

Wall thickness was measured with an optical microscope. The design wall thickness was determined subject to the condition of constant volume of the steel shell. The drawing sequence, the experimental results and calculations are given in Table 1. Fig. 1 shows micrographs of the cross-section of the samples after pass no. 7.

Table 1 – Experimental results

| Pass no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Drawing sequence | 5.5 | 5.0 | 4.5 | 4.0 | 3.6 | 3.25 | 3.0 |
| Diameter (actual value), mm | 5.47 (5.47) | 5.02 (5.02) | 4.47 (4.47) | 3.99 (3.98) | 3.59 (3.59) | 3.24 (3.23) | 3.00 (2.98) |
| Drawing | 1.11 (1.09) | 1.11 (1.10) | 1.17 (1.16) | 1.21 (1.17) | 1.21 (1.16) | 1.21 (1.16) | 1.17 (1.13) |
| Wall thickness, mm: | | | | | | | |
| - design value | 1.01 (1.03) | 1.01 (1.05) | 1.00 (1.05) | 0.95 (1.05) | 0.87 (1.04) | 0.81 (1.05) | 0.75 (1.05) |
| - actual value | 0.97 (0.94) | 1.00 (0.96) | 0.97 (0.97) | 0.88 (0.95) | 0.84 (0.97) | 0.76 (0.95) | 0.72 (0.93) |
| Relative density of the filler | 0.372 | 0.444 | 0.561 | 0.648 | 0.687 | 0.730 | 0.731 |
| Drawing force, kN | 1.57 (1.45) | 1.61 (1.57) | 2.38 (2.15) | 2.45 (2.00) | 2.41 (2.10) | 1.89 (1.60) | 1.45 (1.27) |
| *Note: the values stated without brackets are given for the samples with the filler; in brackets – for a test sample without the filler* | | | | | | | |



a) b)

Fig. 1 – Cross-section of the samples after pass No. 7:
a) the test sample (without the filler); b) the sample with the filler

**Conclusions.** The experiment showed that at a relative density of 0.6 or lower, the filler had little effect on wall thickness and drawing. When relative density is 0.6 or higher, the filler acts as a mandrel, leading to a noticeable decrease in wall thickness, an increase in drawing and drawing force. The difference between actual wall thickness and the design value is explained by variations of wall thickness of the original pipe within the tolerance range.

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## PRINCIPLES OF THERMOMECHANICAL TREATMENT TO INCREASE LIFE TIME OF FERRITIC/MARTENSITIC STEEL

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Heat-resistant ferritic/martensitic steels are based on solid solutions or oversaturated solutions, capable of additional strengthening as a result of dispersion hardening. Grain structure refinement of steel contributes to improving properties of steel [1]. It should be noted that high-alloyed martensitic steels contain a high number of carbide particles and a martensitic phase, which complicate the process of forming the required steel structure by deformation methods [2]. This study shows the effect of deformation and heat treatment (TMT) on the properties influencing life time of the material, using steel 12Cr-2W (EI-961Sh) as an example.

Deformation treatment was carried out using flat rolled products and equal channel angular pressing (ECAP). Subsequent heat treatment (overhardening) leads to weakening of the effect of the deformation texture and the formation of an equiaxed structure with a uniform distribution of second phase particles along the grain boundaries and in the grain body. An additional strengthening factor was the formation of a structure containing twin boundaries.

Using such combination of deformation and subsequent heat treatment (overhardening), it was possible to increase ultimate tensile strength by 53%, up to 1380 MPa, while maintaining ductility at 17%. Such TMT increases fatigue strength by 59 % from 472 MPa after standard treatment to 750 MPa. The impact strength results showed that such TMT increased the impact strength value by 3 times compared with standard treatment and by 1.3 times compared with ECAP.

The experimental results serve as a basis for discussing principles of TMT and the effect of the structure on formed properties.

*The research was conducted as part of the project of the Russian Science Foundation, No. 22-19-00445 a.*

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UDC 621.77

## MASTERING MANUFACTURING OF FASTENERS FOR OJSC MAZ AT OJSC MMK-METIZ

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In 2022, as part of mastering manufacturing of fasteners for the automotive industry, specialists of OJSC MMK-METIZ established collaboration with OJSC MAZ, an automotive manufacturer, specializing in trucks, passenger, towed and specialty vehicles.

OJSC MAZ submitted drawings for the fasteners: bolt for fixing parts of a compensation gear M16x1.5, frame flanged nut M12x1.5, and frame flange screw M12x1.5.

These fasteners have their peculiar features of mechanical properties and geometric parameters, which are to be factored into during manufacturing. One of such features is a locking notch of the flange fasteners. OJSC MMK-METIZ has not manufactured any flange fasteners.

As part of mastering manufacturing of new products, we performed the following work:

- developed and approved drawings for the fasteners with the customer,
- developed the manufacturing process,
- developed a process flow chart for upsetting by passes,
- developed drawings for process tools,
- simulated the stamping process, and
- carried out experimental stamping of the fasteners, developed modes of heat treatment and a zinc coating application.

The analysis of the results contributed to preparing the recommendations for further improvement of the process, which could be used in developing similar products.

UDC 621.77

## UNDERSTANDING THE PROCESS OF ASYMMETRIC FLATTENING OF 12 AND 10 MM ROUND BILLETS IN MILL 400

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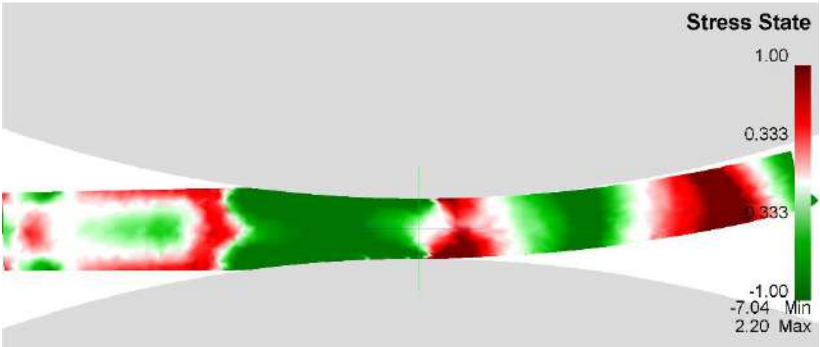
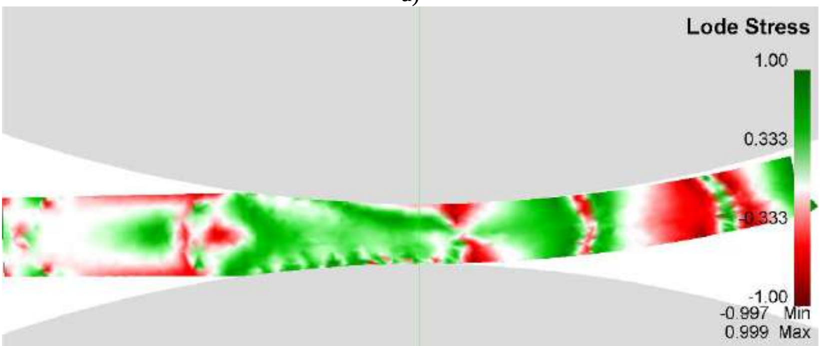
Flattening is a method of rolling round billets in smooth cylindrical rolls, designed for making flat band and for long products industry. High non-uniformity of strain along the width is typical of this process. It is mentioned in the literature on metal forming as a classical example of non-uniform deformation.

This research was aimed at understanding the process of asymmetric flattening in Asymmetric Rolling Mill 400 housed by the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory. 12 and 10 mm round billets made of steel 80 were rolled in one pass and 8.0 mm high bands were obtained. The roll speed ratio varied from $V_1/V_2=1/1$ (symmetrical rolling) to $V_1/V_2=1/5$. Specimens were taken to analyze how their dimensions, microstructure and microhardness changed.

Additionally, a similar series of experiments was carried out in the Deform-3d system. As a result, distribution fields for the stiffness factor and the Lode-Nadai factor (Fig.1) were obtained. When combined, these parameters help analyze the stress state in the billet under deformation [1].




a)




b)

Fig. 1 – Stress state during asymmetric rolling ($V_1/V_2=1/5$) of a round billet:
a) stiffness factor; b) Lode-Nadai factor

The simulation showed that as the roll speed ratio $V_1/V_2$ increases, the share of shear strains in the deformation zone also rises. Fig. 1 shows a rolling option with the roll speed ratio of $V_1/V_2=1/5$. One can see that there are almost no tensile stresses in the deformation zone, while high shear stresses dominate.

Shear strains would be of particular interest when it comes to making items with high accumulated strain and ultrafine-dispersed and nanostructures. However, in the practice of making long-length items such techniques are few. We believe that asymmetric rolling [2, 3] offers one of such techniques.

*The research is funded by the grant of the Russian Science Foundation, No. 23-79-30015, https://rscf.ru/project/23-79-30015.*

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UDC 620.3

## EFFECT OF SEVERE PLASTIC DEFORMATION BY TORSION ON THE MECHANICAL AND CORROSION PROPERTIES OF Mg-1,5%Ca ALLOY

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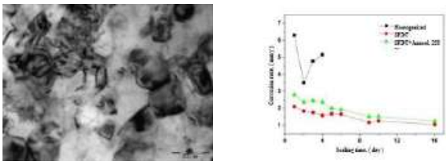
Due to its biocompatibility and biodegradability, magnesium can potentially be used for making implants. The main advantage of magnesium is its modulus of elasticity and density, which are close to those of human bone. However, pure magnesium is lacking strength. To raise the strength of magnesium implants, it is proposed to use binary Mg-Ca alloys [1], as calcium doping helps damaged bone recover by producing hydroxyapatite [2]. At the same time, doping also leads to the formation of a second phase, which might affect the corrosion properties since a microgalvanic matrix-particle phase is also formed. The other approach to achieving enhanced strength would be the production of an ultrafine-grained structure by applying severe plastic deformation in the form of torsion [3]. This paper looks at the ultrafine-grained structure produced in an Mg-1.5%Ca alloy by severe plastic deformation by torsion and at its effect on the mechanical and corrosion performance.

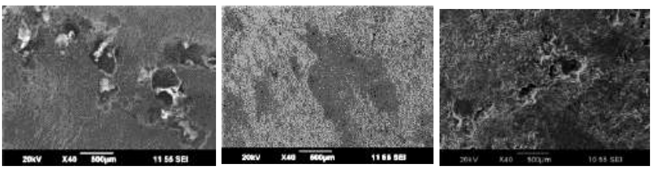
The ultrafine-grained state was produced through severe plastic deformation by torsion. Thus, 10 revolutions were performed at room temperature. Smaller specimens with the work base of 0.6x4.5 $mm^2$ were used for conducting tensile tests. After severe plastic deformation with torsion, the specimens were annealed at the temperatures of 100 $^oC$ to 400 $^oC$ with a 50 $^oC$ interval for one hour and then subjected to cold-water quenching. Ringer’s solution with the constant temperature of 36.6 $^oC$ was used for corrosion testing of specimens, which lasted 16 days.

A structural analysis showed that a nanocrystalline structure with the average grain size of 100 nm was produced by severe plastic deformation by torsion. However, during tensile testing the specimens demonstrated brittle fracture resulting from high internal stresses. Through application of additional annealing cycles, a temperature was identified (250$^{o}$C), at which the ultrafine-grained state is created with the average grain size of 450 nm (Fig.1a), characterized with optimum strength and plasticity. Thus, the strength of the SPDT specimens that had been additionally annealed at 250°C increased by more than three times – from 76 MPa to 250 MPa – compared with the homogenized state, while their plasticity remained unchanged (8%). The deformed specimens were found to be more corrosion resistant than the initial ones (Fig.1b). The specimens in the homogenized state fractured drastically on day 1 (Fig.1b). It was found that the corrosion of particles/eutectic follows the anode reaction. On day 1 of being soaked in Ringer's solution in the homogenized state, the surface of the Mg-1.5%Ca specimens started to see deep pits and stripes where eutectic used to be (Fig. 2a). A typical feature of the SPDT specimens that demonstrated the best corrosion resistance is that specific lines would form on the surface, as well as tiny pits where $Mg_2Ca$ particles used to be [4] (Fig. 2b, c).



a) b)

Fig. 1 – a) Structure of SPDT specimens after additional annealing at 250$^{o}$C;
b) Corrosion resistance chart



a) b) c)

Fig. 2 – Structure as seen through the scanning electron microscope:
a) homogenized state; b) after SPDT; c) after SPDT and thermal annealing at 250°C

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UDC 669.1

## DETERMINING OPTIMAL MODES OF COLD ROLLING AND FINAL ANNEALING TO REDUCE THE GRAIN SIZE OF COVER SHEETS FROM ALUMINUM ALLOYS

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Now, there is a learning process of manufacturing cover sheets in compliance with OST 1 90070-92 at a new rolling complex of OJSC KUMZ. A cladding layer material for sheets is aluminum grade A5, and a base material is D16Ch. Such sheets are applied for aircraft structure covering [1].

Cover sheets should have high ductility [2], one of whose influencing factors is the grain size. According to research [3,4], the grain refinement in aluminum alloy sheets leads to an increase in the ductility characteristics.

The research is aimed at determining optimal modes of cold rolling and final annealing to reduce the grain size of cover sheets from aluminum alloys according to OST 1 90070-92.

When conducting the research, we determined the main process parameters (Table 1). By varying the parameters, we determined a role of every parameter in forming the grain size.

Table 1 – Design matrix

| Experiment No. | Strain before final annealing, % | Annealing temperature, ℃ | Soaking time, min | Rate of cooling down to 260℃, ℃ per hour |
|---|---|---|---|---|
| 1 | 39 | 350-360 | 11 | 35 |
| 2 | 39 | 350-360 | 11 | 25 |
| 3 | 39 | 400-410 | 11 | 35 |
| 4 | 39 | 400-410 | 11 | 25 |
| 5 | 65 | 350-360 | 11 | 35 |
| 6 | 65 | 350-360 | 11 | 25 |
| 7 | 65 | 400-410 | 11 | 35 |
| 8 | 65 | 400-410 | 11 | 25 |

Annealing temperature and the cooling rate were selected factoring into the plant regulatory documents, stating that the annealing mode for alloy D16 to achieve delivery state M: $T_{met}$ = 350-410℃, the cooling rate is 35℃ per hour or less, soaking time is from 10 to 60 minutes.

Table 2 shows the process flow chart for the pilot batch.

Table 2 – The process flow chart for the pilot batch

| Pass No. | Entry thickness, mm | Exit thickness, mm | Deformation per pass, % | Total strain, % | Intermediate annealing | Edge cutting | Sample taking |
|---|---|---|---|---|---|---|---|
| 1 | 7.3 | 5.9 | 19.5 | 16 | | | |
| 2 | 5.9 | 4.8 | 18.6 | 32 | | | |
| 3 | 4.8 | 4.0 | 18.9 | 45 | + | + | |
| 4 | 4.0 | 32 | 20.6 | 19 | | | |
| 5 | 3.2 | 2.6 | 19.5 | 35 | | | |
| 6 | 2.6 | 2.1 | 20.2 | 47 | + | | |
| 7 | 2.1 | 1.7 | 19.2 | 21 | | | |
| 8 | 1.7 | 1.3 | 19.1 | 39 | | | + |
| 9 | 1.3 | 1.1 | 22.3 | 49 | | | |
| 10 | 1.1 | 0.7 | 31.7 | 65 | | | + |

According to Table 2, after 8 and 10 passes on the cold rolling mill we chose 3 control strips of nominal thickness to take samples. These samples were subjected to a metallographic analysis, showing that the previous rate of cold deformation had the maximum effect on the grain size, while annealing temperature and the metal cooling rate had a less effect. Besides, we determined the optimal modes for achieving a reduced grain size of cover sheets, whose cladding layer material was aluminum grade A5, and the base material was D16Ch: the cold strain rate was 50 % or higher, final annealing temperature was 350–360 ℃, the rate of cooling down to 260 ℃ was 35 ℃ per hour.

*The research was carried out as part of the state order for the subject of “Forming”, No. AAAA-A18-118020190104-3.*

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# OPTIMIZED ROLL CALIBRATION FOR STEEL CHANNELS: A NEW PRESENTATION OF PASS SCHEDULE SPACE

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There exists a great variety of roll calibrations so that one and the same rolling mill could be used to make steel sections of particular type [1]. That's why the problem of selecting an optimum calibration for making steel sections of a certain type in a certain rolling mill appears to be of relevance.

The papers [1, 2] describe a technique for finding the optimum roll calibration for making steel channels, which is based on a universal Two-Stage Optimization Concept developed by the Ural Federal University's Department of Metal Forming. This model uses two consecutive stages to find the optimum. Thus, an optimum calibration pattern is defined at the first stage, while the second stage involves calculating the optimum pass schedule. More details on the optimization model and its first stage (i.e. search for an optimum calibration pattern) can be found in the papers [1–3].

The second stage involves searching for an optimum pass schedule. One of the optimality criteria that is to be considered in the first place includes the space of pass schedules (second optimization space). Such space should contain all possible pass schedule options for a selected calibration pattern.

A pass schedule is usually presented as a graph showing reductions by pass or as an equation approximating such graph. Accounting for the constraints, such graph or equation shall represent the space of pass schedules. However, such representation won't work for optimization as it does not allow to reflect all possible pass schedule options. That's why it is proposed to consider such space as an *n*-dimensional space, in which channel wall reduction factors serve as coordinates. The number of space dimensions is dictated by the number of calibration passes. These are the natural space constraints: $\prod_{i=1}^{n_{\text{пр}}} \frac{1}{\eta_i} = \frac{1}{\eta_\Sigma}$, $1 \le \frac{1}{\eta_i} \le \frac{1}{\eta_\Sigma}$. Representation of such *n*-dimensional space does not appear to be possible. That's why Fig. 1 shows a 2-dimensional space of pass schedules allowing for other constraints, which are related to threading conditions, strength or power limitations, etc. A pass schedule is shown as a point in that space. Thus, for a 2-dimensional space it is situated on a section of the hyperbolic arc (in the green region), and for a 3-dimensional space the point is situated on the hyperboloid surface.

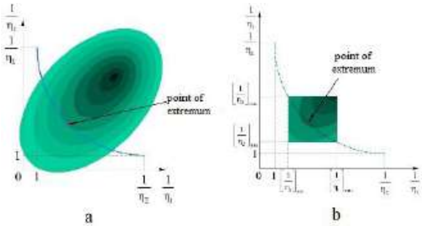


Fig. 1 – Two-dimensional space for pass schedule optimization:
a – no constraints; b – with constraints

Any numerical optimization procedure will work for finding an optimum in a 2-dimensional space. Fig. 2 shows a search for the optimum in a three-dimensional space. The arrows indicate the simplest step-by-step optimization procedure that implements the Gauss-Seidel coordinate-wise method.

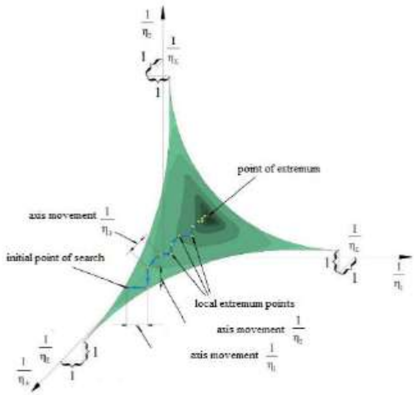


Fig. 2 – Searching for an optimum in a 3-dimensional space of pass schedules

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# CONTROLLING THE QUALITY OF GAUGED BARS FROM STEEL GRADE 35 FOLLOWING A ROBUST PARAMETER DESIGN

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When producing gauged bars, the initial quality of raw materials is one of key factors, influencing the formation of properties of finished products.

OJSC MMK-METIZ receives hot rolled products, whose mechanical properties and hardness are regulated by interstate standards (GOST). The GOST requirements for mechanical properties have a wide range of values, or are not at all limited to the maximum or minimum value. Regarding orders with a narrowed range of mechanical properties and hardness of gauged bars, it is necessary to adjust the manufacturing process depending on the actual values of received raw materials.

The supplied semi-finished products may have the top or bottom threshold values of the acceptable range of properties, and manufacturing gauged bars by the standard technology may lead to inappropriate values of the properties of finished products (hardness, ultimate tensile strength, percentage reduction, percentage elongation, impact strength, etc.). To achieve the required properties, it is necessary to adjust the technology for every batch of rolled products, use the individual resources of a specialist to determine the optimal manufacturing modes. This leads to a delay in manufacturing finished products, equipment downtime and financial losses.

In addition to inaccurate initial data, the manufacturing process is always associated with other noise factors, such as the non-uniform quality of raw materials, imperfect process equipment, operators' mistakes, and imprecise measurement tools [1].

It is currently relevant to develop the methodology of designing the manufacturing processes for gauged bars, factoring into parameter uncertainty of initial data. Now, such field is a robust parameter design. By applying robust optimization, we can develop new technology or improve the existing technology, which is insensitive to variations of noise factors [1].

The conducted research was aimed at designing the manufacturing process for gauged bars from steel grade 35 under TU 14-1-5611-2011, following the characteristics of the received semi-finished products, and analyzing the effect of original properties and hardness of the supplied hot rolled products on the output parameters of the gauged bars.

By analyzing the results obtained during the robust design, we can choose the optimal technology option for its transfer to production, and in practice this will significantly reduce decision-making time to ensure the required characteristics of finished products. These opportunities are especially relevant, when developing new types of products, and improving the manufacturing processes for the existing products.

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## PRODUCTION OF SUPERFINE WIRE AND DEFORMATION RATE

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Deformation rate is a factor that is essential for calculating many parameters in metal forming. Thus, deformation rate can impact strain resistance, which is often recognized with regard to the material behaviour above the recrystallization temperature, but it is not always recognized if the process temperature is below the recrystallization temperature. The relationship between the process rate and the structure and texture of metal in application to the cold drawing of copper wire is described in publications [1, 2].

The following formula is used for calculating the deformation rate in drawing:

$$\xi = \frac{6ln\lambda * tg\alpha}{(\lambda\sqrt{\lambda}-1)*d_1} v_1, \qquad (1)$$

where $\alpha$ – die half-angle; $d_1$ and $v_1$ – die diameter and delivery rate, respectively. The die half-angle in copper drawing is taken equal to about $10^o$, which is attributable to the material properties [3, 4].

As one can see from the formula (1), the die diameter makes a part of the denominator. If we imagine that the diameter is so small that it tends to zero, then the deformation rate approaches infinity. Hence, the influence of the diameter is great, especially if it is very small. It is not common that ferrous metallurgy sites produce fine wire. At the same time, it is quite common in the case of non-ferrous metallurgy industry. Production of superfine copper and gold wires is to be highlighted in this regard [5].

Below is given an analysis of the speed modes used in the drawing of superfine wire made of oxygen-bearing copper grade M00 at Uralkabel JSC, with deformation rates calculated.

From the table one can see that the deformation rates can exceed 100 th $s^{-1}$, which is an enormous value. Some of the publications focusing on the impact of deformation rate during cold working point out that, apart from structural changes, abnormal textures can also be observed in this case. It should be noted that the oxygen-bearing copper wire designed for electrical applications has different properties than the oxygen-free wire designed for electronic applications, and the processes used for the second option may differ.

Table 1 – Dimensional and kinematic copper wire drawing parameters

| $d_0$, mm | $d_1$, mm | $v_1$, m/sec | $\lambda$ | $\xi$, $s^{-1}$ |
|---|---|---|---|---|
| 0.2 | 0.18 | 3.12 | 1.23 | 10383 |
| 0.18 | 0.16 | 3.85 | 1.27 | 14140 |
| 0.16 | 0.15 | 4.87 | 1.14 | 20751 |
| 0.15 | 0.14 | 5.54 | 1.15 | 25122 |
| 0.14 | 0.13 | 6.36 | 1.16 | 30812 |
| 0.13 | 0.12 | 7.38 | 1.17 | 38356 |
| 0.12 | 0.11 | 8.66 | 1.19 | 48575 |
| 0.11 | 0.1 | 10.30 | 1.21 | 62767 |
| 0.095 | 0.09 | 12.47 | 1.11 | 89980 |
| 0.09 | 0.085 | 13.89 | 1.12 | 105647 |
| 0.085 | 0.08 | 15.57 | 1.13 | 125173 |
| 0.08 | 0.075 | 17.58 | 1.14 | 149820 |
| 0.075 | 0.071 | 20.00 | 1.12 | 182792 |

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## CALCULATION OF BROADENING VALUE DURING COLD ROLLING OF THIN CARBON STEEL STRIPS


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Cold rolling of thin strips is the final operation in a long flow of metallurgical production. In this case, even the slightest increase in the conversion factor has a significant impact on the overall cost [1-3]. Width is one of the dimensional parameters of steel sheets. Any significant broadening (or tightening) of the material can lead to either more trimmings or rejects. Assessment of rolled sheets for broadening (tightening) and prediction of these parameters pose an important theoretical and practical problem.

The ratio between longitudinal and transverse strains is determined by a ratio between longitudinal $\sigma_3$ and transverse $\sigma_2$ stresses [1, 2]:

$$\lg\beta = \left(1+\frac{\sigma_2}{\sigma_3}\right)^{-1}\lg\frac{1}{\eta}\,, \tag{1}$$

where $\beta$ – coefficient of broadening; $\eta$ – coefficient of tightening.

We know that [3, 4]

$$\sigma_2 = 0,5\left(\sigma_1+\sigma_3\right). \tag{2}$$

Hence,

$$\lg\beta = \left(\frac{1}{2}+\frac{\sigma_1}{2\sigma_3}\right)^{-1}\lg\frac{1}{\eta}\,. \tag{3}$$

In the first approximation: $\sigma_1 \approx p$ *and* $\sigma_3 = \sigma_x$, *and because* $p-\sigma_T = \sigma_x$, the final result is as follows

$$\lg\beta = \left(\frac{1}{2}+\frac{p}{2(p-\sigma_T)}\right)^{-1}\lg\frac{1}{\eta} \tag{4}$$

Any dependence can be used in the formula (4) to determine *p* and $\sigma_T$ for particular rolling conditions.

Depending on the formula used to calculate *p*, the calculation may include the following stages. Using the given roll radius *R*, the initial yield strength of metal $\sigma_{T.исх.}$ and the trend of how it changes during deformation, which enables to determine $\sigma_T$, the strip thicknesses $h_0$ and $h_1$, the strip tension at mill entry $\sigma_0$ and at mill exit $\sigma_1$, the strip width $b_0$:

– We determine the friction coefficient *f* for the steady process;
– We calculate the absolute and percent reduction achieved in one pass;
– Front and back tension factors;
– Angle of bite α and deformation zone length *l;*
– Angle of friction;
– Size of the neutral angle;
– Neutral plane factor *Z*;
– Neutral plane strip gauge $h_н$;
– Cross-section area reduction in the slip forward zone.

Then we calculate the broadening factor using the formula (4), as well as the broadening value:

$$\Delta b = C_b\left(b_0 e^{\ln\beta} - b_0\right). \tag{5}$$

$C_b$ – coefficient that accounts for the strip width [1-3]:

$$C_b = K(1-\varepsilon)\left(\frac{b_0}{l_x} - 0.15\right)\exp\left(1 - \frac{mb_0}{l_x}\right) + \varepsilon\ , \qquad (6)$$

where $K = \delta^2 / \left(0,85 \cdot \delta^2 - 1\right)$; $m = \delta^2 / \left(\delta^2 - 1\right)$; $\delta = 2 \cdot f_y \cdot l_x / \Delta h$ .

The above dependence was tested when calculating the broadening value in carbon steel strip rolling. The A.P. Chekmarev formula was used for *p* calculation [1, 4].

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# OPERATION OF MULTI-STAND MILL ELECTRIC DRIVES DURING ASYMMETRIC ROLLING

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The term *Asymmetric Rolling* covers several interpretations of asymmetric states that refer to the roll speeds, position, surface temperature, etc. In our case, this term refers exclusively to the kinematic velocity asymmetry and is characterized by the asymmetry parameter – a ratio between the drive motor speeds.

Information about asymmetric rolling first emerged in the middle of the previous century. Outcomes of the first experimental studies were published in the 1970-80s. Some experiments were carried out on a continuous wide-strip hot mill 1700 in Karaganda [1] and on a cold mill 1700 in Cherepovets [2]. In the first case, in the case of a group electric drive, a slight asymmetry of 3-4% was achieved by changing the diameters of the work rolls of the last finishing mill stand. In cold mills, stands have individual electric drives, which enable to realize asymmetric rolling at asymmetry parameters within 1.08…1.1 avoiding work roll slip. At the same time, the authors would repeatedly mention that asymmetric rolling should not be exercised in adjacent stands. In fact, asymmetry was created in either even or odd rolling stands. Such constraints are aimed, first and foremost, at minimizing the effect of asymmetric rolling on the local strip thickness and tension control systems. Only an experiment conducted on functioning equipment can provide a good insight into the effect of asymmetric rolling on electric drives of a multi-stand rolling mill.

Having conducted an experiment on Mill 630 operated by MMK [3], the authors can draw the following conclusions:

1. For a steady rolling operation, the asymmetry parameter should not exceed 1.15. When the asymmetry parameter exceeds 1.2, the motor of the driven roll enters the generator mode (Fig. 1), which can lead to undesirable consequences.

2. In order to remove constraints related to unbalanced torques (currents) of the top and bottom roll drive motors, the load division regulator should be disabled.

3. The existing strip thickness and tension control system adjusts the initial speed setting, and for the asymmetry value to remain constant, an additional asymmetry control loop should be added to the existing speed control system.

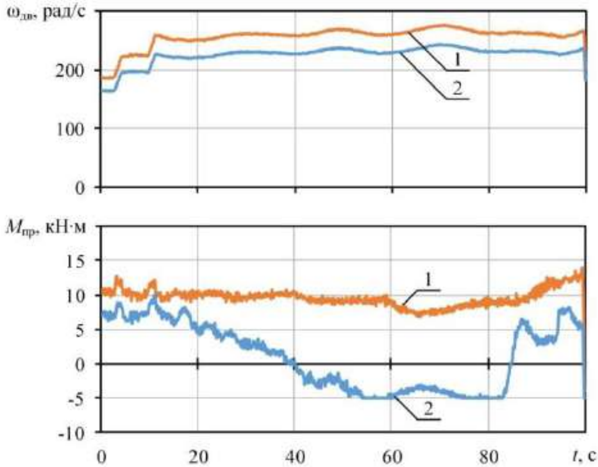


Fig. 1 – Motor speed and rolling torque oscillograph charts:
1 – top roll; 2 – bottom roll

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# UNDERSTANDING THE STRESS STATE IN A WORKPIECE SUBJECTED TO ROTARY PIERCING

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Considerable amounts of hot-rolled pipes are produced in rotary piercing mills designed to turn a solid bar into a shell. Such shells are then used to make semi-finished and final pipes. Modern rotary piercing mills can have cone-, barrel- and cup-shaped rolls. Internal fractures are a well-known phenomenon in screw rolling/piercing caused by axial tensile stresses. Internal fractures may cause defects on the inner pipe surface, hence they should be prevented. The authors of the papers [1-5] examined the effect of various factors on internal fractures occurring along the workpiece centerline. From the above mentioned papers, one can conclude that, in order to minimize the risk of internal fractures, compressive stresses should prevail along the workpiece centerline.

The focus of this paper is on understanding the stress state along the workpiece centerline before the plug nose in piercing mills equipped with cone-, barrel- and cup-shaped rolls. The study was carried out in the QForm programme. For all models, the diameter of the roll body was taken to be 910 mm, the length of the roll body – 630 mm. The diameter and the length of the mandrel were 110 mm and 260 mm, correspondingly. The diameter of the workpiece was 150 mm. The workpiece was made of steel 30KhGSA. The diameter and the thickness of the shell wall were taken to be equal to 160.8 mm and 22 mm, respectively. The reduction of the workpiece across the plug nose was 7.8 %. The gorge reduction was 10 %. The feed angle was equal to 12º in all problem cases. For piercing processes that relied on cone- and cup-shaped rolls, the roll-off angle was 16.5º. In the course of computer modelling, the average normal stress σ and the intensity of shear stresses T were measured along the workpiece centerline before the plug nose, and a stress state index σ/T was calculated [6].

The obtained results were used to build a graph (Fig. 1). From Fig. 1, one can see that the stress state index σ/T was less than zero in all cases, which is indicative of prevailing compressive stresses and therefore a good stress state. Fig. 1 also shows that the lowest stress state index value (σ/T = -0.3) is associated with the use of cup-shaped rolls, whereas the highest one (σ/T = -0.25) – with the use of cone-shaped rolls. For barrel-shaped rolls, the stress state index has an intermediate value: σ/T = -0.27.

A conclusion that can be drawn from the conducted study is that the tool settings and calibration selected resulted in a good stress state along the workpiece centerline before the plug nose, as the stress state index σ/T is less than zero. One can also conclude that the risk of internal fractures along the workpiece centerline is lower when cup-shaped rolls are used than when using cone- or barrel-shaped rolls.

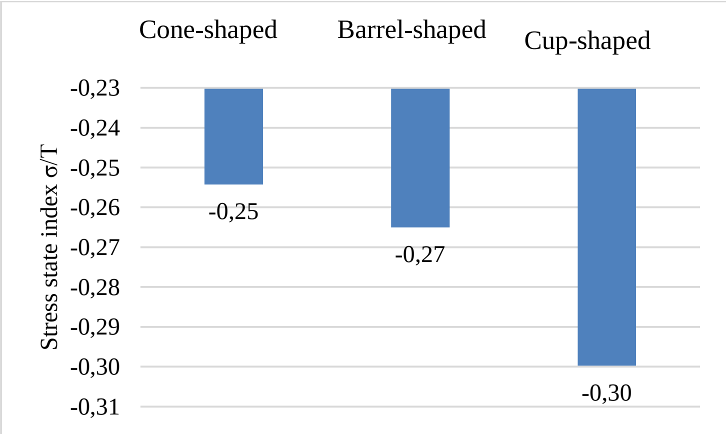


Fig. 1 – Stress state index σ/T

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UDC 621.774

# EXPERIMENTAL STUDY ON THE EFFECT OF FORMING TEMPERATURE ON THE RADIAL SHEAR ROLLING MILL ON THE EVOLUTION OF THE COPPER MICROSTRUCTURE

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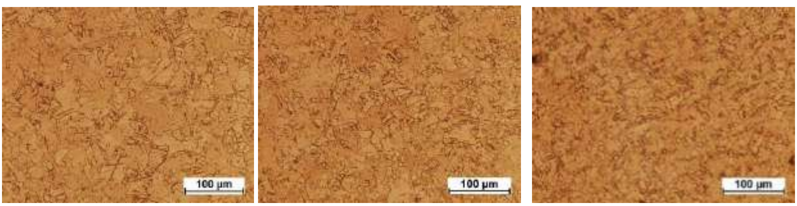
One of the efficient methods of controlling properties of copper, as well as other ferrous and non-ferrous metals, is refinement of its structure to a nano- or ultrafine-grain size, first of all, by severe plastic deformation. One of promising methods of manufacturing long rods with a gradient UFG structure is radial shear rolling [1]. At the same time, a wide range of research papers, including papers [2-3], describes that one of main factors, influencing the potential formation of the UFG structure in various ferrous and non-ferrous metals and alloys, is forming temperature of such metals and alloys. To form the UFG structure, the forming process should occur at temperature, not exceeding the threshold value of the beginning of recrystallization, as an increase in starting forming temperature results in a possibility of dynamic accumulative recrystallization during hot forming, entailing an unfavorable coarsening of the grain. Thus, the temperature mode should be selected so that during hot forming primary recrystallization occurs completely and accumulative recrystallization should be suppressed.

The research is aimed at studying the effect of a process factor of forming on the radial shear rolling mill, such as rolling temperature, on the evolution of the copper microstructure.

To conduct the laboratory experiment, we used rods, 25 mm in diameter and 300 mm long, from copper grade M1. To conduct the planned studies we selected the following forming temperatures for copper rods: 20ºC, 100ºC and 200ºC.

At the first stage, the copper rod, 25 mm in diameter, was rolled at 20ºC on radial shear rolling mill SVP-08. Rolling included four passes, to diameters of 23 mm, 21 mm, 19 mm and 17 mm. At the second and third stages, before rolling on radial shear rolling mill SVP-08, the copper rods, 25 mm in diameter, were heated in the tube furnace by Nabertherm to 100ºC and 200ºC, respectively, with a soaking period of 25 minutes. Then the rods were formed on the radial shear rolling mill to a diameter of 17 mm in four passes with an absolute diameter reduction step of 2 mm, following the above described procedure.

The metallographic analysis of copper (Fig. 1) after radial shear rolling showed that at all the forming temperatures the grain refinement occurred after every forming pass. However, it was also proved that during radial shear rolling at room temperature a grain structure of copper rods was deformed more intensively. At this temperature a minimum average size of the grain after the fourth pass on the radial shear rolling mill was 6.0 μm, while the minimum grain size was 3.1 μm. The advantage of forming of the copper samples on the radial shear rolling mill at room temperature primarily lies in no dynamic recovery processes.



a) b) c)

Fig. 1 – A copper microstructure after 4 forming passes on the radial shear rolling mill at: a) 200ºC, b) 100ºC, c) 20ºC

**Conclusion:** the metallographic studies show that forming temperature produces a significant effect on the potential formation of an ultrafine grain structure in copper grade M1 during its forming on the radial shear rolling mill.

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UDC 621.774.37

## INFLUENCE OF PROCESS PARAMETERS AND MATERIAL PROPERTIES ON STRAIN CAPACITY OF AXISYMMETRIC METALWARE DURING METAL FORMING SUBJECT TO RESIDUAL STRESSES

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The paper presents a method for determining the strain capacity parameter during processing of round bars by plastic deformation methods. The essence of the method is that it is possible to determine a functional relation between the strain capacity parameter and process characteristics, geometry and mechanical properties of the deformable material based on known experimental data about technological residual stresses on the bar surface after drawing.

Strain capacity ψ in paper [1] is calculated as a share of plastic deformation energy minus energy converted into heat. It is found for a number of materials; however, depending on the stress and strain state, mechanical properties of the material and process parameters, it requires computational and experimental adjustment and assessment.

Paper [2] demonstrates a procedure for determining tangential $\sigma_\theta$ , axial $\sigma_z$ residual stresses based on an energy approach, when the components of tensor of residual stresses at $\bar{r} = 1$ on the rod surface after drawing are calculated as follows:

$$\sigma_\theta = \frac{\overline{a_1}}{2\mu}; \ \sigma_z = \frac{\overline{a_1}}{2}, \tag{1}$$

where $\mu$ is the Poisson's ratio.

Parameter $\overline{a_1}$ characterizes the distribution of residual stresses in rods and depends on strain rate $\varepsilon$ [3] during deformation and physical and mechanical properties of the workpiece material:

$$\overline{a_1} = \sqrt{\frac{24\psi\sigma_{s0}E\mu^2}{1-\mu^2}\varepsilon\left(1+\frac{m\varepsilon^n}{n+1}\right)} \tag{2}$$

where *E* is elastic modulus; *m* and *n* are empirical coefficients of material hardening during plastic deformation; $\sigma_{s0}$ is yield strength of the material; $\psi$ is a strain capacity parameter.

Let us write formulae (1) subject to equation (2):

$$\sigma_\theta = \sqrt{\frac{6\psi\sigma_{s0}E}{1-\mu^2}\varepsilon\left(1+\frac{m\varepsilon^2}{(n+1)}\right)};\ \sigma_z = \sqrt{\frac{6\psi\sigma_{s0}E\mu^2}{1-\mu^2}\varepsilon\left(1+\frac{m\varepsilon^2}{(n+1)}\right)} \tag{3}$$

Let tangential residual stresses $\sigma_\theta^*$ on the rod surface after drawing are determined experimentally [4]. Then in compliance with formulae (1) parameter $\overline{a_1}$ will be determined as follow:

$$\overline{a_1} = 2\mu\sigma_\theta^* \tag{4}$$

The same approach may be applied to calculate $\overline{a_1}$, when axial residual stresses $\sigma_z^*$ on the surface of the tube workpiece surface are determined experimentally:

$$\overline{a_1} = 2\sigma_z^* \tag{5}$$

Factoring into relations (2), let us express strain capacity parameter $\psi$ from equation (3), when tangential residual stresses are determined:

$$\psi_\theta = \frac{(1-\mu^2){\sigma_\theta^*}^2}{6\sigma_{s0}E\varepsilon\ \left(1+\frac{m\ \varepsilon^n}{n+1}\right)} \tag{6}$$

and axial residual stresses are determined:

$$\psi_z = \frac{(1-\mu^2){\sigma_z^*}^2}{6\mu^2\sigma_{s0}E\varepsilon\ \left(1+\frac{m\ \varepsilon^n}{n+1}\right)} \tag{7}$$

Then we determine the relation between the strain capacity parameter and the strain rate during forming, reduction value during drawing and various tilt angles of the forming die channel.

The calculation showed that initial resistance to deformation had a considerably less influence on the parameter than the angle of taper. It means that additional costs for manufacturing the material with higher initial resistance to deformation are not a feasible way to decrease the strain capacity parameter, if it is possible to increase the angle of taper of the die.

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## POTENTIAL METAL MOTION PATHS, WHEN PRESSING TWO WORKPIECES


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Pressing of bimetallic bars as a metal core and its surrounding shell faces certain difficulties [1]. Due to the difference in properties, one of the metals gets the preferred motion. Most often, it is the metal with reduced resistance to strain [2].

There is also an option of pressing two workpieces located one by one in the press container. Sometimes, this process is known as a method of pressing ingots following closely. In this case, two workpieces are made of the same metal, and the task is to reduce waste as a result of cutting the front and back parts of the pressed product. Sometimes, the two workpieces are made of different metals, as it happens during the hydrostatic extrusion process to prevent a shot due to high energy accumulated by high pressure liquid [3].

Just like many other tasks of metal forming, a strain state during pressing is now described by the finite element method, mainly [4].

An option of solving the task of pressing two workpieces put one by one in the press container is given below.

To carry out the simulation, we applied DEFORM-2D software suite. The problem type is plastic. Container temperature is 460 °C. Matrix and extrusion ram temperature is 380 °C. Siebel's coefficient of friction is 1. Extrusion ram travelling speed is 4.27 mm/s. The workpiece is Al6061.

Regarding the first option of the problem statement, a workpiece of less ductile metal (the metal selected from the library was TITANIUM-TYPE-1) was used as a front disk.

Then we set the similar problem for the option of using the disk of more ductile metal (the metal selected from the library was DINAlMGSi1).

As you can see in Fig. 1, there is no flow of the material of the front workpiece in respect of the matrix in the radial direction, and there is fracture of the workpiece after pressing out. Fig. 2 shows is an intense flow of metal of the front workpiece in the radial direction, and a cladding layer is formed on the main workpiece during pressing out. However, this cladding layer is not uniform and becomes thinner as the pressed part of the workpiece increases.

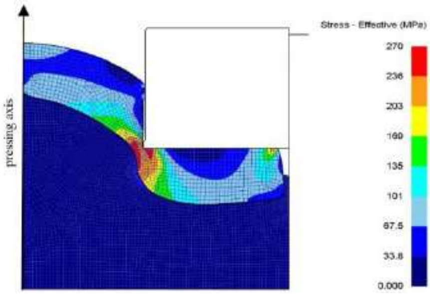


Fig. 1 – Color levels of distribution of effective stresses, when pressing according to the first option

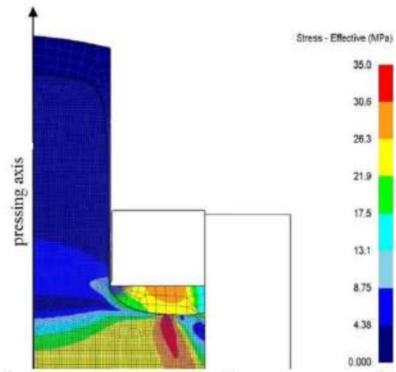


Fig. 2 – Color levels of distribution of effective stresses, when pressing according to the second option

Following the simulation results, we can draw a conclusion that in the first option of pressing, when using the disk of less ductile metal, we cannot produce a bimetallic rod because of metal fracture.

Regarding the second option of pressing, when using the disk of more ductile material, a bimetallic rod has a non-uniform distribution of the cladding layer along length.

*The research was carried out as part of the project of the Russian Science Foundation (No. 22-29-00931 dated 20.12.2021).*

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## ANALYSIS OF THE PRACTICE OF APPLYING THE STRETCHING PROCESS TO REINFORCING STEEL

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The process of cold stretching is widely used in Europe to produce high-plasticity hot-rolled rebars of high quality and with descaled surface and to supply coils of such rebars to consumers offering a wider range of sizes and weights (up to 5 tons inclusive) as compared with the product coming from rolling mills. German rebar producers were first to apply cold stretching [1, 2].

The process involves stretching of hot-rolled rebars while also bending them in rollers with controlled sectional deformation of up to 5% – 8%. This gives a significant enhancement to the stretching process, and namely:

- The process stability rises as, due to sectionally alternating strain [3, 4], the cause of quickly developing strain localization is eliminated;
- The strength is increased at far lesser losses of plasticity or energy than during elongation [5, 6]. This is achieved due to non-monotonous strain, decreased average density of dislocations and their non-uniform distribution by volume, with alternating strain in place [7];
- Because each sectional element undergoes multiple deformation cycles following the elongation-compression pattern, the Bauschinger effect is eliminated when the stretched specimen is further subjected to compression strain;
- During bending, external stresses overlap the residual ones that arise during rolling or drawing. This results in lower surface tensile stresses and may even lead to redistribution of stresses, so that compressive stresses arise at the surface and counterbalance the internal tensile ones [3,4].

In Europe and globally today, cold stretching is included in almost the entire range of classes and references applicable to the production of high-plasticity hot-rolled products, including category C in accordance with Eurocode 2. Rolled rebars are supplied in compact coils within a broad range of weights up to 5 tons and with descaled surface [8].

The machinery used for realizing the cold stretching process can be designed with one or two planes of roller stands used to intensify the alternating deformation process. Fig.1 shows a one-plane panel by Shnell, Italy, which includes a parameter control unit to adjust and fix a given tension and roller arrangement in order to control the dimensional changes and mechanical properties of the workpiece [9].

Fig. 1 – One-plane stretching panel by Shnell, Italy

Russia also knows some positive examples of applying the above process. Only in Russia it is referred to as *SBR*, which stands for *stretching–bending with rebending* [10-12]. This process was tested in 2005-2006 at several sites in the Moscow Region [2, 5, 6] and in Kopeysk in the Chelyabinsk Region, which produce strengthened rebars of A500C grade out of hot-rolled stock of A300C (18G2S and St3Gps steels) and A400 (25G2S and 35GS steels) grades and deform steel wire meant for forming. The lack of a single approach to calculating the process parameters remains the key factor hindering the spread of this process.

*This research was carried out under the following project: A Theoretical and Practical Study into Application of the Stretching-Bending with Rebending (SBR) Technique to Rolled Rebars; Agreement No. 23-29-10046 with the Russian Science Foundation dated April 20$^{th}$, 2023.*

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## A WIRE FINE DRAWING PROCESS FOR MEGA-STRENGTH STEEL CORDS

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The studies are aimed at performing a temperature analysis of a drawing process of fine wire, 0.295MT mm in diameter, and developing a drawing sequence with minimum wire surface temperatures in fine drawing dies.

We developed the fine drawing process for wire 0.295MT from wire stock, 1.85 mm in diameter, steel 100, to reduce wire breakage during stranding of steel cords 2x0.295MT. The development factored into a reason for steel cord breakage during stranding, lying in overstrengthening of the wire surface during fine drawing as a result of dynamic deformation aging of wire steel, depending on wire temperature in drawing mill dies, among other factors.

The phenomenon of deformation aging of steel lies in the interaction between impurity atoms C, N, and H with dislocation centers. This interaction limits mobility of dislocations in grains of the steel structure, reducing ductility of steel. The phenomenon of deformation aging is limited by decreasing drawing temperature. Deformation temperature can be decreased only with a decrease in the rate and degree of deformation. Maximum deformation temperatures during drawing occur on the wire surface, where heating energy depends on energy generated from internal and contact friction. Therefore, it is required to reduce the loss of ductility of the wire surface layers, which receive maximum mechanical loads during steel cord stranding, causing the propagation of cracks in steel cord wire.

Following the adopted physical principle of designing a drawing sequence, we determined die diameters and analytically calculated wire surface temperature in the proposed drawing sequence (Fig.1) at a drawing speed of 8 m/s.

A further search for ways to decrease wire temperature by a numerical simulation of wire deformation in dies led to the following result: reducing the die bearing to 0.3 of the die diameter entailed a decrease in temperature by 25% in the first double die and by 25% in the second double die compared with the die, having length of the die bearing of 0.5 of the die diameter. Wire is colder by 18% between double dies with a shorter die bearing compared with the existing option, having a die bearing of 0.5 of the die diameter.

The analytical and numerical calculations of temperature values were proved with measuring surface temperature of wire, exiting the drawing mill.


Fig.1 – Wire surface temperature change $tn_i$ in °C depending on fine drawing die number i (29 dies, including double dies)

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## R&D WORK AND ITS ROLE IN THE INNOVATIVE DEVELOPMENT OF MMK-METIZ OJSC

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The structure of a major production company is based on a multi-faceted system of links and interactions between divisions and services, offices and departments, aimed at realizing the single objective of producing goods and generating revenues in order to satisfy the shareholders' goals and improve the wellbeing of each and every employee. In this regard, *MMK-METIZ OJSC* is a classical example of a metalware producer. Situated in the south of the Ural industrial cluster, it has been historically and actually functioning similarly to its major Russian counterparts. Apart from pure production functions, the company is also focused on research and development activities, which are often presented as the way to ensure stable production, but which at the same time support in-house innovation. The R&D activities are aimed at developing new types of product, assessing the available production facilities and the capacity of the available machinery, as well as at understanding how necessary reconstruction or revamping might be. The work of the company's researcher is tightly linked to the first person – i.e. the consumer, as it is the consumer that defines the product quality specification. And it is the producer's primary goal to meet the quality specification.

This report describes the company standards that define the procedure of internal research and development work, as well as the procedure applicable when developing and implementing innovative products, adopting innovative materials and conducting R&D activities involving third party educational or research organizations. Today, it is the only way to attract young researchers and more funds to the company's research sphere.

To illustrate MMK-METIZ's innovative activities, this report covers the company's R&D agendas for 2022-2023, the key R&D outcomes achieved, as well as the outcomes of adopting innovative products in 2022 and the innovative products that are to be adopted in 2023. The report analyzes R&D work undertaken by MMK-METIZ in 2020-2022 together with the Bardin Central R&D Institute of Ferrous Metallurgy in Moscow on the following subject: Modern process of producing high-strength fasteners (of grades 10.9, 12.9 and 14.9) out of high-grade steel sections by cold forging to meet the demand of automotive industry and for other critical applications [1, 2], and that undertaken together with *Nosov Magnitogorsk State Technical University* in Magnitogorsk on the following subject: Optimized processes for making cold-deformed steel bars and shaped sections out of conventional and innovative steel grades for railway and automotive industries [3, 4]. MMK-METIZ has received several awards and has been nominated several times for their innovative achievements by the *Metal-Expo* International Industrial Exhibition.

Thanks to the cooperation between MMK-METIZ and Nosov Magnitogorsk State Technical University, the company was able to join the Ural Cross-Regional Research & Education Centre *Innovative Production Processes and Materials* supporting research activities with regional and federal funding, and to take part in programmes funded through governmental contracts. This helped MMK-METIZ to expand its information field in terms of technical and technological innovations.

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# STUDY OF THE INFLUENCE OF HIGH-TEMPERATURE SEVERE PLASTIC DEFORMATION ON PURE NICKEL STRUCTURE

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A great deal of researcher attention is currently drawn by such metal forming technique as severe plastic deformation (SPD). This technique enables to obtain a submicrocrystalline structure in materials, and due to it, they demonstrate enhanced mechanical properties, such as strength, ductility, and damping ability [1, 2]. At the same time, there are data indicating a low thermal stability of the structure, when the strength of the material deteriorates and the grains grow as the result of temperature impact [3]. That's why it is important to find feasible options for severe plastic deformation of metallic materials that would ensure stability of certain characteristics. For this, one needs to collect data on the structure and properties of the material under different forming conditions.

This research was aimed at examining the structure and properties of the materials subjected to SPD at high temperatures. The material selected for the study is nickel of H0 grade produced by high-pressure torsion in Bridgeman anvil (HPT) at 5 revolutions and 4 GPa. Specimens were deformed at the room temperature and then they went through a 10-hour long annealing cycle at the temperatures of 200 ºC and 300 ºC. Specimens deformed at the temperatures of 200 ºC and 300 ºC were also studied.

The authors looked at the structure of specimens of ultrafine-grained nickel after SPD under different temperature impacts. The grain size was analyzed based on transmission electron microscopy images. Data were obtained on how temperature influences the crystallite size, and a relationship was found between the microhardness of deformed nickel and the crystallite sizes (Fig. 1).

The microhardness data are presented as a reciprocal square root function of the grain size. One can see that the data have a good correlation with the classical Hall-Petch trend.

It is demonstrated that the strength of the material tends to drop as the average grain size becomes bigger.

At the same time, an increase of the deformation temperature from 200 to 300℃ had no significant effect, while an increase of the annealing temperature to 300℃ had a considerable impact on the material properties.

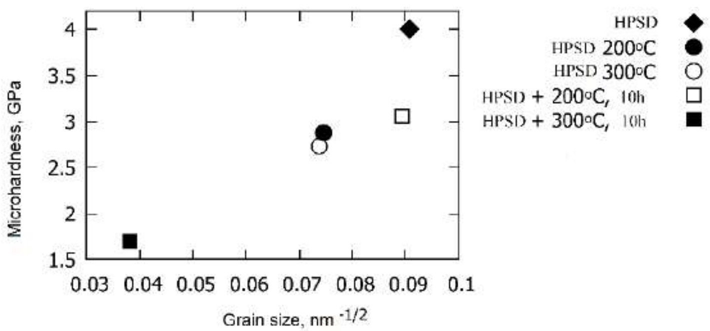


Fig. 1 – Dependence of microhardness versus average grain size in nickel subjected to HPT for 5 revolutions at 4 GPa

The results were obtained using the equipment of the Collaborative Access Center «Testing Center of Nanotechnology and Advanced Materials» of the IMP UB RAS.

*The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme "Function" No. 122021000035-6).*

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UDC 539.8

## INFLUENCE OF ASYMMETRIC ROLLING ON STRUCTURAL CHANGES AND PROPERTIES OF ALLOY Cu-Cr-Zr


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The principles of severe plastic deformation are developed in new methods of metal forming. Structural changes and phase transformations occurring in conditions of high plastic deformation contribute to achieving a new level of a set of physical and mechanical properties. The asymmetric rolling method is derived from the idea and principles of SPD.

This paper presents the studies on the effect of asymmetric rolling on the structure and properties of alloy Cu-Cr-Zr. This alloy is attributed to a special class of electrically conductive copper alloys. A key objective for products from this alloy is to increase strength characteristics, while maintaining electrical conductivity.

Deformation took place at room temperature. Speed of the upper striker was 2.5 rpm, the lower one was 6 rpm. The accumulated strain rate per 1 pass was 0.74-1.14.

The computer simulation demonstrated that a tensile scheme was mainly implemented in the areas of the sample adjacent to the roll with a lower speed and in the middle areas of the sample; a pure shear scheme prevailed in the area adjacent to the roll with a higher speed. In the deformation zone, there are mainly compression stresses, at the entrance to the zone - low tension stresses, and at the exit from the zone - alternating stresses. A grain-subgrain structure with an average fragment size of 235±100 nm was formed in the sample of alloy Cu-Cr-Zr. A cellular structure was observed inside some fragments. Ultimate tensile strength was 425±20 MPa and electrical conductivity was 33% IACS. Alloy Cu-Cr-Zr is dispersion hardenable, therefore, aging was performed at 450 ℃ to increase ultimate tensile strength to 560±20 MPa and electrical conductivity to 82% IACS. The average fragment size remains unchanged, namely 235±85 nm, but fine particles are found along low- and high-angle boundaries. The results of the computer simulation were tested with the results of the structural analysis and mechanical characteristics, and a good agreement was established.

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UDC 669.1

## LAYERED METAL COMPOSITES PRODUCED BY EXPLOSION WELDING

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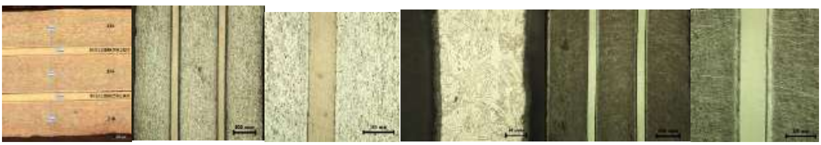
This paper describes layered composite materials made of alternating plates [1-5] by means of explosion welding. For explosion welding, the plates were arranged in parallel and the following process parameters were applied: impact angle $\gamma$ = 20°, velocity of detonation $V_d$ =2,450 m/sec; impact velocity $V_i$=850 m/sec. The height of the explosive layer was 20 mm. The gap between the welded plates was 2 mm [4]. To remove residual stresses after explosion welding, the composites were subjected to heat treatment [3].

The aim of this research study is to examine the structure of the weld zone, the transition zone in multi-layer compositions of dissimilar metallic materials, as well as the strength of the weld both immediately after explosion welding and after heat treatment. Since the initial materials had different melting and recrystallization temperatures, different temperatures in the range of 200 to 500 °C were applied for heat treatment, with the soaking time of 1 hour for the said temperatures [1,2].

*CM II* stands for aluminium alloy D16 and maraging steel [03Х12Н8К5М2ЮТ] (ZI90-VI) with the respective thicknesses of 1 and 0.25 mm. Through metallographic analysis (Fig. 1, a), three zones were distinguished: a duraluminium zone, a maraging steel zone with massive martensite structure, and a narrow transition (stir) zone on both sides of the aluminium-steel interface. The transition zone close to the interface is not uniform and has the thickness of about 15-20 μm (Fig.1, *b-c*).



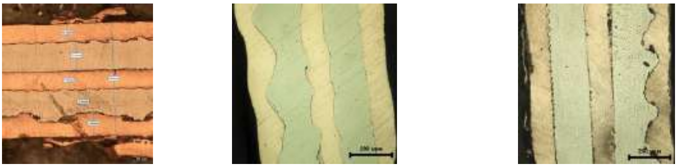
*a* *b* *c* *d* *e* *f*

Fig. 1 – Microstructure of CM II after explosion welding: *a-c* – after pickling with different agents; after heat treatment at 300°C (*e*) and at 500°C (*f*)

The interfacing surfaces are almost smooth. However, one can notice an extremely thin transition layer containing up to 85 at % of aluminium, as well as atoms of iron, chromium and nickel [4]. Looking at the precipitate one could assume that that layer was made of intermetallic phase. The composite produced under these parameters of explosion welding is quite strong, with a flat interface and without burn-offs [5].

The results of the microstructural study of the CM II composite after heat treatment are shown in Fig. 1 (*e, f*). As it was rather difficult to choose the right etching agent for different materials, no noticeable microstructural changes can be observed after heat treatment.

*CM III* was produced by explosion welding of plates of bronze BrBNT1.7 and maraging steel [03Х12Н8К5М2ЮТ] with the respective thicknesses of 0.1 and 0.2 mm. The interface here is not flat but wavy and regions of partial burn-off can be observed near it (Fig. 2).



*a* *b* *c*

Fig.2 – Microstructure of CM III after explosion welding (a) and after different cycles of heat treatment: annealing at 200°C (b) and at 500°C (c)

Aging of the composite in the temperature range of 200…500°C with a 1-hour soaking time did not lead to any significant structural changes in any of the layers (Fig. 2, b, c).

Table 1 – Mechanical properties of composites

| **CM II** | **$\sigma_B$, MPa** | **$\sigma_T$, MPa** | **δ, %** | **CM III** | **$\sigma_B$, MPa** | **$\sigma_T$, MPa** | **δ, %** |
|---|---|---|---|---|---|---|---|
| after explosion welding | 505 | 420 | 6 | after explosion welding | 390 | 375 | 5 |
| annealing at 500°C | 440 | 410 | 13 | annealing at 200°C | 555 | 530 | 7 |
| | | | | annealing at 500°C | 140 | 110 | 15 |

The conducted study showed that explosion welding is a process that helps join together dissimilar materials. The results of the structural study indicate a high quality of the welds.

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UDC 669.717, 669.7.017

## STRUCTURE AND MECHANICAL PROPERTIES OF SHEETS FROM ALLOY Al–2%Cu–1.5%Mn–Mg-Zn (Zr, Fe, Si) PRODUCED FROM CAN SCRAP

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Due to increasing requirements for environmental protection and environment friendly production, recycling of aluminum alloys has become an important area of development of the aluminum industry [1]. Secondary aluminum alloys usually contain a high amount of Fe and Si impurities, which may be even accumulated during recycling [1]. Consequently, an expansion of an acceptable range of Fe and Si content in heat-resistant alloys Al-Cu-Mn is feasible for a wider use of scrap, when producing such alloys.

Railway transport is an important component of industrial infrastructure worldwide. Stability of state economy, national security, and improvement of living conditions and standard of living of people depend on its stable and efficient operation.

Now, researchers are working on manufacturing innovative railway cars with improved technical, economic, strength and dynamic performance. Main attention is devoted to developing railway cars to handle oil products, namely increasing their load capacity and decreasing metal consumption for their structure [2].

CJSC Cheboksary Plant Sespel manufactures products for cargo transportation, including rail tank cars [3]. Such products are mainly produced from sheets of aluminum alloy 5083 (AMg5). Ingots from alloy 5083 require a rather consuming operation, homogenization, before rolling. Alloy 5083 (O: $\sigma_в$=280 MPa, $\sigma_т$=150 MPa, $\delta$=15%) [4] is sensitive to impurities, such as iron and silicon. Therefore, when producing alloy 5083 using scrap materials, its mechanical characteristics become significantly lower [4].

This research focuses on studying the structure and mechanical properties of aluminum alloy 2%Cu–1.5%Mn–Mg–Zn (Zr, Fe, Si**)** (wt.%) at various modes of thermomechanical treatment, using hot rolled and cold rolled sheets as an example. Alloys of such composition do not need homogenization or quenching, and hardening is achieved by annealing due to precipitation of dispersoids $Al_3Zr$ and $Al_{20}Cu_2Mn_3$[5]. The alloys were manufactured from can scrap, containing about 0.5 wt.% of iron and silicon. Copper grade M1 was introduced in its pure form, manganese – as alloy Al–20% Mn, magnesium grade Mg99, and zinc Zn99. The alloy was melted in an electric resistance furnace in a graphite crucible at 790–810°C. A flat ingot, 20x140x180 mm in size, was produced by casting in a graphite mold (the cooling rate was about 20 K/s). Ingots of experimental alloys (without heat treatment) were rolled on a hot rolling mill at 450 ℃ to a thickness of 2 mm. Mechanical tensile tests were performed on the samples cut from hot rolled sheets, 2 mm thick, after single-stage annealing at 400, 450 and 500 ℃ for 3 hours.

The structure and properties of hot rolled sheets from the experimental alloy were studied before and after single-stage annealing. It was found that the experimental alloy had high thermal stability. It was also shown that hot rolled sheets from the experimental alloy had high mechanical characteristics in the annealed state; ultimate tensile strength and yield strength were higher than those of alloy 5083-O at comparable percentage elongation. The experimental alloy does not need homogenization or quenching, which also has a positive effect on environmental and economic performance, when producing this alloy.

*The research was funded by the grant of the Russian Science Foundation, No.20-19-00249-П.*

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UDC 621.771

# TESTING OF ASYMMETRIC COLD ROLLING OF HIGH-CARBON STEEL STRIPS AIMED AT EXCLUDING INTERMEDIATE ANNEALING

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The focus of this research study is to carry out an experimental simulation and to understand if the use of asymmetric rolling at the facilities of MMK's Rolling

Shop 8 can help reduce the number of rolling/annealing cycles when producing high-carbon steel strips. To implement the asymmetric rolling process, one would need a separate work roll drive. At MMK, it is the continuous 5-stand rolling mill housed by Rolling Shop 8 that has that type of equipment.

The existing process flow for making 0.8 mm thick strip out of steel 65G at Rolling Shop 8 involves 2 intermediate annealing cycles after rolling to intermediate thickness:

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

The results of experiments, which were carried out at the NMSTU laboratory, indicate that the 0.8 mm thick strip can be produced out of steel 65G (or similar grades) by employing asymmetric rolling with 1 intermediate annealing cycle as follows:

2.8 mm → 1.3 mm → annealing → 0.8 mm

In terms of possible reduction of the rolling force, the efficiency of asymmetric rolling rises significantly as the reduction degree increases. At 10-15% reductions, asymmetry does not help any more to lower the rolling force. Whereas at reductions exceeding 30-40%, such efficiency rises considerably. Thus, the rolling force during asymmetric rolling with 30-40% reductions corresponds to the rolling force applied during symmetric rolling with 10-15% reductions.

Correspondingly, due to dissimilar work roll speeds, asymmetric rolling can be used to lower the rolling forces, enhance the reduction capacity of the mill stands and thus obtain thinner strip while avoiding using intermediate annealing cycles. This research aims to compare symmetric rolling with asymmetric one in terms of power and forces employed, by conducting trials. It also aims to assess if the number of cold rolling/intermediate annealing cycles can be reduced when producing high-carbon steel strips in the Continuous 5-Stand Mill 630 operated by MMK.

*The research is funded by the grant of the Russian Science Foundation, No. 22-49-02041, https://rscf.ru/project/22-49-02041/.*

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UDC 620.175.6

# EFFECT OF SEVERE PLASTIC DEFORMATION ON THE STRUCTURE AND MECHANICAL PROPERTIES OF ZINC ALLOY Zn-Fe-Mg

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There is a growing demand of society for new implantable materials. One of the types is biodegradable materials that gradually dissolve in the body, having performed a connective or supporting function. Now, much attention is paid to zinc-based materials because zinc has good biocompatibility and the ability to bioresorption at an acceptable rate [1].

This paper presents the study on the effect of the strain rate on the microstructure and mechanical properties of zinc alloy Zn-Fe-Mg. Deformation was performed by a torsion severe plastic deformation (TSPD) method at 20 ℃, 6GPa and a number of rotations from 1 to 10.

A chemical composition of the produced material was analyzed with an X-ray fluorescence spectrometer, Thermo Scientific ARL Optim'X, static tests were conducted on an electromechanical measuring system, Instron 5982. Microhardness was studied with a hardness tester, EMCO- Test DuraJet 10, by the Vickers method as per GOST 9450-60 at a load of 0.1 kg, microstructural studies were conducted with a scanning electron microscope, JEOL JSM-6490LV.

The applied TSPD results in a grain structure refinement, a uniform distribution of $FeZn_{13}$ particles over volume. An increase in a number of rotations entails lower ductility of the samples. The paper describes and discusses mechanisms aimed at increasing strength properties.

The studies were funded by the grant in the field of science from the budget of the Republic of Bashkortostan to render state support to young scientists (NOTs-GMU-2022, Agreement No. 1 dated 13.12.2022). The study was carried out on equipment of Common Use Center Nanotech at Ufa University of Science and Technology.

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UDC 621.771.01

# STUDY ON THE STRUCTURE AND MECHANICAL PROPERTIES OF ALUMINUM ALLOY AD33 AT DIFFERENT PRESSING STAGES

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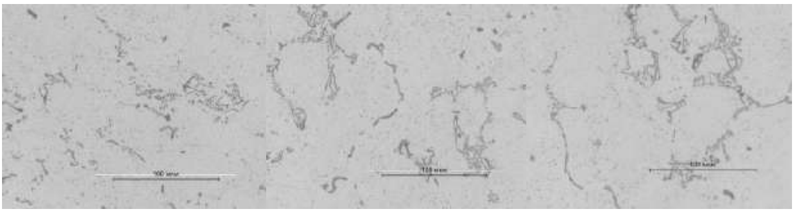
To consider the possibility of using heat treatment to correct the structure of waste of pressed semi-finished products formed due to the features of the technological process, we studied the features of the formation of the structure and a set of the mechanical properties of pressed semi-finished products from aluminum alloys, using the example of aluminum alloy AD33, and also determined the areas of the workpiece, requiring additional heat treatment after initial pressing.

The microstructure was studied on polished micro-specimens taken in a longitudinal section from a peripheral, central zones and a zone of ½ of the radius of the pressed workpiece.



a) b) c)

Fig. 1 – Microstructure of the samples from alloy AD33:
a) periphery; b) ½ of the radius; c) center

It was demonstrated that during the process of pressing, the structure and, consequently, properties were distributed non-uniformly over the cross-section of the workpiece. Deformation conditions have a significant effect on the distribution of the mechanical properties over the cross-section and length of the pressed semi-finished product. This means that the deformation conditions in various parts of the workpiece are significantly different. The maximum spread of the properties between the center and the surface layer is found in the exit part of the pressed workpiece, which can be used for subsequent processing only after additional heat treatment. The most uniform metal deformation is found in the main part of the workpiece.

Regarding successful pressing of scrap, at the subsequent process division it is required to carry out additional heat treatment to eliminate a non-uniform structure after the first cycle of hot pressing of the original workpiece. At the same time, following the determined set of the mechanical properties, it was found that alloy AD33 had a hardness of 55 HV 0.025, was not hardened during deformation, and was characterized by high ductility. The results of this study demonstrated that it was possible to use scrap after additional heat treatment as a workpiece in subsequent stages of hot pressing.

UDC 669.017.3; 669.017.3:620.18

## NEW Al-Ca-Cu SYSTEM FOR DEVELOPING HIGH-TECHNOLOGY ALUMINUM ALLOYS OF A EUTECTIC TYPE

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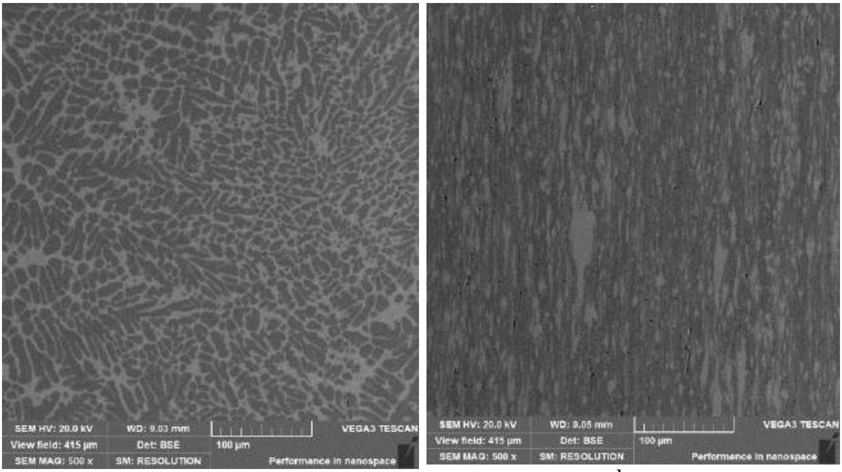
The subject of the research was the Al-Ca-Cu model alloys. The research was aimed at describing phase equilibria set in the aluminum angle of a new Al-Ca-Cu system, and identifying promising concentration fields for new aluminum matrix composite alloys. In the course of the research, we performed an integrated analysis of the structure and properties of the model alloys, showing new, not earlier described, intermetallic compounds $(Al,Cu)_4Ca$, $Al_{27}Ca_3Cu_7$ and $Al_8CaCu_4$ in equilibrium with an aluminum solid solution (Al) [1]. Intermetallic compound $(Al,Cu)_4Ca$ was described as a solid solution based on phase $Al_4Ca$. Copper solubility in the compound achieves 10 at% or 19 wt%, entailing a significant change in the structure of its crystalline lattice and physical and mechanical properties. Phase $Al_{27}Ca_3Cu_7$ was described as a triple compound of strict stoichiometry. Microhardness of the compound is about 420 HV, considerably higher than microhardness of $(Al, Cu)_4Ca$ and higher than microhardness of crystals of $Al_{11}Re_3$ type [2, 3]. Phase $Al_8CaCu_4$ is also a triple compound of strict stoichiometry. This phase has the highest microhardness (~505 HV) and density (4.57 g/cm$^3$). The research conducted and the results showed that the alloys attributed to binary phase area (Al) + $(Al, Cu)_4Ca$ and quasi-binary section $(Al)+Al_{27}Ca_3Cu_7$ could be used as a base for new natural aluminum matrix composites.

Alloys Al3Ca0.5Cu and Al3Ca1Cu were used as examples to demonstrate prospects of the system to form alloys of a eutectic type with a natural composite structure. The alloys have an ultra-disperse eutectic structure (Fig.1) based on phase $(Al,Cu)_4Ca$. The alloys showed high manufacturability at moderate temperature of hot rolling (300 °C). It should be also noted that due to a high quantity of multiple insoluble aluminides, a new eutectic system may be considered to be promising for developing high-technology alloys applied for additive technologies, such as selective laser melting.




a b

Fig. 1 – Microstructure of alloy Al3Ca0.5Cu:
a) in the cast conditions; b) after forming. Scanning electron microscopy

*Key results of the research are presented in paper [1]. The research was funded by the Priority 2030 Federal Program of Academic Leadership, NUST MISIS.*

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UDC 621.77

# EXAMINING THE PARAMETERS OF THE IRE PROCESS FOR MAKING CONDUCTOR WIRES OUT OF AL–TM AND AL–REM ALLOYS

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Defining parameters for the manufacturing of conductor wires with an improved level of thermal stability, strength and electrical conductivity is the key task for the production of long-length semi-finished products for automotive, aviation, and electrical applications [1–4].

All-round non-uniform compression and sign-variable shear deformation in the process of ingotless rolling-extrusion (IRE) of Al alloys with Ce, La, Zr and Fe in combination with drawing and annealing make it possible to achieve a different combination of mechanical, electrical and thermal properties. Therefore, the definition of optimal deformation and temperature/speed parameters to ensure a given level of properties is associated with the creation of an extensive database of experimental data on the metal state after complex processing by IRE and drawing with intermediate heat treatment cycles [2–4].

Tables 1 and 2 and Fig. 1 show some alloy compositions and wire properties after IRE, drawing, and stepped annealing at 300–400–450°C for 50 hours.

Table 1 – Chemical composition of experimental alloys

| Alloy | Al | Ce, La | Zr | Fe |
|---|---|---|---|---|
| 1 | balance | – | 0.2 | 0.2 |
| 2 | balance | – | 0.2 | 1.0 |
| 3 | balance | 0.9 | 0.2 | 0.2 |

Table 2 – Mechanical properties after deformation and stepped annealing

| Alloy | Processing type | *d*, mm | Condition | $R_m$, MPa | *A*, % |
|---|---|---|---|---|---|
| 1 | CRE | 5 | μ = 14.3 | 138 | 20 |
| | Drawing | 4.5 | μ = 17.6 | 133 | 21 |
| | Stepped annealing | 4.5 | 300–400–450 °C, 50 h | 124 | 14 |
| 2 | CRE | 5 | μ = 14.3 | 192 | 42 |
| | Drawing | 4.5 | μ = 17.6 | 168 | 25 |
| | Stepped annealing | 4.5 | 300–400–450 °C, 50 h | 140 | 15 |
| 3 | CRE | 5 | μ = 14.3 | 136 | 29 |
| | Drawing | 4.5 | μ = 17.6 | 118 | 24 |
| | Stepped annealing | 4.5 | 300–400–450 °C, 50 h | 119 | 17 |

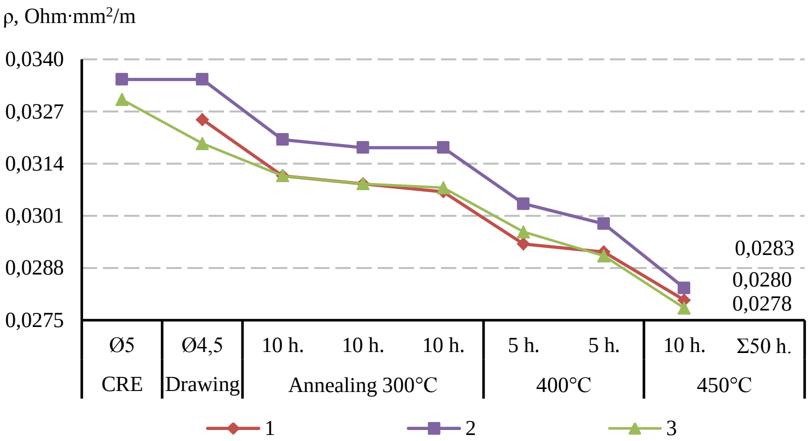


Fig. 1 – Graph showing how the electrical resistivity ρ changes after deformation and stepped annealing

The results showed that the processes of IRE, wire drawing with a drawing ratio μ = 17.6 and stepped annealing at 300–400–450°C for 50 hours of alloys 1–3 make it possible to achieve ultimate tensile strength $R_m$=119–140 MPa; elongation to failure *A*=14–17% and electrical resistivity ρ=0.0278–0.0283 Ohm·mm$^2$/m.

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UDC 669.1

# STRUCTURE AND MECHANICAL PROPERTIES OF BACKWARD EXTRUDED PURE MAGNESIUM

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Magnesium and its alloys are of great interest due to the unique combination of the excellent properties such as low density, high specific strength, suitable biodegradability and biocompatibility. Not only have Mg alloys wide potential applications as structural materials for automotive and aerospace industries, but as functional materials for medicine as well. However, Mg demonstrates low room-temperature plasticity and formability owing to the specific features of HCP-lattice structure [1, 2]. Resent research showed that methods of severe plastic deformation (SPD) such as equal channel angular extrusion (ECAE) or high-pressure torsion (HPT) could be used to enhance Mg alloys plasticity by the significant grain-refinement. Nevertheless, most of these methods were applied at above 150 ℃ [3, 4].

The aim of this study was to investigate the structure, texture and mechanical properties of the as-cast commercially pure magnesium before and after backward extrusion (BE) at room temperature.

The BE was performed on a cylindrical magnesium billet with coarse grains of 10 mm x 3 mm (Fig. 1, a) and twinning areas with grain matrix (0001) orientation. The billet was put in a steel container, a punch penetrated the billet, and metal was flowing in a 1 mm gap between the punch and the container inner wall forming a cup-shaped sample (Fig. 1, b).


a) b) c)

Fig. 1 – Mg before and after BE:
a) initial structure; b) a cup-shaped sample; c) structure after deformation

The wall of the cup-shaped sample was under investigation. After deformation, the heterogeneous structure was obtained with average grain size of 5 µm (Fig. 1, c). The (0001)-texture was detected. Nonetheless, the grains oriented to 90° about (0001)-basal plane were frequently observed indicating twining processes during BE. The tensile test of extruded Mg revealed that the tensile strength was

130.2 MPa, the yield strength was 27.8 MPa, and the elongation was about 14%. It is assumed that the main mechanisms of structure refinement are twinning, slip modes and dynamic recrystallization.

The 1 mm cup wall was rolled to 150 μm and 30 μm foils at room temperature. The deformation was found to cause the increase in the grain size up to 8–10 μm, a sharper basal (0001) texture was formed.

The BE method was successfully applied to obtain the cup-shaped Mg samples of 6-7 mm in diameter, 8 mm in wall height and about 200 μm in wall thickness. Such small cups could be considered as the billets of the thin-wall tubes to design medical stents.

Besides, the following experiments have already shown that the BE method could be used to deform the AZ31 alloy. In that case, AZ31 had to be heated up to 150 °C, however, the wall of the obtained AZ31 cup could be rolled to 200 μm at room temperature.

The results of the study could be useful for a wide practical application and helpful for development of new deformation methods of low-ductility metals at low temperature.

The study was performed in the framework of the state assignment on the themes "Pressure" (No. AAAA-A18-118020190104-3).

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UDC 539.261, 620.187, 691.75

# ANALYSIS OF STRUCTURAL PHASE TRANSFORMATIONS IN ALLOY Zn-1Li-1Mg AFTER SEVERE PLASTIC DEFORMATION

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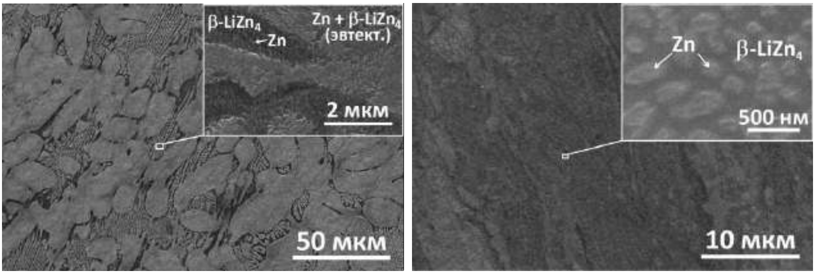
Now, zinc and its alloys show a high potential for their industrial application in medicine due to their high biocompatibility and corrosion resistance [1-3]. To improve physical and mechanical properties of zinc and expand its field of application, it is necessary to alloy zinc with certain biosoluble elements (lithium, magnesium, calcium, and others) and perform various schemes and modes of thermomechanical treatment. Zn-Li-Mg is of a particular interest among various classes of zinc alloys, since, on the one part, it is capable of aging, and, on the other part, it has corrosion resistance and biocompatibility close to pure zinc [3,4]. When applying conventional thermomechanical treatment modes (rolling + annealing), hardening in alloy Zn-1Li-1Mg occurs due to the precipitation of particles $LiZn_4$ and Zn, having mainly needle-like (cylindrical) morphology, which form a grid (Fig. 1 a). In spite of relatively high strength of this alloy (about 400 MPa), now there is still an active search for new thermomechanical treatment modes and schemes aimed at further improvement of its strength properties, which are very relevant.




a) b)

Fig. 1 – Surface of alloy Zn–1Li-1Mg:
a) original coarse-crystalline state; b) after torsion SPD

One of promising areas of mechanical treatment of metals and alloys to refine the structure and form ultrafine grained (UFG) / nanostructured states is a method of severe plastic deformation (SPD). When applying various schemes of SPD, physical and mechanical properties of alloys improve not only due to grain refinement, but also as a result of precipitations of various morphology formed during dynamic aging. In view of this, a torsion SPD method was applied to alloy Zn-1Li-1Mg to achieve record strength properties of this alloy, combining improved biocompatibility and corrosion resistance. The studies showed that the torsion SPD method applied to alloy Zn-1Li-1Mg was accompanied by a growth of strength properties. This fact is explained by refinement of eutectic phases of zinc and $LiZn_4$, and precipitations of zinc particles in eutectic β-$LiZn_4$ and β-$LiZn_4$ particles in eutectic Zn (Fig. 1 b). It was found that zinc particles in eutectic β-$LiZn_4$ were mainly precipitated in a ball shape, whose diameter varied from 80 nm to 450 nm. The detected phases were also identified and evaluated by an X-ray phase analysis. Besides, by analyzing X-ray diffraction patterns of original coarse-crystalline and UFG Zn-Li-Mg alloy, we determined lattice distance, size of coherent scattering areas, lattice micro-distortions, average dislocation density, and a share of edge dislocations in eutectic phases. We made a theoretical assessment of a contribution of various hardening mechanisms to resulting strength of alloy Zn-1Li-1Mg.

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UDC 669.715-17

# EXAMINING THE MODIFYING ABILITY OF 6063 ALLOY RODS PRODUCED BY INGOTLESS ROLLING-EXTRUSION METHOD

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Obtaining rods for the inoculation of aluminum alloys by traditional technologies includes many intermediate technological operations and the use of energy- and metal-intensive shaping equipment, the main type of which is hydraulic extruders and drawing mills. These factors lead to high production costs and low competitiveness.

An alternative to traditional methods is the use of grain refiner rods produced by high-speed crystallization-deformation [1]. Such rods reduce the grain size of the ingot not due to additional crystallization centers, but due to their refined subgrain structure (cluster hardening).

The aim of this research was to carry out a comparative analysis of the modifying ability of various grain refiners when they are introduced into molten 6063 aluminum alloy.

For the purposes of this research, grain refiner rods with a diameter of 9 mm were manufactured using the technology of ingotless rolling-extrusion IRE [2] from aluminum alloy grade 6063. The production waste generated in the course of producing rods by the IRE method from the 6063 alloy was consumed in the form of extruded profile trimmings. The Alkan test was used to determine the modifying ability of the 6063 aluminum alloy.

Analysis of the research results (see the Table) showed that during the crystallization of the 6063 aluminum alloy, most of the ingot is occupied by columnar crystals reaching the length of 7 mm. In the central part, equiaxed grains up to 0.97 mm in size were formed. The introduction of a rod made of the same alloy in the amount of 3-4% obtained by the IRE method into the 6063 melt produces a significant effect on the grain size reducing it to 0.35 mm.

Table – Modifying ability assessment results

| # | Experiment conditions | Grain sizes, mm | Microstructure |
|---|---|---|---|
| 1 | The starting material is a melt of aluminum alloy 6063. | Columnar crystals up to 7 mm. 0.97±0.08 mm equiaxed grains |  |
| 2 | An IRE rod made of 6063 alloy (3-4%) was introduced into the 6063 aluminum alloy melt; a sample was taken after 3 minutes. | Columnar crystals up to 3 mm. 0.35±0.05 mm equiaxed grains |  |
| 3 | A wire made of alloy 6063 (3-4%) shavings was introduced into the 6063 aluminum alloy melt; a sample was taken after 3 minutes. | Columnar crystals up to 4 mm. 0.69±0.07 mm equiaxed grains |  |
| 4 | A section made of 6063 alloy (3-4%) was introduced into the 6063 aluminum alloy melt; a sample was taken after 3 minutes. | Columnar crystals up to 4 mm. 0.64±0.11 mm equiaxed grains |  |
| 5 | A rod of Al-Ti-B obtained by IRE (0.0018%) was introduced into the 6063 aluminum alloy melt; a sample was taken after 0.5 min. | 0.21±0.01mm equiaxed grains |  |

For the comparative analysis, experiments were carried out using waste 6063 alloy sections and wire obtained from shavings of the same alloy as grain refiners. The introduction of such grain refiners under the same experimental conditions failed to produce a similar modifying effect as the one achieved with a rod obtained using the IRE technology. The introduction of 3-4% of the 6063 section into the 6063 aluminum melt reduced the grain size to 0.64 mm in the central regions of the ingot, while most of the ingot is made up of columnar crystals up to 4 mm long. The introduction of 3-4% wire from recycled shavings of the 6063 alloy reduced the grain size to 0.69 mm in the central regions of the ingot, while most of the ingot is also occupied by columnar crystals up to 4 mm long.

Thus, the studies have shown that the IRE technology makes it possible to obtain grain refiner rods from 6063 aluminum alloy waste, which can serve as effective grain refiners for aluminum alloys.

*This research was carried out within the framework of a governmental assignment of the Ministry of Science and Higher Education of the Russian Federation; Research Subject Code: FSRZ-2020-0013.*

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UDC 539.214

## SIMULATION OF STRAIN-INDUCED DISSOLUTION OF Zr IN Al LATTICE

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Alloys of aluminium (Al) and zirconium (Zr) have gained popularity thanks to their properties, and namely: excellent heat resistance and good electrical conductivity. However, their main drawback includes their low hardness (<75 Hv), even after severe plastic deformation. These alloys – which are, in fact, composites of Al and Al3Zr intermetallides – do not experience a strengthening effect because in the equilibrium state Zr does not mix with Al [1, 2].

The focus of this study includes an Al crystallite with grain boundary segregation of Zr. A reference cell, shown in Fig. 1, consists of 26,000 atoms (27.5 nm ×13.5 nm ×12 nm). Atoms of Zr, in the amount of 3 at %, are situated in longitudinal or transverse grain boundaries of a three-dimensional cubic face-centered crystal lattice of Al. Vacancies were also introduced in the reference cell, in the amount of 1% and 5% of all atoms. Such high concentration of vacancies accounts for the fact that the material in view is far from its equilibrium state.

The coordinates and speeds of atoms were set as starting conditions. At the time zero, the starting positions of atoms are defined by the lattice points, while the atom speeds are taken equal to zero. The simulation was conducted at a constant temperature of T=300K. The time step was 1 fs. The study was carried out in LAMMPS simulation package with OVITO software.

A molecular dynamics model was built of a three-dimensional Al polycrystal with longitudinal and transverse segregations of Zr at grain boundaries. A shear strain was simulated and graphs – built that show how stress is governed by strain and the radial distribution function. It was found that a lower strain rate was associated with a higher degree of Zr dissolution in the Al lattice. The vacancies present in the lattice contribute to the dissolution of the Zr segregation.

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UDC 621.771

# FORMATION OF A GRADIENT STRUCTURE IN LOW-CARBON STEELS DURING ASYMMETRIC SHEET ROLLING

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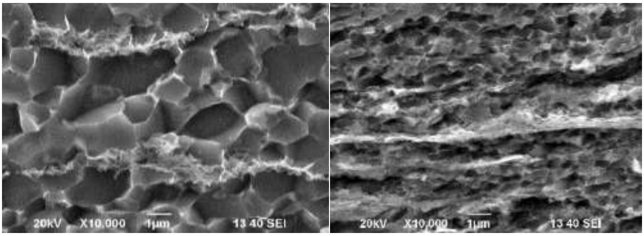
Asymmetric rolling of thin strips from low-carbon steels was conducted on laboratory industrial two-high rolling mill 400 at the Zhilyaev Laboratory of Mechanics of Gradient Nanomaterials at NMSTU. This asymmetric rolling mill has a status of unique research facility as there is no similar equipment in the world in terms of its performance parameters.

A study on the microstructure of low-carbon steels 08ps and 20 showed that asymmetric rolling with a coefficient of work roll velocity mismatch of 5, other conditions being equal, resulted in the formation of a gradient microstructure (Fig. 1). The formation of the gradient structure is explained by dynamic recrystallization as a result of significant heating of the metal strip. After asymmetric rolling of the samples of steel 08ps, there is a uniform structure, consisting of ultrafine, almost equiaxed grains of about 1000 nm in the top part of the cross-section of the strip. At the bottom of the cross-section of the strip there is a fibrous structure with finer fragments of up to 500 nm within individual fibers. After asymmetric rolling of the samples of steel 20, there is a structure consisting of ultrafine, almost equiaxed grains of 1.2 μm in the top part of the cross-section of the strip. At the bottom of the cross-section of the strip there is a clear fibrous structure with finer fragments of up to 800 nm within individual fibers.




a b

Fig. 1 – SEM images of the microstructure of steel 08ps after asymmetric rolling:
a) the microstructure in the top part of the cross-section of the strip;
b) the microstructure in the bottom part of the cross-section of the strip

It was found that the specified conditions of asymmetric rolling of steel 08ps resulted in both an increase in reduction from 62 to 80 % and a decrease in force by 2.5 times per pass in comparison with symmetric rolling. Asymmetric rolling of steel 20 results in both an increase in reduction from 73 to 85 % and a decrease in force by 2 times per pass in comparison with symmetric rolling.

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UDC 621.77

# LOOKING AT THE METAL FLOW IN THE PROCESS OF INGOTLESS ROLLING-EXTRUSION AND UNDERSTANDING THE EFFECT OF ANNEALING ON THE PROPERTIES OF RODS AND WIRES MADE OF Al–Zr–Fe AND Al–Zr–Ce–Fe ALLOYS

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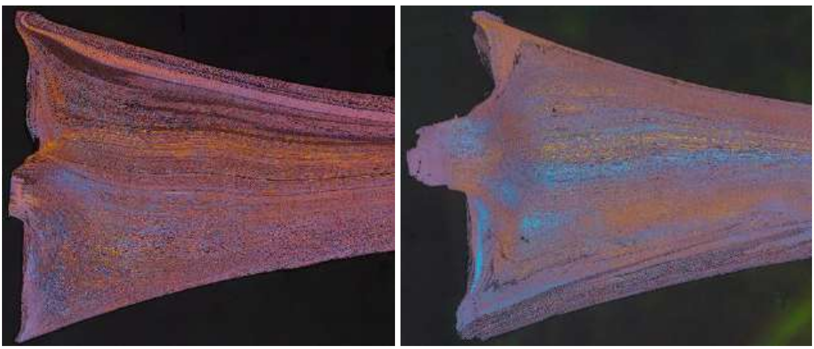
Advancements in electrical engineering, automotive and aerospace industries have led to an increased demand for conductor products made of aluminum alloys with enhanced mechanical properties, electrical conductivity and heat resistance. An effective method for making such products would be the method of ingotless rolling-extrusion (IRE) of alloys with additions of zirconium, cerium, lanthanum, and iron [1, 2, 3].

The purpose of this research was to study the nature of the metal flow in the deformation zone during IRE and to understand the effect of the composition, temperature, and annealing time on the mechanical and electro-physical properties of rods and wires made of aluminum alloys with Ce, La, Zr, and Fe.

The object of research was the extruded residues extracted from the deformation zone after IRE, Ø5 mm extruded rods, Ø4.5 mm wire made of alloys Al–0.2%Zr–1%Fe (Alloy 1) and Al–0.5%Ce–0.2%Zr–0.2%Fe (Alloy 2). The mechanical properties were determined by the tensile method on an LFM 20 testing machine, the electrical resistivity was measured with a VITOK ohmmeter, and the microstructure of the rods was analyzed using a Carl Zeiss Observer 7 Mat optical microscope.

Fig. 1 shows the grain structure of residues after IRE from alloys 1 and 2.



a b

Fig. 1 – The structure of the extruded residues after the IRE process:
a) Al–0.2%Zr–1%Fe alloy; b) Al–0.5%Ce–0.2%Zr–0.2%Fe alloy

The mechanical properties and electrical resistivity of rods and wire after IRE, drawing and annealing are presented in Table 1.

Table 1 – Properties of rods and wire before and after annealing

| Alloy | 1 | 2 |
|---|---|---|
| Ø 5 mm rods after IRE ($\mu_\Sigma$ = 14.3) | | |
| $R_m$, MPa | 192 | 136 |
| ρ, Ohm·mm$^2$/m | 0.0335 | 0.0330 |
| Ø 4.5 mm wire after drawing ($\mu_\Sigma$ = 17.6, $\varepsilon_2$ = 19%) | | |
| $R_m$, MPa | 168 | 118 |
| ρ, Ohm·mm$^2$/m | 0.0335 | 0.0319 |
| Ø 4.5 mm wire after annealing at 300ºC, 30 h | | |
| $R_m$, MPa | 171 | 131 |
| ρ, Ohm·mm$^2$/m | 0.0318 | 0.0308 |
| Ø 4.5 mm wire after annealing at 400ºC, 10 h | | |
| $R_m$, MPa | 149 | 124 |
| ρ, Ohm·mm$^2$/m | 0.0299 | 0.0291 |

The following conclusions can be drawn from this research:

– The flow in the zone of metal extrusion from the die during IRE is characterized by all-round non-uniform extrusion with a more intense shear deformation leading to an additional study of the structure;

– The rod and the wire made of Alloy 1 after IRE, drawing and annealing have higher values of ultimate tensile strength (i.e. 192 and 149 MPa);

– The rod and the wire made of Alloy 2 offer a good combination of heat resistance and electrical conductivity.

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UDC 669.56, 669.5

# MICROSTRUCTURE AND STRENGTH PROPERTIES OF ALLOY Zn-Ag-Cu AFTER SEVERE PLASTIC DEFORMATION

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Zinc and its alloys have been recently considered as potential materials for medical applications as implants for osteosynthesis and vascular stents [1].

The present paper studies the effect of severe plastic deformation (SPD) on the microstructure and strength properties of zinc alloy Zn-Ag-Cu with various ratios of alloying element Ag, namely from 1 to 4%. The samples underwent equal channel angular pressing (ECAP) according to sequence Bc with an angle of crossing channels of 120° at 150-350 °C.

The material becomes stronger with an increase in alloying element Ag. ECAP contributed to increasing ultimate tensile strength and ductility of the material to 430 MPa and 30% of percentage elongation, respectively [3]. The paper presents a detailed analysis of relations and mechanisms of improvement of functional properties.

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UDC 621.77.01

# STUDY ON THE DEFORMATION BEHAVIOR OF STEEL SUPER DUPLEX 25 Cr AND ITS EFFECT ON PROPERTIES OF FINISHED STEEL PRODUCTS

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Duplex stainless steels (DSS) are a family of alloys based on Fe-Cr-Ni, containing comparable volume fractions of δ-ferrite and γ-austenite in the structure [1–3]. Having a unique combination of high corrosion resistance and strength, DSS are more and more applied in the chemical, oil and gas, and shipbuilding industries [4–6]. Standard DSS contain 21–23% of chromium and 4.5–6.5% of nickel. Additives of molybdenum (3–3.5%) and nitrogen (0.08–0.20%) increase resistance to pitting corrosion and ensure additional solid solution hardening. In Russia, the industrial production of duplex stainless steels and products from them is under development. The primary task is to determine the permissible modes of forging or rolling of cast billets, in particular, to determine the limit values and strain rates guaranteeing no hot cracks, and to assess the required energy and power parameters of forging or rolling equipment. To study the deformation behavior of steel under consideration, we simulated hot deformation of cast samples from the ingot, whose chemical composition is given in Table 1, on Gleeble 3800 at 1100 ℃, 1150 ℃, 1200 ℃ and 1250 ℃ at speeds of 0.1 $s^{-1}$; 1 $s^{-1}$ and 10 $s^{-1}$.

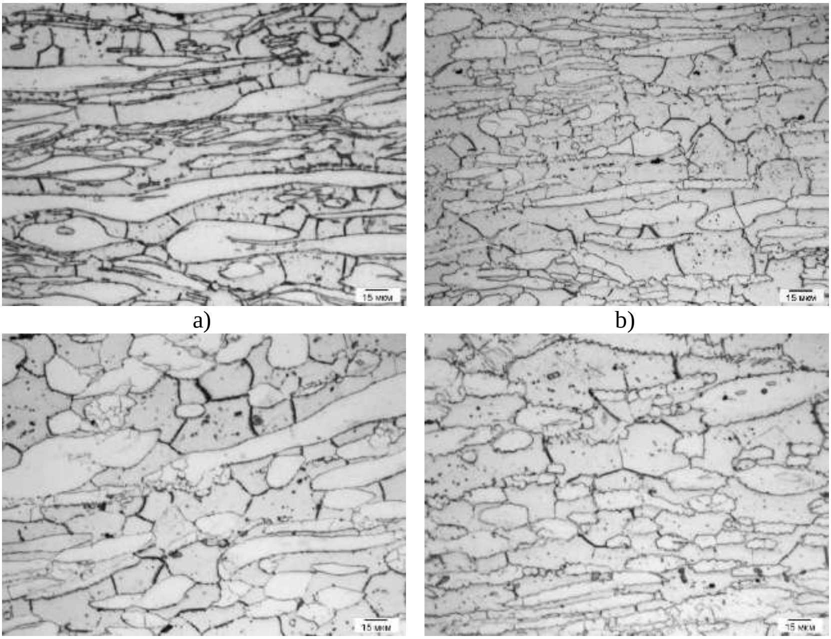
A typical microstructure of steel under study (Table 1), forming during hot deformation, is given in Fig. 1.

Table 1 – Chemical composition of steel under study, wt. %

| C | Mn | Si | Ni | Cr | Cu | Mo | W | V | N |
|---|---|---|---|---|---|---|---|---|---|
| 0.018 | 1.06 | 0.38 | 6.35 | 25.55 | 0.09 | 4.05 | 0.02 | 0.22 | 0.30 |

The microstructure of steel under study in the as-cast state consists of a matrix δ- ferrite and elongated island crystals of γ-austenite. A share of austenite assessed by the area occupied by its crystals in optical microscopy images is ~45%. The ferritic matrix and the boundaries with austenitic areas contain precipitation of secondary phases of different morphology, formed during ingot cooling after crystallization. Experimental flow curves obtained in three-time tests according to the same deformation modes have a similar shape, but slightly differ in yield stresses (by 5% or less) due to a non-uniform cast structure.

Regarding all the deformation modes under study, the ferritic matrix gets a dynamically recrystallized structure demonstrated by an equiaxed grain structure of ferrite. On the other part, most austenite regions are elongated along the normal to the applied compressive load. The degree of elongation of austenite regions and, consequently, deformation perceived by austenite increase with lower temperature and higher strain rate. The microstructure of the samples deformed at 1100 ℃, 1 $s^{-1}$ and 10 $s^{-1}$ does not contain any signs of dynamic recrystallization of austenite. Therefore, the mechanism of weakening of austenite is dynamic recovery (Fig. 1, a). An increase in temperature of deformation at 10 $s^{-1}$ activates initial stages of dynamic recrystallization of austenite. Boundaries of austenite regions gain characteristic serration, individual equiaxed austenite grains are formed (Fig. 1, b). When decreasing the strain rate to 0.1 $s^{-1}$, partial dynamic recrystallization of austenite occurs more fully and in a complete range of deformation temperatures under study (Fig. 1, c, d). Thus, we did not notice a sharp start of dynamic recrystallization with an increase in the strain rate as stated in paper [22].



a) b) c) d)

Fig. 1 – Microstructure of steel Super Duplex 25Cr after various temperature and speed modes of deformation, ×500: a) 1100℃, 10 $s^{-1}$; b) 1200℃, 10 $s^{-1}$; c) 1100℃, 0.1 $s^{-1}$; d) 1200℃, 0.1 $s^{-1}$

At LLC ZMP we produced 2 ingots with a diameter of 450 mm and weight of 1 t each, showing a chemical composition of steel Super Duplex 25Cr (Table 2).

Table 2 – Chemical composition of test ingots, wt. %

| Ingots | C | Mn | Si | P | S | Ni | Cr | Mo | V | Cu | N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SD-1 | 0.018 | 1.06 | 0.38 | 0.006 | 0.006 | 6.35 | 25.55 | 4.05 | 0.22 | 0.09 | 0.30 |
| SD-2 | 0.021 | 1.03 | 0.38 | 0.017 | 0.008 | 6.40 | 25.35 | 4.25 | 0.21 | 0.09 | 0.28 |

The ingots were formed by different modes: ingot SD-1 was forged to a final size of 125 mm in diameter in several passes; ingot SD-2 was forged to a final size of 180 mm in a square section, and then rolled to a final size of 125 mm in diameter.

The test results of mechanical properties after heat treatment (1100 °C, water cooling) are given in Table 3.

Table 3 – Tests of mechanical properties

| Sample No./ type | | $\sigma_B$, N/mm$^2$ | $\sigma_T$, N/mm$^2$ | $\delta_5$, % | $\psi$, % | Hardness, HB | Impact energy $KV_{-46}$, J |
|---|---|---|---|---|---|---|---|
| ingot SD-1 | | | | | | | |
| 1 | longitudinal | 813 | 667 | 27.6 | 71.0 | 234 | 41 |
| 2 | | 805 | 639 | 31.6 | 66.7 | 241 | 40 |
| 3 | transverse | 838 | 646 | 28.0 | 42.7 | 234 | 16 |
| 4 | | 825 | 636 | 25.6 | 30.0 | 234 | 18 |
| ingot SD-2 | | | | | | | |
| 1 | longitudinal | 885 | 688 | 31.6 | 68.1 | 248 | 68 |
| 2 | | 890 | 699 | 29.2 | 65.0 | 255 | 99 |
| 3 | transverse | 848 | 662 | 21.2 | 55.7 | 235 | 43 |
| 4 | | 850 | 659 | 25.2 | 53.2 | 262 | 48 |
| Requirements | | 800 or higher | 550 or higher | 20 or higher | n/a | 310 or less | 35 (unit)/45 (av.) or higher |

At industrial facilities we determined that the scheme of deformation, including rolling operations, ensured achievement of physical and mechanical properties of finished steel products, satisfying the set requirements.

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UDC 669

## PROSPECTS OF MASTERING MANUFACTURING ALUMINUM LAYERED COMPOSITE AMg3/D16/AMg3

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Layered composites from aluminum alloys are in a great demand in the aerospace and automotive industries due to the possibility of combining different properties in one product, such as high specific strength, corrosion resistance, thermal conductivity, etc. [1]. Aircraft engineering applies aluminum alloys to manufacture load-bearing elements, for example, wing panels, fuselage shell, stringers and others. The most suitable basis of a layered composite is high-strength alloys of 2xxx series. The most commonly used alloy is D16, characterized by high specific strength and fatigue strength, as well as low corrosion resistance. To solve this problem, alloy D16 is usually clad with commercially pure aluminum. More advanced combinations include high-strength aluminum alloys of 2xxx series with outer layers from aluminum alloys of 5xxx series. For example, in [2] a promising layered composite is proposed for the aviation industry, namely 2219/5086, and in [3], layered composite 2024/5083.

Main methods for manufacturing layered panels from aluminum alloys are cold, warm or hot roll bonding, as well as accumulative roll bonding. Success of industrial mastering of rolling by one of the methods is determined by achieved strength of layer bonding, which is one of the most important characteristics of a layered composite.

In view of the above relevance, the Institute of Engineering Science of the Ural Branch of the Russian Academy of Sciences developed and mastered a manufacturing process for layered composite AMg3/D16/AMg3 (Fig. 1) for aviation applications. Mechanical tests, microstructural and fractographic studies confirmed high strength of the bonded layers. Fig. 1 shows the bonding zone of alloys AMg3 and D16. As we can see, the initial bonding boundary between the materials is not distinctive due to mutual diffusion processes.

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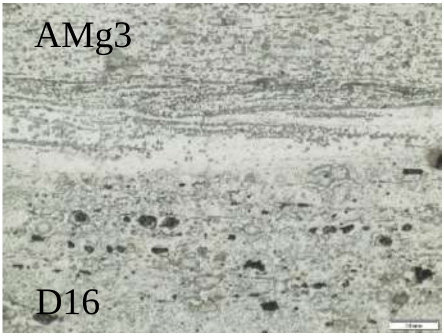

Fig. 1 – Section of layered composite AMg3/D16/AMg3
in the zone of layer bonding

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UDC 620.3

## ANALYSIS OF THE UFG STRUCTURE AND MECHANICAL PROPERTIES OF THE MAGNESIUM ALLOY PRODUCED BY ECAP

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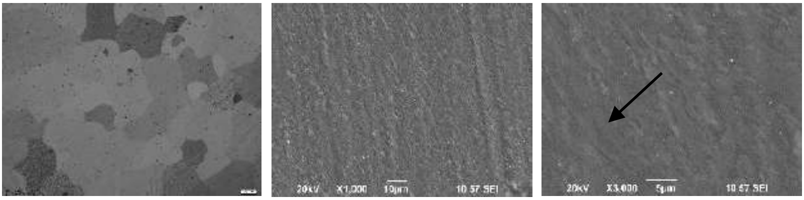
Magnesium attracted great attention in the field of biomedicine due to its unique properties, such as density and modulus of elasticity close to properties of cortical bone. Moreover, biosolubility of magnesium opens up new opportunities in surgery for creating temporary implants. Biodegradable implants are to meet the following requirements: solubility within 3-6 months, biocompatibility with the human body, non-toxicity, and mechanical properties close to bone. However, pure magnesium has low strength properties. Alloying is a method of improving mechanical properties and corrosion behavior of magnesium. We, as well as other authors, studied the effect of several alloying elements on properties of magnesium in previous research [2-4]. Calcium (Ca) and zinc (Zn) are non-toxic to the human body because they are naturally present in it. Therefore, Mg-based alloys containing these elements individually or in a set are under study as suitable materials for the use as biomaterials. This study is devoted to ternary alloy Mg–1Zn–0.15Ca.

To form a UFG state, we applied a method of equal channel angular pressing (ECAP) in 8 passes, while decreasing temperature from 400 to 250℃. The microstructure was analyzed by optical light microscopy and scanning electron microscopy methods. Mechanical tensile tests were performed with small specimens with an operational gage of 0.6x4.5 $mm^2$.

An original structure is non-uniform, consisting of equiaxed grains, 100-800 μm in size (Fig. 1, a).

The structure analysis showed that ECAP resulted in forming elongated grains, 1.8 μm. (Fig. 1, c).

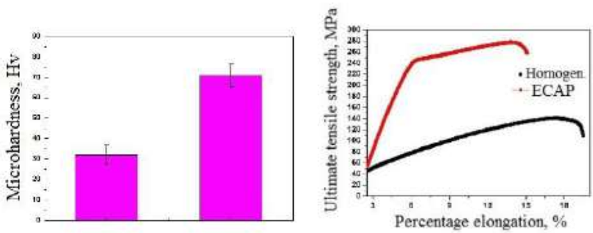



a) b) c)

Fig. 1 – a) Structure of a homogenized state, b, c) Structure in the scanning electron microscope after ECAP

Fig. 2 presents a diagram of microhardness and elongation of the alloy under study in its original state and after ECAP. Microhardness of the homogenized coarse-grain state of alloy Mg-1%Zn-0.15Ca was 32 Hv. As a result of ECAP, the occurred structural changes ensure an increase in microhardness to 71 Hv (Fig. 2, a).

Fig. 2 presents a diagram of elongation of the alloy under study in its original state and after ECAP. Alloy Mg-1Zn-0.15Ca in its homogenized state has higher strength (141 MPa) than pure magnesium (35 MPa) [5]. After ECAP its strength increased to 277 MPa, almost by twice higher as compared with the homogenized state (Fig. 2, b). Following the results obtained, we come to a conclusion about the effect of the average grain size on the alloy strength parameters: the smaller the average grain size is, the higher strength characteristics are.




a) b)

Fig. 2 – a) Microhardness of alloy Mg-1%Zn-0.15%Ca in its homogenized state and after ECAP; b) Curves of mechanical tensile tests on alloy Mg-1%Zn-0.15%Ca before and after ECAP

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UDC 669.717

## IMPROVING THE HEAT TREATMENT TECHNOLOGY OF HOT ROLLED PLATES FROM ALUMINUM ALLOY 7475

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Alloy 7475 is attributed to the system of aluminum alloys of 7xxx series, combining high strength and corrosion resistance in delivery states T73 [1]. The content of the main alloying elements in the alloy: copper (Cu) is 1.2-1.9%, silicon (Si) is 0.1% or less, iron (Fe) is 0.12% or less, manganese (Mn) is 0.06% or less, magnesium (Mg) is 1.9-2.6% [2]. The given alloy is used to produce plates, 6.35-101.6 mm thick, in delivery states T7351 (solid solution heat treatment, tension leveling with a residual strain rate of 1.5-3.0%, artificial aging in a two-stage mode) applied in products of civil aviation equipment, for example, for manufacturing of panels of airplane wings [3].

OJSC KUMZ produces plates from alloy 7475 in delivery state T7351 according to the following process: billet casting, homogenization, hot rolling, solid solution heat treatment (quenching), artificial aging. One of current problems with manufacturing of such plates, while ensuring the required reserve of mechanical properties of 1.5 ksi or higher in standard requirements, is difference in strength properties of samples tested for tensile strength at room temperature, taken from the head and the tail of the original plate. Ultimate tensile strength of the samples from the tail of the plate is higher (the difference in the obtained test results was up to 5 ksi). Such difference in the properties requires an additional cycle of treatment and control of mechanical properties till cutting plates to length, entailing a longer production process.

To stabilize properties at tails of plates, we tried to adjust the heat treatment mode.

The experimental study was conducted with plates, 31.75 mm thick. Solid solution heat treatment of the plates was carried out on a horizontal quenching machine by EBNER. To adjust the heat treatment mode, we decided to decrease speed of the rolling table in the quenching zone by 10% as compared with speed of HT.

Batches of the plates, 31.75 mm thick, were heat treated according to the adjusted mode without any comments on flatness values. A photo of the plate, 31.75 mm thick, from alloy 7475, showing satisfactory flatness after heat treatment according to the adjusted mode, is given in Fig. 1.

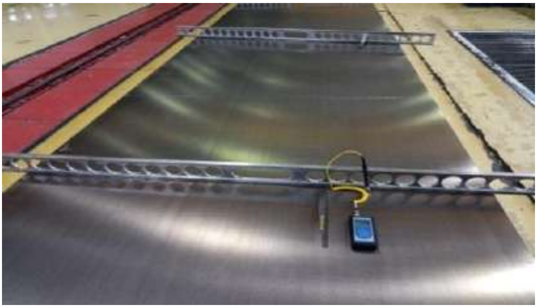

Fig. 1 – The plate, 31.75 mm thick, from alloy 7475, showing satisfactory flatness after heat treatment according to the adjusted mode

Having received the results of the tensile test of such plates at room temperature, we analyzed average values of the ultimate tensile strength deviation in the L and LT directions between the head and the tail of the plates (Table 1).

Table 1 – Average values of mechanical properties of the plates, 31.75 mm thick

| Thickness is 31.75 mm | L | LT |
|---|---|---|
| Average difference in ultimate tensile strength of the head and the tail of the plate (according to the HT mode), ksi | 3.9 | 2.2 |
| Average difference in ultimate tensile strength of the head and the tail of the plate according to the adjusted mode, ksi | 1.8 | 1.5 |

Table 1 shows that despite of the adjusted mode, the head and the tail of the plate have different mechanical properties. However, in the adjusted heat treatment mode, such difference becomes less.

Thus, the adjusted solid solution heat treatment mode of the plates from alloy 7475 in delivery state T7351 contributed to obtaining the required reserve of mechanical properties of the plates, showing a minimum difference in the properties of tails of the plates.

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UDC 621.771

## DEVELOPING COMPOSITIONS OF SPARINGLY DOPED HIGH-STRENGTH COLD-RESISTANT STEELS OF VARIOUS STRENGTH GRADES

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A series of studies has been carried out, upon which compositions of sparingly doped steels were proposed, as well as rational regimes of heat treatment applicable to high-strength cold-resistant hot-rolled steel sheets of various strength grades [1-6]. The requirements to the mechanical properties of high-strength cold-resistant steels are specified in the European standard EN 10025-6 [7].

Doping of steels simultaneously with chromium, nickel, molybdenum, vanadium and niobium leads to a significantly increased cost of continuously cast billets. This research aims to develop compositions of sparingly doped steels and heat treatment regimes that would enable to reduce the cost of this type of product. Test batches of sparingly doped steels were produced in laboratory conditions. In order to understand the effect of doping elements on the mechanical performance and structure of the test steel grades: the concentration of molybdenum was varied from 0.014 to 0.305 %; 0.003 to 0.006 % of vanadium and/or niobium and 0.001 to 0.015 % of titanium were additionally introduced or these elements were completely removed from the composition; the concentrations of carbon, manganese, chromium and silicon were left unchanged.

Test steel grades were produced in a vacuum induction furnace ZG-0.06L. 300 mm thick ingots were pressed in a hydraulic press with a force of 250 tons and with the maximum billet temperature of 1,250°C. The billets were then reduced in a reversing two-high hot mill 500. The ingots were pre-heated to 1,200°C, the end of rolling temperature was 850–950°C. After rolling, the rods were cooled down in calm air. By means of thermal analysis, critical points $Ac_1$ and $Ac_3$ of the studied steels during heating were determined, and CCT diagrams – built reflecting the decomposition of supercooled austenite after the subsequent cooling at various rates.

In the course of metallographic studies, the authors examined the microstructure of the test steels in as-hot-rolled, as-quenched and as-tempered states. After the specimens had been laboratory heat treated following the following regime: quenching from 850 ºC + tempering at 200, 300, 400, 500 and 6,000 ºC, a series of tensile tests (at room temperature) and impact bend tests (at minus 60 ºC) was conducted. The results of the tests were used to analyze how the performance of the test steels is governed by their chemical composition and tempering temperature. Based on the conducted studies, the authors were able to elaborate a substantiated approach to rational doping of high-strength cold-resistant steels designed for the production of hot-rolled sheets. The proposed compositions of sparingly doped steels and heat treatment regimes were tested at Magnitogorsk Iron & Steel Works.

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UDC 621.983

# FINDING WAYS TO OPTIMIZE A PRESSING PROCESS OF ALUMINUM ALLOYS

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Reduced metallurgical waste, and, therefore, increased productivity can be achieved in various ways. One of the ways to increase productivity of pressing facilities is to reduce waste supplied to remelting. The volume of waste materials, in turn, is divided into two types: metal rejected due to a failure to comply with the process modes of deformation or heat treatment, and metal waste due to the features of the technological process. Waste associated with an unrecoverable defect is supplied to the furnace burden for secondary remelting, while the second type of waste can be used at subsequent processing stages. However, to recycle waste without metallurgical divisions, it is required to develop methods for processing metal with removable defects. Moreover, such methods can be either heat treatment or special modes of plastic deformation, or a combination of them.

Regarding the pressing facilities at OJSC KUMZ, we analyzed typical waste of semi-finished products from aluminum alloys that could be reused. The scheme shows how a pressed billet is divided into several parts (Fig. 1).

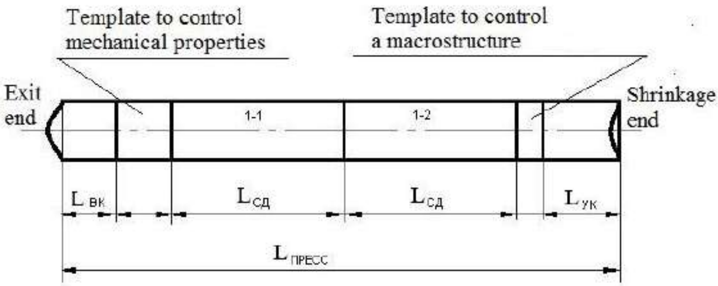


Fig. 1 – Scheme of cutting the front end of the rod after pressing. $L_{ПРЕСС}$ is pressed length of the product; $L_{СД}$ is length of the delivered product; $L_{ВК}$ is length of the exit end cut to waste; $L_{УК}$ is length of the shrinkage end cut to waste; 1-1, 1-2 workpiece numbers in the rod

A share of metal of the exit and shrinkage ends to be cut to waste is a considerable part of length of the delivered product. The highest volume of metal is supplied to remelting at the first pressing stages, when the diameter of the pressed product is from 500 to 800 mm. As the product diameter decreases, this volume decreases proportionally. To assess the possibility of recycling the waste generated at the process stage under consideration, we conducted studies to assess potential types of scrap metal at the exit and shrinkage ends. It was found that, as a rule, the exit ends had the structure of a non-deformed material and did not contain non-removable defects. Thus, it is possible to recycle the exit ends at the area of pressing facilities, excluding the metallurgical division. This will significantly reduce the cost of manufacturing products from aluminum alloys and mitigate the negative environmental impact of metallurgical facilities.

UDC 669.1

## MASTERING MANUFACTURING OF ZINC-ALUMINUM COATED WIRE ON A NEW HEAT TREATMENT AND HOT DIP GALVANIZING LINE BY FIB FOR WIRE 1.0-6.0 MM IN DIAMETER

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Now, in the changing economic situation of the market and continuously increasing requirements of consumers for the corrosion resistance of rolled products, there is a need for mastering new types of products with higher surface corrosion resistance and extended service life [1, 2]. In addition to the required level of protection, in many cases there are special requirements for ductility (deformability) imposed on coatings [3]. According to international practice, zinc-aluminum coatings meet all the above requirements. This paper describes a modern zinc coating with aluminum and mischmetals, when mastering the technology of hot dip galvanizing of wire on a new heat treatment and hot dip galvanizing line by FIB at OJSC MMK-METIZ. Now, the zinc-aluminum coating is used at OJSC MMK-METIZ in manufacturing annealed low-carbon wire, including wire used for gabion structures [4].

A key objective of the research is to analyze main properties of a promising type of the coating from the alloy of zinc with aluminum and mischmetals (ZAMM) and develop the technology of manufacturing low-carbon wire with a zinc-aluminum coating at OJSC MMK-METIZ.

The paper presents the manufacturing process for zinc-aluminum coated wire, the developed operation parameters for manufacturing annealed low-carbon wire with a new type of coating, and the studied requirements for finished products with a ZnAl coating. A metallographic analysis of the samples of zinc-aluminum coated wire was carried out at the laboratory of OJSC MMK-METIZ and the laboratory of PJSC MMK, including an analysis of the location of intermetallic layers of a ZnAl coating (Fig. 1).

As a result of the research, OJSC MMK-METIZ produced zinc-aluminum coated wire, fully complying with the regulatory documentation. It was found that mischmetals and other elements in the molten alloy ensured high corrosion resistance of the coating. The coating structure consists of several layers (the layer with prevailing Al inhibits the corrosion rate).

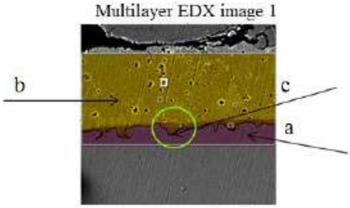


Fig. 1 – Multilayer EDX image of the section: a is steel; b is a ZnAl coating; c is an intermetallic layer (a layer with prevailing Al)

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UDC 621.7.01

# LOOKING AT THE DEFORMATION ZONE TEMPERATURE DURING HOT ROLLING

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In the production of rolled products, it is important to monitor the temperature and adjust it appropriately as the process develops. Temperature fluctuations are of critical importance for the production process as the temperature governs the mechanical properties of the final product (e.g. the yield strength). Besides, temperature fluctuations can impact the microstructure and other characteristics of rolled steel. Different hot rolling process stages can influence the plate temperature in different ways. On the one hand, the plate temperature goes down as the result of air cooling or contact with water and work rolls. And on the other hand, the strain created during rolling leads to a temperature rise in the deformation zone [1-3].

This paper looks at the temperature in the deformation zone and how it changes during hot rolling process. Thermocouples TPK021 were embossed in square steel specimens. The specimens were heated up in a muffle-type furnace MIMP-M to the temperature of 1,050 ºC. The hot specimens were then rolled in a laboratory two-high reversing mill 200 with the total reduction of 50% (Fig. 1).

a) b)

Fig. 1 – Hot steel specimen: a) before forming b) after forming

The temperature data were read off the thermocouples by a programmable logical controller at a 0.01 sec interval and recorded on a personal computer with the help of MasterSCADA. The data were then processed and are presented in the graph in Fig. 2.

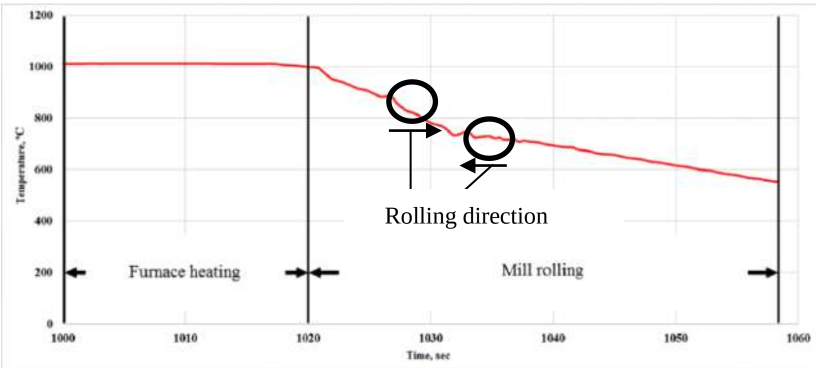


Fig. 2 – Heating and forming of steel specimens

Two reverse passes were performed, with a 25% reduction in each. In Fig. 2, the temperature rise is associated with the mill rolling. The forming ensured a 13°C temperature rise.

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UDC 621.774

## ASSESSMENT OF TUBE WALL THINNING DURING MANDREL BENDING

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The tube cold bending method developed at South Ural State University [1] with additional impact of a rotary mandrel on the bending tube contributed to the improved quality of products, lower bending forces, better smoothness of bending and considerably lower power consumption and economic costs. The steel plastic flow during this type of bending implies a considerable change in wall thickness in some areas [2, 3]. Wall thinning on an external radius is of particular importance.

By applying licensed software MSC.Marc, we simulated bending of tube ∅60 mm with a wall thickness of 4 mm from St10 with mandrel bending with three forming elements at an angle of 30°. Interference was 1 mm. We calculated wall thickness in different points of the cross section.

To compare the results obtained by the computer calculation, we measured wall thicknesses of tubes, 60 mm in diameter, bent by using the new technology in various cross sections. We plated the graphs showing average values of tube wall thicknesses in various points obtained as a result of computer and full-scale experiments (Fig. 1).

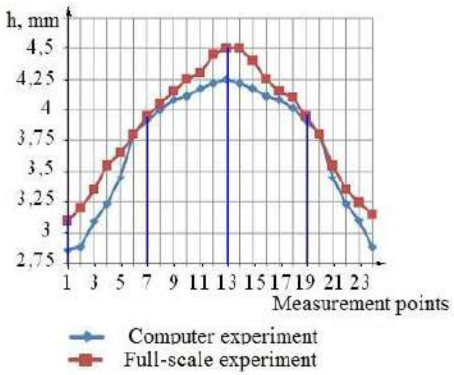


Fig. 1 – Comparison of tube wall thicknesses

Having compared the computer simulation results with actual values of wall thicknesses, we conclude that the deviation does not exceed 6–8%. This indicates the validity of the designed computer model for the actual process of mandrel bending.

When designing the computer model, we also obtained the longitudinal profile of the tube under bending to assess the change in outer wall thickness along the length of the resulting product (Fig. 2). By comparing the actual profile of the bent tube (Fig. 3) with the one obtained during the computer simulation, we also conclude that the computer model almost completely coincides with the actual bending process.

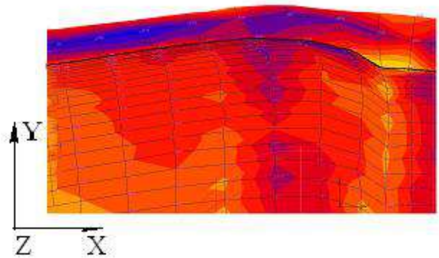


Fig. 2 – Longitudinal section of the outer tube wall in the computer simulation

Fig. 3 – Longitudinal section of the outer tube wall in section

Thus, the developed computer model predicts the value of outer tube wall thinning during mandrel bending. This is of great practical importance for the subsequent operation of products manufactured by the new technology, as tube wall thinning of the tube under bending is one of the most important performance characteristics [4]. Depending on the bending radius, as demonstrated by the calculations, outer wall thinning of the tube under bending is from 15% at $R_{bending}=2.5D_y$ to 40% at $R_{bending}=1.5D_y$.

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# PRESSURE WELDING OF DISSIMILAR MATERIALS BY ASYMMETRIC ROLLING

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At the basis of producing bimetallic materials there lies a process of creating a permanent joint between dissimilar materials that would have high pull and shear strengths. In the bimetal production practice, dissimilar components often come together when they are jointly subjected to plastic deformation or pressure welding [1].

Asymmetric sheet rolling offers an innovative technique for making bimetallic strips. Asymmetry helps minimize the negative effect of contact friction and thus increase compressive stresses and create significant shear stresses in the deformation zone.

Asymmetry can be created due to the following main factors: 1) use of different diameters of the rolls; 2) setting different roll spin rates; 3) creating different material/roll surface friction coefficients; 4) adjusting the heating temperature; 5) use of combinations of the above factors [2, 3].

Asymmetric rolling has a lot of potential as it combines the benefits of standard synchronous rolling and shear welding. During shear welding, normal and tangential forces are applied simultaneously, the welded parts get compressed and at the same time sheared in the interface plane. This helps destroy oxide films [4]. Less normal forces are required for shear welding than for other welding techniques (point welding, seam welding, overlap welding).

In longitudinal rolling (unlike it is in shear welding), the linear surface strains are quite high, which results in partial destruction of oxide films and their distribution along the entire joint area. In spite of the presence of residual films, the strength of the joint remains high.

Asymmetric rolling combines shear strains with strong metal flow across the joint plane forcing out oxide films. And thus conditions are created for intense motion of dislocations and emergence of active centers in the contact zone. In other words, the coming together of juvenile (oxide film free) surfaces becomes more probable.

Before applying pressure to start plastic deformation, one needs to prep the surfaces to be joined together. Common surface preparation techniques will work for asymmetric rolling: 1) clean the surfaces of the work rolls and the workpieces with solvent; 2) clean with wire brushes; 3) install solid films by deformation cladding with flexible tool [5]; 4) install solid films by plating (mainly nickelizing).

Chemical cleaning is not recommended as residual chemicals almost always remain on the surfaces compromising the strength of the resulting weld, which would require that neutralization and passivation were additionally used. Besides, the chemical methods are harmful for the environment as great amounts of solvents end up in the sewer [6].

Mechanical prepping techniques can be practically inconvenient for cold welding of small parts. In this case, heat treatment can be used. For example, aluminium parts can be air baked at 350-400 °C, in which case fatty films burn off the surface [7].

Asymmetric rolling can potentially be used in blank production for sever plastic deformation of thin bimetals. Asymmetric rolling can also potentially be used for creating ultrafine-grained structures and enhancing the strength and plasticity of semi-finished flat products [8].

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UDC 621.77

# PRODUCTION OF SHEET STAMPED SPACE-ROCKET PARTS FROM ALLOY 1580

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Alloys of the Al-Mg system doped with scandium are widely used for the production of flat products in the form of plates and sheets. One of these alloys is 1580 aluminum alloy containing 0.1 to 0.12% of scandium. These alloys are characterized by low specific weight, high processability in hot forming, high strength (see the Table), as well as high corrosion resistance and good weldability [1].

Table – Mechanical properties and composition of alloy 1580

| Alloy grade | Chemical composition | Mechanical properties | | |
|---|---|---|---|---|
| | | $R_m$, MPa | $R_p$, MPa | $A$, % |
| 1580 | Al-5Mg-0.6Mn-0.1Sc-0.12Zr | 380 | 260 | 19 |

Plates with the thicknesses of 22.5 to 35 mm were made by hot rolling from alloy 1580, and sheets up to 2 mm thick – by cold rolling. Further, the authors proposed new methods, devices and technologies for the manufacture of shell rings from plates and thin-walled spherical shells from sheets.

Plates made of alloy 1580 with the thicknesses of 22.5 to 35 mm are used for the production of shell rings, for the manufacture of which a universal device has been developed that can be used for both crank and hydraulic presses (Fig. 1). The advantage of the proposed device is its versatility as it can be used to make shell rings of different diameters, as well as an increased efficiency of the sheet stamping process achieved through the use of a more advanced die design that comprises universal blocks. The latter make it easier to manufacture a stamp while also making it lighter.

2 mm thick sheets are proposed to be used for the production of thin-walled spherical shells of large sizes, with the relative thickness $(S/D)\times100 < 0.5$. Such shells are normally produced by drawing in hydraulic presses from round flat blanks with a diameter of 2 m or more, obtained by cutting.

The method of manufacturing thin-walled spherical shells [2], which includes punching a blank of a given diameter, drawing, annealing, and sizing, differs in that before drawing a part with a ratio of $(S/D)\times100 \leq 0.5$, annular ribs are made in the form of concentric circles (Fig. 2). The total surface area of the ribs in this case should be 70÷80% of the surface area of the finished part, excluding the area of the blank flange.

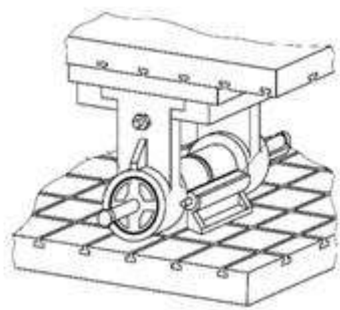

Fig. 1 – General view of a universal stamp assembly for bending shell rings

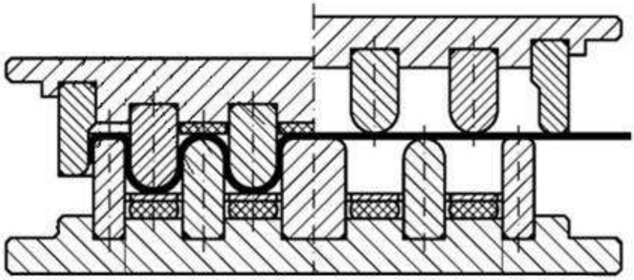

Fig. 2 – General view of a die for forming ring ribs

Thus, a solution to a complex technical problem has been found, and namely, the efficiency of the sheet stamping process and the yield of suitable metal have been increased by reducing the amount of defects in the manufacture of thin-walled spherical shells of large sizes of the same thickness.

*This research was carried out as part of a governmental assignment given to the Siberian Federal University, Project No.: FSRZ-2020-0013.*

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## USE OF EXPERIMENT RESULTS FOR SIMULATION MODELLING OF ROLLING MILL ELECTRIC DRIVES UNDER SPEED ASYMMETRY

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One of the steps to build a simulation model of the rolling mill electric drive system involves describing the deformation zone and accounting for the effect of interstand tensions, if they are present. The techniques applied here are based on the well-known equations of the rolling theory obtained for perfect symmetrical modes: the roll speeds and diameters are the same, while any changes in the temperature or friction coefficients are not accounted for. Any type of asymmetry – kinematic, temperature and so on – makes the physical processes developing in the deformation zone more complicated and makes it impossible to use applied analytical techniques for calculating the parameters of power and forces. Finite element models [1, 2] helped obtain some acceptable results when conducting a theoretical study of asymmetric rolling. A significant drawback of such models is that they mainly describe the processes taking place in the deformation zone from the production point of view while overlooking the operation of the electric drive. The only reliable way to obtain data characterizing the parameters of power and forces of the mill drive would be to conduct an experiment on a functioning mill [3].

In the course of a full-scale experiment that was carried out on a 5-stand mill 630 run by MMK's Rolling Facility 8, some oscillograph charts covering the key coordinates of the main drives (armature current, speed, voltage and others) were obtained. They were used to determine the relationships between the torques of the top (master) and bottom (slave) rolls and the coefficient of asymmetry $K_{as}$ (Fig. 1).

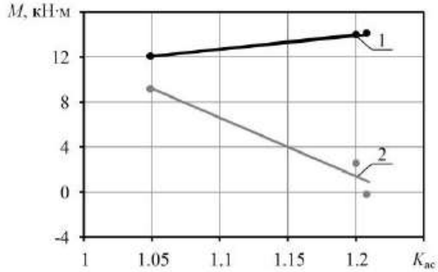


Fig. 1 – Relationships between the rolling torques and the asymmetry coefficient 1 – top roll; 2 – bottom roll

Using the above data, one can build a full-scale model of all main drives of this mill allowing for the existing automatic control systems covering the strip speed, tension and thickness. The block diagram showing such dependences is given in Fig. 2. Such model can be built avoiding giving a detailed description of the deformation zone during asymmetric rolling, and blocks FP 1 and FP 2, which realize the dependences $M_1$, $M_2$ = $f(K_{as})$, help account for the unbalanced load between the top and bottom rolls in the conditions of speed asymmetry.

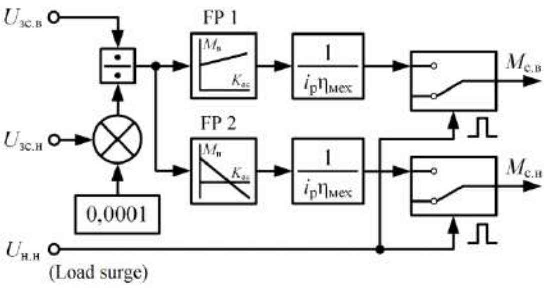


Fig. 2 – Distribution of motor torques between the top and bottom rolls under controlled speed asymmetry

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# AN INTEGRATED STUDY ON PIPE PRESSING PROCESSES BY THE FINITE ELEMENT METHOD

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Mathematical modeling using the finite element method (FEM) is widely used because it is rather accurate and the least labor-consuming [1-4].

Since mastering of new types of products is usually associated with the development of process modes of pipe manufacturing, it is necessary to use modeling of the pipe production process in QForm 2D/3D.

This paper studies 3 processes, where there are difficulties with manufacturing pipes from low ductility steel grades by hot pressing.

The most common surface defects of hot pressed pipes are flaws, breaks, cracks and ripple markings. The greatest influence on the possibility of surface defects on hot pressed pipes is exerted by temperature and strain parameters and tribological features of the process [5].

By modeling the stress and strain state of the surface layers of the workpiece during pressing, we determined the nature of changes in the strain rate, temperature, and stress state along length of the deformation zone. Thus, the simulation revealed that external defects during pressing can be found only at the end of the deformation zone, where the stress state values are within the range of 0-0.58 [6].

The following study was devoted to excluding the formation of defects on the internal surface of blooms in the metal breakaway zone during punch piercing of workpieces. We simulated a workpiece piercing process (Fig. 1) to determine the features of the forming process and possibility of the surface defect formation.

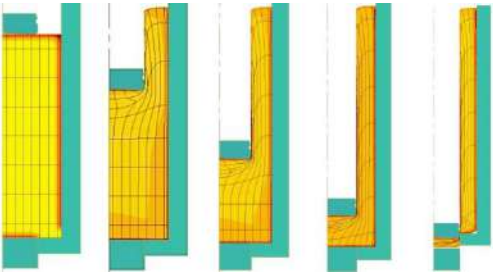

Fig. 1 – Nature of the metal flow during forming

The designed model served as a basis for developing technological measures aimed at excluding the formation of defects on the internal surface of blooms.

The third study lay in reducing tool wear and industrial waste by improving the gaging of press equipment (expanding machines) of a 2500 t piercing press, when manufacturing pipes according to the double expanding technology. As a result of the study, we performed a computer simulation of a stainless pipe manufacturing process according to the technology of expanding with the budenovka-like expanding machine and double expanding with a 2500 t press. We analyzed the gaging of the expanding machines and prepared the recommendations for a potential application of the proposed expanding machines.

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UDC 519.876.5

# COMPUTER-AIDED DESIGN OF SECTION ROLLING INTEGRATED WITH MODELING IN QFORM

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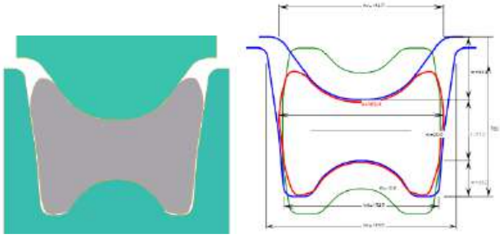
Over 90 % of all the materials subjected to deformation are rolled [1]. Rolling provides workpieces for other forming processes, such as forging, but rolling is also used to manufacture finished products, beams, rails, and other shaped sections for construction, mechanical engineering and railways. Shaped bars are manufactured in several passes; the finished sections may have close tolerance, which can be achieved by careful design of the process and settings of rolling mills. A numerical simulation is used to analyze the flow of material in the deformation zone, predict filling and expansion, forecast the load and torque in every stand, and show how rolling stands interact with one another on a continuous rolling mill. To speed up the simulation of the rolling process using FEM, a special module was developed in QForm software. It applies the double mesh method for deformable materials, the Euler approach for rolls, and a special technique for processing the conditions of contact between rolls and steel.

Meanwhile, success of the rolling technology development mainly depends on the quality of design of rolling grooves, requiring many years of experience. To speed up and automate the design of rolling grooves, we developed a special computer-aided design (CAD) system, namely Kaliber. It combines the design of grooves and the FEM simulation of rolling. CAD ensures storage and use of databases, containing the technological documentation on rolling equipment, calculation of the design of grooves, including steel shape changes, energy, power, speed and temperature parameters of rolling processes, visualization of the cross-section of the deformation zone, preparation of the technological documentation and launch of the simulation project in QForm to check and correct the design of grooves.

Drawing systems of grooves are designed based on a parametric description. Sections of more complex shapes, such as T-beams, I-beams, channels, Z-shaped beams, rails, and others, are designed by dividing into elements with the set deformation and determined transition sections. Designing can be carried out both along and against rolling, including within the framework of one project.

CAD system Kaliber also has a function of rolling simulation based on 2.5D and 3D approaches [2]. Fig.1 shows simulation of rolling in the angular wire gauge based on the 2.5D approach in QForm (Fig. 1, a) and export of the calculation results to Kaliber (Fig. 1, b).



a) b)

Fig. 1 – 2.5D simulation of forming in the groove a) and export of the obtained section to the design system shown in red b)

This research presents an approach, combining design and simulation, when designing grooves of shaped sections. The approach under consideration demonstrates a synergetic effect for practice. It improves the quality of solutions, saves materials, reduces expenses for tools, and requires less time as compared with a separate application of simulation and computer-aided design.

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## OPERATION CONDITIONS OF UPSETTING TOOLS


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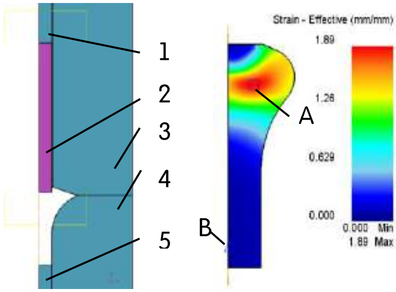
Upsetting tools used in metalware production are exposed to high loads, both static and dynamic loads [1]. In paper [2], the stress and strain state of steel at the first stage of upsetting a self-tapping screw head was calculated by the finite element method. This solution can be used to assess stresses occurring along the profile of the contact surface and determine how high the margin factors for the tool material are.

The process was simulated using FEM in DEFORM-2D. The workpiece for this product is heat treated and sized wire from steel 15Gps with a nominal diameter of 2.82 mm. Steel AISI 1015 was selected as a foreign similar steel grade for 15Gps.

We used an option of calculating 2D setup because in the 2D option we managed to decrease a number of finite elements and speed up the calculation. A complete set of the tools in conditions of this problem was considered as elastic bodies, and the workpiece, as an elastic/ductile material.

The plan of tool positioning is given below (Fig. 1 a).

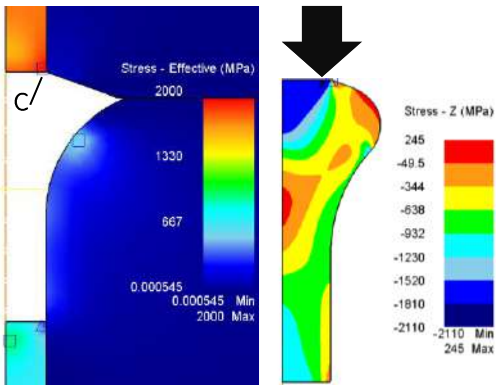



a) b)

Fig. 1 – Stage 1 of upsetting the self-tapping screw head:
a) tool positioning (1 is a pusher, 2 is a workpiece, 3 is a preliminary die, 4 is a heading die, 5 is an ejector); b) distribution of intensity of strain in the workpiece

The above figure (Fig. 1, b) presents maximum A and minimum B of intensity of strain in the workpiece section.

The below figure shows the distribution of intensity of stresses in the upsetting tool (Fig. 2, a) and the distribution of vertical stresses in the workpiece section at the final stage of upsetting (Fig. 2, b).




a) b)

Fig. 2 – Distribution of stresses in the tool and the workpiece:
a) intensity of stresses; b) vertical stresses in the workpiece

Point C (Fig. 2, a) indicates that the highest stresses in the tool are concentrated in the area of contact between the pusher and the deformable workpiece and a hard alloy insert of a preliminary die.

The black arrow (Fig. 2, b) indicates the direction of load of the pusher applied to the workpiece. Maximum stresses in absolute values are found near the contact surface with the pusher.

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UDC 621.77

## A METHOD OF MANUFACTURING Al/STEEL LAYERED COMPOSITES BASED ON AN INTERLOCKING STRUCTURE

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Advanced transport equipment in the automotive, railway and marine engineering requires composite materials with high specific strength, corrosion resistance, reduced weight and cost [1, 2]. These requirements are met by Al/steel layered composites, combining high strength of steels with low density and high corrosion resistance of aluminum alloys.

Manufacturing of composite bimetallic materials is based on the formation of a solid bonding of dissimilar components with a rather high strength of their bonding [3]. To manufacture a layered composite material, it is necessary to manufacture layers and bond them into a layered workpiece. Then, in general, the layered workpiece, consisting of alternating layers of given thickness and chemical composition, is formed and heat treated to ensure the bonding on the contact surface of the layers. In case of delamination or insufficient bonding strength of the bimetal layers, when exposed to static or dynamic mechanical loads, the composite is destroyed completely because of failure of the mechanism of a layer-by-layer load distribution.

We propose a method of manufacturing the layered bimetallic steel-aluminum alloy rolled products (Fig. 1), ensuring an increase in operational properties (a strong bonding of contact surfaces) and their stability in the zone of bonding of the layers [4]. This is achieved due to the rigid bonding between mechanically treated surfaces of the sheet workpieces included in the assembly. All the treated surfaces have a formed toothed profile in the transverse direction to the rolling axis with a height of irregularities of 20-70 µm and an angle of 91÷105° near the top of the toothed profile of the irregularities.

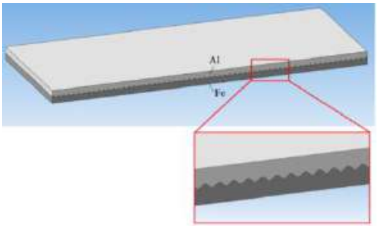

Fig. 1 – Layered composite

Forming interlocking structures on the contact surfaces creates a stronger bonding between the surface layers of metals, ensuring the best adhesion of metals during their deformation due to the destruction of the oxide film and high ductility of the metal in the point of deformation by creating a favorable scheme of the stress and strain state. In turn, this also contributes to reducing metal damage in the area of bonding of the metal layers and increasing strength of the bonding of the surfaces without preheating and applying a cladding layer.

This scheme significantly reduces a manufacturing cycle, while increasing bonding strength of shearing behavior and tear behavior of the layers. Thus, average bonding strength of shearing behavior for composite 1Kh18N9T–AMg6 is 79 MPa, tear behavior of the layers is 170 MPa.

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## UNDERSTANDING THE THERMAL AND STRESS-STRAIN STATE OF METAL DURING ROUGHING MILL ROLLING


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Optimization of hot rolling operations is crucial for obtaining high-quality products. Temperature field distribution can affect both the performance of the rolling mill and the mechanical properties of the final product. This is equally true for rolled products made of electrical steel grades. By changing the hot rolling modes, one can change the structure of a hot-rolled strip and thus define the magnetic properties of the final plate [1].

The authors looked at how the thermal state of metal changed depending on the pass schedule in the roughing mill of the Continuous Wide-Strip Hot Mill 2000 operated by NLMK PJSC [2]. The mathematical description, assumptions and the arrangement of boundary conditions, as well as the use of modular model for solving the problem of roughing mill deformation are given in paper [3].

Simulation of the rolling process was based on steel E3A and the pass schedule given in Table 1. The strain resistance curves and the thermophysical properties of that steel grade used for simulation are based on the experimental study described in papers [3, 4].

Table 1 – Roughing mill pass schedule

| Schedule | Indicator | Roughing stand number | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| No.1 | $h_1$, mm | 215 | 185 | 140 | 80 | 45 |
| No.2 | $h_1$, mm | 235 | 200 | 175 | 100 | 60 |
| - | v, m/sec | 1.0 | 1.5 | 2.0 | 2.5 | 3.2 |

The slab thickness at entry to Stand 1 is 250 mm. The model dimensions of the slab in view are equal to half the thickness (½ h) of the initial size, 20 mm wide and 600 mm long. There are no heat sinks along the width. The slab temperature at the discharge from the furnace is uniform and is taken equal to 1,160 °C. The simulation results are presented as graphs (Fig. 1).

Conclusions. A computer model was built of the stress-strain and thermal state of the strip during hot rolling. The fig.1 below shows the distribution of the accumulated strain and the temperature along the width in the Continuous Wide-Strip Hot Mill 2000. The obtained results were used for analyzing the structure and properties of material as they formed in the hot mill line.

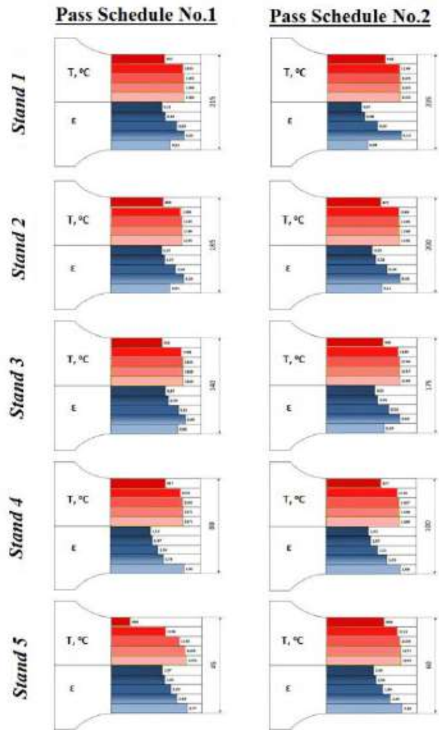


Fig. 1 – Distribution of temperature and accumulated strain along the width during roughing mill rolling

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# UNDERSTANDING THE PROCESS OF COMBINED ASYMMETRIC AND SYMMETRICAL ROLLING OF ALUMINIUM ALLOY D16 STRIP

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This paper examines the possibility to deform aluminium alloy D16 with an up to 98% reduction avoiding heat treatment. The study was carried out at the Zhilyaev Mechanics of Gradient Nanomaterials Laboratory, which houses a unique rolling mill 400. Having conducted this study, the authors applied for an invention with the national authorities. These findings could be useful when developing optimum regimes of combined asymmetric and symmetrical rolling.

Table 1 shows an optimum regime of combined asymmetric and symmetrical rolling:

Table 1 – Optimum regime of combined asymmetric and symmetrical rolling

| | Material D16 | h0 | h1 | h2 | h3 | h4 | h5 | h6 | h7 | h8 | h9 | h10 | h11 | h12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specimen 2 | Gap | | 0,9 | 0,9 | 0,8 | 0,7 | 0,6 | 0,5 | 0,4 | 0,3 | 0,2 | 0 | -0,4 | -0,8 |
| | Thickness, mm | 5,92 | 0,8 | 0,65 | 0,54 | 0,48 | 0,42 | 0,23 | 0,14 | 0,13 | 0,13 | 0,13 | 0,125 | 0,11 |
| | Width, mm | 275 | 27,6 | 27,9 | 28,1 | 28,1 | | | | | | | | |
| | Vtop, rpm | | 2,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 |
| | Vbottom, rpm | | 10,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 |
| | Rolling force, tf | | 39,0 | 19,0 | 19,0 | 18,0 | 19,0 | 20,0 | 17,5 | 21,0 | 29,0 | 48-49 | 98,0 | 150,0 |
| | Av | | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Reduction | | 86% | 19% | 17% | 11% | 13% | 45% | 39% | 7% | 0% | 0% | 4% | 12% |
| | Total reduction | 98% | | | | | | | | | | | | |
| | Remark | Edge trimming was done after the first pass | | | | | | | | | | | | |

The mechanical properties of the strip after the first asymmetric rolling pass with the work roll speed ratio of $V_2/V_1 = 10/2 = 5$ are presented in Table 2.

Table 2 – Mechanical properties of the initial specimen and of the specimen after the first asymmetric pass

| Item | Tensile strength, N/mm2 | Yield strength, N/mm2 | Percent elongation after rupture, % |
|---|---|---|---|
| Initial specimen | 192 | 141 | 6.2 |
| D16 V2V10 (after the first pass) | 283 | 245 | 11.9 |

Having compared the mechanical properties of the initial specimen and the asymmetrically rolled specimen, the authors established that after an 89% reduction the elongation of the specimen (its plasticity) did not decrease, as it would be typical in conventional symmetrical rolling, but it actually rose almost twice. Thus, a unique combination of high strength and high plasticity was achieved.

However, the aim of the study was to reach a total strain of 98%, and it was 89% after the first pass. That's why it was proposed to conduct 11 symmetrical rolling passes in order to achieve the total reduction of 98% required.

Table 1 shows the optimum regime of combined rolling that includes 1 asymmetric and 11 symmetrical passes. It should be noted that 6 mm thick metal was rolled down to the thickness of 0.11 mm without defects or heat treatment.

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## MANUFACTURING A DOUBLE-LAYER MATERIAL, STEEL – POWDER ANTIFRICTION LAYER, BY ROLLING

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Service life of friction units is known to be determined by their design, lubrication quality and, mainly, efficiency of antifriction materials. Now, antifriction materials for friction units are produced by casting (pouring the cladding metal on the surface of a moving steel belt, or by a centrifugal method). Recently, thin-walled double-layer materials (cladding layer thickness is 0.5-1 mm), consisting of compact steel-powder antifriction layer, have become widespread. Such materials should have a low coefficient of friction (0.07 – 0.1) and high load-speed characteristics, as well as be good formability, while porosity is 12 – 15 % [1 – 3]; moreover, pores should be connecting and uniformly distributed over the surface. The difficulty with manufacturing double-layer materials is small thickness of the powder layer, as well as the low contact strength, which leads to delamination during deformation.

To produce a composite antifriction material, we used a base from sheet compact steel St3, 1–2 mm thick, and globular powder of bronze grade BrOF 10-1 with a fraction of 0.3 – 0.4 mm.

The powder layer on the prepared steel base was applied by loose filling and sintered in a furnace, in protective-reducing atmosphere of endogas, at 900 – 920 ℃ for 50–60 minutes.

The studies showed that when a copper sub-layer was applied by electroplating, the formed antifriction layer showed low adhesion to the surface of the steel base due to hydrogen pickup of the base surface during electroplating of the copper layer and internal residual stresses, contributing to the formation of microcracks in the copper coating, and, as a result, delamination of the antifriction layer from the steel base during bending.

Preliminary plastic deformation increased an area of contact between steel and bronze powder; however, after sintering there were areas with a non-uniform transition layer on the contact interface.

Deformation cladding contributed to forming a uniform transition layer, 20 – 25 μm thick, on the interface between the steel base and bronze powder.

To manufacture finished products with the required specification, we designed a tool, combining rolling and bending of the sintered composition. The designed tool was installed on rolling mill CRP – 50 (roll body diameter was 50 mm, rotational speed was 12 rpm, highest pressure of steel on the rolls was 50 kN, electric drive power was 1.0 kW). Percentage reduction during rolling was 35 – 45 %.

The coefficient of friction of the produced material was determined on KFTT01 [4] by registering the tangential component of friction force, arising from the interaction of the loaded ball and the surface of the sample under study, using a strain measuring bridge.

Rolling of the double-layer material after sintering ensured the compaction of the powder antifriction layer from a porosity of 32–35% to optimal 12–15%. The powder layer has a uniform porosity over total thickness; pores are open and connecting to accumulate lubricants efficiently.

Tribotechnical tests of the composite double-layer material showed that the coefficient of friction of the samples was 0.016–0.018, corresponding to the requirements set for bronze-based antifriction materials.

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# SIMULATING AND STUDYING THE EFFECT OF COMBINED THERMOMECHANICAL TREATMENT, INCLUDING INITIAL HEAT TREATMENT AND RADIAL SHEAR ROLLING, ON THE EVOLUTION OF THE COPPER MICROSTRUCTURE

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When developing many severe plastic deformation processes, it was found that, most of all, a UFG structure in metals and alloys was achieved by a high number of deformation cycles. However, to reduce the required number of cycles and achieve the same effect of the grain refinement, it is required to carry out additional initial heat treatment (IHT) of such metals and alloys.

This research is aimed at simulating the structure evolution of copper grade M1 during IHT and subsequent radial shear rolling (RSR).

Regarding IHT modes, we simulated the following processes: heating up to 700℃, water cooling (quenching); heating up to 700°C, cooling with the furnace (annealing). A radial shear rolling stage included three passes with a reduction of 3 mm in every pass. The selected varying parameters were roll rotational speed (40 rpm, 70 rpm and 100 rpm) and workpiece heating temperature before rolling (20°C and 200°C).

The computer simulation showed that the most efficient mode of IHT for copper alloy M1 was quenching at 700℃. The most rational temperature mode of forming the workpieces on the RSR mill is room temperature, as in this case at all the selected speeds a recrystallization process is not started, contributing to an intensive grain refinement in surface layers and on the periphery. Copper heating to 200°C results in a boundary condition of the beginning of recrystallization, and only rolling on the RSR mill at 40 rpm contributes to reducing temperature below this boundary value. Higher roll rotational speed entails additional deformation heating, contributing to recrystallization and suppression of the intensive grain refinement. Therefore, when heating copper alloy M1 up to 200°C, it is not recommended to increase the rolling speed higher than the nominal value.

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# SIMULATION OF ASYMMETRIC ROLLING PROCESS

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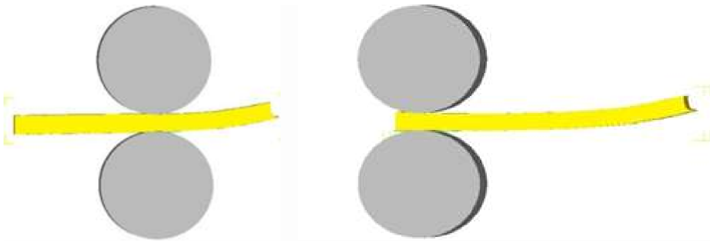
Asymmetric rolling is a process characterized with different angular velocities of rolls, different diameters of work rolls, different roll roughness, and different friction coefficients [1-3].

The main aim of this research is to build a computer model of the first reversing stand of a hot roughing mill 2000.

Using the DEFORM-3D software, the authors built a model of an asymmetric rolling process with different angular velocities of rolls. Slab temperature: 1,200°C, roll diameter: 1,400 mm; angular velocity of the top roll: 1.1 m/sec, that of the bottom roll: 1.3 m/sec. The simulation included three passes, from the thickness of 250 mm down to 150 mm. In the first pass, a 250 mm thick slab was rolled down to 220 mm with the angular velocity of the top roll being 1.1 m/sec and that of the bottom roll being 1.3 m/sec for 1/3 of the slab length (Fig. 1a). Once the material started to deform and a ski-up could be seen, symmetrical rolling conditions were introduced (with the angular velocities being equal) (Fig. 1b). The second pass followed a similar pattern but it included a reverse pass and a reduction from 220 mm down to 180 mm. The final pass was a third pass of the same pattern with the thickness reduced to 150 mm.



a) b)

Fig. 1 – Simulation of asymmetric slab rolling: a) the velocity of the bottom roll is higher than that of the top roll; b) equal angular velocities

The developed computer model of asymmetric rolling in the first reversing stand of the hot roughing mill 2000 helped prevent an emergency, and namely strip beating against the roller table.

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## FEATURES OF FORMATION OF THE STRUCTURE AND PROPERTIES OF ALLOY Co-28Cr-6Mo AFTER RADIAL SHEAR ROLLING

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Co-Cr-Mo alloys are applied in medicine as implant elements [1] due to a combination of high mechanical properties, corrosion resistance, wear resistance and biocompatibility [2]. A main method of manufacturing deformed semi-finished products from Co-Cr-Mo alloys is hot forging [3]. Now, in Russia there are no industrial technologies producing bars from Co-Cr-Mo alloys. The method of radial shear rolling (RSR) proposed in this paper for manufacturing semi-finished products from a medical cobalt-based alloy is currently used to manufacture bars from steels, titanium and other alloys [4]. This research is aimed at conducting experimental tests of hot deformation of Co-Cr-Mo alloy by RSR and analyzing the formed properties and microstructure.

An original ingot from alloy Co-28Cr-6Mo-0.7Ni-0.5Fe-0.3Si (wt. %) produced by vacuum induction melting underwent homogenization annealing (1230 ℃, 6 h) followed by water cooling. The ingots, 57 mm in diameter, were rolled on a three-high RSR mill into bars, 18 mm in diameter, in 8 passes with total drawing coefficient $\mu$=10. Heating temperature of the workpiece before rolling was T=1200℃. Rolling was followed by water quenching. The produced bars were evaluated for mechanical properties ($\sigma_в$, $\sigma_{0.2}$, $\delta$, HV), and analyzed for their microstructure (SEM).

The microstructure of the alloy after RSR is equiaxed dynamically recrystallized with an average grain size of 10-20 μm (Fig. 1). There are also individual round particles of the intermetallic phase, about 20 μm in size. Microhardness of the original specimens after homogenization has a uniform distribution over the cross-section, reaching 255-260 HV (Fig. 2a). Some non-uniform hardness along the cross section of the bar is formed after RSR and quenching. The highest values were recorded in the central part (520±5 HV) and on the surface (480±5 HV). Fig. 2a shows mechanical properties of the original specimen after annealing and the bars produced by RSR in comparison with the requirements of GOST ISO 5832-2009 for hot deformed (HD) semi-finished products ($\sigma_в$=1000 MPa, $\sigma_{0.2}$=700 MPa, $\delta$=12 %). Regarding the specimens produced by RSR, ultimate strength is 1310±59 MPa, yield strength is 790±78 MPa, and percentage elongation is 33±0.3 %.

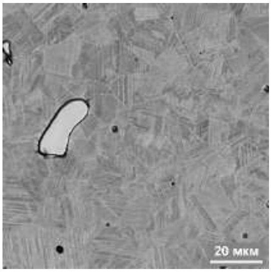
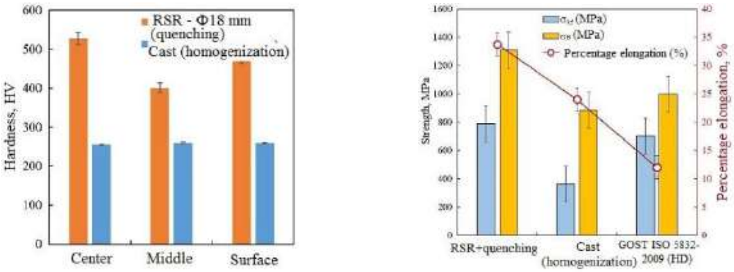



Fig. 1 – Microstructure (SEM) of the specimen after RSR and quenching




(a) (b)

Fig. 2 – Hardness of the specimens in their original and deformed states (a) and mechanical properties of the alloy in comparison with the standard (b)

Thus, mechanical properties of rods produced by RSR in initial testing exceed requirements of the regulatory documentation, especially in terms of ductile properties.

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# ELECTROPLASTIC EFFECT SIMULATED IN A TWO-DIMENSIONAL MONOCRYSTAL

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Electroplastic effect (EE) is a phenomenon when the yield strength of the material decreases and the elongation increases to fracture under the influence of electric current during plastic deformation. EE gained a great deal of attention on the part of researchers and found application in such industrial processes as drawing, rolling, stamping and forming [1, 2]. Even though EE is well-known and widely used in manufacturing, the physical nature of this phenomenon is still unclear.

This research relied on molecular dynamics method, which was used for modelling. The interatomic interaction was described based on the Morse potential. Two dislocations were introduced into the system, by cutting out an atomic chain followed by relaxation. Then the system was subjected to a monotonously rising deformation at a given temperature. The temperature was introduced by putting in random initial displacements of atoms within a given range.

The kinetic energy of the system was increased for modelling of electric current pulses. The objective was to have more energy generated on atoms near the defects, which have a higher potential energy. Thus, local Joule heating was simulated. Then the atoms with a high potential energy (i.e. atoms around dislocations) were tracked with the help of a code, and an average waiting time before plastic deformation was determined based on how they moved in the lattice. Due to the presence of thermal fluctuations in the system, the waiting time is a stochastic value and it was calculated as a mean value after 500 implementations.

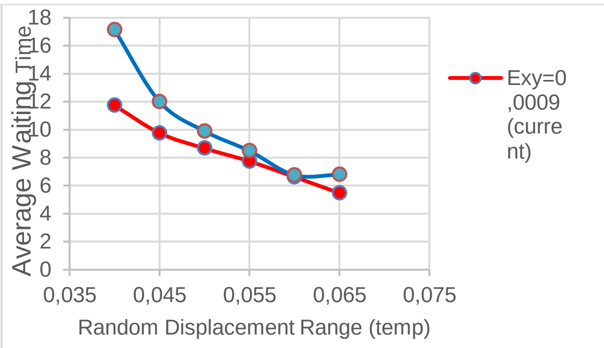


Fig. 1 – Relationship between the average waiting time and the temperature for the following shear strain values: Exy=0.0009. Blue curve stands for values when no pulses were applied, red one – for values when pulses were applied

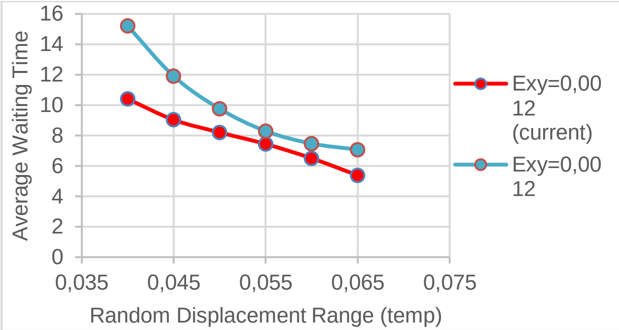


Fig. 2 – Relationship between the average waiting time and the temperature for the following shear strain values: Exy=0.0012. Blue curve stands for values when no pulses were applied, red one – for values when pulses were applied

Graphs (Fig. 1 and 2) were built that show the relationships between the average waiting time and the temperature for the cases when no current was applied and when current pulses were applied. Analysis of the results shows that the electroplastic effect makes dislocations move much easier and faster, which is especially noticeable at lower strains.

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## INFLUENCE OF THE STRAIN RATE ON STEEL HARDENING DURING WIRE DRAWING


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Strain hardening of steel during wire drawing is explained by an increase in the dislocation density up to $10^{15}$ $m^{-2}$, the formation of a cellular dislocation structure, distortions of the crystal lattice and the occurrence of internal stresses. Cold working leads to an increase in strength properties and a decrease in ductility properties of steel. At the same time, even in the last century, it was established that the intensity of hardening of alloys significantly depended on the strain rate.

In case of monolithic drawing, depending on the parameters of the deformation zone, deformation unevenness occurs over the wire cross section. It was established in [1] that an increase in the die half-angle and the friction coefficient negatively influenced the uniformity of deformation over the wire cross section.

At the same time, it has been established by the computer simulation [2] that the die half-angle has a significant effect on the distribution of the strain rate over the wire cross section. Depending on the parameters of the deformation zone and drawing speed, the deformation rate varies from 500 to 12,000 $s^{-1}$.

The maximum strain rate during drawing in monolithic dies can exceed twice as much the average strain rate. An increase in die half-angle α from 3 to 8° leads to an increase in the strain rate up to 2.5 times, while high strain rates at large die half-angles are concentrated in the central part of the wire (Fig. 1).

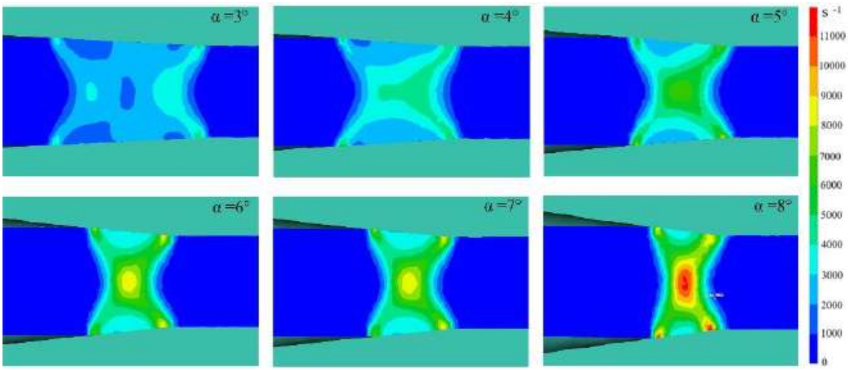

Fig.1 – Results of a numerical experiment at a drawing speed of 40 m/s

High-speed drawing (up to 40 m/s) on modern straight-line drawing machines leads to an increase in the strain rate by up to 5 times. High strain rates lead to an increase in the intensity of steel hardening in those areas where they occur. Therefore, in monolithic drawing, the hardening of steel is influenced by two mechanisms, the first one is associated with the localization of deformation over the wire cross section, and the second one is associated with an increase in the strain rate. Both hardening mechanisms are very sensitive to the parameters of the deformation zone, and the multifactorial nature of the dependence does not provide obvious solutions for choosing the optimal parameters of the drawing process according to this criterion.

For the experimental verification of the results obtained by the computer simulation, we took wire with a diameter of 3.4; 3.2 and 3.0 mm from a wire workpiece with a diameter of 3.5 mm from steel grades 10 and 60S2A with a half-angle die of from 3 to 8°. In laboratory conditions, we also assessed the effect of drawing speed on the distribution of hardness over the wire cross section. To assess the influence of the parameters of the deformation zone on hardening of steel, microhardness was measured over the wire cross section. As an example, the change in hardness in the center of the wire made of steel grade 60S2A after drawing is shown (Fig. 2).

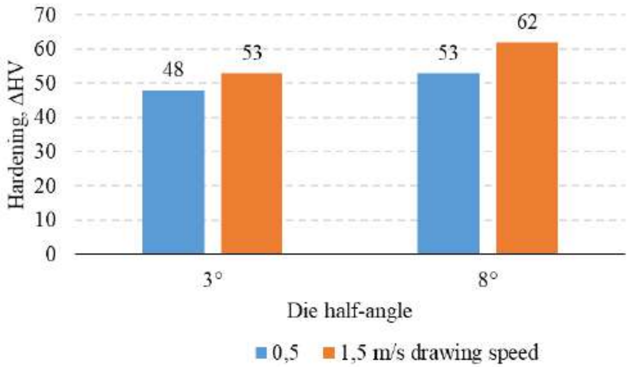


Fig.2 – Hardening of steel grade 60S2A during drawing from a diameter of 3.5 to 3.2 mm in dies with a half-angle of 3 and 8° at 0.5 and 1.5 m/s

The results obtained confirmed the presence of two mechanisms of strain hardening of steel in the monolithic wire drawing. Hardening caused by a change in the strain rate across the wire section is to be taken into account, especially in high-speed drawing.

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UDC 004.896


## APPLICATION OF ARTIFICIAL INTELLIGENCE IN ROLLING SIMULATION


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Application of machine learning algorithms in metallurgy is becoming more and more widespread. Many researchers use modern algorithms for modelling various production processes and successfully integrate them in the production process. By using new refined models one can boost the performance and improve the quality avoiding making a lot of investment. This opens up new opportunities for utilizing the mathematical apparatus of machine learning algorithms on available computers. It should be noted that work in this area was undertaken even 25-30 years ago. But, at that time, limited computing power and data storage capacities would serve as constraints for utilizing the full potential of machine learning.

Today, most of metallurgical companies have accumulated big arrays of structured and unstructured information that need to be organized, processed and – what matters most of all – utilized for optimization of production processes and development of new types of products capable of competing with the leading global counterparts. In steel rolling, machine learning can be used for predicting the properties of rolled steel; solving inverse problems when one needs to determine the chemical composition and processing mode based on preset mechanical properties; determining the roll wear and the friction coefficient; detecting defects and for other problem solving.

An example of utilizing machine learning techniques would be an inverse problem of determining the strain resistance of the rolled material based on commercial rolling operations data. The paper relies on the initial array of data on more than 310,000 passes performed in a commercial reversing hot mill. The gradient boosting technique and a neural network were used for data processing. The coefficient of determination on a test set of data was (R2) = 0.97.

*This research was carried out as part of the Prioritet-2030 programme aimed at providing support for Russian higher education institutions and in the framework of research project PRIOR/SN/NU/22/SP5/26: Developing innovative digital tools for utilizing applied artificial intelligence and innovative statistical analysis of big data in metallurgical production processes.*

UDC 621.771.252.01

## UNDERSTANDING THE EFFECT OF KINEMATIC ASYMMETRY DURING ROLLING ON THE MECHANICAL PROPERTIES OF LAMINAR COMPOSITES

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Many industries, including automotive and aerospace industries, are facing a challenge of reducing the weight of structures while maintaining or even enhancing the mechanical performance of the material. The key mechanical properties that are looked at in this case include strength and plasticity, which are in a clearly inverse relationship. Materials that would be capable to offer high strength combined with high plasticity can be produced by kinematic asymmetry processing. Research to this regard is ongoing in both Russia and such countries as South Korea, China, Germany, Japan and others. The researcher community of Magnitogorsk are looking at new effects of asymmetric deformation during accumulative rolling [1-4]. The Zhilyaev Mechanics of Gradient Nanomaterials Laboratory at NMSTU, which is one of its kind, houses a semi-industrial asymmetric rolling mill 400. Due to its ability to run at the work roll speed ratio of $V_1/V_2 = 10$, it can be described as a unique piece of equipment.

The initial material for asymmetric accumulative rolling included aluminium alloys 5083 and 2024, which were turned into 2 to 4 mm thick composites. Two rolling cycles were performed, the percent reduction varied between 45% and 75%. The rolling was performed in dry rolls, the material was pre-heated at 380˚C for 5-30 minutes. The following work roll speed ratio was applied: $V_1/V_2 = 1…5$.

A series of mechanical tests was carried out on specimens, and the results indicate both increased strength and plasticity compared with the initial state. Figures 1 and 2 show how the elongation and tensile strength would change after the first and the second cycle of asymmetric accumulative rolling.

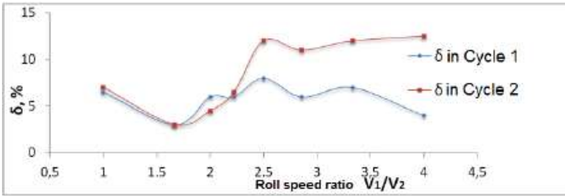


Fig. 1 – Changing δ under asymmetric accumulative rolling

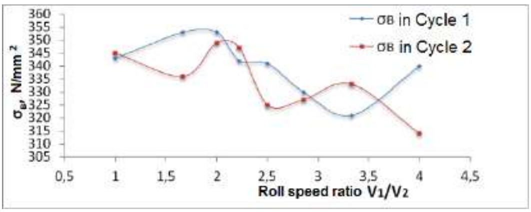


Fig. 2 – Changing $\sigma_в$ under asymmetric accumulative rolling

The authors also found that, at the work roll speed ratio of $V_1/V_2 = 5$ and with the process applied, aluminium alloys tend to melt down in the deformation zone. As the work roll speed ratio rises, the rolling force tends to drop from 1,330 kN down to 600 kN.

*The research is funded by the grant of the Russian Science Foundation, No. 23-79-30015, https://rscf.ru/project/23-79-30015/.*

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UDC 621.73

## ON THEORETICAL STUDY OF STRESS-STRAIN STATE OF MOTOR VEHICLE SUSPENSION SPRINGS DURING SHOT PEENING


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A critical component of the modern vehicle, the quality of which must be given serious attention, is the car suspension [1].

The aim of this research is to study the stress-strain state of vehicle suspension springs during shot peening and to theoretically substantiate the effect of shot peening of large helical coil springs on compression during subsequent pre-stressing.

The front suspension spring 21214-2902712 (Fig. 1) is installed on off-road cars VAZ-2121 Niva (LADA 4×4) [2].

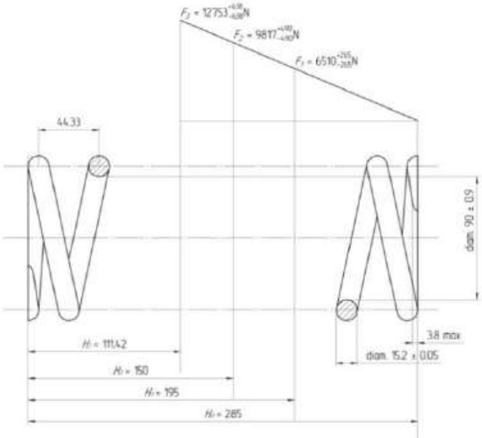


Fig. 1 – Front suspension spring 21214-2902712: $F_1$ – load at preliminary contraction, N; $F_2$ – work load, N; $F_3$ – coil contact load, N; $H_1$ – height at preliminary contraction, mm; $H_2$ – working load height, mm; $H_3$ – compression height before the coils touch, mm

The authors conducted a theoretical study of the stress-strain state of helical cylindrical compression springs used in the suspension of vehicles during shot peening. The stress-strain state of the front suspension spring was studied by mechanical and mathematical methods, as well as the methods of the deformation theory of plasticity – in particular, using the method of small elastic-plastic deformations [3].

It was established that shot peening reduces compression of the front suspension springs during pre-stressing by 2.54% due to a 4.30% increase in the torque in the cross section of the coil.

The following was also determined: the boundary separating the elastic zone from the plastic one in the cross section of the coil during pre-stressing (Fig. 2), magnitude of the torque $M_{to}$ and compression of the spring [2].

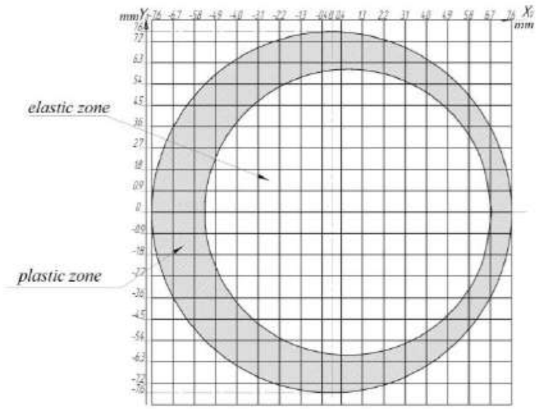


Fig. 2 – Elastic core in the cross section of the coil of the front suspension spring 21214-2902712 when pre-stressed (compression by force $F_3$)

The results of the study can be used for the development of technology for the manufacture and repair of expensive helical coil springs for the car suspension, in particular, for determining the required load of contact pre-stressing, taking into account shot peening.

*This research was funded by the Council on Grants of the President of the Russian Federation (No. SP-3658.2021.1).*

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UDC 621.777

## A COMPARATIVE ANALYSIS OF DEFORMATION OF MAGNESIUM ALLOY MA-14 BY ECAP WITH AND WITHOUT A COPPER COVER

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Recently, the study on the behavior of bioresorbable materials after deformation becomes a relevant area in the research field. These materials include alloys based on zinc, magnesium, and iron. Improving mechanical and corrosion properties of bioresorbable metals is an important objective.

As it is described in [1, 2], to prevent cracking of magnesium and magnesium alloys during ECAP, deformation temperature is maintained over 200 ℃. Main attention is paid to ways to improve plastic deformation, while decreasing temperature of pressing magnesium and magnesium alloys [3, 4]. One of the promising methods of pressing magnesium alloys without defects is the use of a cover from other materials [5, 6].

This paper describes a comparative analysis of deformation of magnesium alloy Mg-Zn-Zr by ECAP with and without a cover from copper alloy M1. The study was conducted using a computer simulation by the finite element method in Deform-3D software suite; experiments were also performed.

The simulation of magnesium alloy MA-14 was at 400℃, the angle of rotation of the pressing channel was 120°, deformation rate was 1 mm/s, diameter of the original sample was 20 mm.

It was found that the use of a copper shell increased average compression stresses, reduced the damage coefficient over the surface of the workpiece, and led to an increase in power parameters. The deformation rates at both types of forming are approximately the same.

We also carried out physical experiments, when magnesium samples were produced in and without a copper cover, the strength limits reach 330 MPa, and a main mechanism of structure formation is dynamic recrystallization.

*The research was funded by the grant of the Russian Science Foundation, No.22-79-10325, https://rscf.ru/project/22-79-10325.*

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UDC 669

# PREDICTING AUSTENITE GRAIN SIZE IN CARBONITRIDE HARDENED LOW-ALLOY STEELS SUBJECTED TO HOT DEFORMATION

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By predicting the austenite grain size during high-temperature deformation by means of computer modelling, one can save the need to carry out some costly and labour-intensive experiments in order to identify optimum regimes of thermomechanical processing. This supports the high relevance of developing appropriate simulation techniques and conducting further research in this area.

The approach described in this paper is a further development of the algorithm [1] that describes the mutual influence of such structural parameters as the average grain size, the dislocation density and the parameters of carbonitride precipitates during thermomechanical processing. However, one of the most serious drawbacks of this model included a model simplification about dividing the simulated specimen into two parts: a deformed one, with high dislocation density, and a part of the material that underwent recrystallization.

For eliminating the said drawback, a distribution histogram was introduced into this model that shows how the bulk material is distributed by dislocation density. It means that each interval with the average dislocation density $\rho_i$ has a corresponding volume share of the material$H_i$. In the course of simulation, the dislocation structure (and the histogram, correspondingly) changes as deformation and recrystallization take place. During deformation and bounce-back, the dislocation density corresponding to the $i$-interval changes by some value $\Delta\rho_i$.

$$\rho_i' = \rho_i + \Delta\rho_i,$$

After that, the histogram is recalculated to the original presentation:

$$H_i = \sum_j H_j X_i^j,$$

where $X_i^j$ – a length ratio of intersection between the *i*- and *j*-intervals. The *j*-intervals correspond to the histogram with altered intervals $\rho_i'$.

The bulk material that corresponds to the *i*-interval of dislocation densities, where $\rho_i > \rho_{cr}$ (where $\rho_{cr}$ – critical dislocation density), undergoes recrystallization. In this case, for all such intervals, the $H_i$ share should shrink, while $H_0$ (the share of the material with the least dislocation density) should expand by the appropriate value:

$$H_0 = H_0 + H_i \cdot (1 - 2^{-\frac{\Delta t}{t_{0.5}}}),$$
$$H_i = H_i \cdot 2^{-\frac{\Delta t}{t_{0.5}}}.$$

Here, $\Delta t$ – time step, $t_{0.5}$ – half recrystallization time.

The changing average size of the austenite grain, allowing for recrystallization-related refinement, can be described with the following expression:

$$\frac{dD}{dt} = M\gamma\left(\alpha\frac{1}{D} - \beta\sum_i\left(\frac{f_i}{r_i}\right)\right) - \frac{D}{3}\frac{dX}{dt}\ln(N),$$

where $D$ – average grain diameter, $t$ – time, $\gamma$ – grain boundary energy, $\alpha$ and $\beta$ – constants, $f_i$ – volume fraction of precipitated second phases of radius $r_i$. $M$ – grain boundary mobility, $X$ – share of recrystallized material, $N$ – number of recrystallized grains per initial grain.

To verify the adequacy of the model, the authors compared (Fig. 1) the simulation data with the experimental ones [2] on the austenite grain size evolution in the Fe-0.05C-1.88Mn-0.04Nb-0.004N (wt %) steel. The comparison showed a satisfactory correspondence between the simulation results and the experimental data.

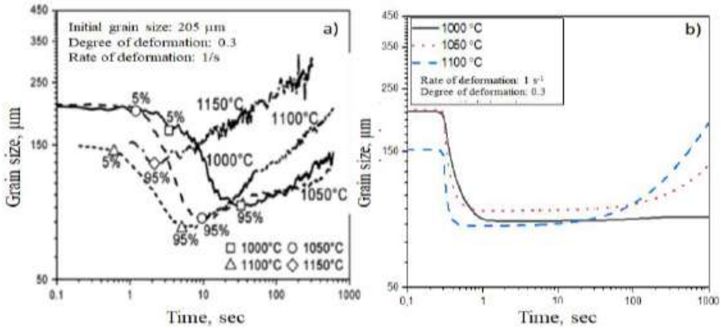


Fig. 1 – Grain-size evolution after deformation:
a) laserultrasonic measurement data [2]; б) simulation data.
Processing conditions are specified in the graphs.

*The research was supported by the Russian Science Foundation; Project No. 22-29-01106.*

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UDC 621.77

# A METHOD OF MANUFACTURING STEEL-CORED COPPER WIRE BASED ON A HYBRID INTERLOCKING STRUCTURE


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Advanced transport machines require composite materials with high specific strength, corrosion resistance, reduced weight and cost [1]. These requirements are satisfied by bimetallic steel-cored copper wire, combining high mechanical properties of the core and high electrical conductivity, corrosion resistance, heat resistance and other special characteristics of the shell material. Requirements for bonding strength of the steel-cored copper wire components constantly become stricter, leading to a need for development of new engineering solutions.

To manufacture bimetallic wire, we propose method [2], ensuring to improve the quality of material bonding by forming an intermediate layer with a hybrid interlocking structure during rolling, before drawing in solid dies (Fig. 1).

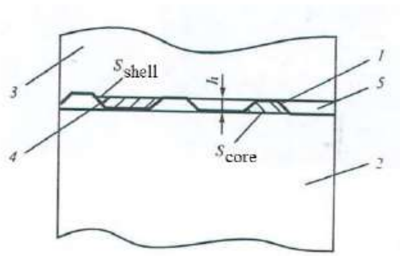


Fig. 1 – Formation of an intermediate layer between the shell and the core during rolling:

1 is a trapezoid raised area on the core; 2 is a core; 3 is a shell from a soft material; 4 is a trapezoid raised area on the shell; 5 is an intermediate layer; h is height of raised areas of the core and the shell; $S_{shell}$ is an area of the raised section on the shell; $S_{core}$ is an area of the raised section on the core

When rolling in a round pass the steel core with threads applied on its surface and the shell (a copper flat narrow strip), the gaps between raised areas are filled with the material of the shell and harder raised areas of the core are introduced into the material of the shell under external pressure by mill rolls. Thus, the workpiece has three formed layers: surface (material of the shell), intermediate, consisting of areas from shell and core materials located one-by-one, and internal layers (material of the core).

Drawing of such workpiece in solid dies is conducted by the scheme of trimetals. This ensures a high level of mechanical bonding of the shell and core metals, laying in the synergetic effect from a sequence of implemented processes:

- threading on the surface of the cylindrical core,
- winding of a strip from a soft component,
- formation of a threaded joint of the core and the shell, when rolling in a detachable round pass,
- formation of the hybrid interlocking structure.

The test results of steel-cored copper wire BSM0 manufactured by the new process comply with the requirements set for the quality of products in GOST 3822-79.

*The research is funded by the grant of the Russian Science Foundation, No.22-19-20073, https://rscf.ru/project/22-19-20073/, and financial support of the Chelyabinsk Region.*

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UDC 621.774.38

# ENHANCED ACCURACY OF TOOL JOINT BILLETS AS A RESULT OF STAMPING PROCESS OPTIMIZATION

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Tool joints are critical components of drill pipes. They are used to join together drill pipes by means of threaded connection [1, 2], which is a quick and consistent way to assemble or dismount drill strings.

The production of tool joints is associated with a problem of excessive thickness non-uniformity during blank stamping. This leads to a higher metal consumption, longer machining cycles and, as a result, a higher final cost of tool joints.

Our report looks at the process that is currently used for the production of tool joints, and we distinguish some factors that may contribute to the thickness non-uniformity of hot-stamped blanks. Among them there are [3-7]:

- Dimensional accuracy of the initial blank;
- Dimensional accuracy and correct set-up of the tool;
- Tool wear;
- Presence of elastic strains;
- Failure to observe the billet heating range;
- Deviation from the process.

This report also covers the results of computer modelling of the hot-stamped blank production process. The simulation was performed in the Qform 10.1.3 programme and aimed at understanding how incorrect set-up of the punch influences the thickness non-uniformity of the final part. A total of 5 simulations were carried out:

- Perfect-world option when the punch is in a perfectly right position;
- The punch is 2 mm off;
- The punch is 1.5° skewed;
- The punch is 0.34° skewed;
- The punch is 2 mm off and 0.34° skewed.

This report also describes certain measures aimed at optimizing the stamping process and analyzing the results of implementing the said measures.

The following measures aimed at improving the thickness non-uniformity of billets for tool joints were proposed and tested in real-life environment:

- Use a punch with a different tip shape;
- A new billet heating temperature range is recommended;
- It is recommended to use saw cutting of billets, instead of cold breaking.

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# NON-UNIFORMITY OF STRAIN DURING BIMETALLIC ROD PRESSING

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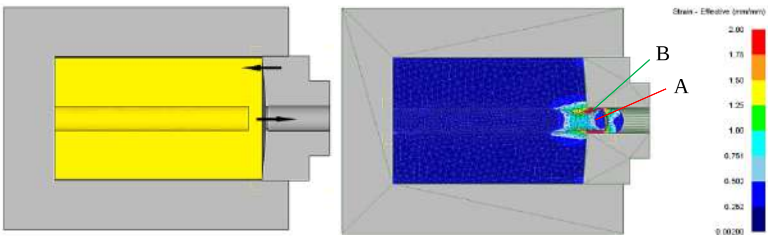
Of relevance today are metal composites that combine the advantages offered by different metals, as they help enhance the performance characteristics of final products, including strength, plasticity, shock absorption and so on [1-3]. It is common to use pressing [4] for manufacturing bimetallic rods.

The authors used the DEFORM software to simulate the process of inverted extrusion of a bimetallic rod, with the core made of aluminium alloy V96 and the cup-shaped sleeve – of AlMg2 alloy. Such combination of alloys will result in a lighter rod while making it more corrosion resistant.

The bimetallic rod has the following dimensions: the sleeve has the outer diameter of 360 mm, the inner diameter of 72 mm, the bottom thickness of 36 mm, the height of 550 mm; the core has the diameter of 72 mm, the height of 514 mm. The diameter of the container is 370 mm. The rod is heated up to 390°C and the container – to 380°C. The pressing speed is 1.0 m/min. The extrusion ratio $\lambda = 28$. The Sybel friction between the sleeve and the core was set equal to 0.95, the one between the sleeve and the tool surfaces – equal to 0.6.

Figures 1a and 1b show the initial assembly for inverted extrusion of bimetallic rods and the initial stage of this process with the respective strain distribution.




a) b)

Fig. 1 – Initial assembly for inverted extrusion of bimetallic rods; the arrows indicate the direction of the metal and the punch (a), the initial stage of inverted extrusion of a bimetallic rod with a strain field (b)

From Fig. 1b one can see that even at the initial forming stage the strain distribution is not even. Thus, in the core of the bimetallic rod the strain is equal to 0.252 (A), whereas at the periphery it is equal to 2.0 (B).

Fig. 2 shows the steady stage of the inverted extrusion process with strain distribution.

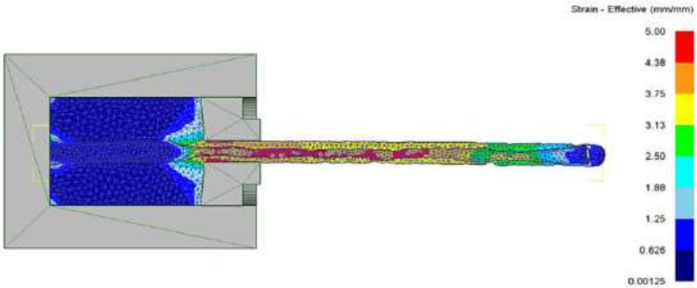



Fig. 2 – Inverted extrusion of a bimetallic rod: Steady process stage with strain distribution

This simulation helped detect the non-uniformity of strain along both the length and the radius of the pressed bimetallic rod, which will translate into non-uniformity of properties. One can also see the non-uniform distribution of the metal layers in a pressed bimetallic rod. So, the conclusion drawn is that in order to produce a bimetallic rod with the core made of aluminium alloy V96 and the cup-shaped sleeve – of AlMg2 alloy with uniform properties, one should use a different process (e.g. cold fluid extrusion) or workpieces of different shape.

*This research was carried out as part of Governmental Assignment No. AAAA-A18-118020190104-3 on the subject Pressure.*

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UDC 621.778

# ROLLING-EXTRUSION OF RODS OF AL-0.5REM ALLOY USING BILLETS AFTER ELECTROMAGNETIC MOLD

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Obtaining long-length deformed semi-finished products of small cross-section by applying classical technologies would lead to a high cost of such semi-finished products, due to the high labor intensity and high energy costs [1]. The authors propose a technology for producing wire from alloys of the Al-REM system, including the production of cast billets in an electromagnetic mold (EMM) and their further processing using a combined rolling-extrusion (EMM+CRE) process [2].

For this research, we used a continuously cast billet with a diameter of 12 mm from an Al-0.5%REM alloy, obtained by casting into an electromagnetic mold (Fig. 1, a). To test the studied deformation modes, experimental studies were carried out on the CRE-200 unit (Fig. 1, b), manufactured on the basis of a DUO 200 rolling mill according to a previously developed method. The chemical composition of the investigated alloy is given in Table 1. Technological modes for obtaining rods are presented in Table 2.


a b

Fig. 1 – Equipment for obtaining rods from Al-0.5REM alloy:
a) drawing of an electromagnetic crystallizer; b) combined processing unit CRE-200

Table 1 – The chemical composition of the investigated alloy

| Alloy | Content, % | | | | | |
|---|---|---|---|---|---|---|
| | Al | REM concentration wt % | Ni | Fe | B | Ti |
| Al-0.5%REM | Balance | 0.5 | 0.2 | 0.15 | 0.001 | 0.001 |

Table 2 – Technological regimes of the EMM+CRE modes for the investigated alloy

| Parameters | EMM+CRE | | | |
|---|---|---|---|---|
| | $T$ = 480 ºC | | $T$ = 550 ºC | |
| | Rod diameter, mm | | | |
| Strain rate $\xi = 0.74\ s^{-1}$ ($n$ = 4 rpm) | 9 | 5 | 9 | 5 |
| Strain rate $\xi = 1.49\ s^{-1}$ ($n$ = 8 rpm) | 9 | 5 | 9 | 5 |

The mechanical properties were determined using the following equipment: Walter + Bai AG LFM 400 kN and LFM 20 kN (Walter + Bai AG, Switzerland), in accordance with GOST 1497-84.

The electrical resistivity ρ was measured on 1 meter long samples using a Vitok ohmmeter according to GOST 7229-76.

The load on the die and rolls was recorded by tensometric equipment, using a ring load cell. As the main recording equipment, a ZET 017-T8 universal strain gauge station with CWW-50tf and CWW-100tf force sensors with a maximum allowable compression force of 500 kN and 1 MN was used.

In the course of this research study, the following conclusions were drawn and the following main results were obtained.

1. Experimental studies have been carried out on the implementation of the EMM+CRE process using a billet of Al-0.5%REM experimental alloy obtained by casting into an electromagnetic mold, while varying the process temperature, speed and degree of deformation.

2. An analysis of the power parameters of the EMM+CRE process was carried out. The forces on the rolls do not exceed 269 kN for the EMM+CRE process at a roll speed of 4 rpm and 241 kN at 8 rpm. The forces on the die do not exceed 172 kN at a roll speed of 4 rpm and 151 kN at 8 rpm.

3. Experimental studies were carried out to study the electrical resistance of rods obtained by the EMM+CRE methods. For almost all rods, the electrical resistance increased uniformly with an increase in the degree of deformation.

*Support for this research was provided under Grant No. 23-29-00028 by the Russian Science Foundation, https://rscf.ru/project/23-29-00028/.*

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UDC 621.777

# DEVELOPING A NEW METHOD OF SEVERE PLASTIC DEFORMATION TO PRODUCE TUBES FROM ZINC ALLOYS Zn-4Ag-Cu

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There are recent active studies on innovative medical techniques applied to restore lost functions of patients. The use of biosoluble (bioresorbable) materials is of particular importance. Such materials include alloys based on Mg [1], Fe [2], and Zn [3-4], and they can significantly reduce expenses for surgical operations and shorten the period of treatment. For example, the use of a high-strength zinc alloy will minimize the size of implants, ensuring less injury during their installation and faster dissolution in physiological environment of the body.

Severe plastic deformation (SPD) is one of the modern tools to improve properties of metallic materials due to intensive refinement of the initial structure to a nano- and ultrafine-grained state [5-7].

This paper studies a new method for producing tubes using direct and equal channel angular pressing schemes. We carried out a computer simulation by the finite element method and experiments revealing the technological features of deformation of zinc alloys Zn-Ag-Cu.

*The research was funded by the Russian Foundation for Basic Research and TUBITAK as part of research project No. 21-53-46017.*

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UDC 621.98.01

## SIMULATION OF DEEP DRAWING OF A HEMISPHERE IN QFORM SOFTWARE MODULE

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Import substitution measures cover not only tangibles, but also software products. To analyze plastic working, now researchers widely use the modules, such as DEFORM, ABAQUS, FORGE and others [1]. QFORM, Russian software developed by LLC QuantorForm (© 1991–2023) with a complete interface in Russian, stands out against foreign modules.

In spite of a specialized version for calculating the stress and strain state of sheet stamping, PAM-STAMP [2], QFORM also deals with solving problems in this field as shown, for example, in the paper [3].

This report presents some results of solving the problem of sheet stamping of a hemisphere (Fig. 1).

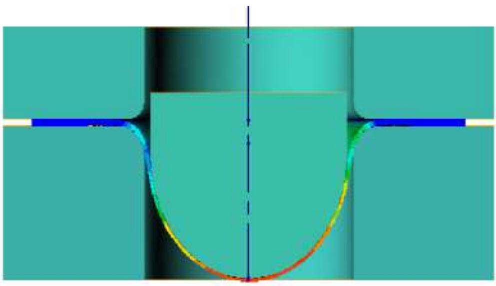

Fig. 1 – A sheet stamping process diagram

Input data for the calculation: initial workpiece diameter is 180 mm, radius of a sphere of a finished part is 40 mm, drawing depth is 52 мм mm, a single-sided gap between the punch and the die is 2.5 mm, the bending radius of the die is 10 mm, tool material is set as absolutely rigid, friction coefficient is 0.3 according to the Levanov's law, tool traveling speed is 10 mm/s, drawing per a single pass. Fig. 2 shows non-uniform strain occurred during stamping.

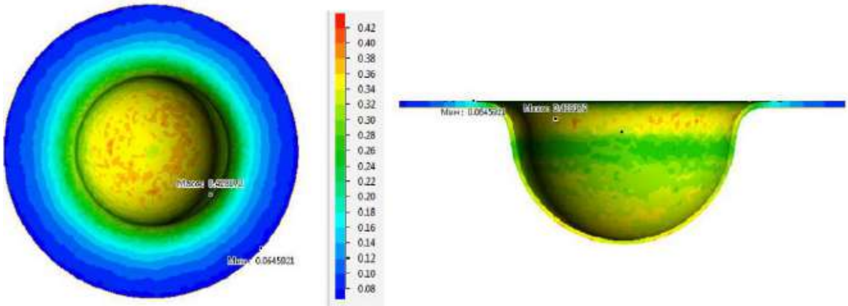


Fig. 2 – Strain rate distribution field as a solution

There is a current great interest in solving the problems of sheet stamping of anisotropic materials. Anisotropy is often found in this area because metal of workpieces is most often produced by sheet rolling, using a continuous effect on metal with a strictly determined direction of tensile and compression strain. At the same time, there is a need for determining relations between stresses and strains in accordance with a specific law of plastic flow, for example, according to Hill's theory [4].

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UDC 669.1

# PRODUCTION OF MULTIPLE-STRAND STEEL ROPES FOR MMK UNDER IMPORT SUBSTITUTION INITIATIVE

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The production sector of the Russian Federation relies heavily on imported equipment, and Magnitogorsk Iron& Steel Works is no exception. Today, Russian production companies are facing sanctions imposed by importing states. Because of this the amounts of necessary equipment and components from abroad have been reduced and in some cases minimized. MMK uses various pieces of foreign machinery that cannot function without steel ropes. It is from such foreign machinery that samples of steel ropes were taken by the Central Laboratory and the long products facility of MMK and sent to MMK-METIZ for investigation, together with inquiries about the possibility to make steel ropes that would have similar properties.

Having examined the samples, the authors determined that they are 8-strand and 10-strand ropes with the respective diameters of 11.0 and 13.0 mm, with a steel core PWRC: the rope and the steel core are made in one stranding cycle. Ropes of such type have a high breaking strength at the standard rupture strength of the wires equal to 1,770-1,960 N/mm$^2$, and a high structural density compared with the ropes made to national standards.

Specialized tandem-type wire rope closing machines are used for making such ropes. There are no such machinery at MMK-METIZ’s disposal. However, having analyzed the existing machinery, the authors established that PWRC ropes up to the diameter of 13.0 mm could be made in a stranding machine equipped with a pre-shaper (SRW 18x400). Using their process pre-calculations, the authors made a prototype PWRC rope with the diameter of 10.0 mm and the following design: 1+5+5/5.

Commercial production of the above described wire rope will help expand the assortment of steel ropes made by MMK-METIZ, satisfy the demand experienced by MMK and other potential consumers, partially lower the dependence of Russian producers on foreign vendors (achieve import substitution), raise the share of high value added products. Such ropes may become a brand with MMK-METIZ making it a single producer of such product in Russia, as there exist no counterparts to date.

UDC 621.9.044

# A FINITE ELEMENT MODEL OF A PROCESS OF CONCRETE FRACTURE BY MAGNETIC PULSE TREATMENT

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Now, there is a problem of separating and crushing strong brittle materials, such as stone, concrete, ceramics. It is traditionally solved by using explosives, cutting, mechanical or hydraulic tools, but this creates a number of difficulties, which are hazardous and dangerous for human health and environment. This problem can be solved by applying the well-known technology of magnetic pulse treatment of materials [1].

Magnetic pulse action is based on converting electrical energy accumulated in an energy storage system into a variable magnetic field, occurring in an inductor. In this case, the action on the sample lies in sending pulses of current, creating magnetic pressure transferred to the slot walls through busbars, along flat parallel thin metal busbars installed in the slot of the sample.

Having conducted a finite element modeling in LS-DYNA software [2], we calculated the relation between the current-carrying single-turn inductor and the concrete sample. The model sizes are given in Fig. 1.

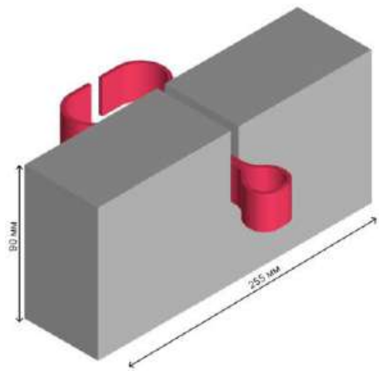


Fig. 1 – The finite element model

Maximum size of one finite element is 1 mm.

To carry out the simulation, we selected the following materials:

- *MAT_PLASTIC_KINEMATIC is for a copper inductor,
- *MAT_WINFRITH_CONCRETE is for a destructible sample.

A bank of capacitors is discharged on the copper single-turn inductor, and current amplitude in the first alternation ($10^{-5}$ s) is 50 kA.

Pressure created in the contact of busbars on the slot walls varies within 30-50 MPa, which is enough to exceed the threshold value of strength of some brittle materials (10 MPa or less). Fig. 2 shows how cracks are formed and propagated in the sample.

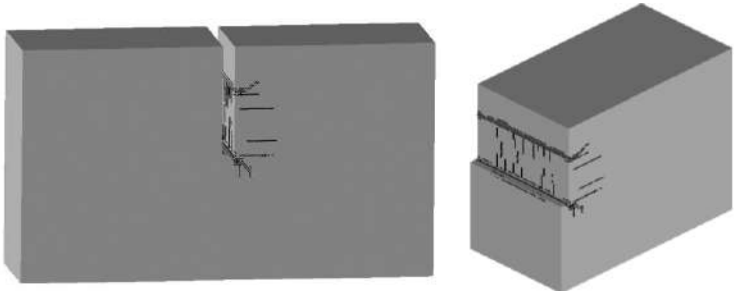

Fig. 2 – Crack formation in a concrete sample

The analysis of the simulation results showed a possibility in principle of using high-voltage discharge of current passed through the single-turn inductor to crush some brittle materials.

The magnetic pulse crushing process described in the paper does not require explosives, cutting, mechanical or hydraulic tools, or create hazardous and dangerous factors for environment and human life and activities. Later, this technology can be applied for both crushing and consolidation of various types of materials, including ceramics and metals.

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UDC 621.9.044

## DEVELOPMENT OF A SMART SOFTWARE COMPLEX FOR CONTROLLING THE PARAMETERS OF SEQUENTIALLY IMPLEMENTED PROCESSES

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The need to use mathematical models in research arises when an object / phenomenon is unavailable for study due to dangerous factors, is far from the researcher in time and space, as well as when experimental research involves great material losses and unforeseen consequences. Metallurgical processes belong to such cases. Mathematical modeling is one of the main tools used to design new and improve the existing technologies for the production of rolled products. With the help of mathematical modeling, it is possible to obtain theoretical information about the power and forces involved in various metal forming processes, to look at how the structure forms in processed metals and alloys, to determine the patterns behind the formation and shaping of various defects in metal products. All this lays the theoretical basis for the development of production processes and optimization of processing modes [1-2].

There is a great number of programs and systems designed for simulation of production processes with further parameter control. The most common of them include DEFORM, QForm, Abaqus, cellular automata, etc. [3]. Such software complexes use modules that contain a certain set of actions that are close in meaning and necessary for the program to build a finite element model and perform specified operations with it [4].

Building of the model and the modeling process are interrelated. The model is created in the process of modeling. The mathematical model includes a set of methods and techniques that are connected by logic and physics of scientific research aimed at obtaining reliable knowledge about an object/phenomenon.

Using the example of hot and cold rolling, we will consider the features of building mathematical models of these processes. When developing a mathematical model of a process, it is important to know the initial data. Conventionally, the initial data are divided into three groups: constant parameters determined by the properties of the processed material; variables determined by the conditions of the process under study and parameters characterizing the adopted calculation scheme of the production process. After defining the source data, it is necessary to describe the interdependencies of the source data (equations, equalities, inequalities, etc.), highlight the internal connections of the model using constraints, equations, equalities, logical and mathematical constructions. Similarly, it is necessary to define external links. Next comes the mathematical modeling itself with further verification of the adequacy of the resulting model. Many mathematical models have been developed based on the above described algorithm that separately simulate hot and cold rolling processes. At the same time, when modeling the cold rolling process, the results of hot rolling simulation are not taken into account. Similarly, when building a mathematical model of hot or cold rolling, the processes of structure formation in the processed material are not taken into account. Therefore, it is necessary to develop a mathematical model that would use logical and mathematical constructions to describe the basic properties of an object, process or system, its parameters, as well as internal and external connections.

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UDC 621.77

## MANUFACTURING ROUTE DESIGN FOR OBTAINING 585 WHITE GOLD ALLOY WIRE FOR THE PRODUCTION OF JEWELLERY CHAINS

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Ø0.25–0.35 mm wire of 585 gold alloy is used for the production of jewellery chains. The wire manufacturing technology includes casting of a Ø8 mm round ingot, followed by cold sectional rolling of a 1.1×1.1 mm square wire rod in 28 passes with intermediate annealing and drawing to a given diameter [1].

An urgent task of the jewellery industry is to reduce the number of rolling passes. Thus, the authors of this paper designed some rational routes for sectional rolling applicable to the AMBIFILO VELOCE ROSEN 180 mill, while taking into account the correct distribution of the elongation coefficients, force through the passes, and the mechanical properties of a wire rod made of 585 gold alloy, with the chemical composition given in Table 1.

Table 1 – Chemical composition of experimental alloys

| Alloy | Au | Ag | Pd | Cu | Zn |
|---|---|---|---|---|---|
| 1 | 58.5 | 21.6 | 10.0 | 8.4 | 1.5 |
| 2 | 58.5 | 26.0 | 8.0 | 5.5 | 1.5 |

The calculation of the rolling route presented in Fig. 1, 2 was carried out in the PROVOL programme [2].

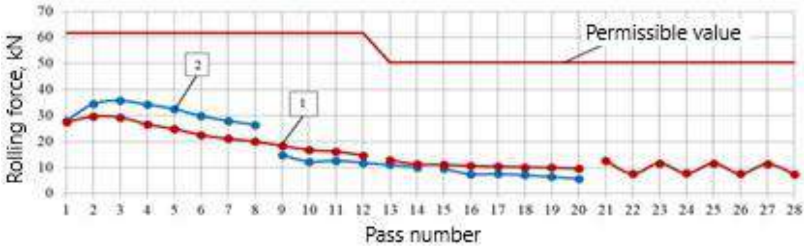


Fig. 1 – Distribution of the rolling force of Alloy 1 between the passes:
1) For the current regime; 2) For the calculated mode

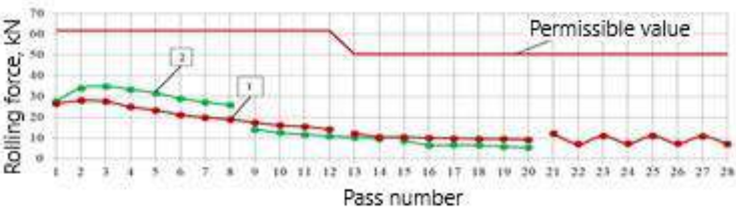


Fig. 2 – Distribution of the rolling force of Alloy 2 between the passes:
1) For the current regime; 2) For the calculated mode

After that, rolling was carried out and the ultimate tensile strength $R_m$ and the elongation to failure *A* were measured by the tensile method on an LFM 20 machine. An AFFRI DM 8 device was used for microhardness measurements. The results are summarized in Table 2.

Table 2 – Properties of wire rod and wire

| Alloy | Operation | Size, mm | Deformation | | | Annealing | | |
|---|---|---|---|---|---|---|---|---|
| | | | $R_m$, MPa | *A*, % | HV, kgf/mm$^2$ | $R_m$, MPa | *A*, % | HV, kgf/mm$^2$ |
| 1 | 1 stage | □ 3.7 | 940 | 4.0 | 307 | 533 | 35.0 | 242 |
| | 2 stage | □ 2.1 | 881 | 2.4 | 292 | 464 | 27.2 | 185 |
| | 3 stage | □ 1.1 | 820 | 1.5 | 294 | 489 | 31.0 | 160 |
| | drawing | Ø 0.25 | 958 | 4.2 | 300 | 560 | 33.0 | 145 |
| 2 | 1 stage | □ 3.7 | 942 | 3.6 | 228 | 450 | 35.0 | 124 |
| | 2 stage | □ 2.1 | 753 | 2.6 | 271 | 430 | 32.0 | 163 |
| | 3 stage | □ 1.1 | 661 | 1.9 | 264 | 434 | 25.0 | 149 |
| | drawing | Ø 0.25 | 879 | 3.6 | 273 | 503 | 39.2 | 139 |

The results of calculations and the investigation of properties confirmed the possibility of manufacturing wire for jewellery purposes with the required level of mechanical properties and a smaller number of sectional rolling passes.

*This research was carried out as part of an assignment given by the Ministry of Science and Higher Education of the Russian Federation; Research Subject Code: FSRZ-2021-0010.*

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UDC 621.774.3

# ANALYSIS AND SELECTION OF A TYPE OF THE TOOL DESIGN FOR COLD PILGER MILLS

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When producing cold rolled pipes, process parameters of rolling mills and steel under deformation are determined by the tool design. The design tool calculation method, method and equipment of its restoration significantly influence pipe deformability and quality, cost of rolling tools, productivity and efficiency of cold (warm) rolling of pipes in general.

The tool design development stages are divided into three generations [1]. The most known tool designs used at pipe plants are described below.

The tool design of the second generation is represented by MISIS and Technology Research Institute NTZ. Common features of such tool design are declining percentage reduction during rolling, a zone of free reduction in diameter and the use of a mandrel with a rectilinear generator [2].

The tool design of the third generation is represented by UralNITI (Ural Technology Research Institute), the tool design of proportional reductions, the tool design by Mannesmann and others. Tool designs of the third generation are characterized by variable taper of the grove and the mandrel. In this case, the mandrel is concave-tapered; there are known tool designs with convex and concave-convex mandrels [2].

The above tool designs factor into geometrical principles of designing longitudinal section of the groove and the mandrel according to the set, but variable rigid functions. A transverse section of the pipe profile is not considered, and its oval shape seems to take no part in deformation.

JSC Pervouralsk New Pipe Plant applies the calculation of the tool design for cold pilger mills according to the Kπ technique developed by Vinogradov A.G., PhD

(Eng.). The Kπ technique is a technique of the fourth generation based on the set law of the operating taper cross section area variation, changing within a wide range, via the elongation ratio with the use of a mandrel, whose generator is transformed from a rectilinear generator to a concave-tapered generator with varied steepness. The Kπ tool design is developed on a mathematical model of deformation in an instant deformation zone of pipes on the cold pilger mill. This enables a variation of up to 5 parameters [3].

Key basic provisions of the technique are as follows [3]:

– a basic shape-generating mandrel is considered to be an exponential function with variable curvature, whose value depends on steel hardening rate and requirements for the ratio between wall thickness and diameter reductions,

– taper of deformation is shaped by changing the cross section area, whose law of variation is determined by the exponential law calculated from the equation: relative reduction of the cross section area of taper of deformation is inversely proportional to the growth of yield strength of steel,

– deformation values and sizes in sections, when transferring from one functional section to another one (from the section of reduction in diameter to the reduction section, from the reduction section to a pre-finishing one), are determined by the set variable functions,

– transfer from cross section area $F_x = F_x/\mu_x$ to its geometry in compliance with the selected shape of the groove. The required width parameter is calculated subject to the set angle of camber. The coefficient of groove width is determined subject to the following factors: relative sizes of the shifted section, flattening of the pipe shape before starting reduction of the wall, the degree of shape broadening during diameter and wall thickness reduction, factoring into allowance for failure to rotate the workpiece to achieve 90°. Then, the taper parameter is calculated, the coefficient of the groove shape and the degree of occupation are determined, and groove radius is calculated.

The Kπ tool design ensures a favorable reduction of deformation parameters and rolling forces even on a tapered mandrel. Regarding high precision pipes, the Kπ tool design, combined with concave-tapered mandrel, ensures compliance with a wide combination of process factors: reduction of the area by 1.5...2.0 times by the end of the reduced area, a uniform distribution of rolling force and close to a uniform distribution of factor $Q$, achieving 1.5...3.5 by the end of the reduced area. The Kπ tool design, combined with a pre-finishing area of slight taper, ensures adjustment of wall thickness and reduces a longitudinal pipe wall thickness variation by 2...3 times.

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UDC 519.685

# APPLICATION OF THE COMPUTER-AIDED DESIGN SYSTEM FOR ASSESSMENT AND IMPROVEMENT OF RELIABILITY OF PARTS AND CONNECTION JOINTS OF PROCESS EQUIPMENT

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Outstanding reliability of process equipment is denominated by a complex of cooperative procedures covering the research stage, design, manufacturing, operation and repair [1]. A special place among the said procedures is given to the engineering process and design, i.e. the period of product creation when all the qualities and capabilities required for the life cycle are laid in it. When designing technical facilities, automated computational modeling arrangements are widely used to make this process more efficient, visual and high speed [2].

Computer-aided design systems are used to create information three-dimensional models of parts and subassemblies of process equipment, drawings of design documentation, visualized images, as well as animated videos of the work of nodes, structures, their installation or step-by-step assembly of equipment [3].

Autodesk Inventor enables you to constructively transpose the controlled plant characteristic and information about external loads to a three-dimensional model. It is used not only for assessment and analysis of operation performance of parts and components of technological machines and lines, but also for improvement of their reliability and durability under specified operating conditions [4]. A grid is generated directly on the model and a statistical analysis of the studied parameters is performed, which makes it possible to determine the stress and strain concentration fields, calculate frequency of natural resonance and account for safety factors. It provides users with an idea of the behavior and correct functioning of process equipment in boundary data.

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# UNDERSTANDING THE MECHANICAL PROPERTIES OF SILICON CARBIDE BRIQUETTES

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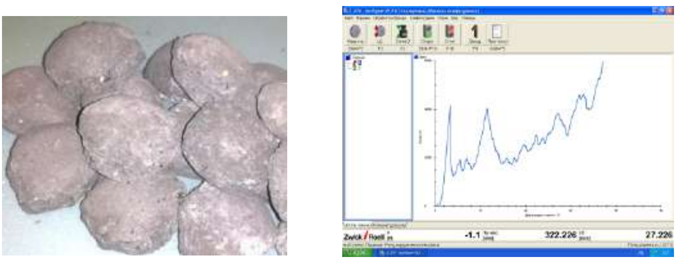
Today, briquetting – or, pelletizing of fine-dispersed materials – is utilized by various industries both in Russia and abroad. For instance, roll briquetting, as an efficient pelletizing technique, ensures high output and cost-effectiveness [1 – 2].

Silicon carbide crystals are used for the production of abrasives, whereas the low-quality product is used for steel deoxidation in metallurgy. Metallurgical silicon carbide is an excellent steel deoxidizer, so it found a wide application in the production of pipe and rail steel. As the size distribution of silicon carbide supplied for the ferrous metallurgy industry is 0.0 to 5.0 mm, it would be best utilized in the form of briquettes. Based on the practice of using liquid glass for silicon carbide briquetting, commercial batches of briquettes were obtained that were made of small size material [3].

The size of the briquettes in view (Fig. 1, *a*) is 40x30x20 mm. The density of briquettes: $2.3 \div 2.4$ g/cm$^3$.

The briquettes were tested in a laboratory of the University Branch in Verkhnyaya Salda on a universal machine Zwick/Roell Z050 with the maximum force of 50 kN. The tests were conducted in accordance with GOST 24765-81: *Iron ore pellets. Method to determine the compression strength*. A test speed range of 10 ÷ 20 mm/min was applied for briquette testing.




a) b)

Fig. 1 – Silicon carbide briquettes (a) and crush test curve

Fig. 1, *b* gives an example nomographic chart of briquette breakdown. The authors determined the force at which the first crack appeared (crushing force) Pp and the breakdown point $\varepsilon_p$. The percent height reduction was determined as follows: $\varepsilon = H_0/H$, where $H_0$ and H – briquette height before and after deformation, correspondingly. The crushing energy can be determined as an area underneath the curve in the chart. 7 tests per point were conducted. The resulting compression charts were processed and the mean values for the test speed of 5 ÷ 20 mm/min are given in Table 1.

Table 1 – Compression chart processing data

| Test Speed, mm/min | $P_p$, kN | $\varepsilon_p$, % |
|---|---|---|
| 5 | 0.9 | 5.0 |
| 10 | 1.4 | 5.0 |
| 15 | 2.2 | 3.0 |
| 20 | 4.1 | 2.5 |

The conclusion that has been drawn from this study is that further research is needed into the mechanical properties of briquettes made of small size materials that are widely used in ferrous metallurgy (e.g. magnesium and calcium oxides, undersized coke and others).

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# Content

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