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Abstract:— The crystallographic texture of the AA1050 aluminum alloy was studied under symmetric and asymmetric rolling in various technological modes of rolling equipment. The rotational speeds of the rolls and the number of passes varied. Rolling aluminum sheet alloy was carried out on an experimental - laboratory installation. The crystallographic texture before and after rolling was investigated using X-ray diffraction. X-ray analysis data was processed using MTEX MATLAB toolbox 75. The pole figures and the texture of the samples of aluminum alloy on the Euler space are given. It was shown that pole figures obtained on the basis of X-ray analysis of samples, rolled by the traditional way, had orthorhombic symmetry, and the sample texture had typical components of traditional rolling, like Cu (copper), Su (with lower intensity) B (Brass).

Index Terms:— Symmetric and asymmetric rolling, aluminum alloy, crystal structure, anisotropy, X-ray analysis, pole figure.

1 INTRODUCTION

Increasing demands on the quality of sheet metal and, in particular, on the accuracy of its size, require improvements in rolling technology, automated systems for designing technological processes, the creation of new and improvement of existing structures of deforming units. Rolling equipment processes both non-ferrous and ferrous metals. Among non-ferrous metals, aluminum and copper alloys are of great practical interest. These alloys are widely used in aircraft manufacturing, mechanical engineering, instrument making and automotive because of their specific properties, such as relatively low specific gravity, high corrosion resistance, heat and electrical conductivity. The high price and limited characteristics of the formation of the pressure treatment are considered the main disadvantages of aluminum sheet, which limit its wider use in various sectors of the economy. In many important industrial applications, as automotive, aircraft, construction, engineering and packing, metal sheets are used in large scales. Especially the aluminum and its alloys are widely spread because of their properties, such as low density and high corrosion resistance. However, the high cost, the limited formability and the relatively low strength are the major drawbacks to wider-scale applications of aluminum components. Forming characteristics of sheet aluminum mainly depend on the change in mechanical hardening during plastic deformation and the anisotropy coefficient, i.e. the ratio of reducing the width and thickness in the tensile test, which depends on the crystallographic texture of the metal. The larger value of the anisotropy coefficient means that during plastic deformation there is a greater shaping with a small change in thickness. Achieving greater shaping can be achieved through the use of asymmetric rolling.

Asymmetric rolling is a promising method of metal forming and is characterized by geometric asymmetry, associated with the diameter difference between two rolls and kinematic asymmetry, determined by the difference in the linear speeds of the rolls. As a result of this process, intense shear plastic deformations occur and shear deformation texture is formed through the thickness of the metal strip, which ensures high quality of products.

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the rolling of asymmetric technology, as well as the influence of the structure on the physicomechanical properties of the

material, is relevant. The purpose of this work is to study the crystallographic texture of the AA1050 aluminum alloy with symmetric and asymmetric rolling under various technological modes of rolling equipment.

2 DESCRIPTION OF THEORETICAL AND EXPERIMENTAL STUDIES

Improvement of technological processes of metal forming and, in particular, the rolling process, is carried out on the basis of theoretical and experimental studies of plastic deformation processes. Thus in the theoretical description of the rolling process uses the mathematical model based on statistical processing results or experimental study on the basis of an elastoplastic deformation theory. However, the formalization of such a process is a rather complex mathematical task. If we consider that a change in the texture of the material due to the structure, it is obvious for topical is the study of crystallography aluminum alloy with symmetric and asymmetric rolling. Increasing requirements for the quality of rolled copper, aluminum, and their alloys requires high accuracy of sheets and a long-term metal, and a reduction in the longitudinal and transverse thickness variations. Reducing the longitudinal and transverse thickness variations can be achieved through the use of asymmetric rolling. Asymmetric rolling reduces the rolling force and energy consumption for the deformation process, reduces the longitudinal and transverse thickness variations, improves the flatness and shape of the strip, allows to quickly control the surface quality, physical and mechanical properties of the material. Analysis of factors that affect broadening and asymmetric rolling technology showed that the most rational and ways to study the effect of the misalignment of the roll speeds on the broadening from the drive and driven rolls is speed asymmetry. During the rolling process, the energy is transferred from rolls to the strip through the friction between cylinders and material's surfaces. While the strip passes between the gap of rolls, its thickness is uniformly reduced, the length is increased while its width remains almost unchanged. The reduction in thickness (r) can be calculated by the following expression [1]:

$$r = \frac{t_0 - t_f}{t_0} \quad (1)$$

where t_0 and t_f are the thickness of the strip before and after rolling, respectively. The elongation causes differences of speed of the material along the strip; the material's speed is higher at the exit than at the entrance of the gap between rolls. The strip moves slower than the rolls at the entrance ($v_0 < \dot{U}$) and faster than the rolls ($v_f > \dot{U}$) at the exit (Fig.1.). The point where the speeds of the strip and rolls are equal ($v = \dot{U}$) is called a neutral or non-slip point [2]. The change of speeds in

different regions is proportional to the change of the roll gap:

$$\frac{U_f}{U_0} = \frac{t_0}{t_f} \tag{2}$$

In the region between the entrance and neutral point the friction force of the roll on the material surface (F_1) moves the strip forward, while friction force (F_2), that acts in the region between neutral point and the exit opposes to the movement of the strip. The difference of the opposing forces is the net friction drag force of the rolling process.



At the neutral point and exit, the net force's conventional causes the increase of F_1 and the non-slip point moves towards exit. The net force can be increased until the F_2 equals zero, i.e. the neutral point reaches the exit. After this point the rolls will start skidding over the strip, the power is not transferred from the rolls to the strip and the strip movement will stop. The projected contact arc length between rolls and the processed material (L_p) can be determined as [3]:

$$L_p^2 = R_0^2 - \left(R_0 - \frac{\Delta t}{2} \right)^2 \tag{3}$$

When the reduction $\Delta t = (t_0 - t_f)$ is very small compared to the rolling radii R_0 , the equation can be simplified to:

$$L_p \approx [R_0 \Delta t]^{1/2} \tag{4}$$

The vertical component of radial load (P_r) is known as rolling load and is given by $P_r \cos \alpha$. In order to calculate specific pressure (p) on the contact area the following expression can be used [5]:

$$p = \frac{P_r \cos \alpha}{b L_p} \tag{5}$$

where b is the width of the strip. The vertical component of P_r varies by change of contact angle α and the maximum value is reached on the neutral point [3]. The typical distribution of

rolling pressure is shown on Figure. 2.

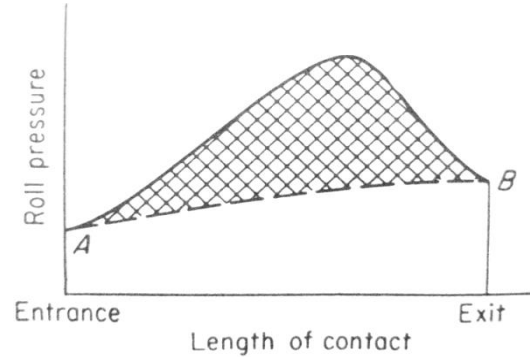


Figure.2. Distribution of roll pressure (p) along the arc of contact [3]

In order to roll a strip, the rolls should not slip on contact surfaces of the sheet. This depends on the friction coefficient between contact surfaces, which can be described by the forces interacting on the system. The projection of the friction force on horizontal axis ($F \cos \alpha$) should be bigger or equal to the rolling pressure projection on the same axis ($P_r \sin \alpha$):

$$F \cos \alpha \geq P_r \sin \alpha \tag{6}$$

That can be rearranged as:

$$\frac{F}{P_r} \geq \frac{\sin \alpha}{\cos \alpha} \equiv \tan \alpha \tag{7}$$

Where F/P_r is, by definition, the friction coefficient μ :

$$\mu \geq \tan \alpha \tag{8}$$

From above equation one can conclude that bigger value of $\tan \alpha$ than friction coefficient causes the slipping of the piece against the rollers. From Figure 1 the relation between rolls radii, projected contact length and contact angle can be written as:

$$\tan \alpha = \frac{L_p}{R - \Delta t/2} \tag{9}$$

Replacing the L_p from eq. (4), one can obtain

$$\tan \alpha \approx \frac{\sqrt{R \cdot \Delta t}}{R - \Delta t/2} \approx \sqrt{\frac{\Delta t}{R}} \tag{10}$$

With substituting equation (8) into (10) it is shown that the maximum reduction depends on rollers radii and the friction coefficient [3]:

$$\Delta t_{\max} = \mu^2 R_0 \tag{11}$$

The use of speed asymmetry makes it possible to adjust the mismatch of the speeds of the rolls in a wide range directly in

the rolling process, and also allows the use of their automatic control systems. But when rolling thin sheets there are difficulties due to the fact that when trying to adjust the profile of rolled sheets, their stability is disturbed: waviness occurs at the edges of the sheets, or the formation of protrusions in the centre of the sheets (warping). Therefore, the main problem of sheet rolling is not an increase in productivity and speed of rolling, but an improvement in the quality of sheet metal. A very important problem is the need to improve the accuracy and the size of rolled products, which leads to the solution of several technological problems like the reduction of longitudinal sheet thickness variation. The task is solved by increasing the rigidity of the rolling stands and at the same time the dimensional accuracy of all the parts of the stands, especially the work rolls and support rolls [4], [5]. Effective ways to implement the finishing machining of the rolls after the assembly of the stand at the working position of the rolls and when they are loaded with an effort equal to the rolling force. The longitudinal thickness variation of the rolled sheets can be adjusted: by changing the position of one of the rolls with push screws; load force change; the change in the ratio of the speeds of the rolls, i.e. using "speed asymmetry"; the creation of tensions, which leads to a decrease in effort, and consequently, to a decrease in the deformation of the stand and the size of the roll gap. Reducing the transverse thickness variation is solved by choosing the optimal roll profiling. The use of wave profiling makes it possible to significantly reduce the transverse thickness variation. The same goal can be achieved using anti-bending systems for working or support rolls. Often, a combination of asymmetric wave profiling and a system of axial movement of the work rolls is used. Since the reason for the violation of flatness is the unevenness of the hood across the width of the sheet, the broadening somewhat helps to improve the flatness, if the compression at the edges of the sheet is higher than in the centre. Therefore, in some cases, the broadening is useful, but when rolling wide sheets it is insignificant. It is known that during rolling there are cases of loss of stability of the deformation process. The main reasons for the loss of stability can be the following factors:

- a) lateral displacement of the sheets in the rolling process, up to the output of the rolled products from the rolls (the so-called "casting onto the frame" occurs). This leads to the termination of the rolling process and, possibly, to an accident;
- b) curvature of the ends of the rolled stock due to asymmetry, either due to the difference in the circumferential speeds of the rolls, or due to uneven heating of the rolled product, or due to differences in lubricant conditions along its surfaces;
- c) loss of stability due to the sheet curvature under uneven deformation along its width: either its extreme sections (at the sheet edges) become wavy, or the flatness of the central section of the sheet is broken. Obviously, the rolling process should be stable and if a certain asymmetry of the process is used, for example, creating a speed asymmetry to control the thickness variation [6], then the values of this asymmetry should be chosen within the limits ensuring the stability of the deformation process. In asymmetric rolling, the forces of the deformation process are significantly reduced compared with conventional rolling. Reducing the rolling force has a great advantage, very large deformations can be transferred to the material for the production of ultra-thin structures, texture modifications and the production of high-strength materials [7]. One of the consequences of the shear component is an

increase in the surface area of the deformed grains to higher values than is possible with pure deformation of simple compression. For example, in the case of austenite, this leads to an increase in crystallization centers for recrystallization or phase transformation. The end result is smaller ferrite grains in comparison with the case of conventional hot rolling [7], [8]. The process of asymmetric rolling in modern production conditions considers the technological process of influencing the parameters of process equipment, as well as the quality of rolled metal [9], [10], [11], [12], [13], [14]. From the above it can be done following output: asymmetric rolling to a metal is a promising method of producing sheet material. The widespread introduction of this method requires a comprehensive study of the technological process of asymmetric rolling, and metallographic research. It is important to study the effect of high-speed asymmetry modes on the structure and mechanical properties of the metal being processed. In the section materials and methods of research, research methods and the tested aluminum alloy are given in more detail.

3 MATERIALS AND RESEARCH METHODS

As demonstrated in this document, the numbering for sections As the material chosen for the study was the aluminum alloy sheet of the European standard 1050 mm 3, the chemical composition of which is given in Table 1. The purpose of the selection of technical pure aluminum lies in the capability and more accurate modeling of microstructure due, crystal structure and properties.

TABLE 1
The chemical composition of aluminum alloy AA1050

El.	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Ga
Qt, %	0,089	0,28	0,002	0,001	0,001	0,001	0,003	0,005	0,011	0,016

Asymmetric and symmetric rolling of sheet aluminum alloy was carried out on an experimental-laboratory setup, the technical parameters of which correspond to the technical parameters of industrial equipment, taking into account the similarity coefficient, equal to 4. In order to achieve the parameters of industrial rolling machine for transmitting force m through the rollers to treat the first material on the basis of calculations of selected smaller roll length and diameter, but produces the same effort, that industrial mill. The device has two cylinders (mill rolls) of the same size with diameters of 180 mm, which rotate at the expense of two independent DC motors. The speed of rotation of the cylinders and the forces on the rolls are controlled by a computer with special software. In the number of revolutions of both cylinders is time in conventional rolling experiment and 15 min⁻¹. In asymmetric rolling, the speed of the upper and lower cylinders was 5 min⁻¹ and 15 min⁻¹, respectively. In all experiments after each pass rolling reduction of thickness of the sample was a 15%. This shows that after 2x, 4x and 6th passes, the thickness of the samples decreased by 28%, 48% and 62%, respectively. Samples treated by symmetric rolling (CR) are always rolled in the same direction. In asymmetric rolling, the tests were carried out in two different sequences: asymmetric sequential (ASRC) and asymmetrically reversible (ASRR) rolling. With ASRC, the rolling direction - RD remained unchanged (Figure 3, a), while with ASRR, the samples were rotated 180° around RD after each pass (Figure 3, b).

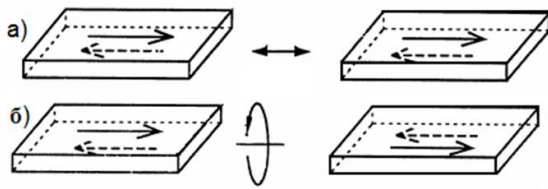


Figure 3 diagrams perform those sequences *hnologicheskikh* operations during prolonged asymmetrically (ASRC) (a) and asymmetrically reversing (ASRR) (b) rolling

To ensure the same slip coefficient value between the surfaces of the rolls and the sample, lubricants were not used, and the working surfaces were constantly cleaned. After each pass in the ASRC experiment (asymmetrical sequential) and ASRR (asymmetrically reversible), distortion angles were measured relative to the vertical position (lines (notch) were drawn on the peripheral part of the sample before rolling with a solid sharp instrument, as shown in Figure 4), which was used in the calculation macroscopic shear deformation:

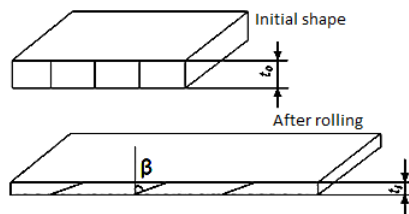


Figure 4 - Type of sample before and after asymmetric rolling: t - sheet thickness before rolling; t_1 - sheet thickness after rolling; β - the angle of rotation of the drawn line after rolling

The mechanical properties characterization of the samples before and after different rolling types was performed by uniaxial tensile test using an universal testing machine Shimadzu Autograph with maximum load capacity 50 kN. The length and width changes were measured by a non-contact video extensometer MFA-25. The ASTM tensile specimen with 10 mm width cut at 0° , 45° , 90° from RD were used. The tests speed was 1.5mm/min, which correspond to initial strain rate of $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$. Crystallographic texture was investigated by X-ray analysis, X-ray obtained in the diffractometer Philips X'pert, equipped with a goniometer for determining the texture in the radiation CuK α . The crystallographic orientation of the grains was studied on the $\{200\}$ and $\{111\}$ planes of pole figures. Samples of the aluminum alloy is mechanically ground and polished and smiling. (Modes and angles of rotation of the goniometer) The obtained X-ray analysis data was processed on a computer using special software MTEX MATLAB toolbox 75. According to the results of processing polar aluminum sample pieces were selected s 1000 orientations and used to calculate the value $\langle M \rangle$ (M-decoding) by means of viscoplastic -samosoglasovannoy mathematical model developed Lebonsonom and Tom [15], [16], [17].

4 Results and discussion

For metallic materials, the preferential orientation of grains is formed during thermomechanical processes, such as solidification, cold or hot rolling, recrystallization, etc.

Crystallographic texture, i.e. The preferential orientation of the grains of polycrystalline materials leads to anisotropy of the properties of materials. The texture of metals in the processing of rolling play an important role in the regulation of plastic and strength properties. In materials science, the term "texture" denotes the preferential orientation of crystallites (grains) in a polycrystalline material relative to any selected planes or directions in the metal space. There are concepts of mechanical texture and crystallographic texture [18]. The mechanical texture is the primary orientation of the grains in the direction of the grains of maximum deformations without taking into account the location of the crystallographic planes and directions in these grains. For example, in cold-rolled metal, grains have a flattened shape in the vertical direction and elongated in the longitudinal direction. If rolling occurred without noticeable broadening, then in the transverse direction the grain size does not change significantly as compared with the initial state. The mechanical texture does not provide much information about the anisotropy of the properties of a deformed metal, but it leads to a decrease in the length of the boundaries in the transverse direction, to the deceleration of intergranular cracks and an increase in tensile strength. More clear picture can be obtained using crystallographic texture. The crystallographic texture represents the preferential orientation of the crystallographic planes and directions relative to the planes and directions chosen in the metal space. For example, when studying the texture of a rolled sheet, it is determined which crystallographic planes of the grains reach the surface of the sheet (i.e., lie in the plane of the sheet) and which crystallographic directions in these grains are oriented along the rolling direction. In crystals, there is a set of equal planes and directions, for example, six planes of type $\{100\}$ and six directions of type $[100]$, then we speak of a $\{100\} \langle 100 \rangle$ texture, where the set of planes and directions is defined by brackets $\{ijk\} \langle hkl \rangle$. Crystallographic textures largely determine the anisotropy of the mechanical and physical properties of metals. Texture management makes it possible to adjust the plasticity during cold deformation of metals, which allows the possibility of reducing the resistance to deformation, and, consequently, the energy consumption for deformation and the cost of the finished product. Therefore, the study e crystallographic texture during the cold rolling is an area of research. There are direct and indirect texture research methods. Indirect methods include methods based on measurements of the anisotropy of mechanical or physical properties, for example, measurements of yield strength or magnetic permeability. Radiographic, optical and metallographic are considered direct methods for studying texture. The direct method enables more adequately simulate crystalline texture and to ultimately effect the physico-mechanical properties of the metal. On this basis, we have chosen a direct x-ray method for studying the texture of aluminum alloy. When compared with initial material, conventionally and asymmetrically rolled samples show substantial differences in mechanical behavior during tensile test (Fig. 34). Namely, it is observed an increase of yield stress and maximum stress () together with strong decrease of the uniform plastic deformation, with the total thickness reduction in rolling. After six passes (which correspond to 62% of reduction) the uniform deformation is less than 2% for all samples and the maximum stress increases up to 130-150 MPa (Fig. 35. c), depending on the test angle and rolling type. More specifically, the highest values of were achieved for

ASRC and the lowest values for CR samples. These differences can have origin on the dislocation structure or/and on the crystallographic texture developed during the pre-strain in rolling. To investigate the contribution of each of these physical mechanisms, texture analyses using visco-plastic self consistent model and TEM observations were performed after different rolling types. To study the anisotropic strain distribution, pole figures were obtained for the initial metal (Figure 3). The results show a strong {100} <001> preferential crystallographic grain orientation, which is typical for recrystallized aluminum sheet. The presence of this component of the texture, known as the component of the cube, which is better described in Euler space (Figure 6) and is usually associated with a low R value.

(cubic) texture components (Figure 9). For both types of asymmetric rolling, the intensity of the ideal shear components in the texture (E {111} <110>, F {111} <112> and H {001} <110>) showed low values, despite the fact that the macroscopic strain of the sample in A S RA has reached (Figure 12).

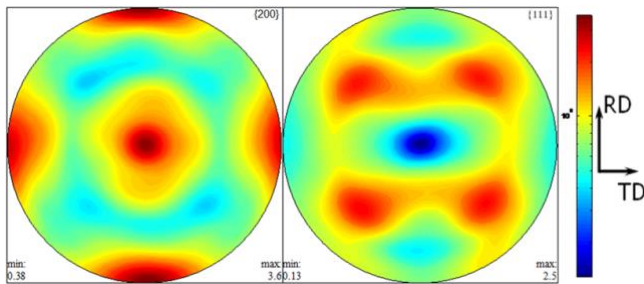


Figure 5- {200} and <111> pole figures of the source metal

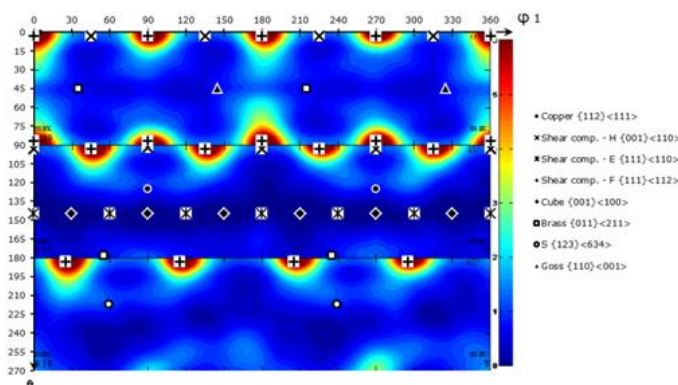


Figure 6- The crystallographic texture of a parent metal on the sections Euler space

Figures 7 - 12 show the pole figures and texture samples on Euler space and subsequent different passages when using different x views s rolling. For samples laminated by the traditional method, pole figures showed orthorhombic symmetry and the texture of the sample had typical components of traditional rolling like Cu (copper), Su (with less intensity) B (Brass). When asymmetrically first rolled to e were other textures are obtained. More specifically, when ASRC - asymmetric continuous rolling was orthorhombic symmetry - it was only of mirror symmetry axis located parallel to the rolling direction. Moreover, the rolling components like Cu, Su and Brass are still preserved with different intensities and have a large fraction, the crystal objects have an orientation close to the ideal texture with shear components. The texture of ASRA - asymmetric reversing rolling can be considered as see the texture CR (Cu, Su, Brass with low intensity) and the original

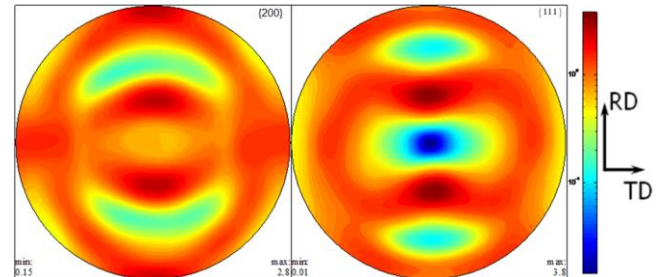


Figure 7- {200} and {111} pole figures CR

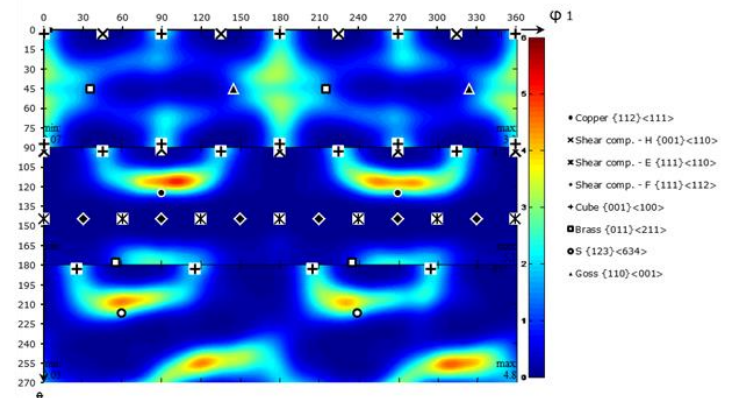


Figure 8 - Crystallographic texture of the CR sample on Euler space, when and 65°. The components of the perfect (fcc) texture are marked with different signs

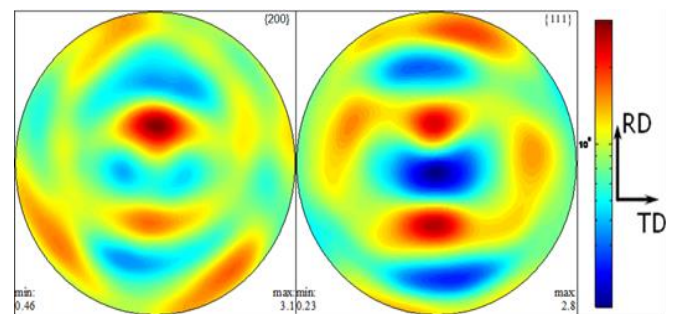
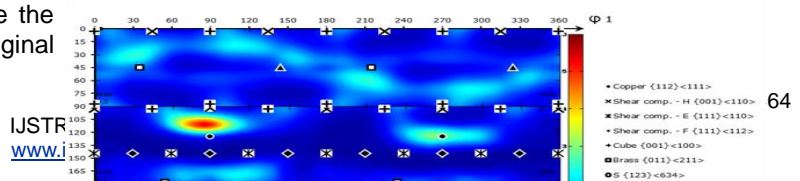


Figure 9- {200} and {111} pole figures ASRC



ASRR reached

Figure 10- Crystallographic texture of the ASRC sample on Euler space, 65° . Components of perfect fcc texture are marked with different signs.

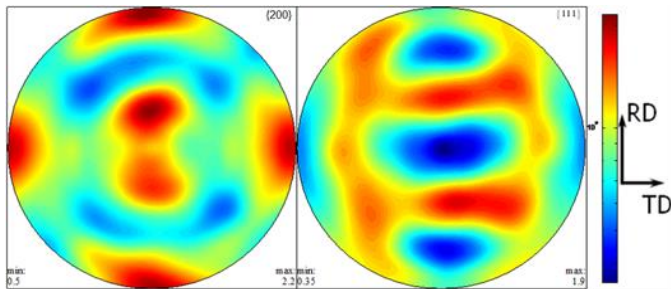


Figure 11- {200} and {111} pole figures of the ASRR sample

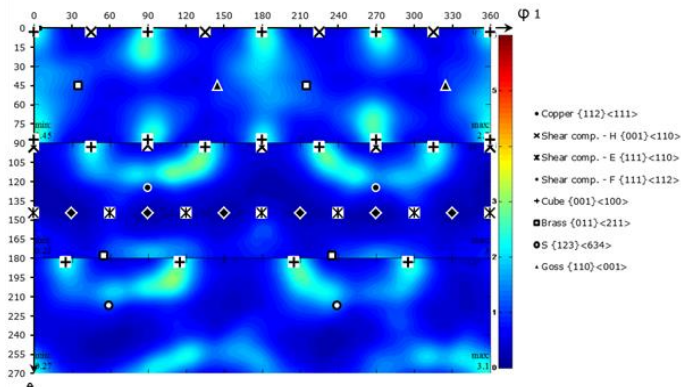


Figure 12- Crystallographic texture of the ASRR sample on Euler space, Components of perfect fcc texture are marked with different signs.

4 CONCLUSION

1. With asymmetric rolling, the deforming forces of the process are significantly reduced compared with conventional rolling. Reducing the rolling force has a great advantage, very large deformations can act on the material for the production of ultrafine - grained structure, texture modification and the production of high-strength materials.
2. It was revealed that the crystallographic structure of the samples obtained symmetric rolling, had a orthorhombic symmetry, and the sample had a texture typical components of conventional rolling,
3. Asymmetric box is obtained and other textures. When ASRC - asymmetric continuous rolling was orthorhombic symmetry, - it has only from the mirror symmetry axis located parallel to the rolling direction.
4. For ASRC - asymmetric long rolling and for ASRR - asymmetric reverse rolling, the intensity of the ideal shear components in the texture (E {111} <110>, F {111} <112> and H {001} <110>) showed low values, in spite of the fact that the value of the macroscopic deformation of the sample during

REFERENCES

- [1] Dieter G.E. (2003). Handbook of Workability and Process Design, ISBN 0-87170-778-0, ASM International.
- [2] Avitzur, B. (1983). Handbook of Metal-Forming Processes, ISBN 0-471-03474-6, Wiley-Interscience Publication, New York.
- [3] Dieter, G. E. (1988). Mechanical Metallurgy SI Metric Edition, McGraw-Hill Book Co.
- [4] Traino A.I. Improving the efficiency of machining rolls sheet mills [Text] / A.I. Traino, V.S. Yusupov, G.K. Nonikov [and others] // Proceedings of the second congress of distributors. - M.: Chermetinformatio AO. - 1998. p. 344-346.
- [5] Lukash A.S. Improvement of the technological process and mathematical model of cold rolling of thin strips of copper and brass to improve their quality. Dissertation of the candidate of technical sciences. -Moscow, 2016, 132 p.
- [6] Brovman M.Ya. Application of the theory of plasticity in rolling [text] / M.Ya. Brovman - M.: Metallurgy, 1965. 247 p.
- [7] Cui, Q and K. Ohori ; Mater. Sci. Tech., Vol. 16, (2000), p.1095.
- [8] Inoue T., Torizuka S. and K. Nagai; Mater. Sci. Tech., Vol. 18, (2002), p.1007.
- [9] Mazur V.L., Nogovitsyn A.V. The theory and technology of sheet rolling (numerical analysis and technical applications). - Dnepropetrovsk: PBA Dnipro -VAL, 2010. - 500 p.
- [10] Golubchenko A.K., Mazur V.L., Binkevich E.V. The influence of the angle of entry of the strip into rolls on the parameters of the rolling process // Metallurgical and mining industry. - 1994. - № 3. P. 20-24.
- [11] Mazur V.L., Golubchenko A.K., Binkevich E.V. Calculation of parameters of the process of hot asymmetric rolling of thick strips // Steel. - 1994. - № 1. P. 39-41.
- [12] Asymmetric hot rolling on a broadband mill / A.G. Svichinsky, E.V. Binkevich, V.L. Mazur, A.K. Holubchenko // Steel. - 1992. - № 11. P. 41-44.
- [13] Calculation and control of the process of asymmetric hot rolling by the method of slip lines and nonlinear programming / A.G. Svichinsky, V.L. Mazur, E.V. Binkevich, A.K. Holubchenko // News of the Russian Academy of Sciences. Metals. - 1993. pp. 70-79.
- [14] Theory and technology of asymmetric rolling / V.A. Nikolaev, V.L. Mazur, A.K. Holubchenko, E.V. Binkevich // M.: Agency "Informat". - 1996. 262 p.
- [15] Lebensohn, RA and CN Tomé (1993). "A self-consistent anisotropic approach for the simulation of plastic degradation : for zirconium alloys." Acta Metallurgicaet Materialia 41 (9): 2611-2624.
- [16] Lebensohn, RA and CN Tomé (1994). "A self-consistent viscoplastic model: prediction of rolling textures of anisotropic polycrystals." Materials Science and Engineering: A 175 (1-2): 71-82.
- [17] Lebensohn, RA and GR Canova (1997). "A self-consistent approach for modeling the two-phase polycrystals : Application to titanium alloys." Acta Materialia 45 (9): 3687-3694.
- [18] Kolbasnikov N.G. Theory metalworking d ION. Physical basis of strength and ductility of metals. Tutorial. St. Petersburg. Publisher SPbGPU, 2004. 268 p.