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MODELING THE PROCESS OF ALTERNATING DEFORMATION OF A STRIP-TYPE PROFILE IN A THREE-ROLLER BENDING-TENSILE DEVICE

Abstract. The use of high-precision profiles in modern mechanical engineering is of great importance in terms of improving the quality of manufactured products and significantly reducing the cost of their production. In Ukraine, the production of high-precision profiles is extremely limited, and the production of strip-type profiles is completely absent. In world practice, the production of strip-type profiles is possible in various ways: hot rolling, hot pressing, cold rolling, or drawing in monolithic or roller drawing mills. Roller dies for the production of shaped profiles have an advantage over monolithic dies, as a greater amount of crimping is possible in one pass. In addition, drawing in roller drawing machines takes place in non-driven rollers in combination with environmentally friendly heat treatment methods without the use of harmful cooling media in the form of lubricants, lead melts, salts and acids. At the same time, the peculiarities of the conditions of plastic equilibrium of the metal of the deformation center during the flattening of a round billet by drawing in roller draws inhibit the development of new profiles, including strip-type profiles with a ratio of their width to thickness of more than two. This is due to the fact that the uneven compression of the wire blank leads to an uneven distribution of stresses across the profile cross-section: in the middle part – compression, at the edges – tension and the presence of tensile force increases the areas of action of tensile stresses and their magnitude in the volume of the deformation center and, ultimately, under certain conditions, causes a significant decrease in plasticity and destruction of the edges of the finished profile. There are two ways to increase the plasticity of a metal – thermal and mechanical. The thermal method, which is widely used in industry, requires significant energy consumption. At the same time, previous studies, including those conducted at the ISI NASU, showed that it is possible to increase the plasticity of metal by means of alternating deformation of profiles, using, for example, equipment for straightening profiles or a scale breaker. At the same time, the results of specific studies of the influence of the parameters of the process of alternating metal deformation on the magnitude of stresses and the nature of their distribution over the cross-section of a strip-type profile are absent in the considered publications. The purpose of the research was to consistently analyze the stress state of the metal throughout the actual deformation center, taking into account the external zones, using a developed and tested mathematical model for calculating the stress-strain state of the metal. It has been established that the mechanism of residual stress occurrence is due to the magnitude of plastic deformation and the inhomogeneity of the distribution of deformations over the thickness of the profile during alternating deformation during its pulling through the DBT. According to the modeling results, it was determined that the maximum values of residual longitudinal stresses formed along the profile cross-section after leaving the DBT are 1.4 times less, regardless of the sign of the stresses, compared to the maximum longitudinal stresses formed under the pressure roller. It is shown that the maximum level of plastic deformations is observed at the beginning of alternating deformations in the DBT device with a decrease in their level at the exit from the DBT, which provides a decrease in the values of residual stresses and potential energy in the column made of St.08 steel.

Key words: alternating deformation, strip-type profiles, roller drawing, bending-tensile device (DBT), compressive stress, tensile stress.

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Introduction. Distinctive features of high-precision profiles and, in particular, strip-type profiles are high uniformity of temporary resistance along the length of the coil, high accuracy of shape and dimensions (tolerance for thickness from - 0.03 to 0.04 mm, and for width up to - 0.01) the width variation within the coil is no more than 0.07 mm, smooth (without ripples) edges with smooth rounding and the ratio of the cross-section width to its thickness is up to 8 [1]. The scheme for the production of high-precision profiles, which has developed in world practice, includes obtaining shaped blanks by hot deformation - hot rolling, hot pressing (the main form change of the metal) and subsequent cold deformation in one to three passes by drawing or cold rolling. Such a technological scheme, with rational process parameters, ensures a fairly high quality of the workpiece and finished metal products. However, according to economic research conducted in Germany, rolling profiles on industrial rolling mills is advisable only if the annual demand for one profile is at least 20 tons. The same conclusion was made by the authors of [2] when analyzing the economic indicators of rolling and hot pressing. Therefore, high-precision profiles can be completely formed by cold deformation using the drawing method in monolithic or roller dies. Roller dies for the production of shaped profiles are superior to monolithic dies, since a greater amount of pressing is possible in one pass. The cream in the roller dies is produced in non-toxic rollers using environmentally friendly methods of thermal processing without the use of wasteful cooling media in the form of oil, melting lead, salts that acid [3-7].

At the same time, the use of high-precision profiles in modern mechanical engineering is of great importance in terms of improving the quality of manufactured products and significantly reducing the cost of their production. For example, the use of steel piston rings instead of traditional cast iron ones allows you to significantly increase the engine life of machines and units, simplify and largely automate the technological process of manufacturing rings, and reduce labor-intensive and environmentally harmful foundry production. In Ukraine, the production of high-precision profiles is extremely limited, and the production of strip-type profiles is completely absent. The production volumes of such products, given the high demand in a wide range of sizes and brands, are relatively small (up to 3 thousand profile sizes with a total volume of 45-50 thousand tons per year) [8], therefore the creation of a specialized enterprise for the production of high-precision profiles and rolled steel strip under these conditions (the cost of equipment is up to 20 thousand US dollars per ton) is economically inexpedient, and the focus on imports makes the economic and technological security of the mentioned sectors of the country’s economy dependent on foreign suppliers.

At the same time, the peculiarities of the conditions of plastic equilibrium of the metal of the deformation center [5-7] during the flattening of a round billet by drawing in roller draws hinder the development of new profiles, including strip-type profiles with a ratio of their width to thickness of more than two. The fact is that the uneven compression of the wire blank leads to an uneven distribution of stresses across the profile cross-section: in the middle part – compression (–), at the edges – stretching (+), and the presence of tensile force increases the areas of action of tensile stresses and their magnitude in the volume of the deformation center and, ultimately, under certain conditions, causes a significant decrease in plasticity and destruction of the edges of the finished profile. There are two ways to increase the plasticity of metal - thermal and mechanical. The thermal method, which is widely used in industry, requires significant energy consumption At the same time, previous studies, including those conducted at the Iron and Steel Institute of Z. Nekrasov of the National Academy of Sciences of Ukraine (ISI NASU), showed that it is possible to increase the plasticity of metal by means of alternating deformation of profiles, using, for example, equipment for straightening profiles or a scale breaker [9, 10]. The authors of most publications that consider the deformation and energy-force parameters of the alternating deformation process in bending-tensile devices (DBT) usually provide only a qualitative assessment of the influence of residual stresses on the overall stress-strain state (SSS) of the rolled material [11-13]. The results of specific studies of the influence of the parameters of the process of alternating metal deformation on the magnitude of stresses and the nature of their distribution over the cross-section of a strip-type profile are absent in the considered publications. While for a reasonable choice of parameters of the process of alternating deformation by the "bending with stretching" method, it is necessary to know the influence of these parameters on the magnitude and nature of the distribution of stresses across the cross-section of the strip-type profile, in order to prevent tensile stresses from reaching critical values. We proposed to solve this problem using the method of mathematical modeling.

The purpose of the research was to consistently analyze the stress state of the metal throughout the actual deformation center, taking into account the external zones, using a developed and tested mathematical model for calculating the stress-strain state of the metal.

Presentation of the main research results. To select a mathematical model of the metals SSS in the process of alternating deformation, an analysis of existing methods for its determination in the process of cold deformation of a strip-type profile in a bending-tensile device was conducted. The analysis showed that for conducting research on the influence of technological parameters of the sign-changing deformation process on the change in the SSS of the metal, the most reliable result is provided by the use of variational methods based on the basic principles of the theory of plasticity [14, 15]. The research was carried out using a mathematical model developed and tested for adequacy at the ISI NASU for calculating the stress-strain state of the metal when pulling strip-type profiles through a bending-tensile device (DBT) [16, 17]. To simulate the alternating deformation of metal by bending with stretching, a single-plane three-roller DBT with a vertical arrangement of rollers was used. The modeling parameters were adopted taking into account the capabilities of the technological equipment of the ISI rolling laboratory. Modeling elastic-plastic alternating bending of metal in the Solid Works Simulation system includes the following stages:

1) model setup – creation of a finite element model of the headquarters, which is placed between the upper and lower rollers;

2) vertical movement of the lower pressure roller upwards to the working position with the provision of fixation of the given displacement

value;

3) applying gravity to the system in the absence of roller movement;

4) providing the speed of rotation of the rollers to simulate the movement of the staff due to the friction forces between it and the rollers;

5) assessment of the elastic unloading of the material after leaving the bending-tensile device (DBT).

The first and third stages are dynamic with the task of translational and rotational movements of the DBT rollers, and the rest are static without the task of roller movement.

To describe the contact interaction between the rollers and the headstock, the built-in capabilities of the Solid Works Simulation system were used, which allow taking into account static and dynamic friction coefficients. In the absence of tangential movements in the contact pair, which corresponds to the upward movement of the pressure roller 2, a static coefficient of friction is used, equal to 0.25, and after the start of the movement of the strip type profile, a dynamic coefficient equal to 0.12 is used.

The scheme of the process of alternating deformation of the strip type profile with a thickness of h = 5.2 mm and a step between the centers of the axes of adjacent rollers of support 1 and pressure 2 and adjacent rollers of pressure 2 and support 3 of the BTD, which was equal to t = 35 mm, is shown in Fig. 1.

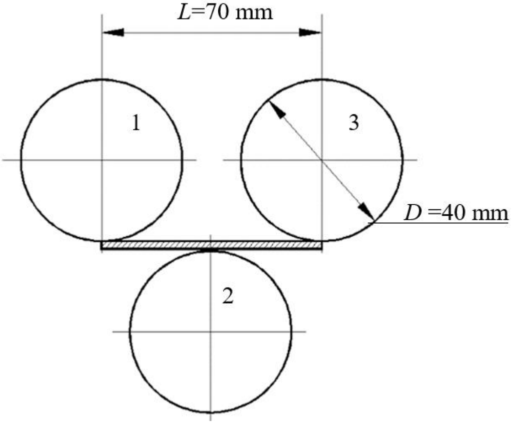

Figure 1 – Scheme of the process of alternating deformation of the strip type profile in a three-roller DBT

The distance between the centers of the axes of the support rollers 1 and 3 was L = 70 mm, and the diameter of the rollers D_r =40 mm, with a vertical displacement of the pressure roller by a distance of 4 mm. The material of the rollers is steel grade 40Cr. The material of the strip type profile is steel grade St.08 with the properties obtained during the testing of the samples. The following characteristics of the strip type profile material were also used in the calculation: density ρ = 7850 kg/m^3; Poinson coefficient ν = 0.3; modulus of elasticity of the first kind E = 2.1·10^5 MPa. The model of the deformed medium is elastic-plastic. A contact interaction with a friction coefficient of 0.25 is determined between roller 2 and the lower surface of the strip type profile.

Calculations of the stress distribution along the thickness of the staff were carried out on a strip type profile length of 150 mm every 3 mm when passing through a three-roller DBT (Fig. 2).

From Fig. 2 it is seen that under the support roller 1, the upper fibers of the material of the strip type profile are compressed, and the lower ones are stretched. Under the lower pressure roller 2, the upper fibers of the material of the strip type profile are stretched, and the lower ones are compressed. Under the support roller 3, the upper fibers of the material of the strip type profile are compressed again, and the lower fibers are stretched.

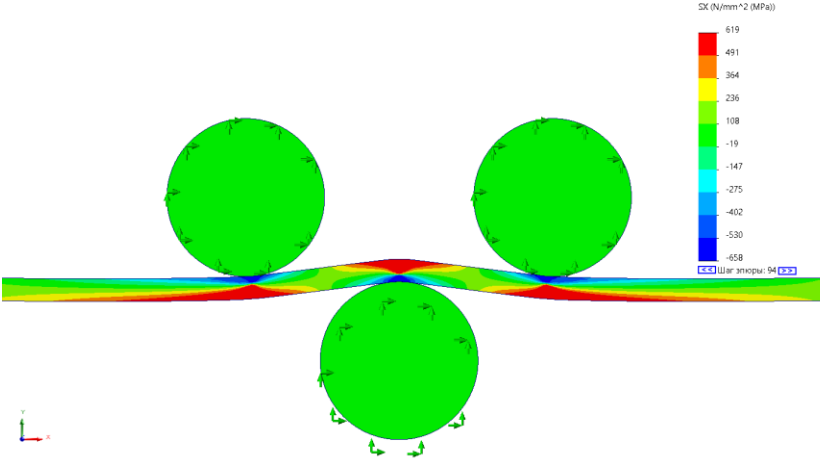

Figure 2 – Stress distribution in a strip type profile made of St.08 steel along the length of the DBT when modeling alternating deformation in a three-roller device with vertical movement of the pressure roller 2 upwards by a distance of 4 mm

According to the results of the modeling, graphs of the distribution of stresses σ in all cross-sections of the of the strip type profile along its length were constructed. As an example, Fig. 3 shows a graph of the distribution of stresses along the thickness of a strip-type profile under support roller 1, and Fig. 4 shows a graph of the distribution of stresses along the thickness of a strip-type profile under pressure roller 2. From the preliminary data analysis, it was determined that the distribution of tensile and compressive stresses across the thickness of the column is complex and significantly non-uniform.

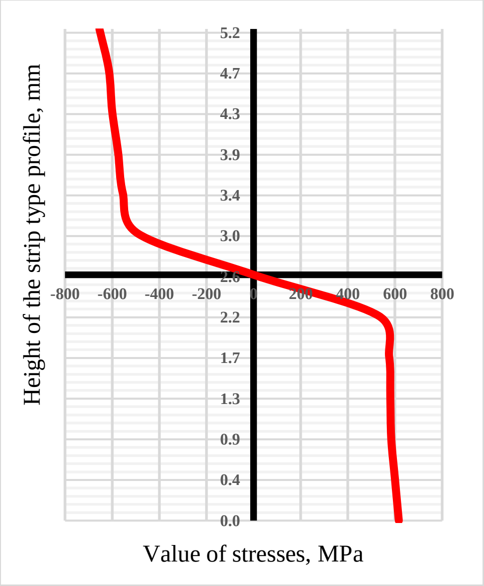

Figure 3 – Distribution of longitudinal stresses along the thickness of the strip type profile under the support roller 1 during alternating deformation, MPa

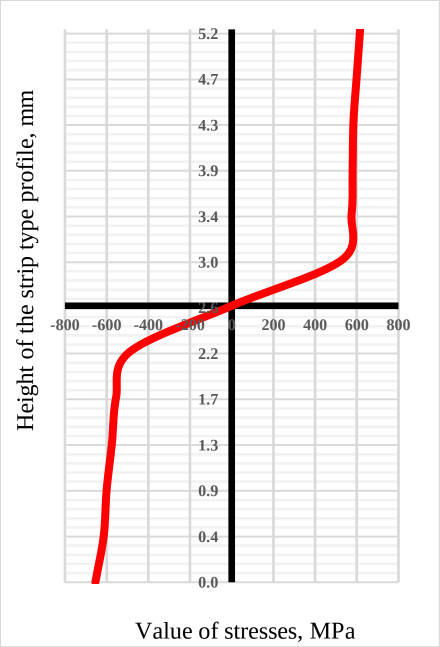

Figure 4 – Distribution of longitudinal stresses along the thickness of the strip type profile under the pressure roller 2 during alternating deformation, MPa

Analysis of the stress state of the staff in the cross section, which is located at a distance of 40 mm to the left of the axis of the support roller 1 (against the direction of alternating deformation), showed that in the upper layer of the strip type profile, the maximum values of compressive stresses are formed, amounting to −155 MPa, and in the lower layer, tensile stresses with indicators up to +348 MPa. The stress difference across the thickness of the strip type profile from the upper layer to the lower layer of the rolled steel is +193 MPa, i.e. tensile stresses prevail.

The maximum values of the stresses (Fig. 3) compressing the upper layer of the strip type profile formed under roller 1 (axis of support roller 1) are equal to −654 MPa. At a height of 2.6 mm from the upper layer of the strip type profile, the values of the compressing stresses are equal to 0 MPa and the sign of the stresses changes from «−» (compressive) to «+» (tensile). The maximum values of the stresses that stretch the lower layer of the strip type profile in this cross-section reach +616 MPa (Fig. 3). But in this case, the stress difference across the thickness of the strip type profile from the top layer to the bottom layer of the rolled steel is −38 MPa, and compressive stresses already prevail, but compared to the previous case, the value of the tensile stress difference is 5 times smaller (38 versus 193 MPa).

In the cross section located at a distance of 3 mm from the axis of the support roller 1 in the direction of the alternating deformation process, the same stresses are formed in the rolled product with the same sign and magnitude as in the cross section located on the axis of the roller 1. In this cross-section along the thickness of the strip type profile, changes in the stress distribution occur at a height of more than 2 mm from the top layer of the strip type profile, and the stress difference also along the thickness of the strip type profile from the top layer to the bottom layer of the rolled steel is −38 MPa.

In the cross-section, which is located at a distance of 6 mm from the axis of the support roller 1 in the direction of the process of alternating deformation in the strip type profile, the same compressive stresses of the same sign and smaller magnitude are formed as in the previous cross-sections (cross-sections located on the axis and at a distance of 3 mm from the axis of the roller 1, respectively). However, these changes occur already at a height of approximately 1.73 mm from the upper layer of the strip type profile. The maximum values of the compressive stresses decrease to −400 MPa, and in the lower layer of the strip type profile, the tensile stresses still reach significant values of +616 MPa. The stress difference across the thickness of the strip type profile in this case from the upper layer to the lower layer of the rolled steel is +216 MPa, i.e. tensile stresses prevail.

In the section from this cross-section in the direction of the pressure roller 2 there is a change in the sign of the stresses on the upper layer of the column from «−» (compressive) to «+» (tensile), and on the lower layer of the column, stresses are formed that have only «+» (tensile).

The uniform distribution of tensile stresses along the thickness of the strip type profile is located at an equal distance (17.5 mm) from the axis of the support roller 1 and to the axis of the pressure roller 2. At the same time, the magnitude of these tensile stresses along the entire thickness of the staff decreases from +362 to +235 MPa. We also see that there are no compressive stresses in this cross section.

From the analysis of the cross-section is located at a distance from the axis of the pressure roller 2 and is 6 mm in the process direction it follows that along the thickness of the strip type profile, tensile stresses with a maximum value of +616 MPa are formed in the upper layer of the strip type profile under the pressure roller 2, and compressive stresses with a maximum value of −273 MPa are formed in the lower layer. The change in the sign of the stresses and their magnitudes occurs in this case at a height of 3.2 mm from the top layer of the strip type profile. The difference in the maximum values of the tensile and compressive stresses along the thickness of the strip type profile is +343 MPa. In this case, compared to the previous section, the tensile stresses increase by 108 MPa (from +235 to +343 MPa).

In the cross-section, which is located in the direction of the alternating deformation process at a distance of 3 mm from the axis of the pressure roller 2, the thickness of the strip type profile is formed with the same stress sign as in the previous cross-section. The maximum compressive stresses on the bottom layer of the strip type profile increase to −527 MPa, and on the top layer of the rolled steel, the tensile stresses are +616 MPa. The difference between the maximum values of the tensile and compressive stresses is +89 MPa. In this case, the change in sign and values of the stresses occurs at a height of more than 3 mm from the top layer of the strip type profile.

The cross section located under the pressure roller 2 (Fig. 4) in the upper layer of the strip type profile, tensile stresses are formed, and in the lower layer – compressive. The maximum values of tensile stresses are equal to +616 MPa in the process of alternating deformation of this strip type profile under the pressure roller 2. At a height of 2.6 mm from the top layer of the strip type profile, the values of the tensile stresses are equal to 0 MPa and the sign of the stresses changes and the maximum value of the compressive stress reaches −654 MPa in the process of alternating deformation of this strip type profile under the pressure roller 2. The difference between the maximum values of the tensile and compressive stresses is −38 MPa.

Thus, modeling the deformation process of the strip type profile in the

DBT, a cyclic change in both the sign of the stresses and the magnitude of these stresses is observed, i.e. it leads to a significant non-uniformity of longitudinal stresses along the thickness of the strip type profile.

After the staff leaves the DBT, the pressure on the strip type profile is relieved, i.e., the strip type profile undergoes elastic unloading, which leads to a decrease and redistribution of internal stresses. According to the results of modeling for the stressed state of a strip-type profile made of St.08 steel, a graph of the stress distribution in the cross-section of the staff after elastic unloading at the exit from the DBT was constructed (Fig. 5) and compared with the stress distribution in the cross-section of a strip-type profile formed under pressure roller 2 (Fig. 4).

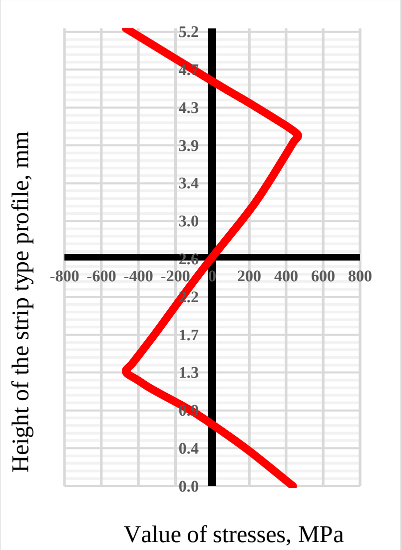

Figure 5 – Distribution of longitudinal residual stresses after of the strip type profile leaves the DBT, MPa

From the analysis of the data in Fig. 4 it is seen that under the pressure roller 2 in the upper layers of the metal, tensile stresses are formed with a maximum value of +616 MPa on the upper layer, and compressive stresses are formed on the lower layer with a maximum value of −654 MPa during deformation in the DBT.

The simulation results show that after elastic unloading (see Fig. 5) there is a change in the sign of the stresses: in the upper layers of the column, compressive residual stresses with a maximum value of −468 MPa are observed and on the lower layer – tensile with a maximum value of +439 MPa, i.e. there is a balancing of residual stresses of the upper and lower surfaces of the strip type profile. A comparison of the maximum values of stresses that arise during the process of alternating deformation under pressure roller 2 and after DBT shows that after elastic unloading they decrease on average by 1.4 times, regardless of the sign of the stresses.

After elastic unloading (see Fig. 5), the nature of the distribution of longitudinal residual stresses along the thickness becomes more complex - the upper fibers of the strip type profile material, which are located along its thickness from the profile surface to 0.8 mm from the upper layer of the strip type profile, are compressed. The maximum value of the residual compressive stresses in the upper layers of the steel strip type profile is −468 MPa. In the middle of the steel sheet at a distance of 0.8 to 2.6 mm from the upper layer of the rolled steel, the sign of the residual stresses changes and the fibers of the steel sheet material are stretched. In this case, the maximum value of the residual stresses stretching the fibers of the steel material is observed at a height of 1.3 mm from the top of the rolled product and is +437 MPa. The difference in the maximum values of longitudinal tensile stresses between those located in the upper layers of the strip type profile under roller 2 (+616 MPa in Fig. 4) and in the metal layers located in the middle of the strip type profile (Fig. 5) after its exit from the DBT is +179 MPa or a 1.4-fold decrease between their maximum values.

Further along the thickness of the rolled product at a height of 2.6 to 4.4 mm from the top layer of the steel, the sign of the residual stresses changes again and the fibers of the rolled material are compressed. In this case, the maximum value of the residual compressive stresses formed at a height of 3.9 mm from the top of the rolled product is −468 MPa (see Fig. 5). In this case, the difference between the maximum values of longitudinal compressive stresses (−654 MPa), which are located on the lower layer of the strip type profile under the pressure roller 2 (see Fig. 4) and at a height of 3.9 mm from the top of the rolled product, is −186 MPa or a 1.4-fold decrease between their maximum values.

Along the thickness of the metal fiber stack, which is located from the bottom surface of the stack to a height of 0.9 mm from the bottom surface of the metal, a change in the sign of the stress is again observed and these fibers are stretched. The maximum value of residual tensile stresses in the lower layers of the strip type profile after its exit from the DBT is +437 MPa.

From the analysis of Fig. 4 it is clear that in the middle of the strip type profile there is a section of metal, located at a distance of 2.0 mm from both the upper layer and the lower layer of the rolled product under the pressure roller 2, which is elastically deformed during the loading process. Due to the presence of elastic deformations in the middle part of the rolled product, potential deformation energy accumulates during processing in the DBT (Fig. 6).

Since irreversible plastic deformations are localized in the surface layers of the rolled product up to 2.0 mm high from the upper layer and up to 2.0 mm from the lower layer of the rolled product, during unloading this part becomes an obstacle to the release of reversible potential energy of elastic deformation. This confirms the distribution of potential energy across the cross-section of the strip type profile under the pressure roller 2. It is the presence of compressed potential energy that leads to the emergence of residual stresses.

When external forces are removed, the accumulated potential energy is spent on restoring the original undeformed state of the strip type profile. Due to this, internal forces arise in the upper stretched surface fibers of the part, leading to their compression, and in the lower compressed surface fibers, on the contrary, to stretching. Thus, after the load is removed, residual compressive stresses arise from above and tensile stresses from below (Fig. 5), these stresses are balanced by stresses arising in the rest of the metal cross-section.

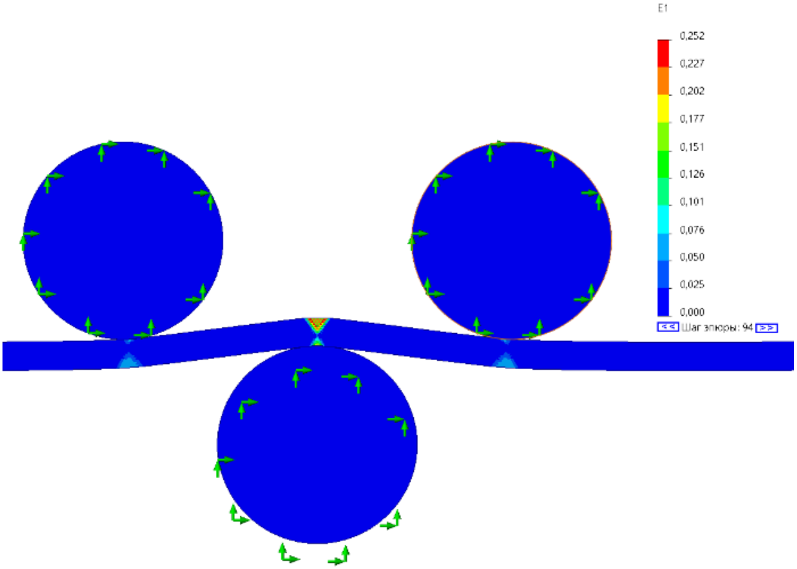

Figure 6 – Distribution of potential energy (J) across the thickness of the strip type profile after unloading when modeling alternating deformation in a 3-roller DBT.

The obtained results allow us to conclude that the mechanism of the occurrence of residual stresses during alternating deformation is due to the inhomogeneity of the deformation distribution along the thickness of the strip type profile.

Based on the modeling results, a graph of the change in potential energy U, which was obtained by summing all values along the thickness of the strip type profile, was constructed, depending on the process time (Fig. 7).

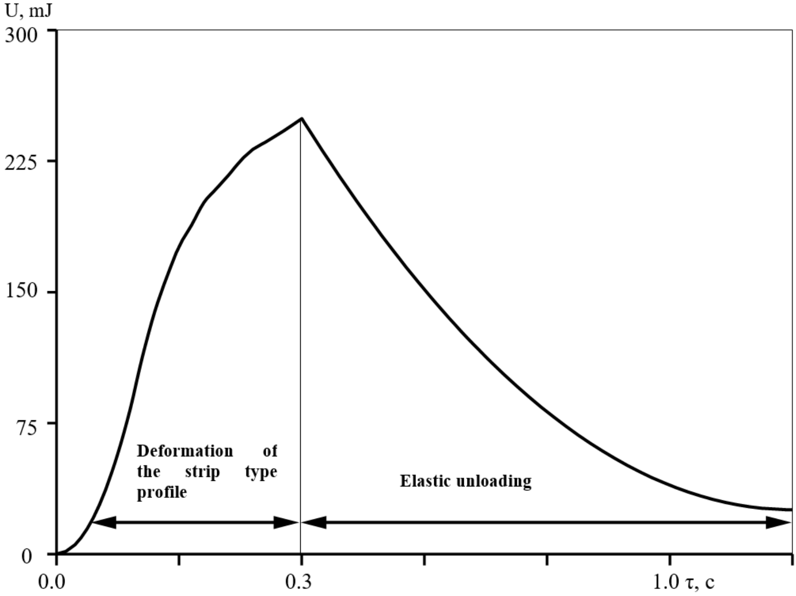

Figure 7 – Change in potential energy depending on the process time.

When the lower roller moved upwards for a time of 0.3 s, an accumulation of potential energy of up to 252 mJ occurred, then during unloading for 0.7 s, an accumulated potential energy of 25 mJ remained in the material.

In contact with roller 2, there is an increase in potential energy, and when the contact point with the roller is removed, there is a decrease. With increasing strength of the material of the strip type profile at the same parameters of alternating deformation, the potential energy increases, its values remain higher even during the passage of the strip type profile between the rollers. But after the headquarters leaves the DBT, the potential energy value decreases from 0.252 to 0.025 J.

Conclusions

The modeling results show that in the process of deformation of the strip type profile in the DBT, a cyclic change in both the sign of the stresses and the magnitude of these stresses is observed, both along the thickness of the strip type profile and along the length of the DBT.

Based on mathematical modeling of the process of alternating deformation of strip type profiles during their pulling through the DBT, the mechanism of residual stress occurrence has been established, which is determined by the magnitude of plastic deformation and the inhomogeneity of the distribution of deformations over the thickness of the profile during alternating deformation.

It is shown that after the profile leaves the DBT, longitudinal residual compressive stresses are formed on the upper part of the strip type profile, and tensile stresses on the lower part of the rolled product. These residual stresses are balanced by the stresses that arise in the middle part of the strip type profile cross-section (Fig. 5).

According to the modeling results, it was determined that the maximum values of residual longitudinal stresses formed along the profile cross-section after leaving the DBT are 1.4 times less, regardless of the sign of the stresses, compared to the maximum longitudinal stresses formed under the pressure roller 2.

It is shown that the maximum level of plastic deformations is observed at the beginning of alternating deformation in the DBT device with a decrease in their level at the exit from the DBT, which provides a decrease in the values of residual stresses and potential energy in the strip type profile of the steel St.08.

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МОДЕЛЮВАННЯ ПРОЦЕСУ ЗНАКОЗМІННОЇ ДЕФОРМАЦІЇ ПРОФІЛЮ СТРІЧКОВОГО ТИПУ У ТРЬОХРОЛИКОВОМУ ЗГИНО-РОЗТЯГУВАЛЬНОМУ ПРИСТРОЇ

Анотація. Використання високоточних профілів у сучасному машинобудуванні має велике значення з погляду підвищення якості виробів, що випускаються, і значного зниження собівартості їх виробництва. В Україні виробництво високоточних профілів вкрай обмежене, а виробництво профілів стрічкового типу взагалі відсутнє. В світовій практиці виробництва профілів стрічкового типу можливо різними способами: гарячою прокаткою, гарячим пресуванням, холодною прокаткою або волочінням в монолітних або роликових волоках. Роликові волоки для виробництва фасонних профілів мають перевагу перед монолітними волоками, так як можливе більша величина обтиску за один перехід. Крім цього волочіння в роликових волоках відбувається в неприводних роликах у поєднанні з екологічно чистими способами термічної обробки без використання шкідливих охолоджуючих середовищ у вигляді мастил, розплавів свинцю, солей та кислоти. Разом з тим, особливості умов пластичної рівноваги металу осередку деформації при плющенні круглої заготовки волочінням в роликових волоках стримують освоєння нових профілів, у тому числі профілів стрічкового типу із відношенням їх ширини до товщини більше двох. Це пов’язано з тим, що нерівномірність обтиснення дроту-заготовки призводить до нерівномірному розподілу напружень за перерізом профілю: у середній частини – стискування, у кромок – розтягування, а наявність тягового зусилля збільшує зони дії напружень, що розтягують і їх величину в об’ємі осередку деформації та, зрештою, за певних умов спричиняє суттєве зниження пластичності і руйнування кромок готового профілю. Підвищити пластичність металу можливо двома способами – термічним і механічним. Термічний спосіб, якій широко застосовується в промисловості, потребує значних витрат енергії. У той же час попередні дослідження, які були проведені в тому числі в ІЧМ НАНУ, показали, що підвищити пластичність металу можливо способом знакозмінного деформування профілів, застосував для цього, наприклад, обладнання для рихтування профілів або окалинозламувача. При цьому результати конкретних досліджень впливу параметрів процесу знакозмінного деформування металу на величину напружень і характер їх розподілу за перерізом профілю стрічкового типу у розглянутих публікаціях відсутні. Мета досліджень полягала в послідовному аналізі напруженого стану металу на всьому протязі фактичного осередку деформації з урахуванням зовнішніх зон за допомогою розробленої та перевіреної на адекватність математичної моделі розрахунку напружено-деформованого стану металу. Встановлено, що механізм виникнення залишкового напруження обумовлено величиною пластичної деформації та неоднорідністю розподілу деформацій по товщині профілю при знакозмінній деформації в процесі його протягування через ЗРП. За результатами моделювання визначено, що максимальні значення залишкових повздовжніх напружень, які сформовані по перерізу профілю після виходу з ЗРП менше у 1,4 рази не залежно від знаку напружень в порівнянні з максимальними повздовжніми напруженнями, які утворюються під натискним роликом. Показано, що максимальний рівень пластичних деформацій спостерігається спочатку знакозмінної деформації в пристрої ЗРП зі зменшенням їх рівня на виході з ЗРП забезпечують зменшення значень залишкових напружень, потенційної енергії в штабі зі сталі Ст.08.

Ключові слова: знакозмінна деформація, профілі стрічкового типу, роликова волока, згино-розтягувальний пристрій (ЗРП), напруження стискування, напруження розтягування.

Посилання для цитування: Моделювання процесу знакозмінної деформації профілю стрічкового типу у трьохроликовому згино-розтягувальному пристрої / В. Г. Раздобрєєв, К. Ю. Ключніков, Д. Г. Паламар, О. І. Лещенко, О. П. Іванов. *Фундаментальні та прикладні проблеми чорної металургії.* 2026. Вип. 40. С. 484-500. https://doi.org/10.52150/2522-9117-2026-40-029

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