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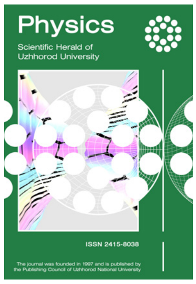

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Investigation of the Stress-Strain State of the Bending Process of Coated Materials

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Abstract

Relevance. The relevance of the study is due to the current trend of using complex profile products from coated materials in various industries, especially in construction, which can significantly increase corrosion resistance, durability, temperature range and manufacturability, and the most common methods of obtaining such products are processing methods pressure, in particular bending, which is a stressful thermal force process that affects the quality and integrity of the pre-applied coating.

Purpose. The purpose of modelling and analysis of the influence of technological parameters of the bending process on the stress-strain state of the workpiece is to prevent the destruction of multilayer coatings and obtain practical recommendations for the manufacture of complex products in flexible production.

Methods. The main method that allows achieving this goal is the method of finite-element analysis of the stress-strain state under different technological conditions of the bending process, such as bending angle, minimum internal bending radius, the location of the workpiece; the parameters of the pro-cessing material (properties of the processing material, the thickness of the coating) remained con-stant, implemented in the software package ANSYS.

Results. The article presents the results of a finite element analysis of the stress-strain state of materials with a multilayer coating in the bending process with different technological conditions. Practical recom-mendations on technological parameters of processing that will allow receiving products without de-fects of the preliminary put covering are given.

Conclusions. The results of the work make it possible to understand in more detail the processes that occur with materials with a multilayer coating during pressure treatment and are of practical value for companies that specialize in the manufacture of products with a complex profile

Keywords: multilayer coatings, ANSYS, finite element analysis, pressure treatment

Introduction

Trends in the development and application of high-tech coated materials for the production of profiles for car components, in the production of furniture and the development of a large number of structures based on bent profiles for the construction industry are due to their high corrosion resistance (increased resistance to precipitation, ultraviolet radiation, exhaust gases, alkaline and acidic aggressive environments), temperature range of application from -50°C to +80°C, resistance to mechanical impact, manufacturability (simplicity, convenience and reliability of fastening), environmental safety and aesthetics [1].

As metal coatings of steel sheets, zinc is most often used to protect the metal from corrosion. Application of a zinc-based metal coating of a certain thickness is carried out by hot or electrolytic method [2]. Hot-melt galvanised steel shows better protective properties and the coating has better adhesion and strength compared to electrolytic steel, so about 70% of surfaces are galvanised from melts.

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During shaping, fracture of the galvanised workpiece surface is observed under considerable contact stresses, and coating sticking to the forming roller is only observed in cases of unsatisfactory output coating quality [3].

Modern methods of coating make it possible to obtain materials with an organic coating that meet a number of requirements: relatively short duration of formation and drying of coatings, good decorative properties, sufficient corrosion resistance and resistance during further processing, and are increasingly used in modern production. Organic coatings can be divided into two groups: liquid coatings and film coatings (Table 1) [4].

Table 1. Polymer coating materials

Type	Marking	Layer thickness range, microns	Standard layer thickness, microns
Liquid coatings			
Polyester	SP	5-40	25
Polyamide modified polyester	SP-PA	25-40	25
Polyurethane	PUR	25-60	25
Polyamide modified polyurethane	PUR-PA	25-60	25
High durable polymer	HDP	25-45	25
Polyvinylidene difluoride	PVDF	25-50	25
Polyvinyl chloride plastisol	PVC(P)	100-200	100-200
Epoxy coating	EP	3-10	10
Film coating			
Polyvinyl chloride	PVC(F)	100-400	100-200
Polyvinyl fluoride	PVF(F)	45	38

Modern trends in construction are the use of combined multilayer coatings (Fig. 1) – a combination of polymer and zinc coatings. Such materials demonstrate increased anti-corrosion properties. The coating can be one-sided or two-sided in various combinations. In the standard version, a protective polymer coating is applied to the front surface of a galvanised steel sheet, and the backside of the sheet is painted [5].

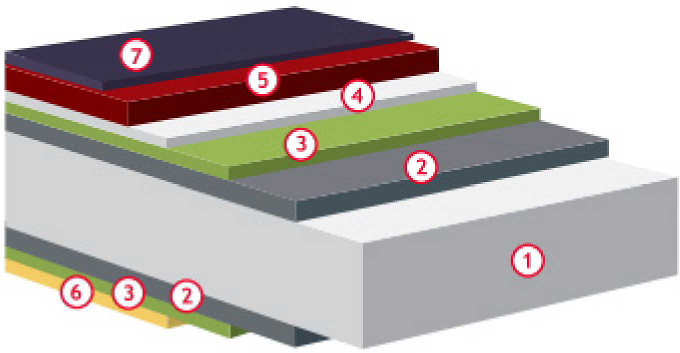

Figure 1. Structure of sheet metal with a combined multi-layer coating: 1-steel sheet (0.4-0.6 mm thick); 2 – zinc layer; 3 – passivation layer; 4 – primer layer; 5 – polymer coating (front side); 6 – protective painting (backside); 7 – protective film if necessary

Polymer-coated sheet steel can be deformed by most known methods: bending, flanging, rounding and deep pulling, and on equipment used for sheet metal processing. From the point of view of profiling, the most important physical and mechanical properties of coatings are their elasticity [6]. The deformation characteristic depends on the substrate material, the zinc layer, and the type and thickness of the coating layer. Using typical equipment and technological characteristics of the deformation process, it is now very difficult to obtain a ready-made profile without defects in the applied coating. The work [7] contains information that defects in the profile surface occur in the form of scuff marks, scratches, destruction of the coating when manufacturing profiles from coated materials for a number of reasons: rigid forming schemes, unsatisfactory quality of forming rollers, uneven gap in the calibre, excessive width of the workpiece, and it is also noted that under equal conditions for materials without coatings defects were not observed.

Analysis of theoretical and experimental works [6; 8-11] in this subject area has shown that when manufacturing profiles from polymer-coated materials, the issues of shaping schemes and the associated stress-strain state of shelves and corner zones remain relevant, ensuring the dimensional accuracy of the cut and the length of the smooth transition zone. Therefore, it is of great interest to improve the quality of finished profiles made of polymer-coated materials to study them from the point of view of the influence of the main deformation conditions on the occurrence of defects in the material and develop a classifier of defects and their causes. Analysis of the stress-strain state of the workpiece material will provide a deeper understanding of the processes that occur in a multi-layer coating. Based on such studies, effective actions will be developed aimed at improving the bending technology for polymer-coated materials.

Materials and Methods

For research in this work, profiles used in construction were selected, in particular profiles of the P and C-type, which are made of sheet material with a thickness of (0.4÷1.0) mm with a polymer coating (Fig. 2). The types of profiles proposed for the study perform several construction and architectural tasks simultaneously – they provide high rigidity and strength, fast assembly, structural reliability, as well as increased corrosion resistance due to the use of polymer coatings and, as a result, a long service life.

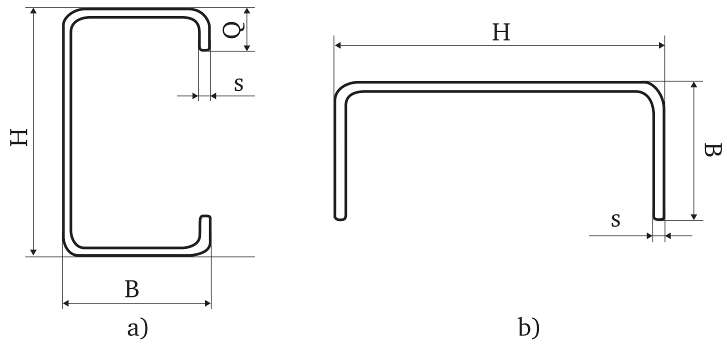

Figure 2. Profile types: a) C-shaped; b) U-shaped

For further calculations, two standard sizes were taken for each type of profile, in order to determine the influence of geometric parameters of the profile on profiling processes. The main geometric characteristics of the profiles are shown in Table 2 according to DSTU 8897:2019 [12] for C-shaped and according to DSTU 8808:2018 for U-shaped [13].

Table 2. Basic geometric characteristics of profiles

Profile type	Basic geometric parameters			
	H, mm	B, mm	s, mm	a, mm
C-shaped	40	40	1.5	8
	80	50	4.0	24
U-shaped	40	40	2.0	–
	80	50	4.0	–

A multi-layer coated metal sheet that includes a zinc layer (obtained from a melt) and a polymer coating (epoxy EP) were chosen because of the highest prevalence of this combination of coatings. The main physical and mechanical characteristics of coatings are shown in Table 3 (manufactured by SSAB, Sweden) [14].

Table 3. Basic physical and mechanical characteristics of coatings

Parameter	Zinc coating	Parameter	Epoxy
Coating thickness, microns		Coating thickness, microns	27
Adhesion, score	1	Adhesion, score	0
Uniformity of coverage, %	5	Reverse impact strength, J	5-10
Porosity, score	1	Elasticity according to Erickson, mm	Not less than 6
Corrosion resistance, pitting occurence	-0.52	Flexural strength 180°	(3-4) “T”
Hardness of units HV0. 02	520	Pencil hardness	F-H-2H
Durability	0.25	Weather resistance, under accelerated tests (in salt fog), time	500

Source: developed on the basis of [15-17]

Profiling is carried out on machines of the SPS and SPP series to obtain C and U-shaped profiles. Characteristic features of the profiling method: the number of transitions 12-22, the number of bending zones up to 12, the bending angle 8-12 degrees, a sequential calibration system, an open calibre type, the width of the workpiece is practically lower than the theoretical one [18].

The work is based on the provisions of the theory of pressure processing of materials and thermophysical laws, solid-state physics, materials science, and the theory of dispersed systems. Finite-element modelling (SEM) of pressure treatment processes, which are widely used by engineers to study the technological processes of manufacturing various parts, was used to model the processes of forming and analysis of the stress-strain state. SEM in the field of sheet material processing and bent profile manufacturing processes makes it possible to obtain the data necessary for creating new highly efficient and economical technological processes. The ANSYS software is effectively used for such research and will also be used in this work. For adequate modelling, it is necessary to enter the correct parameters of the material model. for this purpose, a series of experimental studies performed in the works were analysed [7; 9-11; 19; 20].

Contact modelling during profiling includes determining the maximum pressure zones, determining the curvature of the tool in the contact zone, determining contact forces, comparing them with permissible values for coatings, and establishing acceptable process parameters.

Mathematical statistics methods were used to process research results.

Results and Discussion

A study of the scientific literature led to the conclusion that defects in the coatings of the workpiece in the form of peeling and cracking are characteristic of 60-70% of profiles at the initial stage of profile processing and are the most significant defect for simple section profiles with a base thickness of 1.5-2 mm. Creating a classifier that reflects the dependence of the appearance of this defect on the geometric and technological parameters of the process will help prevent the formation of this defect.

For a more systematic approach to the selection of modelling objects, a classifier of the causes of coating defects has been compiled. The causes of defects in coatings can be divided into three main groups. The first group includes factors related to the choice of equipment. The wrong choice of equipment can lead to an insufficient number of transitions, high processing speed, the lack of additional devices that would allow pre-processing the workpiece before it enters the bending process, this technique reduces the contact pressure in the working transition, but the additional device itself must ensure the safety of the coating. Reducing the profiling speed makes it possible to reduce the impact of the tool on the coating, significantly intensifying the process. The low profiling speed provides a sufficient time interval during which relaxation processes in the coating have time to take place, which has a positive effect on its condition. However, the low speed requirement is a competing factor in terms of process performance. This contradiction can be resolved by optimising the speed characteristics of the process while ensuring the quality of the manufactured profile. The second includes the modes of shaping. The erroneous choice of forming modes is manifested in the irrational determination of configuration schemes by transitions, bending angles by transitions, and the choice of profile bending radii. The third group consists of indicators of the workpiece parameter, which include excessive width of the workpiece $L \geq S$, deviation in the thickness of the workpiece $\Delta = f(S)$, and the initial state of the coated surface (the presence of damage on the surface).

In turn, the method of preventing the destruction of coatings depends on the type of specific profile and the stage of its development and manufacture. At the stage of analysis for the manufacturability of manufacturing a coated profile, optimisation of the profile design based on the requirements for it is used. At the design stage – optimisation of equipment, forming schemes, shape and size of the matrix and punch. At the stage of development and manufacturing – adjustment of equipment, use of additional equipment and lubrication systems. The use of a particular method of preventing the occurrence of coating defects is best considered in an integrated approach in conjunction with other methods.

It is best to use several ways to prevent the destruction of coatings at the same time. For example, optimisation of the technological system for transitions with simultaneous optimisation of the shape of the working parts of the press and its corresponding adjustment, as well as the use of lubricants, can improve the quality of the profile and reduce the likelihood of defects in the coating. Priority is also given to the methods that allow reducing the contact pressure to the greatest extent, namely, methods that lead to optimisation of the profile corner radii at the transitions, the use of additional equipment and lubrication systems. These methods are accepted as the main ones for preventing the occurrence of defects in polymer coatings during bending.

Physical and mathematical models of the sheet workpiece bending process. The best way to choose a model for determining the stress-strain state during bending would be to describe the physical processes that affect changes in the stress state of the material elements of the technological system, and then use them as a logical basis for solving the task. In practice, solving such problems usually requires a large number of search options. Therefore, the problem of significant acceleration of modelling the bending process with various technological parameters that affect the occurrence of defects in polymer coatings becomes relevant and will be discussed later.

Sheet metal bending is a process of elastic-plastic deformation. In most cases, bending is carried out with a significant amount of deformation, in which in the metal, in addition to longitudinal tensile and compressive stresses, radial compressive stresses are created, which occur as a result of the pressure of the extreme layers of the metal on the inner ones and reach the highest value in the neutral layer. For further modelling, the bending scheme shown in Figure 3 [21] was used.

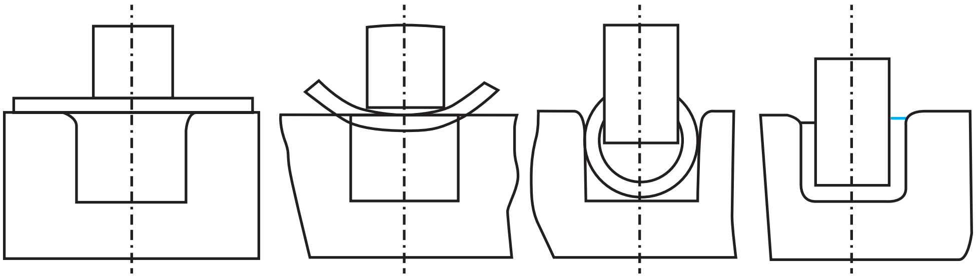

Figure 3. Stages of the two-angle bending (U-shaped) process

With two-angle bending, the workpiece under the punch bends. As the punch continues to move, the ends of the workpiece bend upwards until its ends reach the side edges of the punch. The curvature of the workpiece is preserved until it touches the bottom of the matrix. In this case, the bending angle is less than $\pi/2$ by Δα, and the bending radius R can be bigger than the rounding radius R of the working part of the punch. At the same time, the middle part of the workpiece is bent under the end of the punch. When the punch is further lowered, it is bent at point-blank range with the corners minted.

To build the model it is necessary to take the following basic assumptions: when determining the location of the maximum pressure zone, the contact zone is represented as a spot; when determining the value of the contact pressure during profiling, the workpiece material is assumed to be isotropic, does not strengthen, and is highly plastic. The shape of the workpiece, which is studied in this paper, refers to a wide strip.

Thus, the bending of a wide strip of isotropic material is carried out under conditions of stretching along two axes [18]. Given this factor, the permissible bending radius can be written as (1):

$$\left(\frac{r}{s}\right)_{min} \geq \frac{1-0.5\left(1-\psi_\rho\right)^{-0.47}}{\left(1-\psi_\rho\right)^{-0.47}-1} \tag{1}$$

where ψ_ρ – relative reduction of the cross-sectional area of the sample before the neck is created during tensile tests.

The deformation force during two-angle bending is determined by the fact that it is necessary to bend the workpiece in one press stroke simultaneously in two different cross-sections. At the same time, it should be taken into account that external forces during such bending are applied to the workpiece at two points of its contact with the punch. The shoulder of a two-angle bend is significantly smaller than that of a single-angle bend. In addition, there is a gap z=(1.1...1.3)s between the corner edges of the punch and the matrix, which does not change during bending, and the section of the workpiece that is located under the horizontal edge of the punch departs from it and bends (Fig. 4).

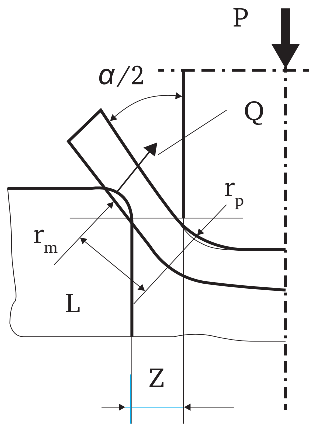

Figure 4. Two-angle bending scheme

Taking into account the above, the bending force when obtaining U-shaped parts for strips with a rectangular cross-section is described by the formula (2):

$$P = \sigma_s \frac{bs^2}{2} \frac{\sin\frac{\alpha}{2} + \mu\cos\frac{\alpha}{2}}{(r_m + z + r_p)\sin\frac{\alpha}{2}} \tag{2}$$

where σ_s – yield strength of the workpiece material; b – width of the workpiece; s – thickness of the workpiece; α – bending angle of the part; μ – coefficient of friction; r_m and r_p – radii of the working edges of the matrix and punch; z – gap between the matrix and the punch.

The stress-strain state during plastic bending depends on the shape and size of the cross-section of the original workpiece.

The permissible tensile strain was determined by the formula (3):

$$[e] = \frac{s}{2R_{BH} + s} \tag{3}$$

The choice of the minimum radius or permissible deformation depends on the requirements for the profile in terms of decorative and protective properties. In general, no characteristic correlation between decorative and protective properties has been observed [7].

When using multilayer coating systems that include metal (zinc) and polymer layers, some loss of the protective properties of the polymer layer does not cause a significant deterioration in the quality of the profile as a whole due to the presence of a zinc sublayer.

As indicated in [18], when bending a wide band, the deformed state is flat (Fig. 5). As a result, normal stresses σ_z in the z-axis occur in the wide band. In the tensile zone, these stresses are tensile, and in the compression zone, they are compressive. Thus, the stress state of a wide band is voluminous both in the stretched zone and in the compressed one. During the increase in the stroke of the punch, when bending, elastic deformation is first performed, then elastic-plastic, when part of the workpiece is deformed elastically, and the other part is plastic, and at the end the entire workpiece is deformed plastically over the entire thickness.

Figure 6 shows a separate simplest element with coordinates ρ and θ.

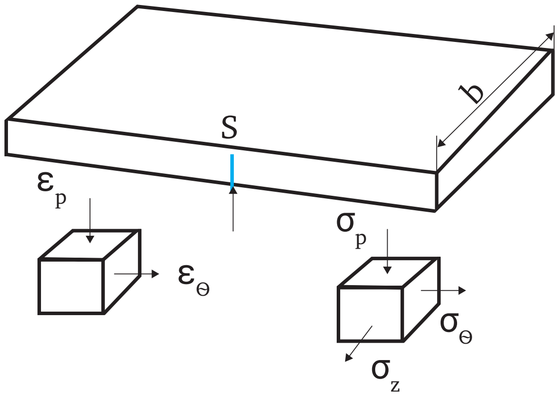

Figure 5. Wide band bending scheme and voltage scheme

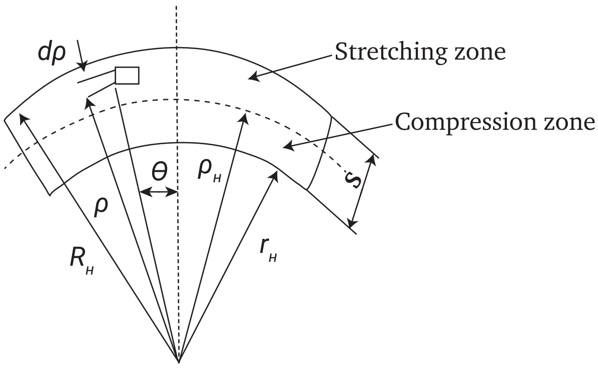

Figure 6. Calculation of wide band bending schemes

The equilibrium equation for an element defined under deformation, taking into account that the stress σ_ρ cause the layers to press on each other, can be written as (4):

$$\frac{\rho d\sigma_\rho}{d\rho} + \sigma_\rho - \sigma_0 = 0 \tag{4}$$

The limiting conditions will be the stresses along the thickness of the workpiece:

- for the stretch zone

$$\sigma_\rho = -\sigma_s \ln\frac{R_{\text{н}}}{\rho} \tag{5}$$

$$\sigma_0 = \sigma_s\left[1 - \ln\frac{R_{\text{н}}}{\rho}\right] \tag{6}$$

- for the compression zone

$$\sigma_\rho = -\sigma_s \ln\frac{\rho}{r_{\text{в}}} \tag{7}$$

$$\sigma_0 = -\sigma_s\left[1 + \ln\frac{\rho}{r_{\text{в}}}\right] \tag{8}$$

Based on these regularities and assumptions, a finite element model of the bending process was constructed in the ANSYS software. Consideration of the properties of materials will not be complete without consideration of the deformation properties of polymers that are part of the coating.

The deformation properties of polymers and metals differ primarily in that polymers have a lower value of yield strength and elastic modulus, but they are more ductile and ready to accept significant tensile and compressive deformations. Accurate determination of the characteristics of coatings is a difficult task, given their variability and dependence on the strain state and the amount of strain force. 1. The composition of coatings in addition to polymers includes additional components: solvents, film-forming agents and others that change the properties of polymers. 2. During the drying process, internal stresses are created in the coating, the value of which depends not only on the type, but also on the coating technology. 3. Depending on the thickness of the coating, its strength changes under the action of adhesion forces [7].

When forming from coated materials, the metal base together with the coating undergoes various types of deformation. When profiling, the bending of the workpiece is characteristic, which is accompanied by large deformations in the bending zone. At the same time, the concept of internal stresses is often used to describe the process of breaking the coating. Such stresses can be created both during the formation process and during the operation of coatings, they reduce the adhesive strength of the coating and lead to defects in the form of cracking and peeling of the coating [22].

When manufacturing bent profiles from coated materials, defects in the latter may occur both due to the poor quality of the coating or its application, and due to the particular application of different forming methods. In this regard, the bending method requires studies of the stress-strain state of the material in the contact zones.

The characteristic areas of damage to coatings are shown in Figure 7. Scheme a) corresponds to the conditions of formation according to the scheme of free bending in an open die or the conditions of formation of a complex profile in a closed die without the application of end forces. Scheme b) is typical for bending in a closed die with the application of end compressive forces. Scheme a) of Figure 7 shows two dangerous zones: the inner contour that comes into contact with the punch, and the zone that directly contacts the curved section of the workpiece from the side of the outer contour of the bend zone. In both zones, along with normal stresses, tangential stresses also act perpendicular to the plane of the presented section.

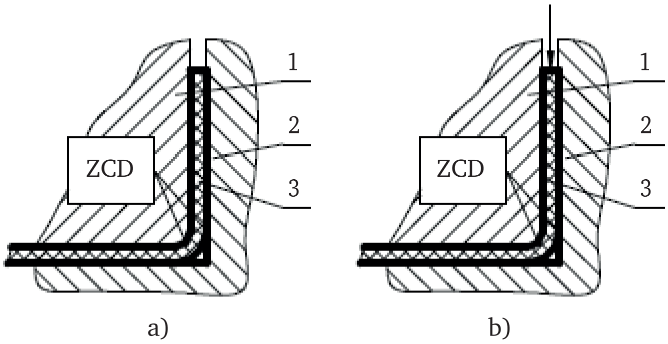

Figure 7. Characteristic zones of damage to the coatings of the workpiece during bending: 1 – punch; 2 – matrix; 3 – workpiece; ZCD – zone of coating damage

It is more expedient to estimate stresses and deformations based on their intensity, since this takes into account the total effect of the tool. For a coated workpiece, the intensity of deformation at the level of the coating is of paramount importance, which, when compared with the allowable deformations of the coating material, will make it possible to identify the limiting parameters of the process. The stress state is detected only in connection with the definition of deformation.

In [23], the indicators of deformation of the coating during pressure treatment are determined, these indicators will be used in the construction of a finite element bending model for the correct operation of the model and obtaining results specifically for the zone of the material of the workpiece with a polymer coating.

The following technological characteristics of the process were used for modelling: a matrix and a punch were used as a tool; the profile was made in 10 technical transitions; the gap between the matrix and the punch corresponded to the thickness of the material under study. The internal radius of the roller corresponded to 3 mm, and was a constant value, which made it possible to perform calculations on one model without its significant changes.

One of the most important steps in finite element analysis is to build a model from finite elements. Recommendations for building a high-quality grid are as follows: 1) an ordered grid is used; 2) it is necessary to avoid tetrahedral shapes for three-dimensional elements; 3) the dimensions of elements should preferably have the same shape; 4) when "hourglass-type" distortions appear, fully integrated elements are used (if the control of distortion parameters does not help); 5) advective rearrangement or ALE method can be used to improve the grid (during deformation) [20]. Based on the above recommendations, an ordered grid of hexagonal ELFORM-1 elements was built, which are fully integrated S / R solid elements with reduced transverse shear blocking. To suppress the curvature of the element shape, we used stiffness control (IHQ) with the parameter QM=0.03-0.1, which is preferable at lower rates of the deformation process, especially if the number of solution steps is large [24].

The workpiece material was determined by the kinematic model (MAT 3), and the punch material was determined by the solid model (RIGID 20).

To display contact parameters in the ANSYS programme, the INTFOR parameter was set. Figure 8 shows the characteristic contact zones between the tool and the workpiece.

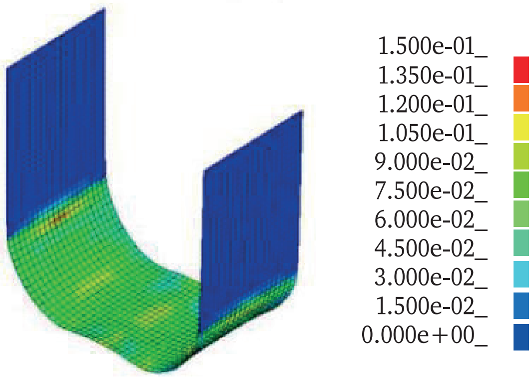

Figure 8. Visualisation of the contact between the punch and the workpiece

Performing calculations using the constructed model made it possible to determine the degrees of deformation during bending at different stages of processing the workpiece and at different parameters of the technological process.

In the course of modelling, it was found that during bending from the outside of the bending zone, internal stresses in the coating rise with increasing degree of deformation (decreasing the bending radius). The results are shown in the graph (Fig. 9).

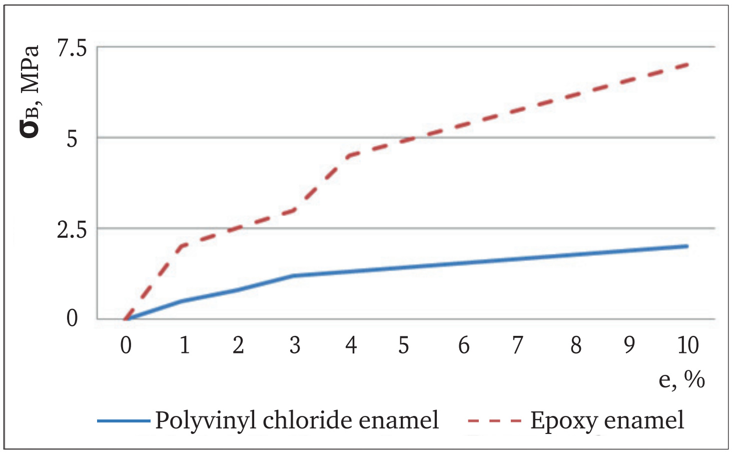

Figure 9. Dependence of the internal stress value on the deformation of the external bending zone

Analysis of the obtained results shows that the greatest significant effect on internal stresses in polymer coatings is played by the bending radius and strain forces. The values obtained in the simulation process correlate with the results obtained for polyurethane coatings given in [7]. Table 4 shows the recommended minimum allowable relative bending radii for a bending angle of 90°.

Table 4. Recommended bending angles for polymer-coated materials

Material	Bending radius
Metal (steel 08k)	0.3
Metal + metal coating	0.5
Metal + metal coating+polymer coating	0.8

It is also worth noting that due to the wide variety of design solutions of profiles, as well as the features of coating, it is not possible to give a single theoretically justified recommendation. Each bending option requires additional research.

Conclusions

1. High quality along with high protective and decorative properties of coated profiles have led to their widespread use in the construction, automotive industry, and in the manufacture of household appliances; at the same time, the cost of profiles obtained from coated materials is 10-15% lower compared to the cost of coated profiles after manufacturing.

2. Metal (zinc, aluminium) and polymer (polyester, acrylic, polyvinyl chloride and other) coatings are used as coatings for sheet materials, but coated materials have not yet been sufficiently studied in relation to the profiling process.

3. The main consumer of coated profiles is the

construction industry, where the most widely used profiles are U and C-shaped cross-section with zinc and polymer coatings.

4. In order to systematise the types of impact on the surface of the workpiece, a classifier of the main causes of defects in coatings is compiled, as well as examples of an integrated approach to prevent the destruction of polymer coatings during moulding.

5. A finite element model of the bending process of coated materials has been developed, which takes into account the behaviour of coatings, both metal and polymer. The adequacy of the obtained modelling results was checked by comparison with experimental values published in the scientific literature, the discrepancy is 5-10%, which is acceptable in engineering calculations.

6. It is established that the main factor affecting the development of defects in coatings during the bending process is the degree of deformation, which can be regulated by the minimum bending radius. In this paper, the recommended bending radii of steel with a galvanised surface and a polymer coating are determined using modelling.

7. Analysis of scientific sources has revealed that the previous technological operation has a significant impact on the development of defects in polymer coatings, that is, for a more accurate analysis, it is necessary to take into account the so-called technological heritage. Also, a significant point that is not included in the proposed model is the presence of relaxation processes in polymer coatings. The above-mentioned behaviour of polymer coatings can be taken into account to further develop research in this area.

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Дослідження напружено-деформованого стану процесу гнуття матеріалів з покриттям

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Анотація

Актуальність. Актуальність дослідження обумовлена сучасною тенденцією з використання складних профільних виробів із матеріалів з покриттям у різних сферах промисловості, особливо в будівництві, що дає змогу значно підвищити корозійну стійкість, довговічність, температурний діапазон застосування та технологічність, а також найпоширенішими методами отримання таких виробів є методи обробки тиском, зокрема гнуття, який представляє собою напружений термічно-силовий процес, що здійснює вплив на якість та цілісність попередньо нанесеного покриття.

Мета. Метою моделювання та аналізу впливу технологічних параметрів процесу гнуття на напружено-деформованого стану заготовки є запобігання руйнування багатошарових покриттів та отримання практичних рекомендацій для виготовлення складнопрофільних виробів в умовах гнучкого виробництва.

Методи. Основним методом, який дає змогу досягнути поставленої мети, є метод скінчено-елементного аналізу напружено-деформованого стану за різних технологічних умов процесу гнуття, таких як кут загину, мінімальний внутрішній радіус загину, розташування заготовки; параметри матеріалу обробки (властивості матеріалу обробки, товщина покриття) залишалися постійними, реалізований у програмному комплексі ANSYS.

Результати. У статті представлені результати скінчено-елементного аналізу напружено-деформованого стану матеріалів із багатошаровим покриттям в процесі гнуття із різними технологічними умовами. Надано практичні рекомендації щодо технологічних параметрів обробки, які дозволять отримати вироби без дефектів попередньо нанесеного покриття.

Висновки. Результати роботи дають змогу детальніше зрозуміти процеси, які відбуваються із матеріалами з багатошаровим покриттям під час обробки тиском та становлять практичну цінність для підприємств, які спеціалізуються на виготовленні виробів із складним профілем

Ключові слова: багатошарові покриття, ANSYS, скінчено-елементний аналіз, обробка тиском