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THEORETICAL AND EXPERIMENTAL SUBSTANTIATION OF THE EXTRACTION PROCESS WITH THINNING BIMETALLIC TUBULAR ELEMENTS OF DISSIMILAR METALS AND ALLOYS

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Abstract. *The article proposes a scheme of the process of manufacturing bimetallic tubular elements by extraction a cylindrical cup of two dissimilar metals without thinning and extraction with thinning cup. At the same time, in the process of extraction in the heated state, the layers of dissimilar metals and alloys are connected and the desired shape of the product is obtained. A mathematical model of deformation of the process of joint extraction with thinning of two dissimilar metals with heating in a flat deformed state is developed. The influence of the deformation value on the dispersion of mechanical energy by bimetal was revealed.*

Keywords: deformation, bimetal tubular elements, stretching with thawing, dispersing of mechanical energy

TEORETYCZNE I EKSPERYMENTALNE UZASADNIENIE PROCESU CIĄGNIENIA Z PRZERZEDZANIEM BIMETALICZNYCH ELEMENTÓW RUROWYCH Z RÓŻNYCH METALI I STOPÓW

Streszczenie*. W artykule zaproponowano schemat procesu wytwarzania bimetalicznych elementów rurowych poprzez ciągnienie cylindrycznego kielicha z dwóch różnych metali bez przerzedzania i ciągnienie z przerzedzaniem kielicha. W procesie ciągnienia w stanie nagrzanym warstwy różnych metali i stopów są łączone i uzyskuje się pożądany kształt produktu. Opracowano matematyczny model odkształcenia procesu wspólnego ciągnienia z przerzedzaniem dwóch różnych metali z ogrzewaniem w płaskim stanie odkształconym. Ujawniono wpływ wartości odkształcenia na rozpraszanie energii mechanicznej przez bimetal.*

Słowa kluczowe: odkształcenie, bimetaliczne elementy rurowe, ciągnienie z przerzedzaniem, rozpraszanie energii mechanicznej

Introduction

Modern trends in the development of the engineering industry are characterized by increased requirements for the quality and performance of products while reducing the cost of their production. To ensure the effectiveness of engineering products in their designs are widely used various metals and alloys with high relative strength, as well as specific functional properties.

Bimetallic tubular elements (BTE) are used in the construction of high-tech engineering products for connecting pipelines of various metals such as aluminum, steel, titanium and others.

Methods of production of BTE are introduced in metallurgical and machine-building production and based on methods of molding and plastic deformation. They are focused on mass and large-scale production. They are economically advantageous to use in small-scale and single production. Methods based on high-energy processes of plastic deformation and diffusion welding, which can be implemented in small-scale production, require specific conditions of implementation and increased safety requirements [8, 12, 16].

The sharp competition of mechanical engineering products in the world market requires the mobility of production, and discrete unstable programs of production of products-production of their single copies. The mobility of production can be provided by using the universal equipment of machine-building enterprises, as well as by creating technologies for the manufacture of bimetallic tubular elements from traditional semi-finished products, such as sheet semi-finished metals and alloys, using non-complex die tooling methods of extraction [7, 14, 20].

1. Problem formulation

The aim of the work is to develop a method of control of the main parameters of working out the technological process of extraction with the refinement of dissimilar sheet materials, which ensure the quality of the connection in the conditions of machine-building enterprises.

2. The stress-strain state of the process of co-extrusion

In this paper, the authors solved the actual scientific and practical problem of improving the efficiency of manufacturing BTE in machine-building production by developing a control method at the stage of development of the technological process, which would allow to determine the parameters of the technological process of extraction with thinning, which ensure the quality (strength) of the connection and allows to predict the performance properties.

The basis of the work is the scientific idea of constructing the process of manufacturing bimetallic tubular elements from individual layers of sheet blanks by extraction with thinning in the heated state, which provides conditions for obtaining a given shape of the product and connecting the layers.

Based on the generalization of scientific publications, a typical scheme of the BTE manufacturing process was proposed, which includes pulling two dissimilar metals without thinning, pulling the cup with thinning in the heated state, followed by cutting the bottom part and removing individual layers of metals [1, 21, 22]. The use of pulling the cylindrical cup with thinning in the heated state provides a connection of layers of dissimilar metals and alloys.

For theoretical analysis of the process used by General equations of the theory of plastic flow in continuum mechanics, based on the specified kinematic model in the form of vector components of the speeds of movement of the metal particles in the deformation zone allow to determine the stress-strain state and energy-power parameters of process of deformation of layers of dissimilar metals subject to the conditions of compatibility of deformations in the limiting surface. To account for the interaction of layers of metals and working of the walls of the matrix and punch on the boundary surfaces is set to the value of the coefficient of friction, and the optimization of the velocity field is performed using the extreme principles of the theory of plastic deformations [2, 6, 9].

Structural changes that occur in the material during plastic deformation significantly affect the dispersion of mechanical energy. Various types of defects in metals and damages at the interface in the bimetal composition, arising during the process cycle of manufacturing BTE, correlated with losses of mechanical energy [2]. To study the effect of deformation on the loss of bimetal mechanical energy samples were made in the form of a rectangular plate width of 4 mm, the working length was 45 mm, one part of the sample cantilever clamped, and at the free end transverse vibrations of the audio frequency. Recording and calculations of the obtained parameters of free damped oscillations were carried out using computer programs Sound Forge i Damping [3, 4, 18].

Time dependences of frequency, amplitude and logarithmic decrement of oscillations were obtained. Spectral analysis by Sound Forge allows you to explore the fundamental frequency and overtones that are present in the recording. Spectrum analysis represents sound vibrations in the frequency domain – the number of oscillations of a certain frequency.

Created a special program Damping gives the opportunity: to carry out frequency analysis of a bandpass signal envelope is recorded with the program Sound Forge sweep time of the free mechanical oscillations of the investigated samples; calculate the logarithmic decrement of damping of vibrations according to one of the harmonics. To do this, the signal is sequentially divided into 2048 samples (about 0.05 seconds) and a fast Fourier transform is performed. The coincidence of the final and initial sample count is controlled. The conversion results are used to calculate the parameters of the total envelope of all harmonics of the sound range 20–20000 Hz, envelope of the frequency band of all harmonics specified by the operator: the value of the amplitude of the envelope of one harmonic, the frequency of the maximum harmonic in a given frequency band [11, 15].

The studied samples were subjected to bending deformation and alignment. One bend and alignment - one deformation cycle. Through 5, 10, 15 and 20 such cycles were measured parameters of free oscillations.

Theoretical analysis of extraction process with the thinning of the multilayer of metals is based on the process of pulling monometal [5, 8, 10] and joint deformation in metals is heterogeneous layers in the hearth of deformation. The first step is the analysis of the stress-strain state of the workpiece from monometallic (Fig. 1).

In the theoretical analysis of extraction with thinning, the following assumptions about the deformed state of the deformation center are accepted:

- the inner diameter of the workpiece wall does not change, and the outer at a significant ratio d/S has minor changes. This allows us to assume that the deformation is realized according to the scheme, which is close to the scheme of plane deformation. Therefore, the velocity of the material particles in the circumferential direction is zero [8, 14];
- we believe that in the deformation zone the radial velocities of the material particles depend on the radial coordinate r and do not depend on the cell coordinate θ.

Then, in general, the components of the velocity vector of the material particles have the form:

$$V_r = V_r(r);\ V_\theta = 0;\ V_z = 0 \tag{1}$$

By integrating (1) together with the condition of compatibility of deformations and the boundary condition that $r = R_B$ the velocity component of deformations $V_r = V_0$, where V_0 – the velocity of movement of material particles, which is equal to the velocity of the punch, is obtained:

$$V_r = \frac{V_0 R_B}{r};\ V_\theta = 0;\ V_z = 0 \tag{2}$$

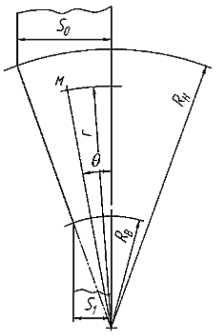

Fig. 1. Calculation scheme of deformation of a monometal in the center of deformations

The speed of deformation is determined by differentiation of the velocity for the respective coordinate:

$$\begin{gathered}\varepsilon_{rr} = -\frac{V_0 R_B}{r^2};\ \varepsilon_{\theta\theta} = \frac{V_0 R_B}{r^2};\\ \varepsilon_{zz} = \varepsilon_{\theta z} = \varepsilon_{zr} = \varepsilon_{r\theta} = 0.\end{gathered} \tag{3}$$

To determine the component of the stress tensor used in equation of the relationship between the deviators of stress D_σ and D_ε strain rate:

$$D_\sigma = \frac{2}{3}\frac{\sigma_i}{\varepsilon_i} D_\varepsilon \tag{4}$$

where ε_i and σ_i – accordingly, the intensity of strain rates and stresses.

We believe that the metal workpiece is ideally plastic that the process is performed under hot (isothermal) plastic deformation $\sigma_i = \sigma_s$.

The average voltage II is determined from the equation proposed by Yu.M. Alekseev:

$$grad\sigma = -\frac{2}{3} div\left(\frac{\sigma_i}{\varepsilon_i} T_\varepsilon\right) \tag{5}$$

where T_ε – strain rate tensor.

Taking into account the limiting condition, at $r = R_H$, $\sigma_{rr} = 0$, the stress tensor components have the form:

$$\begin{gathered}\sigma_{rr} = \frac{2}{\sqrt{3}}\sigma_S \ln\frac{R_H}{r}\\ \sigma_{\theta\theta} = -\frac{2}{\sqrt{3}}\sigma_S\left(1 - \ln\frac{R_H}{r}\right)\\ \sigma_{zz} = \frac{2}{\sqrt{3}}\sigma_S \ln\frac{R_H}{r} - \frac{\sigma_S}{\sqrt{3}}\end{gathered} \tag{6}$$

The obtained results are used for theoretical analysis of two-layer metal extraction.

The kinematic feature of the deformation of a two-layer metal is that at the exit of the deformation center at $r = R_B$ due to the different mechanical properties of the layers, the ratio of the metal thickness changes. This leads to the fact that the limiting surface in the deformation zone is rotated by a certain angle relative to the radial direction (Fig. 2). As a result, the calculated radii of the layers are changed.

When calculating the thickness of the layers after extraction, the physical condition of the joint deformation of the layers in the deformation cell is taken into account-the equality of the tangential stresses normal to the limit surface $\sigma_{\theta\theta_I} = \sigma_{\theta\theta_{II}}$, and also taken into account the relationship of individual layers S_{1B} and S_{2B} at the output of the deformation cell dependence $S_{2B} = S_K - S_{1B}$, where S_K – the total thickness of the workpiece wall after extraction, which is determined by the design of the matrix. The result is an equation for determining the thickness of the first layer [1, 11, 12]:

$$S_{1B} = S_K - e^{A-1} S_{2H}\left(\frac{S_{1B}}{S_{1H}}\right)^A \tag{7}$$

where $A = \sigma_{S_1}/\sigma_{S_2}$ – coefficient of mechanical heterogeneity of two-layer metal.

Velocity fields for both layers:

$$V_{r_i} = \frac{V_0 \dfrac{S_{iB}}{S_{iH} - S_{iB}}(S_{0H} - S_{0k}) ctg\alpha}{r}; \; V_\theta = 0; \; V_z = 0 \qquad (8)$$

where *i* – the index of the layer of metal.

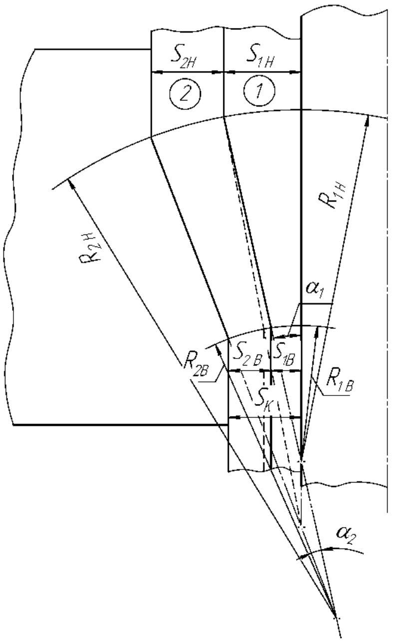

Fig. 2. Scheme of deformation of a two-layer metal in the center of deformations

Components of strain rates in the radial direction for the first and second layers:

$$\varepsilon_{rr_i} = -\frac{V_0 \dfrac{S_{iB}}{S_{iH} - S_{iB}}\left(S_{0H} - S_{0k}\right) ctg\alpha}{r^2}$$

$$\varepsilon_{\theta\theta_i} = \frac{V_0 \dfrac{S_{iB}}{S_{iH} - S_{iB}}\left(S_{0H} - S_{0k}\right) ctg\alpha}{r^2} \qquad (9)$$

$$\varepsilon_{zz} = \varepsilon_{\theta z} = \varepsilon_{zr} = \varepsilon_{r\theta} = 0$$

The components of the stress tensor:

$$\sigma_{rr_i} = \frac{2}{\sqrt{3}}\sigma_{S_i} \ln \frac{\dfrac{S_{iH}}{S_{iH} - S_{iB}}\left(S_{0H} - S_{0k}\right) ctg\alpha}{r}$$

$$\sigma_{\theta\theta_i} = -\frac{2}{\sqrt{3}}\sigma_{S_i} \left(1 - \ln \frac{\dfrac{S_{iH}}{S_{iH} - S_{iB}}\left(S_{0H} - S_{0k}\right) ctg\alpha}{r}\right) \qquad (10)$$

$$\sigma_{zz_i} = \frac{2}{\sqrt{3}}\sigma_{S_i} \ln \frac{\dfrac{S_{iH}}{S_{iH} - S_{iB}}\left(S_{0H} - S_{0k}\right) ctg\alpha}{r} - \frac{\sigma_{Si}}{\sqrt{3}}$$

Kinematic dependences (8) make it possible to calculate the distribution of the radial velocity difference ΔV_r at the interface of the layers along the deformation zone, the length of which is determined by the coordinate *r*. It is shown that:

- the maximum difference in the rates of movement is observed at the entrance of metals to the deformation site;
- layer which has a lower boundary of turnover, ahead of the layer with greater border strength, due to the fact that it thins to a greater extent [13, 14, 15];
- at the output of the deformation cell, the velocity of the layers is aligned [16, 17].

3. Calculation of the parameters of the extraction process with thinning taking into account friction on the boundary surfaces

It is shown that taking into account the friction forces on the boundary surfaces of the layers provides a more accurate solution. For this purpose, the analysis of the energy-power parameters of extraction with with thinning, taking into account the friction forces on the boundary surfaces using the method of power balance.

The power balance equation for the deformation center of each layer has the following form:

$$N_{\sigma_{z_i}} = N_{mp} + N_{mp}^{\text{мс}} + N_{\sigma_{ri}} + N_{\sigma_{\theta_i}} + N_{\tau_{r\theta_i}} + N_{R_{iH}}^{\text{зс}} + N_{R_{iB}}^{\text{зс}} \qquad (11)$$

When solving the equation (11), the friction forces are taken into account by the friction coefficient according to the Amonton-Coulomb law on the boundary surfaces of the workpiece with the matrix – μ_3, and a punch – μ_1, and between the layers of the workpiece – μ_2. Then the total deformation power of both layers is determined by the dependence:

$$\begin{aligned}
N_{\sigma_z} = {} & \frac{2}{\sqrt{3}}\sigma_{S_1}\alpha_1 V_0 \left[\mu_2\left(1 - \ln\frac{S_{1H}}{S_{1B}}\right)\frac{\left(S_{0H} - S_{0k}\right) ctg\alpha}{S_{1B}} - \right. \\
& -\mu_1\left(1 - \ln\frac{S_{1H}}{S_{1B}}\right)\frac{\left(S_{0H} - S_{0k}\right) ctg\alpha}{S_{1B}} + \\
& \left. + \frac{S_{1B}}{S_{1H}} + \ln\frac{S_{1H}}{S_{1B}}\right] + \frac{2}{\sqrt{3}}\sigma_{S_2}\alpha_2 V_0 \qquad (12) \\
& \left[\mu_3\left(1 - \ln\frac{S_{2H}}{S_k - S_{1B}}\right)\frac{\left(S_{0H} - S_{0k}\right) ctg\alpha}{S_k - S_{1B}} - \mu_2 \times \right. \\
& \left. \times\left(1 - \ln\frac{S_{2H}}{S_k - S_{1B}}\right)\frac{\left(S_{0H} - S_{0k}\right) ctg\alpha}{S_k - S_{1B}} + \frac{S_{1B}}{S_{1H}} + \ln\frac{S_{2H}}{S_k - S_{1B}}\right]
\end{aligned}$$

Equation (12) makes it possible to determine the unknown thickness of the first layer taking into account the extreme energy principles of plastic deformation S_{1B} after extraction. Its determination is made by minimizing the power of the process:

$$\frac{\partial N_{\sigma_z}}{\partial S_{1B}} = 0 \qquad (13)$$

Equation (13) is solved by a numerical method of simple iterations. Comparison of the calculation results of the layer thickness with a lower yield point when pulling with the thinning of the workpiece with the initial (S_{0H} = 2.8 mm, S_{1H} = S_{2H} = 1.4 mm) and final S_k = 1.12 mm the thickness of the layers (Fig. 3) shows that when taking into account the forces of friction thinning is manifested to a greater extent than without taking into account the forces of friction. The calculation error does not exceed 10...11%.

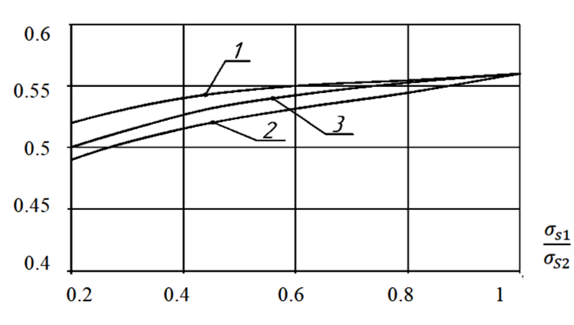

Fig. 3. Comparison of the thickness of the metal layer having a lower yield strength from the coefficient of mechanical heterogeneity: 1 – excluding friction forces; 2 – taking into account friction forces; 3 – experiment

The General solution (13) with the system of equations (8) – (10) allows analyzing the stress-strain state, kinematic and energy-force parameters of the pulling process taking into account the friction forces [18, 19].

The stability of the extraction process with thinning is limited by the destruction of one of the layers of the part due to the achievement of the critical value of the accumulated shear deformation in the deformation zone, which is determined by the use of (9). Taking into account the constancy of the stress state scheme in the established process of stretching, using the V. L. Kolmogorov criterion, a functional is constructed, the minimization of which allowed to determine the maximum degree of wall compression during the process:

$$\Phi = \left| \ln \frac{\sqrt{3}\int_0^t \left[\varepsilon_i(r,\varphi,z,t)\mu\right]dt}{\Lambda\left(\Pi_\sigma\right)} \right| = 0 \tag{14}$$

4. The effect of amount of deformation on the dissipation of the mechanical energy bimetal

In determining the overall strength of bimetal $\sigma_б$ along the connection plane of the components can be used a simplified representation of the theory of combined action, according to which each component makes an independent contribution to the overall strength:

$$\sigma_б = \sigma_1 V_1 + \sigma_2 V_2, \tag{15}$$

where σ_1, σ_2 – strength of the first and second components of bimetal, V_1, V_2 – accordingly, their volume content.

With a slight deformation, each component is deformed elastically. The modulus of elasticity of the bimetal ($E_б$) it can be determined according to the law of additivity:

$$E_б = E_1 V_1 + E_2 V_2. \tag{16}$$

The bond strength at the interface of two metals should be sufficient for their joint deformation.

But the rule of additively does not take into account many factors that can change the properties of bimetal in one direction or another. External load during deformation can cause blocking of dislocations, which increases the strength of the material. The formulas (15) and (16) and the method of their preparation do not take into account the presence of the boundary between the two metals. Bimetal with a developed transition zone can be considered as a three-component and four-component system. In this case, the volume content of the system is represented by the expression:

$$V_1 + V_2 + V_{TZ} = 1 \tag{17}$$

where V_{TZ} – volume content of the transition zone. Then equation (15) in the first approximation takes the form:

$$\sigma_б = \sigma_1 V_1 + \sigma_2 V_2 + \sigma_{TZ} V_{TZ} \tag{18}$$

where σ_{TZ} – the strength of the transition zone between the components of bimetal. The use of (15) and (18) makes it possible to theoretically predict the strength of the bimetal.

It is difficult to determine experimentally the size of the transition zone and the strength of the connection of the two components of bimetal. The use of the structure-sensitive non-destructive method of internal friction in the work allowed establishing the nature of changes in the physical and mechanical characteristics of the transition zone, the components of the bimetal and the strength of their connection under the influence of external influences. Analysis of the magnitude of the defect at the border of the two metals in size and nature of the dispersion of mechanical energy system is promising in determining the optimal technological modes of manufacture of finished parts [16, 21].

Given the integral nature of internal friction, for complex structures it can be written that $Q^{-1} = \sum_{i=1}^{n} Q_i^{-1} + Q_{LZ}^{-1}$, where Q^{-1} – losses of mechanical energy by the structure as a whole, Q_i^{-1} – loss of mechanical energy in each metal that is part of the structure; Q_{LZ}^{-1}- loss of mechanical energy in the transition zone. For bimetal compounds between metals may have a different number of defects: from contact, when metals have a very small number of defects at the junction, to a simple clamp to each other with the possibility of slippage. However, such a structure loses its physical and mechanical properties as bimetal.

During the study, the losses of mechanical energy on the samples that were not deformed and on the samples subjected to different numbers of deformation cycles were determined. The obtained graphs of damped oscillations are presented in Fig. 4.

The analysis of the results shows that in the process of deformation in the material there are damages in the form of vacancies and dislocations, and on the border of the two metals may appear makrocracks. The existing damage had little effect on the graphs of damped oscillations and slight changes in the spectral analysis were observed. Harmonics with frequencies 756 Hz, 4642 Hz, 6340 Hz are observed on all charts. With an increase in the number of harmonic deformation cycles with frequencies of 1820 Hz and 2740 Hz are observed, respectively, at lower frequencies of 1676 Hz and 2658 Hz. After 15 deformation cycles, harmonics appeared at frequencies of 3360 Hz. On the graph without deformations observed harmonic frequency 10349 Hz and increasing the number of deformation cycles frequency (up to 10922 Hz) and its intensity increases (table 1).

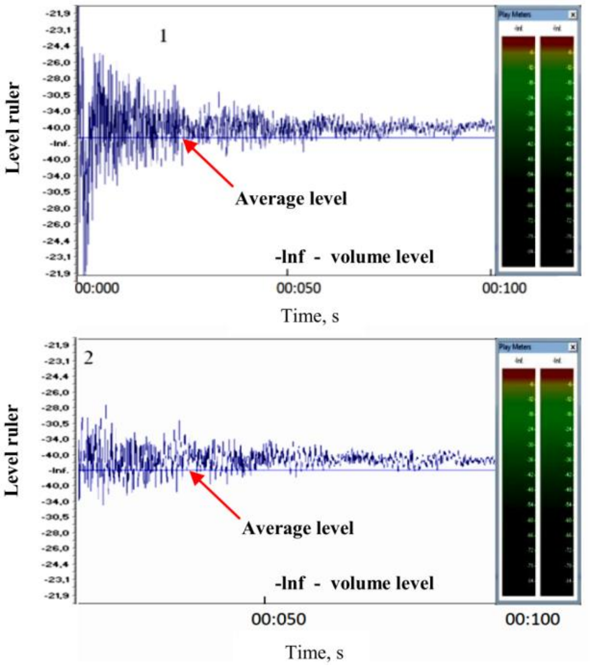

Fig. 4. Experimental studies of bimetal: graphs of free damped oscillations of cantilever clamped samples: 1 – without deformation; 2 – deformation of 50 deformation cycles; spectral analysis of free damped oscillations of samples

Table 1. Changing the frequency of harmonics with increasing number of deformation cycles of the bimetallic strip

Frequency, Hz	0 cycles	5 cycles	15 cycles	30 cycles	50 cycles
0 ÷ 1000	756	756	756	756	756
1000 ÷ 2000	1820	1799	1676		1676
2000 ÷ 3000	2740	2617	2679	2658	2556
3000 ÷ 4000			3292	3364	3313
4000 ÷ 5000	4867	4642	4642	4642	4642
5000 ÷ 6000		5460		5215	5236
6000 ÷ 7000	6565	6361	6340	6340	6299
10000 ÷ 11000	10349	10595		10902	10922

The Damping program made it possible to determine the logarithmic decrement of attenuation, oscillation frequency and amplitude change in the process of vibration damping. The nature of the amplitude decrease from the beginning of attenuation is the same (Fig. 5), but different decay rate. Rapid attenuation of vibrations occurs at the greatest deformation.

Fig. 5 shows that the damping of the oscillations occur with oscillations, on the parameters which affects the amount of deformation cycles.

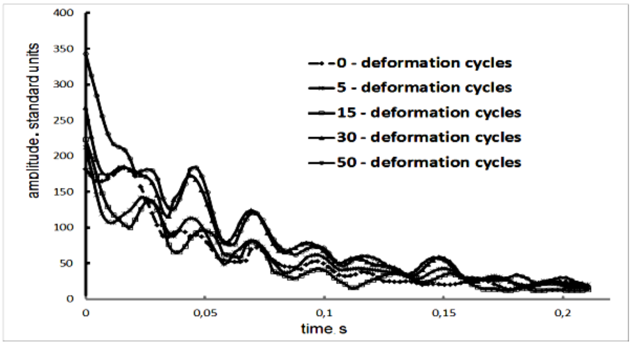

Fig. 5. Graphs of changes in the amplitude of free oscillations of a deformed aluminum-steel bimetal with different amounts of deformation

5. Conclusions

1. The actual scientific and practical task of increase of efficiency of production of bimetallic tubular elements in machine-building production is proved and solved – for the first time on the basis of generalization of results of the analysis of scientific publications the idea is offered, the machine-building concept of process of production of bimetallic tubular elements from separate sheet dissimilar metals is developed, theoretically and experimentally proved with a thinning in the heated state which is based on the existing theories of diffusion connection of dissimilar metals by realization of conditions of joint deformation, pressure, heating on their boundary surfaces.

2. A complex method of theoretical and experimental study of the process of pulling with thinning of a two-layer billet of dissimilar metals is developed. Evaluation of the stress-strain state and energy-force parameters of the process in the deformation zone is performed using the theory of plastic flow in deformation and the basics of the theory of composite materials in the interaction of layers of dissimilar metals on the limiting surface, as well as extreme energy principles of plastic deformation taking into account the friction forces. The substantiation of analytical results and results of numerical modeling is carried out with the help of full-scale experiment with the use of standardized methods on the certified equipment.

3. Using the theory of plastic flow, a mathematical model of deformation of the process of joint pulling with thinning of two dissimilar metals with heating under conditions of flat deformed state was developed, which allowed to establish the relationship between the parameters of the stress-strain state on the limiting surface and the degree of deformation of thin layers with the initial geometric parameters of the workpiece, the mechanical properties of individual layers and the geometry of the working surface of the matrix. It is shown that the error does not exceed 10 for calculating the thickness of layers with an ideal plastic model of metals...14% in relation to experimental data. The use of extreme energy principles of deformation, taking into account the friction forces on the boundary surfaces, has improved the accuracy of determining the thickness of the layers after deformation to 10...11%.

4. As a result of numerical simulation of the process in the CAD / CAE ANSYS and DEFORM-3D system, it is found that for pulling with a degree of deformation, the thinning is 50% for the bimetal of the aluminum+titanium system with a minimum coefficient of friction (μ=0,01) the maximum values of the pulling force do not differ significantly, and when μ= 0.3 there is an increase in the force as well as the work of pulling while reducing the taper angle of the matrix from 10º to 4º by 45...47%. The value of radial stresses on the limiting surface of the layers increases in proportion to the degree of compression, and their maximum value corresponds to the zone close to the output of the matrix and increases with decreasing taper angle of the matrix. In this case, the thinning of the layers depends on the coefficient of mechanical heterogeneity of metals. It is shown that the main obtained regularities of deformation qualitatively and quantitatively with a sufficient degree of accuracy coincide with the results of the calculation of two-layer billets with other mechanical properties, for example, aluminum+brass, aluminum+stainless steel systems and others.

5. Based on the analysis of the stress-strain state and the kinematic interaction, it is found that conditions are created in the deformation zone of the layers that contribute to the diffusion connection of the layers:

- maximum compressive stress on the limiting surface of the layers reaches the boundary of the metal layer flow with less mechanical properties;
- the difference between the axial deformations of the layers, as well as the presence of shear deformations in the interaction of layers on the limiting surface provide the destruction of oxide films, which contributes to the interaction of layers;
- in the zone close to the exit of the matrix, the difference between the movement of the material layers on the limiting surface is reduced to zero;
- the presence of heating layers to the activation temperature contributes to their interaction.

6. On the basis of analytical and numerical results, a constructive and technical solution for the use of an additional angle is proposed β = 1º…2º at the exit of the cone matrix with the base angle α = 7º, this provided a more effective effect of radial compressive stresses on the limiting surface due to the uniformity of their application and increasing the interaction time of the layers. It is also shown that the time of finding the layers in the deformation zone can be effectively guided by the rate of extraction and the length of the deformation zone.

7. The main scientific results obtained by analytical and numerical calculations are experimentally confirmed. It is shown that the maximum error of calculation of power parameters does not exceed 7...10%, the advance of the layer with a lower yield strength does not exceed 9...11%, the deformation layer thickness after extraction with thinning does not exceed 10...14% for the different coefficients of mechanical anisotropy of metals.

In experimental conditions typical BTE were obtained, metallographic analysis of which showed the interaction of layers. Evaluation of the strength of the layers showed that it reaches 80...85% of the shear stress for the alloy with lower yield stress.

8. The influence of the damage value of the material on the dispersion of mechanical energy is revealed: the nature of the course and the type of curves of free damped oscillations in the sound range are changed; the frequency of low-frequency harmonics is changed and does not change for high frequencies; the decay rate is changed.

References

[1] Aliieva L., Zhbankov Y. Radial-direct extrusion with a movable mandrel. Metallurgical and Mining Industry 11, 2015, 175–183.

[2] Alekseev Yu. N.: Questions of plastic flow of metals. Publishing house of the KhSU, Kharkov 1958.

[3] Borys R., Titov V.: Ensuring the quality of the connection of layers from different metals in the manufacture of bietallic tubular elements by drawing. Mechanics and Advanced Technologies 1(85), 2019, 63–70 [http://doi.org/10.20535/2521-1943.2019.85.162508].

[4] Hedayatia O., Koreia N., Adelia M., Etminanbakhshb M.: Microstructural evolution and interfacial diffusion during heat treatment of Hastelloy/stainless steel bimetals. Journal of Alloys and Compounds 712, 2017, 172–178.

[5] Inoue J., Nambu S., Ishimoto Y., Koseki T.: Fracture elongation of brittle/ductile multilayered steel composites with a strong interface. Scripta Materialia 59, 2008, 1055–1058.

[6] Kalyuzhnyi V. L., Aliieva L. I., Kartamyshev D. A., Savchinskii I. G.: Simulation of Cold Extrusion of Hollow Parts. Metallurgist 61, 2017, 359–365.

[7] Lebedev A. O.: Methods and results of the processes of accumulation of damage in metallic materials under different load conditions. Bulletin of NTUU "KPI". Mechanical engineering 44, 2003, 42–57.

[8] Limberg, E. A. Selivanov G. D.: Determination of the specific pressure of filling the fillet radii in the tool for forging of. Metal forming in engineering 17, 1981, 22–27.

[9] Polishchuk L., Mamyrbayev O., Gromaszek K.: Mechatronic Systems II. Applications in Material Handling Processes and Robotics. Taylor & Francis Group, CRC Press, Balkema book, Boca Raton, London, New York, Leiden 2021.

[10] Tallafuss P., Johnston J.: Defects, causes and prevention controls in the continuous bronze/steel bimetal strip sintering process. Engineering Failure Analysis 92, 2018, 34–43.

[11] Shulga M., Krivov G., Fedorenko Yu., Titov V., Akimov V.: Modeling and calculation of structural elements made of heterogeneous materials. Technology, 1996.

[12] Springer H., Kostka A., Payton E. J., Raabe D., Kaysser-Pyzalla A., Eggeler G.: Onthe formation and growth of intermetallic phases during interdiffusion between lowcarbon steel and aluminum alloys. Acta Mater. 59, 2011.

[13] Springer H., Szczepaniak A., Raabe D.: On the role of zinc on the formation and growth of intermetallic phases during interdiffusion between steel and aluminium alloys. Acta Mater. 96, 2015.

[14] Titov V. A.: The influence of diamond smoothing the surface of the steels on the mechanical energy dissipation. Ttov V. A., Mozgovy O. V.: Bulletin of National Technical University of Ukraine "Kyiv Polytechnic Institute". Engineering 54, 2008.

[15] Viala J. C., Peronnet M., Barbeau F., Bosselet F., Bouix J.: Interface chemistry in aluminium alloy castings reinforced with iron base inserts. Composites Part A: Applied Science and Manufacturing 33(10), 2002, 1417–1420 [http://doi.org/10.1016/S1359-835X(02)00158-6].

[16] Wójcik W., Pavlov S., Kalimoldayev M.: Mechatronic Systems I. Applications in Transport, Logistics, Diagnostics and Control. Taylor & Francis Group, CRC Press, Balkema book, London, New York 2021.

[17] Wang T. M., Liang C. H., Chen Z. N., Zheng Y. P., Kang H. J., Wang W.: Development of an 8090/3003 bimetal slab using a modified. J. Mater. Process. Technol. 214, 2014, 347–352.

[18] Wenming Jiang, Guangyu Li, Yao Wu, Xinwang Liu: Zitian Fan Effect of heat treatment on bonding strength of aluminum/steel bimetal produced by a compound casting. Journal of Materials Processing Technology 258, 2018 [http://doi.org/10.1016/j.jmatprotec.2018.04.006].

[19] Xu W. C., Zhang Z. P., Huang K., Shan D. B.: Effect of heat treatment and initial thickness ratio on spin bonding of 3A21/5A03 composite tube. J. Mater. Process. Technol. 247, 2017, 143–157.

[20] Zhbankov I., Perig A., Aliieva L.: Calculation of recovery plasticity in multistage hot forging under isothermal conditions. Springer Plus 69, 2016, 174–180.

[21] Zhbankov I. G., Perig A. V., Aliieva L. I.: New schemes of forging plates, shafts and discs. Int. J. of Advanced Manufacturing Technology 82, 2015, 287–301 [http://doi.org/10.1007/s00170-015-7377-7].

[22] Zhou Li et al.: Analysis of bending characteristics of bimetal steel composite. International Journal of Mechanical Sciences 148, 2018 [http://doi.org/10.1016/j.ijmecsci.2018.08.032].

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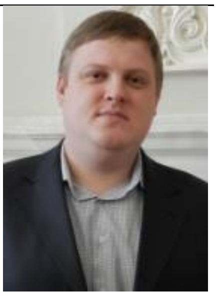

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