Обґрунтовано перспективність гібридного лазерно-плазмового різання металів, запропоновано конструкцію інтегрованого плазмотрона для гібридної різання, а також спрогнозовано результати лазерно-плазмового різання листових вуглецевих конструкційних сталей з використанням такого інтегрованого плазмотрона. Показано, що для мінімізації втрат лазерного випромінювання і отримання максимального проплавлення інтегрований плазмотрон доцільно компонувати за коаксіальною схемою з осьовим розташуванням лазерноного випромінювання і мінімальним нахилом неплавких електродів (одного або більше), відстань від робочого кінця яких до осі лазерного пучка повинна лежати в інтервалі 2...3 мм Діаметр плазмоутворюючого сопла повинен лежати в межах 2–5 мм, а заглиблення фокуса під поверхню листа, що розрізається, при гібридному різанні становити 1–2 мм. Для моделювання процесів лазерного, плазмового та гібридного різання застосовували програмний комплекс SYSWELD, що стало можливим завдяки врахуванню характерного для різання ефекту видалення ділянок розплавленого матеріалу в зоні різання, яке виконувалося шляхом заміни в ході їх розрахунку максимальної температури перегріву на початкову (20 °C). Встановлені основні параметри режимів лазерно-плазмового різання, що дозволяють отримати мінімальний розмір ЗТВ при якості різу, яка наближається до лазерної. При цьому для гібридного різання потрібно енерговкладення приблизно вдвічі менше, ніж для повітряно-плазмового. Підвищення швидкості гібридного різання за рахунок збільшення тиску і витрати робочих газів дозволяє його енерговкладанню зрівнятися з аналогічним показником газолазерного різання при більш ніж трикратному підвищенню продуктивності процесу

Ключові слова: гібридне лазерно-плазмове різання, інтегрований плазмотрон, вуглецева конструкційна сталь, термічний цикл, зона термічного впливу (ЗТВ), параметри режиму

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FORECASTING THE RESULTS OF HYBRID LASER-PLASMA CUTTING OF CARBON STEEL

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1. Introduction

Industrial cutting processes are used to produce blanks or finished parts that are subsequently assembled in structures by one method or another, for example, welding. To reduce cost and improve structure manufacturability, it is necessary to apply such a cutting process that will make it possible to produce parts ready for further assembly in the most simple and high-performance way. At the same time, the dimensional accuracy of such parts, as well as quality of their manufacture, should be as high as possible. Plasma can be considered one of these industrial cutting processes. However, the parts cut by this method have certain disadvantages: relatively low accuracy, relatively large size of the heat-affected zone (HAZ), a saturation of its edges with oxygen and nitrogen. To eliminate these disadvantages, laser cutting can be used. In this case, the disadvantages include increased cost per cut meter and restrictions on the thickness of the cut sheet (usually up to 20 mm for carbon steel). It is advisable to combine these two processes into one hybrid process which eliminates these shortcomings due to the interaction of laser and plasma components. In the case of such combining two processes into one, an issue arises of preliminary choice of cutting modes for certain materials.

2. Literature review and problem statement

Today, plasma cutting is one of the most widespread processes for producing flat parts (blanks) from sheet materials. Typically, such parts are made of carbon steel and used for subsequent assembly (welding) in structures (products of engineering, automotive, shipbuilding industries, etc.). It was shown in [1] that one of the main disadvantages of plasma cutting consists of a significant amount of aerosols and solid particles released during the process. Aerosol characteristics are largely related to cutting parameters such as metal type, cut length and plasma arc current. It was shown that an increase in plasma power significantly contributes to an increase in the total mass and size of released particles. This negatively affects the working conditions of operators and pollutes the environment, especially if it is necessary to cut steel thicker than 10 mm. In addition, as shown in [2], the choice of parameters of the plasma steel cutting process affects:

– edge roughness;
– cutting angle (taper);
– burr formation;
– HAZ size;
– material removal rate;
– cut surface quality;
– metallurgical effects of cutting.

At the same time, proper choice of parameters such as cutting power and speed, torch height and orifice gas pressure improve some quality indicators while degrading others.

Replacement of plasma cutting for laser-plasma cutting can be one of the ways to eliminate these drawbacks of the flat blank cutting process. It was shown in [3] that high efficiency, quality, and reliability have made it possible to obtain better results with a fiber laser than with CO_2 or Nd:YAG lasers conventionally used in metal cutting.

An increase in the length of the caustic throat in the focus zone eliminates the problem of proper radiation focusing, enables the formation of a uniform melt pool throughout processing length and a particularly narrow cut. As shown in [4], the reduction of hydrogen embrittlement is another advantage of laser cutting. However, the laser cutting process has several disadvantages, too. For example, it was shown in [5] that the edges cut by the laser method have a rather high roughness *Ra* and *Rz*. It was proposed to reduce it by centrifugal shot-blasting. It is noted in [6] that operating costs depend on laser power, cutting speed, auxiliary gas pressure, nozzle diameter, the position of the focus point and the blank material. The studies are aimed at reducing sufficiently high operating costs of the process.

The studies conducted in recent decades are aimed at eliminating the main disadvantages of thermal cutting processes by combining them. For example, the use of equipment consisting of a set of cells for processing small-batch products in a wide and diverse assortment is proposed in [7]. Such cells represent a new combination of cutting technologies and contain laser, plasma-arc, water-jet (water-abrasive), stamping and punching processes. A general model was proposed in [8] to solve the problem of optimizing the tool path of CNC laser-plasma-gas-water jet cutting machines. The use of hybrid laser-plasma cutting was proposed in [9]. Such a process makes it possible to achieve high accuracy and quality of cut edges characteristic of laser welding. At the same time, the equipment cost is significantly reduced by replacing approximately half of the laser power with a relatively cheap plasma. In addition, the appearance of a synergistic effect during laser-plasma cutting will make it possible to surpass the performance of both the laser and plasma components [10].

The main problems of using the hybrid laser-plasma cutting process include lack of design solutions for creating an integrated plasmatron and difficulty of choosing ranges of varying the cutting mode parameters. The issue of designing an integrated plasmatron requires a separate study. Substantial attention has been paid in relevant literature to the issue of modeling the cutting processes. For example, an experimental study was carried out in [11] to study the quality of plasma cutting of 309 stainless steel in terms of cut width, roughness *Ra* and HAZ size. The results were used to develop three intelligent forecast models based on genetic algorithm (GA), artificial neural network (ANN) and a hybrid technique of genetically optimized neural network systems (GONN). Laser cutting parameters were simulated in [12] based on variance analysis (ANOVA) followed by optimization using the MATLAB environment.

Based on the approaches proposed in these studies, simulation of hybrid laser-plasma cutting of structural steels can be performed. At the same time, it is advisable to evaluate the results according to the performance criteria (primarily the processing speed) and the cut quality of (for example, according to the HAZ size). In contrast to [11, 12], to analyze the processes of gas-laser, air-plasma, and hybrid laser-plasma cutting, the SYSWELD software package (developed by ESI Group) was chosen as one professionally oriented on welding processes.

Thus, today there is no approach to determining parameters of modes and forecasting results of the process of laser-plasma cutting sheet metal materials, in particular, carbon structural steels.

3. The aim and objectives of the study

The study objective is to forecast the results of laser-plasma cutting sheets of carbon structural steel for improving the efficiency of this process.

To achieve the objective, the following tasks were set:

– to determine the fundamental possibility and prospects of using the hybrid laser-plasma process for cutting sheet metal materials;

– to develop design patterns and determine the main parameters of integrated plasmatron for hybrid cutting;

– to conduct computer simulation of the processes of laser, plasma, and laser-plasma cutting carbon steels using the designed integrated plasmatron.

4. Determining the fundamental possibility and prospects of using a hybrid laser-plasma process for cutting sheet metal materials

When developing the process of laser-plasma cutting sheet metal materials, it is desirable to implement the process in such a way that the results obtained (that is, the roughness of the cut edges, their parallelism, cutting width, HAZ size) are closest to the results of laser cutting. To this end, it is necessary to analyze the combined effect of laser radiation and the arc plasma formed in the plasma forming nozzle on the metal being cut. According to [13], state of the plasma column through which laser radiation passes almost non-interacting with it [14] can be described by a system of equations:

$$\frac{1}{r}\frac{d}{dr}\left(r\chi\frac{\partial T}{\partial r}\right)+\sigma E^2+\mu P-U=0; \quad (1)$$

$$\frac{1}{r}\frac{d}{dr}\left(r\eta\frac{\partial u}{\partial r}\right)-\frac{dp}{\partial z}=0\ , \quad (2)$$

where r is the radial coordinate; $T(r)$ is the temperature; $u(r)$ is the axial velocity of plasma; $\chi(T)$ is the thermal conductivity; $\sigma(T)$ is the electrical conductivity; $\mu(T)$ is the coefficient of laser radiation absorption; $U(T)$ is the volumetric density of radiation power; $\eta(T)$ is the coefficient of dynamic viscosity of plasma; E is the electric field strength; dp/dz is the gradient of gas-static pressure in the channel; $P(r)$ is the power distribution in the laser beam. The values of E and dp/dz are determined from the conditions of total current conservation:

$$I=2\pi E\int_0^R \sigma r\mathrm{d}r \quad (3)$$

and total gas flow through the channel:

$$G=2\pi\int_0^R \rho ur\mathrm{d}r, \quad (4)$$

where I is the arc current; G is the gas flow rate; $\rho(T)$ is the plasma density; R is the radius of the channel of the plasma forming nozzle through which plasma and laser radiation pass. Moreover, boundary conditions for equations (1), (2) are as follows:

$$\frac{\partial T}{\partial r}\searrow_{r=0}=0;\ \ \frac{du}{dr}\searrow_{r=0}=0;\ \ T\searrow_{r=R}=T_w;\ \ u\searrow_{r=R}=0, \quad (5)$$

where T_w is the temperature of the cooled channel walls.

Numerical study of the interaction of a laser beam and plasma of the arc discharge column in the channel of the plasma-forming nozzle with inner diameter d was carried out using dependences (1)–(5) indicates its effectiveness at $I/d\leq 30$. In strongly compressed arcs ($I/d\geq 40$ A/mm), the axial temperature of plasma exceeds 20,000 K and its further increase caused by the action of laser radiation results in a drop of plasma conductivity. Therefore, $I/d\leq 30...40$ A/mm was chosen as the most suitable range of I/d values. Thus, the inner diameter of the nozzle should be 2–5 mm for currents of the order of 80–200 A.

The study shows that when implementing a hybrid laser-plasma process, the laser beam can be considered not only as one of the blank heating sources but also as a tool for controlling the technological characteristics of the arc plasma. Interaction of laser radiation and arc plasma produces a synergistic effect. It consists of additional compression of a direct-acting plasma arc by improving the breakdown condition in a narrow plasmatron that occurs when laser radiation acts on metal. In addition, the anode region of the plasma arc is «attached» to the zone of action of the focused laser beam acting on the cut front while the effect of anode spot wandering is eliminated. The resulting combined effect of two energy sources on the processed material is non-additive, that is, its effect is greater than the sum of effects of each of these sources taken separately. This synergistic effect makes it possible to use the laser-plasma process as an innovative controlled source with a high energy density for welding, cutting and various types of heat treatment of metals.

5. Developing the design diagram and determining the main parameters of the integrated plasmatron for hybrid cutting

When choosing the basic scheme of integrated plasmatron for laser-plasma cutting, several options were considered. For example, the coaxial or paraxial arrangement of laser radiation axis relative to the plasmatron axis, use of an arc of direct or indirect action. To take into account the advantages and disadvantages of these options, some well-known prototypes were considered. For example, focused radiation from a solid-state Nd:YAG laser with a power of up to 200 W and an indirect plasma arc with the power of up to 1.0 kW were used for hybrid cutting of stainless steel up to 2 mm thick [15]. In this case, the plasmatron in which argon was fed into the nozzle-anode was placed vertically under the cut plate and the laser head in which air was supplied into the nozzle was set at an angle of 60° to the plate surface. Such hybrid cutting has made it possible to double speed compared to the laser cutting speed while keeping the cut width and the HAZ size close to it. It was found that the optimal ratio of power inputs from the plasma jet and the laser beam in the metal being cut should not exceed 3:1. For combined cutting using a direct-action arc, it was recommended in [16] to choose an approximately equal power ratio. The best result was shown by the integrated plasmatron design in which both components of the hybrid process were located on one side of the cut sheet [15, 16].

Proceeding from the principles of standardization and unification, it is advisable to use a standard tungsten pin cathode in the developed design of the integrated cutting plasmatron. For currents of the order of 100–200 A, a 4.0 mm diameter non-consumable electrode is commonly used. According to the data of [17, 18], to obtain maximum penetration, distance from the working end of the non-consumable electrode to the axis of the laser beam should lie in the range of 2...3 mm. At smaller distances, there is a danger of electrode destruction under the impact of laser radiation. At larger distances, a decrease in penetration depth is observed. It is caused by the disappearance of the effect of the «linkage» of the anode region of the arc with the laser heating spot. The beam focus should be deepened relative to the product surface and be adjustable within certain limits.

Review of published data and the authors' studies have allowed us to develop a design diagram for a unique integrated plasmatron for laser-plasma cutting (Fig. 1). Such a scheme features continuous protection of non-consumable tungsten electrode (cathode) with inert plasma-forming gas (argon). In this case, the active cutting gas (oxygen) is supplied directly to the cutting plasma-forming nozzle. In order to prevent the active cutting gas from contacting the tungsten electrode, its flow rate should be taken less than or equal to the flow rate of the plasma-forming gas. To improve the quality of the cut and increase the service life of the electrodes, the laser radiation is fed coaxially along the axis of the plasma forming nozzle. On both sides of it, two 4.0 mm diameter electrodes are installed at an angle of up to 35° and their sharpening angles may differ. Usually, these angles must be close to 60° for cutting. According to the proposed scheme, an integrated plasmatron was built. It implements the process of laser-plasma cutting (Fig. 2, *a*, *b*).

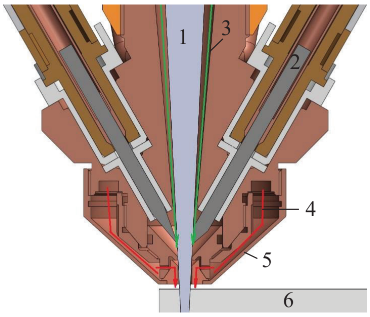
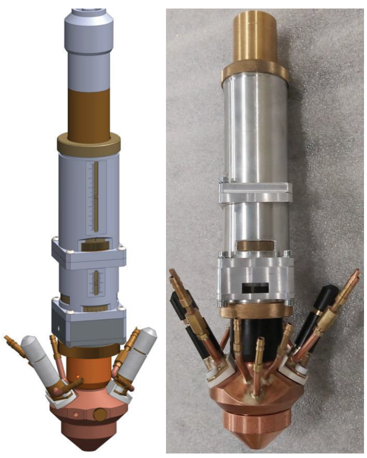


Fig. 1. Design diagram of an integrated plasmatron for laser-plasma cutting: 1 — laser radiation; 2 — tungsten cathode; 3 — plasma-forming gas (argon); 4 — cutting gas (oxygen); 5 — cutting nozzle; 6 — part



a *b*

Fig. 2. Integrated plasmatron for laser-plasma cutting: *a* — three-dimensional model; *b* — physical appearance

Based on [15–18], it can be assumed that the main parameters of the developed integrated plasmatron should be as follows: laser radiation power up to 5.0 kW and cutting current up to 200 A (at a voltage of up to about 100 V). With the help of such a plasmatron, a series of technological experiments were carried out. This has made it possible to verify the accuracy of forecast results obtained by computer simulation that are given below.

6. Computer simulation of processes of laser, plasma and laser-plasma cutting of carbon steels

For reasons of widest application in industry, two types of steels were chosen for simulation of laser-plasma cutting: St. 3sp (analog Q235) and 09G2S (analog SB49) (Table 1). To simplify the process of computer simulation, generalized thermophysical characteristics of structural carbon steels given in Table 2 were used. Based on [1–4], conventional technological schemes and modes (Table 3) for plasma and laser cutting 5- and 10-mm steel sheets were chosen.

To simulate the heat source of thermal cutting, the J. Goldak model was used [19] (Fig. 3). According to this model, the heat source was represented as a double ellipsoid. To calculate each of the three thermal cutting processes under consideration, the SYSWELD software package, a finite element model (Fig. 4) of a steel sheet with dimensions of at least 400×200×δ mm cut linearly (the cut zone is shown in red in Fig. 4) was constructed. Since the finite element method is an approximate method with accuracy depending on grid pitch, a grid with a smaller pitch was used in the area of the heat source and that with a larger pitch was used in other zones (Fig. 4).

The finite element method used in the calculations is based on the assumption that the body can be represented as a set of elements connected to each other only in nodes. The relationship of nodal changes in temperature over time is set using the temperature matrix of the element. At the stage of preprocessing preparation of the model, the database necessary for calculation is created, a coordinate system is set, geometric models are constructed, material properties, type, and analysis, boundary conditions are set, a finite element grid is built and the element type is assigned. Next, thermal analysis is performed with an analysis time of 600 seconds until complete cooling. The design was modeled by a voluminous 8-node element. The number of elements was 42,000. The SYSWELD software package was used for modeling.

Table 1

Chemical composition of steels St. 3sp (analog Q235) and 09G2S (analog SB49), wt. %

Steel grade	C	Si	Mn	Ni	S	P	Cr	V	N	Cu	As
St. 3sp (Q235)	0.14–0.22	0.15–0.30	0.40–0.65	≤0.3	≤0.050	≤0.040	≤0.3	–	≤0.010	≤0.3	≤0.08
09G2S (SB49)	≤0.12	0.5–0.8	1.3–1.7	≤0.3	≤0.035	≤0.03	≤0.3	≤0.12	≤0.008	≤0.3	≤0.08

Table 2

Generalized thermophysical characteristics of structural carbon (low-carbon) steel under normal conditions

Material	Density r, kg/m^3	Specific heat *c*, J/(kg·°C)	Heat conductivity factor λ, W/(m·°C)	Thermal diffusivity *a*, m^2/s	Specific heat of evaporation *E*, kJ/kg	Melting temperature T_m, K	The temperature of the start of phase transitions T_{AC3}, K
Carbon steel	7830	494	42	$15{\cdot}10^{-6}$	6,088	1,833	1,123

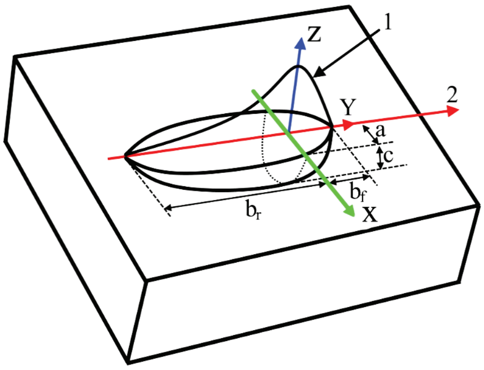


Fig. 3. Diagram of the model of a distributed volumetric heating source having the shape of a double ellipsoid (heat input is opposite to the *z* axis direction and welding direction coincides with the *x* axis) [19]

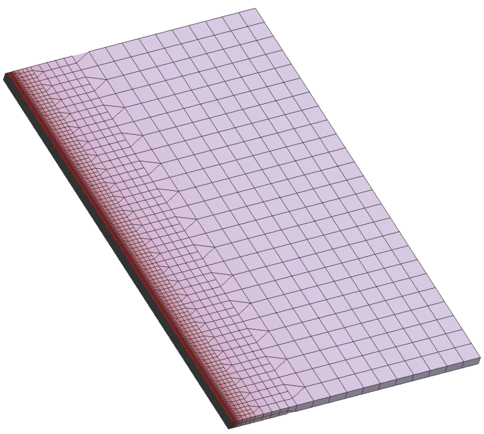


Fig. 4. A finite-element model of distribution of temperature fields in a linearly cut steel sheet with a thickness of δ=5 and 10 mm in the SYSWELD software package

Combination of temperature matrices of individual elements in the global temperature matrix of the body necessary for performing calculations makes it possible to write down conditions of thermal equilibrium of the body:

$$C(T)\rho(T)\frac{\partial T}{\partial t}= =\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right), \quad 0<z<\delta,\ t>0, \tag{6}$$

where $C(T)$, $\rho(T)$, $\lambda(T)$ is the effective heat capacity of the metal (taking into account the latent heat of fusion), density and thermal conductivity, respectively; x, y, z are the Cartesian coordinates (the heat source moves along the x coordinate with speed V); δ is the thickness of the cut metal plate; t is the time coordinate.

At given temperatures, the action of which varies over time, and with the known global temperature matrix, solution of the system of equations of thermal equilibrium (balance) allows one to find all the nodal values of temperature depending on the time of action of the heat source, and hence, temporary changes in temperature within each element. Thus, the spatiotemporal distribution of body temperatures was determined [20].

Over the entire height of the cut plate heated by a laser, plasma, or hybrid laser-plasma heat flux $q(t)$ for a time t, a linear heat source with a radius R_{las}, R_{pl} or R_{las}, and R_{pl}, respectively, is formed. In the case of hybrid cutting, the surface will be heated first by the plasma source, then by the sum of the laser and plasma sources and, finally, again by the plasma source. The time constant (exposure time) in each of these three cases will equal:

$$t_1=\frac{R_{pl}-R_{las}}{V};\quad t_2=t_1+\frac{2R_{las}}{V};\quad t_3=t_2+t_1. \tag{7}$$

Then the heat flow will act on the cut plate:

$$q_\Sigma(t)\begin{cases} q_{pl}, & 0<t<t_1 \\ q_{pl}+q_{las}, & t_1<t<t_2 \\ q_{pl}, & t_2<t<t_3 \end{cases}, \tag{8}$$

where

$$q_{las}=A(T)\frac{P_{las}}{\pi R_{las}^2}$$

is the heat flux introduced by laser radiation,

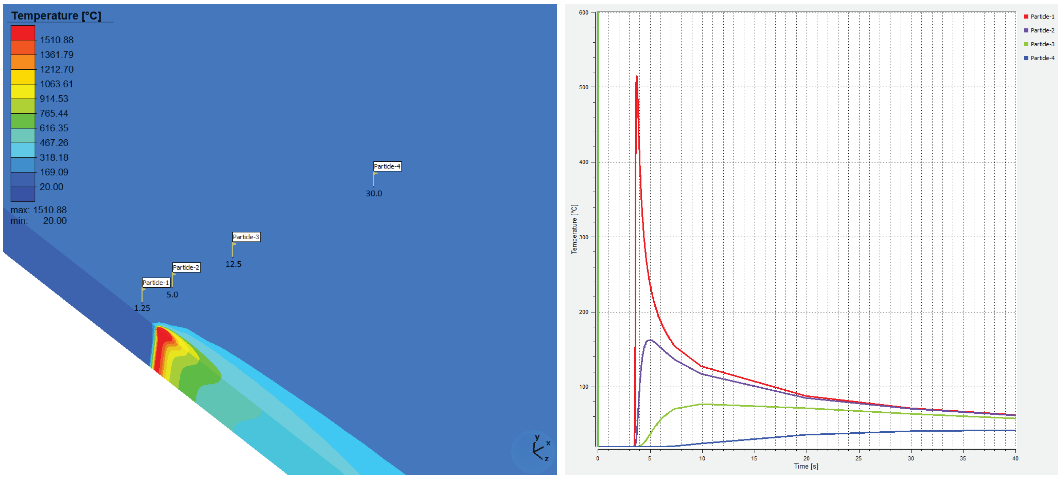
$$q_{pl}=A(T)\frac{P_{pl}}{\pi R_{pl}^2}$$

is the heat flux introduced by the arc plasma. Such heat fluxes create a volumetric heating source in the cut plate the shape of which is shown in Fig. 3.

In the course of computer simulation, according to the recommendations of [1–4], the modes of cutting processes were selected (Table 3), according to which the temperature distribution in the edges of the cut and the thermal cycles of the studied processes were determined using the SYSWELD software package (Fig. 5–10). These calculations were performed according to the regime parameters selected separately for laser (Fig. 5, 7) and for plasma (Fig. 6, 8) cutting, and then the obtained results were integrated to obtain the forecasted results of laser-plasma cutting (Fig. 9, 10).

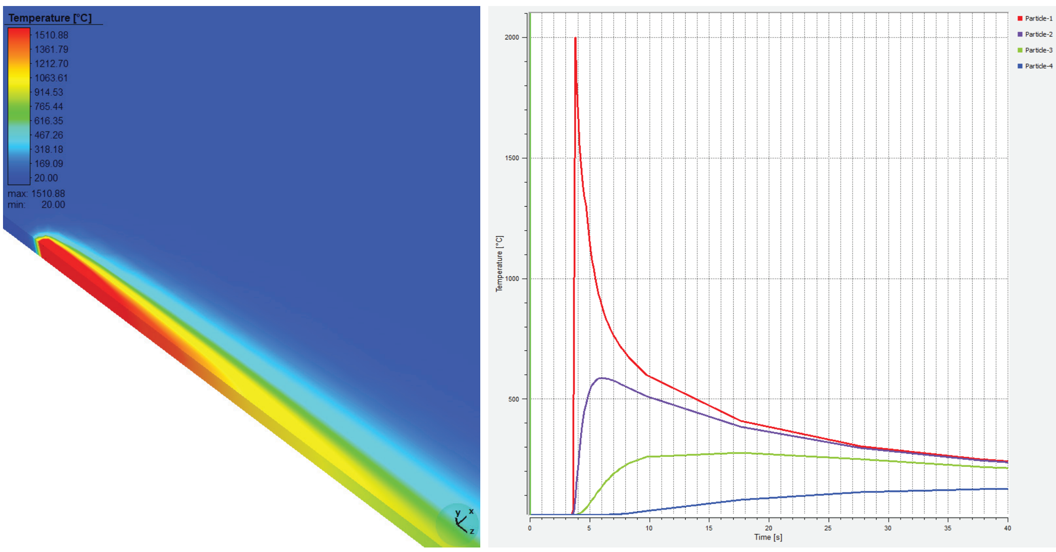
When performing such a simulation, the characteristic for cutting effect of removing sections of molten material in the cut zone was taken into account by replacing, during the calculation, their maximum superheat temperature with the initial temperature (20 °C). The heat source operating during the cutting process was considered linear, cylindrical, uniformly distributed over the height of the cut plate. The main criteria by which the parameters of the regimes of laser-plasma cutting were chosen were obtaining a guaranteed through a cut (parallelism of the cutting edges) in combination with the minimum HAZ size at the cutting edges.

The forecasted parameters of the hybrid laser-plasma cutting modes obtained as a result of the finite element modeling are listed in Table 3. In the process of calculations, these parameters were chosen according to the criteria for minimizing the HAZ (HAZ size up to 0.2 mm for δ=5 mm and about 0.2–0.3 mm for δ=10 mm) and obtaining the highest speed for the given power of the heat source process (about 240 m/h for δ=5 mm and about 120 m/h for δ=10 mm). As a plasma-forming gas in hybrid cutting, it is advisable to use one that does not harm the operation of the non-consumable electrode. This is usually argon. However, such a gas is not suitable for cutting carbon steel. Therefore, argon can be recommended as additive oxygen (for example, up to 50 %) introduced into the cutting head so that it does not come into contact with a non-consumable tungsten electrode.



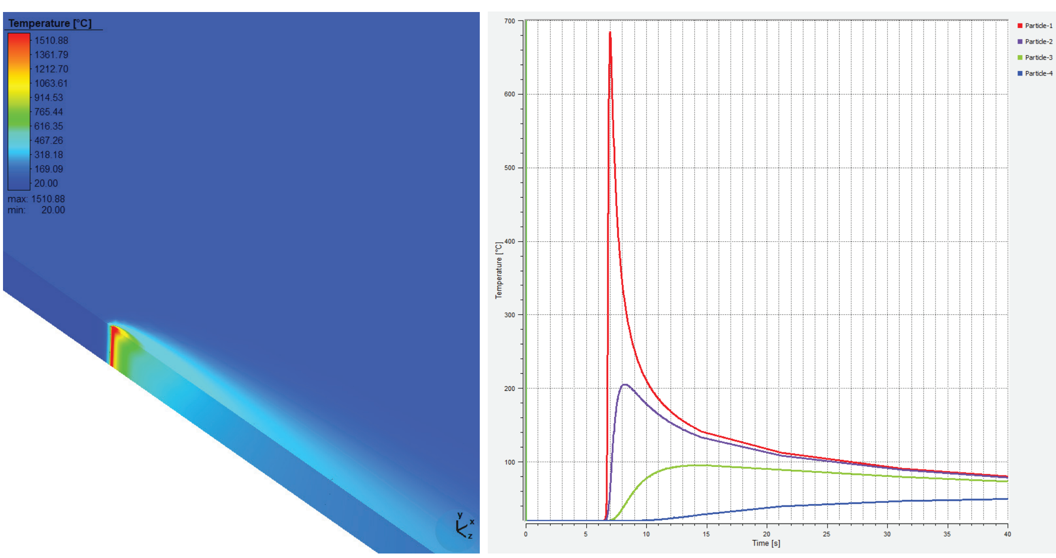
a *b*

Fig. 5. Laser cutting of steel δ=5 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* — model of the process; *b* — thermal cycles



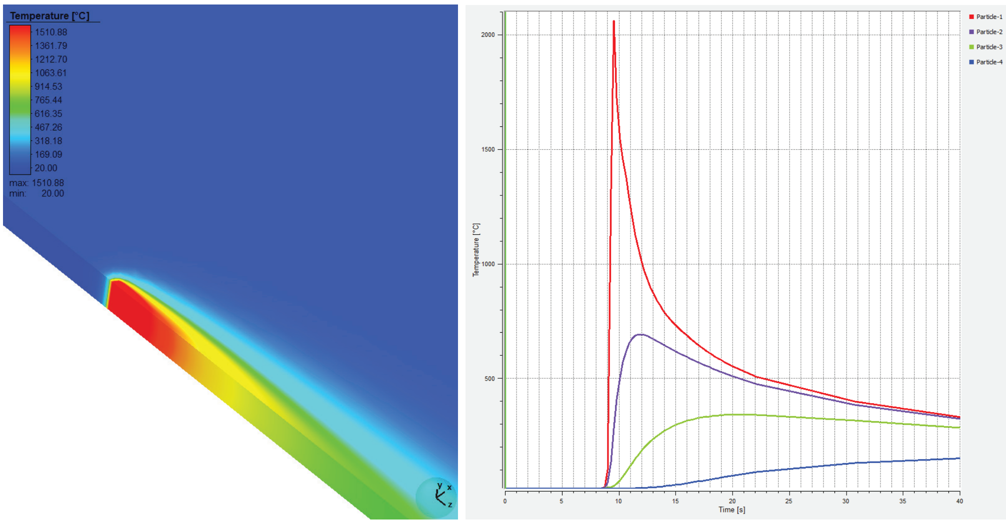
a *b*

Fig. 6. Plasma cutting of steel δ=5 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* — model of the process; *b* — thermal cycles



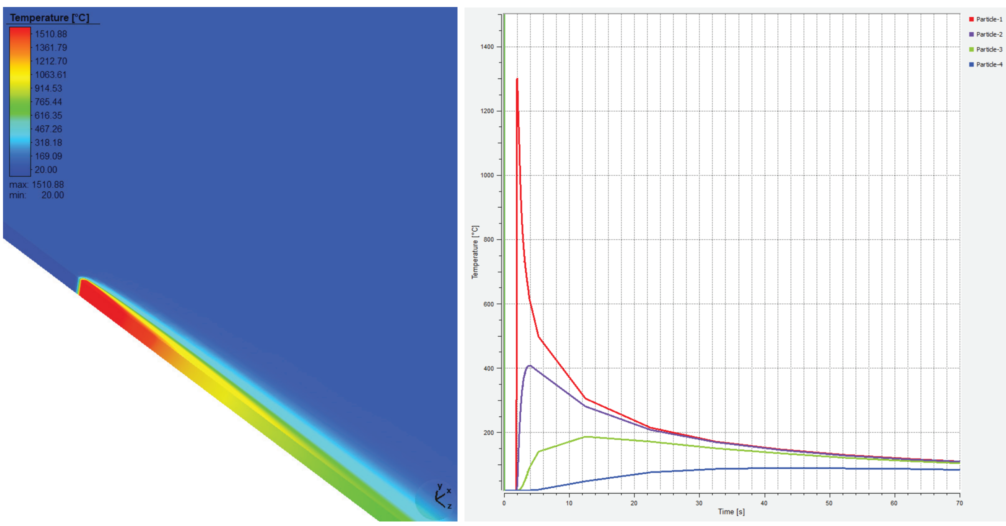
a *b*

Fig. 7. Laser cutting of steel δ=10 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* — model of the process; *b* — thermal cycles



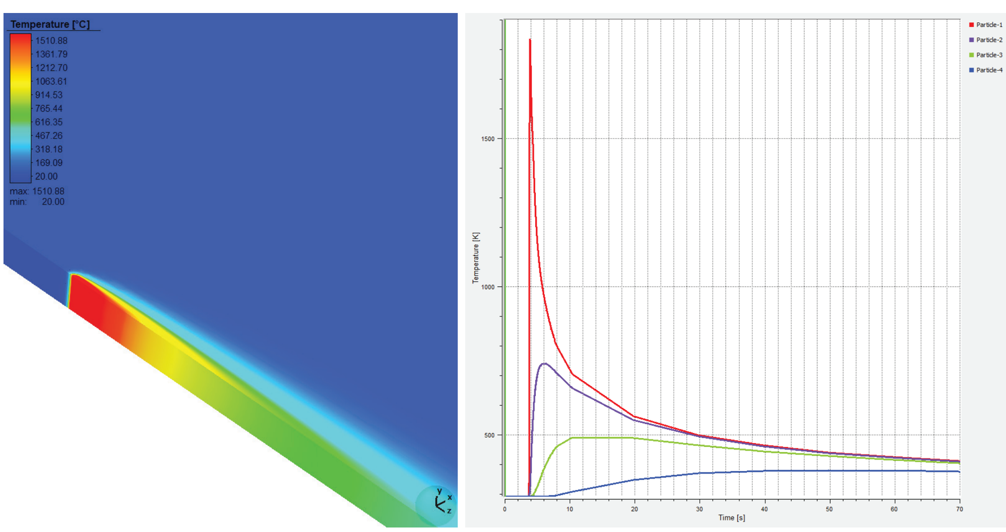
a *b*

Fig. 8. Plasma cutting of steel δ=10 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* – model of the process; *b* – thermal cycles



a *b*

Fig. 9. Laser-plasma cutting of steel δ=5 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* – model of the process; *b* – thermal cycles



a *b*

Fig. 10. Laser-plasma cutting of steel δ=10 mm (isotherms are taken at a distance of 1.25, 5.0, 12.5 and 30 mm from the edge of the cut): *a* – model of the process; *b* – thermal cycles

Table 3

Forecasted results of the parameters of the regimes of laser (with oxygen), air-plasma and hybrid laser-plasma cutting, ensuring parallel cutting edges with a minimum size of HAZ

Steel sheet thickness δ, mm	Cutting method	Heating spot dia. d, mm	Cutting speed V, mm/s	Current I, A	Heat source power, W	Heat input $E_{\Sigma}=E_{las}+E_{pl}$, J/mm
5	Laser	0.4	35,0	–	1,700	$E_{las}\approx 50$
	Plasma	~3.0	33.33	100...120	8,000...10,000	E_{pl}=240...300
	Hybrid	~2.5	66.67	100...120	10,000...12,000 (1,700+8,000...10,000)	E_{Σ}=150...180
10	Laser	0.4	18.33	–	2,000	$E_{las}\approx 110$
	Plasma	~3.0	13.33	140...160	10,000...12,000	E_{pl}=750...900
	Hybrid	~2.5	33.33	140...160	12,000...14,000 (2,000+10,000...12,000)	E_{Σ}=360...420

7. Discussion of results of forecasting the laser-plasma cutting of structural carbon sheet steels

As can be seen from a comparison of the obtained linear energies of the laser, plasma, and hybrid processes (Table 3), the selected parameters of the laser-plasma cutting mode provide approximately half the energy input than the air-plasma cutting process. This, accordingly, makes the process under consideration more promising. At the same time, this indicator of laser-plasma cutting is approximately three times higher than the energy input of the gas-laser cutting process which casts doubt on the possibility of replacing laser cutting with a hybrid one. However, literature data, for example [15], argue that laser-plasma cutting can significantly increase the processing speed compared to laser cutting without compromising the quality of the cut. In all likelihood, with an increase in the speed of hybrid cutting by about 2–3 times, its energy input is equal to that of gas laser cutting. Moreover, the performance of the first is no less than 3 times higher than the performance of the second. It can be suggested that to improve the results of hybrid cutting including further reducing the size of the HAZ by increasing the cutting speed, it is advisable to increase the flow rate and pressure of the working gases (argon and oxygen).

The fundamental possibility and prospects of using a hybrid laser-plasma process for cutting sheet metal materials are associated with the emergence of a synergistic effect, which consists of three main aspects:

– additional compression of the direct-acting plasma arc by improving the breakdown conditions in a narrow plasma plume arising from the action of laser radiation on the metal and consisting of ionized vapors of the base metal and plasma-forming gas;

– elimination of the effect of wandering of the anode spot due to the «binding» of the anode region of the plasma arc to the zone of action of the focused laser beam;

– improving the absorption of laser radiation by the base metal due to its heating by a direct-acting plasma arc.

Moreover, according to dependences (1) to (5), the most suitable range of I/d values is $I/d\leq$30...40 A/mm which for currents of the order of I=80–200 A corresponds to the inner diameter of the nozzle d=2–5 mm.

To implement the laser-plasma cutting process, an original design of an integrated plasmatron was proposed based on the coaxial arrangement of the laser radiation axis and the lateral placement of ∅4.0 mm tungsten cathodes at angles of up to 35° (Fig. 1). Operability of this design is based on continuous protection of a non-consumable tungsten electrode (cathode) with an inert plasma-forming gas (argon). In this case, cutting becomes possible due to the supply of active cutting gas (oxygen) directly into the plasma forming nozzle. The main parameters of this plasmatron are as follows: laser radiation power: up to 5.0 kW, cutting current: up to 200 A (at a voltage of up to about 100 V).

For computer simulation of the processes of laser, plasma and laser-plasma cutting of carbon steels performed using the designed integrated plasmatron, the finite element method was used. For this, the heat source was presented in the form of a double ellipsoid (Fig. 3). The condition of thermal equilibrium (6) allows us to determine temporary changes in temperature within each element. The cut is modeled as a linear heat source created by the heat flux (8) acting for a period of time (7) on the corresponding point on the surface of the cut plate.

As a result of calculations using the SYSWELD software package, temperature distribution in the edges of the cut and the thermal cycles of the processes of laser (Fig. 5, 7) and plasma (Fig. 6, 8) cutting were determined. The results obtained were compared with published data [1–6, 11–12]. It was found that the data obtained coincide with the literature with an accuracy of 10 %, which is acceptable in technological calculations.

Then, similar calculations were performed for the laser-plasma cutting process (Fig. 9, 10) which has made it possible to forecast parameters of cutting regimes for 5- and 10-mm thick carbon steel (Table 3). To verify the results of the forecast, corresponding experiments were carried out using the integrated plasmatron shown in Fig. 2. As a result, it was found that the data forecasted coincide with the experimental data with an accuracy of 10 %. This allows us to recommend them as a guide when choosing technological modes.

The results obtained are valid in conditions of using laser radiation with a power of up to 2.0 kW in combination with a direct current plasma current of up to 200 A. Moreover, the design of the integrated plasmatron proposed in the work allows the use of radiation with a power of up to 5.0 kW. With further development of this study, the question of the feasibility of increasing the power of laser radiation will be studied.

This study is primarily a scientific forecast. The experiments, in general, confirm the correctness of the results obtained. However, to clarify the impact of parameters of the laser-plasma cutting mode on the results obtained, a significant amount of technological research is required.

8. Conclusions

1. The manifestation of the synergistic effect in the hybrid cutting of carbon steel sheets with a thickness of 5 mm or more with a ratio of laser and plasma powers from 1:1 to 1:3 provides an increase in productivity (2–3 times compared with plasma

cutting) which makes it promising for industrial applications. Laser-plasma cutting makes it possible to minimize heat input into the metal being cut and at the same time obtain a sufficiently accurate high-quality cut at a relatively low cost per meter.

2. The designed integrated plasmatron is calculated for radiation power up to 5.0 kW and current up to 200 A. Minimization of laser radiation losses and maximum penetration in it are achieved through the use of a coaxial configuration. In this case, the axial arrangement of laser radiation is combined with the minimum inclination of non-consumable electrodes with distance from the working end of which to the axis of the laser beam lies in the range of 2–3 mm. The diameter of the plasma-forming nozzle lies in the range of 2–5 mm and the focus deepening under the surface of the cut sheet during hybrid cutting is 1–2 mm.

3. A computer simulation was performed using the SYSWELD software package. The regime parameters were selected according to the criteria for minimizing the HAZ value and approximating the cut quality to the laser one. It was found that hybrid laser-plasma cutting of structural carbon steels with a thickness of 5 and 10 mm is advisable to carry out at speeds of 240 and 120 m/h, respectively, with a radiation power of up to 2 kW and currents from 100 to 160 A (power ratio approximately 1:1). The use of the SYSWELD software package was made possible by taking into account the characteristic of the cutting effect of removing sections of molten material in the cutting zone performed by replacing the maximum superheat temperature with an initial one (20 °C) during the calculation. In this case, the heat source acting during the cutting process was considered linear, cylindrical, uniformly distributed over the height of the cut plate with a diameter corresponding to the diameter of the heating spot of the corresponding type of thermal cutting.

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– No. 2018A050506058 Research and Application of Hybrid Laser and Arc Welding Technology with High Power on High Strength Steel for Shipbuilding.

References

1. Lee, M.-H., Yang, W., Chae, N., Choi, S. (2019). Aerodynamic diameter distribution of aerosols from plasma arc cutting for steels at different cutting power levels. Journal of Radioanalytical and Nuclear Chemistry, 323 (1), 613–624. doi: https://doi.org/10.1007/s10967-019-06967-y
2. Asmael, M., Cinar, Z., Zeeshan, Q. (2018). Developments in Plasma Arc Cutting (PAC) of Steel Alloys: A Review. Jurnal Kejuruteraan, 30 (1), 7–16. doi: https://doi.org/10.17576/jkukm-2018-30(1)-02
3. Pramanik, D., Kuar, A. S., Sarkar, S., Mitra, S. (2020). Effects of Cutting Angle on Multiple Quality Characteristics for the Micro-cutting of Thin 316L Stainless Steel Using a Low Power Fiber Laser. Lasers in Engineering, 45 (1-3), 109–131.
4. Sheng, Z., Guo, X., Prahl, U., Bleck, W. (2020). Shear and laser cutting effects on hydrogen embrittlement of a high-Mn TWIP steel. Engineering Failure Analysis, 108, 104243. doi: https://doi.org/10.1016/j.engfailanal.2019.104243
5. Skoczylas, A., Zaleski, K. (2019). Effect of Centrifugal Shot Peening on the Surface Properties of Laser-Cut C45 Steel Parts. Materials, 12 (21), 3635. doi: https://doi.org/10.3390/ma12213635
6. Jović, S., Radović, A., Šarkoćević, Ž., Petković, D., Alizamir, M. (2016). Estimation of the laser cutting operating cost by support vector regression methodology. Applied Physics A, 122 (9). doi: https://doi.org/10.1007/s00339-016-0287-1
7. Ghosh, S. K., Beitialarrangoitia, J. C., Douglas, S. S. (1993). An automatic process-planning strategy applied to a flexible two-dimensional cutting facility. Journal of Materials Processing Technology, 37 (1-4), 61–81. doi: https://doi.org/10.1016/0924-0136(93)90081-g
8. Petunin, A. (2019). General Model of Tool Path Problem for the CNC Sheet Cutting Machines. IFAC-PapersOnLine, 52 (13), 2662–2667. doi: https://doi.org/10.1016/j.ifacol.2019.11.609
9. Khaskin, V., Korzhyk, V., Bernatsky, A. et. al. (2018). Analysis of features of technological schemes of processes of laser-plasma cutting and welding. Austria-science, 20, 34–43.
10. Krivtsun, I., Khaskin, V., Korzhyk, V. et. al. (2019). Analysis of the main mechanisms and regularities of the synergistic effect in hybrid laser-arc processes. Colloquium-journal, 18 (42), 10–20. doi: https://doi.org/10.24411/2520-6990-2019-10596
11. Masoudi, S., Mirabdolahi, M., Dayyani, M., Jafarian, F., Vafadar, A., Dorali, M. R. (2018). Development of an intelligent model to optimize heat-affected zone, kerf, and roughness in 309 stainless steel plasma cutting by using experimental results. Materials and Manufacturing Processes, 34 (3), 345–356. doi: https://doi.org/10.1080/10426914.2018.1532579
12. Gadallah, M. H., Abdu, H. M. (2015). Modeling and optimization of laser cutting operations. Manufacturing Review, 2, 20. doi: https://doi.org/10.1051/mfreview/2015020
13. Gvozdetskiy, V. S., Krivtsun, I. V., Svirgun, A. A., Chizhenko, M. I. (1990). Raschetnaya otsenka vliyaniya lazernogo izlucheniya na harakteristiki plazmy stolba dugi v kanale sopla. Avtomaticheskaya svarka, 8, 8–14.
14. Rayzer, Yu. P. (1974). Lazernaya iskra i rasprostranenie razryadov. Moscow: Nauka, 308.
15. Krivtsun, I. V. Gibridnye lazerno-dugovye protsessy svarki i obrabotki materialov (obzor). Available at: https://studfile.net/preview/428483/
16. Steen, W. M. (1980). Arc augmented laser processing of materials. Journal of Applied Physics, 51 (11), 5636–5641. doi: https://doi.org/10.1063/1.327560

17. Utsumi, A., Matsuda, J., Yoneda, M., Katsumura, M. (2002). Effect of base metal travelling direction on TIG arc behaviour. Study of high-speed surface treatment by combined use of laser and arc welding (Report 4). Welding International, 16 (7), 530–536. doi: https://doi.org/10.1080/09507110209549571
18. Cho, W.-I., Na, S.-J. (2007). A Study on the Process of Hybrid Welding Using Pulsed Nd:YAG Laser and Dip-transfer DC GMA Heat Sources. Journal of Welding and Joining, 25 (6), 71–77. doi: https://doi.org/10.5781/kwjs.2007.25.6.071
19. Goldak, J. A., Akhlaghi, M. (2005). Computational welding mechanics. Boston. doi: https://doi.org/10.1007/b101137
20. Bofang, Z. (2018). The Finite Element Method: Fundamentals and Applications in Civil, Hydraulic, Mechanical and Aeronautical Engineering. John Wiley & Sons Singapore Pte. Ltd. doi: https://doi.org/10.1002/9781119107323

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EFFECT OF THE TOOL GEOMETRY ON THE FORCE MODE OF THE COMBINED RADIAL-DIRECT EXTRUSION WITH COMPRESSION

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Досліджено можливості використання енергетичного методу для розрахунку енергосилових параметрів процесів холодного видавлювання деталей складної конфігурації. Запропоновано математичну модель процесу комбінованого послідовного радіально-прямого видавлювання з обтисненням з наявністю трикутних кінематичних модулів. Використання кінематичних модулів трикутної форми з криволінійними та прямолінійними межами дозволило описати осередки інтенсивної деформації, що відповідають сталій стадії процесу деформування. Запропоновано використовувати верхню оцінку потужності сил деформування кінематичного модуля трикутної форми зони переходи від радіальної течії металу до прямого видавлювання. Це дозволило отримати величину приведеного тиску деформування в аналітичному вигляді як функцію від геометричних та технологічних параметрів процесу видавлювання. Похибка у порівнянні із чисельними розрахунками без застосування верхньої оцінки не перевищує 0,2–1 %. Роль параметру оптимізації відіграє $a \in (0,1)$, що відповідає за форму криволінійної границі внутрішнього трикутного кінематичного модуля. Отримано аналітичний вираз оптимального значення параметра α та проаналізовано змінення величини приведеного тиску деформування за різних співвідношень геометричних параметрів процесу. Встановлено, що оптимальне значення кута нахилу твірної оправлення β знаходиться в межах від 20° до 30° для різних співвідношень процесу деформування.

Обґрунтовано, що використання комбінованого послідовного видавлювання при виготовленні порожнистих деталей з фланцем, у порівнянні з використанням простих схем деформування, підвищує технологічні можливості процесу. Підтверджено недостатню вивченість схем процесу комбінованого радіально-прямого видавлювання з обтисненням деталей типу втулка та брак рекомендацій щодо розрахунку енергосилових параметрів процесу. Розроблена на основі енергетичного методу розрахункова схема даного процесу дозволяє прогнозувати силовий режим для сталої стадії для різних технологічних параметрів процесу деформування. Отримані дані щодо оцінки оптимальних параметрів конфігурації інструменту сприятиме розробці відповідних конструкторсько-технологічних рекомендацій

Ключові слова: комбіноване видавлювання, верхня оцінка, кінематичний модуль, енергетичний метод, процес деформування, деталі з фланцем

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1. Introduction

Cold extrusion processes provide high surface quality and precise sizes of stamped blanks and components. This, in turn, reduces or eliminates the need for additional machining by cutting [1, 2]. The most common conventional extrusion techniques are the longitudinal (inverse and direct) extrusion methods, which are characterized by the flow of the