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FEATURES OF USING AIR-PLASMA CUTTING TECHNOLOGY FOR MANUFACTURING OF HELICAL FLIGHTS AND AUGER BILLETS

Vasyl Vasylkiv

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *The features of manufacturing helical flights and auger billets, implemented by air-plasma cutting in a spiral of thick-walled tubular and piece hollow blanks are described in article. It allows to obtain such blanks from high-alloy, corrosion-resistant and heat-resistant steels, the processing of which is difficult by pressure and cutting. The conditions for the rational use of such technologies are determined.*

Key words: *manufacturing, helical flight, auger billet, air-plasma cutting, shaping scheme, cost.*

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Statement of the work. In modern production, machine parts such as screws, which are obtained from helical flights (HF) and auger billets (AB), are becoming more and more widely used. The mentioned auger billets can be one-piece (when the helical spiral is constructed together with the shaft on which it is placed) or combined (when the helical flight is fixed to the shaft by welding, gluing, etc.) [1].

Nowadays, the machine building industry has a significant range of versions of technological processes for the manufacture of HF and AB by forming processing [2–11] and machining [5, 7, 12–16], casting of metals and alloys [5, 17], welding [2, 5], assembling [2, 5], molding from polymeric materials, ceramics and rubber [5, 18], powder metallurgy [5], as well as a combination of such technologies [18, 19]. However, in some cases, economically and technologically their use is impractical. For example, in the process of producing AB by milling cylindrical workpieces from high-strength materials, considering the low rigidity of the tool used (small-diameter end mills) and the cutting flights, the processed screw surface is crushed. The use of stamping, winding and rolling methods is limited by the requirements for the physical and mechanical properties of the material (shaping is possible only from highly ductile materials). The technological equipment of machine-building enterprises does not always allow for the implementation of high-performance methods, such as strip rolling, simultaneous continuous casting with rolling of molten metal [17], etc.

Analysis of available investigation results. Plasma cutting of various materials is one of the most advanced methods of manufacturing. Despite the fact that this technology was invented more than 100 years ago, it was widely used in mechanical engineering only more than 30 years ago [20, 22]. It is actively used to cut tubular products and for cutting machine elements from rolled sheet metal.

Among the plasma cutting methods, air-plasma cutting (APC) technology is becoming increasingly widespread. Compared to other thermal cutting methods, it provides the following advantages: insignificant thermal deformation of the processed material; high cutting speed for metals up to 50 mm thick; the quality of work is practically unaffected by the main defects of the metal product (rust, dirt or paint) and the mirror properties of certain steels; improved surface quality without efflorescence, significant mill scales and over-hardening; the ability to implement the technology in various conditions, with products placed in any spatial position [21–24]. This process is characterised by such indicators as the flow rate (pressure) of the

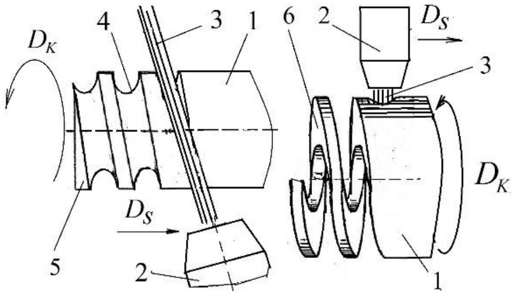
Corresponding author: Halyna Oliinyk; e-mail: galina_olijnyk@ukr.net

plasma-forming medium, cutting current, arc voltage, distance between the material surface and the nozzle tip, cutting speed and thickness of the material. The influence of these parameters on the performance of this technology and the quality of the surfaces obtained when cutting various steels, as well as the optimisation of such processes and the use of CNC systems for their implementation, are considered in [20–27].

APC is an effective new method of forming HF and AB. It can be carried out using a plasma arc or a plasma jet. In both cases, the process of such cutting involves simultaneous melting and removal of the molten material from the cutting cavity by an air-plasma flow. At present, this technology is widely used only for cutting sector ring billets from rolled sheet metal in the production of sectional HF [10]. The research [18] conceptually describes the prospects for using APC to produce HF and AB. However, there is lack of sources on the application of such a process for shaping the above-mentioned billets from tubular products and initial hollow blanks.

The aim of the investigation is to investigate the peculiarities of implementing new methods of manufacturing HF and AB based on the use of APC processes.

Statement of the problem. The production of a AB is carried out by air-plasma cutting of a part of the material along a helical line from the surface of an artificial workpiece with the formation of a helical groove using an air-plasma flow tangent to a concentric surface that bends around the profile valley of such a helical groove (Fig. 1, a) [28]. When using the round shape of the plasma torch nozzle outlet, depending on the penetration rate and the angle of inclination of the air-plasma flow relative to the workpiece axis, it is possible to obtain such workpieces mainly with a round, ellipsoidal, or parabolic cross-sectional profile of the helical groove. For the shaping of the HF, the through air-plasma cutting of the wall of a hollow blanks is carried out along the helical line using an air-plasma flow located in a plane that passes through the longitudinal axis of such a workpiece (Fig. 1, b) [29]. In both cases, the displacement along the helical line is obtained as a result of the implementation of the kinematic sum of the rotational motion D_K of the workpiece and the linear displacement D_S of the air-plasma flow or the workpiece.



a b

Figure 1. Scheme of shaping a AB (a) and a HF (b): 1 – artificial workpiece, 2 – plasma torch, 3 – air-plasma flow, 4 – helical groove, 5 – auger billet, 6 – helical flight

In this investigation, the above-described methods of shaping the above-mentioned workpieces are the **object** of research.

Results of the research. It is advisable to use these methods when producing HF and AB from hollow blanks, as well as from a special type of thick-walled tubular steel, which, according to GOST 8734-75, is characterised by the ratio of the outer diameter to the wall thickness in the range from 3 to 12.5. Regulatory documents governing the structural parameters of thick-walled steel pipes: DIN 2448, DIN 17175, DIN 17121, ASTMA335/A335m**,** EN 10210-1,2 EN 10216-(1-4), GOST 8734-75, GOST 8732-78, TU 14-161-184-2000, TU 14-3R-44-2001, etc.

In modern production, screw products are mostly made from materials such as St3, 10kp, 65g, 08kp, 12H18N9T, 12H18N12T. When using this method, the HF and AB can be produced from a wide range of materials that is used to make the above-mentioned thick-walled steel pipes. Examples include carbon steels of grades 10, 20, 20H; alloy steels of grades 09G2S, 30HGSA, 30HGS, 14331, 15H5M, 501, 502, K41545, etc. Thus, there is a possibility of wider use of steels with anticorrosive properties (09G2S, 13Mn6, 9MnSi5) in the construction of screw products. For example, high-quality HF with different pitches T of flights, heights B of flights from 44 to 50 mm and outer diameters of 164 mm, 351 mm, 377 mm, 408 mm, 430 mm, 450 mm, 485 mm and 555 mm can be manufactured from 20, 09G2S, 45, 40H, 30HGSA and other steels.

According to the cross-sectional shape, the pipes can be divided into round, rectangular, square, oval and other types. They can be used to produce HF and AB with the outer edge of flights of the appropriate shape. The use of special hollow blanks significantly expands the range and sizes of the obtained screw products.

Experimental studies have shown that it is impractical to manufacture HF and AB from copper, aluminium and their alloys using the APC method. Since these materials have high thermal conductivity and heat capacity, they require a more powerful arc than steel cutting. For example, APC of a hollow copper billet produces excess metal (burrs) at the edges of the helical spiral. In addition, for shaping spirals with a flight height B of 30 mm to 60 mm, the cutting speed is very low, and its numerical value is in the range of 0.3 m/min to 0.7 m/min. Brass is cut at a 20–25% higher speed. Good quality of the surface of the flights is usually achieved only in the case of producing a HF from $B \leq 30$mm aluminium with a current of 200A. In general, it is possible to produce screw products from aluminium and aluminium-based alloys with $B \leq$ 120 mm, and copper products with $B \leq 80$mm. In addition, in the process of manufacture of copper and aluminium HF, it is necessary to use a special plasma-forming medium (nitrogen or nitrogen-hydrogen and argon-hydrogen mixtures). It is also economically unreasonable to use the proposed technology for the manufacture of HF and AB from general-purpose steels (A284Gr.D, A57036, A573Gr.58, K02701, A283A, A366, materials in accordance with DSTU2651-94), structural carbon steels (A568M, 1008, 1010, G10080, G10100, A619, A622, 1045 and their analogues in accordance with GOST1050-88, GOST9045-93), and steels that have increased and high machinability (4135, G41350, 1120, 4137405, MT405, S40500, steels in accordance with GOST1414-75). Helical flights and auger billets made from such materials need to be manufactured using less energy-consuming methods (winding, stamping, rolling, cutting). Therefore, this technology should be used for the manufacture of HF and AB from steels that are difficult to process by pressure and cutting. Such materials include low- and high-alloy, corrosion-resistant, heat-resistant steels and alloys (309, GH2036, N06025, NiCr20Ti, MT309S, 15H12WMF, 11562, 30HGSNA, steels in accordance with GOST 5632-72). The possibilities of manufacturing high alloy high-strength (maraging) steels, such as N18K9M5T, N12KH15M10, N10KH11M2TU, are also expanding.

Plasma cutting of metal is carried out using equipment consisting of a current source, a unit of equipment, a manual or mechanized plasma torch, and equipment to ensure the movement of the plasma torch relative to the billet along a helical line (lathes with the plasma torch on a caliper). The plasma-forming and cooling compressed air at a pressure of 3.5–6.0 atm can be obtained from an individual compressor or from an existing workshop pipeline.

Figure 2. Overall view of a HF

In the producing of HF, a plasma torch or a protective casing is placed in the cavity of the billet to prevent the cut products from entering the inner edge of the produced spiral. The distance between the plasma torch nozzle and the billet should not exceed 10–15 mm and be constant, as it affects the angle of inclination of the helical surfaces of the flights: the greater is the angle, the greater is the angle of inclination of the helical surfaces.

To produce a HF, first it is necessary to cut a rectilinear groove on a fixed workpiece that is tangent to the helical line of the flight placement. Its depth is equal to the height of the flight. The groove is formed by simultaneously reducing the cutting speed and moving the plasma torch vertically, inclining it at an angle to the longitudinal axis of the workpiece along the direction of the helical line. For this purpose, it is necessary to reduce the consumption of plasma gas by 20–30%. After the groove is formed, the workpiece is rotated and the plasma torch is moved longitudinally along the workpiece axis. When producing a HF (Fig. 2), the process of plunge milling from the end of the hollow blank leads to springing of the HF and thus complicates the process of further cutting. Therefore, such plunge milling should be performed by forming on the workpiece wall a through hole, remote from its end. In the case of such a hole produced by the APC method, its diameter is larger than the width of the cut, i.e. the distance between the flights.

The minimum pitch of the HF is equal to the sum of the cutting width and the thickness of the flight. In this case, the cutting width is calculated as follows

$$l = 1,6 K_{Tc} d_{noz} ,$$

where d_{noz} is the diameter of the plasma torch nozzle, and K_{Tc} is the material coefficient, which takes into account the type of material and the pitch of the screw line.

For example, in the manufacture of HF with a coil height of 35 mm to 50 mm from 12H18N10T steel, if a nozzle with a diameter of 3 mm is used, for a current of 290–310A, voltage of 180–200V, the air consumption Q is 50–60 l/min, the cutting speed is 0.5–0.7 m/min, and the distance between flights will not exceed 5–7 mm. The minimum cutting width for B=20 mm is 2.5 mm.

In general, with an increase in the numerical values of welding current and voltage, the height of the nozzle above the cut surface and a decrease in cutting speed, the overall width of the cut increases, therefore, the depth of the helical groove increases, and with the increase in the flow rate of the plasma-forming gas, the depth of the helical groove decreases.

In the process of APC of certain structural steels, an increase in nitrogen in the layers adjacent to the cut surface is observed (up to 0.33% with a nitrogen content of 0.018% in the source metal). When such spirals with a thickness of less than 12 mm are subsequently welded to the shaft, pores and fistulas appear under the flux layer. This phenomenon is not observed for other welding methods. In addition, on the inner edge of the flights on the surfaces of HF from structural steels, especially high-carbon steels (C>0.3%), quenching structures may appear, and in billets from chromium-nickel steels, carbides may be formed, if the steel does not contain stabilising elements. On the edges of aluminium alloy flights, the metal has a dendritic structure; foreign inclusions in the form of gas bubbles are observed. When cutting HF with a flight height of 50 mm, the total length of the heat affected zone is 1.5–2 mm for high-alloy steel (12H18N9T) and 6–7 mm for low-carbon and low-alloy steels.

The maximum cutting speed, depending on the current strength and flight parameters, can be determined by the formula

$$\mathrm{V}_{HF} = 140 I K_M K_{TM} B^{-1}, \quad \mathrm{V}_{AB} = 140 I K_M K_{TM} \Big/ \sqrt{T^2 + \left(0,5D\right)^2 - \left(0,5d\right)^2} ,$$

where V_{HF} and V_{AB} are the cutting speeds, respectively, for obtaining the HF and AB, mm/min; I – current intensity; K_M – coefficient that takes into account the material grade: for carbon steels K_M = 0.9...1.0, for aluminium alloys K_M = 0.6, for copper alloys K_M = 0.4, for heat-resistant steels K_M = 0.8; K_{TM} – coefficient that takes into account the size of the flight pitch and the consumption of plasma-forming gas (K_{TM} = 0.8...0.9); D, d – diameters of the outer and inner edges of the flight, respectively.

Fig. 3 shows the results of studying the effect of the APC rate on the formation of the profile of the cross-section of the flights of the HF and AB for of placing the air-plasma flow in a plane passing through the longitudinal axis of such a billet. The figure shows that this method provides the following results:

a) AB with a significant roughness of the screw surfaces due to the failure to cut through the hollow workpiece from the inner edge of the flights (C);

b) HF with a cross-sectional profile in the form of: a trapezoid with convex curved (D) and straight (E, F) sides, but with different volumes of inter-flight space; a rectangle (G); an inverted trapezoid with curved convex sides (H).

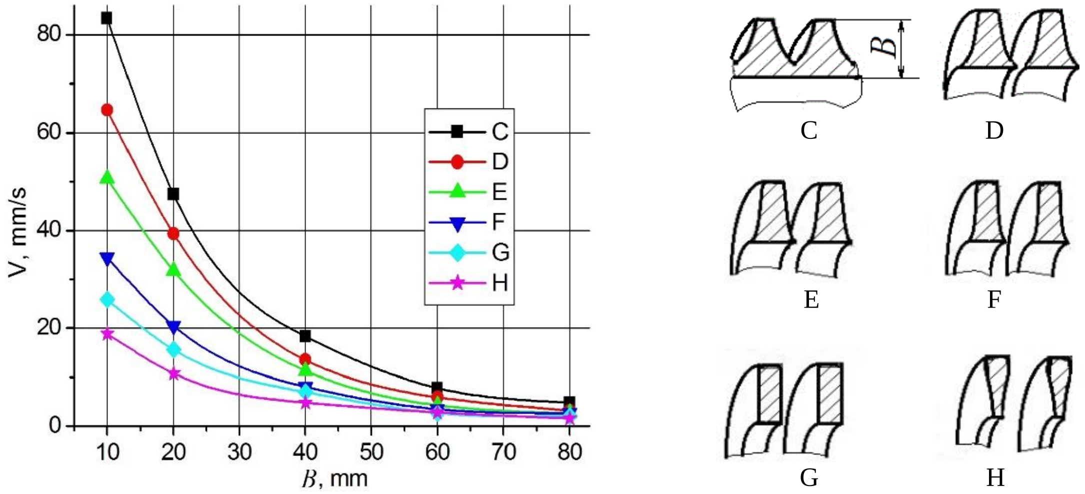


Figure 3. Dependence of the cutting speed of a hollow blank made of low-carbon steel on the height and shape of the cross-sectional profile of the HF and AB flights (I = 300A, Q = 90-120 l/min., d_{noz} = 3 mm)

In order to obtain a AB, the plasma torch movement speed must exceed the speed of the cutting cavity formation by the full wall thickness of the workpiece, causing the metal not to be cut through. In the area between the curves C and D, the possibility of double arc formation increases. Profile D is characterized by the presence of a great depth of the cast area of the heat affected zone. As the cutting speed is limited (pos. E and F), the quality of the billets improves, although energy and material consumption increases and cutting performance decreases. The rates in the zone between F and G ensure practical parallelism of the side helical surfaces of the flights (at cutting speeds 1.5-2.5 times lower than the maximum); this reduces the roughness of such surfaces and the HF can be used without additional machining. However, right angles of cut are always positioned to the right in the direction of the helical movement of the cutter. The flame that extends beyond the lower plane of the processed material is 15 to 20° behind the vertical axis. The formation of HF with a profile H and a flight height of more than 40 mm is caused by different penetration and milling rate of the outer and inner edges of the hollow blanks. In this case, at low plasma torch movement speeds, the width of the cut cavity increases, the quality of helical surface formation decreases, and the probability of double arc formation increases.

If the optimal cutting conditions are not observed, the HF and AB may form influxes in the form of small rollers and metal droplets along the lower edges of the flights.

We studied the cost of manufacturing HF depending on the height of the flight for two types of production: v (flight length up to 50 m) and mass (flight length up to 2000 m) (Fig. 4) for two types of materials (carbon structural quality and alloy steels (steels 45, 18H2N4VA, 20H) (material group 1) and corrosion-resistant (stainless) steels (AISI 321, AISI 316Ti) (group 2). The cost of the work consists of the cost (P1, P2) of preliminary punching of the hole and the cost (Q1–Q4) of cutting one flight with an outer edge length of 1 m. The figure shows: Q1 and Q2 – the cost of manufacturing a HF from steels of the first group for one-off production and mass production, respectively; Q3 and Q4 – the cost of manufacturing a HF from steels of the second group for one-off production and mass production, respectively; P1 and P2 – the cost of one burning of a hollow billet made from steels of the first and second groups, respectively.

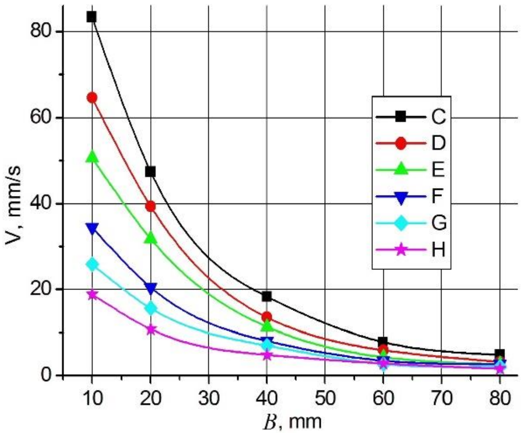


Figure 4. Dependence of the cost of manufacturing of the HF on the height of the flight for different types of production and different materials

Figure 4 shows the feasibility of using the discussed technology in different types of production facilities due to the low cost of work. The cost of such a APC is on average 4 times lower than laser cutting. At the same time, the production of the above-mentioned HF and AB from both groups of materials in mass production is 20–25% cheaper than in one-off production. The cost of producing HF in both types of production from stainless steels is 49–52% higher than when they are produced from materials of the first group. Thus, the process of producing such flights and billets from stainless materials in one-off production has the highest cost, and the production of such flights and billets from Group I steels in mass production is the cheapest. The cost of burning steels from the first group in mass production is 25–64%, and in one-off production it is 18-48% of the cost of producing 1 m of outer flight edge. Similarly, the cost of burning materials of the second group in a single-unit production ranges from 18% to 64% and in a mass production it ranges from 24% to 85% of the cost of producing 1 m of the outer edge of a flight. It happens due to the difficult conditions of burning the hole, the duration of the process and the intensive operation of the expensive plasma torch nozzle caused by contact with molten metal. Therefore, in order to reduce the cost of implementing such a process when producing HF with $B \geq 20$ mm, it is desirable to carry out a technological transition by pre-drilling or milling a special hole. The air-plasma flow is then directed into such a hole at the initial stage of the APC. Obtaining such a hole by cutting materials using a blade tool can significantly reduce the runout of expensive nozzles and electrodes due to the absence of a technological transition of burning the hole.

The quality and accuracy of products manufactured by the APC method from structural carbon steels, stainless steels or aluminium alloys with a thickness of 5...60 mm are regulated by GOST 14792-80. However, modern equipment and cutting methods make it possible to produce HF and AB with quality and accuracy indicators higher than those set by this standard. The quality of the side surfaces of the spirals is characterised by 3–4 classes of angles of cut according to ISO9013. Taking into account GOST14792-80, the roughness of the formed helical surface as a cutting surface can be determined by measuring the height of profile irregularities at 10 points on a base length of 8 mm. When using CNC equipment that provides a constant cutting speed and positioning accuracy of up to 0.1 mm, the roughness of the side surfaces of the flights Rz=160...300μm can be achieved. Under rational cutting mode, the resulting billets are characterized by a slight darkening of the cut edge, a shallow thermal heating zone, the absence of burr, spit and deep hardening of the cut edge (no more than 1 mm from the cut edge). In some cases, further machining of screw surfaces is required.

Conclusions. The paper proposes new technological methods for obtaining HF and AB based on the use of the processes of APC of thick-walled tubular and artificial hollow workpieces. The peculiarities of their implementation are described. In particular, the

inexpediency of using this technology in the manufacturing of the above-mentioned flights and billets from non-ferrous metals and their alloys, as well as general-purpose steels, structural carbon steels, and steels of increased and high machinability is substantiated. It has been shown that APC is effective in the processing of materials (high-strength, corrosion-resistant, heat-resistant and heat-resistant steels and alloys), the processing of which by pressure and cutting is difficult. The results of a study of the influence of cutting speed on the shape of the cross-sectional profile of the flights of the above-mentioned HF and AB are presented. A study of the cost of the production of one flight of HF, the length of the outer edge of which was 1 metre, depending on its height, for one-off and mass types of production and two types of materials (carbon structural quality and alloy steels, as well as corrosion-resistant steels) was carried out. In particular, it was found that the production of these billets from both groups of materials in mass production is 20–25% cheaper than in one-off production. The cost of obtaining HF in both types of production from stainless steels is 49–52% higher than when they are obtained from materials of the first group. The ratio of the cost of burning the above materials at the initial stage of the APC in different types of production to the cost of cutting 1 m of the outer edge of the flight was determined. The analysis of the cost of work has shown the prospects of using the considered technologies in different types of production.

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ОСОБЛИВОСТІ ВИКОРИСТАННЯ ТЕХНОЛОГІЇ ПОВІТРЯНО-ПЛАЗМОВОГО РІЗАННЯ ДЛЯ ВИГОТОВЛЕННЯ ГВИНТОВИХ І ШНЕКОВИХ ЗАГОТОВОК

Василь Васильків

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Запропоновано нові технологічні способи отримання гвинтових (ГЗ) і шнекових (ШЗ) заготовок, які базуються на використанні процесів повітряно-плазмового різання товстостінних трубних та штучних порожнистих заготовок. Описано особливості їх реалізації. Зокрема, обґрунтовано недоцільність застосування такої технології при виготовленні згаданих заготовок із міді, алюмінію та їх сплавів, а також сталей загального призначення, конструкційних вуглецевих сталей, а також сталей підвищеної та високої оброблюваності різанням. Її доцільно використовувати при виготовленні заготовок із матеріалів (високоміцних, корозійностійких, жаростійких та жароміцних сталей і сплавів), обробка яких тиском і різанням є ускладненою. Висвітлено результати дослідження впливу швидкості різання на форму профілю поперечного перетину витків згаданих заготовок. Показано, що запропонований спосіб забезпечує отримання ШЗ зі значною шорсткістю гвинтових поверхонь через непрорізування порожнистої заготовки зі сторони внутрішньої крайки витків, а також ГЗ профіль поперечного перерізу яких має форму трапеції з опуклими криволінійними, а також з прямолінійними бічними сторонами, але з різним об'ємом міжвиткового простору; прямокутника; оберненої трапеції з криволінійними випуклими бічними сторонами. Проведено дослідження вартості виконання робіт щодо виготовлення ГЗ залежно від висоти її витка для двох типів виробництв: одиничного (довжина витків до 50 м) та серійного (довжина витків до 2000 м) і двох видів матеріалів (вуглецеві конструкційні якісні та леговані сталі (сталі 45, 18Х2Н4ВА, 20Х) (група матеріалів 1) та корозійно-стійкі (нержавійні) сталі (AISI 321, AISI 316Ti) (група 2). Вартість виконання робіт складається з показників вартості (Р1, Р2) попереднього пробивання отвору та вартості (Q1-Q4) вирізування одного витка, довжина зовнішньої крайки якого становила 1 м. Зокрема встановлено, що виготовлення згаданих заготовок з обох груп матеріалів у серійному виробництві на 20–25% дешевша, ніж в одиничному. Вартість отримання ГЗ в обох типах виробництв із нержавійних сталей на 49–52% більша, ніж при їх отриманні з матеріалів першої групи. Визначено співвідношення вартості пропалювання згаданих матеріалів на початковому етапі повітряно-плазмового різання в різних типах виробництв відносно вартості вирізування 1 м довжини зовнішньої крайки витка. Запропоновано рекомендації щодо зниження вартості реалізації такого технологічного переходу. Аналіз вартості виконання робіт показав перспективність використання розглянутої технології в умовах різних типів виробництв.*

Ключові слова: *виробництво, гвинтова заготовка, шнекова заготовка, повітряно-плазмове різання, схема формоутворення, вартість.*

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