Practical usage of study results of the porous materials weldability from corrosion-resistant steels when creating stamp-welded products with desired properties

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Abstract. It is shown that a significant factor limiting the use of porous powder materials for the manufacture of die-welded products is low tensile plasticity and insufficient weldability. Porous meshing materials (PMM) made of steel 12Cr18Ni10Ti (X10CrNiTi18-10) have the necessary technological and operational properties for the manufacture of permeable die-welded elements. The conditions for the formation of a weld in PMM fusion welding are affected by the porosity and the ratio of the thermal conductivity coefficients along the thickness of the welded edges and in the direction perpendicular to the movement of the welding source. Technologies for argon-arc welding of a heat exchanger-evaporator sleeve, electron-beam welding of filter elements with a housing, which are implemented in the manufacture of preproduction models, have been developed.

Introduction

The development of modern engineering requires the creation of new power plants and devices with high efficiency coefficient and functioning reliability. The transition to more intense operating parameters of units operation made it necessary to solve a number of problems, one of which is the creation of technological processes for the manufacture of structures that provide protection from high temperatures, oxidizing environments, the ingress of mechanical particles, as well as their rational cooling.

An increase in the temperatures and speeds of energy carriers led to an increase in heat fluxes to the walls, the most effective way of cooling which is to supply gas to the boundary layer through a porous shell [1,2]. In addition, the use of devices with permeable elements makes it possible to reliably maintain the required temperature on the wall surface, reduce friction forces, and reduce or eliminate their mechanical erosion.

The desire to increase the reliability of modern pneumatic and hydraulic systems leads to increased requirements for the purity of the liquids and gases used in them. In the process of creating the design of filters, an important step is a reasonable choice of permeable elements [3,4], which should provide the necessary fineness of cleaning, have high permeability and the necessary mechanical properties in the entire range of operating temperatures and loads. At the same time, particles washed out of the permeable material during operation should not get into the cleaned media. In addition, filters must meet the requirements of corrosion resistance. In this case, the porous preforms used for
the manufacture of permeable elements of various configurations must have the necessary technological properties [5].

The effective functioning of structures largely depends on a reasonable choice of porous preforms, the type and dimensions of which are determined from the conditions of optimal compliance of their properties and the requirements for them. Porous materials include fabrics made of artificial and natural fibers [6], mesh made of metal wires, blanks obtained from metal powders [3,4,7] and fibers, perforated sheets [8] and some others.

The analysis of the structures of the units and their operating conditions has allowed us to establish that the most promising are porous materials based on metal, which have the required permeability, pore size, and high mechanical and technological properties.

The use of filter elements as blanks was found in woven mesh of corrosion-resistant steels. The fineness of cleaning liquids and gases with a single layer of a grid reaches 20...40 μm [3]. Some improvement in filtering performance can be achieved as a result of multi-layer mesh briquettes.

Studies of the stampability and weldability of woven meshes showed their low technological properties due to significant anisotropy and the movement of wires relative to each other during plastic deformation. In addition, the disadvantages of the meshes include the possibility of increasing the bore sections of the cells during sheet stamping, fusion welding and product operation.

The creation of permeable materials based on metal fibers (PFM) was of great interest, primarily due to the possibility of achieving high porosity, which can reach 0,98. Investigations of the effect of compaction parameters on the structure and properties of PFM by A.G. Kostornov and his co-workers [9]–[11] showed that these materials have high hydraulic and mechanical properties.

The data presented indicate the feasibility of using PFM blanks for the manufacture of capillary structures of heat pipes and intake devices that supply liquids against gravity or in zero gravity, as well as permeable elements with a fineness of filtration 2...10 μm. In addition, these materials with a porosity of 0,76...0,80 have a 2...6 times higher damping ability than aluminum with an equal mass-to-area ratio. Due to the high anti-vibration and sound-absorbing properties, fiber materials have found application in the manufacture of structural elements used in the operation of precision instruments, electronic equipment, machine tools and turbines. However, the lack of data on the formability and weldability of fiber materials does not currently allow us to recommend them for the manufacture of stamped products with desired properties.

Experimental studies of the hydraulic, filtering, mechanical and technological properties of porous powder materials (PPM) made of corrosion-resistant steels have shown that the main advantage of this type of permeable workpieces is the ability to retain mechanical particles up to 2 μm in size when filtering liquids and gases [3,7]. A significant factor limiting the use of PPM for the manufacture of permeable products is low formability since the elongation of these materials at break does not exceed 1,5%.

The possibility of manufacturing permeable products of large sizes and complex shapes from PPM is inextricably linked with the problem of obtaining welded structures by connecting porous elements. At the same time, the joints of the product elements must have a minimum seam width, maximum relative strength in the absence of cracks and other through defects in the seam or in the heat affected zone, and also minimal oxidation of the internal and external surfaces. The results of the study of the weldability of PPM under argon-arc welding (ARAW) showed that when the porosity of the base material is Π = 0,4...0,5 (P = 0,4...0,5), due to the presence of closed pores in them, the main defect is the through «fistula» in the weld formed during ejection metal in the process of melting. In this case, the relative strength of the butt joints does not exceed 0,7...0,9. In addition, the use of ARAW is limited, since wide seams are formed, which significantly reduce the filtration surface.

The experiments on electron beam welding (EBW) of PPM blanks using standard equipment showed the possibility of obtaining equal strength joints. However, as a result of the uneven structure characteristic of highly porous PPM, burn-throughs occur in butt welded joints in areas with large pore sizes. To obtain high-quality welds in the manufacturing process of products from PPM grade PCr18Ni15 (powder made from high alloy steel Cr18Ni15), it was proposed in [12] to use
the remaining linings from compact steel 12Cr18Ni10Ti, the melting temperature of which is lower than that of the welded workpieces.

The analysis of designs, manufacturing techniques and operating conditions of elements for cleaning from mechanical contaminants of liquids and gases [3,4,12], heat protection systems of rocket engines [3,13], shells of turbine blades of combined-cycle plants [14]–[16] and gas turbine engines [1,17,18], capillary intake devices [9], etc. showed that the porous mesh materials (PMM) made of 12Cr18Ni10Ti steel possess optimal properties. PMM is made by hot rolling in vacuum envelopes of a briquette of woven nets. These materials provide specified operational characteristics and have high mechanical [19, 20, 21] and technological properties [22], which makes it possible to produce die-welded structures with desired properties and the required configuration.

The existing results of theoretical and experimental studies in the field of pressure welding and hot rolling of multilayer sheets [22]–[25] were used to create sheet porous mesh materials.

**Research Methodology.** The difference between PMM and porous powder materials is a pronounced anisotropy of properties. The ratio of the coefficients of the effective thermal conductivity of the edges in thickness ($\lambda_\perp$) and in the direction perpendicular to the movement of the welding source ($\lambda_W$) has a significant effect on the formation of a weld under conditions of fusion welding. In addition, when welding highly porous workpieces, which are characterized by low thermal conductivity in thickness, the formation of defects of various types is possible depending on the size.

Thus, for workpieces with a high value $\lambda_W$ as a result of intensive heat removal in the sheet plane, the penetration depth decreases and the temperature gradient increases along the width of the weld pool, which, in turn, can lead to a gap in the weld during crystallization (Fig. 1). And when welding the same workpieces in the direction, which is characterized by a low value, there is no fusion of individual wires in the edges of the connected elements with the weld metal. Such defects arise as a result of the action of surface tension forces at the boundary of the molten metal of the melted wires and the weld pool.

![Figure 1](image.png)

*Figure 1.* The nature of the penetration of PMM based on P60 filter meshes with a parallel arrangement at $\Pi = 0.4$ ($P = 0.4$) in conditions of automatic argon-arc welding.
In addition, the experiments showed that for workpieces with high thermal conductivity anisotropy in the sheet plane, the width of the impermeable zone (weld) does not depend on the direction of welding, but increases with decreasing thermal conductivity in the direction of the thickness of the welded edges [22].

A study of the weldability of PMM from steel 12Cr18Ni10Ti showed that with a decrease in porosity and an increase in the ratio, the quality of welded joints increases. For the manufacture of highly porous welded structures, it is advisable to use PMM with a lower value of thermal conductivity anisotropy in the sheet plane. To this end, it is advisable to use PMM based on meshes with square cells located at an angle of 45° [22].

The study of the mechanical properties of tensile butt joints made by fusion welding made it possible to establish that with an increase in the porosity of the base material, their relative strength decreases. Improving the quality of joints of highly porous workpieces can be achieved by using special edge preparation, providing an increase in their thermal conductivity and a decrease in porosity.

One of the effective ways to improve the quality of welded joints of workpieces from multilayer PMM with a porosity of more than 20% is to seal the welded edges, which can be realized by cold deformation between the rotating rollers of the seam welding machine. The effect of edge compaction on the relative strength of butt joints was studied on PMM samples 2...5 mm thick with a porosity of 0,3...0,5. Sealing the edges provides a decrease in porosity to 0,20...0,25. The test results showed that cold deformation of the edges made it possible to increase the strength of butt welded joints made by automatic ARAW by 15...20% (Fig. 2).

![Figure 2. The effect of porosity of the base material and rolling of the edges on the relative strength of welded joints.](image-url)
The variety of parameters that determine the properties of welded joints of PMM blanks greatly complicate the ability to assess the impact of each of them on the quality of products. The choice of the optimal welding technology is based on a comparison of several options and can be most effectively carried out by analyzing mathematical models.

The rational values of the ARAW and EBW modes of butt joints are determined on the basis of communication equations obtained using the theory of similarity and the method of regression analysis. Using the obtained equations and criterion dependencies for calculating the linear energy and the width of the weld when welding compact steel 12Cr18Ni10Ti, we obtained the equations for the approximate calculation of the energy required for the formation of butt joints in EBW, as well as the width of the weld in ARAW:

\[ q / \sqrt{V_w} = 20 \cdot h_p \cdot T_M \cdot (1 - P) \cdot \sqrt{\lambda_\perp \cdot C_C \cdot \rho_C}, \]  
\[ S_S = 0.17 \cdot q / T_M \cdot (1 - P) \cdot \sqrt{\lambda_\perp \cdot C_C \cdot \rho_C \cdot V_w \cdot h_p}, \]

where \( q \) — the effective power of the welding source; \( T_M \) — the melting temperature of the material; \( V_w \) — welding speed; \( \rho_C \) — density of compact material; \( C_C \) — heat capacity of compact material 12Cr18Ni10Ti; \( h_p \) — the thickness of the blanks from PMM; \( S_S \) — the width of the seam.

Research results and discussion. The performed ARAW experiments on porous 12Cr18Ni10Ti steel workpieces made it possible to establish that high-quality welded joints can be obtained at the lowest possible current at which the weld root is penetrated. Automatic welding of butt joints with a speed of more than 30 m / h requires a process with a higher current strength, which for workpieces with porosity of more than 30% leads to the formation of undercuts in the fusion zone, and at \( V_w < 10 \) m / h the weld width sharply increases. Therefore, the optimal welding speed should be in the range from 10 to 30 m / h, and with an increase in the porosity of the workpieces, the speed decreases. To reduce the probability of undercut formation in the fusion zone, it is advisable to weld products with a porosity of more than 0.2 with filler material.

In order to reduce the width of the seam, the possibility of using pulsed argon-arc welding was investigated. The experiments showed that the pulsed mode is suitable for welding workpieces with porosity of less than 0.2, and at higher values burns and undercuts are formed. The use of filler material partially eliminates these defects, but leads to a significant increase in the width of the seam.

An analysis of the obtained dependences and the results of experimental studies allowed us to develop technological processes for manual and automatic argon-arc welding with a non-consumable direct current direct current electrode of direct polarity of structural elements with porosities from 0.05 to 0.5. The study of the dimensions of the weld joints showed that expression (2) gives overestimated values. However, it can be used for approximate calculations of the width of the tightness of the zone of welded products at the design stage.

A study of the mechanical properties of butt welded joints under uniaxial and biaxial tension made it possible to establish that with an increase in the porosity of the base material, a decrease in relative strength occurs, the value of which at a porosity of more than 20% can be described by the following empirical dependence:

\[ \sigma_W / \sigma_{Bx,y} = 1.3 - 1.5 \cdot \Pi, \]

where \( \sigma_{Bx,y} \) — tensile strength of PMM under uniaxial tension in the direction of the wire mesh; \( \sigma_W \) — the strength of the butt welded joint with the same porosity in the direction of the wire mesh.

Electron beam welding is the optimal type of welding of porous workpieces when creating filter elements for fine cleaning of liquids and gases from mechanical impurities. To develop welding
technology and study the strength of welded joints, studies were carried out in which the beam current strength, welding speed, and workpiece porosity were varied. The intervals of variation of the parameters given in Table 1, was determined based on the analysis of expression (1). The value of the relative strength of welded joints $\frac{\sigma_W}{\sigma_{BX,Y}}$ was taken as the optimization parameter.

Table 1. Main levels and intervals of variation

| Parameters       | Levels | Intervals of variation | Dimension |
|------------------|--------|------------------------|-----------|
| Beam current     | lower−1| zero 0 | upper +1 | 10 | μA |
| Welding speed    | 20     | 35     | 50     | 15 | m/h |
| Porosity         | 0.15   | 0.25   | 0.35   | 0.1 | – |

In the process of welding, the diameter of the focal spot, the magnitude of the focal length, and the accelerating voltage were not changed and were maintained respectively equal to $d_f = 0.5$ mm, $l_0 = 120$ mm, $V_f = 30$ kV. The value $\sigma_{BX,Y}$ for PMM with a porosity of 0.35 and 0.15 was 190 and 300 MPa, respectively. As a calculation model, a polynomial of the first degree was adopted, the calculation of the coefficients of which allowed us to obtain the following regression equation:

$$\frac{\sigma_W}{\sigma_{BX,Y}} = 0.804 + 0.075 \cdot I - 0.023 \cdot I \cdot V_f + 0.0057 \cdot V_f.$$

An analysis of equation (3) showed that when the porosity of the base material is less than 0.25%, an increase in the relative strength can be achieved by increasing the welding speed, and when the porosity is more than 0.25, a decrease in the welding speed leads to an increase $\frac{\sigma_W}{\sigma_{BX,Y}}$. In this case, the beam current equal to 0.45...0.65 mA, slightly affects the strength of the connection.

Metallographic studies revealed the presence of undercuts in the places where the wires are not fused with weld metal, the number of which increased with increasing porosity. The width of the welds obtained on samples with a thickness of 2.8...3.8 mm when varying the parameters of the welding mode changed insignificantly and amounted to 2.5...3.0 mm.

The study of the influence of the thermal welding cycle on the change in the hydraulic and structural characteristics of porous billets showed that the decrease in the permeability of welded joints is proportional to the weld area, while the pore sizes in the fusion zone do not change.

In the manufacture of welded structures, one must take into account the requirement of manufacturability, which is ensured by a rational choice of the workpiece material, the shape of the elements to be welded, the type of connection, the type of welding and measures to improve the quality of products. To obtain welded structures with high performance, one should strive to use PMM with lower porosity and minimal anisotropy of properties in the sheet plane.

In the case when it is necessary to obtain products from highly porous materials, an increase in the quality of welded joints can be achieved by increasing the thermal conductivity in the direction of the thickness of the edges to be welded, and if possible, using diffusion welding.

The results of the studies were used in the design and manufacture of die-welded bushings of heat exchangers-evaporators and filter elements with a given refinement and permeability.

The development of aviation and space technology requires the creation of thermal control systems for aircraft. Particularly noteworthy is the use of devices such as a heat exchanger-evaporator using a porous material in which the heat supplied to the outer surface is absorbed as a result of the evaporation of the refrigerant.
Of considerable interest for the manufacture of a permeable element (sleeve) of the heat exchanger is PM based on metal meshes. The manufacturing technology of heat exchangers-evaporators using PMM is developed in accordance with the requirements of the technical specifications, which consisted of the following:

– the design of the sleeve of the heat exchanger (Fig. 3) is a pipe made of PMM with a size of 30x2 mm and a length of 180 mm;

– the sleeve should be made of steel 12Cr18Ni10Ti;

– the power of the heat exchanger must be at least 160 watts.

To ensure these requirements, studies were conducted using sheet PMM made by welding by rolling filter meshes of plain weave P60 (GOST 3187-76) [3]. The porosity of the blanks was 0.20 and 0.45. To obtain a heat exchanger sleeve, a technology has been developed for the manufacture of welded pipes, the molding of which was performed on a rolling mill 10-60 of the design of VNIIMETMASH. Automatic ARAW of the formed continuously moving billet was carried out on a mill in a special chamber.

![Figure 3](image3.png)

**Figure 3.** The scheme of the heat exchanger-evaporator: 1 — housing; 2 — sleeve; 3 — flange.

The calibration used after welding made it possible to produce welded pipes of the required sizes (Fig. 4). The choice of the welding mode of pipes was carried out according to the results of studies of the technology of argon-arc welding of butt joints.

![Figure 4](image4.png)

**Figure 4.** Welded pipe from PMM.
The quality of the welded pipe joint was evaluated by external inspection and metallographic studies, which showed that the formation of pipes from a material with the studied porosity provides the desired geometry without breaking the welded joints of the wires, i.e. without stratification of preparations. The manufactured pipes were connected to the flanges of compact steel 12Cr18Ni10Ti manual ARAW. The sleeve thus obtained was pressed into the heat exchanger body. A general view of the heat exchanger-evaporator is shown in Fig. 5.

![Figure 5. General view of the heat exchanger-evaporator: 1 — housing; 2 — pipe from PMM; 3 — flange.](image)

The test of the obtained units was performed in laboratory conditions according to the following scheme. The tested heat exchanger was installed in the duct, in which the fans provided the required air flow. A pressure $P = 0.133$ Pa was created in the internal cavity of the heat exchanger. As a refrigerant, distilled water was used, which was supplied through channels in the heat exchanger body, where it evaporated. The capacity of the heat exchanger-evaporator was estimated by the maximum amount of completely evaporated water without the formation of ice grains.

The test results are given in table. 2, it was established that the use of PM based on metal meshes with porosity of 0.20 and 0.45 in heat exchangers allows to obtain the required power. In this case, an increase in heat exchanger power can be achieved by increasing the porosity of the sleeve material and increasing the flow rate of the refrigerant.

| Sleeve Porosity | Temperature air in front heat exchanger, °C | Air consumption, 1/s | Depth of vacuum, Pa | Power of the heat exchanger-evaporator, W |
|-----------------|--------------------------------------------|---------------------|-------------------|----------------------------------------|
| 0.20            | 40                                         | 22.5                | 0.133             | 180                                    |
| 0.45            | 40                                         | 22.5                | 0.133             | 200                                    |
| 0.45            | 40                                         | 40.0                | 0.133             | 266                                    |

The studies of weldability of PMM and the developed EBW technology of porous preforms were used in the design and manufacture of die-welded filter elements with a fineness of 10...12 microns, a sketch of which is shown in Fig. 6.
Figure 6. A sketch of the filter, providing fineness of cleaning 10...12 microns: 1 — axis; 2 — filter elements; 3 — sleeves.

Figure 7. The macrostructure of the end connection of the filter elementsx40

The technological process for the manufacture of filters includes EBW of porous elements with an axis, sleeves and between each other. Filter elements were made by sheet stamping PMM with a thickness of 0,5 mm and Π=0,45 (P = 0,45), obtained by welding by rolling nets with square cells, the size of which was a = 0,04 mm (GOST3826-82), located at an angle of 45°. Porous preforms after ultrasonic cleaning in freon were installed in special devices that ensure the assembly of welded elements and their rotation.
Welding was carried out at a current of 5...6 mA at an accelerating voltage of 50 kV with a focal spot diameter of 1 mm. The welding speed was 6.3 m / h when connecting the filter elements with the axle and sleeves, and 22 m / h between them. Figure 7 shows the macrostructure of the welded end joint of the porous elements. The quality control of welded joints of the filter under hydrostatic testing showed that the probability of obtaining a defect-free welded joint is 0.96.

Conclusion
1. The weldability of porous materials is determined by the chemical composition, shape, size of the structural elements and porosity of the welded edges. With increasing porosity and particle size of the powder, the mechanical properties of the PPM decrease, and the ranges of fusion welding, characterized by cracking, expand.

2. It has been established that during PMM fusion welding, in addition to the porosity, the conditions for the formation of welded joints are significantly affected by the ratio of the coefficients of effective thermal conductivity in thickness $\lambda_\|$, and in the direction perpendicular to the movement of the welding source $\lambda_\perp$. As the ratio $\lambda_\perp / \lambda_\|$ increases and the porosity of the edges decreases, the quality of the welded joints increases.

3. The EBW technology of filter elements of die-welded filters with the required properties and ARAW of the permeable sleeve of the heat exchanger-evaporator made of PPM based on corrosion-resistant steel 12Cr18Ni10Ti were developed. The results of bench tests showed that the developed technological processes make it possible to obtain products that fully meet the requirements of the technical specifications. The introduction of filters in the units of hydro and pneumatic systems increased the operational reliability of power plants.

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