Design of energy efficient inductors for connecting pipelines of oil and gas equipment

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Abstract. The article deals with the problem of soldering the installation connections of equipment using induction heating methods. The analysis of the subject area has been carried out. Methods for obtaining permanent connections of oil and gas equipment are considered. A comparison of the characteristics of energy sources for welding is carried out, and the characteristics of the efficiency of methods for obtaining permanent joints are also given. Induction brazing is considered as an alternative method for obtaining permanent joints, namely, an inductor for soldering fittings and flanges. The calculations of the required power of the equipment, used for soldering the field connections of the equipment, have been made. As a result of the work, the authors calculated the main parameters of the inductor for soldering the flanges of the fittings and designed sets of inductors with a diameter of $D_y = 40$ mm, $D_y = 50$ mm, $D_y = 80$ mm for soldering the flanges of the fittings.

1. Introduction

Currently, there are various ways to obtain permanent joints of equipment, the most common of which are: manual arc welding, gas welding and plasma welding. To identify the advantages of induction soldering in comparison with the widespread methods of obtaining permanent joints, we will conduct a comparative analysis of these methods.

All metal welding processes are carried out by introducing thermal or mechanical energy, or both at the same time. The main criteria for choosing a welding process for the manufacture of a specific product are: technical feasibility of using the process; the quality of the resulting connection; energy and economic efficiency of the process. To find the optimal solution, it is necessary to analyze only the last
For a comparative assessment of various types of welding, it is advisable to use specific efficiency indicators. The calculation of the unit costs of energy, labor or funds per unit area of the connection makes it possible to obtain universal criteria for the effectiveness of any way in which the connection is made.

Energy efficiency is determined by the total energy consumption per unit of connection area.

Economic efficiency is assessed by the productivity of the process and specific costs per 1 m of the weld length or per 1 kg of deposited metal.

Comparison of the efficiency of various welding processes shows that fusion welding processes are more energy intensive than mechanical and thermomechanical ones. For example, to make a butt joint of steel rods with a diameter of 20 mm arc welding requires a specific energy equal to 1800 J/mm², flash butt welding - about 400 J/mm², friction welding - about 130 J/mm².

Energy sources for welding are usually characterized by an effective thermal power \( g \), the highest specific power in the heating spot and the area of the latter. The energy characteristics of the main thermal energy sources for welding and cutting are presented in table 1.

Their comparison shows that the electric and plasma arcs have the highest specific power in the heating spot [1-3].

When choosing an energy source for welding specific products, one should consider the technical feasibility of using this source, the efficiency of the process (energy and economic), as well as the quality and reliability of the products obtained.

The energy concentration of thermal sources can be estimated by the power density in the heating spot. However, welding is possible only up to a power density of 10²…10⁴ W/mm², since high power densities lead to splashes and intense evaporation of the material, which is useful only for cutting and dimensional processing of products. The power density of the beam and the energy coefficients of deposition, melting and others are suitable for evaluating only certain types of energy sources or welding methods. To assess the effectiveness of different classes of welding processes and different methods of welding and brazing, it is advisable to use the values of the specific energy required for welding a given joint [4-6]. Based on the foregoing, it is necessary and advisable to carry out a comparative analysis of common methods of welding with induction brazing according to the following criteria: temperature of the method, average weld width, effective efficiency, minimum specific energy. Let's summarize the information received in a comparative table (table 2).

| Energy source                  | Temperature, °C | The smallest area of the heating spot, cm² | The highest specific power in the spot, kW/cm² |
|-------------------------------|-----------------|------------------------------------------|-----------------------------------------------|
| Oxygen-acetylene flame        | 3000…3500      | 10²                                      | 50                                            |
| Electric arc                  | 6000…7000      | 10³                                      | 10²                                           |
| Plasma arc in gases: hydrogen, nitrogen | 5000…8000 | 10⁴                                      | 10²                                           |
| Argon, helium                | 10000…20000    | 10⁴                                      | 10²                                           |

| Method            | Temperature, °C | Average joint width, cm | Effective efficiency | Minimum specific energy, kJ/cm² |
|-------------------|-----------------|-------------------------|----------------------|--------------------------------|
| Gas welding       | 3000…3500      | 2.0                     | 0.45-0.65            | 95.0                           |
| Arc welding       | 6000…7000      | 2.0                     | 0.4-0.7              | 128.5                          |
| Plasma welding    | 5000…20000     | 1.5                     | 0.5-0.75             | 60.0                           |
| Induction brazing | to 1100         | from 0.05               | 0.70-0.85            | 42.0                           |
Thus, after conducting a comparative analysis of existing methods, it can be concluded that the use of induction soldering can increase the efficiency, accuracy and quality of obtaining permanent joints due to the lowest consumption of the minimum specific energy per square centimeter of the heated surface and the minimum possible thickness of the soldered seam.

2. Materials and methods

Inductors can be divided into two types:

- Inductor of simultaneous heating - when the area of the heated surface of the inductor is equal to the area of the heated part.
- Inductor of continuous-successive heating - the area of the inductor is less than the surface area of the part, and in this case the part is moved along the inductor, gradually heating the entire part.

The basis for the design of inductors is the surface effect. It consists in the fact that the secondary current in the workpiece has the same direction as the current in the inductor, which is located nearby. In this case, the induced current is, as it were, "attracted" to the inductor. This is due to the fact that closely spaced currents flowing in one direction are attracted. If the inductor is immersed in liquid metal and a large power (tens of kW) is supplied to it, the metal is squeezed out of the inductor under the action of MHD forces and small amounts of it may even hover over the inductor in the air. By using specially shaped inductors, ultrapure melting of a small amount of metal levitating in a vacuum or protective gas can be carried out. To increase the efficiency of the inductor, it is necessary to place it as close as possible to the workpiece. In practice, this is from 2 mm to several centimeters.

Power to the inductor is usually supplied by means of a high-frequency transformer without a core (with an air core), the primary winding of which is the coil of the oscillating circuit, and the secondary winding is one wide turn of copper sheet (electromagnetic concentrator or eddy current concentrator). The inductor must be matched to the secondary winding of the high-frequency transformer, i.e. have approximately the same inductance. To reduce the inductance of multi-turn inductors, they are made from several parallel turns [7-9].

Induction soldering is performed with the heating of the soldered section in the inductor coil. A high-frequency current is passed through the inductor, as a result, the soldering point is heated to the required temperature. Protection of the product from oxidation is achieved by conducting the heating process in a vacuum or in a protective environment and the use of fluxes. The inductor is in the form of a loop or spiral made of red copper. The shapes and sizes of the inductor depend on the design of the soldered product [10-12]. The induction-heated soldering circuit is shown in figure 1.

![Figure 1](image_url)

**Figure 1.** The main types of inductors for soldering. 1 - inductor; 2 - details; 3 - solder; a, b - solder wire; c - solder flat ring.
In induction brazing, depending on the type of parts to be connected, wire (figure 1a and 1b) and flat rings (figure 1c) can be used as solder. In all cases, the parts are placed in the magnetic field of the inductor. As a result of the effect of a magnetic field on the metal of the product, eddy currents are formed, which cause heating of the parts. The intensity of heating depends on the type of inductor, the power of the generator, the kind of metal, the size of the structure, etc.

3. Result and discussion

Mass of the heated metal volume (1), kg:

\[ G = 0.45 \cdot m \]  

(1)

where \( m \) is the mass.

The minimum and maximum frequencies of the inductor \( f \) (frequency interval) are calculated by the equation (2), Hz:

\[ \frac{3 \cdot 10^6 \cdot p}{\mu \cdot D_2^2} \leq f \leq \frac{6 \cdot 10^6 \cdot p}{\mu \cdot D_2^2} \]  

(2)

where \( p = 2 \cdot 10^{-8} \) Ohm m – electrical resistivity of a copper inductor;

\( D_2 \) – product diameter, m;

\( \mu = 1 \) - relative permeability of metal, p.u.

In this work, according to the calculated frequency range, we will choose power supplies from the following series of standard frequencies \( f \): 500, 1000, 2500, 4000, 8000 Hz.

The depth of wave penetration into the inductor material is calculated by expression (3), mm:

\[ \Delta = 503 \cdot \sqrt{\frac{p}{\mu \cdot f}} \]  

(3)

where \( f \) - frequency of the selected power supply.

Net power (4) used to heat the workpiece, kW:

\[ P_{net} = \frac{C \cdot G \cdot (t_{end} - t_{init})}{\tau_{heat}} \]  

(4)

where \( C \) - specific heat of the part material at the melting point of the solder, kJ/kg·°C; \( G \) - load weight; \( t_{end}, t_{init} \) - respectively, the end and initial temperature of the metal, where \( t_{end} \) corresponds to the melting point of the solder, \( t_{init} \) corresponds to the ambient temperature (\( t_{init} = 200 \) °C); \( \tau_{heat} \) - heating time, s.

The heat loss power (5) is calculated on the basis of Fourier’s law as the power transferred by thermal conductivity from the inner surface to the outer surface (in contact with the inductor) through a single-layer cylindrical lining, kW:

\[ \Delta P_{hit} = \frac{(t_1 - t_2) \cdot \mu}{z_T} \]  

(5)

where \( t_1, t_2 \) - respectively, the internal and external temperatures of thermal insulation (lining); for calculations take \( t_1 = t_{end} \) (end temperature of the heated billet), \( t_2 = t_{water} \) (temperature of cooling water at the outlet of the inductor); \( z_T \) - thermal resistance of the lining (6):

\[ z_T = \frac{\ln \left( \frac{D_1}{D_2} \right)}{2 \cdot \pi \cdot \lambda} \]  

(6)
where \( \lambda = 0.7 + 0.64 \cdot 10^{-3} \cdot t_{\text{avg}} \) - the thermal conductivity coefficient of chamotte, in simplified calculations I accept \( t_{\text{avg}} = t_{\text{end}} \).

\[
D_3 = D_2 + 0.01 \quad (7)
\]

\[
D_1 = D_2 - 0.01 \quad (8)
\]

where \( D_1, D_3 \) - respectively, the outer and inner diameters of the thermal insulation.

Inner diameter of the inductor, m:

\[
D_4 = D_2 + 2 \cdot h \quad (9)
\]

where \( h \) - air gap between the inductor and the heated part. It is usually chosen within 2-5 mm if \( D_1 \leq 50 \text{ mm} \), and 5-10 mm, if \( D_2 > 50 \text{ mm} \).

Power consumption in load (10), kW:

\[
P_2 = 1.05 \cdot (P_{\text{net}} + \Delta P_{\text{H}}) \quad (10)
\]

where 1.05 – coefficient that considers losses in metal guides along which the part moves; \( P_{\text{net}} \) - net power, power used to heat the part; \( P_{\text{H}} \) - heat loss power [20].

Let's calculate the inductor based on the data for the first type and the first version for the nominal pressure \( P_y = 0.6 \text{ MPa} \) (6 kgf/cm²) according to ATK 24.218.06-90 “fittings for vessels and welded steel apparatus”. For the calculation, we will use the widespread material for fittings and pipes 12KH18N10T and, accordingly, the PSr45 solder suitable for it, the melting point of which ranges from 665 to 730 °C.

Let's calculate the electrical parameters of the inductor at \( D_y = 500 \text{ mm} \) and \( D_2 = 530 \text{ mm} \), calculations according to formulas (1) - (10). Let's summarize all the initial and received data, configuring in the calculations, in Table 3.

| Name                        | The quantity |
|-----------------------------|--------------|
| 1. Solderable metal         | 12KH18N10T   |
| 2. Final heating temperature, °C | 730          |
| 3. Diameter of a part, \( D_3 \), mm | 530          |
| 4. Inner diameter of the inductor, \( D_4 \), mm | 550          |
| 5. Heating time, s         | 120          |
| 6. Mass of heated metal volume, kg | 27.23        |
| 7. Calculated frequency, Hz | 210 < \( f < 420 \) |
| 8. Selected frequency, Hz  | 2500         |
| 9. Depth of wave penetration into the inductor material, mm | 1.423        |
| 10. Useful power, kW       | 92.638       |
| 11. Power of heat losses, kW | 136          |
| 12. Power consumption in loading, kW | 240.07      |

As a result of the calculation of the main electrical parameters of the inductors, it can be concluded that all the values of the nominal diameters \( D_y \) of the fittings of the first type and the first design for the conditional pressure \( P_y = 0.6 \text{ MPa} \) (6 kgf/cm²) according to ATK 24.218.06-90 for vessels and apparatus of steel welded "meet the required conditions for the possibility of brazing by induction heating. Let us take the following characteristics for the installation of induction soldering of the flanges of the fittings: installed power 300 kW, power supply 380V with a frequency of 50 Hz, frequency of the power supply converter 2500 Hz. Based on the results of calculations of the electrical parameters of the inductors for soldering the flanges of the fittings of the vessels and apparatus operating under the nominal pressure of \( P_y = 0.6 \text{ MPa} \), we have determined the necessary parameters of the installation for induction soldering, now it is necessary to start designing the inductors.
We will design a set of three inductors for soldering of flanges of fittings for the following dimensions $D_y$ according to ATK 24.218.06-90: $D_{y1} = 40$ mm; $D_{y2} = 50$ mm and $D_{y3} = 80$ mm. We will make inductors from hollow copper tubes in accordance with GOST 617-90. Let's summarize all the initial and received data, configured in the calculations in table 4.

| Name                                                | $D_{y1}=40$ | $D_{y2}=50$ | $D_{y3}=80$ |
|-----------------------------------------------------|-------------|-------------|-------------|
| 1. Solderable metal                                   | 12KH18N10T  |             |             |
| 2. Final heating temperature, °C                     | 730         |             |             |
| 3. Diameter of a part, $D_z$, mm                      | 45          | 57          | 89          |
| 4. Inner diameter of the inductor, $D_4$, mm          | 55          | 71          | 105         |
| 5. Heating time, s                                   | 120         |             |             |
| 6. Mass of heated metal volume, kg                    | 0,9         | 1.08        | 2.07        |
| 7. Calculated frequency, Hz                          | 940 $< f <$ 450 $< f <$ 425 $< f <$ 900 $< f <$ 850 |
| 8. Selected frequency, Hz                            | 2500        |             |             |
| 9. Depth of wave penetration into the inductor material, mm | 1.423       |             |             |
| 10. Useful power, kW                                 | 3.061       | 3.674       | 7.042       |
| 11. Power of heat losses, kW                         | 10.97       | 14.16       | 21.94       |
| 12. Power consumption in loading, kW                 | 14.73       | 18.72       | 30.43       |

As a result of the work, an inductor was designed and presented in the form of drawings in figures 2-4.

**Figure 2.** Inductor for soldering the fitting $D_y = 40$mm. 1 - Contour; 2 - Tube.
4. Conclusion
The article designs inductors for induction soldering of equipment wiring connections using induction heating methods. In the course of the work, the analysis of the subject area was carried out. Methods for obtaining permanent joints of oil and gas equipment are considered. The authors compared the characteristics of energy sources for welding, and also gave a characteristic of the effectiveness of
methods for obtaining permanent joints. It is proposed to use the induction heating method to obtain permanent connections of fittings and flanges. Calculations of the required capacity of the equipment used for the soldering of oil and gas equipment have been performed. As a result of the work, the authors calculated the main parameters of the inductor for brazing the flanges of the fittings and developed sets of inductors with a diameter of \( D_y = 40 \text{ mm} \), \( D_y = 50 \text{ mm} \), \( D_y = 80 \text{ mm} \) for brazing the flanges.

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