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Ensuring the technological strength when welding the shaft with flange of auto-vehicles

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Abstract. In engineering, the use of highly loaded shafts with flanges is mainly intended for additional attaching of various technological equipment. At the same time, the shaft-flange fitting is performed using an annular weld. Next, parts such as gears, pulleys, bushings, etc. are mechanically attached to the flange. The work considers the achievement of the technological strength of the shaft-flange fit when using arc welding methods. It has been established that the emergence of dangerous defects such as weld cracks is possible. The cause for this is a number of structural, technological and metallurgical restrictions. It is shown that it is expedient to apply welding technological schemes that make it possible to minimize areas of structural heterogeneity. It is proposed to use a transition layer made of low-carbon material, which is characterized by high plastic properties. As a result, the creation of a barrier layer in the zone of structural heterogeneity is achieved. The plastic intermediate weld contributes to the partial relaxation of residual stresses of welding and increases the crack resistance of the welded joint as a whole.

1 Introduction

Currently, the use of different methods of obtaining a shaft-flange structure is determined by the purpose of this machine part, geometric dimensions, structural design, use in the relevant industries, the amount of operating loads, etc. In particular, the following main designs and their varieties should be highlighted:

– cast structural elements, which are now almost out of use due to increased metal consumption, labour intensity and the need for additional heat treatment;

– welded-forged elements of the shaft-gear type, which are used in the manufacture of turbines, when it is necessary to ensure the appropriate strength and the specified structural performance;

– welded parts, which have the widest use in industry due to the possibility of obtaining a combination of complex geometric shapes with the provision of given structural requirements.

As compared to cast or forged elements, welded elements are characterized by lower metal consumption and labour-intensiveness, while simultaneously increasing the productivity and cost-effectiveness of the manufacturing process [1, 2]. This issue is relevant for highly loaded shafts, when it is necessary to ensure the transmission of significant torque forces and the attachment of the gear to the shaft has limited strength. The significant dimensions of the shaft often do not make it possible to obtain an effective cross-section at the place of attachment of the gear without a significant increase in the cost of the materials used, an increase in the amount of machining and labour costs in general. The use of welding technologies makes it possible to simplify the preparation and manufacture of such structural elements. In particular, welding of a special flange to the shaft is used, which will be later an additional fastening element for working parts such as a gear or a pulley.

At the same time, improving the operational characteristics of the welded shaft-flange structure (in order to increase the permissible working loads) is achieved by increasing their strength characteristics and by combining dissimilar materials. However, this leads to difficulties in ensuring crack resistance of the welded joint. The most typical is a combination of alloyed shaft material and low carbon steel gear-wheel. As a result, such a welded joint is characterized by the formation of hardening structures in the material of the shaft and the weakening of the surrounding seam areas of the flange. Besides, technological cracks are formed, which are different in nature: hot cracks during the crystallization of the seam and cold ones after the structure cools down. The physical and mechanical characteristics of the welded joint material change.

Therefore, studying ways to solve the problems of welding dissimilar materials and ensuring their technological strength is one of the main directions of this work. In particular, it is advisable to use a special technology that involves the implementation of intermediate layers to stabilize the properties of the welded joint.

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Object and subject-matter of research

The object of research is the welded connection of a shaft made of alloy steel with a flange made of low-carbon steel. The subject-matter of the study is the strength and crack resistance of the metal of the welded joint of the shaft-flange fit.

Purpose and objectives of the study

The purpose of the conducted research is to ensure the technological strength and operational characteristics of the welded joint of the shaft made of alloy steel and the flange made of low-carbon steel.

To achieve the goal, a number of tasks were solved in the work:

– perform an analysis of welding problems and crack resistance of the alloyed shaft and low-carbon flange;
– set technological parameters of welding for the shaft and flange;
– perform modeling of the cross-section of the intermediate plastic bead;
– investigate the chemical composition of the developed welded joint.

Practical significance of the obtained results

A technological scheme for welding the flange to the shaft is proposed, it involves making the intermediate bead of low-carbon steel. This makes it possible to separate in time the processes of heating the shaft and welding the flange. As a result, the crack resistance of the welded joint increases and its technological strength is ensured.

The design dimensions of the intermediate bead, taking into account the conditions of heat removal into the base metal, have been studied and established. The parameters of the welding regime for a low-carbon steel bead on an alloyed shaft have been developed taking into account its physical and mechanical properties.

The dependence of the properties of the thermally affected zone of the alloyed shaft on the applied technology of welding with heating was studied. The necessary conditions for ensuring the crack resistance of the metal have been determined.

2 Analysis of Literary Sources

Welding of a complex-loaded shaft made of alloy steel and a flange made of low carbon steel necessitates the study and solution of a number of technological and metallurgical problems. In particular, the following difficulties can be identified when obtaining a defect-free connection: welding dissimilar materials; ensuring resistance against hot cracks; increased resistance to the formation of cold cracks; obtaining uniform-strength welded joints, etc. All of them are interconnected by the structural and technological performance of the welded part. The combination of these factors with real conditions only aggravates their negative impact [1 – 3, 5].

1. The emergence of structural inhomogeneity in a welded joint, which is characteristic of heterogeneous materials, leads to the formation of a structural-phase composition different from the initial state [1 – 3]. In the case of welding a shaft-flange fit, such a zone will be characterized by areas with structures of hardening in the zone of thermal influence of the shaft and by zone carbon weakening in the vicinity of the seam of the flange. Weakening of the flange occurs as a result of a decrease in the carbon content as a result of counter-diffusion to chromium from the alloyed material of the shaft and the formation of stable carbides. The main ways of influencing the size of the zone of structural heterogeneity should include:

– limiting the heat treatment temperature of the welded joint to prevent the emergence of a complex residual stress state. The cause is the difference in coefficients of linear expansion of heterogeneous materials. As a result, there is a jump-like change in stresses in the fusion zone, which can lead to the fracture of the material in this area [1, 2]. Therefore, the use of preheating is possible only up to low temperatures and must be well justified;
– the emergence of martensitic interlayers in the fusion zone. This is due to the excessive dissolution of the more doped material by the less doped one. This occurs especially often with increased penetration of the metal (typically during preheating). As a result, there is a transition layer with low-plastic structures and a gradual change in chemical composition from one metal to another. The increase of this layer to critical dimensions leads to the emergence of cracks [1, 4];
– increase in transition interlayers due to post-welding heating. The experience of obtaining heterogeneous welded joints [1 – 3] shows that in this case it is possible to re-intensify processes when heated to critical temperatures. In this case, they are from 350 0C and above. Then, the processes of diffusion of chemically active elements begin to intensify themselves, which will lead to the growth of the transition interlayer. At the same time, increasing the duration of heating has a similar effect as the maximum heating temperature. Therefore, when developing the welding technology of the shaft and flange, it is advisable to use methods that limit or eliminate the need for post-welding heat treatment;
– limitation of the content of carbide-forming elements and their influence on the formation processes of structural heterogeneity. It was established [4, 5, 7, 8] that structural heterogeneity is manifested depending on the content of alloying elements, their type and thermodynamic activity. In particular, the intensity of the influence increases with the increase in affinity to carbon of the remaining alloying elements. At the same time, the atomic content of elements that are not bound to carbon (and not the total mass of a given alloying element) is important. Therefore, it is advisable to use methods that prevent the movement of these elements during heating of the structure (production of transition interlayers) and the introduction of appropriate welding materials;

2. The occurrence of hot cracks during the welding of the shaft and flange is mainly due to the increased carbon content in the base metal and the presence of harmful impurities such as sulfur and phosphorus [5 - 8]. This combination, together with temperature deformations during welding, leads to the formation of cracks at the stage of crystallization of the weld metal. Compression temperature deformations, at the stage of shaft cooling, cause tensile stress in the connection. As a result, cracks are initiated in the cross-section of the weld. The use of ordinary quality low-carbon steel for the production of flanges leads to the fact that the content of harmful impurities such as sulfur and phosphorus increases in the weld metal. The increased carbon content in the shaft metal leads to its growth in the weld metal. Therefore, it is necessary to control the content of sulfur and phosphorus in welding materials, in particular in electrode wires, to limit the proportion of the base metal in the weld metal, and to apply technological schemes that help reduce the harmful impact of temperature deformations and stresses.

Cold cracks in the shaft-flange fit are probably due to the presence of an increased carbon content in the high-strength alloy material of the shaft. Such cracks emerge in the seam zone, less often in the weld metal. They are caused primarily by the presence of hardening structures, the difference in the chemical composition of the base metal and the weld, as well as the possible influence of atomic hydrogen in the material [1-3, 5, 7-11]. The main measures to prevent cold cracks include:

– use of thermal cycle regulation methods. In particular, by changing the parameters of the thermal cycle, it is possible to achieve different cooling rates of the metal of the welded joint [9]. As a result, there is a decrease in the content of hardening structures, prevention of the formation of a coarse-grained structure of the seam metal, and a decrease in overheating of the seam areas [8, 10];

– in the case when preheating is important from a technological point of view, it should be combined with the parameters of the welding mode with low-power heating sources [10]. This creates conditions for the martensitic transformation to occur in the high-temperature region;

– use of welding materials with high plastic properties. This will make it possible to reduce the intensity of welding stress growth and ensure their reduction due to relaxation [11];

– reduction of residual moisture in the metal of the seam and near-seam areas, which negatively affects the rate of cold crack formation processes [12];

– preliminary surfacing of the welded edges, which creates conditions for the formation of such a stress state that counteracts the main one and also prevents the formation of grain boundary breaks during welding of the main seam [12, 13].

3. Obtaining equal-strength welded joints is often difficult when manufacturing this type of welded structures. This is due to the use of high-strength steels, which are mostly supplied in a pre-heat-treated state [8, 10]. As a result of welding, there is not only a redistribution of the structural-phase composition, but also the initial thermal strengthening of the base material is levelled [12, 14]. When performing arc processes, a cast structure of the weld metal is formed, this is significantly different from the base metal [11, 13]. Increasing its strength due to the introduction of carbon is limited due to the formation of cracks. Therefore, more complex doping systems are used [11, 14]. This approach, in its turn, worsens obtaining a chemically uniform material of the welded joint. Therefore, various heterogeneous layers are observed here, which can negatively affect the workability of the welded part as a whole [15, 16].

Therefore, when choosing welding materials, it is advisable to try to bring the chemical composition closer to the base metal. It is expedient to ensure uniform strength achieved by elements present in the base metal, take into account the probability of the occurrence of various low-melting eutectics, which contribute to the formation of hot cracks.

3 Results and Discussion

1. Outline of the problem of the product. The paper examines the issue of ensuring technological strength during welding of shaft-flange mounting parts which are made of dissimilar materials. Two continuous circular welds of angular cross-section are used here. The weld leg of the weld seam is 6.0 mm. The material of the flange is low-carbon steel of the VSt3ps grade (EU analogue is RSt37-2), its thickness is 8.2 mm, and its diameter is 200 mm. It functions as a fastening element for the gear and ensures alignment with the shaft. The used shaft has a continuous cross-section with a diameter of 74 mm in the place of welding of the flange. The total length of the considered shaft is 485 mm, and its material is medium-alloyed steel of 40 Cr grade (EU analogue is 37Cr4).

Analysis of the welded structure shows that it is quite technologically convenient from the point of view of welding and mechanization. The process is performed in the lower position with a fusible electrode of solid cross-section in a medium of protective gases. However, the emergence of cracks in welds and in near-seam areas is observed. They can occur both during the welding process and after storage of finished products. Metallographic analysis of the samples obtained from the finished structure showed that cracks appear not only at the surface, they are also possible in the cross-section of the deposited metal. Therefore, it is important to pay attention to the full complex of manufacturing technology of a welded part of a shaft with a flange to eliminate this type of defects.

The analysis of the peculiarities of the implementation of the technological process and the used welding materials showed that in this case the occurrence of hot cracks in the weld seam and cold cracks in the surrounding areas is characteristic. The formers, hot cracks, are probably due to insufficiently high-quality selection of used welding materials. The latters contain a relatively high level of harmful impurities such as sulfur and phosphorus. To prevent cold cracks, it is advisable to study the causes of their emergence and ways to eliminate them.

2. Analysis of the properties of the material of the elements of the welded structure. Steel grade 40 Cr belongs to the class of medium-alloy structural chromium materials. It is characterized by limited welding ability, but has high strength characteristics. This steel is intended for the manufacture of shafts, gear shafts, plungers, axles, rods, and other elements that work in difficult environmental conditions. The high mechanical properties of steel 40 X ensure the bearing of significant operating loads without destruction.

When welding 40 Cr steel, it is important to establish the equivalent carbon content to determine the weldability group. This makes it possible to pre-evaluate the need for heat treatment of the structure. We use the following expression when setting the carbon equivalent [6, 14]:

$$C_{equ} = C + \frac{\mathrm{Mn}}{6} + \frac{Si}{24} + \frac{Ni}{10} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14} \qquad (1)$$

According to literature data [5 – 8] and the determined chemical composition of the shaft, it was established that practical recommendations for carbon equivalent limits (C_{equ} > 0.45 %) are significantly exceeded. Thus, based on the results of using expression (1), it was established that the equivalent content is within the range from 0.643 % at the content of the minimum values of alloying elements to 0.833 % at the maximum content of the elements, according to the permissible limits of the content of chemical elements in steel. This steel should be assigned to the third group in terms of weldability. That is, it is recommended to use preheating for this steel before welding.

The material of the flange (steel grade VSt3ps) belongs to low-carbon steels of ordinary quality. That is, according to [5, 6, 14], good welding is achieved without additional special heat treatment. Using the data of the chemical analysis of the flange and the recommendations of the special literature [5 - 8], the value of the carbon equivalent was determined according to expression (1). Here it ranges from 0.307% for the minimum allowable values of elements of VSt3ps steel to 0.428% for the maximum content of elements in steel, respectively. Therefore, VSt3ps grade steel for flange production has good weldability.

3. Determination of linear welding energy. Obtaining a high-quality connection in the considered shaft-flange fit should take into account the properties of dissimilar materials and the need to comply with two requirements:
1) prevention of the formation of cold cracks in the seam zone and in the seam itself on the side of steel 40 Gr;
2) ensuring the minimum weakening of the areas of the zone of thermal influence of the VSt3ps steel flange.

The above-mentioned conditions contradict each other. This is due to the fact that in the first case it is necessary to warm up the areas around the seams to improve the structure of the welded joint. In the second case, the process should be implemented on the strictest welding modes with minimal heat input. It is necessary to minimize the duration of stay of the base metal of the flange at above critical temperatures. That is, to provide relatively high heating and cooling rates.

Therefore, in accordance with [4 - 6], the main criterion for calculating technology parameters and modes of the most productive methods of single-pass and multi-layer welding in long segments should be the maximum allowable cooling rate $w_{\mathrm{allowable}}$, which makes it possible to perform welding without cracks in the seam zone and in the seam itself. Preferably, this rate of cooling of the base metal ($w_{\mathrm{allowable}}$) is taken in accordance with the characteristics of the seam zone. This is due to the fact that the metal of the weld, as a result of the use of a less alloyed filler metal, is characterized by a higher resistance to the formation of cold cracks [5 – 8].

When welding medium-strength austenitic steels, the selected value of the cooling rate often needs to be adjusted to obtain the specified mechanical properties of the joint metal. For this, an additional criterion is a certain interval of cooling rates (w_{optimal}), in which optimal mechanical properties are ensured in the near-seam zone and in other areas of the connection. For 40 Cr steel, the optimal interval of cooling rates based on changes in the structure and properties of the weld zone is from 4.0 to 14 degrees per second, using approaches given in the specialized literature [5 - 9] have been used.

According to the analysis of the welded structure and the recommendations from the special literature [5 – 9], we accept the conditions for welding the bead onto massive part. Special nomograms [5 – 8] were used to determine the value of optimal specific (per unit length) welding energy (q/v) when surfacing the bead. They establish the relationship between the cooling rate and the specific (per unit length) welding energy for different metal thicknesses. Nomograms will set the specific (per unit length) welding energy for different temperatures of preheating (T_{heating}): without heating; 100 ^{0}C; 200 ^{0}C; 300 ^{0}C; 400 ^{0}C.

Applying this approach [5 – 8] for various special nomograms, we determined the welding energy per unit length when performing preheating (Table 1).

Table 1. Recommended values of specific (per unit length) welding energy when surfacing the bead

Heating temperature, ^{0}C	none	100	200	300	400
Range q/v, kJ/cm	70.8-241.6	50-208.3	29.1-104.1	15-62.5	7-25

The analysis of the obtained results shows that the use of preheating makes it possible to effectively reduce the specific (per unit length) welding energy in the case of welding a bead onto the surface of a shaft made of 40 Cr steel. At the same time, increasing the heating temperature not only reduces the value of the recommended specific (per unit length) welding energy, but also ensures a narrowing of the recommended range. This makes it possible to more accurately cover the recommended field of parameters of the welding regime and reduce the probability of neglecting random disturbances, which can lead to the emergence of hardening structures. It is advisable to use the obtained results in the future when developing the parameters of the surfacing regime when performing welds.

4. Setting the parameters of the welding regime was carried out according to the recommendations of the specialized literature [7, 8] and the construction of the welded structure (annular seam). The following regime parameters are recommended for automated welding of the shaft and flange in shielding gases (Table 2).

However, it is necessary to refine the process parameters in accordance with the determined specific (per unit length) welding energy. For this purpose, we use the following formula [8]:

$$q / v = I_{weld} \cdot U_{arc} \cdot \eta / v_{welding} \, , \qquad (2)$$

where q/v is the specific (per unit length) welding energy of the arc, J/cm; I_{weld} is the welding current, A; U_{arc} is the voltage on the welding arc, V; $v_{welding}$ is the welding speed, cm/s; η is the effective heating efficiency.

Table 2. Recommended parameters of automatic welding [7, 8]

d_{el}, mm	I_{weld}, A	U_{arc}, V	$v_{welding}$, m/hour	l_{el}, mm	q_{gas}, litres/min
1.2	190 - 200	20	20	11	10

Therefore, according to the recommended welding parameters (Table 2), we will get a specific (per unit length) welding energy value of 6183 J/cm. The obtained value of the specific (per unit length) welding energy can be partially satisfied only when the shaft is heated before welding to temperatures above 400^0C. At the same time, resistance against the formation of cold cracks is ensured. However, the high heating temperature has a negative effect on the crack resistance of the shaft metal. Therefore, while adjusting the parameters of the welding regime, the issue of increasing the specific (per unit length) welding energy of the process was studied. Below (Table 3), the value of the specific (per unit length) welding energy in the range of surfacing speeds from 5 to 25 m/hour is investigated.

Table 3. Specific (per unit length) welding energy at different speeds of arc movement

$V_{welding}$, m/hour	25	20	15	10	5
q/v, J/cm	4896	6183	8158	12242	24479

Therefore, to ensure a high-quality welding process, it is necessary to preheat the elements to temperatures above 300 ^{0}C and reduce the welding speed.

Taking into account the features of semi-automatic welding and the need for energy efficiency in industrial production, it is advisable to adjust the speed and temperature range comprehensively. Hence, the recommended parameters of the shaft and flange welding regimes are presented in (Table 4).

Table 4. Parameters of the welding regime for a shaft with flange

d_{el}, mm	$T_{heating}$, ^{0}C	I_{weld}, A	U_{arc}, V	$v_{welding}$, m/hour	l_{el}, mm	q_{gas}, litres/min
1.2	320	210	20	10	11	10

According to the obtained results, at a welding speed of 10 m/hour and heating up to a temperature of 320 ^{0}C, we will obtain such a specific (per unit length) welding energy that satisfies the optimal range of cooling speeds of a welded joint made of 40 Gr steel.

5 Study of the process diagram of shaft-flange welding. The analysis of literature data [9, 12 - 16] shows that the structural component connection of the shaft-flange is characterized by increased rigidity. This can negatively affect crack resistance due to the following factors:

– heating leads to a temporary increase in the diameter of the shaft;
– welding of the flange to the heated shaft increases the local stiffness in the cross-section of the joint;
– cooling of the shaft leads to the emergence of tensile stresses in welds;
– values of stresses can exceed the critical value and lead to the emergence of cracks in welds not only at the stage of crystallization of the weld pool, but also at the beginning of operation of the welded structure [13 – 15].

Therefore, such a design scheme has no practical application at significant heating temperatures. This is especially relevant in the considered case, when the heating temperature is sufficiently high and is 320 ^{0}C.

In this work it is proposed to separate in time the technological processes of heating and welding by means of the use of an intermediate bead. In particular, in this case, it is advisable to apply surfacing of an additional bead according to the scheme shown in Fig. 1. In this case, it is advisable to use an intermediate bead made of low-carbon highly plastic material.

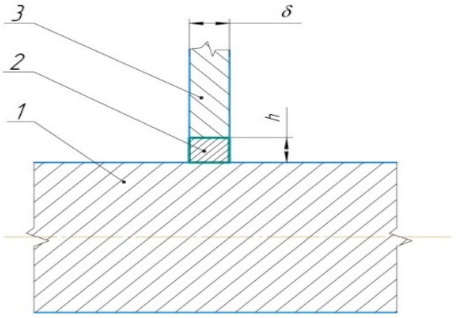

Fig. 1. Structural diagram of the coupling of the shaft with flange

The following designations are used here: 1 – shaft (steel 40 Gr); 2 – intermediate bead; 3 – flange (steel VSt3sp); h – height of the bead; δ – thickness of the flange.

Then the welding sequence of this shaft-flange fitting will be as follows:
– preliminary heating of the shaft (1) to a temperature of 320 ^{0}C;
– welding of the intermediate bead (2) of the specified value of h made of low-carbon steel to the surface of the shaft (1);
– welding of the flange (3) to the welded bead (2) without heating.

The surfacing of the intermediate bead made of a plastic material will ensure the emergence of less stresses in the welded joint, since its structural dimensions are significantly less than that of the welded flange. As a result, the rigidity of such a structure is less. The use of low-carbon electrode wire will make it possible to reduce carburization of the intermediate bead. The plastic properties of the low-carbon material of the intermediate bead contribute to the relaxation of temperature and residual welding stresses. At the same time, the danger of formation of hardened structures in the weld seam and the problem of welding dissimilar materials are reduced.

The width of the intermediate bead must correspond to the thickness (δ) of the flange, and its height (h) is set from the following condition: the value of heating of the intermediate bead (2) around the shaft (1) when welding it with the flange (3) should not exceed the temperature A_{c1} (for the material of shaft). This will ensure the absence of structural transformations in the metal of the shaft. The proposed technological scheme makes it possible to eliminate the danger of hardening structures and significantly reduces the value of tensile stresses in the welded joint of the shaft and the flange.

6. Modeling of the height of the bead. To determine the height of the intermediate bead, the approaches of the theory of welding processes [6, 9] were used. In particular, the methods of modeling temperature fields during welding make it possible to determine the dimensions of the zone whose temperature was above the given value.

To find the unknown value of the zone (l), which was heated above the given temperature (T_l), it is necessary to set the coordinate of point A on the isotherm with temperature ($T = T_l$). Then the maximum temperature will be at a distance ($y = l$). From here, this temperature (T_l) can be calculated [6, 9]:

$$\frac{\partial T}{\partial x} = 0 . \tag{3}$$

In our case, we use the expression to calculate the temperature when the bead is welded onto a bulky body [6, 9]:

$$T_l = \frac{q}{2\pi\lambda R}\exp\left[-\frac{\upsilon}{2a}(x+R)\right]. \tag{4}$$

Then, solving expressions (3) and (4) together, we get:

$$\frac{\partial T}{\partial x} = -\frac{q}{2\pi\lambda R^2}\cdot\exp\left[-\frac{\upsilon}{2a}(x+R)\right]\cdot\left[\frac{x}{R}+\frac{\upsilon}{2a}(x+R)\right] = 0 . \tag{5}$$

The next stage is to set $z = 0$ and take into account the fact that $l^2 = y^2 = R^2 - x^2$. Hence, expressions (4) and (5) can be represented as follows in a parametric form:

$$\frac{\upsilon \cdot l}{2a} = \pm\frac{\rho_3}{1+\rho_3}\cdot\sqrt{1+2\rho_3} \tag{6}$$

$$\frac{T_l \cdot 4\pi\lambda a}{q\upsilon} = \frac{1}{\rho_3}\exp\left[-\frac{\rho_3}{1+\rho_3}\right] \tag{7}$$

where $\rho_3 = \frac{\upsilon R}{2a}$.

Knowing the value ρ_3, it is possible to determine the value $y = l$ by means of the dimensionless criterion $\frac{\upsilon \cdot l}{2a}$, using approaches described in the specialized literature [5 – 9] are used. Thus, using the nomogram for the case of surfacing a bead onto the surface of a semi-infinite body (Fig. 2), for a known value of $\frac{T_l \cdot 4\pi\lambda a}{q\upsilon}$ we find the corresponding values of ρ_3.

It was established [5, 6, 9] that the value of the critical temperature for 40 Cr steel is $A_{c1} = 743\ {}^0C$. The parameters of the welding regime, which are listed above in the Table. 4, make it possible to calculate the dimensionless criterion $\frac{T_l \cdot 4\pi\lambda a}{q\upsilon}$, where the temperature is T_l taken to be equal to $743\ {}^0C$. The values of heat conductivity and thermal conductivity are taken as follows: $a = 0.085\ cm^2/s$, $\lambda = 0.402\ J/cm \cdot s \cdot \deg ree$, and welding speed $v = 0.28\ cm/\mathrm{s}$.

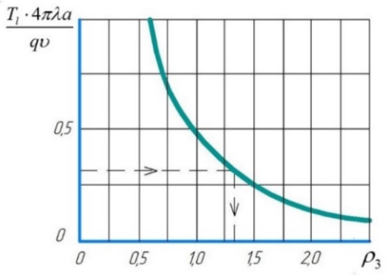

Fig. 2. Nomogram for finding ρ_3

According to (2), the effective heat capacity is $q = 3570\ W$. Then the value of the dimensionless criterion $\frac{T_l \cdot 4\pi\lambda a}{qv} = 0.331$. Using the nomogram in Fig. 2 we establish that $\frac{\upsilon \cdot l}{2a} = 1.3$. Hence, the size of the area that was heated above the temperature $A_{c1} = 743\ {}^0C$ during welding of the flange and the temperature the intermediate bead is 1.105 cm.

Based on the structural fit of the shaft-flange and the peculiarities of the implementation of the technological process of welding, we accept the height of the intermediate bead as 10 mm. The width of the intermediate bead is assumed to be equal to the thickness of the flange. It is obvious that it is difficult to ensure such a height of the intermediate roller without the use of special equipment. In this case, two ring forming bushings were used, which were made of copper and fitted onto the shaft before welding. Next, welding of the intermediate bead was carried out. Copper bushings were removed before welding the flange.

6. Setting the chemical composition of the welds of the shaft-flange structure. To ensure the crack resistance of the weld metal, in particular to prevent the occurrence of cold cracks, it is important to use plastic steels. This will make it possible to relax temporary welding stresses during welding, create conditions for "healing" of grain boundary breaks and ensure the shift of the martensitic transformation to the region of high temperatures [4 – 6].

According to the recommendations of the special literature [5 – 7, 11, 13, 14], the Sv-08 AA electrode wire with a diameter of 1.2 mm was used. It provides plastic material due to low carbon content.

Alloyed electrode wire was used to weld the obtained intermediate bead to the flange, in particular, OK

AristoRod 69 wire from ESAB [5 – 7, 11, 13, 14]. A complex alloying system is used here which ensures high strength of the deposited metal when welding in gases. According to the sources used [5 – 7, 11, 13, 14], the strength of the deposited metal is up to 800 MPa, and the yield is up to 730 MPa in the medium of a mixture of protective gases (80% Ar+20% CO_2).

The chemical composition of the deposited metal was determined according to the proportion of filler and base metals of the weld. The content of each element was determined by the formula [7]:

$$E_{bead} = \eta \cdot E_{element} \cdot A + E_{base} \cdot B , \qquad (8)$$

where E_{bead} is the content of the element in the deposited intermediate bead; η is the coefficient of transition of the chemical element from the filler wire; $E_{element}$ element content in filler metal; A is the the proportion of deposited metal; E_{base} is the element content in the base metal; B is the proportion of base metal in the bead.

Analysis of the features of the implementation of the technological process shows that the share of the base metal in the deposited material will increase most intensively in the first pass. The rest of the passes will be characterized by a gradual decrease in the content of the base metal, and the influence of the chemical composition of the Sv-08 AA wire will increase. At the same time, one should take into account the increased surfacing speed compared to the manual arc method. The following initial data are used for calculations: $B = 0{,}32\ \%$; $A = 0{,}68\ \%$; $\eta = 0{,}7$.

Using formula (8) and data on the chemical composition of the metal of the shaft and electrode wire Sv-08AA, the chemical composition of the deposited metal of the intermediate layer was determined (Table 5).

Table 5. Chemical composition of the deposited metal of the intermediate layer on the shaft, %.

C	Mn	Si	Ni	Cr	S	P
0.163	0.327	0.069	0.215	0.304	0.021	0.021

According to the obtained results, it can be concluded that the deposited metal of the intermediate layer is chemically close to the main metal of the flange. At the same time, the amounts of remaining alloying elements that strengthen ferrite and ensure crack resistance (manganese, silicon, chromium) are sufficiently high. The content of harmful elements such as sulfur and phosphorus is much lower than in the used VSt3ps steel. That is, the necessary crack resistance of the weld is ensured, and the materials and technology used meet the quality requirements of the welded joint.

4 Conclusions

The analysis of the welded structure of the shaft and flange showed that it is technologically convenient from the point of view of welding. However, the traditional technology of arc welding leads to the emergence of cracks, both during the welding process and after the storage of finished products. It is shown that the welding of alloy steel 40 Cr of the shaft and low-carbon steel VSt3sp of the flange leads to a number of problems of a metallurgical and technological nature, there is a tendency to the formation of cold cracks.

According to the determined optimum cooling speed of the shaft material, the parameters of the welding regime and preheating temperature (up to 320 ^{0}C) as well as the reduction of the welding speed were set. It was established that in order to ensure the necessary crack resistance of the connection, it is necessary to separate in time the processes of heating the shaft and welding the flange. For this purpose, an intermediate welded bead made of low-carbon steel was used. Modeling of the geometric parameters of the intermediate welded bead was carried out in order to prevent the formation of hardening structures in the main metal of the shaft.

Modeling of the properties of the welded bead was carried out taking into account the chemical composition of the filler wire and that of the base metal. It is shown that the chosen welding technology ensures the necessary chemical composition and obtaining a high-quality welded joint.

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