STRUCTURE AND PROPERTIES OF ARC-WELDED JOINTS ON STEEL 10G2FB

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Structural transformations in the HAZ metal of steel 10G2FB under the impact of the arc welding thermal cycles and their effects on the mechanical properties of this region of a welded joint were investigated. The range of permissible cooling rates of the HAZ metal at temperatures of 600–500 °C, providing properties of the welded joints at a level of requirements to the base metal and their high resistance to delayed, brittle and laminated fractures, was identified.

Keywords: *arc welding, high-strength steels, welded joints, CCT diagram, martensite and bainite transformations, cooling rate, hardness, diffusion hydrogen, cold cracks*

Intensive development of a container shipment, conditioned by establishment of the international transporting corridors, resulted in a necessity of designing and mastering of a production of special container car platforms which should completely fulfill the requirements on load-carrying capacity and type of transporting containers of a carrier. Besides, such a rolling stock should have an advanced reliability and being economical in running. 72 t load-carrying capacity and 22 t light weight are the optimum parameters for this car taking into account 23.5 t of an allowable axle load.

The shaped and sheet rolled products of 09G2, 09G2D, 16D, St3 and other steels with up to 350 MPa yield strength are used in manufacture of the load-carrying welded structures of a freight rolling stock in Ukraine and CIS countries up to present time. However, an application of higher strength steels is necessary for manufacture of new generation freight cars. The specialists of VNIIZhT [1] believe that the steels with more than 390 MPa yield strength which are characterized by higher ductility ($\delta_5 > 19$ %) and impact toughness ($KCU^{-60} > 29.4$ J/cm^2, $KCV^{-60} > 19.6$ J/cm^2) are to be perspective for manufacture of load-carrying welded structures of the rolling stock. Such steels should have good weldability and being mass produced at the domestic metallurgical complexes.

10G2FB grade steel mostly fulfills specified requirements as shown by analysis of roll metal produced by Ukrainian metallurgical enterprises. This steel is widely used in manufacture of large diameter pipes for the main pipelines [2, 3] and produced in accordance with TT 227-21–2008 specification. The requirements to chemical composition of sheets of 10G2FB steel are the following, not more, wt.%: 0.15 C; 0.35 Si; 1.70 Mn; 0.02 P; 0.01 S; 0.02–0.03 Al overall; 0.01–0.03 Ti; 0.08 Nb; 0.01 W; 0.30 Mo. The mechanical properties of 10G2FB steel sheets make not less than $\sigma_y = 490$ MPa; $\sigma_t = 565$ MPa; $\delta_5 = 28.5$ %; $KCV^{-60} = 69$ J/cm^2; $KCU^{-60} = 59$ J/cm^2.

The aim of the present paper consisted in an investigation of weldability of high strength 10G2FB grade steel taking into account special requirements to a steel rolled metal designed for freight car building [1]. Structural transformations in the HAZ metal of 10G2FB steel under the impact of the welding thermal cycles and their influence on the mechanical properties of given region of the welded joint, steel susceptibility to formation of cold and laminated cracks, steel reaction to burnian, and brittle fracture resistance of the welded joints were studied in accordance with these requirements.

The samples cutout from 18.7 mm thick sheets of the following chemical composition, wt.%: 0.08 C; 0.249 Si; 1.57 Mn; 0.05 V; 0.05 Nb; 0.006 [N]; 0.007 S; 0.013 P, were used in the investigations. Such indices as $\sigma_y = 531$–581 MPa; $\sigma_t = 610$–660 MPa; $\delta_5 = 24.8$–26.3 %; $\psi = 62.0$–64.8 %, $KCU^{-60} = 220$–324 J/cm^2; $KCV^{-60} = 204$–300 J/cm^2 are characteristic for the mechanical properties of steel in as received conditions after thermomechanical treatment. The extreme values of mechanical property indices correspond to tests of the samples cutout across and along the rolled metal, respectively. It should be noted that the steel has sufficiently high indices of ductility ($\psi_z = 65.0$–69.7 %) in the axis z direction indicating its high resistance to the laminated fracture.

10G2FB steel differs by high ductile properties. An evidence of this fact is the results of the traditional impact toughness tests as well as steel reaction to burning by welding arc in accordance with GOST 23240–78. The main point of the latter test method, regulated by normative documents for selection of rolled metal in car building, lied in obtaining of a low-plastic lens on the surface of sample under the effect of arc burning and determining its influence on steel susceptibility to transion in a brittle state under the impact load application. The shape and dimensions of the sample corresponded to a notched specimen for impact bend tests.

The results of given tests correlate with the same indices obtained for the O-notched base metal specimens for impact bend and make KCU^{-60} = 346 J/cm^2, i.e. critical temperature of 10G2FB steel transition in the brittle state are below −60 °C.

The analysis of a CCT diagram of austenite decay (Figure 1) and the microstructures of corresponding samples (Figure 2) gives sufficient idea of kinetics of structural transformations in the areas of overheating of the HAZ metal. The investigations were carried out on a high-speed dilatometer of the «Gleeble-3800» complex [4]. Cylindrical samples of 6 mm diameter and 86 mm length were heated up to 1200 °C temperature at 150 °C/s rate and then cooled down with the different cooling rates (from 1.5 up to 55 °C/s) in a temperature range of 600–500 °C in accordance with preset welding thermal cycles character for base modes of low-carbon steel arc welding.

Austenite transformation takes place in a ferrite-bainite area at cooling rates up to $w_{6/5}$ = 20 °C/s (Figure 1, curves *1*–*3*). Thus, the most coarse-grained structure is formed in the area of HAZ metal overheating at cooling rates $w_{6/5}$ = 1.5 and 3.0 °C/s. The hypoeutectoid polygonal ferrite and pearlite precipitate along the grain boundaries, and globular bainite of two morphological modifications, i.e. 1850–2030 MPa microhardness low-carbon (high-temperature) and 2140–2430 MPa microhardness low-temperature bainite (see, Figure 2, *a*, *b*), is formed inside the grains. Rarely an acicular ferrite with Widmanstaetten orientation is observed inside the grains.

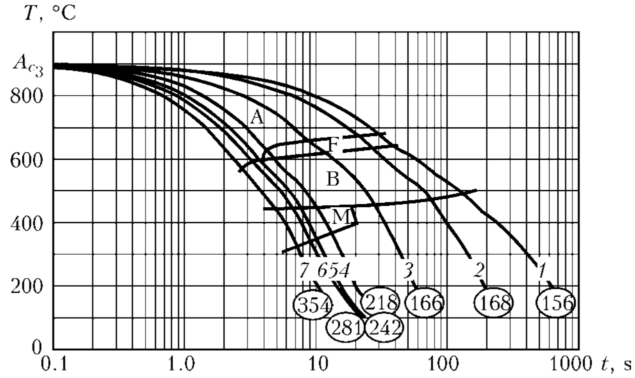

Figure 1. CCT diagram of austenite transformation of 10G2FB steel: *1* — $w_{6/5}$ = 1.5; *2* — 3; *3* — 10; *4* — 30; *5* — 38; *6* — 45; *7* — 55 °C/s; A — austenite; B — bainite; F — ferrite; M — martensite; figures in circles — Vickers hardness

The width of overheating area and size of grain somewhat decrease in cooling with 10 °C/s (see Figure 1, curve *3*). In comparison with 3 °C/s rate the structural changes consist in a reduction of the amount of hypoeutectoid polygonal ferrite and low-carbon bainite (*HV* 1920–1970 MPa) as well as in increase of the amount of higher carbon bainite (*HV* 2360 MPa) (see Figure 2, *c*). It is almost complete suppression of the pearlite transformation and only the single cases of its presence are observed in the structure.

The further decrease of the width of overheating area and size of grain is observed at 20 °C/s cooling rate. The hypoeutectoid polygonal ferrite is rarely found along the grain boundaries in the structure of area of the HAZ metal overheating. The structure of such a metal consists mainly of a low-temperature

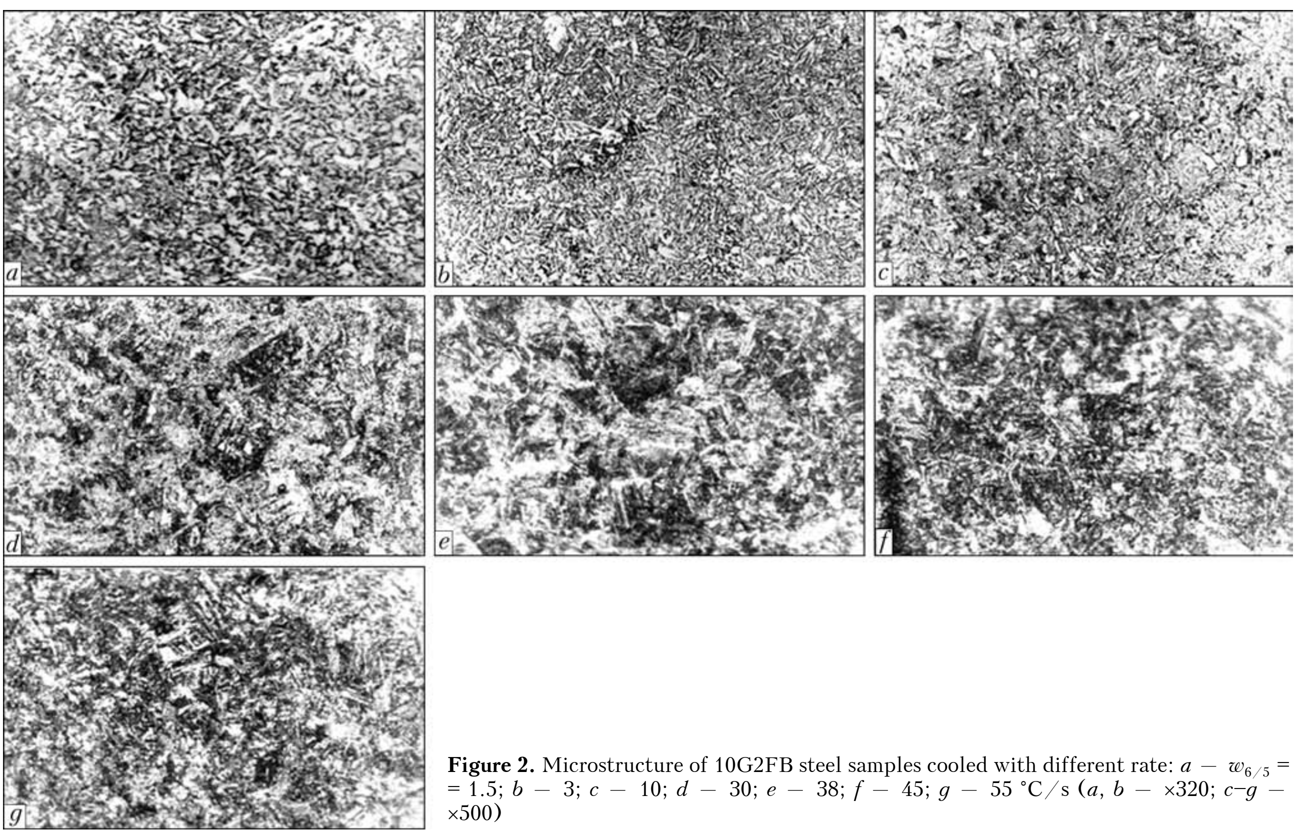

Figure 2. Microstructure of 10G2FB steel samples cooled with different rate: *a* — $w_{6/5}$ = 1.5; *b* — 3; *c* — 10; *d* — 30; *e* — 38; *f* — 45; *g* — 55 °C/s (*a*, *b* — ×320; *c*–*g* — ×500)

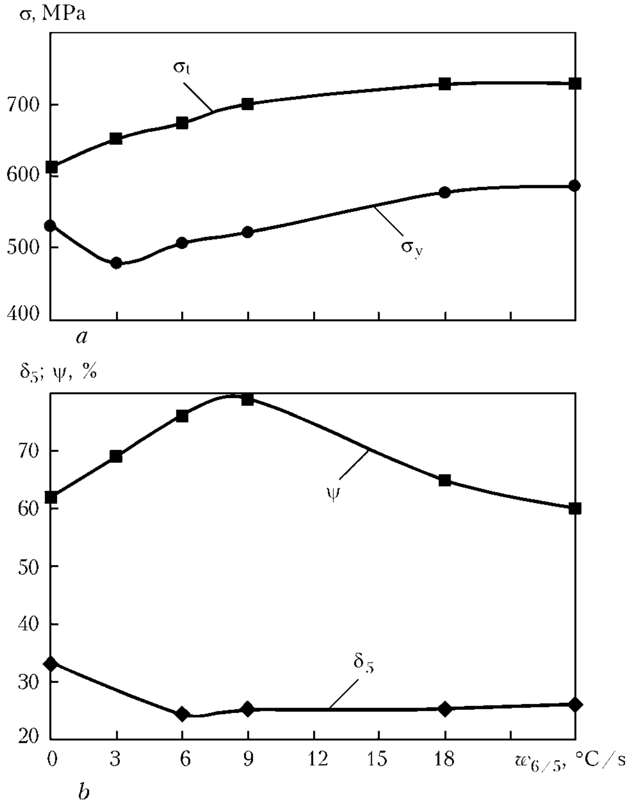

Figure 3. Influence of cooling rate on indices of strength (*a*) and ductility (*b*) of simulated HAZ metal

bainite (globular with *HV* 2100–2360 MPa) plus high-temperature low-carbon bainite (*HV* 1850–2030 MPa) in smaller amount.

The width of overheating area and size of grain at cooling with 30 °C/s rate (see Figure 1, curve *4*) are the same as at $w_{6/5}$ = 20 °C/s. The hypoeutectoid polygonal ferrite is absent in the structure of overheating area and high-temperature bainite (*HV* 1750–2000 MPa) is rarely found. The structure almost completely consists of the globular bainite (*HV* 2140–2280 MPa) (see Figure 2, *d*).

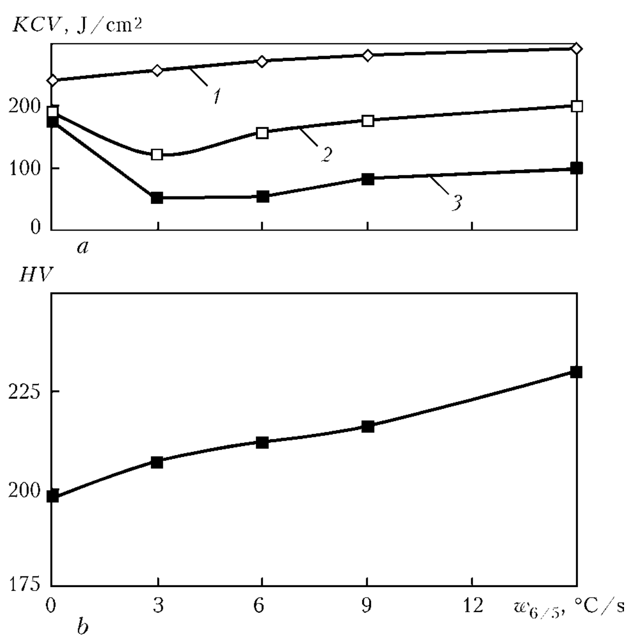

Figure 4. Influence of cooling rate on impact toughness (*1* — +20; *2* — −20; *3* — −40 °C) (*a*) and hardness (*b*) of overheating area of the HAZ metal

An increase of cooling rate from $w_{6/5}$ = 30 up to 55 °C/s (see Figure 1, curves *4*–*7*) develops the conditions for increasing a level of austenite overcooling and decreasing a temperature of its transformation, respectively. At that the diffusion processes are stopped and austenite transformation takes place on a shear mechanism with formation of a bainite- martensite structure. The temperature of beginning of martensite transformation virtually does not change and makes 440 °C while the temperature of transformation ending decreases from 370 to 310 °C at increase of cooling rates. As a result, it can be claimed that the overcooled austenite has a high strength in 10G2FB steel HAZ metal.

The structural components also change in a percentage ratio. Thus, if at $w_{6/5}$ = 30 °C/s cooling rate the metal structure includes 83 % of bainite, 12 % of martensite and non-equiaxed being the rest with *HV* 218 hardness (see Figure 2, *d*) than the structure will consist of 35 % of martinsite and 65 % of bainite with *HV* 354 hardness at maximum cooling rate $w_{6/5}$ = 55 °C/s (see Figure 2, *g*).

The structural transformation differences in 10G2FB steel set depending on welding thermal cycles have an influence on the mechanical properties of welded joints as well as their resistance to brittle and delayed fracture.

A method described in study [5] was used for evaluation of the mechanical properties and brittle fracture resistance of the welded joints. 150 × 12 × 12 mm samples cut from investigated metal and exposed to the welding thermal cycles (heating up to 1250 °C with 200 °C/s rate and cooling with different rates in the range of 24–2.5 °C/s) were used for tensile and impact bend tests. Obtained results show that at investigated cooling rate range mechanical properties (Figure 3) and *KCV* indices of impact toughness of the HAZ metal (Figure 4, *a*) change insignificantly at $w_{6/5} \geq 6$ °C/s. Hence, in welding of 10G2FB steel the minimal allowable cooling rate of the HAZ metal is reasonable to limit by 6 °C/s value taking into account increasing requirements made to low-alloy steels on the level of international standards ($KCV^{-40} > 47$ J/cm^2).

In the specified range of cooling rates the hardness of metal in the HAZ overheating area changes insignificantly and remains in the limits of *HV* 198–230 (Figure 4, *b*).

The resistance of welded joints to formation of cold cracks was evaluated on Implant samples [6] using rigid T-joint samples [7].

The sample-inserts of 6 mm diameter, having a stress concentrator in a form of spiral groove with 0.8 mm step and 0.1 mm radius of rounding, were tested in the first case. The welding of samples, positioned in the holes of 18.7 mm thick base plate being rigidly fast in a test unit, was carried out in following

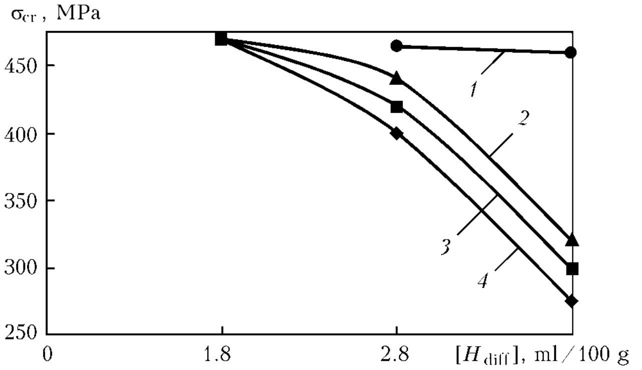

Figure 5. Dependence of critical stresses on concentration of the diffusion hydrogen and cooling conditions of the HAZ metal during testing by Implant method with preheating to 90 (*1*), 60 (*2*), 40 (*3*) °C and without preheating (*4*)

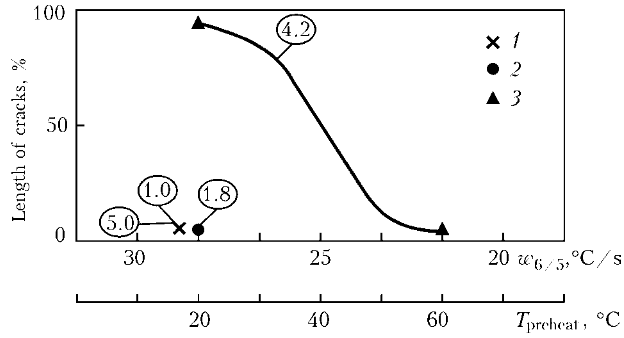

Figure 6. Influence of cooling rate $w_{6/5}$, preheating temperature $T_{preheat}$ and diffusion hydrogen content (figure in circles) on length of cracks in 10G2FB steel joints («rigid T-joint» sample): *1* — flux-cored wire Megafil 821R in CO_2 welding; *2*, *3* — ANP-10 electrodes

mode: I_w = 160 A, U_a = 25 V, v_w = 9 m/h using 4 mm diameter ANP-10 electrodes. The rate of welded joint cooling was varied by changing a preheating temperature of the base plate. Its values were determined on the oscillograms of welding thermal cycles for high-temperature areas of the HAZ metal in the sample-inserts. The amount of diffusion hydrogen in the deposited metal was determined by a pencil test method using a water glycerine solution as a locking liquid. Loading of the sample was performed in a course of its cooling to 100–50 °C temperature after welding.

The welding of «rigid T-joint» samples from 18.7 mm thick steel was performed with ANP-10 electrodes of 4.0 mm diameter as well as in CO_2 with flux-cored wire Megafil 821R of 1.2 mm diameter in modes providing close values of energy input for specified welding methods. The temperature of the samples before welding was changed in the range of 20–90 °C.

The results of Implant samples testing indicate that 10G2FB steel welded joints have a high resistance to cold crack formation in welding without preheating at limited up to 1.8 ml/100 g content of the diffusion hydrogen in the deposited metal. In given case the failure of the samples does not occur under σ_{cr} = = 475 MPa loads (Figure 5) being close to the yield strength of steel. An increase of diffusion hydrogen concentration to 4.2 ml/100 g under given welding conditions leads to a decrease of critical loads to 275 MPa (Figure 5) and, as a consequence, to reduction of welded joint resistance to cold crack formation.

The resistance of welded joints to cold crack formation can be increased using preheating to 90 °C (see Figure 5, curve *1*).

The data of «rigid T-joint» sample tests (Figure 6) correspond well with obtained results. The application of ANP-10 electrodes with low content of diffusion hydrogen up to 1.8 ml/100 g as well as Megafil 821R flux-cored wire in CO_2 welding allows widening the range of cooling rates to $w_{6/5}$ = 20 °C/s providing sufficient resistance to cold crack formation.

Usage of mentioned above welding consumables allows obtaining the weld metal with mechanical properties close to that of 10Kh2FB steel. It is proved by the results of welded joint mechanical tests given in the Table.

The sheets of 10G2FB grade steel was recommended for manufacture of the load-carrying welded metal structures of new generation freight cars based on carried out complex of tests. Specified steel and technological processes for its welding developed together with the specialists of OJSC «Kryukovsky railway car building works» were implemented in manufacture of 13-7024 model flat-car. The high rolling and strength characteristics of given flat model made from 10G2FB steel were confirmed in a course of the full-scale preliminary, acceptance and certification tests carried out by SE «Ukrainian research institute for rail car building». Based on that, it was accepted for serial production and certified in CR of the Certification register system of federal railway transport of Russian Federation by interdepartmental commission.

Mechanical properties of welded joints under investigation

Welding consumable	Weld metal							Welded joint			
	σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	KCV^{+20}, J/cm^2	KCV^{-20}, J/cm^2	KCV^{-40}, J/cm^2	σ_t, MPa	KCV^{+20}, J/cm^2	KCV^{-20}, J/cm^2	KVC^{-40}, J/cm^2
Electrodes ANP-10	485.4	645.4	27.65	69.7	159.0	84.0	56.0	630.5 (failure along BM)	238.5	150.2	92.8
Flux-cored wire Megafil 821R (CO_2)	533.3	573.2	25.80	78.1	256.0	79.5	23.4	573.3 (the same)	213.6	170.0	143.3

Note. Average values of the test results of not less than three samples are given.

More than 1500 flat-cars, manufactured on OJSC «Kryukovsky railway car building works» are successfully used at the railways of CIS and Baltic countries at present time.

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STRENGTH OF BRAZED JOINTS ON HEAT-RESISTANT NICKEL ALLOY INCONEL 718 PRODUCED BY USING PALLADIUM BRAZING FILLER METALS

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Comparative investigations were carried out to study strength of high-temperature vacuum brazed joints on heat-resistant nickel alloy Inconel 718, made by using filler metals of the Pd–Ni–Cr–Si, Pd–Ni–Co–Cr–Si and Pd–Ni–Cr–B systems and experimental filler metal of the Pd–Ni–Cr–Ge system. The experimental filler metal was shown to have a high potential for ensuring specified short- and long-time strength of the brazed joints.

Keywords: *brazing, heat-resistant precipitation-hardening nickel alloy Inconel 718, brazing filler metal, nickel, palladium, short- and long-time strength*

Materials for high-temperature applications include heat-resistant high nickel-based alloys (superalloys), whose high mechanical properties are achieved primarily as a result of solid-solution strengthening and intermetallic and carbide reinforcement. The main contribution is made by dispersed inclusions of the phase based on Ni_3Al intermetallic, i.e. the so-called γ'-phase, the amount of which depends on the aluminium and titanium content of an alloy. Alloys with a low content of the γ'-phase have good weldability, whereas those with a high content of the γ'-phase (e.g. over 60 %) are considered unweldable [1]. It is this fact that usually determines the choice of a joining method for this structure or the other.

However, in practice there may be situations where the choice of the joining method is determined not by a material, but by design peculiarities of a product. Such a case is considered in this article.

A workpiece (centrifugal wheel) is a structure of the cylindrical shape with complex-configuration blades milled out on its external surface, and it was necessary to join a 3 mm thick covering disk to the top surface of the blade by the permanent joining methods. The workpiece material was Inconel 718, which is a well-weldable alloy. However, it was impossible to manufacture a product by arc or electron beam welding because of the absence of access inside the workpiece to perform welding. A variant of welding to the blade through the covering disk by its through penetration with the arc or electron beam was unfeasible, as the width of the blade in the zone where it adjoins the covering disk was only 2 mm. A variant of electron beam heating of the surface of the covering disk to melt the filler metal placed in the gap between the sheet and blade was not approved either. As a result, brazing was chosen as the most promising joining method for this application.

Much research efforts in different countries all over the world have been dedicated to development of filler metals for brazing high alloys, and brazing filler metals of different system have been suggested. These filler metals have one feature in common, consisting in the fact that they are the eutectic-containing alloys. Therefore, to achieve high mechanical properties, it is necessary to apply diffusion holding at high temperatures. Moreover, most of these filler metals are intended for repair brazing, rather than for fabrication of complex structures. So, it was desirable to have a filler metal with a solid solution structure, which would have high strength characteristics at any brazing cycle.

Available are such filler metals based on the Mn–Ni and Ni–Pd systems. The second system holds more promise for vacuum brazing, where it is necessary to provide high corrosion resistance of the brazed joints. Known in the art is filler metal PZhK-1000, which is used in industry to braze high-temperature application parts. This filler metal was applied to make specimens for short-time tensile strength tests at 20 and 550 °C,