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.

1. *OST 32.153–2000*: Rolled metal for freight car bodies of new generation. Introd. 18.09.2000.
2. Semyonov, S.E., Rybakov, A.A., Goncharenko, L.V. et al. (2005) Deformation ageing of pipes of controlled rolling steel. *Tekhnich. Diagnostika i Nerazrush. Kontrol*, **4**, 39–43.
3. Efron, L.I., Nastich, S.Yu. (2006) State of production of sheet and coiled stocks for spiral-welded pipes of strength category up to X1000. *Chyorn. Metallurgiya*, **11**, 68–81.
4. Grigorenko, G.M., Kostin, V.A., Orlovsky, V.Yu. (2008) Current capabilities of simulation of austenite transformations in low-alloyed steel welds. *The Paton Welding J.*, **3**, 22–24.
5. Sarzhevsky, V.A., Sazonov, V.Ya. (1981) Unit for simulation of welding thermal cycles on the base of MSR-75 machine. *Avtomatich. Svarka*, **5**, 69–70.
6. Makarov, E.L. (1981) *Cold cracks in welding of alloy steels*. Moscow: Mashinostroenie.
7. Hrivnak, I. (1984) *Weldability of steels*. Ed. by E.L. Makarov. Moscow: Mashinostroenie.

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,

as well as for long-time strength tests. The specimens were brazed at a temperature of 1230 °C, which is a bit lower than the recommended temperature (1250 °C) for this filler metal [2]. Nevertheless, the short-time strength test results were sufficiently high (Table), whereas the long-time strength values did not always correspond to the specified limit. So, the task was to decrease the brazing temperature by correcting the composition, stabilise the strength values and, what is also very important, improve ductility of the alloy, the rolling of which involves much difficulties. Two ways were tried out: change in alloying of solid solution, and replacement of an element that forms eutectic with palladium. Such an element in filler metal PZhK-1000 is silicon, which does not dissolve in palladium but forms eutectic with it at 4 wt.% (at approximately 810 °C). In this case, three intermetallics Pd_5Si, Pd_9Si_2 and Pd_3Si were formed by peritectic reactions at temperatures of 810, 823 and 1045 °C, respectively [3].

Alloying of palladium with germanium instead of silicon looks more preferable. Solubility of germanium in palladium is approximately 2 % at 775 °C, and is practically absent at 200 °C. Therefore, there are no grounds to fear embrittlement in alloying with germanium within the above limits. At the same time, one might expect strengthening of the palladium-base solid solution in cooling.

Silicon forms solid solution with nickel (approximately up to 5 %) at 700 °C. So, some increase in solubility of silicon when alloying palladium with nickel could be expected. At the same time, solubility of germanium in nickel is approximately 12 % at 200 °C, this evidencing its preference. Solubility of germanium in chromium is also somewhat higher, compared to silicon.

Therefore, germanium can be used as an alloying element in alloys of the Pd–Ni–Cr–Si system in much higher amounts without the risk of embrittlement. It means that these alloys must be more pressure treatable in order to produce thin foils.

The Co–Pd system can be used to produce a filler metal with the solid solution structure. The constitutional diagram of this system comprises minimum at a lower temperature compared to the Ni–Pd system, the range of the concentrations where there is no melting interval being wider. Moreover, no transformations were observed within the melting interval of interest. That is, this diagram looks more favourable on the face of it. In addition, considering an unlimited solubility of nickel and cobalt, one might expect that the partial replacement of nickel by cobalt could also be favourable.

Hence it follows that it would be of interest to study the effect of probable replacement of nickel by cobalt on structure and rolling ability, as well as the effect of germanium on the same parameters.

Short-time tensile strength of brazed joints on alloy Inconel 718 at room and increased temperature

Filler alloy No.	Brazing temperature, °C	Brazing time, min	Tensile strength, MPa, at test temperature, °C	
			20	550
1	1230	5	1275	980
1	1230	10	1310	1060
2	1230	5	1210	950
2	1230	10	1210	970
3	1230	5	1190	
3	1230	10	1260	1030
3	1220	10	1290	1000
4	1080	90	1230	685
4	1085	120	1080	880

This study shows the possibility of producing heat-resistant brazed joints with a high level of static short-time (at room and increased temperature) and long-time strength (at increased temperature and different load values) by an example of precipitation-hardening nickel alloy Inconel 718 and brazing filler metals based on the Ni–Pd system.

The studies were carried out by using multi-component heat-resistant alloy Inconel 718 (IN 718) in the as-received state, having the following nominal composition, wt.%:

(50–55)Ni–(17–21)Cr–18Fe–(4.75–5.50)Nb–
(2.8–3.3)Mo–(0.65–1.15)Ti–
(0.2–0.8)Al–≤1Co–0.06C.

The following consumables were used as filler metals for brazing alloy Inconel 718: commercial filler metal PZhK-1000 (Pd–Ni–Cr–Si system) (filler metal 1), and experimental filler metals based on the Pd–Ni–Co–Cr–Si (filler metal 2), Pd–Ni–Cr–Ge (filler metal 3) and Pd–Ni–Cr–B (filler metal 4) systems (see the Table).

The experimental filler metals were used in the form of rolled foils about 50 μm thick, the standard filler metal — in the form of a foil about 100 μm thick, and filler metal 4 — in the form of a strip (30–50 μm) produced by the super rapid quenching method.

Butt brazed joints were made to conduct metallographic examinations and study mechanical characteristics of the brazed joints. The foil type filler metal was placed in the gap. The specimens were fit up by resistance welding using the TKM-7 machine, with nickel straps fixed to a specimen end face. Brazing of the specimens with the experimental filler metals was carried out at temperatures of 1220–1250 °C for 5–10 min in a vacuum furnace with a work space rarefaction of $1 \cdot 10^{-2}$ Pa by using radiation heating. Brazing parameters were optimised on the butt (Figure 1, *a*,

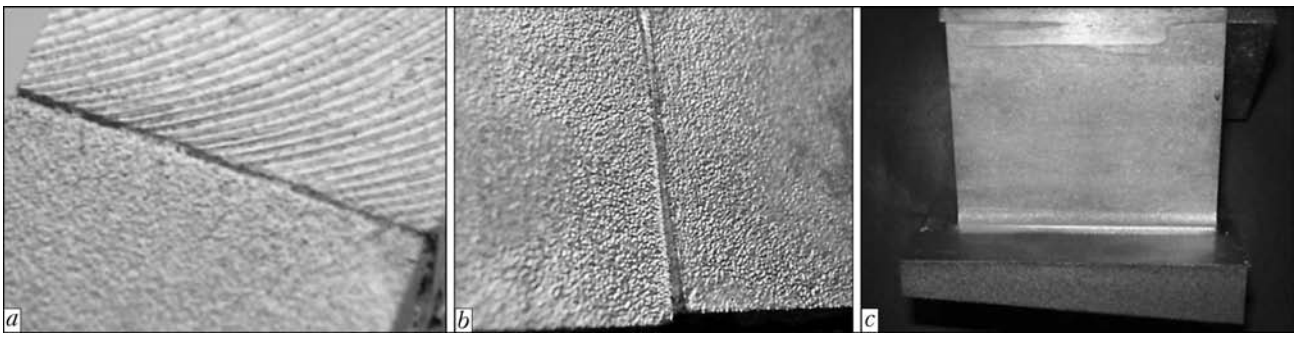

Figure 1. Appearance of butt brazed joints produced, respectively, at T_{br} = 1250, 1230 °C (*a*, *b*), and of T-joint produced at T_{br} = = 1230 °C (*c*)

b) and T-joint specimens (Figure 1, *c*). Standard mechanical test specimens (according to GOST 1497, GOST 9651 and GOST 10145) were turned from the butt joints. The time of brazing using filler metal 4 was increased to 90 and 120 min to ensure diffusion of boron from the seam to the base metal and decrease the amount of borides in the seam.

After brazing and before the mechanical tests the specimens were subjected to heat treatment, leading to strengthening of alloy Inconel 718 as a result of precipitation of the strengthening phases. The heat treatment parameters were as follows: hardening at 1050 °C and holding for 1.5 h, air cooling, ageing at 760 °C and holding for 10.5 h, cooling with furnace to 650 °C at a rate of 55 °C/h, holding at this temperature for 8.5 h, and air cooling. In the strengthened state, the value of tensile strength of alloy Inconel 718 at room temperature was 1338 MPa, and at 650 °C — 965 MPa. Tensile testing machine IMCh-30 was used for short-time tensile tests at room temperature, and machine IM 12A — at 550 °C. Machine MP-3 was used for long-time tensile tests. In the long-time tensile tests the specimens were heated to 550 °C and held for 2 h. And then the required load was applied to them.

As shown by examinations of the brazed butt and T-joint specimens, filler metals 1–3 at a temperature of 1250 °C featured good fluidity and spread well over the substrate of Inconel 718. Flowing out of the filler metal from the brazing gap and its spreading over the surface of the base material was observed. No fillets were formed at the given temperature, and porosity of the brazed seams could be visually observed (see Figure 1, *a*).

The brazing conditions were optimised on butt and T-joint specimens. Decreasing the brazing temperature

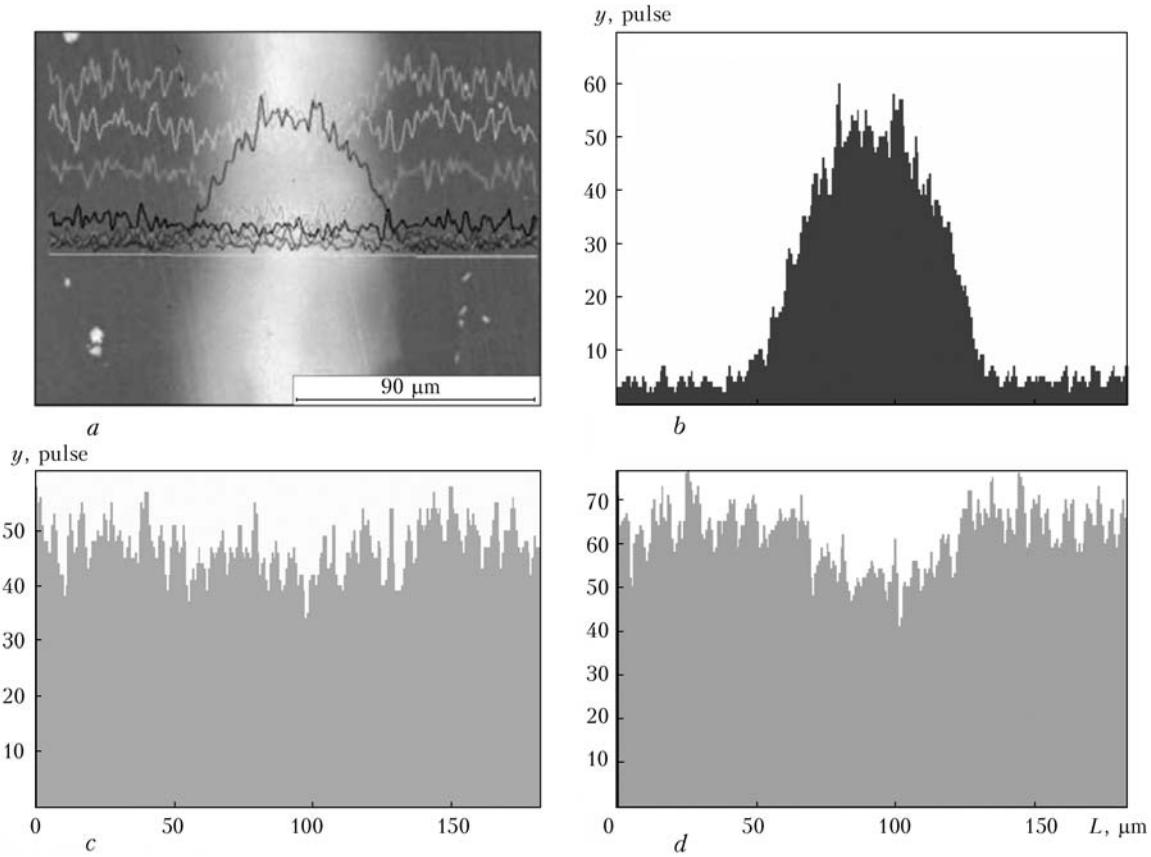

Figure 2. Microstructure of the brazed seam (*a*) and distribution of palladium (*b*), nickel (*c*) and chromium (*d*) in it

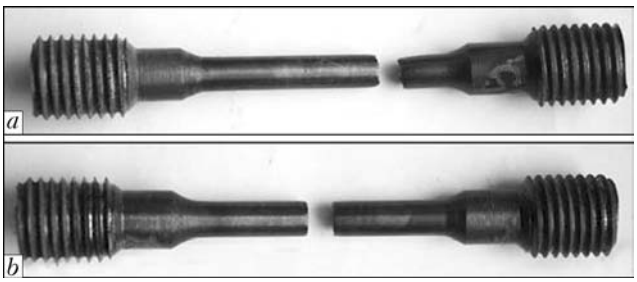

Figure 3. Fracture of brazed specimens after long-time tensile strength tests: *a* — base metal; *b* — seam metal

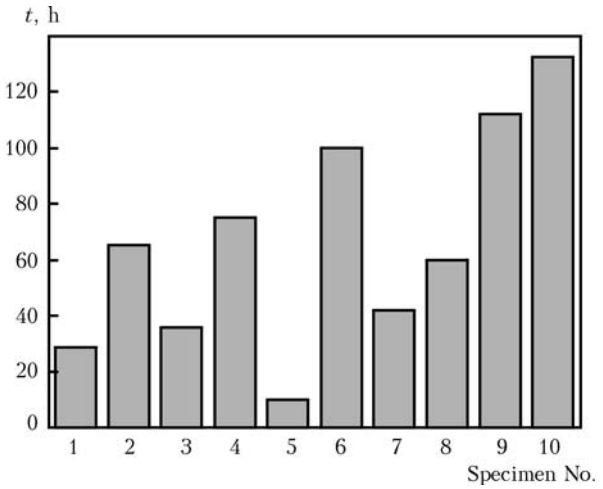

Figure 4. Long-time strength of brazed joints produced by using commercial filler metal Pd–Ni–Cr–Si (specimens 1 and 2) and experimental filler metals Pd–Ni–Co–Cr–Si (3, 4), Pd–Ni–Cr–B (5, 6) and Pd–Ni–Cr–Ge (7–10)

when making the butt joints with brazing filler metals 1 and 2 to 1230 °C, and with brazing filler metal 3 to 1210–1230 °C led to formation of the minimal sizes of the fillets, and caused no erosion of the base metal (see Figure 1, *b*). Brazing of the T-joints featured good formation of thin and dense fillet regions (Figure 1, *c*).

The brazed seams had a homogeneous structure (Figure 2, *a*), nickel was uniformly distributed in the base and seam metals (Figure 2, *c*), the amount of palladium gradually increased in width of the seam from the base metal to the central part of the seam (Figure 2, *b*), and the base metal contained a bit more chromium (Figure 2, *d*).

Results of the short-time tensile strength tests of the brazed joints at room temperature showed that all the brazing filler metals under investigation provided high strength of the joints (from 1080 to 1310 MPa, see the Table). Fracture of the brazed joints occurred in the base metal. The maximal mean values of tensile strength (1292.5 MPa) were obtained by using filler metal 1. The 5 min increase in the brazing time led to a 2.7 and 4.7 % increase in the mean tensile strength values when using filler metals 1 and 3, respectively, the mean tensile strength value for brazing filler metal 3 being 1290 MPa. Filler metal 2 provided the sufficiently consistent strength values, but at a lower level (1210 MPa), independently of the brazing time.

Alloying the Pd–Ni–Cr–Si system filler metal with cobalt increased ductility of the brazed joints approximately twice, this being evidenced by the values of elongation (15.2–16.0 %) and reduction in area (18.0–19.7 %). The high values of ductility and, correspondingly, reduction in area (22.5 %) and elongation (10 %) were obtained by using experimental filler metal 3.

The trend in distribution of strength properties between the filler metals used persisted in the high-temperature tests, which were carried out at a temperature of 550 °C (see the Table). The mean tensile strength values in brazing with filler metals 1 and 3 was approximately identical and equal to 1020 and 1015 MPa, respectively. The lower mean values were obtained when using filler metals 2 (960 MPa) and 4 (783 MPa). The minimal values of strength of the joints brazed with the Pd–Ni–Cr–B system filler metal were caused by the presence of boron, which is characterised by low solubility in nickel. During isothermal brazing it diffused from the seam into the base metal and precipitated along the grain boundaries of the base metal in the form of borides, this having a negative effect on the strength properties.

Maximal ductility at a temperature of 550 °C was provided by the filler metal alloyed with cobalt, the elongation of the brazed specimens ensured by it ranging from 10 to 80 %. Ductility of the brazed joints produced by using the experimental filler metal was a bit lower and equal to 4–12 %.

In the long-time strength tests conducted at a temperature of 550 °C and load of 785 MPa the specimens fractured in the base metal in brazing with filler metal 1 after 29 h, and with filler metal 2 after 75 h (Figure 3, *a*), as well as in the seam metal brazed with filler metals 2–4 (Figure 3, *b*).

The best results were exhibited by the brazed joints produced by using experimental filler metal 3 (Figure 4). Two specimens out of the four ones fractured after the 42 and 60 h tests. Specimens 9 and 10 did not fracture after 112 and 130 h (Figure 4), this being more than two times higher than the required life time.

Filler metal 3 was used to produce the T-joint specimens, which successfully passed the tests under a load of 220 and 300 MPa, their conventional endurance limit being $6.2 \cdot 10^6$ and $8.7 \cdot 10^6$ cycles.

CONCLUSIONS

1. As proved by investigations of the brazed joints on heat-resistant nickel alloy Inconel 718, the boron-containing Pd–Ni–Cr–B filler metal does not allow achieving the required strength and ductility of the brazed joint both at room and increased temperatures.

2. In evaluation of short-time tensile strength at room temperature, an increase in the brazing time (from 5 to 10 min) was found to lead to a 2.7 and 4.7 % increase in mean tensile strength when using

the commercial 1 and experimental 3 filler metals, respectively.

3. The maximal value of short-time tensile strength equal to 1310 MPa (at T_{test} = 20 °C) was achieved in brazing heat-resistant alloy Inconel 718 with the commercial filler metal based on the Pd–Ni–Cr–Si system. However, the brazed joints tested to long-time tensile strength had an insufficient life time within a range of 29–60 h.

4. The experimental Pd–Ni–Cr–Ge filler metal provides the short-time tensile strength value at a level of that of the base metal equal to 1230–1290 MPa, and ensures the consistent results in long-time tensile strength tests at a temperature of 550 °C and load of 785 MPa. The brazed specimens did not fracture after the tests even for 112 and 132 h, this being more than two times in excess of the required life time.

1. Seams, Ch., Hagel, V. (1976) *Heat-resistant alloys*. Moscow: Metallurgiya.
2. (2003) *Reference book on brazing*. Ed. by I.E. Petrunin. Moscow: Mashinostroenie.
3. (1999) *Constitutional diagrams of binary metal system*: Refer. Book. Vol. 3. Ed. by N.P. Lyakishev. Moscow: Mashinostroenie.

FEATURES OF WELD FORMATION AND PROPERTIES OF ALUMINIUM AND MAGNESIUM ALLOY JOINTS UNDER SIMULATED SPACE CONDITIONS

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Features of weld formation in welded joints of aluminium and magnesium alloys made by electron beam welding under the influence of varying gravity forces and low temperatures are given. Influence of the above factors and content of dissolved hydrogen in the base metal on joint strength, defect formation and loss of alloying elements from the weld metal is shown.

Keywords: *electron beam welding, flying laboratory, aluminium alloys, magnesium alloys, gravity conditions, low temperature, liquid nitrogen, dissolved hydrogen, porosity, strength, alloying element evaporation, X-ray microprobe analysis*

Aluminium and magnesium alloys are the main structural materials for aerospace vehicle construction [1–4]. It is probable that already in the near future a real need may arise for application of welding under the conditions of near-earth space or on the Moon surface [5, 6]. These can be mounting-assembly operations in construction of space complexes or repair-preventive operations, associated with guaranteeing long-term service of operating systems [7]. Analysis of the range of welding operations performed in space shows that it will be most often necessary to join materials from 0.5 up to 4.0 mm thick. In this connection, selection of the welding process is an important factor in obtaining an objective assessment of welded joints of aluminium alloys of the mentioned thickness under these conditions. Here it is necessary to apply such a basic criterion as producing high quality welded joints equivalent to the base metal, without pores or cracks, without lowering the ductility of weld or near-weld zone at minimum losses of alloying elements in the welded joint [8]. Taking the above-said into account, application of EBW is the most effective in construction of space structures requiring a high reliability of joints, minimum weight and volume of the used hardware, complete automation of the welding process and its low energy intensity [5].

In fusion welding of aluminium alloys on the ground, the weld and HAZ develop various macro- and microdefects [9], which lead to lowering of joint strength and ductility, and sometimes also to a loss of their tightness [10, 11]. Development of such defects is also possible in welding of these materials under the space flight conditions (presence of microgravity, low temperature, deep vacuum). In addition, initial composition of the used material has a certain influence [12]. The nature of running of a number of physical processes changes significantly: gravity forces are completely or partially absent, role of thermocapillary and chemical convection rises abruptly, phase separation is practically completely absent because of the difference in density, influence of surface tension forces and adhesion increases greatly [13–15].

The purpose of the conducted research consisted in studying the influence of the enumerated factors on the quality of weld formation and properties of welded joints of AD0, AMg3, AMg6, 1201 aluminium alloys and IMV-2 magnesium alloy. Investigations were performed at the change of gravity in the range of g/g_0 from $1 \cdot 10^{-2}$ up to 2 (where g_0 is the free fall acceleration, and g is the effective acceleration) and fixed sample temperature of +20, –100, –120 and –196 °C.

During investigations through-thickness penetration beads on plates and welding of butt joints of the above alloys 2.0 and 2.5 mm thick were performed.