1. Lebedev, V.K., Tabelev, V.D., Pismenny, A.S. (1983) Pressure butt brazing of steel pipelines. *Avtomatich. Svarka*, **9**, 25–27.
2. Lebedev, V.K., Tabelev, V.D., Pismenny, A.S. et al. (1989) High-temperature brazing of tubes for exploration drilling. *Ibid*., **5**, 28–30.
3. Pismenny, A.S., Shinlov, M.E., Buzhenetsky, A.I. (1995) Application of induction braze-welding for joining of oil range pipes. *Ibid*., **12**, 35–38.
4. Pismenny, A.S., Prokofiev, A.S. (2002) Press welding of pipes using activating materials. *The Paton Welding J*., **7**, 19–23.
5. Prokofiev, A.S., Pismenny, A.S., Bondarev, V.A. et al. (2001) Induction braze-welding of no-accessory T-joints in pipes. *Ibid*., **4**, 43–47.
6. (1989) *Handbook of steels and alloys grades*. Moscow: Mashinostroenie.
7. Larikov, L.N., Ryabov, V.R., Falchenko, V.M. (1975) *Diffusion processes in solid phase welding*. Moscow: Mashinostroenie.
8. Pismenny, A.S., Skachko, Yu.N. (2006) High-frequency heating. Heating of metal in pressure welding. In: *Machine building*. Vol. 3, 4: Technology of welding, brazing and cutting. Ed. by B.E. Paton. Moscow: Mashinostroenie.
9. Davidenkov, N.N., Belyaev, S.E., Markovets, M.P. (1945) Caracterization of main mechanical properties of steel using hardness measurement. *Zavod. Laboratoriya*, **10**, 964–973.
10. Sichikov, M.F., Zakharov, B.P., Kozlova, Yu.V. (1947) About determination of mechanical properties without tensile tests. *Ibid*., **12**, 1463–1471.
11. Kuchuk-Yatsenko, S.I., Kazymov, B.I. (1967) Optimal thermal cycle in resistance butt welding of 12Kh1MF steel. *Avtomatich. Svarka*, **6**, 24–27.
12. Forostovets, B.A. (1972) Peculiarities of joint metal structure in fusion welding. *Ibid*., **4**, 9–13.
13. Markovets, M.P. (1979) *Determination of mechanical properties of metal by hardness*. Moscow: Mashinostroenie.
14. Gulyaev, A.P. (1989) To problem of mechanical properties of structural steels. *Materialovedenie i Termich. Obrab. Materialov*, **7**, 23–25.
15. Shmykov, A.A. (1956) *Handbook of heat-treater*. Moscow: Mashgiz.

EVALUATION OF STRESS-STRAIN STATE OF DISSIMILAR WELDED JOINTS FROM 10KH13G18D + 09G2S STEELS

A.I. GEDROVICH[1], **S.A. TKACHENKO**[1] and **I.A. GALTSOV**[2]

[1]V. Dal East-Ukrainian National University, Lugansk, Ukraine

[2]Lugansk National Agrarian University, Lugansk, Ukraine

The features of determination of residual welding stresses on full-scale samples from 10Kh13G18D + 09G2S dissimilar steels are considered. A dependence is established between the size of the zone of plastic strains and longitudinal residual welding stresses on the applied technologies of gas-shielded welding, modes and heat inputs. Positive influence of the technology of cold metal transfer on residual stresses and dimensions of plastic strain zones in dissimilar steel joints is conformed.

Keywords: *residual stresses, welding modes, heat input, welds, near-weld zone, plastic strain zone, magnetic properties*

The cars of diesel-driven and electric trains being used at present time in Ukraine and CIS countries have two doors, car length up to 21.5 m and maximum capacity up to 240 persons. Car bodies are manufactured from low-carbon and low-alloy steels in a form of sheet, bar and plates (including cold bent sections) as well as steel castings separate elements of which, according to statistics, require a repair or change already after 5–6 years of running [1] due to high corrosion.

The main trend of development of a design of the electric and diesel-driven trains of this type is the maximum reduction of structure weight at retention or increase of the amount of seats with simultaneous providing of the necessary technical characteristics [2]. The elements and units of cars are subjected to corrosion, abrasive wear and temperature fluctuations in running along with multiple mechanical and alternating dynamic loads.

Steels having the following mechanical properties: σ_t = 500–550 MPa, σ_y = 400 MPa, δ = 21 % are recommended to use for cars engineering based on experience of running and experimental and theoretic investigations of R&D institutes VNIIZhT and VNIIV. Low-carbon and low-alloy steels used at present time do not fulfill the requirements mentioned above.

There is a world practice experience of application of stainless chromium-nickel steels of austenite class for skin of cars in transport industry with the aim of reaching more long-term resource of their running.

Stainless nickel-free 10Kh13G18D grade steel [3] was developed and recommended for manufacture of cars by the I.P. Bardin TsNII Chermet (Moscow, Russia) instead of 12Kh18N10T and 08Kh18N10 steels in order to provide the necessary requirements and economy of expensive nickel. This steel is characterized by high ductility in pressing and cavitation resistance, therefore it is good in application for body skin, and more cheap low-alloy higher strength 09G2S steels for framework elements of the body structures of cars. Application of 09G2S steel for framework elements of the body allows reducing the thickness of parts from 3.0–8.0 to 2.5–7.0 mm, and usage of 10Kh13G18D stainless steel in cold-worked state — skin thickness from 2.5 to 1.5 mm. As a result, it is expected that at significant increase of the car dimensions the weight will not change and its life time will increase.

It is well-known that a working capacity of welded structures significantly depends on thermo-mechanical properties occurring in area of the weld, values of

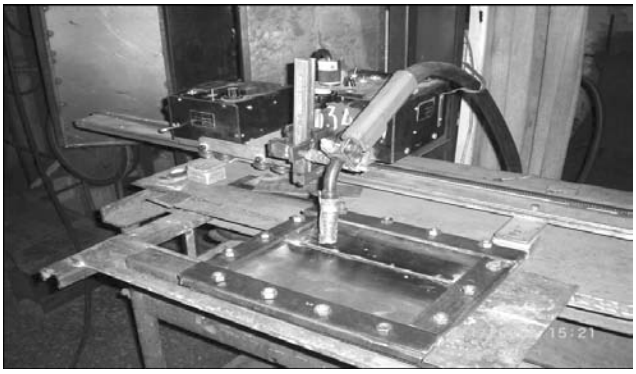

Figure 1. Laboratory unit for welding of the samples from dissimilar steels 10Kh13G18D + 09G2S

plastic strain and level of longitudinal residual stresses σ_x [4, 5], which in the welded joints can reach a yield strength σ_y of a metal to be welded and more, and transverse stresses at two-dimensional stressed state can not be higher than $0.75\sigma_y$ [4]. A purpose of the present paper, therefore, is to investigate the dependences of formation of zones of plastic strains and longitudinal residual stresses in welding of 10Kh13G18D + 09G2S dissimilar steels.

The study was carried out in experimental way. Numerous investigations showed [3–8] that the residual welding stresses, which can exceed the material yield strength in welding of low-carbon structural steels and reach the yield strength [6] in welding of Cr–Mn corrosion-resistant steels, are formed in welded joints and units as a result of effect of welding thermal-deformation cycle. The longitudinal stresses are tensile as a rule and being the result of different level plastic strain in welding heating and cooling [5]. The dependences of their distribution in an active zone are studied well enough and plastic strain in it reaches 1–2 % [4, 5] in welding structural steels (St3, 14G2 and etc.).

The differences in formation of the longitudinal residual stresses σ_x in welding of pearlite steel 09G2S and austenite steel 10Kh13G18D are conditioned by the fact that austenite stainless steels have a low heat conduction coefficient, high coefficient of linear expansion and tendency to hardening. The presence of plastic strain and fields of high residual first-kind tensile stresses leads to austenite decomposition, i.e. phase transformation and occurrence of α-phase, in the weld zone and near-weld zone according to study [6]. Distribution of the residual welding stresses [6, 7] in this zone can be qualitatively considered on a content of α-phase in the welded joint. In this study a zone of plastic strains on the area of welded joint from the side of pearlite steel was determined on yield bands [4] and longitudinal residual stresses — on a change of magnetic properties of steel (magnetic permeability) [5].

The plates of 125 × 300 × 1.5 mm size (steel 10Kh13G18D), the thickness of which corresponded to the thickness of metal of the car skin, and 125 × × 300 × 2.5 (7) mm size plate from steel 09G2S were used for investigations. Higher thickness 7 mm corresponded to the joints of skin with the car body frame. The samples were previously ground and polished. Polished samples were lap assembled and their welding was carried out using semi-automatic machines A-547U and TRS-3200 CMT (Figure 1). At that Sv-08Kh20N9G7T grade welding wire of 1.2 mm diameter and shielding gas mexture ($Ar + CO_2$) in a «conductor» assembly jig as well as CMT technology were used.

The following conditions were applied in welding by semi-automatic machine: A-547U: I = 110–120 A; U_a = 20–21 V; v_w = 17–22 m/h; q_w = 3350 J/cm; and I = 106 A; U = 15.9 V; v_w = 38.2 m/h; q_w = = 1105 J/cm for TRS-3200 CMT semi-automatic machine.

The zone of plastic strains *Bn2* (Figures 2 and 3) on 10Kh13G18D austenite steel was etched after welding by Fray etching agent, then after the zone boundaries became apparent the etching agent was washed out with alcohol, the sample was dried and etching by Amberg–Kalling etching agent carried out. After the boundaries of plastic strain became clearly apparent the sample was wiped out by alcohol and dried.

The zone of plastic strains *Bn1* (see Figures 2, 3) in the area of welded joint from the side of 09G2S pearlite steel was determined on yield bands — Chernov–Luders lines. Longitudinal residual stresses σ_x in

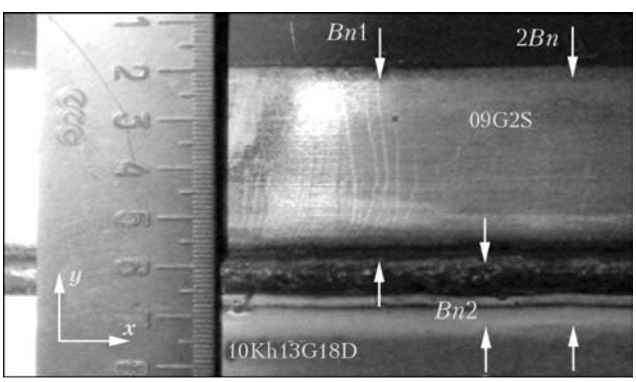

Figure 2. Sizes of the plastic strain zones *Bn1*, *Bn2*, *2Bn* of a sample of lap welded joint from steels 10Kh13G18D (δ = 1.5 mm) and 09G2S (δ = 2.5 mm) in welding by A-547U semi-automatic machine

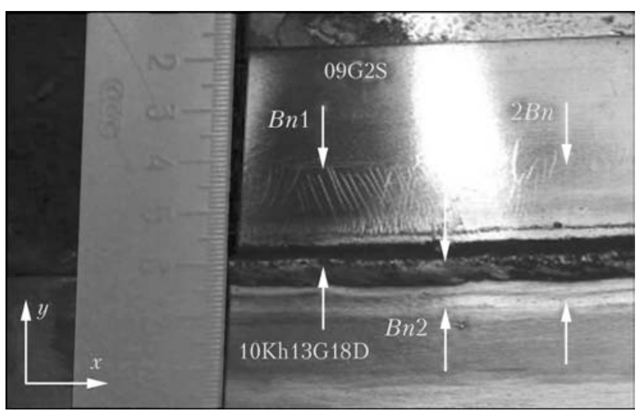

Figure 3. Sizes of the plastic strain zones *Bn1* and *Bn2* of a sample of lap welded joint from steels 10Kh13G18D (δ = 1.5 mm) + 09G2S (δ = 2.5 mm) in welding by TRS-3200 CMT semi-automatic machine

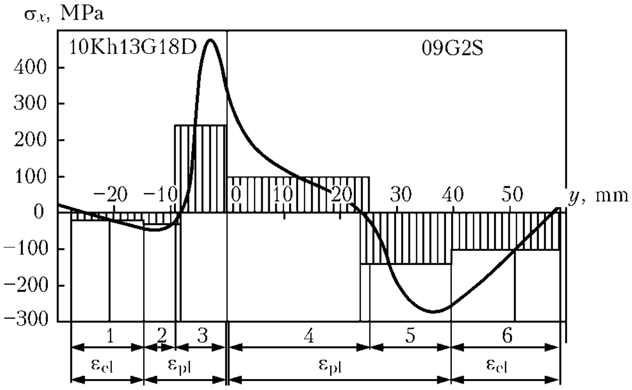

Figure 4. Character stressed zones of the welded joint from steels 10Kh13G18D (δ = 1.5 mm) + 09G2S (δ = 2.5 mm) in welding by A-547U semi-automatic machine (for 1–6 see the text)

10Kh13G18D steel were evaluated according to the procedures of study [5]. The common zone *2Bn* of plastic strains of dissimilar joint 10Kh13G18D + 09G2S was determined after etching in the central part of the welded joint with a portable binocular microscope MPB-3. An error of measurement made 0.025 mm. Five measurements were performed to calculate the average value. The end areas of 60 mm length were not considered in order to eliminate an influence of end effect. The experiment was repeated three times. The average value of *2Bn* zone, therefore, was determined on data obtained from 15 observations. Photography was carried out by digital camera.

Distribution of longitudinal residual stresses σ_x along the *OY* axis was determined after the welded joint complete cooling. The tensile stresses appear in austenite steel 10Kh13G18D since it has significantly larger reduction of volume in comparison with 09G2S ferrite-pearlite steel, and compression stresses compensating them (Figure 4) form in the area of ferrite-pearlite steel. The fields of residual stresses in single and dissimilar joints are close to each other and differ only by some displacement of diagram in the direction of steel with smaller heat conduction (in this case in the direction of austenite steel) (Figure 5). These stresses in most cases cannot be relieved by heat treatment and develop a danger of service failure as well as change of structure in time. After making a comparison of the diagram of residual stresses σ_x and sizes of the zone of plastic strains in welded joints obtained in welding of samples by A-547U and TRS-3200 CMT semi-automatic machines, the following conclusions can be done:

- reduction of the level of tensile stresses σ_x by 5.3 % and size of the plastic strain zone *2Bn* by 45.5 % is observed in samples from 10Kh13G18D (δ = = 1.5 mm) + 09G2S (δ = 2.5 mm) steels in welding with semi-automatic TRS-3200 CMT machine;
- reduction of the level of tensile stresses σ_x by 5.3 % and size of the plastic strain zone *2Bn* by 21.3 % takes place in samples from 10Kh13G18D (δ = = 1.5 mm) + 09G2S (δ = 7 mm) steels in welding with semi-automatic TRS-3200 CMT machine.

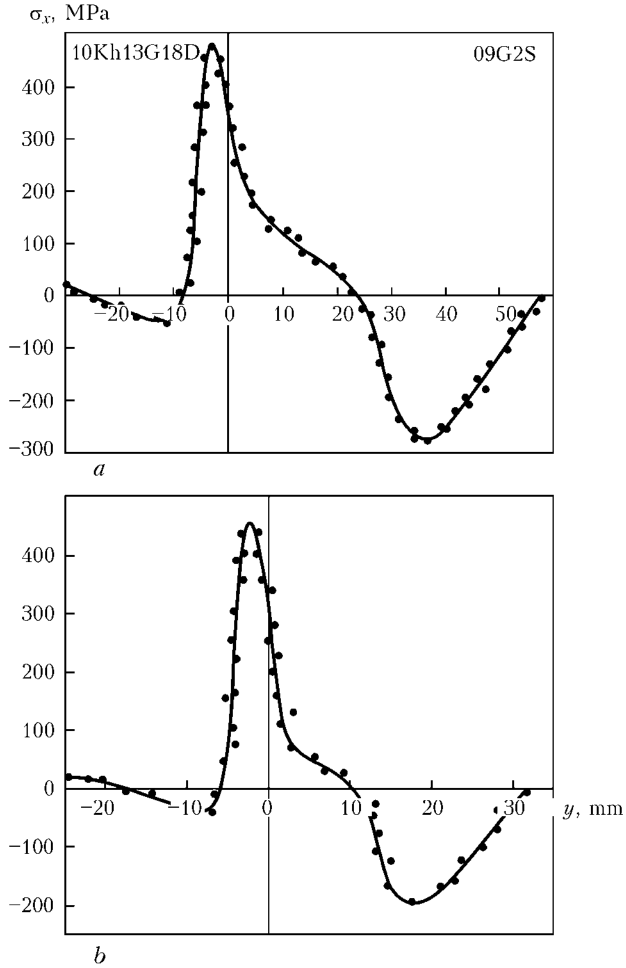

Figure 5. Diagrams of residual stresses σ_x in the welded joints from steels 10Kh13G18D (δ = 1.5 mm) + 09G2S (δ = 2.5 mm) obtained with A-547U (*a*) and TRS-3200 CMT (*b*) semi-automatic machines

Based on analysis of the plastic strain zones *2Bn* of the welded joint from 10Kh13G18D (δ = 1.5 mm) and 09G2S (δ = 2.5 mm) and diagrams of residual stresses σ_x in samples welded by A-547U semi-automatic machine (see Figure 4) the following stress zones can be outlined:

1 — zone of compression stresses σ_x (≈ 16 mm) is situated in the HAZ base metal (from the side of austenite steel) and has no plastic strain in welding. The level of maximum compression stresses is –45 MPa, average value is –27 MPa;

2 — zone of maximum compression stresses σ_x (≈ 6 mm). The metal is also situated in HAZ and suffers from the plastic strain in the process of welding cycle. The level of maximum compression stresses is –50 MPa, average value is –40 MPa;

3 — zone of maximum tensile stresses σ_x. The weld and near-weld zone (≈ 9 mm) from the side of austenite steel are situated in the area of plastic strains. The level of maximum tensile stresses is 475 MPa, average value is 250 MPa;

4 — zone of maximum tensile stresses σ_x. The weld and near-weld zone (width of ≈ 23 mm) from the side of ferrite-pearlite steel are situated in the area of plastic strains. The level of maximum tensile stresses is 350 MPa, average value is 100 MPa;

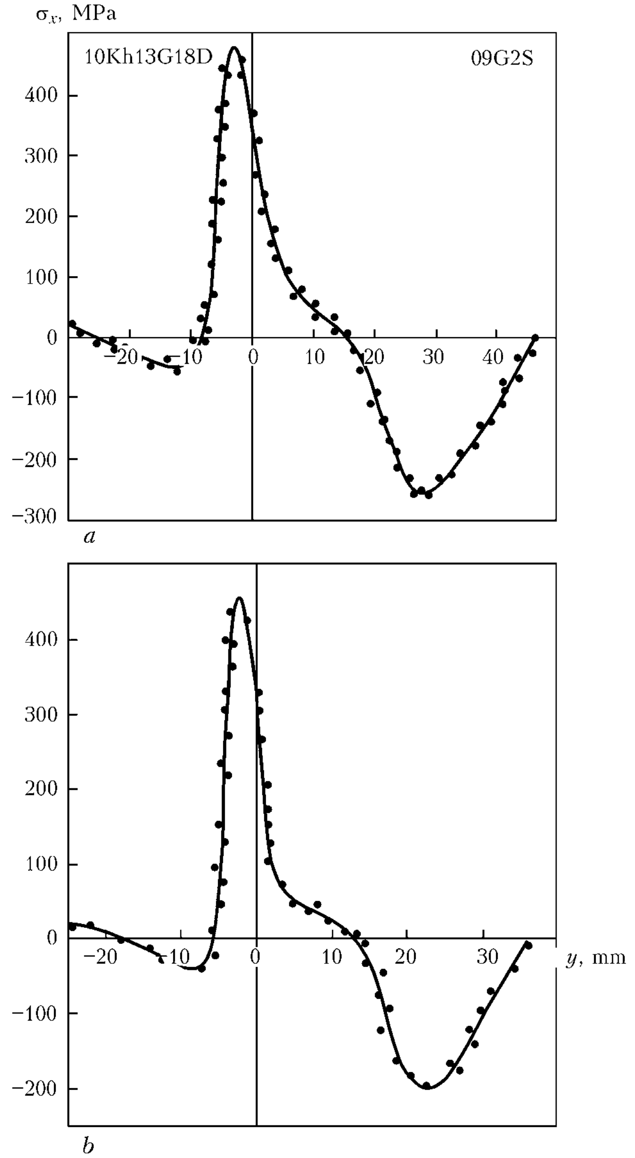

Figure 6. Diagrams of residual stresses σ_x in the welded joints from steels 10Kh13G18D (δ = 1.5 mm) + 09G2S (δ = 7 mm) obtained with A-547U (*a*) and TRS-3200 CMT (*b*) semi-automatic machines

5 — zone of maximum compression stresses σ_x ($\approx$ 17 mm) are situated in the base metal which suffers from the plastic strains in the process of welding. The level of maximum compression stresses is −270 MPa, average value is −140 MPa;

6 — zone of compression stresses ($\approx$ 19 mm) are situated in the base metal, which undergoes no plastic strains in welding. The level of maximum compression stresses is −230 MPa, average value is −100 MPa.

It follows from the analysis of obtained experimental data that the maximum tensile residual stresses, which 6.6 % higher over the yield strength of the material (σ_y = 450 MPa), are observed in zones 3 and 4. The plastic strain zones are identical to the described above and differ only in sizes of the plastic strain zones and values of stresses in welding of the samples using TRS-3200 CMT semi-automatic machine.

Theoretical calculation on a method described in study [4] was carried out in order to verify integrity of the data obtained as a result of the experiments carried out for determination of the size of zones of plastic strains *2Bn* which appear in welded joints from dissimilar steels (10Kh13G18D + 09G2S). Data obtained in welding of the samples using semi-automatic machines A-547U and TRS-3200 CMT were taken as a basis for calculation and comparative analysis.

Comparison of the data on the size of plastic strain zones showed that the disagreement between the experiment and theoretic calculation does not exceed 5 %.

CONCLUSIONS

1. Size of the plastic strain zone *2Bn*, which consists of the zone of plastic strain *Bn1* (HAZ from the side of ferrite-pearlite steel) and *Bn2* (HAZ from the side of austenite steel), where *Bn1* > *Bn2*, was determined in experimental way in welding of dissimilar steels.

2. Presence of significant longitudinal tensile stresses σ_x in HAZ metal from the side of austenite steel and compression stresses in HAZ metal from the side of ferrite-pearlite steel was determined.

3. Advantage of application of CMT technology for achievement of minimum plastic strain zone in welded joints from dissimilar steels was verified in experimental way.

1. Basov, G.G., Golubenko, A.L., Mishchenko, K.P. (2003) Conception for development of type of advanced motorized-car rolling stock for Ukrainian railways. In: *Transact. on problems of implementation and mastering of production in Ukraine of motorized-car rolling stock based on unified intermediate car*. Lugansk: Mashinostroenie.
2. Bereznitsky, V.A., Sergienko, N.I., Shcherbakov, V.P. (2003) Application of stainless and low-alloy steels for cars of diesel- and electric trains of maximum passenger capacity. *Ibid*.
3. Goldshtejn, M.I., Grachev, S.V., Veksler, Yu.G. (1985) *Special steels*. Moscow: Metallurgiya.
4. Gedrovich, A.I. (1998) *Plastic strain in welding*. Lugansk: UUGU.
5. Kasatkin, B.S., Prokhorenko, V.M., Chertov, I.M. (1987) *Stresses and strains in welding*. Kiev: Vyshcha Shkola.
6. Gedrovich, A.I., Tkachenko, A.N., Tkachenko, S.M. et al. (2007) Peculiarities of structure and properties formation in 10Kh13G18D steel fusion zone. *The Paton Welding J.*, **4**, 20–24.
7. Sagalevich, V.M., Saveliev, V.F. (1986) *Stability of welded joints and structures*. Moscow: Mashinostroenie.
8. Kurdyumov, G.V., Utevsky, L.M., Entin, R.I. (1977) *Transformations in iron and steel*. Moscow: Nauka.