Structure and Phase Composition of 09G2S Steel Modified by Different Types of Welding

Aleksandr N Smirnov 1,2,a, Natal'ya A Popova 3,4, Elena L Nikonenko 3,5, Evgenii A Ozhiganov 1,2, Nikolai V Ababkov 1,2, Nina A Koneva 3

1 OOO ‘Kuzbass Center for Welding and Control’, 33/2, Lenin Str., Kemerovo, 650055, Russia
2 T.F. Gorbachev Kuzbass State Technical University, 28, Vesennyaya Str., Kemerovo, 650000, Russia
3 Tomsk State University of Architecture and Building, 2, Solyanaya Sq., Tomsk, 634003, Russia
4 Institute of Strength Physics and Materials Science SB RAS, 8/2, Akademicheskii Ave., Tomsk, 634021, Russia
5 National Research Tomsk Polytechnic University, 30, Lenin Ave., Tomsk, 634050, Russia

E-mail: a agalvas.kem@gmail.ru

Abstract. The paper presents the transmission electron microscopy (TEM) investigations of the structure and phase composition of the type 09G2S weld steel modified by four types of welding, namely: electrode welding and electropercussive welding both with and without the introduction of artificial flaws. Artificial flaws are aluminum pieces. TEM investigations are carried out within the heat-affected zone, i.e. between the deposited and base metal, at 0.5 mm distance to the former. Welding electrode of the type E50A is used for welding 09G2S steel specimens. It is shown how the type of welding affects the steel morphology, phase composition, defect structure and its parameters. After each type of welding, the dislocation structure is polarized. This, however, does not cause internal stresses which can destroy the specimen.

Introduction

At present, the technological development in all industries is impossible without welding applications. Welded joints are part of the majority of structures. Modern technology utilizes many types of welding [1-10]. However, each type has its own strengths and weaknesses. The structure and phase composition of metal which form during welding affect physical-mechanical properties of final products [11-14]. Changes in the structure and phase composition of welded items caused by a long-term operation, and particularly deformations they are often subjected to, might lead to negative consequences [11, 13, 14]. Therefore, the quality improvement and the reliability of welded joints are being considered as a high priority until now. The solution to these problems is based on knowledge of processes that determine the formation and properties of welded joints. This is the case of the heat-affected zone (HAZ) between the deposited and base metal. It is HAZ that provides dangerous stress concentrators which lead to the formation of cracks and various defects [14], thereby decreasing the strength and safety of welded items [11-13]. Knowledge of the structure and phase composition of
material, and particularly HAZ, could be useful not only for the assessment of strength properties of welded item, but also for predicting the behavior of welded joint during its operation.

The main objective of the paper is to explore HAZ (between the deposited and base metal) structure and phase composition depending on the type of welding.

**Materials and methods**

Four types of welding were used to investigate the welded joint, namely: 1) electrode welding without the introduction of artificial flaws; 2) electrode welding with the introduction of artificial flaws; 3) electropercussive welding without the introduction of artificial flaws; 4) electropercussive welding with the introduction of artificial flaws. Artificial flaws represented pieces of aluminum. The type 09G2S steel was used as a weld material the chemical composition of which is summarized in the Table below. Electrode of the UONI-13 brand (type E50A) was used for welding the type 09G2S steel specimens. Its chemical composition is also given in the Table. The steel specimens were plates having the test portion of 200×15×4 mm³ in size. The welded joint occupied the central part of the test portion of the specimen. Specimens were preliminary macroetched with a 4 % aqueous HNO₃ solution to visualize the deposited metal and heat-affected zones. The width of the welded joint did not exceed 12 mm, while that of HAZ was not over 5 mm.

**Table. Chemical composition of steel and welding electrode (wt.%)**

|       | 09G2S | E50A |
|-------|-------|------|
| C     | 0.09  | 0.09 |
| Si    | 0.5–0.8| 0.42 |
| Mn    | 1.3–1.7| 0.83 |
| Ni    | ~0.3  | –    |
| S     | ~0.04 | 0.022|
| P     | ~0.035| 0.024|
| Cr    | ~0.3  | –    |
| N     | ~0.008| –    |
| Cu    | ~0.3  | –    |
| As    | ~0.08 | –    |
| Fe    | ~96–97| –    |

A method of electroerosion cutting was used to obtain the test foils. They were cut parallel to the welded joint. The transmission electron microscopy (TEM) investigations were performed nearby the HAZ at 0.5 mm distance to the deposited metal. Observations of thin foils were carried out on an EM-125 transmission electron microscope with 125 kV accelerating voltage and 25000× magnification. TEM images are used to measure the volume fractions of the steel morphology within the HAZ; the size of α-phase fragments; size, density distribution and volume fractions of carbide particles; scalar and excess dislocation densities; bending-torsion amplitude of the crystal lattice; amplitudes of internal stresses.

Phase identification was carried out using the known methods. With this view, microdiffraction patterns calculated by the reference values of the crystal lattice parameters were used. The size and volume ratios of observed phases were measured using the TEM images confirmed by the microdiffraction patterns and dark-field images obtained in reflections of the respective phases. Linear sizes and scalar dislocation density of the structural elements were detected on micrographs using the secant method in accordance with the standard procedures. Two types of internal stresses are determined: 1) shear stress (stress fields created by the dislocation structure) and 2) long-range or local stress [15].

**Results and discussions**

It has been found that the steel matrix in the weld metal is α-phase after each type of welding, *i.e.* a solid solution of carbon and alloying elements in α-Fe with the body-centered cubic (BCC) crystal system. Depending on the welding type, the structural components of α-phase are lamellar perlite, ferrite and martensite as illustrated in Fig. 1.

Ferrite is mostly fragmented after using each type of welding (Fig. 1a). A fragmented substructure consists of dislocation subboundaries (fragment’s walls) and the inner space with or without dislocations [16]. The fragments are mainly isotropic [11], *i.e.* $L/D \approx 1$, where $L$ and $D$ are respectively longitudinal and transverse sizes of the fragment. These fragments contain a reticulated dislocation structure. Rounded carbide particles – cementite – are observed on these dislocations. After using various types
of welding, the average size of these particles ranges between 10-20 nm, and their volume fraction in fragmented ferrite is not over 0.5%.

After each type of welding, martensite is observed either in the form of parallel laths which are not practically misoriented relative to each other (Fig. 1b) or separate lamellae (Fig. 1c). Unlike lamellar martensite which forms during the electropercussive welding, lath martensite forms at electropercussive welding with the introduction of artificial flaws. At the interface between martensite laths, lamellar cementite particles are present. They are ~15×40 nm in size and the volume fraction of them is not over 1%. Inside martensite laths austenite ($\gamma$-phase) is observed in the form of separate islands. Its volume fraction is ~3%. Cementite particles are not found in lamellar martensite, but there are austenite ($\gamma$-phase) layers. The average size and the volume fraction of these layers is 0.3×0.07 μm and ~3% respectively. After using the electrode welding without the introduction of artificial flaws, martensite is not found in the weld metal.

Perlite is lamellar regardless of the type of welding. As Tushinskii et al. report in [17], lamellar perlite is a conglomerate of alternating parallel (or almost parallel) layers of ferrite and cementite. In other words, lamellar perlite is a layered aggregate with clearly marked anisotropy conditioned by the crystalline structure and contrasted properties of consisting phases. Cementite is a solid and brittle phase, while ferrite is soft and plastic. The contrast observed in mechanical properties of cementite and ferrite is stipulated by their chemical composition and the type the crystal lattice. Thus, ferrite has a BCC crystal system, while cementite being a chemical compound of carbon and iron (Fe₃C), has an orthorhombic lattice. Perlitic grains usually concentrate inside the structure of fragmented ferrite (Fig. 1 d) and have the size of not over 0.5 μm.

Figure 2 demonstrates the dependence of the quantitative parameters of the weld metal structure on the type of welding. One can see that the welding process affects, first of all, the structural components

![Fig.1. TEM images of structural elements of weld metal: a – fragmented ferrite (electrode welding); b – lath martensite (electrode welding with introduction of artificial flaws); c – lamellar martensite (electroperccussive welding); d – perlite (electroperccussive welding with introduction of artificial flaws) Fig.1. TEM images of structural elements of weld metal: a – fragmented ferrite (electrode welding); b – lath martensite (electrode welding with introduction of artificial flaws); c – lamellar martensite (electroperccussive welding); d – perlite (electroperccussive welding with introduction of artificial flaws)](image-url)
of the weld metal. Thus, the introduction of artificial flaws during the electrode and electropercussive welding results in the reduction of the volume fraction of ferrite and the increase in that of perlite and particularly martensite.

We already mentioned above that the dislocation structure is reticular in each structural component. The measurements show that the scalar dislocation density depends on the welding type (see Fig 2). The dislocation structure of steel is polarized after welding that is indicated by bend extinction contours observed in each structural steel component. Measurements of bend extinction contours allow detecting the bending-torsion amplitude of the crystal lattice [15]. In general, the bending-torsion amplitude $\chi$ can be found from $\chi = \chi_{pl} + \chi_{el}$, where $\chi_{pl}$ is its plastic component and $\chi_{el}$ is its elastic component. Experiments show that during the electrode welding with and without the introduction of artificial flaws, the bending-torsion amplitude $\chi$ in each structural component and the material as a whole, is described only by the plastic component, i.e. $\chi = \chi_{pl}$. This indicates to its plasticity and $\rho > \rho_{\pm}$ and $\sigma_{sh} > \sigma_{l}$ are true [15], i.e. the scalar dislocation density $\rho$ is higher than the excess dislocation density $\rho_{\pm}$, and the shear stress amplitude $\sigma_{sh}$ exceeds the long-range stress amplitude $\sigma_{l}$. The electropercussive welding with and without the introduction of artificial flaws leads to the plastic-elastic bend of the crystal lattice, i.e. $\chi = \chi_{pl} + \chi_{el}$. The contributions of $\chi_{pl}$ and $\chi_{el}$ to different structural components are different. It is observed that $\rho < \rho_{\pm}$ and $\sigma_{sh} < \sigma_{l}$ in the whole material (Fig. 2).

According to Fig. 2, the weld metal structure subjected to the electrode welding is characterized by the lowest values of $\rho$, $\rho_{\pm}$, $\sigma_{sh}$ and $\sigma_{l}$. This means that the hardening of weld metal in this case will be the lowest as compared to other types of welding. The introduction of artificial flows in electrode welding enhances the quantitative parameters ($\rho$, $\rho_{\pm}$, $\sigma_{sh}$ and $\sigma_{l}$) of the structure, thereby leading to a stronger hardening of material [15]. The electrode welding with the introduction of artificial flows
modify the weld metal structure more significantly than the electropercussive welding. At last, at the electropercussive welding with the introduction of artificial flows, the amplitude of long-range internal stresses is practically two times as high as the amplitude of shear stress (see Fig. 2) on the average in the material. On the one hand, this hardens the material, and on the other facilitates microcracking in the weld metal.

Conclusions

TEM investigations were conducted for the structure and phase composition of the type 09G2S weld steel modified by four types of welding, namely: electrode welding and electropercussive welding both with and without the introduction of artificial flows. The following results were obtained:
- Regardless of the type of welding, lamellar perlite, ferrite and martensite are the structural components of the weld metal. Their volume fraction depends on the type of welding;
- The introduction of artificial flaws during any type of welding leads to the destruction and elimination of perlitic component and the increase in the amount of fragmented structure in ferrite;
- The steel structure after the electrode welding has the lowest values of $\rho$, $\rho_s$, $\sigma_{sh}$, and $\sigma_l$ as compared to other types of welding;
- The introduction of artificial flaws during any type of welding leads to the decrease in the quantitative parameters ($\rho$, $\rho_s$, $\sigma_{sh}$, and $\sigma_l$) of the defect structure in each structural component;
- At the electropercussive welding with the introduction of artificial flows, the amplitude of long-range internal stresses is practically two times as high as the amplitude of shear stress on the average in the material. On the one hand, this hardens the material, and on the other facilitates microcracking in the weld metal.

References

[1] Ju. Hu, et al. Structure and performance of welding joint of Q235 steel welded by SHS welding, Front. Mech. Eng. China. 2010. No. 5 (2). Pp. 189-193.

[2] B.A. Grinbreg, Elkina O.A., Antonova O.V., et al. Peculiarities of Formation of Structure in the Transition Zone of the Cu-Ta Joint Made by Explosion Welding. The Paton Welding Journal, 2011. No. 7. Pp. 20-25.

[3] V.E. Rubtsov, S.Yu. Tarasov, A.V. Kolubaev One-Dimensional Model of Inhomogeneous Shear in Sliding. Physical Mesomechanics. 2012. V.15. No. 5-6. Pp. 337-341.

[4] S.F. Gnyusov, V.A. Klimenov, Yu.V. Alkhimov, et al. Formation of Ti Structure and Corrosion Resistant Steel at Laser Welding. Svarochnoe proizvodstvo [in Russian]. 2012. No. 1. pp. 17-22.

[5] N.V. Boiko, et al., Structure of titanium alloy austenitic steel welds formed by pressure welding with intermediate coatings, Met. Sci. Heat Treat. 2013. V.54. pp. 9-10.

[6] F. Foadian, M. Soltanieh, M. Adeli, M. Etminanbakhsh, A Study on the formation of intermetallics during the heat treatment of explosively welded Al-Ti multilayets, Metal. Mater. Trans. A. 2014. V. 45A. No. 4. pp.1823–1832.

[7] M.Yu. Kollerov, S.D. Shlyapin, Gusev D.E et al., Metally [in Russian]. 2015. No. 6. pp. 32-36.

[8] E.S. Konovalenko, et al., Izvestiya vuzov. Fizika [in Russian]. 2015. V.58. No. 6-2. pp. 137-141.

[9] N.M. Rusin, A.L. Skorentsev, E.A. Kolubaev Dry Friction of Pure Aluminum Against Steel, Journal of Friction And Wear 2016. V. 37. No. 1. pp. 86-93.

[10] N.A. Popova, et al., Structure and Phase Composition of Deformed Heat-Affected Zone of the Weld Steel St3, AIP Conf. Proc. 2016. V.1772. P. 030006 (1-6).

[11] A.N. Smirnov, E.V. Kozlov, Substructure, Internal Stress Fields and Destruction of Steam Lines in Steel 12KhfMF [in Russian]. Kemero: Kuzbassvuzizdat, 2004. 163 p.

[12] V.P. Gagauz, et al., Structure, Phase Composition and Mechanical properties of Thick Welded Joints [in Russian]. Novokuznetsk: SibGIU, 2008. 150 p.

[13] A.N. Smirnov, et al., Damageability of Welded Joints, Spectral-Acoustic Control [in Russian]. Moscow: Mashinostroenie, 2009. 240 p.
[14] A.N. Smirnov, et al., Gradient Structures at Metal Cutting [in Russian]. Kemerovo: Sibirskaya izdatel'skaya gruppa, 2013. 179 p.
[15] N.A. Koneva, E.V. Kozlov, Regularities of Substructural Hardening Rus. Phys. J. 1991. V. 34. No. 3. pp. 224-236.
[16] E.V. Kozlov, N.A. Popova, N.A. Koneva, Fragmented Substructure in BCC Steels at Deformations, Izv. RAN. Seriya fizicheskaya [in Russian]. 2004. V.68. No. 10. pp. 1419-1427.
[17] L.I. Tushinskii, A.A. Bataev, L.B. Tikhomirova, Steel Structure and Strength. Novosibirsk: Nauka, 1993. 280 p.