Finding ways to improve the performance of welded joints based on controlled heat input and use of shock-mechanical treatment

Yu N Saraev1, I S Kamantsev2, A A Grigoryeva1, A V Kuznetsov2, V M Semenchuk1 and A S Nepomnyashchii1,3

1 Institute of Strength Physics and Materials Science of SB RAS, Tomsk, Russia
2 Institute of Engineering Science UB RAS, Ekaterinburg, Russia
3 National Research Tomsk Polytechnic University, Tomsk, Russia

Abstract. The paper summarizes the study’s results of welded joints fatigue failure obtained by arc welding with controlled and uncontrolled heat input and shock-mechanical treatment. Based on energy parameters of the mode fixed in welding process of samples obtained at various technologies, the experiments on determination of their fatigue life were performed. The results of numerical estimation of fatigue failure of welded joints made of 09G2S steel are presented. The positive influence of shock-mechanical treatment on test samples durability is shown.

Keywords: welding, controlled heat input, shock mechanical treatment, fatigue failure, electrode, product, microstructure.

1. Introduction
One of the most common methods for producing responsible purposes metal structures is welding. However, despite its undeniable advantages [1], this method of metalworking has disadvantages, one of which is the appearance of pronounced zones of structural heterogeneity in non-removable joints [2]. Their appearance is associated with repeated melting and subsequent crystallization of the weld metal from the melt, when the newly crystallized metal acquires a structure whose parameters differ significantly in size from the structural components of the welded metal [3, 4].

Previous studies have allowed us to determine the main reasons affecting the structure formation of zones of permanent joints [5]. The directions due to which it is possible to reduce structural heterogeneity and reduce the level of post-welding stresses by additional hardening treatment are substantiated [6]. In the present work we performed researches related to the study of features of the stages of fatigue failure, including the appearance of fatigue macro-crack, its development and failure of the test sample.

The approach for numerical estimation of fatigue fracture of welded joints is proposed. It allows to take into account both the structural heterogeneity of the joint caused by welding processes, and the influence of subsequent surface hardening treatment.

2. The work purpose
Increase the operational reliability of welded joints of metal structures for responsible purposes by using welding methods with controlled heat input and shock mechanical treatment (SMT) of zones of permanent connections.
3. Methods and techniques of the experiment

Steel 09G2S was selected as the test material. Welding was carried out using GERON UONI 13/55 electrodes with a diameter of 3 mm, UONI-13/MOROZ electrodes with a diameter of 3 mm and LB-70K electrodes with a diameter of 4 mm, as well as FEB-315 "MAGMA" equipment implementing the adaptive pulse-arc welding method [7]. The chemical composition of the used electrodes is shown in Table 1.

| Electrode brand                  | C, %  | Si, % | Mn, % | Ni, % | Mo, % | S, %  | P, %  | KCV, J/cm² | σ₀, MPa | Rel. elong. δ₅, % |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------------|---------|-----------------|
| LB-70 KRU, Russia               | 0.078 | 0.494 | 1.388 | 0.123 | 0.374 | 0.011 | 0.015 | ≤73 при -40°C | 640     | 23              |
| GERON UONI-13/55, Russia        | 0.09  | 0.42  | 0.83  | -     | -     | 0.022 | 0.024 | 260         | 540     | 29              |
| UONI-13/MOROZ, Russia           | 0.075 | 0.3   | 0.7   | 2.8   | -     | 0.010 | 0.017 | 210         | 660     | 22              |

The welding process mode is shown in Table 2, when MCW – modulated current welding process, \( U_{\text{avg}} \) and \( I_{\text{avg}} \) – average voltage and current of arc, \( I_{\text{p}} \) and \( t_{\text{p}} \) – pulse current and pulse time, \( I_{\text{b}} \) and \( t_{\text{b}} \) – break current and break time. Typical waveforms of current and arc voltage are shown in figure 1. Welding of plates was carried out in the lower position in two passes on the direct current mode (DCW) and low-frequency modulation of the energy parameters of welding process (MCW). After welding the obtained samples were subjected to shock mechanical treatment [8], carried out using a technological complex consisting of ultrasonic generator UZGT 0.5/27 and a shock tool of the "bumblebee" type. The scheme for processing the heat-affected zone (HAZ) is shown in figure 2.

| № | Welding mode | Seam layer | Electrode brand                     | \( U_{\text{avg}}, V \) | \( I_{\text{avg}}, A \) | \( I_{\text{p}}, A \) | \( I_{\text{b}}, A \) | \( t_{\text{p}}, s \) | \( t_{\text{b}}, s \) |
|---|--------------|------------|-------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 23| DCW          | seam       | UONI-13/MOROZ, Ø3                   | 25                       | 91                       | -                        | -                        | -                        | -                        |
|   |              | filling    | LB-70 K, Ø4                         | 23                       | 152                      | -                        | -                        | -                        | -                        |
| 4M| MCW          | seam       | UONI-13/55, Ø3                      | 19.5                     | 70                       | 100                      | 30                       | 0.3                      | 0.3                      |
|   |              | filling    | UONI-13/55, Ø3                      | 21                       | 88                       | 120                      | 30                       | 0.3                      | 0.3                      |

The oscillation frequency of the instrument corresponded to 27 kHz, the generator power was 800 W, and the static pressure force was 100 N. Four shocker were used. In this technology the method of transmission and transformation ultrasound energy to the processed product by means of rod shock elements (indenters) moving along the axis of the oscillatory system with small (relative to the carrier frequency of stochastic shock pulse) wave length was realized. In this type of processing, the shock tool needle marks in the form of a circle with the diameter of 1-2 mm remain on the surface and a thin overlay layer is formed.

Definition of influence of welding process modes and subsequent surface shock treatment of the near-weld zone on fatigue durability is carried out on the samples cut from the butt weld of 09G2S steel. The geometric dimensions of the samples were 6×11×60 mm. Cyclic loading was performed on a high-frequency test machine MIKROTRON (RUMUL) according to a three-point bending scheme with a loading frequency of 100 Hz. The orientation of the sample is selected from the condition of maximum tensile stresses at the boundary of the fusion zone of the weld subjected to deformation...
treatment. The natural concentrator was the near-weld zone of the welded joint. The orientation of the sample and the load application axis are schematically shown in the figure 3.

![Figure 1](image1.png)

**Figure 1.** Waveforms of the main parameters of arc current and voltage modes during DC welding (a) and with pulse changes in energy parameters (b).

![Figure 2](image2.png)

**Figure 2.** The scheme of tool application for SMT of metal.

![Figure 3](image3.png)

**Figure 3.** Scheme of sample loading during testing.

During the research, we compared the results of samples tests obtained by direct current welding and low-frequency modulation of welding process energy parameters, with and without additional processing. The loading force was calculated from the condition of creating a stress concentrator in the zone equal to 400 MPa. In order to exclude possible sample slippage on the supports, the cycle asymmetry coefficient was taken equal to R=0.1. The controlled parameters for fatigue loading were: the number of loading cycles until the appearance of the fatigue crack ($N_{cr}$) and the number of cycles until the fatigue crack reaches the specified length $l_{cr}$=5 mm ($N_{total}$). The moment of fatigue crack appearance was fixed by the beginning of loading resonance frequency change of the "sample-machine" system by the diagrams "change of loading frequency - number of cycles" recalculated in the survivability diagrams. The obtained experimental data were compared with the results of numerical modeling.

4. The results of research and their discussion

4.1. Experimental results of determining the durability of welded joints.

The most experimental studies of welded joints fatigue are performed using standard samples. However, in this case, the all complex of factors influencing resistance to failure of welded joints, including the factors defining bearing ability of joints, is not taken into account [9].
To take all factors into account when calculating durability and modeling the fracture process, it is necessary to take into account the fact that the fatigue failure process is multistage, and in general it is divided into two qualitatively different stages. Thus, at the initial stage of cyclic loading $N_{st}$ there is the accumulation of damage, leading to the initiation of a crack-like defect. This stage is structurally sensitive. At the second stage the crack is spreading in the volume of the material.

To increase fracture resistance at the first stage, SMT was applied that leads to plastic deformation which provides a favorable combination of residual stresses in relation to the level and type of applied stresses at exploitation. Experimental data on fatigue durability of welded joints are presented in table 3 as minimum and maximum number of cycles $N_{st}$ and $N_{total}$ for each series of samples.

**Table 3.** Experimental data on fatigue life of 09G2S steel welded joints.

| Series of samples | $N_{st}$ without SMT and with SMT | $N_{total}$ | Notes |
|-------------------|----------------------------------|------------|-------|
| 23 without SMT    | $3.79 \times 10^5$-$5.80 \times 10^5$ | $5.04 \times 10^5$-$8.53 \times 10^5$ | Number of cycles before crack formation 200000 (1.4 times) |
| 23 with SMT       | $7.50 \times 10^5$-$8.0 \times 10^5$ | $1.01 \times 10^5$-$1.10 \times 10^6$ | Number of cycles before crack formation 275000 (1.35 times) |
| Subtotal, Series 23 | Number of cycles before the defect formation 295000 (1.61 times) | Number of cycles before crack formation 321500 (1.44 times) | The increase of the number of cycles from defect appearance without SMT to sample failed after SMT 570000 (2.2 times) |
| 4M without SMT    | $1.50 \times 10^5$-$2.0 \times 10^5$ | $2.56 \times 10^5$-$3.16 \times 10^5$ | Number of cycles before crack formation 111000 (1.63 times) |
| 4M with SMT       | $2.2 \times 10^5$-$\infty$ | $3.3 \times 10^5$-$\infty$ | Not failed |

Comparative analysis of the samples test results shows that shock mechanical treatment significantly increases the basic number of loading cycles before a macro crack occurs. For example, the average number of cycles at which the initial defect formation occurs in samples of the 23 series is: without SMT – $4.8 \times 10^5$, and after SMT – $7.75 \times 10^5$ (the difference is 295000 cycles, or increase in 1.61 times). In this case, the total number of cycles before the main crack formation is: without SMT – $6.785 \times 10^5$, and after SMT – $10.5 \times 10^5$ (the difference is 371500 cycles, or increase in 1.55 times).

It should be noted that in addition to the heat input determined by the parameters of the mode and method of welding, the chemical composition and properties of welding materials can have a significant impact on the fracture nature. Because the electrodes of different strength classes were used in the experiment, the stability assessment of the tested samples provided for study of separate influence of the applied electrodes brands welded on direct current, both without further shock treatment and with treated surface. So, for example, at testing of 23 series samples, the class of welding electrodes corresponded to class K-60 (UONI 13/Moroz) and K70 (LB-70K). As a rule, these electrodes have complex alloyed composition, which increases their sensitivity to the thermal cycle of welding, and consequently leads to an increase in the level of residual stresses. Despite of this fact, SMT helps to remove or redistribute residual stresses in the studied samples, which increases their fatigue strength by 1.5-1.6 times.

Welding method is very important. Earlier the influence of power parameters of welding modes on structure of received joints was established [10]. The microstructures of the samples obtained by DCW and MCW are different (figure 4). The dendrite-like structure of 23 series sample (DCW) contains larger grains compared to the microstructural elements of 4M series sample (MCW). The sizes of
dendrite-like grains in the second case are smaller, which confirms the previously established effect of structure refining as a result of pulse changes in the energy parameters of the welding mode. For example, the 4M series of samples is welded using low-frequency modulation of the energy parameters of the mode. At the same time, despite the fact that the samples are welded with electrodes of a lower strength class, but due to the controlled heat input from the moment of the defect birth to the moment of the main crack formation, the total number of cycles is 111000 (increases by 1.63 times, or by 63%). In comparison with 23 series samples such increase exceeds the enhancing effect from application of SMT by 23-28%. In addition, the 4M series samples application remained undestroyed after SMT that confirms a significant increase of their service life under fatigue loading conditions.

Figure 4. The microstructures of weld obtained by DCW (1) and MCW (2).

4.2. Numerical estimation of welded joints fatigue failure.

An important direction in the evaluation of fracture resistance of welded joints is modeling of material behavior and calculation of durability of welded joints. In this work we consider an approach to calculating of fatigue crack propagation kinetics in the welded joint and compare the results of numerical modeling and experimental results on the example of butt welds with additional surface hardening treatment.

When describing the processes leading to failure, there are difficulties associated with the existence of the preliminary – Incubation stage, which may not be accompanied by changes in any parameters registered by non-destructive testing. Besides, for elements of constructions with welded joints it is necessary to take into account the influence of heterogeneity of macro- and microstructure of a material and presence of defects.

The necessity to evaluate the residual life of structures by the criterion of crack initiation at complex parameters of loading requires the introduction of the concept of damage. This term reflects the development of certain physical processes leading to gradual formation of different types microdefects in the material. The quantitative definition of damage is based on phenomenological models that give an integral assessment of the material state. These models relate the evolution of the damage parameter with changes in other parameters of the system mechanical state. As the damage accumulates, the moment approaches when the value reaches a certain limit which is associated with the macro-crack appearance [11].

At the same time, in the method of calculating the residual life of welded joints must take into account the elements of the plasticity theory, fracture mechanic and damage mechanic. At the same time, most variants of plasticity theory are developed for materials with a single-phase structure. The real materials are multi-phase, while speaking about welded joints it should be noted that they are also structurally heterogeneous, both on micro and macro levels. For this class of materials, properties at each point of the selected volume are the same only within a certain zone. In the plasticity theory of
structurally heterogeneous materials, considering the material as a composite, take into account the properties of individual phases obtained for example in the process of heat treatment; while the volume content of the phases and their properties do not change in the deformation process, and the properties of the deformed material is determined by the amount of the allocated phase. However, it is not possible to draw a complete analogy with the micro-heterogeneous weld, because the operational loading of welds should be considered not only as an integral characteristic of the heterogeneity influence, but in addition to this it is necessary to take into account the influence of the borders of heterogeneous components. In a welded joint, the processes of damage accumulation should be considered separately for each volume element, as competing with each other or complementing each other. In this case, macro-failure can be achieved in any of the elements depending on the type and level of the applied external action.

The process of resource exhaustion can be considered as a process of successive accumulation of scattered micro-damage in each material particle of the loaded part. The proposed approach is based on experimental data showing that the process of damage development is universal in a certain sense and does not depend on the type of loading [12]. The observed commonality of fracture patterns at different types of loading is determined by the physical nature of materials and processes occurring in them during loading (1). The analysis of experimental dependence of accumulated inelastic deformation before fracture during multi-cycle loading on its thermomechanical parameters shows that it is qualitatively similar to the dependence nature of accumulated metal deformation before fracture or plasticity, which is observed in the developed plastic flow, on the same thermomechanical parameters. The value of accumulated inelastic deformation before failure, as well as plasticity of the metal, turns out to be a structurally sensitive characteristic and acts as some property of the material, that is determined by its chemical composition and structure. At the same time, it is a function of the state and depends on the type and scheme of the stressed state of the metal, strain rate (loading frequency) and temperature.

\[ \sigma^\alpha N = \sigma^\alpha_{RK} N_0 \]  

where \(\alpha\) – the degree index characterizing the properties of the material; \(\sigma\) – the current stress; \(\sigma_{RK}\) – the given stress when the stress state changes, \(N_0\) – the current number of cycles; \(N\) – the number of cycles according to the Weller diagram.

Taking into account the above, the general approach for description of processes of damages accumulation and failure in welded joint is applicable. Let us assume that the material of the part in each individual section is isotropic and the type of damage (micro-cracks) does not change during loading. Let's consider fatigue failure as a process of successive accumulation of scattered micro-damage in each material particle of a deformed part. The material damage is estimated by the scalar parameter, the value of which changes from 0 (initial state) to 1 (formation of a macro crack). Let's break the trajectory of motion of the particle in question into sections of the so-called monotone deformation, where the values of all components of the moving particle deformation rate tensor does not change the sign. Then on each section the damage is determined by the kinetic equation, while the function including in the equation and characterizing the intensity of damage increase is determined from experiments and depends on the scheme and type of stress state, thermomechanical parameters of the loading process and the nature of the material (2).

\[ S_d(\sigma_M, n) = S_{B0} - k_s n^m, \]  

where \( k_s = \frac{S_{M1} - \sigma_M}{N^\alpha}, \)  

is a generalization of the strength criterion of single loading on cyclic one, and \(S_{B0}\) – the damage in the initial state of the material, \(N\) – the durability according to Weller's diagram, \(\sigma_M\) – the average stress for each mode in the investigated point; \(m\) – the degree parameter determined empirically.

The total damage of a particle in all areas of monotonic deformation during cyclic loading will consist of the sum of damages in degree \(\alpha\) at each area. In this case, the degree \(\alpha\) is also a function of
the type of stress state, and is the determining ratio of the problem, and its value can be determined from the data of the multi-cycle fatigue test (4).

\[ \alpha = \frac{3.3}{\log \sigma - \log \sigma_{\text{ss}}}, \]  

(4)

where \( \sigma_{\text{ss}} = \frac{2\sigma_{j}}{(1-R)K - (1+R)\psi}, \)  

(5)

\( R \) – the cycle asymmetry coefficient, \( \sigma_{j} \) – the endurance limit; \( K \) – kinetic coefficient.

The numerical modeling of the fatigue crack growth kinetic in a sample with a concentrator in the form of a welded joint was carried out at the first step by the finite element method. The size of elements was chosen so that the step of fatigue crack discrete growth was not more than 0.2 mm. This is due to the size of the localized plastic deformation zone at the apex of the crack, where there is degradation of material properties and failure of the elemental volume of material. The main criterion was the average value of stresses on the normal to the surface of the sample where the initial fatigue crack depth of 5 mm is formed, that is the main calculation zone (crack length from the experiment). The criterion of elementary volume failure and subsequent growth of the fatigue crack was the achievement of strength limit of the average stress value (6).

\[ \sigma_{M} = \sigma_{M}, \]  

(6)

Then the change in the sample geometry was made by excluding the failed volume equal to the element line. The next steps were performed in the same way taking into account the exhaustion of strength in each subsequent volume accumulated at previous loading stages. Since the structure of the material has a random character, the calculation was carried out in the range limited by degree coefficient \( \alpha \). Double bending in the diagrams arises as a result of sample volume discretization on elements and as a consequence the resulting boundary effect (figures 5 and 6) [13].

To calculate the case of a sample without a hardened surface, the material properties were the same for the entire length of fatigue crack propagation. The criterion for passing a crack of a sample section 0.2 mm long was considered to be the achievement of the average stress value in the cross-section of the strength limit value. In fact, in this case we calculated damage accumulation for each subsequent section along the path of fatigue crack propagation taking into account the values of accumulated damage at previous loading stages. For the calculation of a sample with a hardened surface, it was assumed that the depth of the hardened layer is 0.8 mm. For the first three layers of the hardened layer it was assumed that in these layers the values of internal compressive stresses were 200 MPa. For the last hardened layer, the internal compressive stresses were 120 MPa, for the first non-hardened layer the compressive stresses were assumed to be 30 MPa, and for the second layer 15 MPa. The rest of the material was considered the initial one.

The results of numerical modeling in comparison with experimental data are presented in figures 5 and 6.

The experimental data demonstrate high survivability of welded joints. Thus, the calculated data show the minimum number of cycles before the main crack formation and its subsequent distribution in the material taking into account the external hardened layer in case of surface plastic deformation (SPD) and presence of residual stresses from the welded joint. That is, the results of numerical modeling are performed from the condition of the upper estimate.
5. Conclusion

As a result of the performed experimental studies and numerical modeling the fields of possible kinetics of fatigue crack growth were obtained.

When comparing the test results of the samples with and without treatment of the near-weld zone it was established:

1. The presence of a hardened layer leads to a decrease in the growth rate of the crack and a significant increase in the incubation period preceding its origin and beginning of its propagation.

2. To increase the failure resistance it is advisable to use SMT, which leads to plastic deformation, providing creation of favorable combination of residual stresses in relation to the level and type of applied stresses at operation. SMT contributes to the removal or redistribution of residual stresses in the investigated samples, that increase their fatigue strength by 1.5-1.6 times.

3. It is experimentally confirmed that the previously established effect of epy relationship of energy parameters of welding modes with the structure of the resulting compounds is amplified in case of additional shock mechanical treatment. Thus the samples with higher structural homogeneity, received with application of MCW and additional SMT, have higher
values of crack resistance on 23-28 % in comparison with the samples welded on direct current without SMT.

4. The obtained results correlate with the experimental data obtained earlier, what indicates the possibility of using numerical analysis approaches in durability estimation and calculation of accumulated damage of the near-weld zones of welded joints.

6. References
[1] Volchenko V N, Yampolsky V M, Vinokurov V A and Frolov V V 1988 Theory of Welding Processes: Textbook for Universities on Spec. "Equipment and Technology of Welding Production" (Moscow: Higher school) p 559
[2] Saraev Yu N, Bezborodov V P, Perovskaya M V and Semenchuk V M 2019 Proc. Int. Conf. on Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures (Published by AIP Publishing) https://doi.org/10.1063/1.5132173
[3] Saraev Y N, Bezborodov V P, Gladkovskiy S V and Golikov N I 2017 Improving the reliability of metallic structures in service in the conditions with low climatic temperatures by efficient application of advanced methods of modification of the zone of the welded joint Weld. Int. 31 pp 631–6
[4] Saraev Yu N, Bezborodov V P, Grigorieva A A, Golikov N I, Dmitriev V V and Sannikov I I 2015 Distribution of residual stresses in welded joints in 09G2S steel produced by adaptive pulsed-arc welding Weld. Int. 29 pp 131–4
[5] Saraev Yu N, Gladkovskiy S V and others 2017 High-Tech Technologies in the Projects of RSF. Siberia, ed S G Psakhie and J P Sharkeev (Tomsk: NTL Publishing house) pp 134–202
[6] Panin V E, Klimenov V A, Bezborodov V A et al 1993 Substructure and phase transformations at the ultrasonic shock treatment of martensitic steel Phys. and Chem. of Mat. Proc. 6 pp 77–83
[7] Saraev Yu N Priority from June 16, 2008 The Method of Adaptive Pulse Arc Welding The patent for the invention № 2410216 (Russia)
[8] Panin V E 2006 Influence of the ultrasonic shock treatment on the structure and fatigue resistance of the welded joints of high-strength steel VKS-12 Phys. Mesomech. 2 pp 85–96
[9] Trufyakov VI 1973 Fatigue of Welded Joints (Kiev: Naukova Dumka) p 215
[10] Saraev Yu N, Gladkovskiy S V, Lepikhin S V, Kamantsev I S, Lunev A G and Perovskaya M V 2018 Research of influence of the energy parameters of the arc welding modes by the covered electrodes and the control algorithms of their change on characteristics of the impact toughness and crack resistance of the obtained welded joints Metal Proc. (technology, equipment, tools) 2 pp 100–15
[11] Kolmogorov V L, Burdukovskiy V G and Kamantsev I S 2009 Damage prediction at the multicycle loading Factory laboratory. Diagnostics of Materials 5 pp 45–7
[12] Kolmogorov V L 2001 Mechanics of Metal Working by Pressure. Textbook for high schools. 2nd ed. (Ekaterinburg: USTU-UPI) p 836
[13] Mironov V I 2014 Consideration of the cyclic degradation of material and the anomaly of mechanical properties of the surface layer in the calculation of survivability of plate with a hole Prob. of Strength 5 pp 69–75

7. Acknowledgments
The research is supported by RSF grant No. 16-19-10010-II.