VII International Congress on Energy Fluxes and Radiation Effects
(EFRE 2020) September 20 - 26, 2020, Tomsk, Russia

4th International Conference on New Materials and High Technologies (4th NMHT).

# Mechanical Properties of Welding Joints of High-Strength Steel under Dynamic Loading


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# Outline

- Motivation of research.
- Macro- and microstructure characterization in the welding joints zone of high-strength steel.

  The results of experimental studies on damage and fracture of titanium alloys under dynamic loading.
- Results on numerical simulation of mechanical properties of welding joints of high-strength steel under dynamic loading.
- Conclusions

# Motivation of researches

Modern technologies for the production of critical steel structures of pipeline systems, machines, and large industrial and public buildings, bridges are widely used welded joints of elements made of high-strength steels.

To assess the strength of these structures under shock and explosive impacts, which may be the result of terrorist attacks and accidental explosions, numerical modeling techniques are considered that take into account the microstructure of welded joints and welding technology.

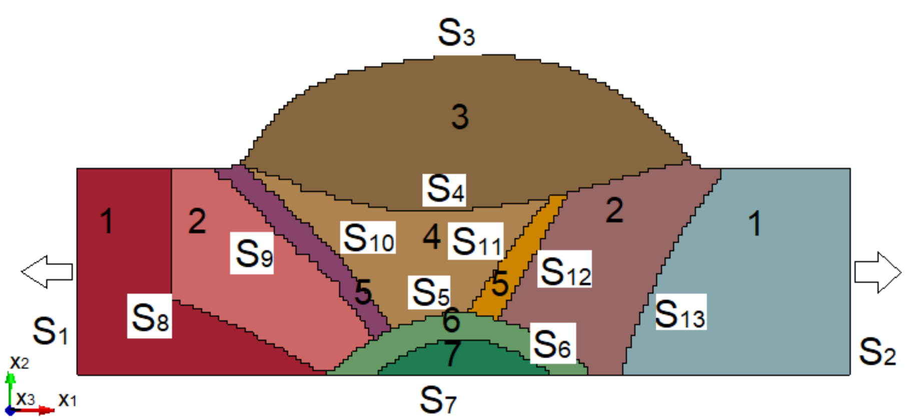
Hea et al. (IOP Conf. Series: Mater. Sci. and Eng., vol. 677, pp. 022020, December 2019.) showed that the strength of welded joints of high-strength steel structures is determined by damage to the welds and the zone of their thermal influence at a high strain rate of explosive loads.

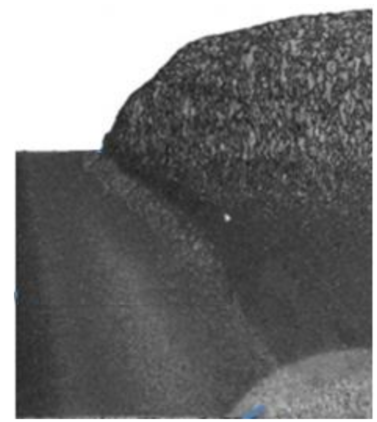
The peculiarity of the prediction of the dynamic strength of welded joints of steel structures is due to the fact that the material of the welded joint is more sensitive to the strain rate compared to welded steels. As a rule, the yield strength of the weld material at high strain rates increases significantly compared with the static case.

- The need of using the fracture criterion of welded joints, taking into account the relationship between critical plastic strain and the stress triaxiality for individual welding zones was substantiated experimentally by Paveebunvipak et al. (Materials & Design, vol.160, pp. 731-751, December 2018.)
- The mechanical heterogeneity of the microstructure can lead to a significant localization of deformations in the welding zone under dynamic loads.
- As a result of plastic deformation of the welded joint, cracks can nucleate and propagate in it.
- The aim of this work is to study the dynamics of fracture and deformation at high strain rates of welded joints of thick-walled steel panels using a model that takes into account the inhomogeneous structure in the welding zone and changes the mechanical properties at the mesoscale level.

# Macro- and microstructure characterization

The deformation and fracture of a welded joint of 6 mm thick plates of 09G2S steel, created by pulsed $CO_2$ arc welding, were studied under tension under conditions of quasi-static and dynamic loading.



Base material is marked as 1.
Region 2 corresponds to the heat affected zone (HAZ).
Microstructures of 3, 4, 7 regions of welded zone depend on the chemical composition of the electrode material.
For silicon-manganese steel (09G2S), these regions have quenching structures.
The region 5 is a fusion zone of the base material and the electrode material.

Figure - Scheme of boundary conditions of a loaded welded joint of steel plates

# Numerical simulation of strain and fracture of welding joints of high strength steel

## Modelling and material parameters

Computational model was established by LS-DYNA software to simulate the deformation and crushing behavior of welding joints of high strength steel.

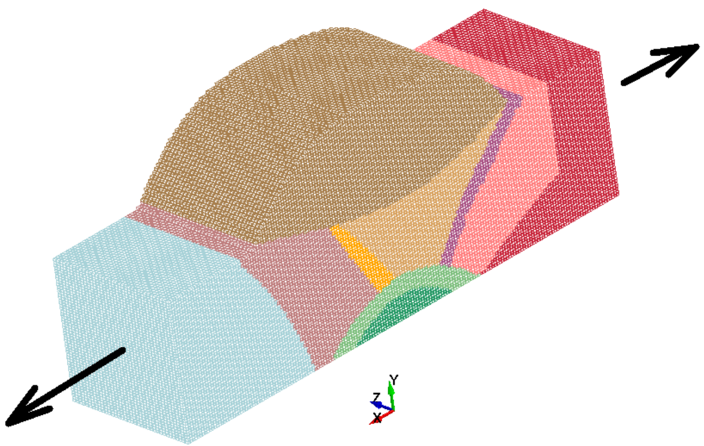


Figure. Cell model of  structured welded joint.

The computational model uses the theoretical basis of continuum damage mechanics.

The system of equations includes:

Conservation equations ,

Kinematic relations,

Constitutive relations,

Relaxation equation for the deviatoric stress tensor.

Equations of damage evolution and fracture criterion.

$$\frac{d\rho}{dt} = \rho\frac{\partial u_i}{\partial x_i}, \quad \frac{\partial \sigma_{ij}}{\partial x_j} = \rho\frac{du_i}{dt}, \quad \rho\frac{dE}{dt} = \sigma_{ij}\dot{\varepsilon}_{ij}$$

$$\dot{\varepsilon}_{ij} = (1/2)[\partial u_i / \partial x_j + \partial u_j / \partial x_i)\ , \ \dot{\omega}_{ij} = (1/2)[\partial u_i / \partial x_j - \partial u_j / \partial x_i)$$

$$\sigma_{ij} = \sigma_{ij}{}^{(m)}\varphi(f), \ \sigma_{ij}^{(m)} = -p^{(m)}\delta_{ij} + S_{ij}{}^{(m)}$$

$$p^{(m)} = p_x^{(m)}(\rho) + \Gamma(\rho)\rho E_T, \ E_T = C_p T,$$

$$p_x{}^{(m)} = \frac{3}{2}B_0 \cdot ((\rho_0/\rho)^{-7/3} - (\rho_0/\rho)^{-5/3})[1 - \frac{3}{4}(4 - B_1)\cdot((\rho_0/\rho)^{-2/3} - 1)]$$

$$DS_{ij}^{(m)} / Dt = 2\mu(\dot{\varepsilon}_{ij}^{e} - \delta_{ij}\dot{\varepsilon}_{kk}^{e} / 3\ )\ ,$$

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p}\ , \ \dot{\varepsilon}_{ij}^{p} = \dot{e}_{ij}^{p} + \delta_{ij}\dot{\varepsilon}_{kk}^{p} / 3, \ \dot{e}_{ij}^{p} = \lambda\partial\Phi / \partial\sigma_{ij}, \quad \dot{\varepsilon}_{kk}^{p} = \dot{f}_{growth} / (1 - f)$$

The GISSMO model was used for damage and fracture analysis of silicon-manganese steel under tension. The yield criterion has a form:

$$\sigma_s = \sigma_s^{(m)} [1 - (\frac{D - D_c}{1 - D_c})^F],$$

where $\sigma_s$ is the yield stress of damaged medium, $\sigma_s^{(m)}$ is the yield stress of condensed phase of material, $D$ is the damage parameter, $D_c$ is the critical values of damage, $F$ is the fading exponent.

$$D = (\varepsilon_{eq}^p / \varepsilon_f)^q$$

where $\varepsilon_f$ , $q$ are constants of material.

The final stage in ductile fracture comprises in the damage coalescence into the fracture zone.

This causes softening of the material and accelerated growth of the damage parameter $D$ until the local fracture of the material particle.

The model of ductile fracture requires values of 4 parameters.

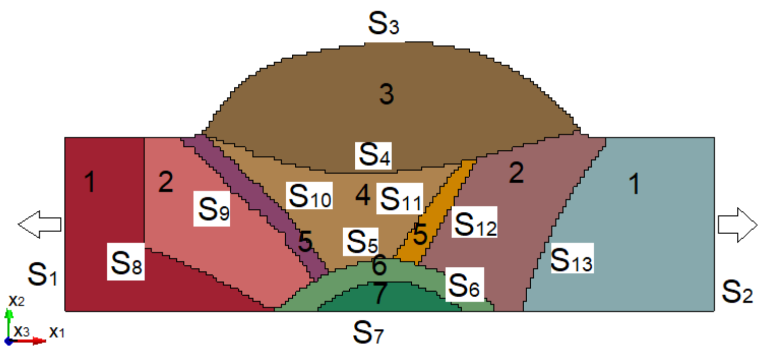
The model parameters for silicon-manganese steel were determined by numerical simulation of experiments on the tensile samples in the velocity range from 20 to 200 m/s.

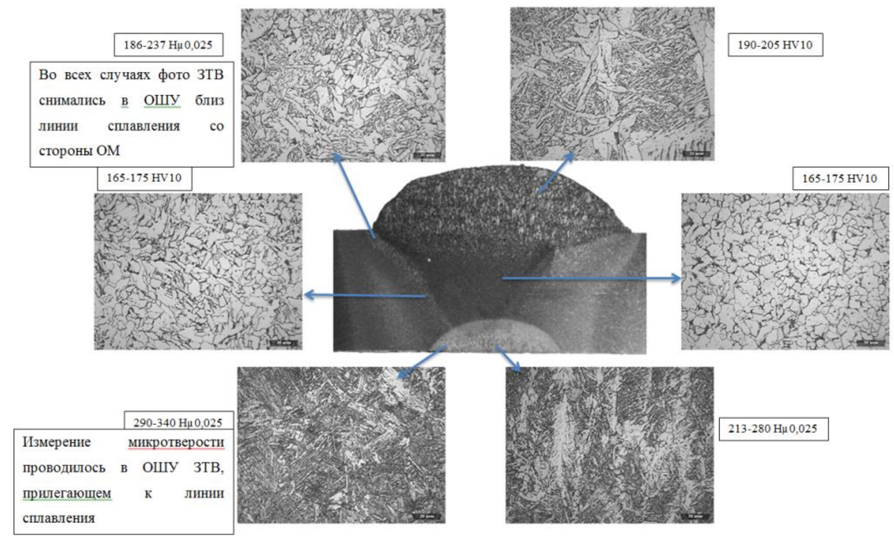
Plastic flow was described within the Prandtl–Reuss theory with the Von Mises criterion. The flow stress of silicon-manganese steel under loading has been described using a modification of the Zerilli–Armstrong model :

$$\sigma_s^{(m)}(\varepsilon_{eq}^p, \dot{\varepsilon}_{eq}, \mathrm{T}) = \mathrm{C}_0 + \mathrm{k}_h \mathrm{d}_\mathrm{g}^{-1/2} + [\mu(\mathrm{T}) / \mu(295\,\mathrm{K})] \times$$
$$\times \{\mathrm{C}_5 + (\varepsilon_{eq}^p)^{0.5} C_2 \, exp[(-C_3 + C_4 \, ln(\dot{\varepsilon}_{eq} / \dot{\varepsilon}_0))T]\},$$

where $\varepsilon_{eq}^p = [(2/3)\varepsilon_{ij}^p \varepsilon_{ij}^p]^{1/2}$ , $\dot{\varepsilon}_{eq} = [(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}]^{1/2}$ ,

$\dot{\varepsilon}_0 = 1.0\,s^{-1}$, $C_0$, $C_2$, $C_3$, $C_4$, $C_5$, n are the material constants, T is the absolute temperature, $k_h$ = 660 MPa μm$^{1/2}$ is the coefficient of the Hall-Petch relation, $d_g$ is the grain size.
Constants of the Zerilli-Armstrong constitutive equation for 09G2S silicon-manganese steel are $C_5$=0 GPa. Constants $C_2$ , $C_3$, $C_4$, and $C_0 + k_h d_g^{-1/2}$ are shown in Table .

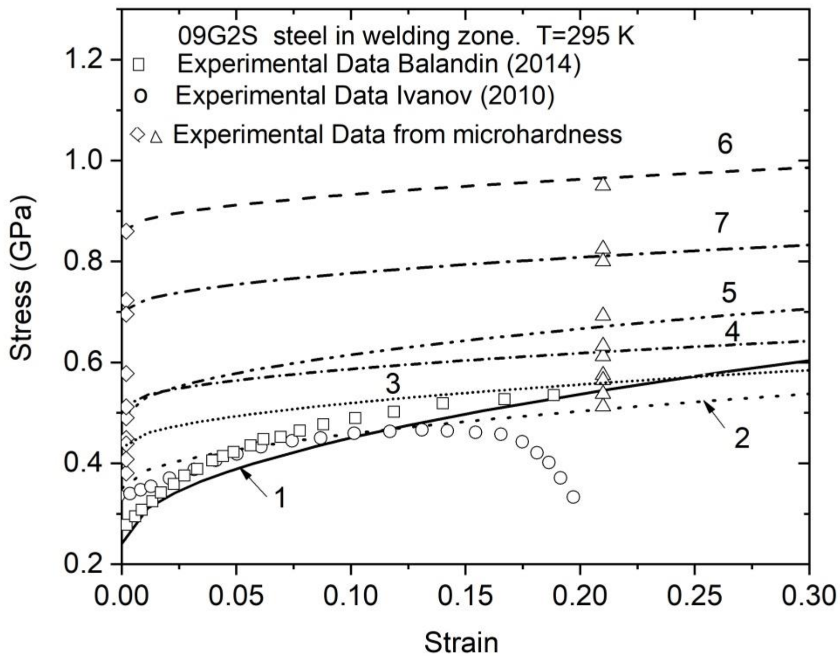


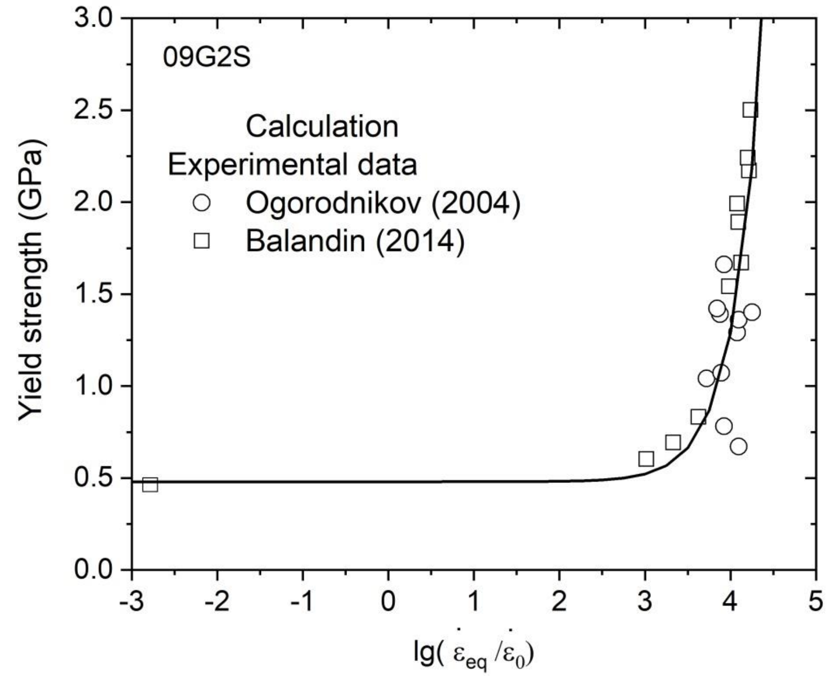

$$\sigma_s^{(m)}(\varepsilon_{eq}^p, \dot{\varepsilon}_{eq}, T) = C_0 + k_h d_g^{-1/2} + [\mu(T)/\mu(295\,K)] \times$$
$$\times \{C_5 + (\varepsilon_{eq}^p)^{0.5}\, C_2 \exp[(-C_3 + C_4 \ln(\dot{\varepsilon}_{eq}/\dot{\varepsilon}_0))T]\},$$

Table . Constants of model for regions of welded zone.

| Constants | $C_0+k_h d_g^{-1/2}$, GPa | $C_2$, GPa | $C_3$, $K^{-1}$ | $C_4$, $K^{-1}$ |
|---|---|---|---|---|
| region 1 | 0.275 | 1.05 | 0.0018 | 0.00028 |
| region 2 | 0.35 | 0.62 | 0.0018 | 0.00028 |
| region 3 | 0.48 | 0.47 | 0.00162 | 0.000252 |
| region 4 | 0.35 | 0.62 | 0.0018 | 0.00028 |
| region 5 | 0.57 | 0.38 | 0.00162 | 0.000252 |
| region 6 | 0.86 | 0.23 | 0.00162 | 0.000252 |
| region 7 | 0.7 | 0.28 | 0.00162 | 0.000252 |




Stress-strain curves for regions in the weld zone of 09G2S steel.




The dependence of the flow stress on the logarithm of the normalized strain rate.

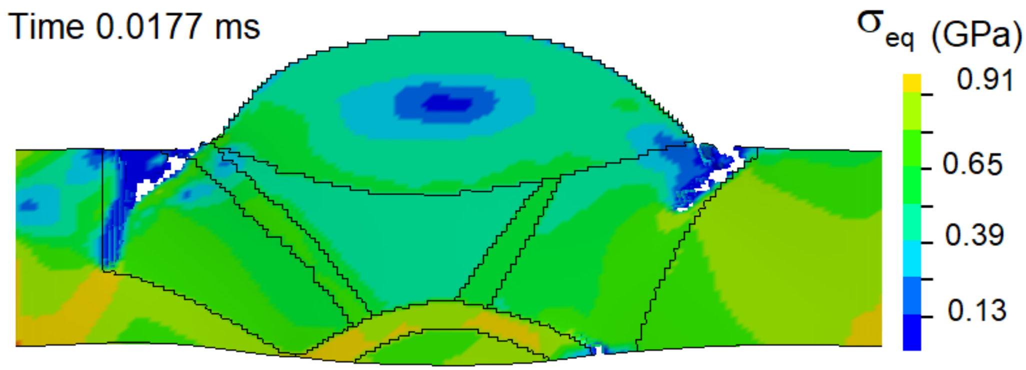



Figure. Equivalent stress in welded joint steel plates under tension at 200 m/s.

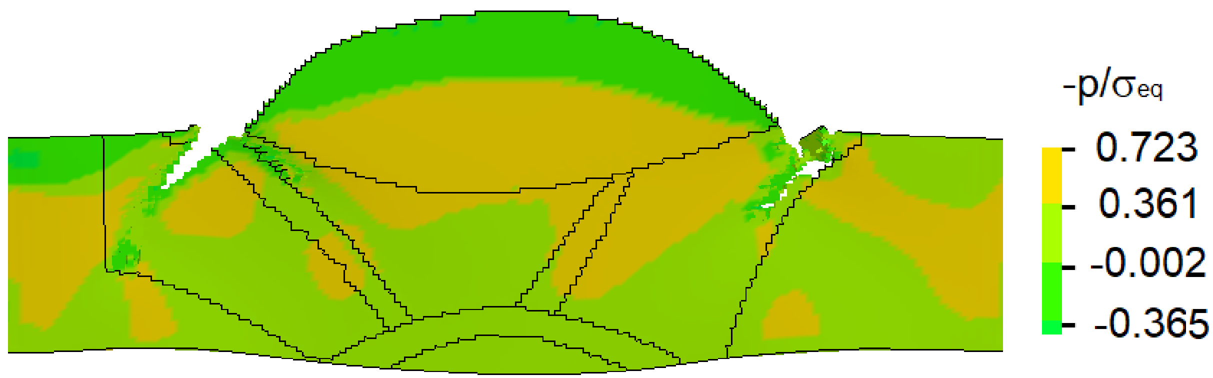



Figure. The stress triaxiality factor in a damaged welded joint steel plates under tension at 200 m/s.

The heterogeneity of the field of equivalent stresses and the parameter of the stress triaxiality factor causes the localization of plastic deformation near the weld boundary. The heterogeneity of the field of equivalent stresses and the stress triaxiality parameter causes the localization of plastic deformation near the weld boundary.

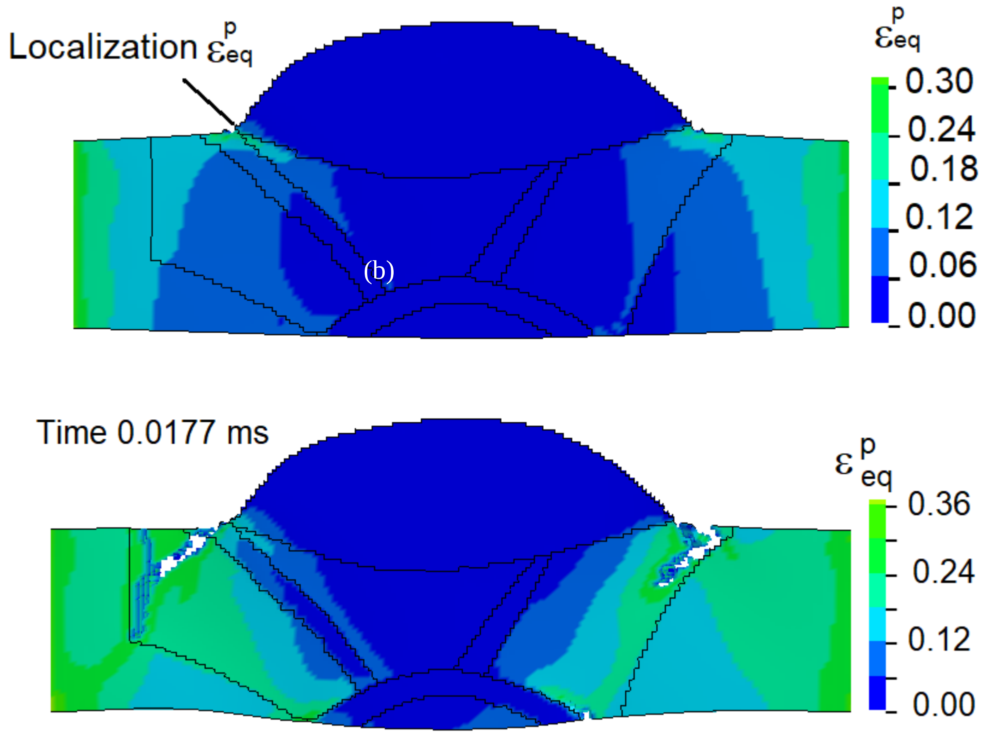



Figure. Equivalent plastic deformation in the weld zone under tension at a velocity of 200 m/s.

Figure shows the distribution of damage parameter in the welding zone of steel plates under tension at high velocity.

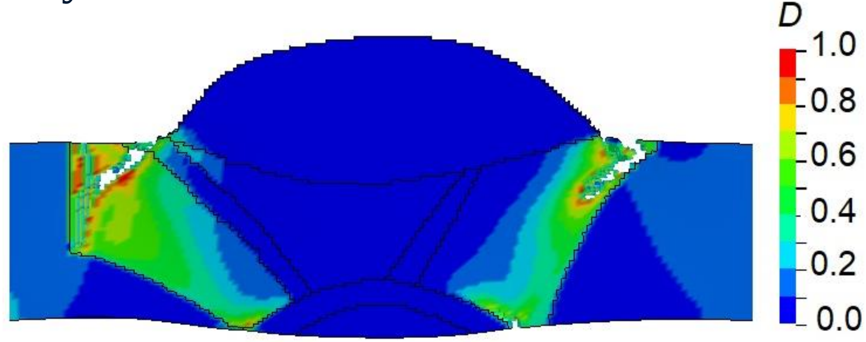



Figure. Damage and crack formation of welded joint 09G2S steel plates under tension at the velocity of 200 m/s.

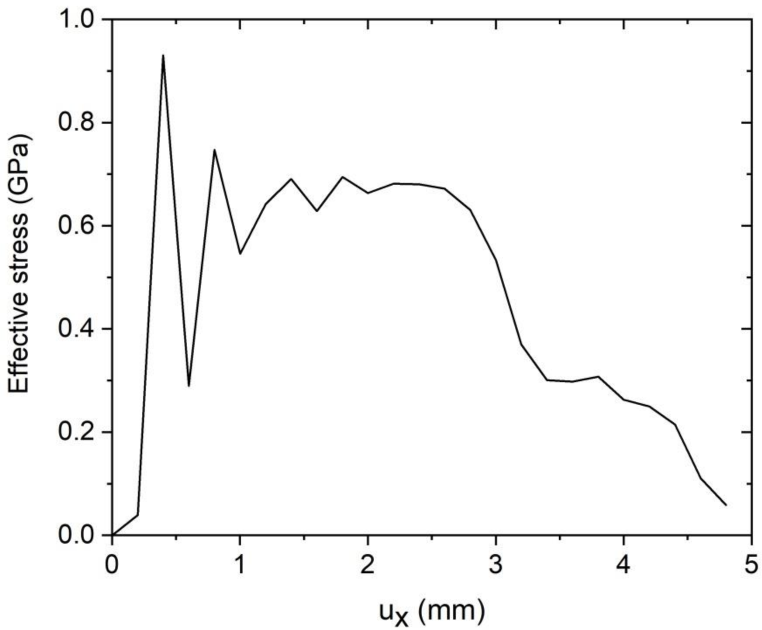



Figure. Effective tensile stress in the welded joint of 09G2S steel plates at a strain rate of ~ 9.09 $10^3$ $s^{-1}$

Damage kinetics in silicon-manganese steel is connected with macroscale plastic instability. This paper presents the experimental and theoretical results that demonstrate the importance of an adequate description of the processes of instability of deformation in silicon-manganese steel.

# CONCLUSIONS

- A physical and mathematical model is presented for predicting the mechanical behavior of welded joints of steels under dynamic loads, taking into account the change in the properties of the material in the welding zone.

- The strains to fracture of the weld zones of silicon-manganese steel showed significantly larger scatter range than those of ferritic steel.

- The fracture of welded joins at high strain rates depends on relationships between critical plastic strains and stress triaxiality for the individual weld zones.

**ACKNOWLEDGMENT**

This work was supported by the Russian Science Foundation (RSF), grant No. 16-19-10010П. The authors are grateful for the support of this research.

Thank you for attention.